

Material Recovery and Waste Form Development Strategic Plan



Material Recovery and
Waste Form Development



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CONTENTS

ACRONYMS	VII
1.0 INTRODUCTION	1
2.0 BACKGROUND TO USED NUCLEAR FUEL MATERIAL RECOVERY AND WASTE FORM DEVELOPMENT	4
2.1 The Nuclear Fuel Cycle	4
2.2 Aqueous-Based Reprocessing of UNF	6
2.3 Electrochemical-Based Reprocessing of UNF	7
2.4 Fluoride Volatility-based Reprocessing of UNF	8
3.0 THE MRWFD MISSION AND STRATEGIC OBJECTIVES	9
3.1 The MRWFD Mission	9
3.2 MRWFD Strategic Objectives	10
3.2.1 Optimize Use of Fissile Resources for Power Generation	10
3.2.2 Minimize Required Geological and Near-Surface Repository Capacity	10
3.2.3 Minimize Proliferation Risk	11
3.2.4 Support Reduction of Environmental Emissions of Radioactive and Hazardous Materials to Zero	11
4.0 MRWFD TECHNOLOGY MATURATION STRATEGY	14
4.1 Technology Scaling Strategy	16
4.2 Technology Feed Material Strategy	16
4.3 Use of Artificial Intelligence and Machine Learning	17
5.0 MRWFD INTERFACES	18
5.1 Other DOE NE-4 Programs	19
5.1.1 EBR-II Driver Fuel Processing	19
5.1.2 Materials Protection Accounting and Control Technologies Campaign	19
5.1.3 DOE NE-42 Systems Analysis and Integration Campaign	19
5.1.4 DOE NE-42 Advanced Fuels Campaign	19
5.1.5 Implementation	20
5.2 Other DOE Offices and DOE Agencies	20
5.2.1 DOE NE-5 Nuclear Reactors	20
5.2.2 DOE NE-8 Spent Fuel and High Level Waste Disposition	20
5.2.3 Advanced Research Projects Agency – Energy	20
5.2.4 National Nuclear Security Administration	21
5.2.5 Implementation	22
5.3 Universities	22
5.3.1 Implementation	23
5.4 Industry	23





5.4.1	Implementation	23
5.5	International Programs	23
5.5.1	United Kingdom	23
5.5.2	France	24
5.5.3	Japan	24
5.5.4	International Atomic Energy Agency	24
5.5.5	Organization for Economic Cooperation and Development – Nuclear Energy Agency	25
6.0	ORGANIZATIONAL PRINCIPLES	27
6.1	Organizational Breakdown	27
6.2	Organizational Dynamics.....	27
6.3	Campaign Organization Structure	28
6.4	Roles and Responsibilities	29
6.4.1	National Technical Director	29
6.4.2	Deputy National Technical Director	30
6.4.3	Control Account Managers	30
6.4.4	Work Package Managers	31
7.0	MRWFD TECHNICAL PRIORITY AREAS	32
7.1	Electrochemical Processes and Innovative Salt Systems	34
7.1.1	Priority Area 1 – Bridging Technical Gaps	35
7.1.2	Priority Area 2 – Maintaining Leadership Through Process Optimization.....	35
7.1.3	Priority Area 3 – Championing New Electrochemical Technologies	35
7.1.4	Priority Area 4 – Cultivating Cross-Cutting Technologies.....	35
7.2	Advanced and Innovative Aqueous Processes.....	32
7.2.1	Priority Area 1 – Demonstrate Advanced Voloxidation	32
7.2.2	Priority Area 2 – Mature Uranium Recovery in the Direct Extraction Process.....	32
7.2.3	Priority Area 3 – Mature U/TRU Recovery in the Direct Extraction Process.....	33
7.2.4	Priority Area 4 – Np and Tc Selective Ligands for Direct Extraction	33
7.2.5	Priority Area 5 – Direct Extraction Modeling	33
7.2.6	Priority Area 6 – Fluoride Volatility	34
7.3	Off-Gas and Waste Forms.....	35
7.3.1	Priority Area 1 – Establishing Options for Salt Waste Forms	36
7.3.2	Priority Area 2 – Developing Options for Iodine and Noble Gas Management.....	36
7.4	Chemical Decladding.....	37
7.4.1	Priority Area 1 – Establish Sulfur Monochloride (S ₂ Cl ₂) Process Technologies	37





7.4.2	Priority Area 2 – Demonstrate S_2Cl_2 for Decladding Aluminum Fuel	37
7.4.3	Priority Area 3 – Demonstrate S_2Cl_2 for Decladding Zirconium Fuel.....	37
7.4.4	Priority Area 4 – Demonstrate UAlx Processes Compatible with the Fuel Cycle Facility	38
8.0	MRWFD CAMPAIGN RISKS AND OPPORTUNITIES	39
8.1	Funding and Budget Risks	39
8.2	Facility and Infrastructure Risks	39
8.3	Workforce and Talent Risks	40
8.4	Regulatory and Licensing Risks	40
8.5	Industry and Commercial Landscape Risks.....	41
8.6	Geopolitical and Policy Risks	41
8.7	Supply Chain and Materials Risks.....	41
8.8	Commercial and Political Opportunities	42
9.0	CONCLUDING REMARKS	43
10.0	REFERENCES	45
	APPENDIX A: TECHNOLOGY READINESS LEVEL CRITERIA	47
	APPENDIX B: GUIDANCE FOR DEVELOPMENT AND EXECUTION OF WORK PACKAGES.....	53

FIGURES

Figure 1.	The Nuclear Fuel Cycle	5
Figure 2.	Evolution of Aqueous Reprocessing Technologies	6
Figure 3.	Summary Flow Diagram of Aqueous Reprocessing Approaches	7
Figure 4.	Summary Level Flow Diagram of Electrochemical Reprocessing Approaches	8
Figure 5.	Improved Repository Use from Reprocessing	11
Figure 6.	MRWFD Interfaces	18
Figure 7.	MRWFD Campaign Organizational Principles	28
Figure 8.	MRWFD Campaign Organization	29

TABLES

Table 1.	Characteristics of Fuel Cycles	5
Table 2.	Comparison of Past and Future Emissions from Reprocessing Plants	12
Table 3.	Summary Definition of Each TRL	15





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ACRONYMS

AFC	Advanced Fuels Campaign
AI	artificial intelligence
ARPA-E	Advanced Research Projects Agency – Energy
ATR	Advanced Test Reactor
CAM	control account manager
CD	Critical Decision
CRP	coordinated research project
CUI	controlled unclassified information
CURIE	Converting UNF Radioisotopes Into Energy
DEHiBA	N,N-di(2-ethylhexyl)-2-methylpropanamide
EBR-II	Experimental Breeder Reactor-II
FCT	Fuel Cycle Technologies
INL	Idaho National Laboratory
GAIN	Gateway for Accelerated Innovation in Nuclear
GBS-CWF	glass-bonded sodalite ceramic waste form
HALEU	high-assay low-enriched uranium
IAEA	International Atomic Energy Agency
LWR	light water reactor
MC&A	material control and accounting
ML	machine learning
MOPPA	mono-(1,1,3,3-tetramethylbutyl)phenyl phosphoric acid
MPACT	Materials Protection Accounting and Control Technologies
MRWFD	Material Recovery and Waste Form Development
MSR	molten salt reactor
NEUP	Nuclear Energy University Program
NNSA	National Nuclear Security Administration
NOFO	notice of funding opportunity
NRC	Nuclear Regulatory Commission





NTD	national technical director
OECD-NEA	Organization for Economic Cooperation and Development – Nuclear Energy Agency
ONWARDS	Optimizing Nuclear Waste and Advanced Reactor Disposal Systems
PICS:NE	Program Information Collection System for the Office of Nuclear Energy
PUREX	Plutonium Uranium Extraction
QRL	quality rigor level
R&D	research and development
RD&D	research, development, and demonstration
REDOX	REDuction-OXidation
SF&HLWD	Used Fuel and High Level Waste Disposition
SNF	spent nuclear fuel
THORP	Thermal Oxide Reprocessing Plant
TRL	Technical Readiness Level
TRU	transuranics
UNF	used nuclear fuel
WP	work package
WPM	work package manager





1.0 INTRODUCTION

The U.S. Department of Energy's Office of Nuclear Energy (DOE-NE) is responsible for advancing nuclear science and technology to meet the nation's energy, environmental, and economic needs. Within this structure, NE-4 is the nuclear fuel cycle innovation and research arm, focusing on early-stage and crosscutting research, development, and demonstration (RD&D) that underpins future nuclear systems. Its mission is to develop the scientific foundations, tools, and technologies needed to enable safer, more efficient, and more sustainable nuclear energy, while reducing technical risks before large-scale deployment. The Material Recovery and Waste Form Development (MRWFD) campaign is a DOE-NE program focused on advancing technologies that enable a more sustainable and efficient nuclear fuel cycle. Its central mission is to develop advanced fuel recycle technologies that improve resource utilization, reduce the burden on geologic repositories, limit proliferation risks, and enhance overall economics.

To achieve this, MRWFD works on recovering valuable materials from used nuclear fuel (UNF), including uranium, transuranics (TRU), and fission products, and enabling their reuse. The program is expanding beyond traditional uranium recovery to include more comprehensive recycling approaches that maximize material recovery while minimizing waste streams. It also addresses challenges across a wide range of fuel types, including those from advanced reactors, while supporting common technology needs and workforce development. The program is closely engaged with commercial developers to ensure program research addresses broad technology needs applicable to recycling in the United States.

Overall, MRWFD serves as a critical enabler of advanced nuclear energy systems by providing the technologies and scientific understanding needed to recycle fuel and safely manage process waste. In doing so, it reduces key technical and economic barriers to closing the fuel cycle and supports the long-term viability of nuclear energy.

The MRWFD campaign's core mission is to develop advanced fuel recycle technologies to improve resource utilization, reduce repository burden, limit proliferation risk, and improve economics of the nuclear fuel cycle. The campaign also emphasizes integrated, crosscutting innovation. Its RD&D spans separations technologies, head-end processing, off-gas capture, and durable waste form development, bringing together expertise in radiochemistry, materials science, and systems analysis. By leveraging national laboratory capabilities and supporting university partnerships, it contributes to both technology development and workforce growth. Overall, MRWFD provides the scientific and engineering foundation needed to safely recycle nuclear materials and manage process waste, helping enable a more sustainable and resilient nuclear energy future.

The MRWFD campaign has been at the leading edge in developing several significant breakthrough technologies over the last decade. These breakthrough technologies include:

- The Co-Decontamination (CoDCon) process is a variant of the PUREX technology that is designed to generate a combined uranium and plutonium product. The process offers enhanced proliferation resistance since no pure plutonium is ever separated.
- The Actinide Lanthanide Separation Process (ALSEP) is an aqueous process designed to separate minor actinides (americium and curium) from lanthanide and other fission products in a single step. Before ALSEP, the approach involved two processes using two different extractants because of the chemical similarity between the minor actinides and lanthanide fission products.





- The campaign has been at the international forefront of developing the electrochemical process for recycling UNF. Notable breakthroughs have been development of a solid cathode for recovering uranium-transuranium metals and an electroreduction technology to facilitate processing oxide UNF.
- The campaign has sponsored the development of specific waste forms for a variety of process wastes arising from the recycle of UNF. For example, ceramic and glass-ceramic waste forms can accommodate higher concentrations of fission products and minor actinides compared to the established borosilicate glass waste form.
- Solid media have been developed to absorb noble gases (krypton and xenon) from the headend off-gases. This technology has proved a viable alternative to the established but complex and energy-intensive baseline of cryogenic distillation.
- The ZIRCEX technology uses chlorine gas to react with the zirconium cladding and subsequently dissolve it to separate it from UNF for either recycle or disposal. The campaign has identified less hazardous reactants and is developing the technology to operate at a lower technology.

This strategic plan is intended to direct the technology maturation undertaken by the MRWFD campaign. The MRWFD campaign resides in the DOE-NE Office of Materials and Chemical Technologies (DOE NE-43). After placing the campaign into technical and political context, this plan describes the campaign's mission and strategic objectives, followed by a strategy for approaching technology maturation and the priority areas for each of the campaign's technical programs. Organizations and programs directly relevant to the campaign are described, followed by the campaign's organization and its risks and opportunities.





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2.0 BACKGROUND TO USED NUCLEAR FUEL MATERIAL RECOVERY AND WASTE FORM DEVELOPMENT

2.1 The Nuclear Fuel Cycle

In the U.S., nuclear power plants generate about 67 GW, or 20% of commercial electric power and almost half of the nation's low-carbon electricity generation. Moreover, nuclear energy is projected to expand in the U.S., with a goal of tripling current levels by 2050, adding ~200 GW of new nuclear power generation capacity through the construction of new reactors across the country; this includes plans to add 35 GW of new capacity by 2035 and maintain a sustained pace of 15 GW per year by 2040. However, nuclear power plants also produce highly radioactive UNF that results from the nuclear fission process. UNF must be isolated from the environment for thousands of years to protect human health and the environment.

The Nuclear Waste Policy Act (P.L. 97-425), as amended, designated Yucca Mountain, NV, as the only candidate site for a national deep geologic repository for the disposal of UNF and other high-level nuclear waste. However, political and legal opposition to the project has indefinitely delayed the licensing, construction, and operation of the proposed Yucca Mountain repository. As a result, about 91,000 metric tons of UNF is stored at nuclear plant sites around the United States and grows by about 2,000 MT each year awaiting disposal.

Direct disposal of UNF, as currently planned in the United States consistent with the Nuclear Waste Policy Act, is called the open (or "once through") nuclear fuel cycle. However, interest in alternative nuclear fuel cycles in the U.S. has renewed among some policymakers and stakeholders primarily because of their potential to reduce the volume and toxicity of nuclear waste.

Alternative "closed" nuclear fuel cycles look to recover fissile material from the UNF for recycle into nuclear reactors. About 95% of UNF consists of uranium from the fresh fuel that was originally loaded into the nuclear reactor and 1% consists of fissile plutonium produced from irradiating uranium. The remaining 4% of UNF consists of highly radioactive fragments of uranium and plutonium (fission products) that must be dispositioned and other actinides (primarily neptunium, americium, and curium).

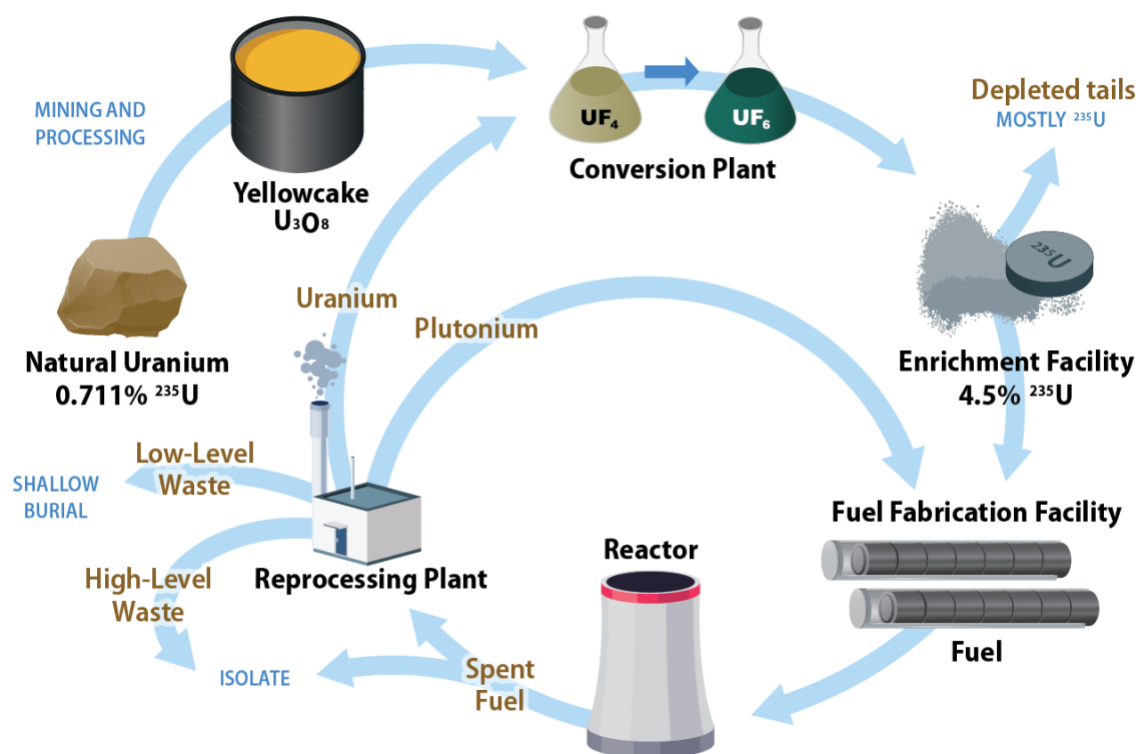
Fissile material can be recovered from UNF by a variety of technologies of varying levels of maturity demonstrated at laboratory and industrial scales. Fissile material recovery is known as "reprocessing." Recovered material, such as uranium, can then be fabricated into fuel for recycle into reactors as illustrated in Figure 1. The U.S. developed technology for the reprocessing of UNF during World War II and during the Cold War operated some of the largest reprocessing facilities in the world, primarily for nuclear weapons material production. Commercial reprocessing activities in the United States ended during the 1970s and early 1980s because of rising costs and policy concerns about the potential worldwide growth of stockpiles of weapons-usable plutonium.

Various degrees of closed fuel cycles can be envisioned and are summarized in Table 1. In principle, recycling all UNF actinides either to thermal or fast spectrum reactors could eliminate the need for permanent disposal except for fission products, which would be immobilized in glass or other material acceptable to the repository. A fully closed fuel cycle could be expanded to recover selected fission products for either short-term storage so those with short half-lives will decay to stable isotopes or alternative applications.





Partially closed cycles can also be envisioned. The least partial fuel cycle would include recovery of only uranium and its fabrication into nuclear fuel for recycle to thermal or fast reactors. At the next level, plutonium and uranium would be recovered together (to minimize proliferation risk) for recycle to either thermal or fast reactors. There are two groups of material recovery technologies that stand out for their relatively high maturity and these are described in the following sections.



Source: U.S. Government Accountability Office, Commercial Spent Nuclear Fuel - Congressional Action Needed to Break Impasse and Develop a Permanent Disposal Solution, GAO-21-603, 2021.

Figure 1. The Nuclear Fuel Cycle

Table 1. Characteristics of Fuel Cycles

Fuel Cycle	Material Recovered and Recycled	Material Disposed
Open	None	Complete untreated fuel
Partial closed	Uranium in thermal or fast reactors	All transuranic actinides and fission products in glass
Partial closed (plus)	Uranium and plutonium in thermal or fast reactors	Minor actinides and fission products in glass
Fully closed	All actinides in thermal or fast reactors	Fission products in glass
Fully closed (plus)	All actinides in thermal or fast reactors Select fission products for decay storage and/or alternative industrial applications	Remaining fission products in glass





2.2 Aqueous-Based Reprocessing of UNF

Aqueous-based technologies were developed as part of the Manhattan Project and subsequently the Cold War. The bismuth phosphate precipitation technology was deployed at Hanford for the Manhattan Project to separate plutonium for weapons purposes. Later, during the early Cold War, a solvent extraction technology called REDuction-OXidation (REDOX) marked a significant development in aqueous-based separations in improving selectivity for plutonium. Plutonium Uranium Extraction (PUREX), a solvent extraction technology, was developed and deployed in the late 1950s at Hanford and Savannah River to separate uranium and plutonium. The PUREX technology forms the basis for all subsequent commercial reprocessing plants in Russia, the United Kingdom, France, and Japan.

The PUREX technology is based on the selective extractant tri-butyl phosphate, but variations on the flowsheet exist primarily on how the plutonium REDOX state is manipulated with consequences for the quantity of high-level waste produced. The amount of high-level waste has been continuously reduced with each evolution of aqueous-based technologies and development in waste management practice as illustrated in Figure 2. Note that the technologies are represented by their plant names. In particular, the PUREX plant at Hanford operated with evolutions of the PUREX technology. The PUREX technology reached its final deployed evolution in the Thermal Oxide Reprocessing Plant (THORP) at Sellafield, United Kingdom, La Hague, France, and Rokkasho Mura, Japan. These industrial plants have high capacity, processing up to 5 metric tons of UNF per day.

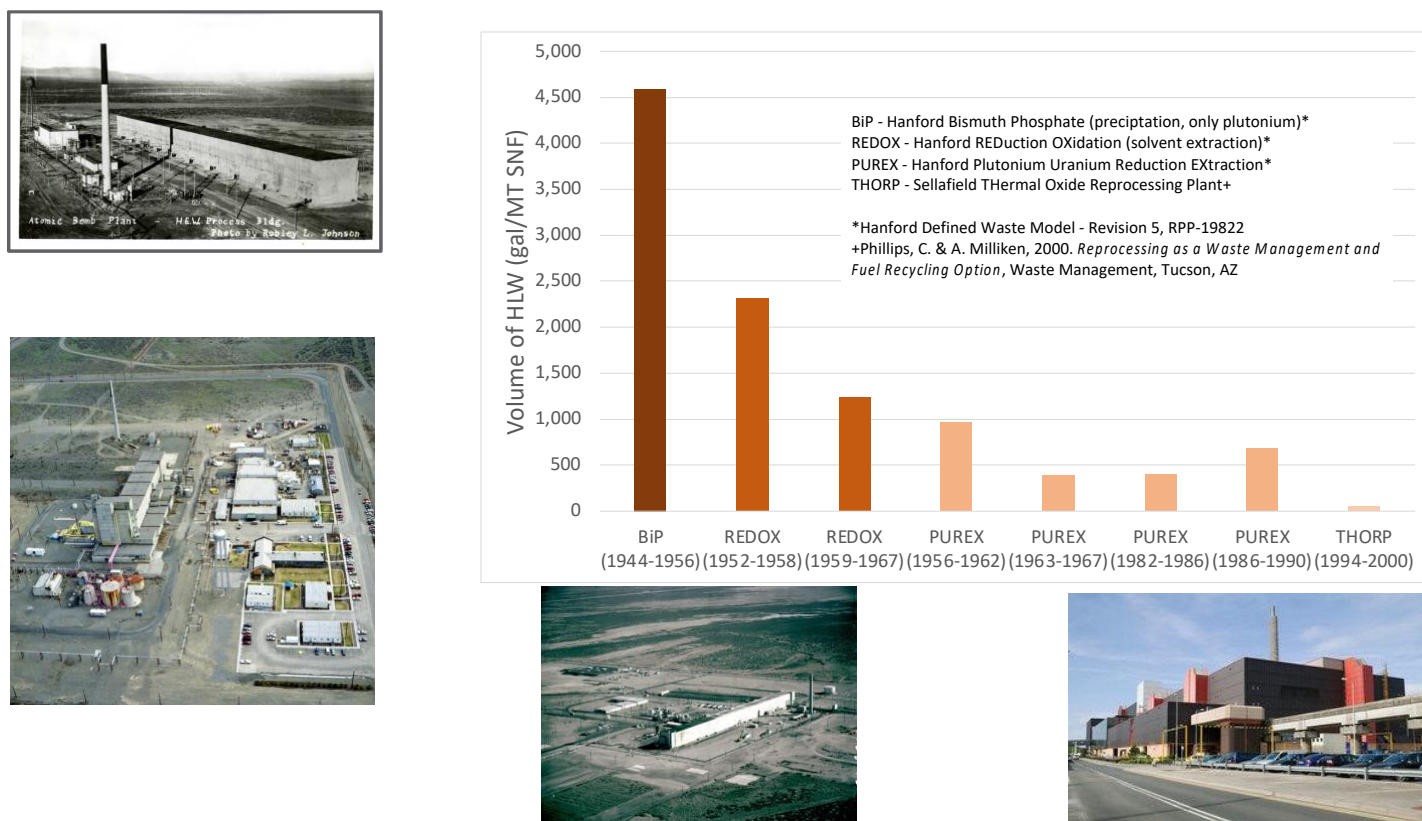


Figure 2. Evolution of Aqueous Reprocessing Technologies





Figure 3 shows a schematic of the process operations involved in aqueous-based reprocessing of UNF. The UNF is first typically treated by simple disassembly and chopping of fuel elements. Alternative treatment technologies might include voloxidation or chemical decladding. The treated UNF is then dissolved, typically in hot nitric acid with volatile fission products captured from the off-gas. Dissolution is followed by separation and purification of the desired UNF constituents before conversion into a powder form suitable for fuel fabrication. Waste products from separations and purification and off-gas treatment are immobilized for disposal or decay storage.

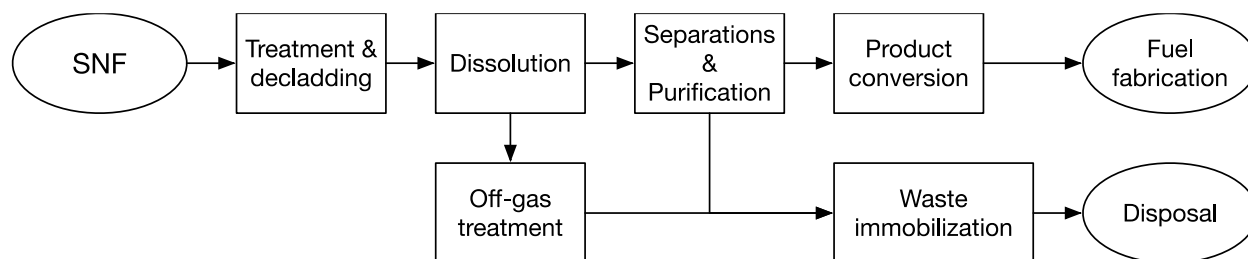


Figure 3. Summary Flow Diagram of Aqueous Reprocessing Approaches

2.3 Electrochemical-Based Reprocessing of UNF

DOE has been advancing electrochemical processing of UNF since the 1980s, originally as an essential component of the Integral Fast Reactor concept at Idaho and Argonne national laboratories. The Integral Fast Reactor program was terminated in 1994, but the metallic UNF from the program's sodium-cooled fast reactor, Experimental Breeder Reactor-II (EBR-II), required treatment to produce waste forms suitable for geologic disposal. Electrochemical processing of EBR-II's UNF continues to produce ceramic and metallic waste forms suitable for disposal while also recovering uranium. In addition, flowsheets based on the electrochemical technology have been developed and tested to recover TRU actinides that supports a closed fuel cycle. The electrochemical technology is arguably preferred for reprocessing metallic UNF over aqueous-based technologies because it generates a metallic product that can be directly processed into fuel for recycle. That said, oxide UNF can also be reprocessed by electrochemical means if it is first electrochemically reduced to metallic form.

Electrochemical actinide separations are accomplished in an electrorefiner but, like aqueous-based separations, other unit operations are needed to prepare the UNF and to process the separated product. Figure 4 illustrates a simplified flow diagram of the typical electrochemical process.



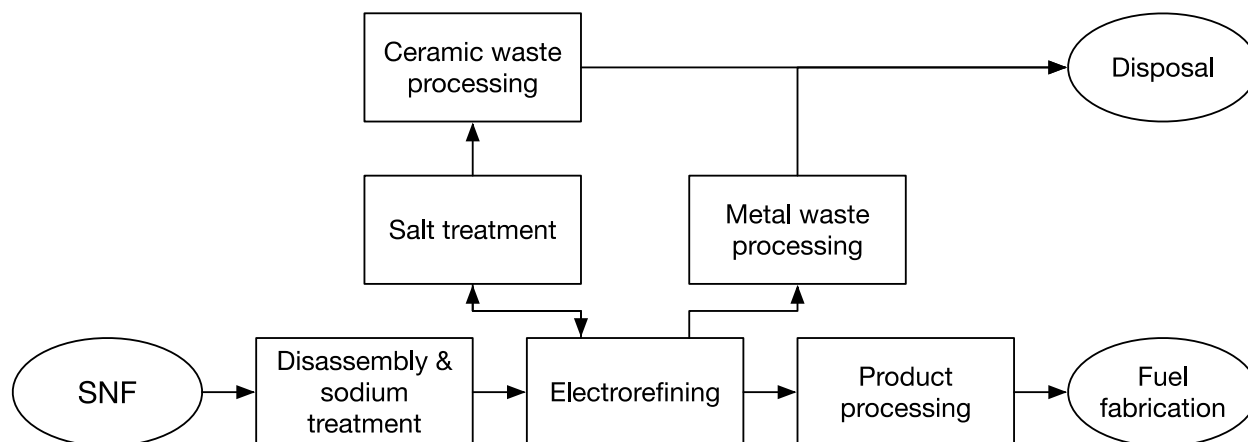


Figure 4. Summary Level Flow Diagram of Electrochemical Reprocessing Approaches

UNF assemblies are disassembled and the pins are mechanically chopped into segments. The pin segments are loaded into a basket from the electrorefiner. Volatile fission products are released into the inerted cell atmosphere and captured in the atmosphere control system. Electroreduction of oxide UNF occurs at this stage if applicable. Electrorefining is an electrochemical process in which an impure metal is purified and is conducted in a molten salt that contains approximately 3-8 wt% uranium trichloride at elevated temperature (e.g., 500°C) in a lithium/potassium chloride (LiCl-KCl) eutectic melt. The metal waste form from the electrorefiner contains the noble metal fission products and cladding and is processed for geologic disposal. A fraction of the electrorefiner's molten salt is treated to separate fission products and then recycled. The salt can also be periodically processed for disposal as a ceramic waste form by occluding it into zeolite, mixed with glass powder and heated to create a sodalite waste form. Product actinides separated in the electrorefiner are processed to prepare them for fabrication into fuel.

Development of the electrochemical approach has not progressed beyond engineering scale, with most work performed in the U.S. and, to a lesser extent, South Korea.

2.4 Fluoride Volatility-based Reprocessing of UNF

The less mature fluoride volatility method is based on the direct fluorination of powdered used fuel with fluorine gas (F_2) or other strong fluorinating agents such as nitrogen trifluoride (NF_3) in a flame fluorination reactor or a fluidized bed, where volatile fluoride species, mostly uranium hexafluoride (UF_6), are separated from the non-volatile species, including trivalent minor actinides and the majority of the fission products. The volatilization of Np and Pu depends on the operating conditions, high flame temperatures, and overstoichiometric fluorine increases their release. Lower flame temperature and sub-stoichiometric fluorine minimize it. Other volatile species include noble metal fission products (Tc, Mo, Ru, Rh, Nb, etc.), Se and Te, noble gases (Ar, Kr, Xe), and, if present, C, H, Br, I. Although considerable work was performed in the 1950s, development of the fluoride volatility approach has not progressed beyond laboratory scale in the U.S. this century. Internationally, a small engineering-scale demonstration was accomplished in the Czech Republic in the early 2000s.





3.0 THE MRWFD MISSION AND STRATEGIC OBJECTIVES

3.1 The MRWFD Mission

Nuclear energy is one of the most resilient, environmentally sustainable, and reliable energy sources on the grid today. DOE-NE works to advance nuclear energy science and technology to meet the nation's energy, environmental, and economic needs. As an applied energy research and development (R&D) organization, DOE-NE enables innovation, supports unique research infrastructure, and solves crosscutting challenges facing the nuclear energy sector to:

- 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 a high-performing organization.

Despite its prominent role, nuclear energy's use presents challenges, such as mounting stockpiles of UNF and high-level waste and a potential for proliferation. Long-term resolution of these challenges entails developing sustainable systems that reduce waste while improving resource utilization and safety. To achieve its goals and objectives and to provide policymakers with tools to make informed decisions, DOE-NE 4, Office of Nuclear Fuel Cycle has established four R&D campaigns:

- **Systems Analysis and Integration** is developing systematic, transparent, and objective processes to screen and evaluate a wide variety of proposed fuel cycles to identify potential solutions.
- **Advanced Fuels** supports both existing and next-generation reactors by developing accident-tolerant light water reactor (LWR) fuel and advanced proliferation-resistant fuels for sustainable fuel cycles.
- **Used Fuel Disposition.**
- **Material Protection, Control, and Accountability Technologies** supports security and safeguards by developing tools and techniques to prevent the misuse of nuclear material.
- **Material Recovery and Waste Form Development** is developing innovative processes to recover uranium and other materials from UNF while minimizing proliferation risk, reducing losses, and minimizing waste. This campaign also seeks transformational breakthroughs in waste forms suitable for geologic repository environments.

The MRWFD campaign advances recycling technologies to establish a robust nuclear fuel supply chain and reduce waste consistent with the DOE-NE Strategic Plan Fiscal Years 2026 to 2030. The mission of the MRWFD campaign is to mature technologies applicable to recycling constituents of UNF with four strategic goals in mind:

- Optimize use of fissile resources for power generation.
- Minimize capacity requirements for geological and near-surface repositories.
- Minimize proliferation risk.
- Reduction of environmental emissions of radioactive and hazardous materials.





The campaign's four strategic goals are not endpoints in themselves but continuously evolve as new information and technology comes to light. Therefore, this strategy is not exclusively directed toward an ultimate physical endpoint but on the level of maturity expected from its technology development activities.

DOE has issued guidance for technology maturation and metrics to indicate the maturity of technologies applicable to its mission. This guidance is promulgated in DOE Guide 413.3-4A, *Technology Readiness Assessment Guide* (DOE 2015). The metric specific to technology maturity is the Technology Readiness Level (TRL), which ranges from 1 (least mature) to 9 (most mature). The word “readiness” in the metric indicates the purpose of technology maturation (or R&D) to ultimately be the application of the technology in an industrial production facility. Given that the purpose of technology maturation is for application, there is an alignment of TRLs and the Critical Decision (CD) milestones outlined in DOE Order 413.3B, *Program and Project Management for the Acquisition of Capital Assets* (DOE 2023).

TRL 4 is the recommended maturity level to support CD-1, *Analysis of Alternatives*, and has been judged appropriate for initial U.S. commercial consideration. This level of maturity is further supported by the synonymy of “alternatives” with “options” in the FCT program's goal of conducting science-based, engineering-driven research to fully evaluate and characterize the selected sustainable fuel cycle *options*. Therefore, the MRWFD campaign targets TRL-4 for its technology maturation activities. In this way, the campaign is ready to support, with technical options, the federal or commercial capital acquisition of UNF recycle facilities. Certain maturation activities applicable at higher TRLs than 4 may be warranted and directed by the campaign leadership. Generally, though, higher TRLs can only be completely achieved with an active facility design and construction and commissioning project. Broadly, TRL-4 consists of validating the technology at laboratory or bench scale (typically no larger than a tenth of full-scale) with a broad range of simulants and smaller range of actual UNF if considered beneficial.

3.2 MRWFD Strategic Objectives

The following sections expand on the elements of the MRWFD mission outlined in Section 3.1 as strategic objectives.

3.2.1 Optimize Utilization of Fissile Resources for Power Generation

As the dominant source of nuclear fuel, uranium is mined in many countries and internationally traded as a commodity. There is concern that if the global use of nuclear power grows, the supply of uranium for fuel could tighten and lead to challenges securing fuel at economically viable prices in an environmentally sustainable manner. New reactor designs and fuel cycle options may help to alleviate concerns about fuel resources and waste management by enabling the extraction of more energy from UNF. Doing this would reduce the amount of fuel required to maintain the reactor fleet while leaving less used fuel to be managed. This strategic objective aims to develop technologies that facilitate the extraction of residual uranium and potentially other fissile actinides from UNF.

3.2.2 Minimize Required Geological and Near-Surface Repository Capacity

The capacity of geologic repositories is limited by the allowable packing density of UNF to manage decay heat. Therefore, this strategic objective looks to develop technologies that effectively and efficiently separate actinides and fission products with high decay heat (e.g., americium-241 and cesium-137, respectively) for alternate management. Examples of alternate management include transmutation of





long-lived actinides in a fast-spectrum reactor or decay storage of short-lived fission products. This strategic objective is exemplified by the work of Wigeland et al. (2006), who projected the improvement in repository (drift) loading resulting from separation of high heat-emitting TRU and fission products. Part of their work is illustrated in Figure 5, which shows the potential increase in drift loading resulting from increasing separation of cesium-137 and strontium-90. That said, the concentration of radionuclides in all wastes, whether destined for geologic or near-surface disposal, should be maximized within the acceptance constraints of the disposal facility. The aim of this objective is to develop technologies for extracting high-heat actinides and fission products from UNF and stable waste forms maximizing radionuclide loading.

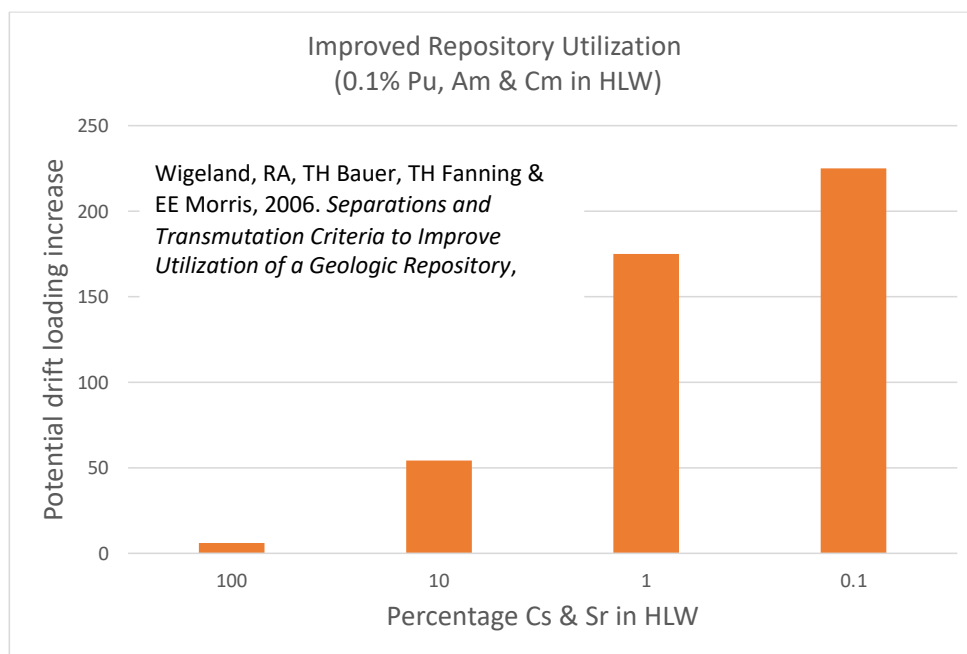


Figure 5. Improved Repository Utilization from Reprocessing

3.2.3 Minimize Proliferation Risk

Commercial PUREX flowsheets implemented to date at industrial scale have separated pure plutonium for subsequent storage with a long-term goal of fabrication into mixed oxide (a mixture of uranium and plutonium oxides) LWR fuel or fast reactor fuel. However, the separation of pure plutonium has increasingly become recognized as a nuclear proliferation risk. This strategic objective looks to develop technologies that prevent separating pure plutonium and monitor the content of process streams for plutonium.

3.2.4 Support Mitigation of Environmental Emissions of Radioactive and Hazardous Materials

Environmental releases are of broad public and political concern. Technical and economic solutions for reducing and mitigating environmental impacts are therefore needed to satisfy regulatory release limits and to assure potential host sites that the environment will be protected.. Historically, PUREX reprocessing plants have released to the environment radionuclides difficult to capture, such as iodine-





129, tritium, and krypton-85. Such intentional environmental releases will likely challenge public acceptance in the future. This strategic objective looks to develop technologies that effectively and efficiently capture radionuclides in gaseous and liquid effluents and stable waste forms in which to immobilize them. Arm and Butcher (2009) compared then-current approved environmental releases from THORP, Sellafield, to those planned by EnergySolutions in their future U.S. reprocessing plant conceived as part of the Global Nuclear Energy Partnership project. Table 2 presents the result of that comparison and illustrates the additional technologies needed to capture previously released radionuclides.

Table 2. Comparison of Past and Future Emissions from Reprocessing Plants

Radionuclide	THORP, Sellafield	EnergySolutions, Global Nuclear Energy Partnership
Iodine-129	Discharged to sea	Captured, immobilized and dispositioned as Greater-than-Class C low-level waste
Krypton-85	Aerial discharge	Captured for decay storage
Carbon-14	Captured immobilized & stored for geologic storage	Captured, immobilized & dispositioned as Class A/B low-level waste
Tritium	Discharged to sea	Options being explored
Arm, ST & EJ Butcher. 2009. Treatment and Disposal of Process Wastes Arising from the Recycle or Used Nuclear Fuel in the USA. Waste Management, Phoenix, AZ.		





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4.0 MRWFD TECHNOLOGY MATURATION STRATEGY

The technology maturation process adopted by the MRWFD campaign follows DOE Guide 413.3-4A (DOE 2015) and the principles outlined by Dixon et al. (2019). The technology maturation process uses a scale of TRLs that are linked to the federal critical decision milestones outlined in DOE Order 413.3B. This link ensures that technologies are sufficiently matured to enable informed policy and capital project decisions and minimize project risk. As stated in the MRWFD campaign mission, the campaign targets TRL-4 to support CD-1, *Analysis of Alternatives*. The definition and description of each TRL is provided in DOE G 413.3-4A and is repeated in Table 3. Therefore, R&D plans should aim to advance technologies to succeeding readiness levels up to TRL-4 within the MRWFD campaign. A technology may regress in the TRL scale as new applications for a technology are identified (e.g., resulting from new fuel cycles or end uses). Regression should not be considered “bad,” but simply facilitates management of the technology’s maturation for the new or modified application.





Table 3. Summary Definition of Each TRL

Relative Level of Technology Development	Technology Readiness Level	TRL Definition	Description
Technology Development	TRL-4	Component and/or system validation in laboratory environment	The basic technological components are integrated to establish that the pieces will work together. This is relatively “low fidelity” compared with the eventual system. Examples include integration of ad hoc hardware in a laboratory and testing with a range of simulants and small-scale tests on actual UNF. Supporting information includes the results of the integrated experiments and estimates of how the experimental components and experimental test results differ from the expected system performance goals. TRL-4 is the first step in determining whether the individual components will work together as a system. The laboratory system will probably be a mix of on-hand equipment and a few special purpose components that may require special handling, calibration, or alignment to function.
Research to Prove Feasibility	TRL-3	Analytical and experimental critical function and/or characteristic proof of concept	Active R&D is initiated. This includes analytical studies and laboratory-scale studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative tested with simulants. Supporting information includes results of laboratory tests performed to measure parameters of interest and comparison to analytical predictions for critical subsystems. At TRL-3, the work has moved beyond the paper phase to experimental work that verifies that the concept works as expected on simulants. Components of the technology are validated, but there is no attempt to integrate the components into a complete system. Modeling and simulation may be used to complement physical experiments.
Basic Technology Research	TRL-2	Technology concept and/or application formulated	Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are still limited to analytic studies. Supporting information includes publications or other references that outline the application being considered and that provide analysis to support the concept. The step up from TRL-1 to TRL-2 advances the ideas from pure to applied research. Most of the work is analytical or paper studies with the emphasis on understanding the science better. Experimental work is designed to corroborate the basic scientific observations made during TRL-1 work.
	TRL-1	Basic principles observed and reported	This is the lowest level of technology readiness. Scientific research begins to be translated into applied R&D. Examples might include paper studies of a technology’s basic properties or experimental work that consists mainly of observations of the physical world. Supporting information includes published research or other references that identify the principles that underlie the technology.





Justifying and documenting a technology attaining each TRL becomes an important activity within the campaign and draws on the TRL calculator questions provided in DOE G 413-4A. The calculator questions, adjusted for MRWFD campaign purposes, are detailed in Appendix A. Two important elements of the technology maturation strategy are technology scaling and selecting appropriate feed material for maturation activities. These elements are expanded on in the following sections.

4.1 Technology Scaling Strategy

Engineering judgment should be employed to determine the laboratory or bench scale to use for each subject technology but is typically smaller than one-tenth scale at TRL-4. Nonetheless, the scale and configuration of equipment tested or used should be sufficient to represent the full-scale features under investigation.

Laboratory or bench scale is interpreted as less than one-tenth the scale of the plant (typically fitting on a laboratory bench, fumehood, or glovebox), although application-specific engineering judgment should be applied. Laboratory-scale systems are used for process development with the means to closely control conditions such that responses can be accurately correlated to changes in those conditions. Typically, the laboratory-scale tests use standard off-the-shelf laboratory equipment except where needed for the specific technology. Results from laboratory-scale tests should lead to a process block flow diagram or low-fidelity process flow diagram. On the other hand, engineering-scale tests are mainly used to test the feasibility and stability (“robustness”) of a process, especially from an operations perspective. Engineering-scale equipment is typically a smaller version of full-scale such that testing enables finalization of design.

The term “technology components” has, intentionally, a very broad meaning. For an instrument or other piece of hardware, the components are reasonably understood using the common understanding of the term. For a flowsheet technology, components might be the parts of the flowsheet serving a specific purpose. For example, a solvent extraction flowsheet based on a new organic extractant could have components related to extraction, scrubbing, stripping, and even solvent washing. Put another way, the components in this case refer to the unit operations described in a block flow diagram of the flowsheet concept.

4.2 Technology Feed Material Strategy

The chemical and physical characteristics of simulants should be representative of those expected from any pre-processing of actual UNF to prepare it for treatment with the subject technology (e.g., acid dissolution). Further, test simulants should cover the range of chemical and physical characteristics expected of actual UNF arising from fuel cycles applicable to the subject technology. Campaign staff are encouraged to apply ASTM Method C1750-21, *Standard Guide for Development, Verification, Validation, and Documentation of Simulants for Hazardous Materials and Process Streams*, in developing simulants.

ASTM Method C1750-21 provides general considerations for the development, verification, validation, and documentation of performance-based simulants for high-level waste sludge. However, the underpinning concepts are equally applicable to UNF. As described by that standard, the first step should be to determine the purpose of the simulant in testing for the specific performance metric of the subject technology. The key processing properties required for development of the simulant can then be identified. Simulant requirements relative to those properties are then specified, and simulant design and





preparation methodology follow. Finalization of the simulant design is achieved once verification and validation confirms that the simulant meets the requirements throughout the testing duration.

For EM applications, the range of simulants corresponds to the range of chemical and physical properties of the waste to be processed. Interpretation of the term is relatively straightforward given the waste likely arises from a variety of sources. For UNF, one metric resulting in a range of chemical properties will be burnup. Other considerations could be the type of UNF (e.g., accident-tolerant fuels) and initial enrichment. Additionally, the range of physical and chemical properties of the feed to the subject technology arising from a preceding operation should be considered. For example, the range of simulants for an advanced UNF dissolution technology could be representative of those arising from voloxidation.

Consistent with the TRL-4 definition, results of tests with simulant should be verified in as many cases as practical with actual UNF consistent with material availability, safety, ALARA (as low as reasonably achievable), cost, and project risk criteria. Actual UNF must be pre-processed to simulate the anticipated full-scale application before it is used to test the subject technology. Therefore, tests with actual UNF must be planned with MRWFD campaign management so that other projects can leverage the activity.

4.3 Use of Artificial Intelligence and Machine Learning

The MRWFD campaign is actively preparing for greater use of artificial intelligence (AI) and machine learning (ML) in its activities. For example, campaign reports beginning in 2012 are consolidated into a searchable and centralized location (a SharePoint file server) that can be interrogated by AI tools. The campaign is also assessing whether it should copy reports and underlying data to a high-performance computer to facilitate development of AI agents specific to its technical area. As well as reports, the campaign is also planning for its researchers to provide data sets either as appendices to reports or standalone files (e.g. spreadsheets) that could be analyzed by future AI/ML tools.





5.0 MRWFD INTERFACES

This section describes the organizational and programmatic interfaces important to the MRWFD campaign in order of their organizational proximity. As illustrated in Figure 6, organizations and programs important to the MRWFD campaign include the following.

- Other NE-4 campaigns
 - Processing the UNF from EBR-II
 - Materials Protection Accounting and Control Technologies (MPACT)
 - DOE NE-42 Advanced Fuels Campaign (AFC)
- Other DOE Offices and DOE Agencies
 - DOE NE-8 Used Fuel and High Level Waste Disposition (SF&HLWD)
 - Advanced Research Projects Agency – Energy (ARPA-E)
 - National Nuclear Security Administration (NNSA)
- Universities (through DOE-NE’s Nuclear Energy University Program, NEUP)
- Industry (through DOE-NE’s Gateway for Accelerated Innovation in Nuclear, GAIN, program)
- International programs and organizations

The following sections describe these programs and organizations and their relevance to the MRWFD campaign.

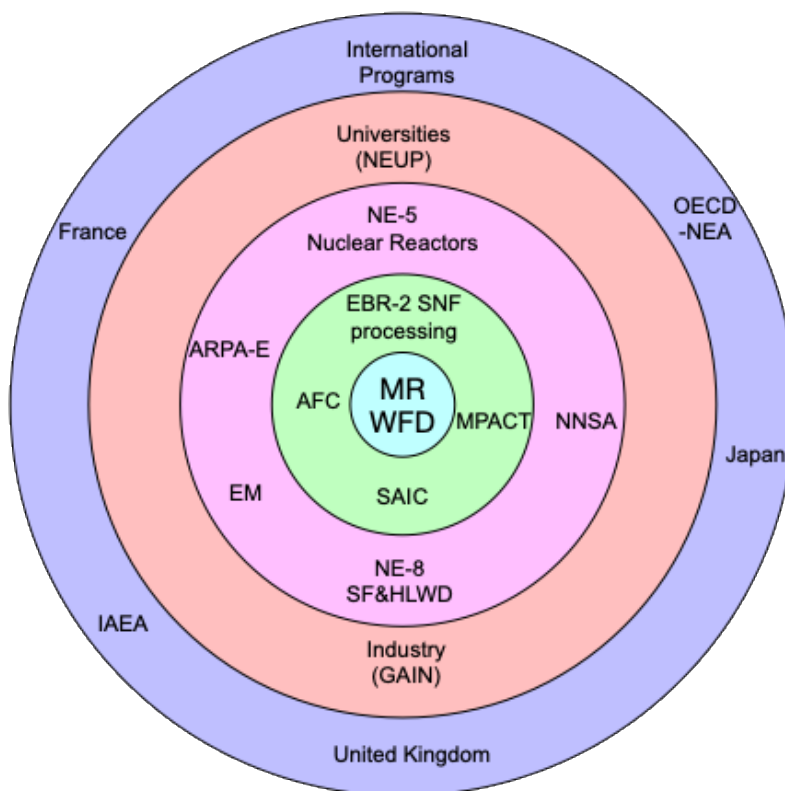


Figure 6. MRWFD Interfaces





5.1 Other DOE NE-4 Programs

5.1.1 EBR-II Driver Fuel Processing

EBR-II driver fuel treatment is an electrometallurgical process (pyroprocessing) that converts sodium-bonded metallic fuel from EBR-II into stable waste forms and usable uranium. Located at Idaho National Laboratory (INL), this method treats hazardous sodium-bonded fuel by separating uranium from fission products using high-temperature molten salt baths, facilitating final waste disposal and producing high-assay low-enriched uranium (HALEU) for advanced reactors. The processing information acquired through EBR-II driver fuel treatment is valuable to MRWFD in a variety of ways, notably including fission product behaviors during engineering-scale operations.

5.1.2 Materials Protection Accounting and Control Technologies Campaign

The MPACT mission is to support the U.S. nuclear fuel cycle front and back-end technology developers to effectively and economically address domestic safeguards requirements at facilities regulated by the Nuclear Regulatory Commission (NRC) by:

- Developing innovative technologies, analysis tools, and advanced integration methods for nuclear material control and accounting (MC&A).
- Engaging with government and industry stakeholders early in the technology development process to enable a cost-effective implementation of safeguards and security by design.
- Supporting the development of advanced reactors via MC&A support for enabling processes such as HALEU and advanced fuel fabrication, storage, and transportation.
- Working with the U.S. national laboratories, U.S. nuclear industry, and U.S. universities through directly funded R&D programs.

MPACT is important to the MRWFD campaign because nuclear material recovered from UNF requires control and accounting. Ideally, recovery processes should be matured with MC&A in mind.

5.1.3 DOE NE-42 Systems Analysis and Integration Campaign

The Systems Analysis and Integration campaign develops and implements analysis processes and tools and performs integrated fuel cycle evaluations to provide information to objectively and transparently inform the DOE-NE as decisions are made about overall R&D directions and to integrate them across common fuel cycle goals. This campaign uses information from MRWFD to develop fuel cycles for evaluation. Results from the evaluations then help MRWFD to prioritize maturation activities and define scope.

5.1.4 DOE NE-42 Advanced Fuels Campaign

The AFC is responsible for leading R&D activities related to nuclear fuels and materials development. This primarily focuses on accident-tolerant fuels technology for current LWRs and metallic alloy fuels for advanced sodium-cooled fast reactors.

The AFC is important to the MRWFD campaign because actinides recovered from UNF would be fabricated into new advanced nuclear fuel for recycle into thermal and fast spectrum reactors.





5.1.5 Implementation

MRWFD's relationships with other NE-4 campaigns are maintained and developed through the monthly performance review meetings, participation in campaign reviews, and ad hoc meetings. These relationships are important for MRWFD in understanding the trends and subjects of interest to maintain overall consistency in federal fuel cycle endeavors.

5.2 Other DOE Offices and DOE Agencies

5.2.1 DOE NE-5 Nuclear Reactors

The Office of Advanced Reactors, NE-52, is leading DOE's activities in advanced reactor development. Of special interest to the MRWFD campaign is the Molten Salt Reactor (MSR) campaign within NE-52 because there is commonality in the molten salts used for electrochemical reprocessing of UNF. As a result, several staff associated with the MRWFD campaign also work projects for the MSR campaign. At the technical level, there is a very active interface between the campaigns.

5.2.2 DOE NE-8 Spent Fuel and High Level Waste Disposition

In FY2027, DOE's Office of SF&HLWD will combine the former Office of Disposal R&D and Office of Collaboration Based Siting into the Office of Siting and Disposal. These offices are developing an Integrated Waste Management system for storage, transportation, and disposal of spent nuclear fuel (SNF) and high-level radioactive waste.

The Office of SF&HLWD and the MRWFD campaign both represent the back-ends of alternative nuclear fuel cycles. The former has historically been responsible for implementing current U.S. policy for SNF (the open fuel cycle), whereas the latter matures options for closing the nuclear fuel cycle for potential changes in policy toward a closed fuel cycle. Recently, NE-8 has rolled out a plan to site and open Nuclear Lifecycle Innovation Campuses through State-led initiatives. These Campuses must include used fuel disposition, (borehole or deep geologic repository disposal), but may also include facilities for reprocessing, fuel fabrication, or other elements of the fuel cycle. DOE's negotiations and plans for these Campuses have been highly opaque, so the division of responsibilities is yet uncertain. Nonetheless, moving forward with the plans will rely on yet-to-be-determined changes to the Nuclear Waste Policy Act, which may include changes to nuclear waste definitions. Thus, the Office of SF&HLWD is important to the MRWFD campaign because the former represents the authority on currently stored and new LWR and advanced reactor SNF, and because plans and policy are rapidly changing that may further entwine the two offices through shared Campus interest or statutory changes in responsibilities.

5.2.3 Advanced Research Projects Agency – Energy

ARPA-E has a focused mandate within the federal government to identify and support outlier energy technologies, but bringing these innovations to market requires collaboration with a range of other federal and state agencies. ARPA-E also foster strong relationships with the DOE's Applied Technology Programs, such as the MRWFD campaign. ARPA-E tracks key early indicators that illustrate how the advanced R&D funded by the Agency translates to commercial, market, and industry impacts, including partnership with other government agencies. ARPA-E manages two programs of direct interest to the MRWFD campaign:





- **Converting UNF Radioisotopes Into Energy (CURIE)** seeks to develop innovative separations technologies, material accountancy, and online monitoring technologies, as well as designs for a reprocessing facility that will enable group recovery of actinides for advanced reactor feedstocks, incorporate in situ process monitoring, minimize waste volumes, enable a \$.01/kilowatt-hour (kWh) fuel cost for advanced reactor fuels, and maintain disposal costs in the range of \$.01/kWh.
- **Optimizing Nuclear Waste and Advanced Reactor Disposal Systems (ONWARDS)** seeks to develop and demonstrate breakthrough technologies that will facilitate a 10x reduction in advanced reactor waste volume generation or repository footprint. In addition, ONWARDS aims to advance development of high-performance advanced reactor waste forms while maintaining exemplary safeguards standards and global back-end costs in the accepted range of \$1/megawatt-hour.

The CURIE and ONWARDS programs are important to the MRWFD campaign because they are both focused on the back-end of the fuel cycle. ARPA-E programs foster collaborations between industry, universities, and national laboratories to mature technologies that industry, by itself, would consider too risky from a return standpoint. Therefore, the ARPA-E programs incorporate an industrial perspective to the maturation of technologies that may have been initiated by the MRWFD campaign.

Of tangential interest to the campaign is the ARPA-E High Performance Optimized Recycled Nuclear Isotopes for Gen IV Reactors (HORNIG) program. The HORNIG program seeks to overcome key technical and economic barriers that have historically prevented the use of TRU fuels in commercial reactors and to create a path to domestic nuclear fuel security by supporting the design, fabrication, and qualification of TRU fuels. The program will fund coordinated, multidisciplinary efforts to deliver transformative advances in fuel performance, manufacturability, cost, and regulatory readiness. HORNIG projects will design and test TRU-based fuel systems, improve fuel cost and manufacturability, and shorten qualification timelines from decades to less than 7 years. This program could theoretically generate requirements for reprocessing flowsheets.

5.2.4 National Nuclear Security Administration

The NNSA is a semi-autonomous agency within DOE responsible for enhancing national security through the military application of nuclear science. NNSA maintains and enhances the safety, security, and effectiveness of the U.S. nuclear weapons stockpile; works to reduce the global danger from weapons of mass destruction; provides the U.S. Navy with safe and militarily effective nuclear propulsion; and responds to nuclear and radiological emergencies in the United States and abroad.

The NNSA's Office of Defense Nuclear Nonproliferation initiated the Nonproliferation Stewardship Program in 2020 to provide an enduring pipeline of nonproliferation subject matter experts to the DOE/NNSA laboratories. This program provides nonproliferation-relevant science and technology opportunities through modernized facility infrastructure through hands-on experimental work and associated modeling and simulation. One important project of interest to the MRWFD campaign is Athena. The Athena project aims to reinvigorate and sustain U.S. expertise in the nonproliferation challenges associated with material recovery from irradiated nuclear fuel. The primary goals involve modernizing facilities and equipment across the multi-laboratory team and leveraging the equipment to build expertise and leadership across the complex through innovative science and technology.

The Athena project aims to reinvigorate and sustain U.S. expertise in the nonproliferation challenges associated with material recovery from irradiated nuclear fuel. The primary goals involve modernizing facilities and equipment across the multilaboratory team and leveraging equipment to build expertise and





leadership across the complex through innovative science and technology. It is important because it is focused on modernizing the same experimental capabilities and developing the same staff that can be employed by the MRWFD campaign. While the capabilities and staff are likely being developed on established reprocessing technology, they are directly translatable to maturing the advanced technologies of interest to the MRWFD campaign.

5.2.5 Office of Environmental Management

In April 2026, DOE Office of Environmental Management (EM) issued a Request for Applications that specifically focuses on a commercial-scale demonstration to recycle defense-related spent nuclear fuel at INL. The project is designed to recycle fuel from EM's existing inventory, specifically 3,400 unused fuel elements from DOE's Advanced Test Reactor, into HALEU. The DOE is offering a long-term lease of federal land at the Idaho Nuclear Technology and Engineering Center. At the time of writing this strategic plan, DOE EM is reviewing submissions. How the MRWFD campaign will interface with this mission is currently unclear.

5.2.6 Implementation

Some senior MRWFD staff are also engaged on activities associated with other DOE offices and agencies. The position of these staff can be leveraged to provide MRWFD leadership with insight on the activities of those other offices and agencies. MRWFD staff will be appointed to track the progress of those activities of interest to the campaign and report on a periodicity to be agreed upon.

5.3 Universities

DOE-NE's primary interface with universities is through the NEUP, which seeks to align the nuclear energy research being conducted at U.S. colleges and universities with DOE-NE's mission and goals. The Consolidated Innovative Nuclear Research R&D program supports university-led projects that focus on the needs and priorities of DOE-NE, including fuel cycle, reactor concepts, and NE mission supporting research.

Integrated research projects represent the program-directed component of the NEUP by providing R&D solutions that are the most directly relevant to the near-term, significant needs of DOE-NE R&D programs. Integrated research projects are significant 3-year awards for projects that address specific research issues and capability gaps identified and defined by DOE-NE R&D programs and are intended to develop a capability within each specified area. These projects are multidisciplinary and require multi-institutional partners spanning multiple scientific, engineering, and, where appropriate, economics and public-policy disciplines. Teams are encouraged to include multiple universities and non-university partners (e.g., industry/utility, national laboratory, and international). Industry partners are strongly encouraged and may receive funding support from the project. International partners are equally encouraged on a non-government funding basis.

The NEUP provides a valuable alternative capability resource and perspective to the MRWFD campaign where individual projects coincide with the campaign's mission. Additionally, NEUP students represent the future workforce for the MRWFD campaign.





5.3.1 Implementation

There is no formal engagement of MRWFD staff in university programs, but some could be engaged in the NEUP in reviewing proposals, monitoring progress, and reviewing reports. Others may be collaborating with university staff on projects outside of the campaign (e.g., ARPA-E projects). Other ad hoc interactions occur between campaign and university staff at conferences and other forums. All these interactions contribute toward maintaining and developing relationships with university staff and can be leveraged to provide MRWFD leadership with insight on the campaign-relevant activities of universities.

5.4 Industry

The MRWFD campaign's interactions with industry are key to its technology transfer and commercialization activities. Information and informed opinion are periodically solicited from industry experts and leaders to inform MRWFD campaign activities and plans, either under contract or by participation in campaign review meetings.

DOE-NE's GAIN program is a framework for establishing private-public partnerships that looks to bridge the gap between innovators in the private sector and the research capabilities of national laboratories.

Like NEUP, the GAIN program provides a valuable alternative perspective to the MRWFD campaign where individual projects coincide with the campaign's mission. However, sometimes protected intellectual property precludes a technology's maturation in the MRWFD campaign.

5.4.1 Implementation

Like the university interface, there is no formal engagement of MRWFD staff with industry. However, campaign staff are involved in reviewing proposals for funding from the Small Business Innovation Research program and are involved in non-campaign-funded projects collaborating with industry. Other ad hoc interactions occur between campaign and industry staff at conferences and other forums. All these interactions contribute toward maintaining and developing relationships with industry and can be leveraged to provide MRWFD leadership with insight on the campaign-relevant activities of industry.

5.5 International Programs

There are three countries and two international organizations that pursue interests and activities akin to the work of the MRWFD campaign. These organizations and the mechanisms of collaboration are briefly described below.

5.5.1 United Kingdom

Collaboration between the U.S. and UK governments on nuclear energy R&D is formalized in a Cooperative Action Plan from 2018. The scope of this strategic plan is covered by the working group for fuel cycle technologies, which meets on annually.





5.5.2 France

The French and U.S. governments collaborate on civil nuclear energy via the DOE-CEA Bilateral Committee, specifically Working Group 2, Separations and Waste Forms. Recently proposed information sharing is planned on the topics of laboratory-scale voloxidation and direct extraction.

Informal collaboration occurs at international conferences and other venues. In particular, Orano Federal Services has a strong presence in applying French fuel cycle experience to the U.S. market. Fruitful relationships between campaign and Orano staff have developed over the years to leverage French experience for the MRWFD campaign.

5.5.3 Japan

Research between the U.S. and Japan is coordinated through the Civil Nuclear Energy Working Group and specifically Project Arrangement NE-09, “Fuel Cycle Research and Waste Management.” Ongoing collaboration includes electrochemical reduction of used oxide fuel and waste form processes. Japanese collaborating organizations include the Japan Atomic Energy Agency and the Central Research Institute of Electric Power Industry.

5.5.4 International Atomic Energy Agency

The International Atomic Energy Agency (IAEA) brings together research institutions across the globe to collaborate on coordinated research ranging from isotopes and radiation applications in agriculture, human health, industry, hydrology, and terrestrial and marine environments to nuclear energy and economic studies and nuclear safety and security. The coordinated research is implemented primarily via coordinated research projects (CRPs). Each CRP typically brings together a range of research institutions from a range of countries at different stages of socioeconomic development, who work together for between 3 to 5 years.

There is currently one IAEA activity related to the MRWFD campaign, involving the development of a report *Nuclear Fuel Cycle Options for Existing and Future Reactor Types*. A recent CRP involving the campaign was completed in 2016 “Processing Technologies for High Level Waste, Formulation of Matrices and Characterisation of Waste Forms.” A currently active CRP, “Challenges, Gaps and Opportunities for Managing Used Fuel from Small Modular Reactors,” is of indirect interest since some of the work concerns treatment of UNF.

In addition to coordinated research, the IAEA organize and hosts consultancy meetings and technical meetings that bring together workers in specific fields to exchange information. These meetings can sometimes lead to coordinated research.

Additionally, there are technical groups that advise the Deputy Director General of the Department of Nuclear Energy. One such group of direct interest to the campaign is the Nuclear Fuel Cycle Options and Spent Fuel Management group, which focuses on nuclear fuel cycle options with an emphasis on spent fuel management (storage, reprocessing and recycling), innovative fuel cycles for advanced reactors and nuclear materials management.





5.5.5 Organization for Economic Cooperation and Development – Nuclear Energy Agency

The Organization for Economic Cooperation and Development – Nuclear Energy Agency (OECD-NEA) assists its member countries in maintaining and further developing, through international co-operation, the scientific, technological, and legal bases required for safe, environmentally sound, and economical use of nuclear energy for peaceful purposes. It provides authoritative assessments and forges common understandings on key issues as input to government decisions on nuclear energy policy and to broader OECD analyses in areas such as energy and the sustainable development of low-carbon economies. The NEA operates through a series of specialized standing technical committees, with the NEA providing the secretariat and coordination services. These specialized standing technical committees and subsidiary bodies represent the major areas of the Agency's program, each of which oversees various specialized working groups and task groups. These groups are composed of experts from member countries who both contribute to the program of work and benefit from its results. The groups periodically publish the results of their work. There are three fuel cycle technology expert groups of interest to the campaign:

- **Fuel Recycling and Waste Technology.** This expert group is exploring fuel cycle technologies that are applicable to MSRs through a project called “CRITICAL Evaluation of fuel Management during and after MSR operation” (CREAMM).
- **Trends in the Nuclear Fuel Cycle.** This ad hoc expert group investigates trends in the latest progress and future trajectories in the nuclear fuel cycle.
- **Back-End Strategies.** This expert group identifies aspects of significant importance to countries' decisions on whether to deploy partially and fully closed nuclear fuel cycles and how to deploy them.

Campaign staff may interact with their international colleagues on specialized standing technical committees and their subsidiary working groups and task groups.





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6.0 ORGANIZATIONAL PRINCIPLES

6.1 Organizational Breakdown

While there are likely many ways in which the MRWFD campaign could be organized, an organization based on technology type and maturity is logical given its mission to develop technologies to support a potential CD-1. As already described, there are two broad groups of technologies characterized by the approach taken to separating the desired constituents of UNF: aqueous based and electrochemical based. For example, “aqueous separations” includes aqueous dissolution and other pretreatment of UNF, precipitation and conditioning of separated material, as well as the separations themselves. Special technical initiatives might also warrant their own organizational element. For example, the fourth strategic objective highlights where technology advancements are needed to separate radionuclides that historically have been discharged into the environment.

Finally, an organizational breakdown based on technology maturity is warranted. The transition from TRL-3 to TRL-4 marks the significant step from conducting fundamental research to prove scientific feasibility to applied research that develops the technology to demonstrate engineering feasibility. The experimental and theoretical approaches undertaken at TRL-2 and TRL-3 can be significantly different from those implemented at TRL-4.

6.2 Organizational Dynamics

Leadership of each organizational element approximately corresponds to the management roles required in the Program Information Collection System for the Office of Nuclear Energy (PICS:NE). As shown in Figure 7, work package managers (WPMs) control the technical scope, budget, and schedule at a project or task level and they report to control account managers (CAMs) who manage the work for their program. The CAMs manage the programmatic organizations at the first level in the MRWFD campaign. The CAMs then report to the national technical director (NTD), who manages the campaign and reports to the DOE NE-43 federal manager.



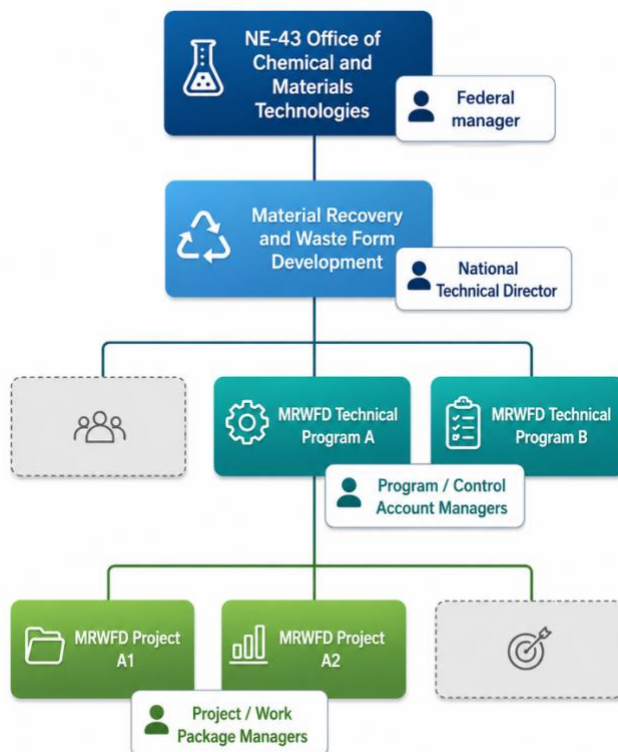


Figure 7. MRWFD Campaign Organizational Principles

Proposals for new technologies or development of current technologies consistent with the MRWFD campaign's strategy are encouraged at all levels of the campaign and should be routed through the campaign management structure. The technical background included in proposals for new technologies should include a TRL assessment that demonstrates the technology is at least TRL-1.

6.3 Campaign Organization Structure

Figure 8 shows the current organization of the MRWFD campaign. The organization is consistent with the control accounts and work packages set up in PICS:NE for the campaign. The names of individuals are correct at the time of publication but can easily change during the course of a year. The control accounts and work packages become important for this plan later in discussing the strategic goals for the campaign's technologies and their long- and short-term visions.



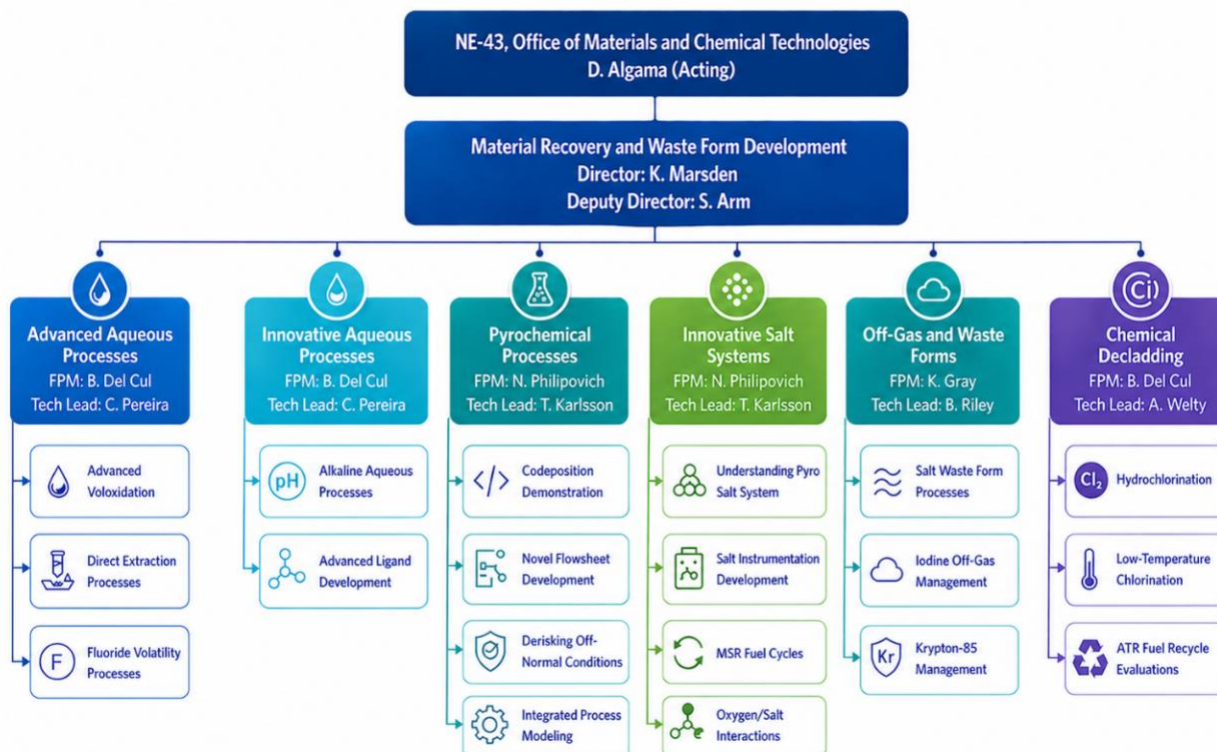


Figure 8. MRWFD Campaign Organization

6.4 Roles and Responsibilities

This section outlines the formal management roles within the campaign and their responsibilities. Responsibilities should be discharged consistent with the strategic plan.

6.4.1 National Technical Director

Overall responsibilities of the MRWFD campaign NTD include:

- Directs technical area leads (and typically PICS:NE CAMs) in the management of groups of work packages.
- Directs PICS:NE WPMs through the technical area leads in the management of work packages.
- Executes approved work plans and monitors activity progress and quality of technology maturation for assigned work packages consistent with program requirements.
- Leads evaluation of proposals for work on new technologies or applications of existing technologies.
- Acts as the primary point of contact for federal staff on campaign matters.
- Leads the campaign leadership team in MRWFD communications.
 - MRWFD strategic plan and strategic implementation plan, and their periodic revisions
 - Annual accomplishments summary report
 - Other program communications (e.g., datasheets)





- Leads organization and conduct of annual technical area meetings.
- Leads organization and execution of annual campaign meetings.
- Leads coordination of work between technical areas or control accounts.
- Prepares baseline change proposals when needed.

6.4.2 Deputy National Technical Director

Overall responsibilities of the campaign deputy NTD include:

- Assists the leadership team in MRWFD communications.
 - MRWFD strategic plans and their periodic revisions
 - Annual accomplishments summary report
 - Other program communications (e.g., datasheets)
- Assists with organizing and conducting annual technical area meetings.
- Assists with organizing and conducting annual campaign meeting.
- Assists with broader coordination between technical areas.
- Assists with reviewing work package and milestone performance and quality.
- Assists as general backup for the NTD for DOE.

6.4.3 Control Account Managers

CAMs can also be known as technical area leads. Cost and schedule management (PICS:NE) responsibilities of CAMs include:

- Participates in annual work scope, schedule, and budget planning.
- Communicates program direction to WPMs.
- Prioritizes work scope within technical area.
- Identifies milestones and deliverables.
- Monitors work execution on schedule and within budget.
- Provides Control Account Summary monthly performance reporting in PICS:NE.
- Participates in Monthly Performance Review status teleconference as needed.
- Participates in applicable annual program review meetings.
- Proposes baseline changes, as applicable.

Technical management responsibilities include:

- Coordinates and optimizes work scope within assigned technical area.
- Integrates the work scope of the technical area into the campaign.
- Oversees all technical aspects within assigned technical area.





- Develops and proposes new work scope on existing or new technologies.
- Works with WPMs to develop proposals for new work scope.
- Presents new work scope to the campaign leadership.

6.4.4 Work Package Managers

WPMs have project management (PICS:NE) responsibilities, including:

- Develops and maintains baseline work scope, schedules, and budgets according to program guidelines, including those outlined in Appendix B.
- Provides monthly performance reporting in PICS:NE.
- Communicates status of milestones to NTD and CAM with anticipated late or missed milestones being communicated 30 days before due date.
- Participates in Monthly Performance Review status teleconference as needed.
- Prepares milestone completion notification documentation.

Technical management responsibilities include:

- Oversees the execution of work.
- Performs and leads specific scope as defined in approved work packages.
- As assigned by the CAM, leads collaborative efforts between national laboratories to optimally complete the scope of the work package.
- Develops and proposes new work scope on existing or new technologies.





7.0 MRWFD TECHNICAL PRIORITY AREAS

The MRWFD campaign's work scope is guided by a 5-year strategy organized around the technical areas with priority areas that collectively advance UNF recycling from current operational needs through longer-range commercial deployment. The strategy is designed to balance near-term priorities – such as resolving immediate technical challenges in existing systems and sustaining current operations – with longer-term investments in process optimization, technology innovation, and cross-cutting infrastructure. Together, the priority areas ensure that the campaign maintains technical leadership in aqueous, electrochemical, and fluoride volatility reprocessing technologies. By pursuing incremental improvements to proven processes alongside higher-risk, higher-reward innovations, the strategy targets the United States to establish a technically mature and commercially viable domestic fuel recycling capability over the coming decade.

7.1 Advanced and Innovative Aqueous Processes

The advanced aqueous technical area is developing an advanced voloxidation and direct extraction integrated process which has promise as a simplified aqueous approach with improved management of challenging volatile fission products and improved proliferation resistance. The direct extraction process dissolves and purifies the majority of the uranium while leaving a fraction behind with the transuranium and fission product elements in solid form. The campaign is scaling and demonstrating this approach with representative UNF. Additionally, the campaign is reinvigorating the fluoride volatility approach to recycling UNF, which has received little attention since the 1950s. This approach has advantages in recycling high burnup UNF given it is a dry process.

7.1.1 Priority Area 1 – Demonstrate Advanced Voloxidation

Advanced voloxidation is the first step in processing after used fuel is declad, which enables its dissolution directly into an organic solvent. Voloxidation is the conversion of irradiated UO_2 fuel to a higher oxide of uranium via oxidation at elevated temperature. To enable direct dissolution, the irradiated UO_2 is reacted with NO_2 to yield a fine UO_3 powder. The basic technology has previously been demonstrated, and the current effort is the production of a UO_3 powder containing TRU and fission product oxides and with physical properties to consistently meet the direct dissolution targets. Voloxidation also evolves volatile fission products, targeting iodine, which is difficult to recover via aqueous processing. The program will define the processing conditions and scale up the process equipment to meet product recoveries at a scale with eventual translation to industrial equipment. The product must be suitable for direct dissolution, and the equipment must be designed to accommodate remote operations, including the loading, unloading, and transfers of material between unit operations.

7.1.2 Priority Area 2 – Mature Uranium Recovery in the Direct Extraction Process

The initial strike of the direct dissolution process dissolves voloxidized irradiated UO_3 powder in a nitrate-loaded solvent consisting of the extractant DEHiBA [N,N-di(2-ethylhexyl)-2-methylpropanamide] dissolved in dodecane or kerosene. The goal of the process is to consistently dissolve 95% of the uranium in the irradiated UO_3 powder into the solvent, leaving the remaining 5% of uranium in a solid phase that also contains all remaining actinides and fission products.





The dissolution process generates three immiscible phases: uranium-loaded solvent; water released upon extraction of uranium; and the undissolved U, TRU, and fission products as mixed oxides and nitrates, though some nitrate will dissolve in the water phase. The equipment must allow for rapid dissolution to minimize radiation effects on the solvent, as well as complete separation and recovery of the three separate relatively clean phases. The organic phase will be stripped of U by solvent de-extraction; therefore, additives to the solvent or the process conditions must not impact stripping. The program will define the operating conditions that consistently achieve the dissolution targets and develop prototype equipment that enables eventual scale-up to industrial equipment. Key processing requirements include controlled addition of fuel powder, rapid dissolution, efficient phase separation, and material transfers that can be done remotely at scale.

7.1.3 Priority Area 3 – Mature U/TRU Recovery in the Direct Extraction Process

The second strike of the direct dissolution process dissolves the uranium, plutonium, and possibly neptunium that were not dissolved in the first strike in a different organic solvent using an extractant selective for U and Pu, and possibly Np, such as a nitrate-loaded solvent consisting of the extractant MOPPA [mono-(1,1,3,3-tetramethylbutyl)phenyl phosphoric acid] dissolved in dodecane or kerosene. The goal of the process is to consistently dissolve all of the residual U and Pu remaining in the undissolved solids in the solvent, leaving the fission products and minor actinides as solid nitrates and oxides. The dissolution process generates three immiscible phases: U- and Pu-loaded solvent, water released upon extraction of U and Pu, and the undissolved TRU and fission products as mixed oxides and nitrates. It is likely that some nitrate will dissolve in the water phase. As with the uranium extraction, the process equipment must allow for rapid dissolution to minimize radiation effects on the solvent, and efficient separation and the recovery of the three separate relatively clean phases. The collected organic phase will be stripped of U, Pu, and Np by solvent de-extraction. The program will define the processing conditions that consistently achieve the dissolution targets and design the prototype equipment that enables eventual scale-up to industrial equipment. Operations include controlled addition of feed powder, rapid dissolution, efficient phase separation, and material transfers. The solvent must be readily stripped of uranium and recycled, so additives, such as hold-back agents, and processing conditions must not impact dissolution or stripping.

7.1.4 Priority Area 4 – Np and Tc Selective Ligands for Direct Extraction

In the first strike of the direct dissolution process, Tc is coextracted with the uranium into the solvent phase and stripped from the solvent together with the U. Np is also extracted if it is present as Np(VI), so it must be reduced to Np(IV) or Np(V), which are not extracted by DEHiBA; otherwise, it must be selectively stripped from the solvent after dissolution. Separation of the Tc from U requires an additional ion exchange step. In the second strike of the direct dissolution process, both Np and Tc will dissolve to an extent.

In either process, the extraction of these species may be mitigated by the addition of complexants or hold-back agents that selectively bind to Np and/or Tc, preventing their extraction by DEHiBA or MOPPA. In stripping, these complexants may enable selective stripping of Tc and Np from the primary U or U/Np products, if desirable. The campaign is identifying candidate sulfonamide ligands with desired attributes for complexes with either Tc or Np and developing synthesis schemes for these ligands. The identified ligands will then be tested to verify that they display the desired selectivity for Tc or Np in these solvent systems. Finally, they will be tested with process feeds to verify the observed selectivity under process





conditions to determine if there are any detrimental impacts to the dissolution or stripping processes where they may be used.

7.1.5 Priority Area 5 – Direct Extraction Modeling

Process models are critical to the efficient design of process flowsheets for testing and implementation with process equipment. Computer codes for predicting distribution coefficients for solvent extraction and for designing detailed liquid-liquid extraction separations, and dissolution of UNF in nitric acid are established. However, codes that model the direct dissolution and extraction of UNF into an organic solvent do not yet exist, nor does a model for voloxidation.

The program plan is to adapt existing models and data for used fuel dissolution and solvent extraction, such as the AMUSE code, to the direct dissolution process as the chemistries are related. However, as a three-phase process, the new code will be developed specifically for direct extraction. By developing an extensible platform, additional processes can be integrated with the dissolution processes, including voloxidation, ion exchange, and off-gas capture. The final code will enable a complete mass balance for the facility as implemented.

7.1.6 Priority Area 6 – Fluoride Volatility

Fluoride volatility is used to separate different volatile fluoride species according to relative differences in volatilities and reactivities with surfaces. The process first separates volatile components of used fuel that has been fluorinated from non-volatile components. In used fuel, UF_6 , NpF_6 , PuF_6 , and several transition metal fission product fluorides are volatile at low pressures and temperatures sufficiently above ambient. Because NpF_6 and PuF_6 are less volatile and more reactive than UF_6 , they can be captured on a solid adsorbent composed of UF_4 or UF_5 . Several of the volatile transition metal fission product fluorides are more volatile than UF_6 and are not captured on the adsorbent.

The programmatic plan is to identify conditions under which UF_6 remains bound by the UF_5 adsorbent while fission product fluorides are not captured, and conditions under which UF_6 can be effectively separated from NpF_6 and PuF_6 by selective adsorption of the latter two species on UF_5 . The program will identify the appropriate conditions that achieve these separations at small lab-scale, and will then design equipment to enable scale-up of the process as required to recover reactor-grade UF_6 from used fuel.

7.2 Electrochemical Processes and Innovative Salt Systems

Electrochemical processing is a high-temperature, non-aqueous technology for recycling UNF, primarily through electrorefining in a molten salt bath. The molten salt provides benefits with an absence of neutron moderators and immunity to radiation and thermal damage. The campaign is bridging technical gaps to deployment and optimizing key process steps. Although ideal for metallic fuels, the campaign is expanding the processes with head-end and process treatment steps to accommodate diverse advanced reactor fuels. Key technology developments include a new U/TRU co-deposition process providing improved separation factors from challenging fission products, advances in predictive modeling, recovery of high value materials from UNF, and technologies to reduce waste. Near term ambitions for electrochemical processing will be to assess off-normal conditions to derisk commercial deployment.





7.2.1 Priority Area 1 – Bridging Technical Gaps

This area addresses immediate and near-term operational challenges. This includes managing the liquidus temperature of the Mk-IV electrorefiner salt as sodium and fission products accumulate, developing sacrificial electrodes to protect salt systems from moisture and oxygen ingress, optimizing voloxidation for finer particle sizes to improve separations efficiency, establishing salt cleanup and recycle capability to extend salt life and reduce waste, clarifying the iodine mass balance in electrochemical systems, improving corrosion control through better understanding of chloride and fluoride potentials, and developing experimental approaches to characterize off-normal and accident conditions.

7.2.2 Priority Area 2 – Maintaining Leadership Through Process Optimization

Improving the performance and understanding of existing electrochemical processes is the focus of this area. Key activities include developing optimized salt-metal separation systems (bottom pour, distillation, centrifugation), building working models of electrochemical test systems, demonstrating cadmium-free solid U/TRU co-deposition in LiCl-KCl, developing mitigations for oxygen electrode fouling in oxide reduction, establishing predictive modeling of uranium dendrite morphology, and developing an “electrochemical processing toolkit” for monitoring and process control in molten salt systems.

7.2.3 Priority Area 3 – Championing New Electrochemical Technologies

This area pursues longer-range innovations to expand the range of fuel types and processing approaches available. This includes evaluating innovative oxide reduction and electrorefining systems, evaluating LiCl-only electrochemical processes, establishing the feasibility of oxide dissolution as a replacement for oxide reduction and electrorefining, addressing R&D gaps for MSR fuel cycles through liquid-liquid extraction and fluoride salt technologies, establishing competencies in fluoride-based electrochemical reprocessing including fluoride distillation processes, and exploring innovative approaches for UAlx, TRISO, and other non-LWR fuel types.

7.2.4 Priority Area 4 – Cultivating Cross-Cutting Technologies

This priority area provides the sustained infrastructure and collaborative framework needed to support the other three goals on an ongoing basis. This includes proactive stewardship of the nation's electrochemical testbeds, pursuing high-value engineering-scale technology demonstrations useful to industry, determining licensing needs for commercial electrochemical processing facilities to inform R&D priorities, coordinating with notice of funding opportunity (NOFO) awardees to avoid duplication, continuing small high-risk/high-reward innovation proposals, maintaining active industry collaboration, and integrating with other DOE-NE campaigns to identify cross-cutting opportunities.

7.3 Off-Gas and Waste Forms

The Off-Gas and Waste Forms Technical area focuses on increasing the technical readiness of key solutions to achieve U.S. regulatory needs, such as EPA 40CFR190 regulations for iodine, and waste forms which can successfully encapsulate salt wastes. Notably, the campaign is leading international research in copper-based sorbents for iodine, potentially offering a much less expensive, non-regulated under the Resource Conservation and Recovery Act, and ten-fold increase in iodine loading solution versus the current silver-based state of the art sorbent. The campaign is also developing a glass waste





form capable to directly dissolve and encapsulate salts with a simple melting and mixing process, potentially dramatically simplifying salt waste disposal.

7.3.1 Priority Area 1 – Establishing Options for Salt Waste Forms

Long-term solutions are being studied for treatment and immobilization of salt wastes generated from electrochemical processing of EBR-II fuel for disposal. The two general pathways are being explored: (a) full salt immobilization options and (b) partitioned salt options.

The baseline process for full-salt immobilization is the glass-bonded sodalite ceramic waste form (GBS-CWF) process, but other options are being considered, including a single-step vitrification using a glass frit. For the GBS-CWF process, work is ongoing to dramatically simplify the waste form production baseline approach by eliminating powder preparation steps (i.e., using larger-sized reagents and salt), eliminating the salt occlusion step, and reducing processing temperatures and times. Additionally, scale-up of this simplified approach is planned for fiscal year 2026.

For partitioning salt, the most promising pathway is halide removal (dehalogenation), considering that the halogen content limits solubility in all known candidate waste form systems. The current work for dehalogenation evaluation is ongoing with organic acid reagents, and the properties of the resulting borosilicate glass products after mixing with glass-forming additives and performing high-temperature vitrification are being studied, including chemical durability, phase distribution, and microstructural analyses. The waste form products resulting from organic acid dehalogenation have the potential to increase salt cation loading in the final waste form by more than 10× compared to that of the GBS-CWF.

7.3.2 Priority Area 2 – Developing Options for Iodine and Noble Gas Management

Off-gas scrubbing is needed for aqueous and electrochemical reprocessing and during operation of MSRs to meet regulatory and environmental release requirements for these facilities. Three of the primary off-gas elements/radionuclides of concern in all these processes are ^{85}Kr , Xe, and ^{129}I .

The baseline sorbent system for radioiodine is silver mordenite (reduced IONEX Ag-900, AgZ), but additional technologies and materials are being explored that include solid sorbents with higher decontamination factors and higher overall loading capacities. Testing and evaluation of new materials includes static and dynamic iodine testing on (a) sorbents with higher Ag-content than Ag-900 (9-13 mass% Ag) [e.g., Ag-faujasite (26 mass% Ag), Ag-chabazite (18 mass% Ag), Clariant AC6120 (12 mass% Ag)], (b) sorbents without silver due to its complications with disposal and high associated costs (e.g., Bi-based sorbents, Cu-based sorbents), and (c) liquid scrubbers (e.g., caustic).

Additional options are being explored to improve sorbent performances by increasing bed lifetimes and bed capacities by including NO_x removal upstream of the iodine solid sorbent bed since NO_x exposure degrades all chemisorption-based active sorbents.





For noble gas (^{85}Kr , Xe) capture, the baseline capture process is cryogenic distillation, but solid sorbents with higher operating temperatures (target: near room temperature) are being explored. For solid sorbent development, ongoing efforts include materials exploration, materials production, engineered form production of promising candidate materials, and extensive testing on these materials. The goals of the experimental testing are to compare breakthrough times, loading capacities, selectivities, regeneration, specific surface area, as well as other properties.

7.4 Chemical Decladding

Chemical decladding is a group of technologies aimed at removing zirconium or aluminum cladding from UNF. Chemically decladding zirconium cladding could facilitate its recycle for fabricating fuel hardware. Chemically decladding aluminum has benefits for waste management because established processes typically dissolve the aluminum and fuel together such that the aluminum contributes to the HLW volume. The primary approach under development uses a chlorinating liquid to effect decladding through the formation of dissolved ZrCl_4 or AlCl_3 at low temperature and atmospheric pressure. Another process using molten lithium to dissolve aluminum and is potentially compatible with processing aluminum-clad fuel at INL. RD&D is progressing to simulated UNF before demonstration with representative actual UNF.

7.4.1 Priority Area 1 – Establish Sulfur Monochloride (S_2Cl_2) Process Technologies

Foundational S_2Cl_2 process technologies needed to support both aluminum- and zirconium-based systems will be developed. All activities will be conducted to identify and solve the practical problems associated with advancing S_2Cl_2 processes to engineering scale. This includes identifying compatible materials of construction, producing surrogate fuel plates to support testing, and creating processes for solvent regeneration and UCl_3 recovery. The effort also emphasizes developing and implementing on-line monitoring to track solvent condition, understand the effects of radiation on chlorination behavior, and identify reliable pumps and seals, and integrating these elements into functional bench- and engineering-scale systems. Together, these activities provide the underlying scaffold for a viable, scalable chlorination process with the necessary materials, controls, and performance data to support further development.

7.4.2 Priority Area 2 – Demonstrate S_2Cl_2 for Decladding Aluminum Fuel

A viable pathway for reprocessing of aluminum-clad fuels, such as those from the Advanced Test Reactor (ATR) located at INL, will be developed and demonstrated. This includes developing a reliable method to extract AlCl_3 from the solvent and recovery of uranium from the fuel in a form compatible with further purification for reuse. An integrated half-scale process capable of recovering uranium fuel particles from depleted UAlx -bearing fuel plates will be established to develop and optimize operating parameters. In addition, the objective includes advancing this capability to a hot-cell environment by demonstrating the integrated system with half-length irradiated fuel plates. Together, these efforts aim to validate the technical feasibility and scalability of the S_2Cl_2 process for aluminum decladding under both surrogate and radiological conditions.

7.4.3 Priority Area 3 – Demonstrate S_2Cl_2 for Decladding Zirconium Fuel

Priority Area 3 focuses on a low-temperature approach for decladding zirconium fuels using S_2Cl_2 . This includes developing a fundamental understanding of and a reliable method for extracting ZrCl_4 from the





solvent, as well as establishing an integrated half-scale process to recover uranium from zirconium-clad fuel materials. The objective also advances to hot-cell demonstration by enabling testing of the integrated system with half-length irradiated fuel plates. Collectively, these efforts aim to validate the effectiveness and scalability of the S_2Cl_2 process for zirconium decladding under both surrogate and radiological conditions.

7.4.4 Priority Area 4 – Demonstrate UAlx Processes Compatible with the Fuel Cycle Facility

UAlx processing technologies that are compatible with the Fuel Cycle Facility will be developed to provide a viable pathway to ATR fuel reprocessing and ensure continued efficient use of available hot-cell space. Several promising technologies have been identified and are at various stages of development. Activities include developing and demonstrating lithium-based aluminum decladding with associated lithium recovery, evaluating the feasibility of uranium electrorefining from solid or molten aluminum, and investigating gallium-based decladding processes including aluminum dissolution, uranium recovery, and gallium recycle. In parallel, viable technologies will be compared and assessed based on Fuel Cycle Facility compatibility, implementation cost, and processing timelines for ATR fuel. Any new technologies will have to compare favorably to the best of these to be considered further. The most promising approaches will be demonstrated at bench scale using irradiated fuel to support down-selection and future deployment.





8.0 MRWFD CAMPAIGN RISKS AND OPPORTUNITIES

8.1 Funding and Budget Risks

The most immediate risk to the MRWFD campaign is funding instability. The campaign requires sustained, multi-year investment to advance technologies through successive scales of demonstration. Interruptions in funding can disrupt long-running experimental campaigns, result in loss of specialized staff, and delay milestone completion in ways that are difficult and costly to recover from. Changes in Congressional appropriations, shifts in DOE-NE budget priorities, or competition for resources from other campaigns could compress or redirect the planned work scope.

Mitigation Approaches:

- Maintain a clearly prioritized, tiered work scope that identifies which activities can absorb budget reductions with minimum programmatic impact and which can be deferred, enabling rapid and coherent responses to budget changes.
- Maintain a portfolio of activities spanning short-term operational priorities and longer-range technology development, ensuring that some near-term, high-visibility deliverables are always in progress to demonstrate value and sustain sponsor confidence even in constrained budget environments.
- Coordinate with other DOE-NE campaigns to identify shared priorities and cost-sharing opportunities that can sustain critical activities even when individual campaign budgets are constrained.

8.2 Facility and Infrastructure Risks

The MRWFD campaign depends heavily on several unique but aging national laboratory facilities. Equipment failures, facility maintenance outages, safety-driven operational restrictions, or loss of facility authorization could significantly disrupt experimental programs.

Mitigation Approaches:

- Advocate for equipment maintenance and inspection programs for all critical electrochemical testbed infrastructure, with particular attention to high-risk components.
- Develop contingency experimental plans that identify alternative facilities or scaled-down experimental approaches that can be substituted if a primary testbed becomes unavailable, minimizing the impact of facility outages on milestone completion.
- Invest in design improvements and materials selection for new and replacement equipment to extend operational lifespans.
- Proactively invest in testbed stewardship as a continual cross-cutting activity, ensuring that facility condition assessments, safety basis updates, and infrastructure investments are addressed before they become critical path issues.





8.3 Workforce and Talent Risks

The MRWFD campaign requires a highly specialized technical workforce with broad expertise. This expertise is concentrated in a relatively small number of individuals at the national laboratories who carry institutional knowledge accumulated over decades of fundamental and applied research activity. Retirements, attrition, or difficulty recruiting and retaining qualified personnel, particularly given competition from the growing commercial nuclear sector, could create capability gaps that are difficult to fill quickly. The university talent pipeline supported through NEUP awards and partially mitigates this risk but cannot fully replace experienced practitioners in the near term.

Mitigation Approaches:

- Actively support the university talent pipeline through NEUP awards, graduate student internships, and postdoctoral appointments to ensure a steady flow of early-career researchers into the campaign.
- Implement structured knowledge capture practices to reduce dependence on tacit knowledge held by individual experts and facilitate onboarding of new personnel.
- Develop formal mentoring and succession planning processes that pair early-career researchers with experienced practitioners in critical technical areas before retirements or departures create gaps.
- Coordinate across the labs to share specialized expertise, reducing the risk that the departure of a single individual creates a critical capability gap at either institution.

8.4 Regulatory and Licensing Risks

The near-term technical area strategies assume that regulatory engagement with the NRC progresses in a manner that allows licensing-relevant data to be generated in a timely and targeted way. However, the absence of well-exercised regulatory framework for commercial reprocessing facilities in the U.S. represents a significant source of uncertainty. If NRC develops new or unexpected data requirements, if the regulatory pathway for reprocessing proves more complex than anticipated, or if safeguards and nonproliferation concerns lead to additional restrictions on certain process chemistries or fuel types, the MRWFD campaign's scope and timeline may need to be substantially revised.

Mitigation Approaches:

- Engage with NRC to build a shared understanding of the licensing pathway, identify data needs as early as possible, and reduce the risk of late-stage surprises requiring costly additional work.
- When necessary, conduct a regulatory gap analysis to identify where current data does and does not address anticipated licensing requirements, and use this to prioritize activities that fill the most critical gaps.
- Engage the safeguards and nonproliferation community, including the MPACT program to ensure process designs incorporate safeguards and proliferation resistance by design, reducing the risk of late-stage regulatory objections.





8.5 Industry and Commercial Landscape Risks

The relevance and prioritization of specific technical activities in the near-term is partly predicated on assumptions about which advanced reactor and fuel recycling concepts will gain commercial traction over the strategy period. If the commercial landscape shifts – for example, if MSR deployment timelines accelerate or decelerate significantly, if certain fuel types gain or lose industry interest, or if NOFO awardees pursue technical directions that overlap more than expected with MRWFD activities – the campaign may need to rebalance its portfolio to remain aligned with actual industry needs and avoid duplication.

Mitigation Approaches:

- Maintain active engagement with industry partners and NOFO awardees through semi-annual coordination meetings and annual industry workshops to stay current with evolving commercial priorities and adjust the MRWFD campaign’s portfolio before misalignment becomes significant.
- Structure the work scope around broadly applicable technology platforms and unit operations rather than optimizing narrowly for a single commercial concept that may not ultimately be deployed.
- Maintain an agile work scope and be able to pivot to new technologies if necessary.
- Conduct annual portfolio reviews that explicitly assess the continued relevance of each major technical activity against the current commercial landscape, with clear criteria for adding, modifying, or discontinuing activities.

8.6 Geopolitical and Policy Risks

Broader geopolitical developments and shifts in U.S. energy and nonproliferation policy could alter the strategic context for the MRWFD campaign’s work. Changes in U.S. policy on UNF reprocessing, shifts in international safeguards requirements, or disruptions to uranium supply chains that change the economic case for recycling could all affect program priorities and resource levels. Conversely, increased urgency around domestic fuel supply security, as has been seen with HALEU availability concerns, could accelerate certain aspects of the program, particularly those tied to near-term material recovery missions.

Mitigations:

- Monitor evolving U.S. energy and nonproliferation policy through active engagement with DOE-NE policy offices, ensuring the program is positioned to respond quickly to shifts that affect the strategic case for recycling.
- Coordinate with the DOE Office of Environmental Management and NNSA to identify synergies between electrochemical R&D and used fuel management, waste disposition, and nonproliferation missions, broadening the program’s policy relevance and potential funding base.

8.7 Supply Chain and Materials Risks

Several aspects of the MRWFD campaign’s work scope depend on access to specific materials and equipment. Delays in acquiring surrogate materials, restrictions on the transfer of irradiated fuel between facilities, or supply chain disruptions affecting specialty equipment and materials could delay experimental campaigns and push milestones beyond planned completion dates.





Mitigation Approaches:

- Initiate material acquisition activities well in advance of experimental needs, pursuing multiple parallel procurement sources for critical materials and equipment where possible.
- Identify and qualify non-radioactive surrogate materials that can advance process development in non-radiological facilities while irradiated fuel acquisition is pending, maximizing productive use of available experimental time.
- Build schedule contingency into campaigns that depend on irradiated or TRU materials, recognizing that regulatory approvals and inter-facility transfers routinely introduce unpredictable delays.
- Maintain an inventory of commonly used consumables to buffer against supply chain disruptions that might otherwise cause immediate experimental interruptions.

8.8 Commercial and Political Opportunities

There has recently been a resurgence in commercial interest for reprocessing and recycling UNF, with individual vendors expressing interest in pursuing aqueous, electrochemical, and fluoride volatility technologies. Additionally, the President's Executive Order "Reinvigorating the Nuclear Industrial Base," signed on May 23, 2025, says:

It is the policy of the United States to... maximize the efficiency and effectiveness of nuclear fuel through recycling, reprocessing, and reinvigorating the commercial sector.

Thus, there are both commercial and political drivers toward reprocessing and recycling UNF that present an opportunity for the MRWFD campaign to expand its technical activities and influence. The opportunity can be realized with the following measures:

- Aligning technical program priority areas to commercially viable options.
- Increasing vendor participation in campaign reviews and planning activities by invitations to program reviews or under contract for consultancy, for example.
- Active participation in national and international forums and conferences.





9.0 CONCLUDING REMARKS

This strategic plan has described a strategy for the MRWFD campaign that is consistent with current U.S. policy, technology maturation guidance, and national trends in terms of the following.

- Strategic objectives
 - Optimize utilization of fissile resources for power generation
 - Minimize required geological and near-surface repository capacity requirements
 - Minimize proliferation risk
 - Support reduction of environmental emissions of radioactive and hazardous materials to zero
- Technology maturation consistent with DOE guidance
- Organizational interfaces ranging from NE-4 through international relevant to the work of the campaign
- Campaign organization
 - Technical programs
- Technical program priority areas
 - Electrochemical processes and innovative salt systems
 - Advanced and innovative aqueous processes
 - Off-gas and waste forms
 - ZIRCEX and advanced chlorination
- Campaign-level risks and opportunities
 - Funding and budget
 - Facility and infrastructure
 - Workforce and talent
 - Regulatory and licensing
 - Industry and commercial landscape
 - Geopolitical and policy
 - Supply chain and materials
 - Commercial and political opportunities





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Appendix A: Technology Readiness Level Criteria





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This appendix describes the criteria that should be assessed to determine the Technology Readiness Level (TRL) of a technology. The TRL title is followed by the overall question to be answered, followed by the criteria in terms of concept development, testing, and modeling and simulation.

TRL-4: Complete Technology and/or its Components Validated in the Laboratory

Has laboratory-scale testing of the technology, like full-scale, been completed in the laboratory?

Concept Development

1. Key process variables/parameters fully identified and preliminary hazard evaluations have been completed and documented.
2. Metrics for measuring technology performance against requirements have been established.
3. Analysis completed to establish technology's component compatibility (do components work together).
4. Scalable equipment prototypes have been produced (components made larger than laboratory scale).
5. Scaling documents and designs of equipment have been completed.

Testing

1. Tested laboratory-scale technology components are surrogates for full-scale components.
2. Individual technology components tested in laboratory or by supplier.
3. Multiple technology components tested at laboratory scale using performance-based simulants.
4. Laboratory test requirements, derived from technology requirements, are established.
5. Available technology components assembled into the laboratory-scale test arrangement.
6. Planning for prototypical laboratory-scale tests completed.
7. Laboratory experiments with available components show that they work together.
8. Technology demonstrates basic functionality in the laboratory, to include test and validation of safety functions.
9. Controlled laboratory environment used in testing.
10. Low-fidelity (approximate) technology integration and engineering completed in the laboratory.
11. Process/parameter limits and safety control strategies are being explored.





12. Key physical and chemical properties have been characterized for a range of feeds.
13. A limited number of simulants have been developed that approximate the range of used nuclear fuel (UNF) feed properties.
14. Laboratory-scale tests on a limited range of simulants and real UNF have been completed.
15. Scale-up relationships are understood/accounted for in technology development program.
16. Manufacturing processes for key equipment and chemicals have been identified.
17. Developmental manufacturing processes for key equipment and chemicals assessed in laboratory.

Modeling and Simulation

1. Modeling and simulation used to simulate some components and interfaces between components.

TRL-3: Analytical and Experimental Critical Function and/or Characteristic Proof of Concept

Has the technology's concept been proven in a laboratory environment?

Conceptual Development

1. Key process parameters/variables and associated hazards have begun to be identified.
2. Paper studies indicate that the technology components ought to work together.
3. Performance metrics for the technology are established (what must it do).
4. Scaling studies have been started.
5. Analysis of present state of the art shows that technology fills a need.

Testing

1. Testing completed with a simple simulant that includes the principal chemical and physical characteristics affecting technology performance.
2. A comprehensive performance-based simulant has been developed that approximates key feed properties.
3. Predictions of elements of technology's capability validated by analytical studies.
4. The basic science has been validated at the laboratory scale.





5. No technology components, only basic laboratory research equipment to verify physical principles.
6. Laboratory experiments verify feasibility of application.
7. Sources of key hardware and chemicals for laboratory testing identified.
8. Scientific feasibility fully demonstrated.
9. Laboratory-scale tests on a simulant have been completed.
10. The individual technology components have been tested at the laboratory scale.

Modeling and Simulation

1. Science known to the extent that mathematical and/or computer models and simulations are possible.
2. Predictions of elements of technology's capability validated by modeling and simulation.

TRL-2: Formulation of Technology Concept

Has the technology concept and/or application formulated?

Concept Development

1. Potential need of the application has been identified.
2. Basic components of the technology have been identified.
3. The scope and scale of the problem to be solved with the technology has been determined.
4. Preliminary strategy to obtain TRL-4 developed (e.g., scope, schedule, cost).
5. Capabilities and limitations of researchers and research facilities are known.
6. The experiments required (research approach) to achieve TRL-3 are known.

Testing

1. Paper studies show that application of the technology is feasible.
2. A performance-based simulant has been conceptualized.
3. Technology components have been partially characterized for performance.
4. Rigorous analytical studies confirm basic principles.





5. Analytical studies reported in scientific journals/conference proceedings/technical reports.
6. Individual components of the technology work (no real attempt at integration).

Modeling and Simulation

1. Performance predictions made for each element.
2. Modeling and simulation only used to verify physical principles.

TRL-1: Observation and Reporting of Basic Principles

Have the basic technology principles been observed and reported?

1. “Back of envelope” performance-based simulant defined.
2. Physical laws and assumptions used in new technologies defined.
3. Paper studies confirm basic principles.
4. Initial scientific observations reported in journals/conference proceedings/technical reports.
5. Basic scientific principles observed and understood.
6. Know where, why, and how the technology is beneficial.
7. Research hypothesis formulated.
8. Basic UNF characterization data exists to proceed.
9. Know who would perform research and where it would be done.





Appendix B: Guidance for Development and Execution of Work Packages





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This appendix describes the guidance for control account managers (CAMs) and work package managers (WPMs) to follow during the development and execution of work packages.

General Work Package Guidance

PICS (Program Information Collection System) is DOE-NE's program planning and authorization tool. It captures the scope, budget, and authorizations to be spending funds on these topics. PICS provides a single, standardized source of truth for planning, executing, tracking, and reporting DOE-NE research and development projects, allowing laboratory management, National Technical Directors, and DOE Program Managers to make informed technical and financial decisions throughout the project lifecycle. It can also be viewed as the work package managers' way to communicate to the CAM, NTD, and DOE on the status of their projects.

Roles & Responsibilities

Role	Primary Responsibility	PICS Responsibilities	Typical Monthly PICS Workflow
WPM (Work Package Manager)	Executes and/or enables the technical work and manages individual work packages.	Updates technical progress, percent complete, milestone status, deliverables, resource needs, technical accomplishments, risks, and issues. Provides the technical information that feeds PICS reporting but typically does not approve baselines or funding changes.	- Update technical accomplishments and percent complete. - Update milestone and deliverable status. - Identify technical risks, issues, and opportunities. - Forecast remaining work and resource needs. - Submit monthly inputs to the CAM for review.
CAM (Control Account Manager)	Owens the technical scope, schedule, and cost for one or more control accounts. Generally serves as the technical lead for the overall technical subject.	Develops work packages; manages scope, schedule, and cost within the control account; reviews and approves WPM inputs; updates forecasts; identifies risks and issues; recommends baseline changes; and certifies monthly PICS reporting.	- Review and validate WPM updates. - Update cost and schedule performance. - Analyze variances and develop corrective actions. - Update forecasts (ETC/EAC), as needed. - Certify monthly PICS status prior to submission.
NTD (National Technical Director)	Provides programmatic oversight for a DOE-NE technical area across the national laboratory complex.	Reviews annual work scope, monitors technical progress across laboratories, evaluates milestone completion, ensures alignment with DOE program objectives, recommends funding adjustments, reviews PICS performance reports, and communicates technical priorities.	- Review laboratory progress reports. - Assess technical performance against program objectives. - Evaluate milestone completion and overall portfolio health. - Identify technical gaps and emerging priorities. - Recommend funding or scope adjustments to DOE, as appropriate.
DOE Program Manager	Serves as the federal owner of the DOE program and associated funding.	Establishes program direction, approves budgets and baselines, authorizes funding, reviews laboratory performance, approves major baseline changes, evaluates milestone completion, and uses PICS to monitor execution, spending, schedule performance, and program outcomes.	- Review portfolio-wide PICS status and financial execution. - Monitor schedule, cost, and milestone performance. - Approve baseline and funding changes, as required. - Provide strategic direction and priorities. - Report program performance to DOE leadership and stakeholders.

Yearly Work Package Planning

Scope - The work package scope is the foundation of the PICS entry and should clearly communicate what work will be performed, why it is important, and what outcomes will be achieved. The scope should be written at a level that provides DOE and program management with a clear understanding of the





planned work while allowing flexibility for some adaptation as the project evolves. The scope should focus on the technical objectives, major work areas, and expected deliverables, rather than detailed experimental procedures or day-to-day activities. A well-written scope should describe the work for the entire period of performance and demonstrate how it supports DOE program goals.

Objective - The Objectives section should clearly define the technical outcomes the work package is intended to achieve during the fiscal year. Objectives should be written as high-level, outcome-focused statements that describe the capabilities, knowledge, products, or technologies that will be developed or demonstrated. Avoid listing detailed tasks, experimental procedures, or routine activities. A well-written objective should allow a reviewer to quickly understand what success looks like at the completion of the work package.

Assumptions & Prerequisites - The Assumptions and Prerequisites section should identify the key assumptions and dependencies upon which successful execution of the work package relies. These statements should focus on conditions that are outside the direct control of the WPM and could significantly impact the project's ability to meet its objectives if they are not satisfied. This section is not intended to describe project risks or routine project management activities.

Activities & Milestones - While no work package is the same, it is recommended that you break up your activities into logical tasks which are the right size to be reasonably planned and make sense for your milestones. M4s are generally planning activities or the conclusion of minor research. M3s are to report on significant activities, funded at ~\$300k or greater. M2s are pre-defined and will be pre-loaded into the applicable WP. Always review these carefully and communicate early if there are major issues. Any milestone delays should be socialized in advance. It is expected that M3's and M4's should be appropriately included leading up to M2 milestones. We plan activities for a fiscal year, do not plan activities or milestone into the next fiscal year unless discussed with the CAM or NTD in advance.

Activities - Activities define the major technical work areas required to achieve the work package objectives. They should provide a logical framework for organizing the work throughout the fiscal year without becoming a detailed project schedule. Activities should describe what major work will be performed, not every experiment, meeting, or individual task.

Milestones - Milestones are the measurable technical accomplishments that demonstrate progress toward completing the work package objectives. They should represent meaningful outcomes, not routine activities, and provide clear evidence that the project is advancing as planned. Milestones should represent meaningful accomplishments that demonstrate measurable progress toward the work package objectives. In most DOE-NE work packages these are technical accomplishments, but milestones may also represent key decision points, technology demonstrations, or major deliverables. Each milestone should have a clear completion criterion and, whenever possible, produce a tangible outcome that can be objectively verified.

Within PICS, milestones should be a separate item subordinate to the from the associated "activity" containing the funding spread. The "criteria for completion" tab of the milestone deliverable form should be used to provide additional detail on technical objectives of the milestone necessary for the intent to have been met, not to state administrative plans such as "a report will be uploaded into PICS."





Milestone Levels

Level	Description	Typical Use	Notes
M1 – Program Milestone	Major accomplishment with significant DOE or campaign-level impact. Typically represents completion of a major program commitment or strategic objective. These milestones are relatively rare within individual work packages.	Major DOE deliverables, engineering-scale demonstrations, qualification packages, integrated technology demonstrations, major campaign commitments.	Never use, unless a rare circumstance exists or directed by NTD.
M2 – Project Milestone	Major accomplishment within a project or work package that demonstrates successful achievement of the primary technical objective. This is typically the most significant milestone within an annual work package.	Complete technology demonstration, complete integrated experiment, validate a prototype, complete a major process demonstration.	Status of M2s is provided monthly to DOE-HQ.
M3 – Technical Milestone	Significant technical accomplishment supporting the primary project objective. These milestones demonstrate measurable technical progress and often lead to completion of an M2 milestone.	Complete process optimization, validate a computational model, complete characterization campaign, establish operating parameters, complete test matrix.	Any edits or delays to M3s are provided monthly to DOE-HQ. Delays should be socialized in advance.
M4 – Supporting Milestone	Supporting accomplishment or intermediate deliverable that enables subsequent technical work. M4 milestones should be used sparingly and only when formal tracking of an intermediate accomplishment is beneficial.	Complete design package, complete data package, complete down-selection, submit topical report, complete supporting analysis.	Not reported to DOE but monitored monthly. Delays or edits should be socialized in advance.

Budget Planning - The work package budget should support successful execution of the planned scope, activities, milestones, and deliverables. While the total work package budget is pre-populated in PICS, WPMs are responsible for developing a realistic monthly spending plan that aligns with the technical schedule and laboratory financial systems. Budget plans should accurately reflect the work expected to be performed and be actively managed throughout the fiscal year to minimize significant variances.

- When developing the budget, WPMs should:
- Recognize that the overall work package budget is pre-populated in PICS; only the monthly budget distribution is planned by the WPM.
- For INL work packages, ensure the final monthly budget spread is consistent with the INL COBRA financial system.
- Align planned expenditures with the work package scope, activities, milestones, and schedule.
- Include all anticipated costs, including labor, materials, analytical support, facility usage, procurements, travel, and subcontracts, as applicable.





- Plan approximately 20% carryover into the first quarter of the following fiscal year, when appropriate, to mitigate potential continuing resolution delays.
- If a larger carryover is anticipated, plan it realistically and budget only for the work that can reasonably be executed during the fiscal year.
- Monitor spending throughout the year and update forecasts as project conditions change.
- Minimize significant budget variances, as large underruns or overruns require explanation during DOE-NE monthly program reviews.
- **Best Practice:** Budget to execute the planned work—not to spend the available funding. A realistic budget accurately reflects when work will occur, supports successful completion of milestones, and demonstrates effective planning and execution. Avoid creating a budget spread that will show dramatic underspending toward the end of the year.

Follow your individual laboratory expectations to plan the monthly budget distribution. For INL work packages, final PICS monthly budget spreads must be based on data from INL's COBRA financial system. Each WP budget is reported to NE-4 in a monthly DOE-HQ program review meeting. Significant variances are flagged and must have an explanation.

Note - When entering Q3 and your WP is 75% underspent, this is poor messaging to program leadership about your ability to plan and execute research.

Carryover - Plan ~20% of your budget as carryover into the next fiscal year to mitigate funding delays associated with continuing resolution. This is easily done by having an Activity titled, "Carryover"

Monthly Reporting - The second week of the month, WP managers will be notified by the system to enter a bulleted text summary of accomplishments in PICS. Take a few minutes to think about "Look Aheads," which might be interesting or notable experiments, hosting of conferences/workshops, or similar interesting items that could be used to help highlight our program to DOE-HQ.

Your input is harvested for DOE's monthly review meetings to highlight the value gained for the expenditures. Short summary paragraphs of the accomplishment and its value to the program are ideal. If you enter vague explanations of accomplishments just to fill in the text box, this is not a productive use of anyone's time. We all recognize that not every WP has substantive accomplishments every month; in that case, a few sentence reminder of working on topic X in preparation for the upcoming milestone would be appropriate.)

Missed Milestones - Missed or delayed level 2 and level 3 milestones are tracked by DOE and reported on their own slide in the monthly program review. These should be identified as far in advance as achievable. The important thing is to help provide information to help the program articulate to DOE the significant efforts made to accomplish the milestone (although possibly ultimately unsuccessful), and how we will recover.





Milestones and Reporting - Generally, milestone reports can be completed with your laboratory's template and document tracking numbers, but it is preferable to use MRWD's template, especially when multiple institutions are involved. In this case, the report number is still from the lead institution, as DOE-NE no longer has its own document tracking system. Reports uploaded into PICS must have been cleared for public release through your laboratory's clearance process. If the milestone was not appropriate for a report, notice of milestone completion can be done as a memorandum to the NTD, with copies to CAM and federal program manager. It is required that the memorandum reference the work package, milestone numbers, report title, and lab identifier number.

Quality Level - The Quality Rigor Level (QRL) of most of our research is 3. Paper studies and literature surveys are QRL 4. For QRL 3, we are no longer required to do QA cover pages and are instead covered by DOE Order 414.1 (this is a check box on the milestone submittal form). Below this checkbox you will simply list your technical reviewer (usually internal to your lab).

Export Control - PICS is not suitable for export controlled or similar information. In the event your deliverable report is controlled unclassified information (CUI), a memorandum should be uploaded to PICS which provides a suitable short summary, references the milestone, and directs the reader to an appropriate point of contact and backup point of contact at your laboratory to receive the full CUI report. Memoranda uploaded into PICS must have been cleared for public release through your laboratory's clearance process. You must email the CAM, NTD, Deputy NTD and federal program manager with a copy of the milestone report.

BCP

A Baseline Change Proposal (BCP) is the formal process used to request approval for significant changes to an approved work package baseline. The project baseline consists of the approved scope, schedule, budget, milestones, and deliverables. A BCP helps ensure that significant changes are properly documented, reviewed, and approved before implementation, maintaining an accurate and traceable project baseline. Not every change requires a BCP; routine technical adjustments that do not affect the approved baseline can typically be managed through normal project execution. When in doubt, WPMs should consult program leadership to determine whether a BCP is required.

A BCP should be considered when:

- The approved technical scope changes significantly, or in a way that wouldn't be clear to program leadership.
- Milestones or deliverables are added, deleted, or significantly modified.
- The project schedule changes in a way that affects the approved baseline.
- The approved work package budget changes beyond established laboratory or program thresholds.
- Additional funding results in new scope, additional milestones, or expanded project objectives.
- Budget reductions require descopeing work or modifying planned deliverables.
- DOE or the NTD directs a significant change in project priorities or objectives.





A BCP should include:

- A clear description of the proposed change.
- The reason for the change.
- The impact on scope, schedule, budget, milestones, and deliverables.
- The benefits, risks, and justification for the proposed change.
- Any impacts to other work packages or projects.

Acknowledgments - For all milestone document, acknowledgments must be given to all team members that were not included as authors. Acknowledge facilities and include the acknowledgment of the MRWFD campaign.

Deliverable Preparation for Archiving - It is expected that all the authors of the milestone document have had an opportunity to read and provide feedback. Milestones should have been peer-reviewed as well as gone through technical editing. If AI was used to help write the document it should be noted. Technical reports should include basic information to clarify the background, problem statement and equipment used. Raw and curated datasets including uncertainty bands (where applicable) should be uploaded to PICS with the report. Datasets should be uploaded as Excel or delimited (CSV) spreadsheets.

Disclaimer on Reports and Presentations - A disclaimer note to include in reports and presentations:

This report/presentation was prepared as an account of work sponsored by an agency of the United States Government; here the Office of Materials and Chemical Technologies' Material Recovery and Waste Form Development (MRWFD) program. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Example - PICS Work Package

Scope

Optimize shrouded U/TRU codeposition from a LiCl-KCl-UCl₃-CeCl₃ molten salt and demonstrate the optimized process using the SPYRE electrorefiner. Characterize the recovered product to evaluate deposition performance, uranium/TRU composition, and the effectiveness of the shrouded codeposition design. Results will support advancement of electrorefining technologies for improved actinide recovery.





Objectives

- Optimize operating parameters for shrouded U/TRU codeposition.
- Demonstrate shrouded codeposition on the SPYRE electrorefiner targeting a U/TRU ratio of approximately 1:1.
- Characterize the recovered product using elemental and isotopic analyses.
- Assess the effectiveness of the shrouded codeposition design to support future pyroprocessing development.

Presumptions and Prerequisites

- SPYRE and supporting hot-cell facilities remain available as scheduled.
- Required salt, uranium, and TRU feed materials are available.
- Radiological operations and analytical laboratory support are available.
- Funding and work authorization remain in place throughout the period of performance.

Activities and Milestones

Activity	Level - Associated Milestone	Deliverable
Activity 1 – Shrouded Codeposition Process Optimization	M3 - Complete optimization of shrouded codeposition operating parameters and establish conditions for engineering-scale demonstration.	Optimization summary documenting selected operating parameters.
Activity 2 – SPYRE Demonstration and Performance Evaluation	M2 - Complete the SPYRE shrouded codeposition demonstration and verify performance through elemental and isotopic characterization of the recovered product.	Technical memorandum or data package documenting operating conditions, analytical results, and evaluation of process performance.
	M4 - Document recommendations for future shrouded codeposition development based on demonstration results.	Technical summary or internal report with conclusions and recommended path forward.

