INL/RPT-23-75299

Nuclear Fuel Cycle and Supply Chain (NFCSC) Technical Monthly August FY-23

Changing the World's Energy Future

August 2023

Idaho National Laboratory

INL/RPT-23-75299

Nuclear Fuel Cycle and Supply Chain (NFCSC) Technical Monthly August FY-23

August 2023

Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Office of Nuclear Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

CONTENTS

FIGURES

Nuclear Fuel Cycle and Supply Chain (NFCSC) Technical Monthly August FY-23

1. ADVANCED FUELS CAMPAIGN (AFC)

1.1 Industry FOA

1.1.1 FRAMATOME ATF FOA

[INL] Completed all FY23 work and drafted report for 30GWd burnup samples.

[INL] ATF-2C began irradiation April 26,2023 in the Advanced Test Reactor 2A Loop Cycle 171A and reached 93 effective full power days of irradiation at the end of August 2023.

Completed M3FT-23IN020102021 Issue ATF-2 Irradiation Testing Report - 8/31/2023.

1.1.2 GE ATF FOA

[INL] Completed APT analysis on Ironclad samples, completed SEM work and micromechanical preparation on Ironclad samples.

1.2 ATF Lab Activities

1.2.1 AFC COORDINATION AND INTEGRATION

[INL] FY24 Planning Package presentations were made by the NTD to HQ staff at headquarters, and work package development began after receiving direction to proceed on the major scope objectives discussed.

The FY23 draft update to the AFC Campaign Execution Plan was completed on time and delivered on August 21, 2023.

1.2.2 ATF FABRICATION PROPERTIES

[INL] The L3 milestone “Assessment and initial fabrication of novel ATF dopants” was completed on August 25th. There is interest within the commercial nuclear power sector to increase the discharge limits of light water reactors fuel rods above the current limit of 62 GWd/MTU. Extension above the current licensed discharge limit would require increases to the enrichment of the fuel above the standard 5% U-235 loading in the range of 7-9%. This increased fissile loading requires a reassessment of plant neutronics and an evaluation of burnable absorbers as well as fission gas release to mitigate longer term neutronics and performance concerns, respectively. Lanthanide-doped UO_2 is proposed to control the k_{eff} at the beginning of the irradiation cycle and support long term neutron economy, thus enabling longer discharge burnups. This report presents an assessment study of Ln-doped UO_2 fabrication at various dopant levels to understand the impacts on sintering and microstructural properties. Moreover, this report also sheds light on the solid-solution behavior of Ln-doped and Si-doped UO_2, which is a proposed additive to improve the thermomechanical performance and minimize pellet clad mechanical interactions. The microstructural data is complemented by EDS and XRD and compared with results published in the literature. These preliminary results will be used for future neutronic evaluations of reactor performance for which we will be working together with Brookhaven National Laboratory. In addition, these evaluations will inform for the potential of looking into engineered mixtures of additives. (A. van Veelen and J. White)

1.2.3 ATF CORE MATERIALS

[INL] Summary of In Situ Strain Analysis of Cr-coated Zircaloy-4 Cladding via Digital Image Correlation, Mackenzie Ridley, Samuel Bell, Dan Sweeney, Danny Schappel, Nathan Capps. This level 2 milestone addressed the mechanism(s) for cladding deformation during a design basis accident such as a loss of coolant accident through an accelerated testing framework. Three-dimensional digital image correlation capabilities were successfully established to measure cladding deformation *in situ* during loss of coolant accident testing. From the literature, deposition of Cr-coatings on Zircaloy-4 have shown enhanced resistance to cladding rupture when claddings were pressurized and subjected to rapid heating rates. This work successfully visualized the deformation process to develop a mechanistic understanding for why increased temperature capabilities occur with Cr-coatings. Such information is vital to improve model efforts regarding the qualification of accident tolerant fuel cladding candidates, such as Cr-coated Zircaloy-4, FeCrAl alloys, and SiC/SiC composites.

Fiberoptics were successfully employed to measure axial cladding temperature during a 5°C/s heating rate tests with pressurized tubes. A novel isothermal pressure-step test was developed for the Severe Accident Test Station at Oak Ridge National Laboratory to rapidly measure stress exponents during cladding deformation, where Cr-coated Zircaloy-4 and uncoated baselines show the same stress dependence to deformation. The temperature dependent deformation process was also found to be the same between Cr-coated and uncoated claddings, as published in our latest journal manuscript [1] and presented at Environmental Degradation of Materials in Nuclear Systems International Conference in St. John's, Canada. (M. Ridley, C. Massey, S. Bell, N. Capps, High temperature creep model development using in-situ 3-D DIC techniques during a simulated LOCA transient, Ann. Nucl. Energy. 193 (2023) 110012. https://doi.org/10.1016/j.anucene.2023.110012.)

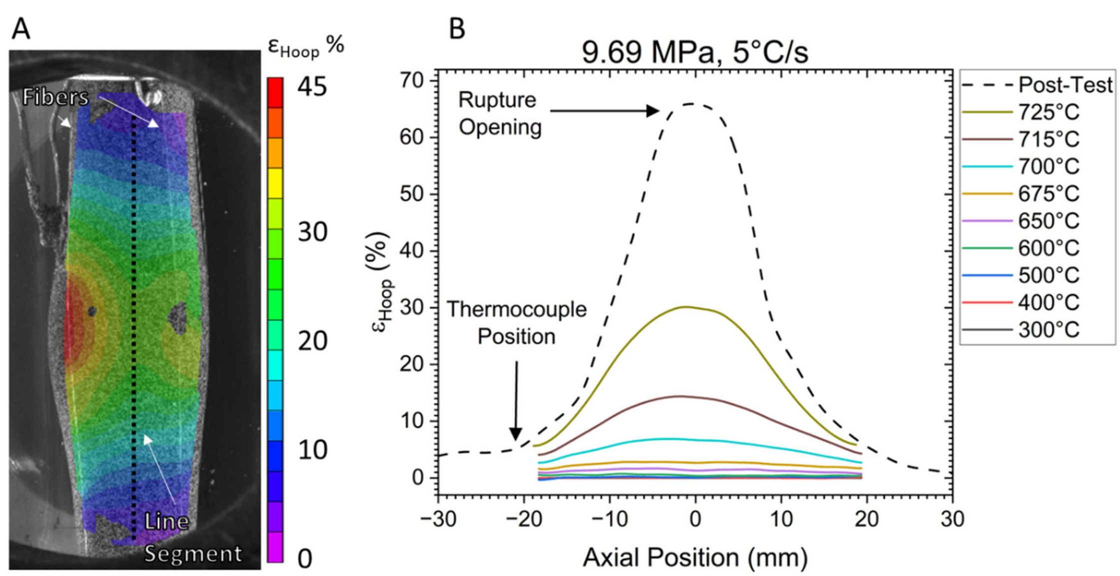


Figure 1. Zry-4 pressurized to 9.69 MPa and heated at 5°C/s with optical fibers to monitor temperature distributions across the axial length of the cladding during deformation. A) DIC camera image with hoop strain map overlaid, B) hoop strain line profile as a function of temperature.

[LANL] The L4 milestone (M4FT-23LA020202031: High temperature microscale mechanical testing of irradiated Cr coated Zircaloy) will be completed on schedule and the final report will be delivered before the project finish date.

[LANL] The L2 milestone M2FT-23LA020202045 High temperature ring pull testing of Cr coated Zircaloy was completed. This work included ring pull tension testing at 300 and 600 C for three sample types: i) Zircaloy-4, ii) Zircaloy-4 with a Cr coating applied with HiPIMS (PVD) and iii) Zircaloy-4 with a Cr coating applied with cold spray deposition. Tests indicate that the Cr coating increases high temperature strength. Figure 1 below shows the effective stress and strain curves for ring pull tests at (a) 300 °C and (b) 600 °C. The control samples are from the same Zircaloy-4 tube as the cold spray coated samples. It is clear the cold spray samples have significantly higher strengths than the control material. Even the HiPIMS samples had higher strengths than the control material at 300 and 600 °C despite the thinner coating thickness than the cold spray samples.

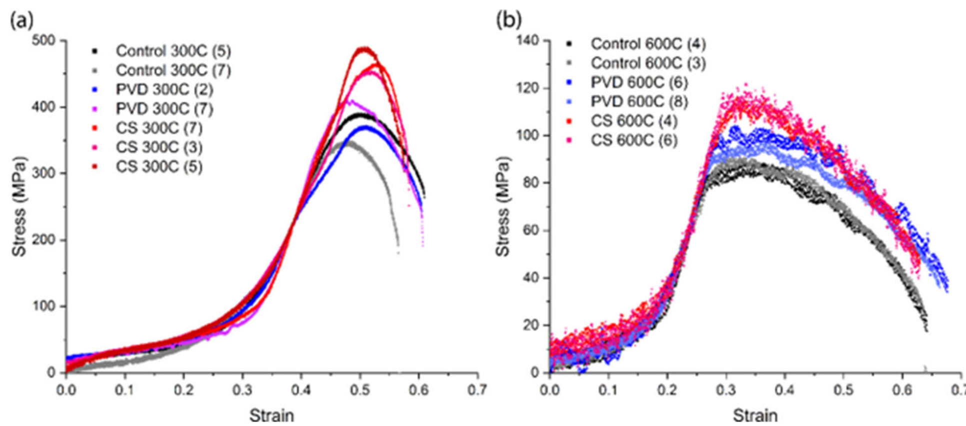


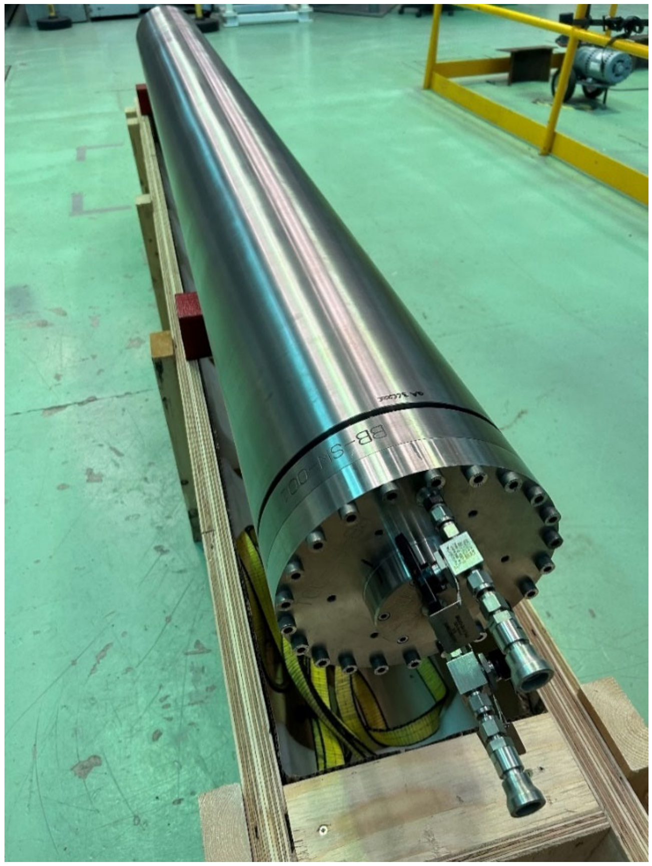
Figure 2. Effective stress-strain curves for ring pull testing at (a) 300 °C and (b) 600 °C. The numbers after the sample names indicate the specific ring tested.

The differences in how the sample variants compare at high temperature shows the importance of performing mechanical testing at all relevant application temperatures. Additionally, testing at high temperatures with a ring pull setup is beneficial compared to other techniques due to the i) small material volumes needed for samples, and ii) simple sample machining.

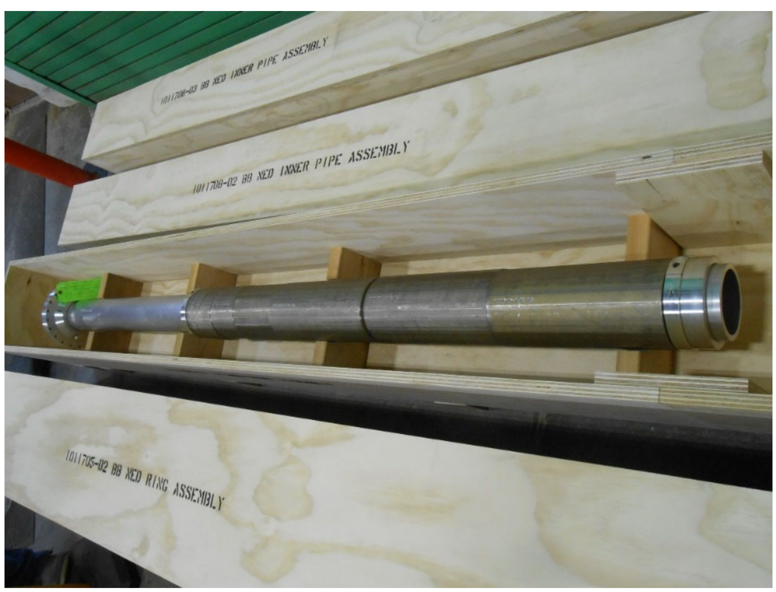
1.2.4 ATF Safety Testing

[INL] Safety analysis required to transition to the new irradiation containment vehicle continued. The cladding tube for the fourth rodlet was cut to size after being hydrided to the desired concentration. Pellets for both rodlets were test fit in their respective cladding tubes in preparation for rodlet assembly and welding.

[INL] Nu-Tech completed fabrication and testing of Big-Broad Use Specimen Transient Experiment Rig (BUSTER). Big-BUSTER has been received at MFC-720 and ready for use.



[INL] Advanced Test Reactor (ATR) Fabrication shop completed fabrication and testing of Big-BUSTER Neutronic Equivalent Device (NED). Big-BUSTER NED has been received at MFC-720 and ready for use.



[ORNL] Advanced Multiscale Microscopy Characterization of High Burnup LWR UO_2 Before and After LOCA Testing, Casey McKinney, Chad Parish, Jesse Werden, Tyler Gerczak, Jason Harp, Lauryn Reyes, Nathan Capps. Multiscale microscopy techniques were leveraged to understand the mechanisms that render high burnup fuel susceptible to fragmentation under loss-of-coolant accident (LOCA) conditions. Segments capturing the as irradiated and post-LOCA tested state of the fuel were characterized by optical microscopy (OM) and scanning/transmission electron microscopy (S/TEM). Comparison of the fuel cross-sections before and after LOCA testing showed that the high burnup structure (HBS) at the periphery and dark zone regions in the center of the fuel underwent significant fine fragmentation during the transient test, shown in Figure 1. The different extent of this dark zone region in the fuel center seems to be dependent on the power history of the sample. Previous microstructural analysis utilizing scanning electron microscopy (SEM) coupled with electron backscatter diffraction (EBSD) showed that the dark zone had increased porosity and a high density of subgrains within the parent grains. S/TEM analysis of the dark zone region did not show significant differences in the nanoscale structure of the as-irradiated samples. In the LOCA tested samples, the S/TEM analysis showed an increase in the number of nanoscale bubbles in the samples. Additionally, in the LOCA tested samples, there were zones around some fission gas bubbles that were denuded of Xe, as can be seen in Figure 2. The increase of nanoscale bubbles in the LOCA tested samples and presence of a denuded zone around some of the bubbles may be related to the fragmentation behavior, but additional characterization is needed to understand the crystallographic contribution to these behaviors.

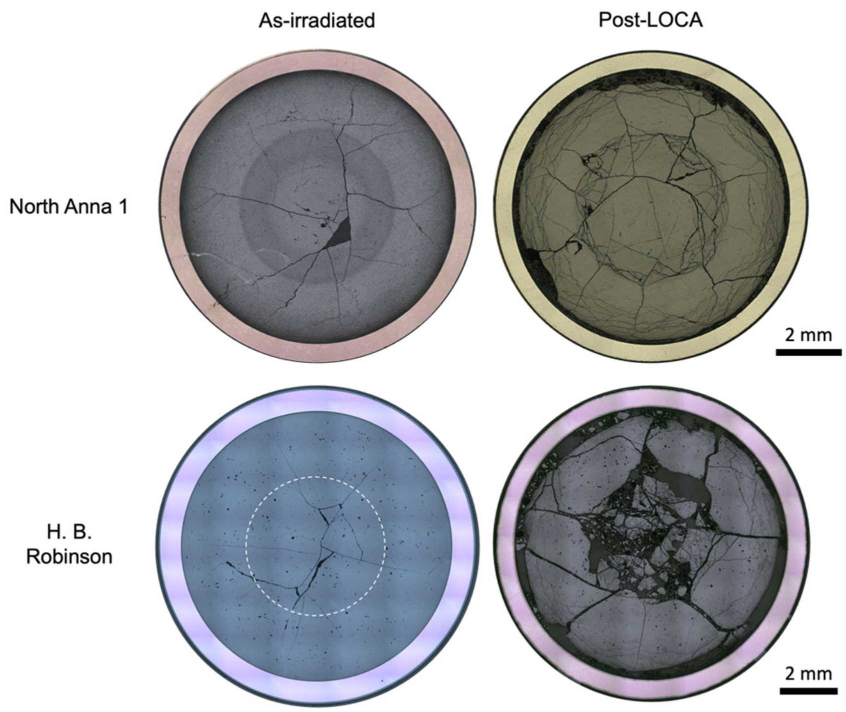


Figure 3: Optical micrographs capturing the condition of the as irradiated and post-LOCA tested segments from the North Anna 1 and H. B. Robinson rods. The white dotted circle in the H. B. Robinson as-irradiated micrograph depicts the location of the dark zone as determined by higher magnification examination.

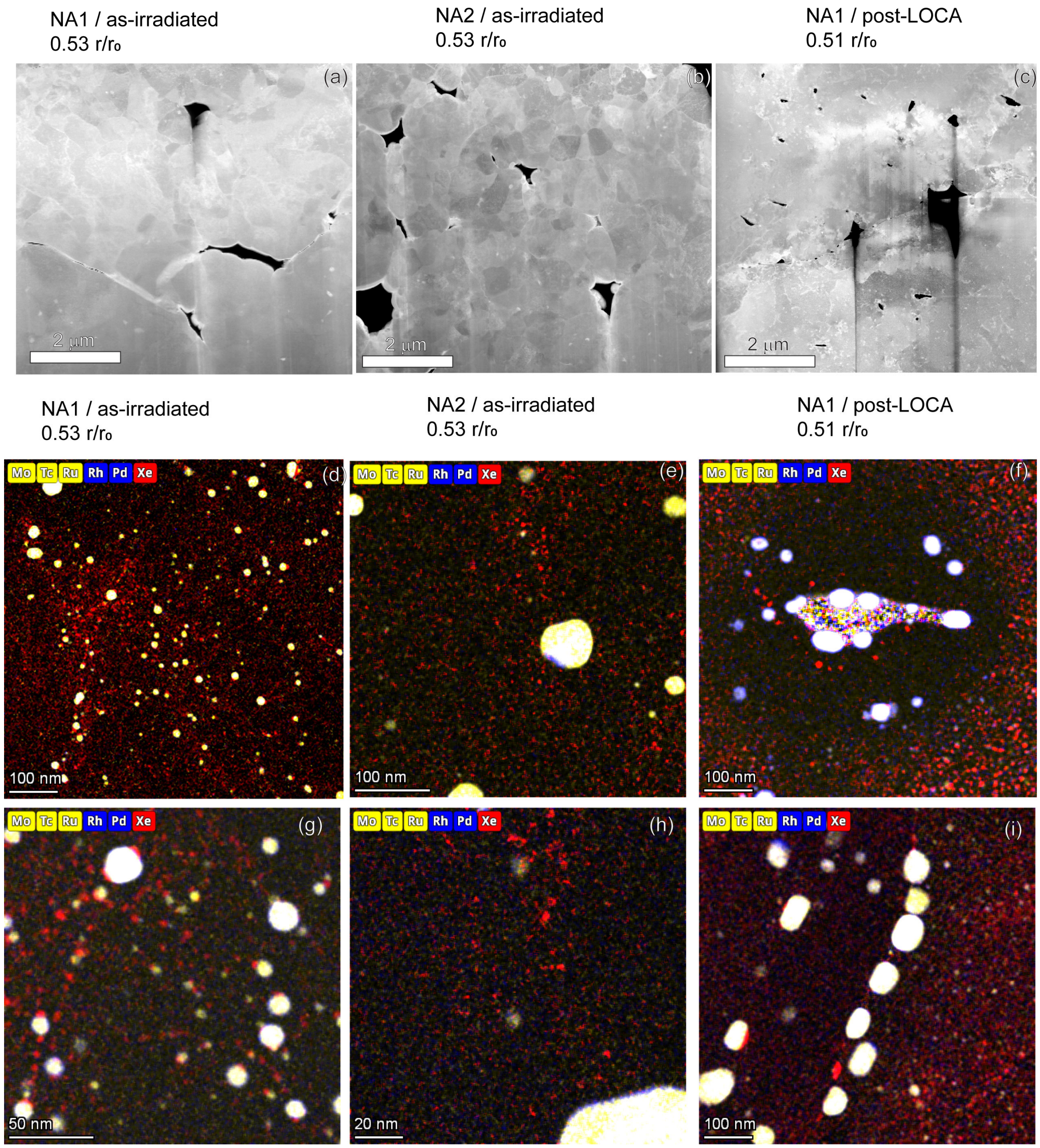


Figure 4. Comparisons of irradiated and post-LOCA tested samples at approximately the same radial distance, ~0.53 r/r0. X-rays maps are computed as weight%, with 3×3 or 5×5 moving averaging prior to quantification. Regions of vacuum (i.e., panel f center) are non-physically noisy due to zero count rates.

1.2.5 ATF Post Irradiation Examination

[INL] The second Annual Post Irradiation Examination Workshop was held at INL on August 8 and 9 to bring the ATF PIE needs community together to discuss current technology and facility status and get industry feedback on current needs and work forecasts. A panel session was held with invited DOE, industry, fuel vendor, and laboratory staff to discuss the strategic path forward for the future of the ATF mission.

Efforts continued with preparing the Certificate of Compliance revision to the BRR cask to support the planned shipments of ATF LTR segments between the DOE PIE facilities, with Source term calculations for bounding load analyses in process.

Preparations for the NAC-LWT cask shipment of ATF lead test rods from Byron NGS to INL continued with bi-weekly planning meetings conducted with BGS, WEC, INL, and support staff as required to complete actions needed for the shipment planned in December.

1.3 Advanced Reactor Fuels

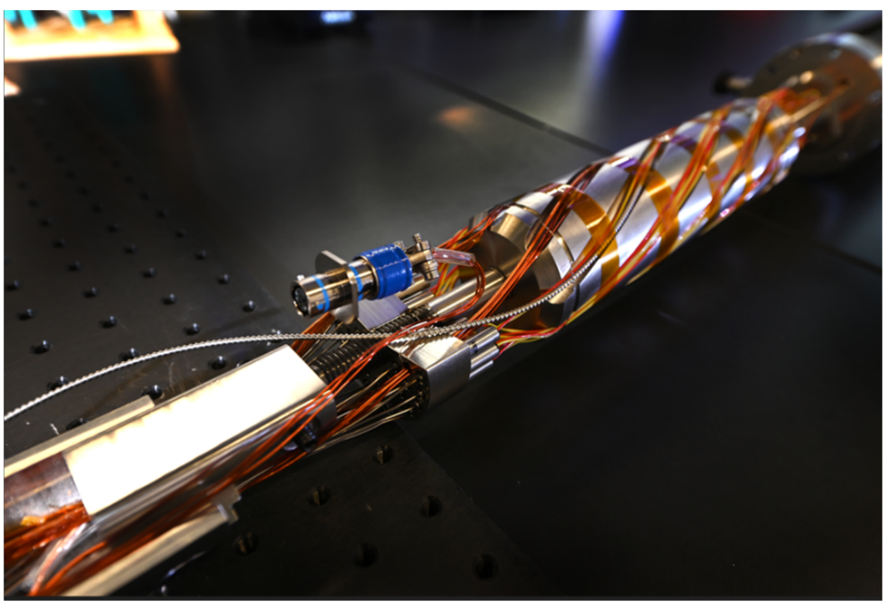
1.3.1 AR Irradiation Testing

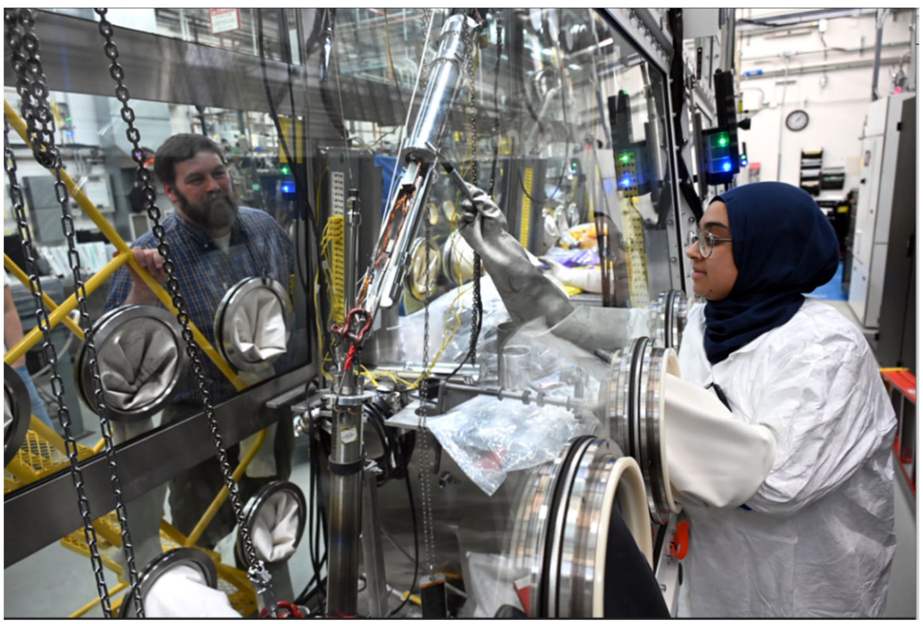
[INL] ATR 171B-1 FAST-1 irradiations did experience a short three-day outage early in the cycle to repair a damaged experiment gas-line, but irradiations were restarted and remain on-going. Preparations are on-going to support a mid-November shipment to HFEF. Additional irradiation support hardware fabrication (cadmium-lined baskets & flux-wire monitors) is mostly complete. Flux-wire monitors are done, and cad baskets are expected to be completed at the end of the fiscal year.

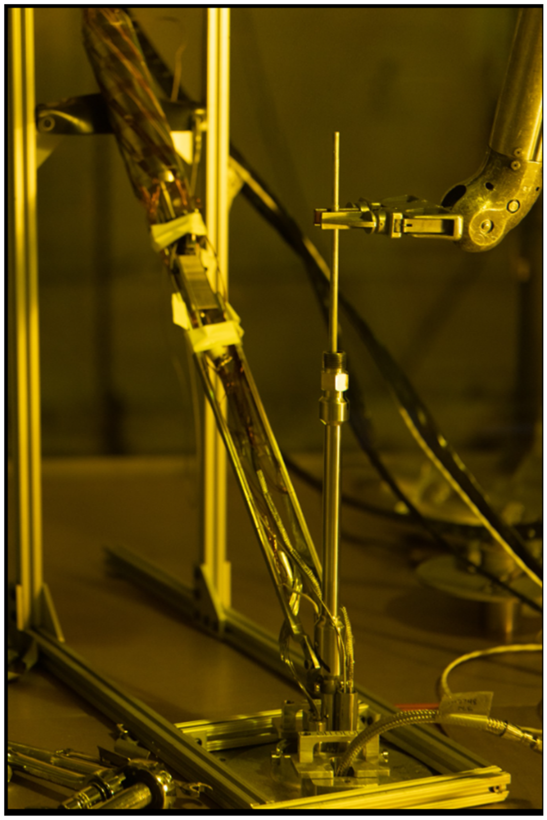
FAST-1 destructive exams recommenced with GASR operations. EBR-II legacy PIE was also started. Additional FY2023 PIE work is leveraging MFF legacy fuel available in the hot cell to expand the database on FCCI, thermophysical properties, and swelling on prototypic U-10Zr fuel pins. This work is supported by on-going BISON modeling and sectioning of the first MFF pin. MFF sectioning of the first pin is now complete including preparation of SEM and thermophysical samples to be analyzed in the coming months.

1.3.2 AR Safety Testing

[INL] The THOR experiment required a lot of ingenuity to troubleshoot issues and successfully operate. One of the challenges we faced was sodium leakage, which was a new phenomenon that had not been observed in the development phase or in the previous capsules. We are making some design changes to address this issue, but the THOR system is still ready for experiments across all our facilities thanks to the hard work done this year. Here are some pictures of the hardware and assembly process.







1.3.3 AR Performance Assessment

[INL] Placed an order for the glovebox.

Completed initial drawings for fire enclosure around Test Loop

Level 3 milestone FT-23IN020305033 “Submit Draft LI Procedure” was submitted on August 30th.

1.4 Silicon-Carbide Cladding

1.4.1 SiC Cladding Lab Activities

[ORNL] The milestone M3FT-23OR020501024 titled “Comprehensive characterization on stress corrosion cracking of SiC composite tubes” is on track. Mechanical tests of several SiC composite tube specimens at 1,000°C under steam and inert environments were conducted using a unique test capability at ORNL. The experiments were aimed at identifying key material degradation behavior under environments relevant to loss-of-coolant accidents of light water reactors. The milestone report will be submitted in September.

1.4.2 SiC Cladding (FOA)

[ORNL] Procurement of capsule components for irradiation experiment of GA SiC/SiC composite coupons was initiated. Design activities for irradiation of SiC fibers and SiC tubes are in progress.

[INL] Preliminary design activities continued for a new ATF-2 design that will follow the ATF-2C irradiation. The ATF-2D design consists of four tiers and each tier holds six pin specimens. Tier 1 (bottom tier) will hold SiC-clad specimens with UO2 fuel pellets. Tier 2 will hold Framatone fueled pins. Tier 3 will hold pressurized water reactor type fueled pins, and Tier 4 (top tier) will hold Japan

Atomic Energy Agency/Mitsubishi Heavy Industries fueled pins. ATF-2D is planned for insertion in the Advanced Test Reactor 2A Loop during Cycle 175A ~ January 2025 and will be irradiated for 18 steady-state (non-PALM) cycles until ~ June 2031.

1.5 Capability Development

1.5.1 ATR Loop Installation

[INL] Completed demonstration of the mechanical design of the I-loop prototype. A test train with articulating u-joints successfully installs into an I-Loop Tube with an offset.

Figure 5. I-Loop Test Train in I-Loop Tube Prototype

[INL] Completed conceptual design for the resin addition tank, warm waste drain system, hot waste drain system, cable tray system and initiated preliminary design. Design features the ability to swap between organic and inorganic media to handle a fueled specimen cladding breach.

Utilized a chemical injection system concept to eliminate the need of a Boron addition tank.

Completed inspection and final assembly of the nominal test train prototype.

Figure 6. I-Loop Test Train Prototype

[INL] Completed test run of SST Prototype ILT.

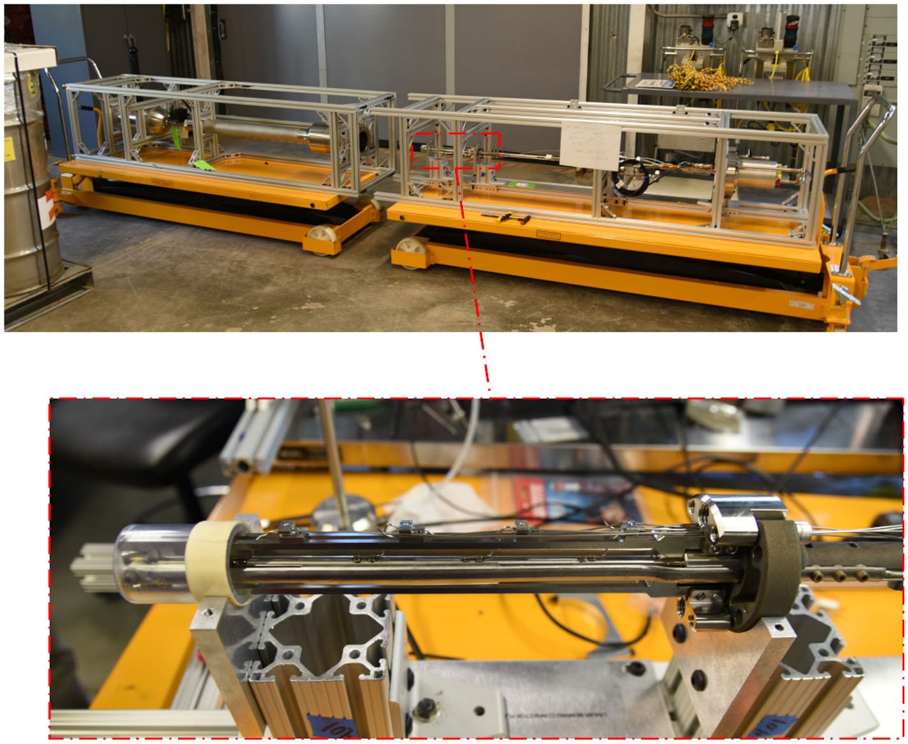
Completed test train insertion into the SST prototype- PEMP notable outcome.

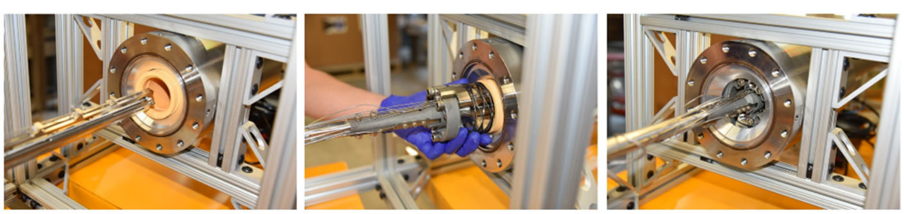
Finalized design documents for the Transfer Shield Plate – MkII and Shield Cylinder – MkII. Design documents allow the procurement to proceed to the request for proposal (RFP) phase.

1.5.2 TREAT LOCA Testing Infrastructure

[INL] Final assembly of the TWIST LOC-C-1 experiment was completed on 08/22/2023 at Advanced Fuel Facility (AFF) and is ready for transport to TREAT for first irradiation.

Final Assembly included: leak checking the capsule, testing the functionality of blow down valve, adding water to the expansion tank and sealing at the correct pressure, and performing functionality measurements on the instrumentation.





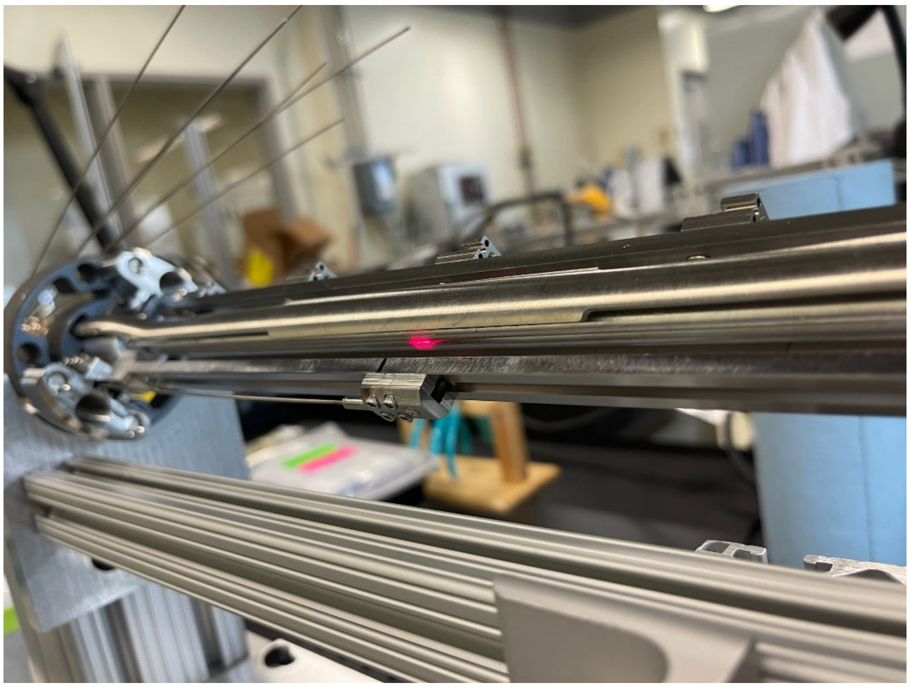
[INL] MSL constructed Infrastructure cabling that will connect the experiment to the data acquisition system. This cabling is to be used to support all of the LOC-C experiments.

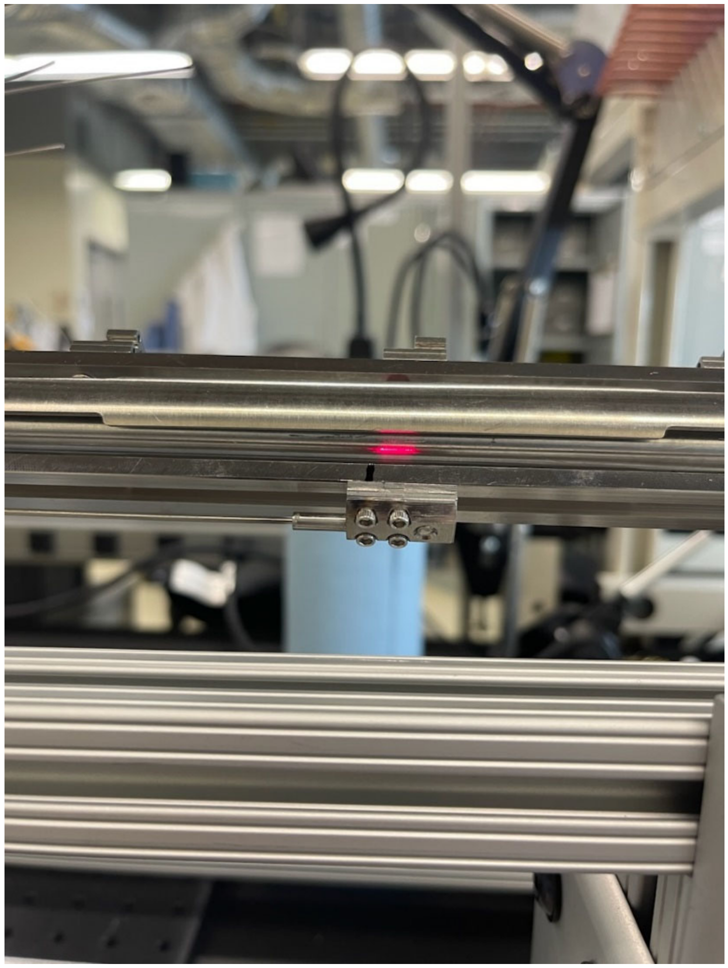
Cables constructed were connected to the physical LOC-C-2 assembly instruments to verify operation.

Assembly of TWIST LOC-C-2 was initiated at Measurement Science Lab (MSL) including mechanical component assembly and instrumentation deployment.

The pyrometer instrument deploys a custom fabricated housing to fix the orientation of the fiber to the desired location at the centerline surface on the rodlet and provides a non-contact method to measure specimen cladding temperature after blowdown. This is the first time this custom housing is being deployed. Induction brazing was developed and performed for the optical pyrometer. This instrument was then assembled for inclusion in the LOC-C-2 experiment.

Included are photos of the deployed pyrometer in the custom housing with a red light applied to the connector at the top. These photos show the fiber correctly positioned on the cladding surface and help illustrate how this instrument will collect temperature using fiber optics.





1.5.3 REFABRICATION AND INSTRUMENTATION CAPABILITY

[INL] Submitted TC welds on rodlets for analysis.

Began re-design of remote welding systems to incorporate a Swagelok end cap that would accommodate longer and larger diameter fuel rodlets.

For more information on Material Recovery and Waste Forms Development contact Ken Marsden (208) 533-7864.

2. MATERIAL RECOVERY & WASTE FORM DEVELOPMENT CAMPAIGN

2.1 Zircex

[INL] Completed milestone *M4FT-23IN030201018* with a draft manuscript submitted to the NTD. Said manuscript is undergoing export control prior to submission to the *Journal of Nuclear Materials* (Impact Factor = 3.555, 2023). To support the continued development of this process, we present new data on the identities and absorbed gamma dose dependence (≤ 22 MGy) of degradation products arising from the radiolysis of neat sulfur monochloride (S_2Cl_2) and thionyl chloride ($SOCl_2$) under ambient irradiator temperature conditions (~35.0 ± 1.0 °C). Interrogation of the irradiated sulfur chlorides by UV-vis and Raman absorption spectroscopies provided more conclusive identification of their degradation products, specifically sulfur dichloride (SCl_2) for both species and chlorine (Cl_2), sulfur dioxide (SO_2), and sulphuryl chloride (SO_2Cl_2) for $SOCl_2$. The observed degradation products were found to decay as a function of time post-irradiation. These findings are fortuitous for process development, as it suggests the potential for a solvent regeneration mechanism, which would be beneficial for process longevity and cost effectiveness.

[PNNL] PNNL has tested model operation in real-time analysis software and the Raman instrument is ready to ship back to INL.

[ORNL] The final version of the M2 was distributed to laboratory program leads and DOE-HQ. Activities that will be documented in the M3 report include recycling and reuse of S2Cl2 and measurement of chlorine carryover with separated U after removal of Al cladding. Advanced chlorination was presented at the American Chemical Society National Fall Meeting in San Francisco in two posters and an oral presentation.

2.2 Waste Forms & Off-Gas Capture

[ANL] Tests with iron phosphate materials made using different cooling rates have been completed and analyzed to assess the effect of crystallization on chemical durability. The report "Durability assessments of quenched and slow-cooled iron phosphate waste form materials" has been drafted and is under review. It will be issued in September. Insights gained will be applied to further development of material formulation and production conditions. Other iron phosphate materials made using different reagents and under different conditions as part of a NEUP in progress at University of Nevada-Reno (lead) will be sent to Argonne for testing. Waste form-related issues were discussed at off-gas capture planning meetings to coordinate sorbent development and waste form production.

[ORNL] Off-Gas & Waste Forms, FT-23OR03010403, (L. Martin) The accomplishments of the off-gas and waste forms was participation in the road mapping exercise lead by INL.

[PNNL] Notifications were sent to waste form experts and interested parties inviting them to the US DOE Cermet Workshop in October 2023 sponsored by DOE-NE and being organized and led by PNNL and ANL staff. Several candidate MOFs precursor chemicals predicted from AI/ML prediction were ordered. Several precursor chemicals were received, and synthesis of these MOFs are in progress. PNNL completed M3FT-23PN030104049 with a report titled "Data gap assessment for iodine waste form model". The report also contained a working database of available data on iodine waste form durability from the MRWFD Campaign and the open literature. The database also contains previously unpublished data provided by colleagues at National Nuclear Laboratory (UK), showing continued collaboration between programs. The database will help guide the Campaign on where data is needed as work is done to refine and populate the Iodine Waste Form Degradation Model and down-select candidate waste forms for future testing. PNNL will be completing testing of novel gas cell in the next two weeks.

2.3 Aqueous Separations

[ANL] Work continues on the development of DEHiBA D-value models and their incorporation into AMUSE v5. Models for HNO_3, U(VI), Pu (IV), Np (IV), Np(V), and Np (VI) have been developed and implemented in an uncompiled version. Am (III) and Li have also been implemented as constant D's because the values are very low. Li data were available because $LiNO_3$ was used as a salting agent with other components. The U(VI) model is being updated to synchronize with the revised HNO_3 model. Available data for Zr and Tc remain to be evaluated.

Kinetic data for the extraction of Ce (IV) by 30 v/v% TBP and 1 M DEHiBA from molar HNO3 were collected using the microfluidic solvent extraction system, as was kinetic data for the stripping of Ce (IV) from 1 M DEHiBA by 0.1 M HNO_3. Phase separation data needed for the calculation of dimensionless dispersion numbers for the two systems under extraction conditions were also gathered. While bulk phase separation for both was rapid, the DEHiBA system formed an unstable water-in-oil emulsion that persisted for >1 hour before clarifying. The fraction collector has been received by Argonne and is anticipated to be available next week for setup and initial testing.

[PNNL] The report Demonstrating the accuracy of DEHiBA chemometric models under static conditions (PNNL-34646) was completed and issued to fulfill milestone M3FT-23PN030101049. This report describes the use of visible (vis) absorbance, near infrared (NIR) absorbance, and Raman spectroscopy to identify and quantify chemical analytes such as UO_2^{2+}, Pu(IV), Pu(VI), Np(IV), Np(V), Np(VI), and HNO_3 in both aqueous and organic solution phases relevant to the uranium separation process using the extractant N,N-di-(ethyl-2-hexyl)isobutyramide (DEHiBA). These optical spectroscopic tools exhibited good applicability to the multiple chemical analytes in this system. The report also discusses the results from building chemometric models for the quantification of the relevant analytes. The resulting algorithms are able to accurately measure concentrations of the target analytes within both the aqueous and organic phases. Generally, uncertainties of ~1% are observed for Raman and visible analytes of U(VI), HNO_3, Pu (IV), and Pu (VI) within the aqueous phase. Uncertainties for Np species measured via visible and NIR were slightly higher, ranging from 1% - 5% depending on the analyte and model. This is likely due to the lower concentration ranges used for modeling. Within the organic phase, uncertainties for all analytes were generally around 3%.

2.4 Pyro/Molten Salt Processing

[ANL] Reports were drafted summarizing the results of assessments of issues relevant to Cs management in pyroprocessing and the application of pyroprocessing methods to pebble-type fuels such as TRISO. Those reports will be issued in early September. A report on actinide/lanthanide separation factors has been drafted and is under final review. That report will be issued in late September. Measurements of sediments in salt are in progress to assess dependence on oxygen and moisture in atmosphere. Further analyses of co-deposition products are in progress. Design of cathode for up-graded cell is in progress to incorporate advanced sensors.

2.5 Innovative Aqueous Separations

ORNL] Aqueous Separation Science & Novel Processes, FT-23OR03040201 Advanced voloxidation with NO_2 has been proposed as a head-end reprocessing scheme for used nuclear fuel with the objective of converting UO_2 to higher oxides and partitioning volatile fission products into the gas phase. Studying reaction mechanisms, characterizing products, and quantifying volatile fission product emissions on spent fuel is challenging. Thus, multiple batches of Simfuel have been produced and tested under realistic NO_2 voloxidation conditions. The powders produced at each oxidation and attempted nitration step were characterized for phase, morphology, and microstructure. Additionally, 15 experiments were conducted to study the reaction between CsI and NO_2 with the objective of optimizing conditions that lead to iodine partitioning into the gas phase. The following variables were tested to evaluate their impact on iodine volatilization efficiency: temperature, time, purge time, ratio of NO_2:CsI, CsI particle size, and multiple NO_2 charges. Depending on the conditions tested, between 0% and 95% of the iodine was partitioned into the voloxidation off-gas. As a result, it is recommended that the solid-gas reaction interface be promoted by mechanical agitation. Multiple purges of the system with inert gas and recharges with fresh NO_2/O_2 may help volatilize iodine as well. Finally, it was discovered that a voloxidation flowsheet that involves recirculation through an iodine sorbent bed results in the consumption of the reagent needed for the voloxidation process (NO_2) due to reaction with the silver-based iodine sorbents.

A draft report is available for limited circulation – designated official use only export controlled information. It is undergoing internal review at Oak Ridge National Laboratory and is password protected.

[PNNL] The inductively coupled plasma optical emission spectroscopy (ICP-OES) instrument that was procured through the MRWFD campaign was put into full radioactive operation. This had immediate positive impact in supporting completion of milestone M2FT-23PN030101041, Demonstrate reduced feed volume of 50% for a DEHiBA-based U recovery flowsheet. In this case, an alternative method for determining uranium concentration was needed because the planned method (visible spectrophotometry) suffered from interferences by other components present in the test solutions. The ICP-OES allowed project staff to complete the uranium (and technetium) measurements in a timely manner, without relying on a separate analytical laboratory which would have resulted in a weeks-long delay.

[SRNL] A solid solution containing depleted uranium and neodymium was prepared for use in a series of direct extraction experiments. Preparation of the solid solution completes milestone M4FT-23SR030402034, "Prepare initial solid solution containing uranium and a lanthanide element." The solid solution was prepared by initially dissolving neodymium nitrate hexahydrate in a uranyl nitrate solution. The metals were precipitated with ammonium hydroxide, filtered, and calcined at nominally 600 °C to produce the oxide solution. The rate of the neodymium oxide extraction will be measured using UV-Visible spectroscopy, initially for comparison to kinetic data obtained for the direct extraction of neodymium oxide (only) into 30 vol % TBP. Kinetic data will also be obtained simultaneously for the uranium oxide during the extraction experiments.

[INL] Work scope complete. Manuscript officially published: G.P. Horne*, R.P. Morco, A.R. Cook, and S.P. Mezyk, Dioctyl Ether Radiolysis Under Used Nuclear Fuel Reprocessing Conditions: Foundational Knowledge for the Development of Sacrificial Ligand Grafts. *Radiation Physics and Chemistry* 2023, *213*, 111217. DOI: https://doi.org/10.1016/j.radphyschem.2023.111217

2.6 Innovative Salt Systems

[ANL] Development of resistance tomography tool for managing contaminants in molten salt are in progress using UCl3-bearing eutectic salts. Various salt samples were analyzed to quantify measurement uncertainties in support of MPACT. Argonne participated in discussions addressing safeguards-by-design requirements for electrorefiners. Report on experimental in situ chlorination method and results is being drafted. Plans for chloride gas chlorination electrode are in progress. Staff continued to participate in ANSWER working group and is developing a program overview document.

[INL] In August, FY23 experiments, and modeling efforts completed on the salt crystallization scope. The research team has nearly completed a manuscript on the results of the work and will be submitting the manuscript for publication in September. Experiments drew to a close on moisture and oxygen effects on salt systems as it relates to development of in situ protection tools.

[ORNL] A milestone report for the chlorine reference electrode was finalized and submitted which completed that milestone. Solid solutions of UO2 with La2O3, Nd2O3, and Ho2O3 at 1,300 °C were synthesized in an H2 atmosphere. Solubility measurements for the obtained compounds were performed, however, X-ray analysis could not be completed because the instrument is being repaired. X-ray analysis is needed to correctly interpret the solubility results. But in UO2-La2O3 and UO2-Ho2O3 systems, the U concentration in the melt is very low, or even zero, in the case of the UO2-Ho2O3 system. In the UO2-Nd2O3 system, the concentration of U and Nd in the melt is approximately the same. These measurements will be repeated to ensure proper characterization of the material. For the zone refining, the gas flow system has been constructed and the supports for the flow tubes have been made and installed. We are in the process of performing initial tests with a low melting temperature salt.

For computational work, we have made progress in assessing phase equilibria for the pure aluminum chloride melt using machine-learned forcefields (MLFF) coupled with two different approaches. The first is through the direct simulation of the two-phase system with a DeePMD forcefield, in which the relative concentrations of dimers (Al_2Cl_6) in liquid and vapor phases connect directly to the vapor-liquid coexistence region in the density-temperature phase diagram. The other approach employs a method known as thermodynamic integration (TI) to compute relative free energies between two states (e.g., vapor and liquid) using the MLFF implemented in VASP. However, several challenges exist when applying TI to our pure aluminum chloride system, but we have recently been able to compute chemical potentials of pure lithium chloride melts (which exhibit significantly less short-range ordering than aluminum chloride). We will continue to develop both approaches and will compare the ability of the two methods and MLFFs to predict phase equilibria for the pure aluminum chloride melt.

[PNNL] PNNL has received another ATR fiber and is testing sensor responses.

For more information on Material Recovery and Waste Forms Development contact Ken Marsden (208) 533-7864.

3. MPACT CAMPAIGN

3.1 Campaign Management

3.1.1 NTD & Management Support

[LANL] Federal Program Manager, Control Account Manager, Deputy, and National Technical Director worked with LANL web developers to draft the conceptual design of the MPACT website. The Federal Program Manager, Deputy and National Technical Director briefed industry representatives from SHINE, CURIO, and Oklo on the MPACT program and discussed potential areas of cooperation. Federal Program Manager, Control Account Manager, Deputy, and National Technical Director worked with a graphics designer to develop an MPACT logo. Federal Program Manager, Deputy and National Technical Director participated in coordination calls with the DOE/NE Advanced Reactor Safeguards & Security (ARSS) program, the DOE/NNSA Advanced Reactor International Safeguards Engagement (ARISE) program, and the DOE/NNSA International Nuclear Security program. Federal Program Manager, Control Account Manager, Deputy, and National Technical Director participated in the NE-4 Planning Package meeting.

[BNL] Assisted Federal Program Manager and National Technical Director with preparing work plans and budgets for FY24, coordinating with other programs supporting advanced reactor technology, and reviewing NEUP proposals.

3.1.2 MPACT Website Development

[LANL] Website developers have been working with the MPACT management team to structure the website. The landing page and secondary pages have been drafted.

3.2 Front-End Domestic Safeguards

3.2.1 Enrichment Plant

[SNL] Classified information has been ingested and converted to a digital format for continued reference/use. A "requirements" document has been generated, which identifies the specific steps to be completed within the modeling work, how these steps contribute to the final goal, and what constraints exist.

3.2.2 Fuel Fabrication - Standards

[ORNL] Completed work on HEPA filter waste measurement approaches to provide Westinghouse with a more accurate and safer way to measure and handle this waste stream.

3.3 Back-End Domestic Safeguards

3.3.1 Electrochemical & Aqueous spike-based Reprocessing NMAC

[INL] All R&D activities for FY23 have been successfully completed as planned. Some highlights are: (1) the uncertainty improvement by Eu-154 removal and longer data acquisition are very successful, (2) the very high radioactivity of Cs-137 in the salt samples affected gamma spectroscopy measurements and detection limit. The success of FY23 clearly shows us the future R&D needs for demonstration and deployment of the Na-22 based radioactive tracer dilution for total mass determination.

3.3.2 FIELD TEST SUPPORT

[INL] Supported operations in the analytical lab (sample analysis) and HFEF (single bubbler test), as well as meetings with ARN and LANL to coordinate on PM/NMA.

[LANL] LANL and INL personnel have worked through noise issues with the INL Plutonium Scrap Multiplicity Counter (PSMC). The noise was related to the proximity of signal runs. A repair was developed and LANL and INL personnel will implement the repair in September 2023.

3.3.3 MOLTEN SALT PM/NMA

[ANL] The deliverable report for M3FT-23AN040103052 is being prepared.

[INL] Coordinated with LANL and ANL on PM/NMA tasks/planning for next year. Single bubbler test in HFEF continued and several weeks of data are available. Results are promising.

3.3.4 REPROCESSING SAMPLER

[ANL] The sampler has been completed and is being prepared for shipment to INL. The deliverable report for the project has been written and is now undergoing internal review.

3.3.5 SAFEGUARDS MODELING SUPPORT

[SNL] Modeling tools are being updated to the new F-cubed layout. Zircex modeling work is being finalized.

3.3.6 MOLTEN SALT SAMPLING & ANALYSIS (WITH MRWFD)

[ANL] The final report for this project is being prepared in collaboration with INL.

[INL] Continued collaboration with ANL and a combined report for respective milestones is being drafted.

3.3.7 PSMC – KM200 COMMERCIALIZATION

[LANL] The charge calibration circuit has been tested and works correctly so that an identical signal can be applied to all KM200s for tuning without the need for high voltage and tubes. The dead time correction circuitry has also been tested with a successful outcome. Some minor adjustments are being tried to get better results.

3.3.8 ECHEM SSBD (WITH MRWFD)

[ANL] The deliverable report is being finalized for the end of year milestone.

[INL] An outline of the assessment report has been created.

3.3.9 MICROCALORIMETRY

[LANL] Continued to provide support to INL in performing system optimization. Measurements on electrorefiner and oxide reduction samples are continuing. Additional detector assemblies have been repaired and tested at NIST and the University of Colorado. Will travel to INL early in FY24 to install the remaining assemblies.

[INL] Continued operation of the ucal instrument, optimization runs for the bias voltage. Measured first OR salt sample. This sample had high activity levels due to high beta. Gamma-ray counts were relatively low, and the spectra was not great; will compare to HPGe data.

3.4 Safeguards Education

3.4.1 NMAC TRAINING & SAFEGUARDS PRACTITIONER DEVELOPMENT

[SNL] Safeguards Practitioner Guidance Document was completed and will serve as reference material for the NMAC training course.

3.4.2 DOMESTIC SAFEGUARDS TRAINING

[ORNL] Contract placed with key resource to support this effort.

For more information on MPACT contact Mike Browne at (505) 665-5056.

4. SYSTEMS ANALYSIS AND INTEGRATION (SA&I) CAMPAIGN

4.1 CAMPAIGN MANAGEMENT

[**ANL, BNL, INL**] Attended the NE-4 planning package meeting on Aug 1-3 and provided the campaign FY 24 planning package.

[**ANL, BNL, INL, LLNL, ORNL, PNNL, SNL**] Continued the discussion and prioritization of the potential work scope for FY 2024 to accommodate the feedback from the NE-4 planning package.

4.2 NUCLEAR ENERGY SYSTEM PERFORMANCE (NESP)

4.2.1 US ENERGY SECURITY AND SELF-SUFFICIENCY ANALYSES

[INL] Staff worked on drafting the report on technology road mapping for the fuel cycle facilities needed to support the ARDP concepts.

4.2.2 NUCLEAR ENERGY CONTRIBUTIONS TO ADDRESS CLIMATE CHANGE AND DECARBONIZATION

[**ANL, INL**] Iterated with the Digital Content Team of DOE-NE to develop a blog statement on the report "Assessment of Nuclear Energy to Support Negative Emission Technologies."

[**ANL, BNL, INL**] A series of ERCOT grid models were developed to simulate severe weather events based on future climate change conditions. The results inform that future weather scenarios led to very large amounts of unserved energy when disputable and firm energy (biopower, coal, natural gas, nuclear, etc.) capacity in the grid was low.

[**BNL**] Performed literature survey of severe weather events and impact of climate change on power systems (Contribution to NESP#7).

[**INL, ANL**] In support of the C2N Stakeholder Guidebook, staff completed economic impact analyses then ran analyses on GHG emissions associated with economic impacts. Delivered draft contributions which involved a description of C2N market opportunities, infrastructure repurposing, and discussion on nuclear technology options. Staff worked on drafting the milestone report.

4.2.3 ASSESSMENT OF EMERGING NUCLEAR ENERGY TECHNOLOGIES

[SNL] In July, staff identified an issue regarding the speed at which the database was returning in formation was identified but no solution has yet been found. In addition, the rejection of an invitation to a DPE colleague to access the Nuclear fuel Cycle Options Catalog identified a problem with the system that is supposed to allow non-SNL personnel to access the catalog. The issue has not been resolved and has been escalated up the management chain.

4.2.4 QUICK TURN-AROUND STUDIES

[**ANL, BNL, INL, ORNL**] To evaluate the value of residual U-235 in the HALEU used nuclear fuel (UNF), collected the discharge fuel compositions of advanced reactors and microreactors with HALEU fuels. Values of the residual U-235 in recovered uranium (RU) from HALEU UNF will be evaluated by comparing costs for three cases: 1) cost for recovering uranium vs. cost for making fresh equivalent enriched uranium, 2) fuel cycle cost of down-blending fuel in PWR vs. fuel cycle cost of fresh LEU in PWR, and 3) cost for reuse the RU after re-enrichment vs. cost for HALEU fuel without recovering the residual U-235.

4.2.5 COLLABORATION WITH OTHER CAMPAIGNS AND PROGRAMS FOR NUCLEAR PERFORMANCE

[INL] Staff worked on drafting the report on R&D maturation for silver mordenite in iodine capture.

4.3 ECONOMIC AND MARKET ANALYSIS FOR NUCLEAR ENERGY SYSTEMS (EMANES)

4.3.1 NUCLEAR COST MODELING AND TECHNO-ECONOMIC ANALYSIS

[INL] Staff completed and submitted the M3 milestone which addresses cost estimation based on data from the MARVEL reactor.

[**ANL**] Provided analysis and writeup on cost impacts of collocation and separate location of the CAT II and CAT III enrichment facilities for production of HALEU above 10% enrichment. Provided review and comments on the overall draft report.

[**INL**] Staff completed processing cost data from the MARVEL reactor and then completed the milestone report. The staff submitted the report for review to the NTDs from SA&I and MRP who each provided comments back to the staff. Comments were addressed and incorporated into the final report.

[SNL, INL] Staff reviewed and edited the July's draft report that examines areas of storage, transport, and disposal of HALEU spent nuclear fuel that could affect the economics of these activities, compared to storing, transporting, and disposing of LEU spent nuclear fuel generated by a typical LWR. The intent is to include this information in the next update of the Advanced Fuel Cycle Cost Basis report. Staff also worked on cost modules for fuel fabrication in the Cost Basis Report, specifically working to get modules through the review process.

4.3.2 COLLABORATION WITH OTHER CAMPAIGNS AND PROGRAMS FOR NUCLEAR ECONOMICS

[INL] In support of the collaborative study on Kr/Xe cost sensitivities, staff completed drafts of the costing approach and results. Review of the results found a counter-intuitive result, so the staff followed up with consultation with experts in the MRWFD Campaign to clarify understanding.

4.4 SA&I Advanced Nuclear Fuel Availability (ANFA) Support

4.4.1 SA&I HALEU SUPPORT

[**ANL, ORNL**] Submitted the report entitled "Options to Address Enriched Uranium Shortage for Large-Scale Reactor Deployment" by E. Hoffman, et al. This report is the deliverable in the fulfillment of the Level 3 milestone, M3FT-23AN050104013 under the work package of "FT-23AN05010401 SA&I HALEU Assessment - ANL."

This study assessed domestic needs of front-end fuel cycle services, which include the demands of natural uranium (NU), conversion, low (<5%), medium (5-10%), and high (10-20%) assay low enriched uranium, including the potential domestic sources of NU or alternatives to reduce demand for NU (e.g., enrichment of previously generated DU tails). The assessment was performed drawing from projections of nuclear demand to address the net-zero emissions economy in the United States. This study shows that the nuclear energy demand is sensitive to the nuclear capital cost and decarbonization policy, and the required front-end fuel cycle services varies depending on the nuclear energy demand and the reactor and fuel deployment scenarios. In general, except for the low bound nuclear demand case with high *capital cost and no decarbonization policy, the front-end fuel cycle service capabilities of United States and Western countries are insufficient. In addition, this study shows the magnitude of the impact on levelized cost or the economic viability of certain alternatives.*

[BNL] Completed peer review for the HALEU task 1 deliverable that was submitted.

For more information on the Systems Analysis and Integration contact Brent Dixon (208) 526-4928.