Molten Salt Reactor
PROGRAM

Updates on the Operation of Argonne's Pumped Actinide Molten Salt Loop

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Chemical and Fuel Cycle Technologies Division

Argonne National Laboratory

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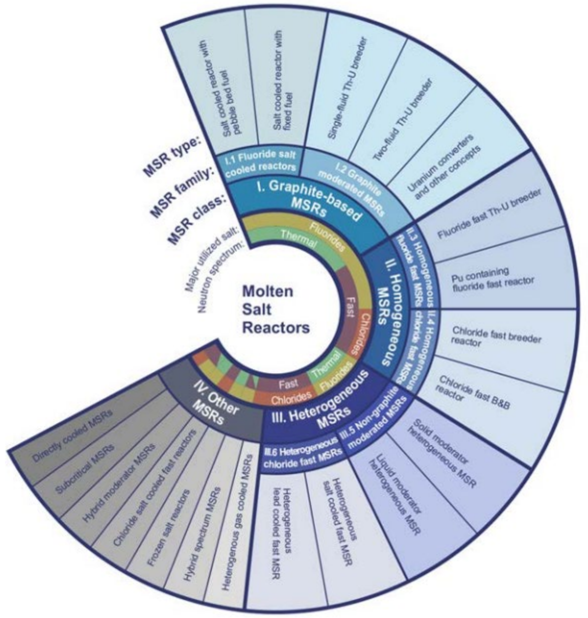
MSR-Relevant Testing Environments

The wide variety of MSR designs creates a need for flexible, modular testing environments to support technological development and fundamental studies.

To address this need, Argonne has installed pumped molten salt flow loops in large-scale gloveboxes located in our transuranic laboratories.



Molten salt reactor taxonomy[1]

Survey of US-Based MSR-Relevant Flow Systems*

Name	Facility/Laboratory	Salt type	Thermal or forced convection?	Flexibility/ Modularity	Actinide-bearing or FHR-relevant salt?	Size	Realistic flow conditions?	Scalable/ Capable of Mass Production?	References
Liquid Salt Test Loop (LSTL)	Oak Ridge National Laboratory	FLiNaK	Forced						[17]
Facility to Alleviate Salt Technology Risks (FASTR)		$MgCl_2$-NaCl-KCl	Forced						[17,18]
Thermal Convection Loops		FLiNaK, FLiBe, $MgCl_2$-NaCl-KCl	Thermal						[19,20]
Molten Salt Test Loop (MSTL)	Sandia National Laboratory	Nitrate salts for Solar Applications	Forced						[24]
Separate Effects Loop	Argonne National Laboratory	Chloride Salt	Forced						[21]
In-glovebox Actinide Salt Loops		Chloride Salt	Forced						This work
Modular Flow Instrumentation Testbed (MFIT)		Chloride Salt	Forced						[39-41]
NEXT Lab Molten Salt Test System	Abilene Christian University	FLiNaK	Forced						[31]
Molten Salt Research Reactor (MSRR)		FLiBe-U	Forced						[30,31]
INL Thermal Convection Loop	Idaho National Laboratory	Chloride Salt	Thermal						[64]
Molten Salt Tritium Transport Experiment (MSTTE)		FLiNaK	Forced						[22,23]
Engineering Test Unit (ETU)	Kairos Power	FLiBe	Forced						[32]
Salt Test Loops		FLiBe	Forced						[33]
Instrumentation Test Unit (ITU)		FLiNaK	Forced						[43]
Integrated Effects Test Loop	TerraPower	Chloride	Forced						[34]
Microloops		Chloride	Thermal						[35]
Shaft Seal Test Facility (SSTF)	University of Michigan	FLiNaK	Forced						[47]
Chloride Flow Loop	Virginia Tech	$MgCl_2$-NaCl-KCl	Forced						[27]
Liquid Salt Flow Loop	University of Wisconsin Madison	Nitrate, chloride, and fluoride salts	Forced						[26]
FliBe TCL		FLiBe	Thermal						[25]
Integrated Research Project (IRP) FLiBe Loop	Massachusetts Institute of Technology Collaboration with UC-Berkeley, NCSU, and ORNL	Fluoride salts	Forced						[28, 29]
Copenhagen Atomics Salt Loops	Loops deployed to various US institutions	Various fluoride salts	Forced						[36]

*Based on publically available literature and sources

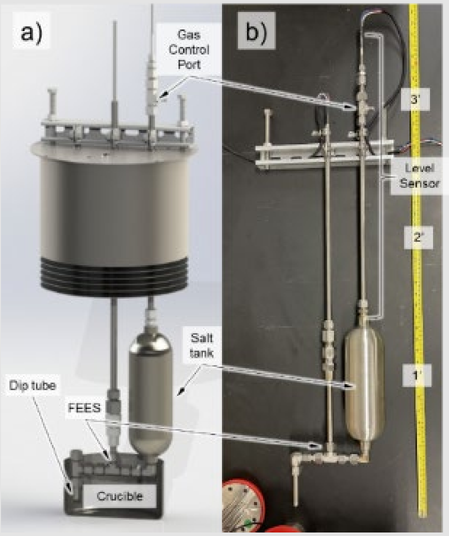
Survey of domestic molten salt loops[2]

[1]Status of Molten Salt Reactor Technology, TR-489 IAEA 2024
[2]ANL/CFCT-25/23

Flow Systems for Sensor Development

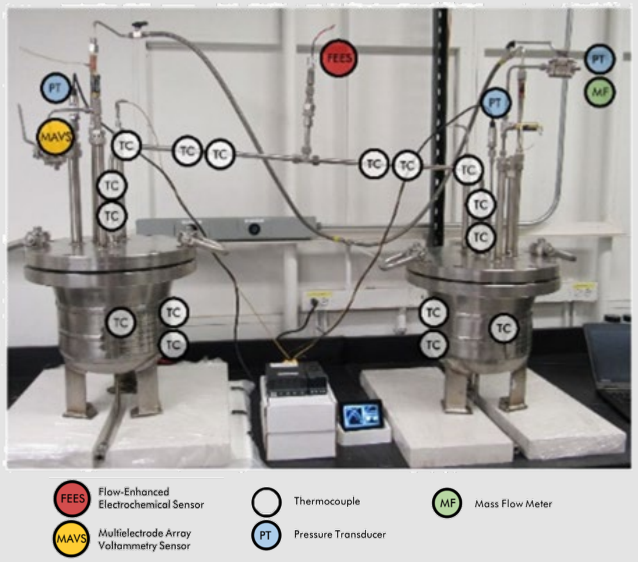
To move beyond static testing, Argonne has developed a variety of molten salt flow systems to support the development of key technologies for in-line and on-line flow conditions.

Mini Flow Systems for Sensor Development



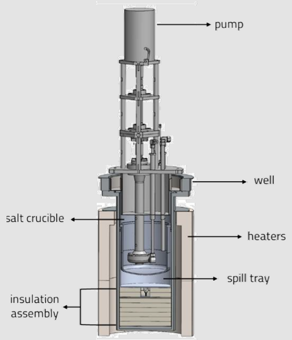
- Flow rates: 0.01 to 0.5 L/s
- Non-rad and radiological versions

Modular Testbeds for Long-term Assessments



- Flow rates: 0.01 to 3 L/s
- Radiological operations: >4 years of active operations in total

In-Glovebox Flow Loops for U/TRU Salts



- Non-isothermal loops capable of operations with a variety of U/TRU salts
- Four loops currently being installed

Engineering-Scale Secondary Effects Loop

- Engineering-scale flow loop with suite of monitoring and control capabilities

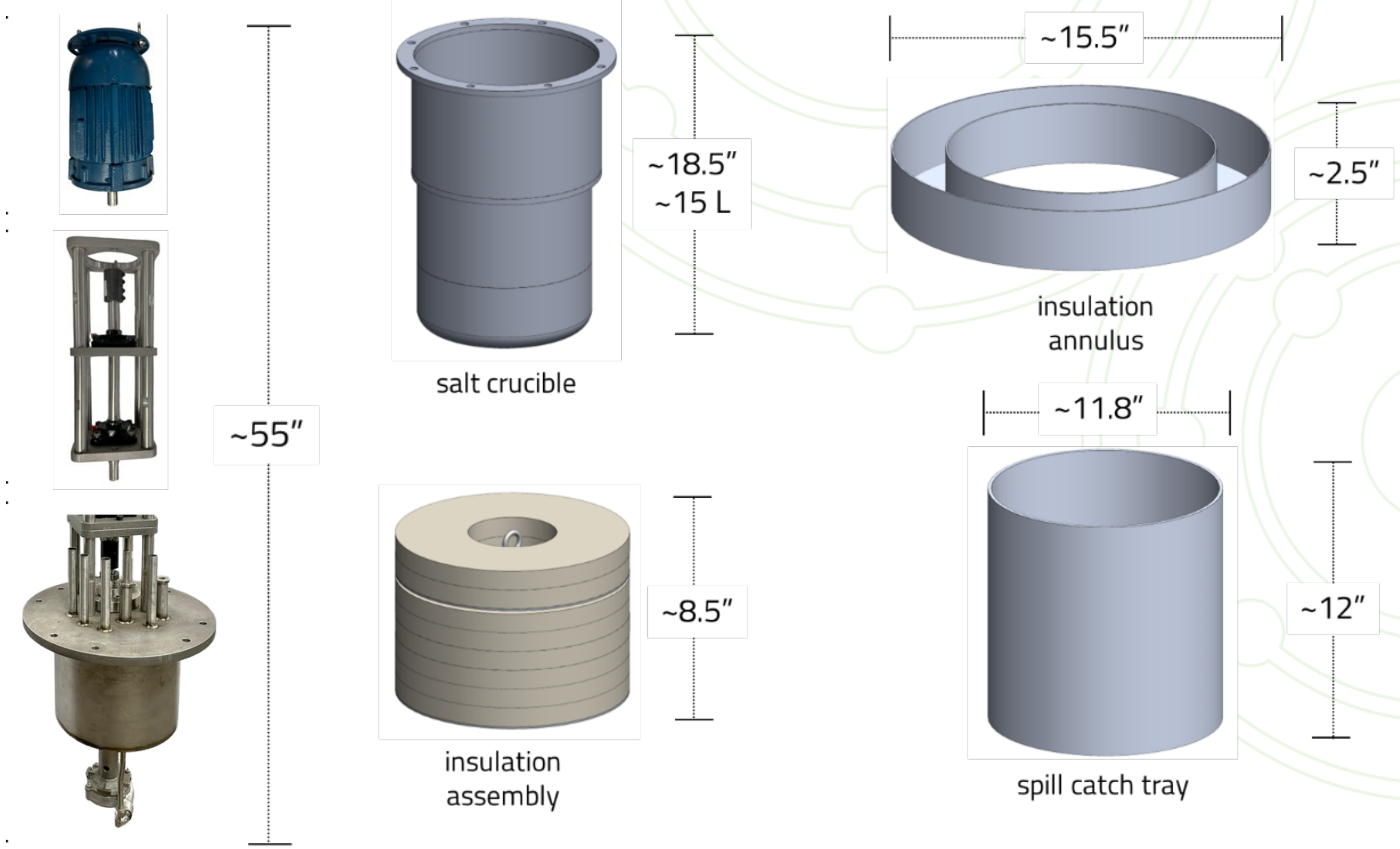
Pump Assembly and Design

All components of the pump and supporting equipment are designed as modular systems.

- Intended to support flexible upgrades and modifications as needed.
- Custom pump procured from HTSD Inc.

Molten salt reactor technologies can be evaluated at engineering scales and under relevant operating conditions.

- e.g.: flow rates, non-isothermal conditions, etc.



Renderings of the assembled pump along with the salt crucible, insulation assembly, annulus, and the spill catch tray.

Pump Performance and Operation

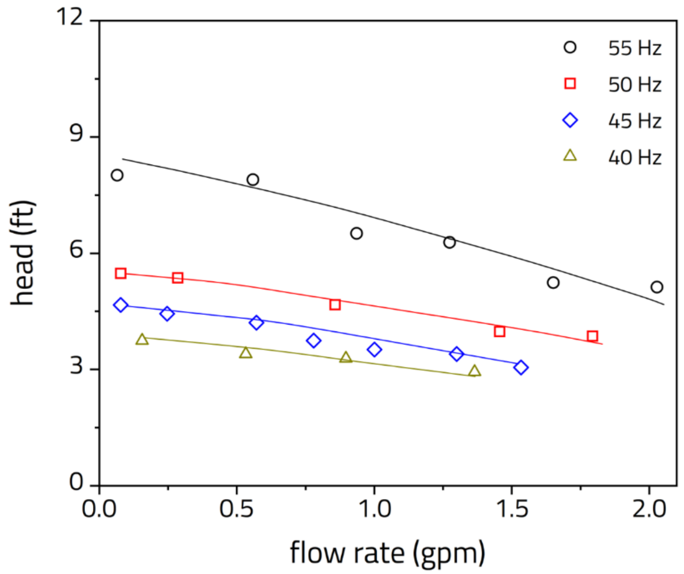
Initial Testing

Water testing was conducted to evaluate pump performance in well-understood and controlled environments.

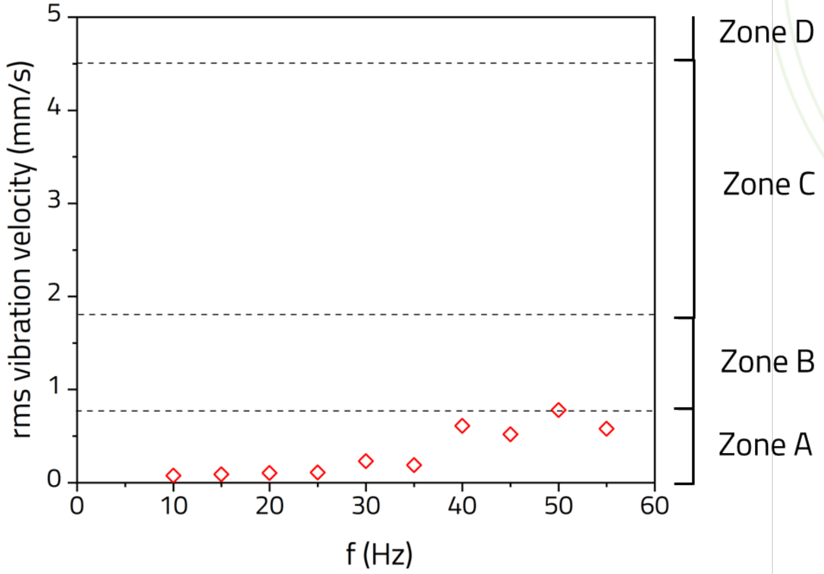
Relationships from water tests can then be extended to molten salt operation.

- Pump head pressure as a function of flow rate and controller input was collected and used to inform molten salt operation in glovebox environment.

Photo of water test loop



Pump performance curve



Pump vibration levels

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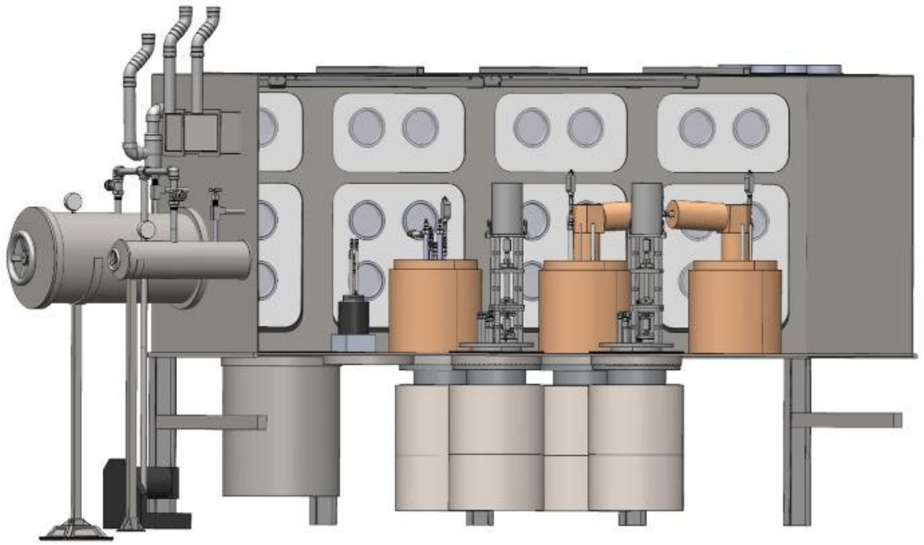
Molten Salt Loop Installation and Operation

Actinide-bearing Molten Salt Loop

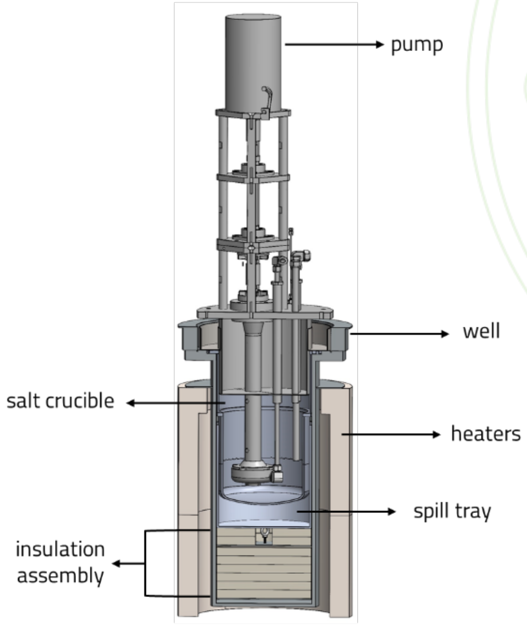
Actinide salt loop was installed in a large-scale radiological glovebox in FY25.[1]

High-actinide concentration ($NaCl$-KCl-UCl_3) salt is being synthesized. Long term measurements were conducted in benchtop-scale tests to inform salt chemistry and corrosion control mechanisms.



Cross-section rendering of radiological glovebox

Photo of installed pump



Cross-section rendering of loop

[1]ANL/CFCT-25/23

Molten Salt Loop Installation and Operation

Non-Radiological Molten Salt Loop

To ultimately inform radiological pump operations, a second non-radiological molten salt loop was installed in FY26.

- Using well-understood salt chemistries will (1) decouple the effects of salt and loop performance, and (2) provide experience in operating the loop.

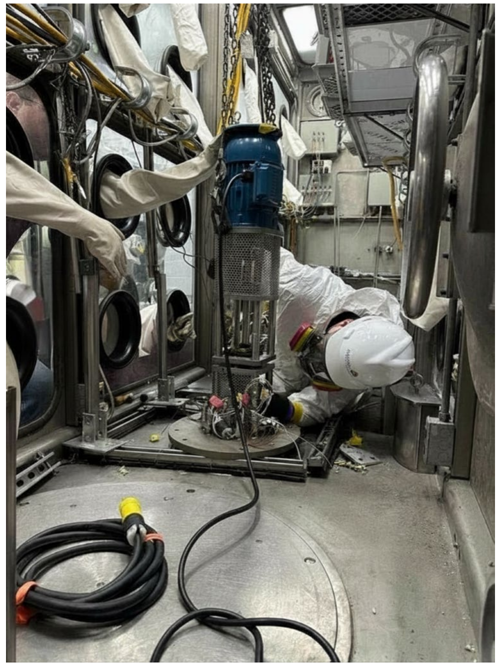
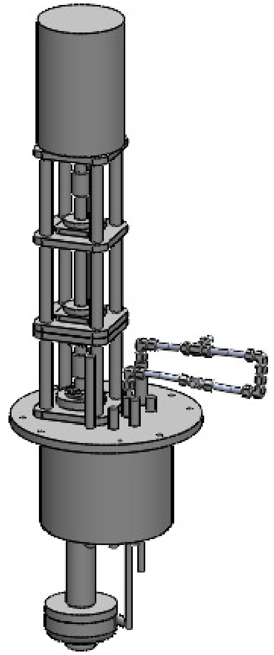


Photo of pump installation

Photo of non-radiological pump



Rendering of molten salt pump and loop.

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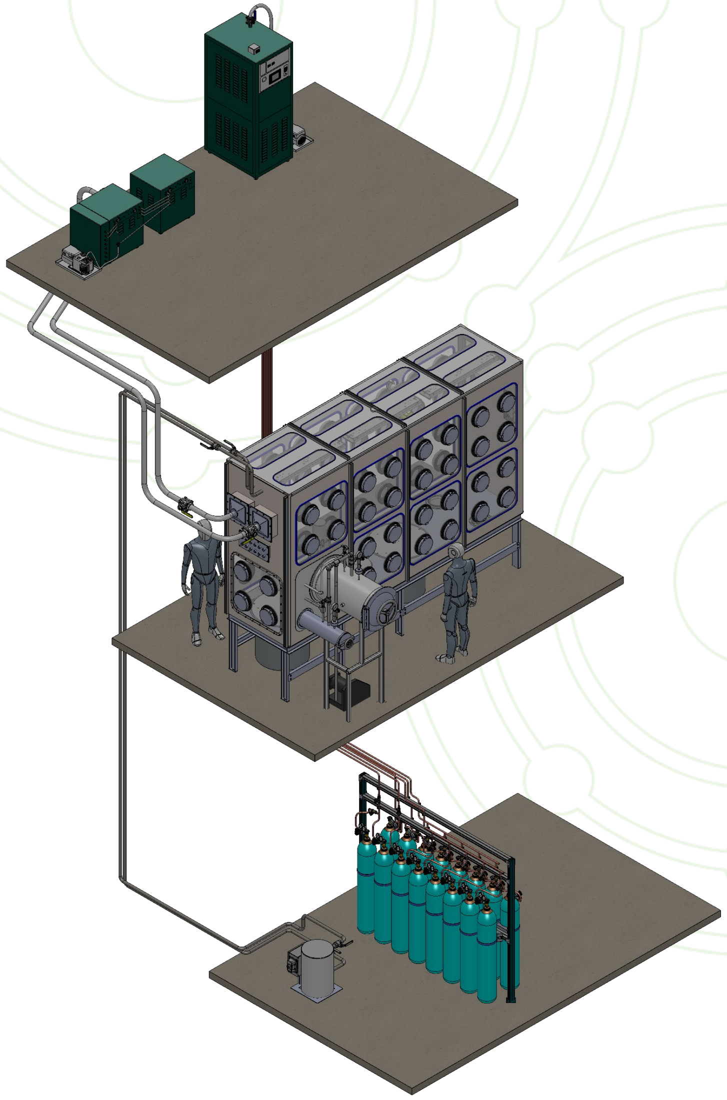
In-Glovebox Flow Loop Setting

Argonne's Flow Systems Development Gloveboxes are excellent environments to test pumped loops containing MSR-relevant fuel salts

- Located in Pu laboratory
- Gloveboxes enables easy handling of high hazard salts
- Inert atmosphere eliminates moisture and oxygen ingressions
- Updated glovebox chillers and cooling systems allow for thermal regulation of multiple flowing systems

Photo of one of Argonne's multi-level radiological gloveboxes



Rendering of one of Argonne's multi-level flow systems gloveboxes

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Molten Salt Loop Operations

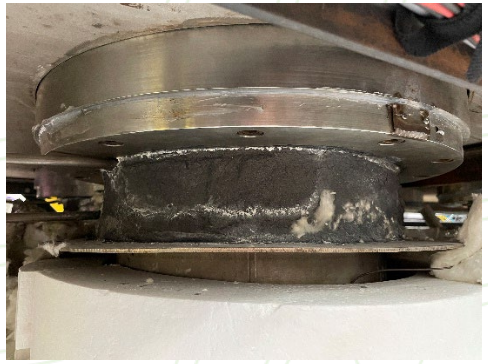
Updated Infrastructure

Argonne's gloveboxes are equipped with multiple level thermal management systems intended to support simultaneous operations of several engineering-scale molten salt systems.

These systems include:

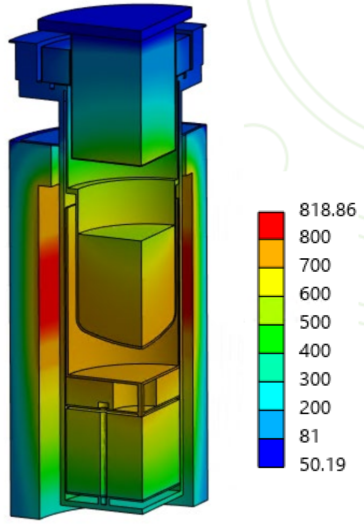
- Atmospheric chillers and heat exchangers to manage internal glovebox temperatures
- Cooling coils positioned around glovebox flanges to protect seals
- Automated redundancies to ensure temperature limits are maintained

Mezzanine-level cooling jackets



Mounted cooling coils

Service-level chiller



Simulated thermal profile

Monitoring and Control of Salt Chemistry

Implications of Contaminant Species

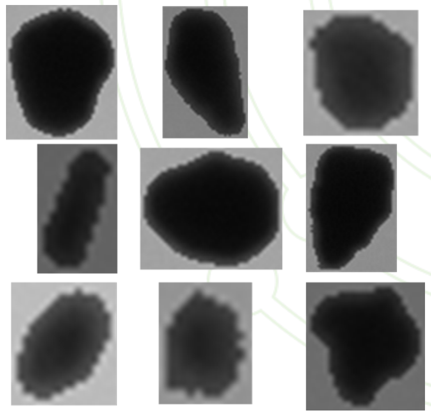
Overview and Introduction

Careful control of salt chemistry is needed to mitigate the deleterious effects of undesired contaminants

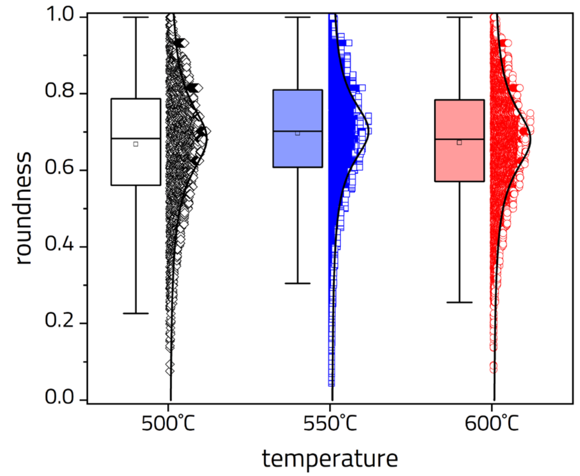
- e.g.: $U^{4+} + 2O^{2-} \rightarrow UO_{2(solid)}$
- e.g.: $Cr_{(alloy)} \rightarrow Cr^{2+} + 2e$

Maintenance of salt chemistry within ideal operating windows minimizes:

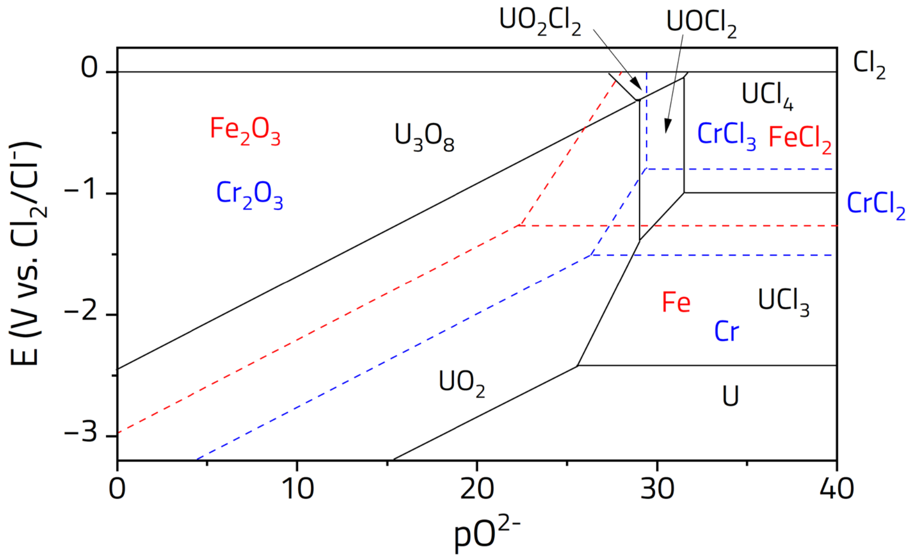
- Structural corrosion,
- Solid-phase formation,
- Material accountancy concerns, and
- Operational disruptions



Particle images of isolated solid oxides



Dynamic image analysis results of oxide particles



Littlewood diagram of high actinide concentration salt

Implications of Uncontrolled Salt Chemistry

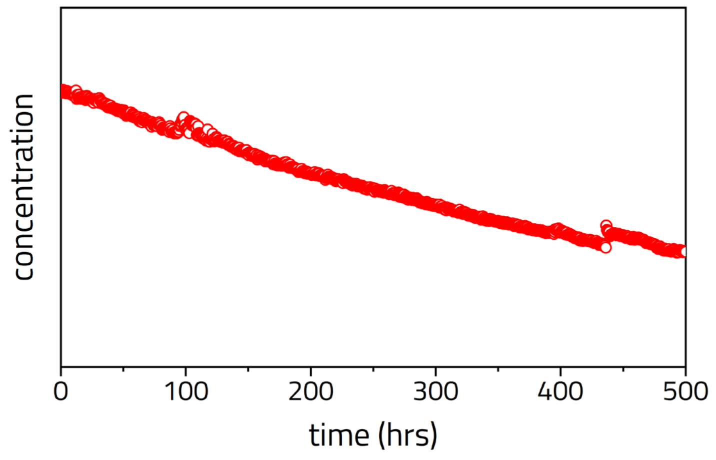
Characterization of Corrosion and Material Consumption in Molten Chlorides

Bench-top testing of representative salts (i.e. high concentration actinides, chlorides, and fluorides) was conducted to inform molten salt pump operation.

In the absence of salt chemistry control mechanisms:

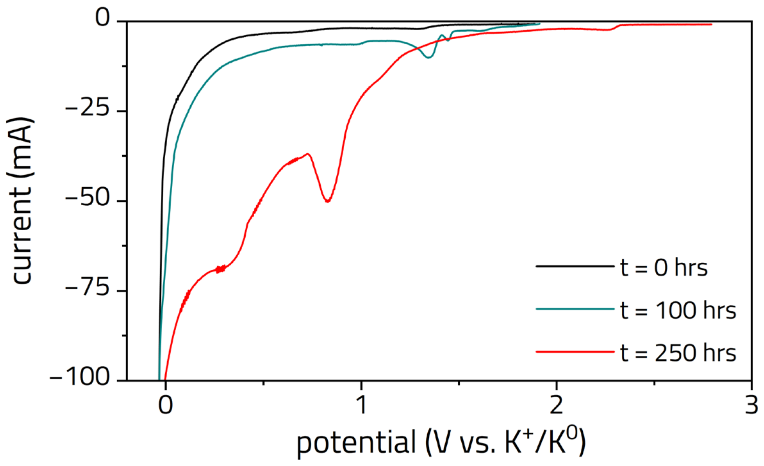
- Redox active material was consumed over time, and
- Corrosion products were observed in all salt systems.

Chloride salt



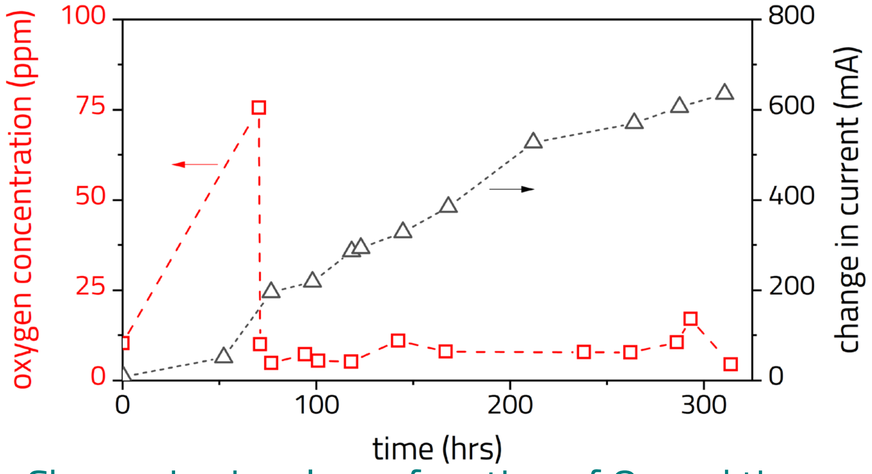
Temporal consumption of redox material

Fluoride salt



Time-evolution of electrochemical response

High concentration actinide salt



Change in signal as a function of O_2 and time

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Implications of Uncontrolled Salt Chemistry

Characterization of Corrosion in Molten Chlorides

Extents and rates of corrosion were quantified through ex situ SEM of salt-wetted and vapor-exposed stainless steel.

- In inert glovebox environments, calculated corrosion rates range from <100 μm/yr (i.e. several orders of magnitude below systems exposed to atmospheric ingressions[1]).
- Various potential corrosion pathways (e.g. crevice, intergranular, pitting) can be observed and is dependent on local environment.

salt-wetted   vapor-exposed

SEM micrograph of 316 SS in contact with salt for 500 hours

SEM micrograph of 316 SS exposed to salt vapor for 500 hours

[1]ANL/CFCT-25/17

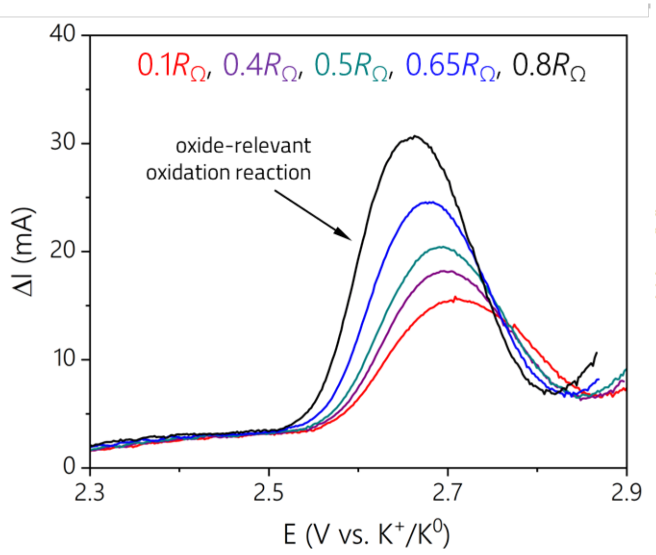
Implications of Uncontrolled Salt Chemistry

Characterization of Oxides in Molten Fluorides

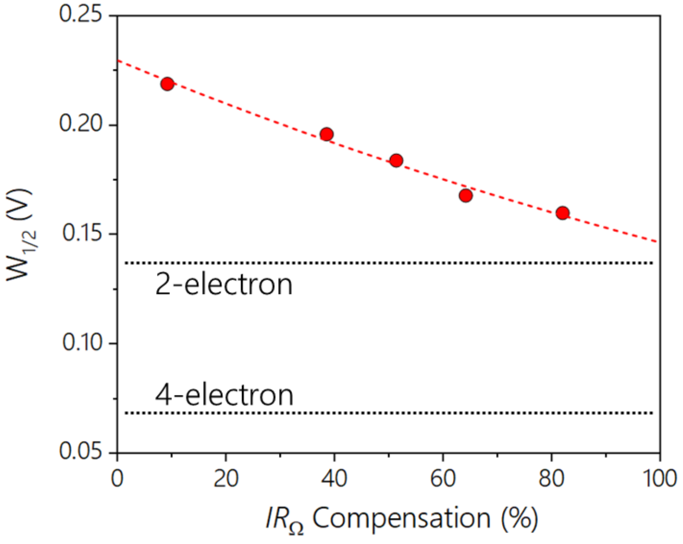
Quantitative and mechanistic characterization studies of dissolved O^{2-} was conducted using square wave voltammetry in molten fluoride salts.

Commonly reported 2-electron reaction can be explained via:

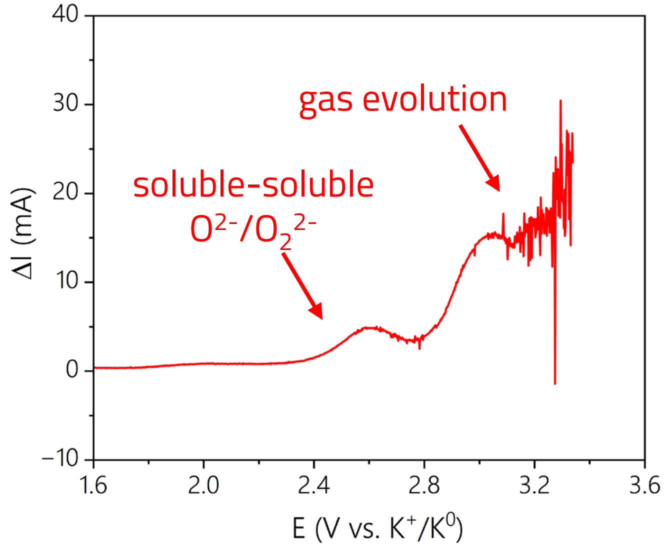
$$2O^{2-} \rightarrow O_2^{2-} + 2e$$
$$O_2^{2-} \rightarrow O_2 + 2e$$



IR-compensated SWVs



Data converging to values predicted by 2-e reactions



SWVs of O^{2-} in FLiNaK

N. A. Shaheen and N. C. Hoyt, JES, 172, 086502 (2025).

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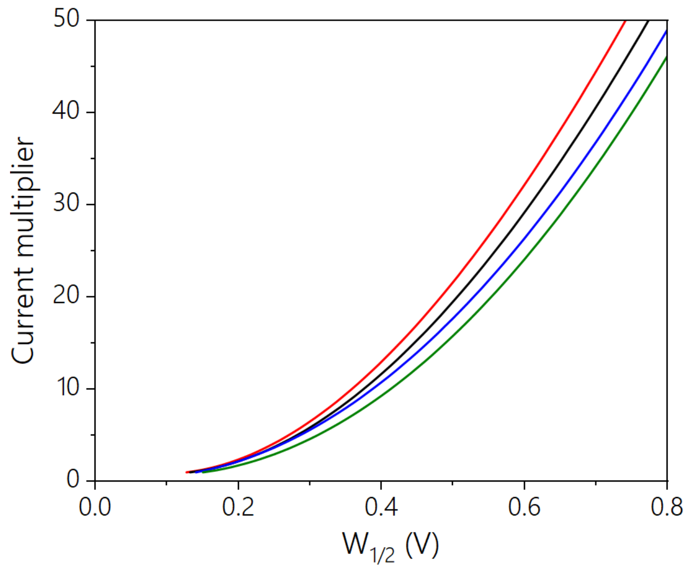
Implications of Uncontrolled Salt Chemistry

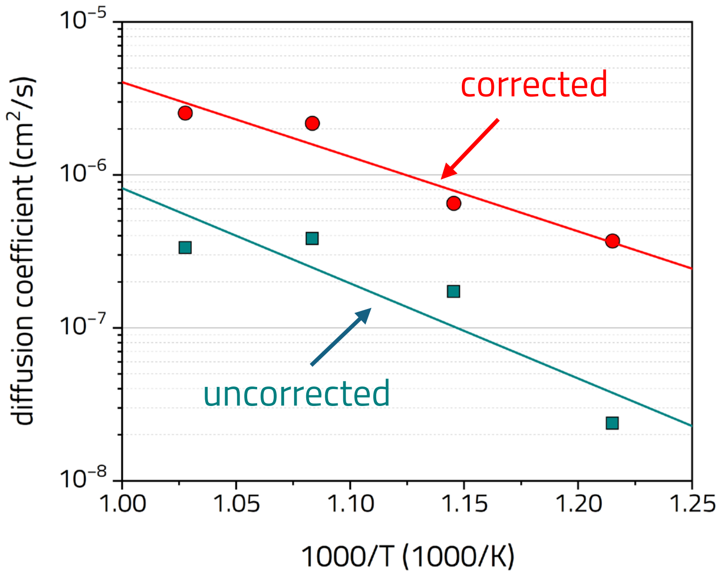
Characterization of Oxides in Molten Fluorides

Theory-derived correction factors extracted from simulations were used to support quantitative analysis of square wave voltammograms involving dissolved oxides.

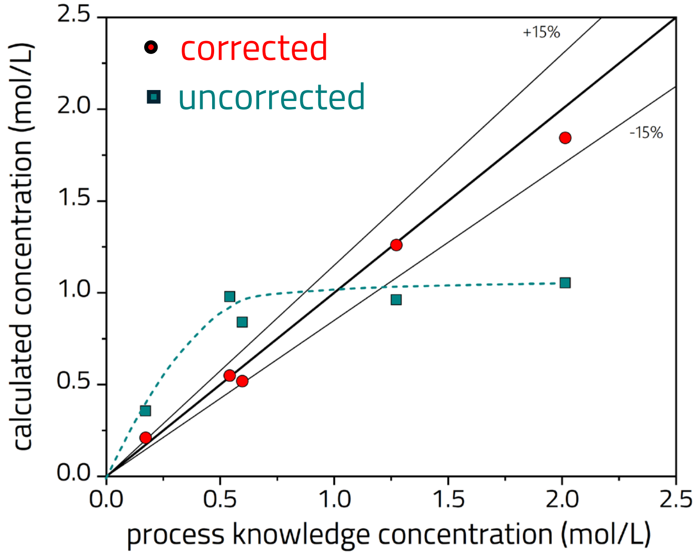
The use of these correction factors linearized Arrhenius plot and parity data such that more accurate analysis may be conducted.



Correction factors at different temperatures



Arrhenius plot of diffusion coefficients



Corrected and uncorrected parity plot

N. A. Shaheen and N. C. Hoyt, JES, 172, 086502 (2025).

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Controlling Salt Chemistry

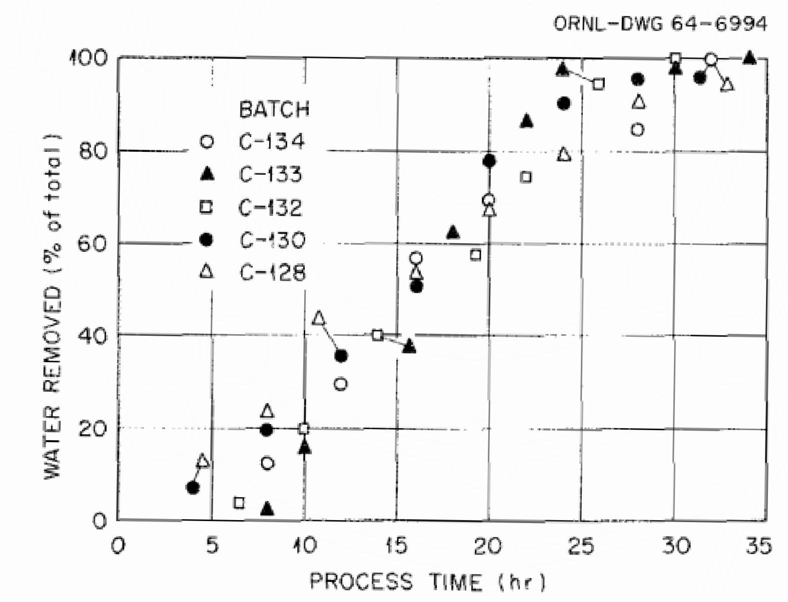
Corrosion Control Systems Overview

Oxidative environments and the unmitigated release of corrosive gases can be mitigated through effective salt chemistry and corrosion control.

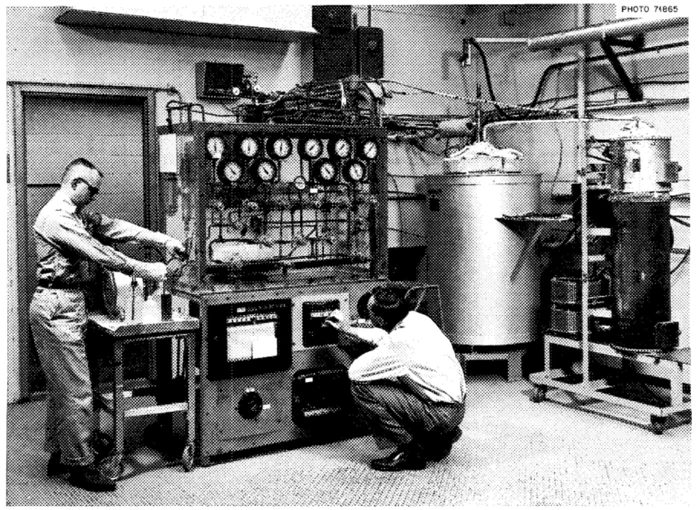
Such systems have been previously reported:

- MSRE utilized ZrF_4 and HF/H_2 sparging for O_2 scavenging and moisture removal, respectively.[1]
- Contemporary literature detail similar approaches, but industrial-scale efficacy is still poorly understood.

Process automation is needed to support the advancement of reactor operation as well as maintaining fuel salt purity.



Water removal as a function of HF/H_2 treatment for MSRE fuel



Manual operation of MSRE fuel fabrication.

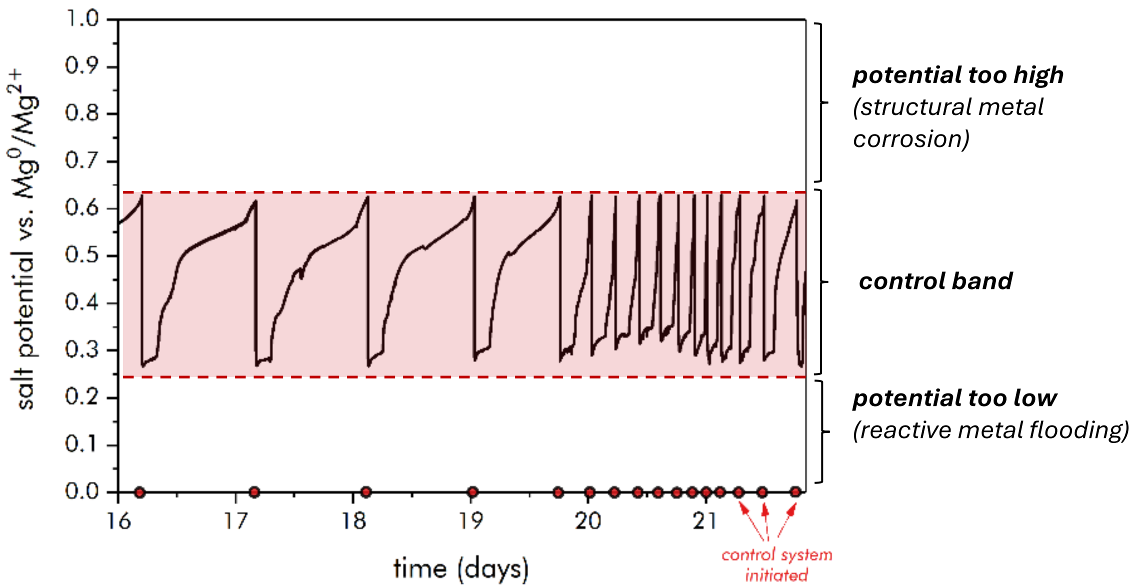
[1]J. H. Shaffer, ORNL 4616, 1971.

Mechanisms to Control Salt Chemistry

Oxygen and Corrosion Control System

Argonne has previously demonstrated the efficacy of corrosion control mechanisms (e.g. reactive metals) to maintain operation within pre-determined operating bands.[1]

- Planned integration of Argonne's ILEX© Automation[2] software for targeted deployment if deviations from control band occur.



Salt potential monitoring and control

Photo of Argonne's automation software interface[2]

ANL/CFCT-20/40

[2]Developed under DOE NE5 ARSS Program

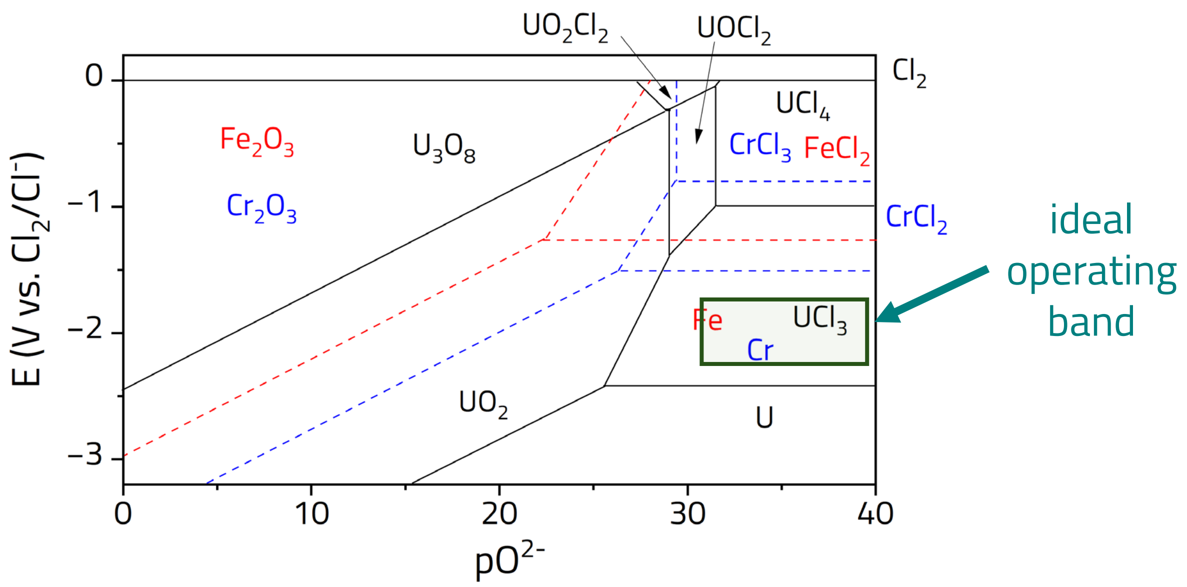
Mechanisms to Control Salt Chemistry

Oxygen and Corrosion Control System

Salt control mechanisms will be deployed to maintain salt potential and oxide activity within ideal operational bands.

Several deployment-ready, modular control systems are integrated into the pumped loop system.

- Dynamic utilization of these systems provides a holistic approach in maintaining long-term salt purity and pump operation.



Littlewood diagram of high actinide concentration salt with ideal control band

Argonne's suite of process monitoring and salt chemistry control hardware

Engineering-Scale Salt Synthesis

Approximately 100 kg of uranium metal has been procured to support additional salt synthesis activities (NaCl-KCl-UCl_3).

- Engineering-scale salt synthesis is necessary for testing and advancing technologies under MSR-relevant conditions.

Uranium metal being prepared for transfer to Bldg 205

Photo of uranium metal pyrophoricity testing

Milestones and Achievements

Presentations and Publications:

Conference Presentations:

N. A. Shaheen and N. C. Hoyt (2025) "On the electro-oxidation of oxides in molten FLiNaK." 248th ECS Meeting, Chicago, IL.

N. A. Shaheen, T. Kim, W. Doniger, A. Polke, D. Penley, K. Stasior, M. Jubinsky, and N. Hoyt (2026) "Quantification and mitigation of uncertainty for material accountancy measurements in molten salt systems" ANS Global *(contributed to)*.

A. Polke, et al., (2026) "Advanced Salt Monitoring for Safeguards of the Nuclear Fuel Cycle." ANS Global *(contributed to)*.

Publications:

N. A. Shaheen and N. C. Hoyt (2025) "Electrochemical characterization of dissolved oxides in molten FLiNaK." *JES*, 086502.

N. A. Shaheen, T. J. Kim, A. Polke, K. Stasior, D. Johnson, and N. C. Hoyt, "Design and Operation of In-Glovebox Pumped Molten Salt Loops", in preparation.

N. A. Shaheen, T. J. Kim, and N. C. Hoyt, "Corrosion control mechanisms in molten salt systems", in preparation.

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