U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

Overview of the Molten Salt and Molten Salt Reactor Research in the United States

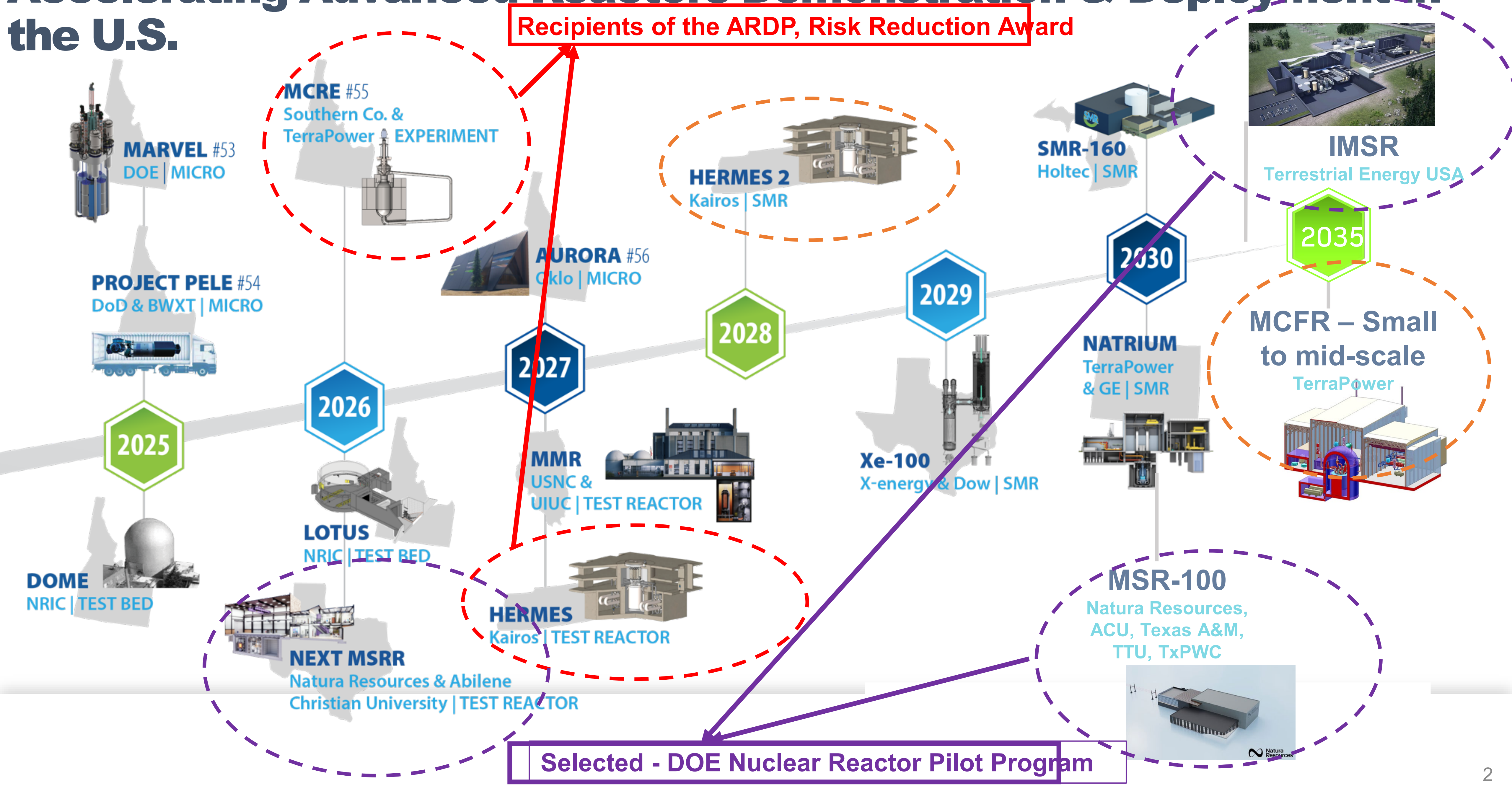
Dr. Patricia Paviet
National Technical Director

GIF MSR pSSC meeting

9-10 December 2025

PNNL-SA-218354

Accelerating Advanced Reactors Demonstration & Deployment in the U.S.



Some Challenges

Chemistry Challenges

Gaps in thermophysical and thermochemical properties of molten salts, Actinide fluoride and chloride bearing mixtures. Irradiation studies on chloride fuel salt .

Cl-37 Enrichment and separation

Off Gas Management Monitoring and development of sensors

Integrated off gas system with adequate capture

Understanding aerosol, bubbles formation

Safety Demonstration and Regulation

Novel Designs and Fuel Cycles: MSRs employ innovative designs and fuel cycles, necessitating thorough safety demonstrations and regulatory approval. Developing safety cases and regulatory frameworks for MSRs is a key condition for its success.

Molten Salt Clean-up, Processing on-line, in-line, at-line, off-line

Purification from salt contaminants (fission products, corrosion products, lanthanides….)

Recovery of valuable material

Fuel Salt Processing: The online processing of liquid fuel salts to extract fission products and manage the chemistry of the salt mixture is one of the most promising aspects of MSRs. However, this area needs further investigation and demonstration to ensure reliability and efficiency.

Material Challenges

Finding materials that can withstand this harsh chemical environment, resist corrosion, endure high temperatures, and tolerate neutron fluxes over long periods remains a significant challenge. This includes testing and qualifying new alloys, composites, and coatings that can meet the demanding conditions of MSR operation.

Scale-up and Commercialization

Scaling Up Technology: Transitioning from experimental or small-scale models to full-scale commercial reactors involves significant challenges in scaling up the technology and demonstrating its economic viability at a commercial level.

VISION - The DOE-NE MSR campaign serves as the hub for efficiently and effectively addressing, in partnership with other stakeholders, the technology challenges for MSRs to enter the commercial market.

SALT CHEMISTRY

Thermophysical and Thermochemical Properties of Molten Salts –
Experimental and Computational
Salt purification and synthesis

TECHNOLOGY DEVELOPMENT

Off-Gas Management
Radionuclide Release Monitoring,
Sensors & Instrumentation
Salt Loops: LSTL & FASTR; MSTTE; ASL; SAAF

NATIONAL AND INTERNATIONAL MSR SAFETY

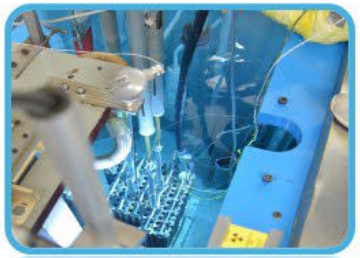
Guidance on reasonable approaches to demonstrating safe and economic commercial prototype molten salt reactors.

Mission: Develop the technological foundations to enable MSRs for safe and economical operations while maintaining a high level of proliferation resistance.

1) MSRs can provide a substantial portion of the energy needed for the U.S. to have energy security, energy independence.
2) There is a need for an abundant energy for the foreseeable future for data centers, desalination, process heat, hydrogen production...

SALT IRRADIATION

Fuel salt irradiation and post irradiation examination capabilities
NRAD, ATR
Under Advanced Fuel Cycle Campaign



MODELING & SIMULATION

NEAMS Tools & MELCOR utilized for
- Species Tracking
- Accident Scenario
- Mechanistic Source Term...

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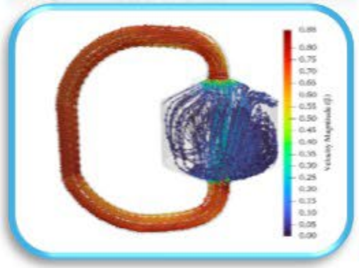
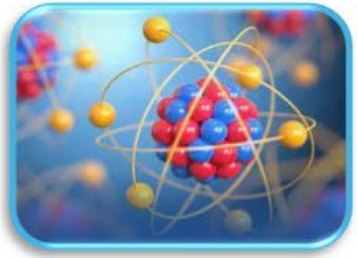


MSR RADIOISOTOPES

Developing new Technologies to separate Radioisotopes of Interest to the MSR Community.



Molten Salt Reactor PROGRAM

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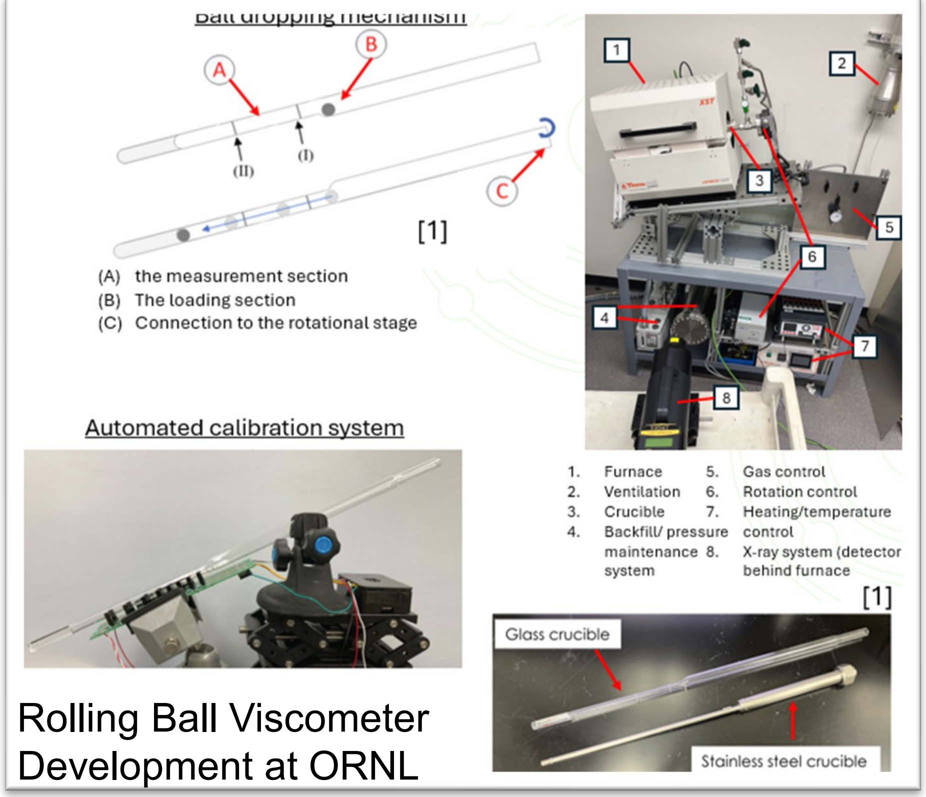
Molten Salt Chemistry

MSR Program – Chemistry Expertise

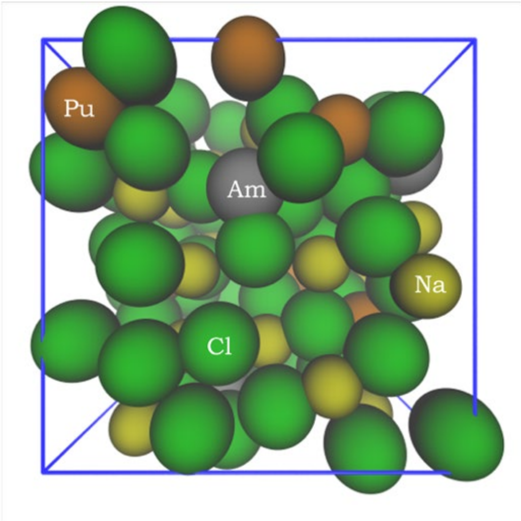
- Development of synthesis and purification of molten salts
- Determination of thermal properties of molten salts
  - Density
  - Heat Capacity
  - Viscosity
  - Vapor pressure
  - Thermal conductivity
  - Thermal diffusivity
  - Salt fluid inclusion characterization
- Using Ab Initio Molecular Dynamic to extrapolate thermophysical properties data of molten salt
- Measurement Uncertainty and the Effect of Impurities on Molten Salt Properties
- Two Databases
  - MSTDB –TP and MSTDB-TC
- Development of enrichment and separation capability for Cl-37 production (100g to 1 kg scale)



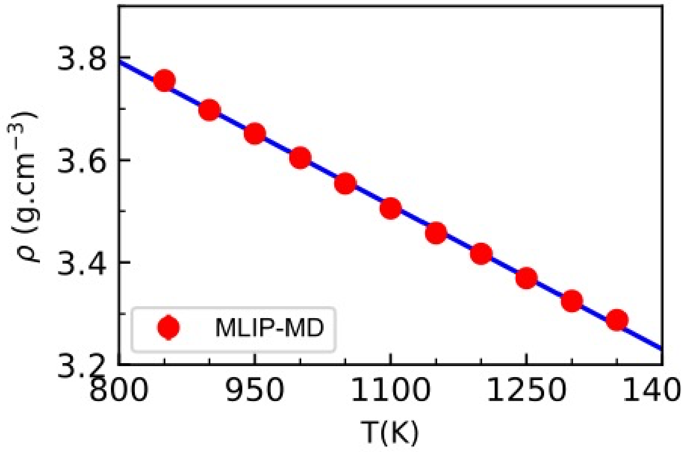
Rolling Ball Viscometer Development at ORNL

AIMD and MLIP to determine Thermal properties of $PuCl_3$-$AmCl_3$-NaCl (31 mol% $PuCl_3$ and 14 mol% $AmCl_3$)

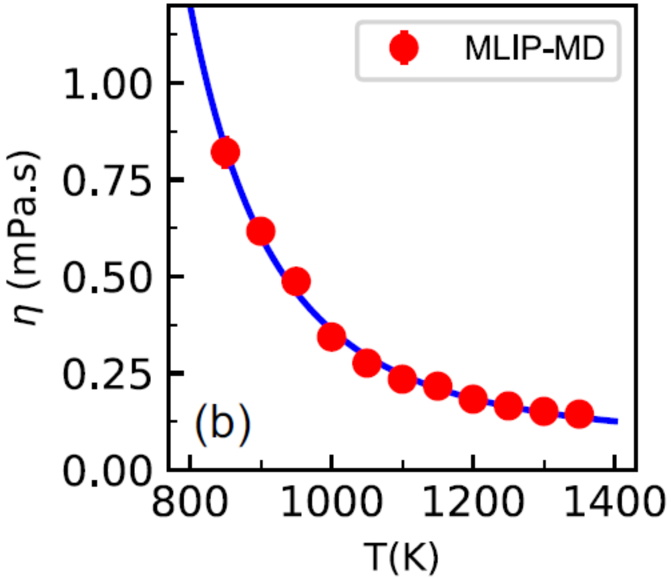
- First evaluation of the thermophysical properties of $AmCl_3$-$PuCl_3$-NaCl, which is relevant to fast spectrum molten salt Reactors.
- Calculated will be compared with experimental data being determined at Idaho National Laboratory



Simulation box with Cl in green, Na in yellow, Pu in orange, and Am in grey.



Temperature dependence of density



Temperature dependence of viscosity

Molten Salt Reactor PROGRAM

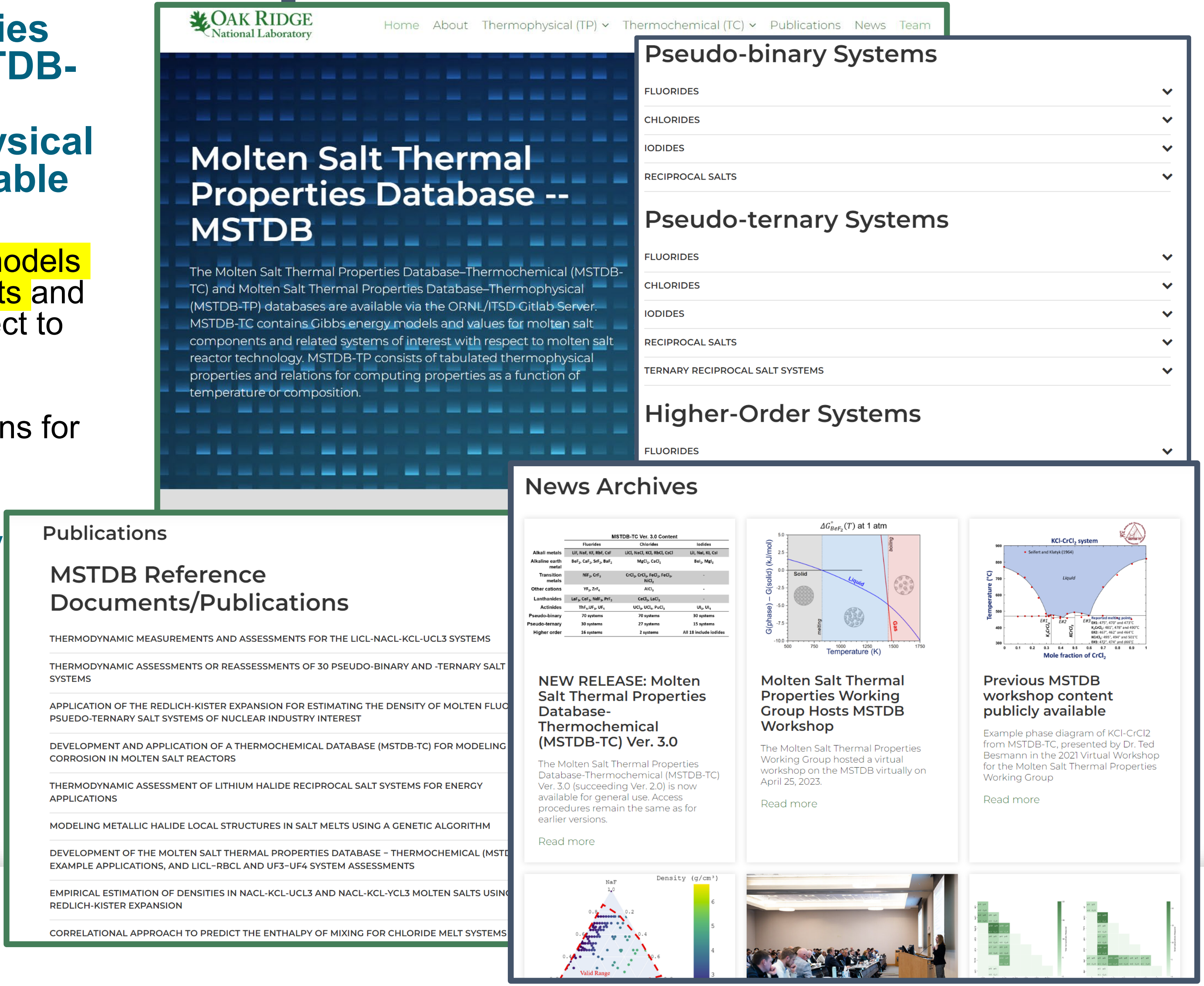
U.S. DEPARTMENT of ENERGY
Office of Nuclear Energy

Manh Thuong Nguyen, PNNL report SA-38386, SEP 2025

Molten Salt Thermal Properties DataBase MSTDB

- **The Molten Salt Thermal Properties Database–Thermochemical (MSTDB-TC) and Molten Salt Thermal Properties Database–Thermophysical (MSTDB-TP) databases are available via the ORNL/ITSD Gitlab Server.**
  - **MSTDB-TC** contains Gibbs energy models and values for molten salt components and related systems of interest with respect to molten salt reactor technology.
  - **MSTDB-TP** consists of tabulated thermophysical properties and relations for computing properties as a function of temperature or composition.
- **MSTDB has >320 users currently**

Available @ https://mstdb.ornl.gov



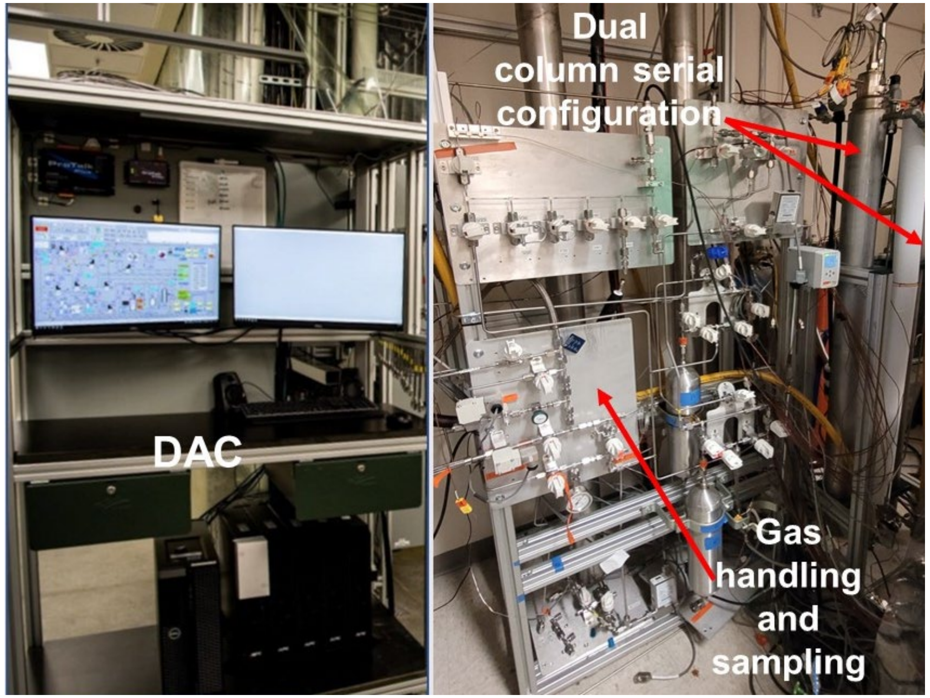
OAK RIDGE National Laboratory | NEAMS | UNIVERSITY OF South Carolina | Molten Salt Reactor PROGRAM

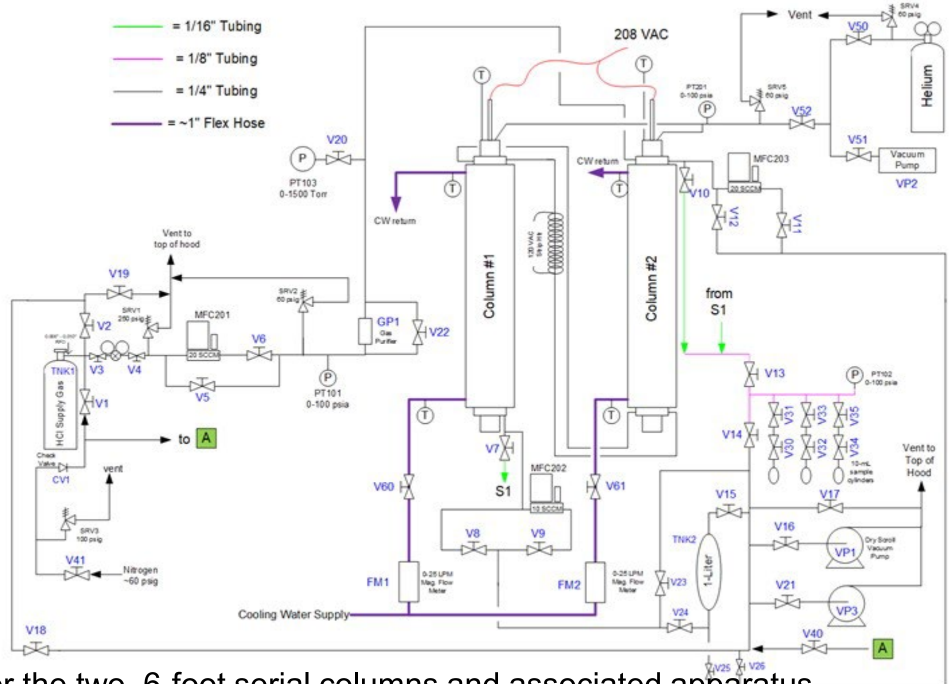
Thermal diffusion isotope separation system for enrichment of ^{37}Cl

- Concern to Reactor Longevity:
- The $^{35}Cl(n,p)^{35}S$ reaction, which decays back to ^{35}Cl. Accordingly, yields of sulfur will accumulate in the salt. For a properly reduced fuel salt, the likely form of the sulfur would be S^{2-}. A few thousand ppm S (as S^{2-}, S^{0}) are corrosive to Ni, Mo and additionally react with fertiles. $UCl_3 + S = U_xS_{y\,(ppt)}$, $PuCl_3 + S = U_xS_{y\,(ppt)}$

- The $^{35}Cl(n,\alpha)^{32}P$ produces radio-phosphorus ($t_{1/2}$= 14d) that also decays to more sulfur. P can interact with these MOCs as PCl_3 or more reduced forms of phosphorous

B. McNamara, IAEA/NEA MSR Fuel cycle workshop, 3-7 NOV 2025





P&ID for the two, 6-foot serial columns and associated apparatus

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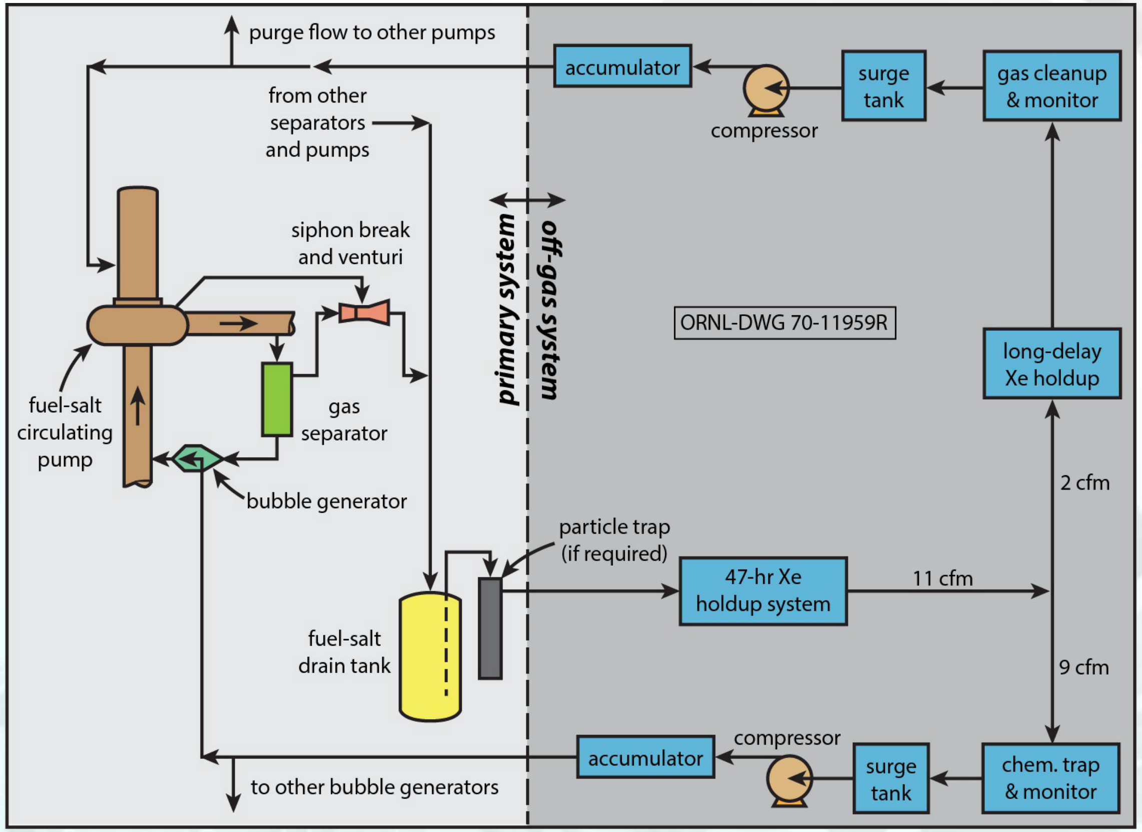
Integrated Off-Gas Management

The off-gas serves as the pressure boundary, required for safety and licensing. Its role will be determined by the configuration of the reactor and associated processes.



- Liquid fueled versus liquid cooled
- Salt circulation and definition of pressure boundary
- Salt composition: chloride versus fluoride
- Reactor materials: graphite, alloys, moderator

For each type of reactor, must assess off-gas requirements.

- Define the requirements (temperature/pressure/flow rate) of the complete off-gas system, including auxiliary units, & needed redundancy
- Define loading – He, trace impurities, particulates, vapor pressures of salt species (ICl, IFx, T), daughter production, revolatilization
- Assess decay heat handling
- Share commonalities where possible

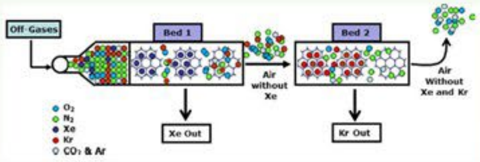
MSR Off-Gas	Advanced Fuel Cycle Off-Gas	Pyroprocess Off-Gas
No cooling	Cooled fuel > 5 years	Cooled fuel > 5 years
Continuous operation over several years	Batch process	Batch process
Low carrier gas flow rate (He)	Carrier gas will be air/H2O/NO2	Inert gas (Ar) – stagnant?
Salt aerosols, volatile FP, acidic gases, noble metal particles, H-3	Kr-85, I-129, C-14, H-3 in gas phase	Low FP load in gas phase

Technology Development and Demonstration
Multi-faceted approach to investigation of technologies for MSR off-gas systems

Component Testing

Large Scale Test Loop

Xe/Kr separation in MOF

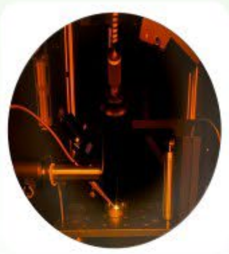


Radionuclide Identification/Speciation

Raman Spectroscopy

405 nm 532 nm 671nm

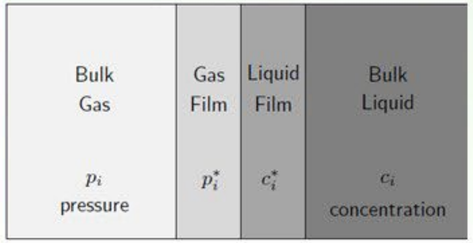
Laser Induced Breakdown Spectroscopy



Gas/Liquid Interface

Bubble Measurement

Source Term Modeling

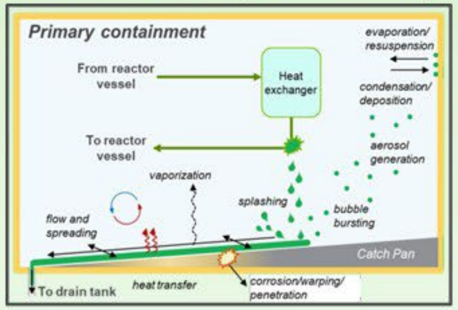


$$c_i^* = p_i H$$

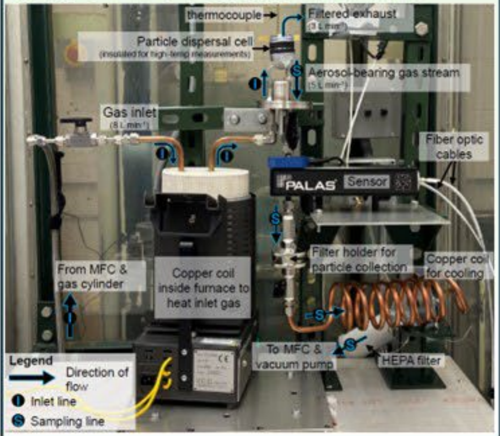
$$p_i^* = c_i / H$$

Spill Test

Engineering Scale Salt Accident Analysis Facility

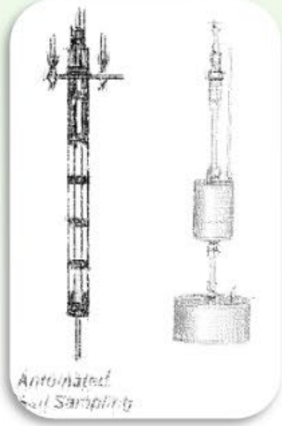


Salt Aerosol Concentration and Size Measurements



Sensors/Salt Chemistry

Salt Composition
Redox
Salt Level



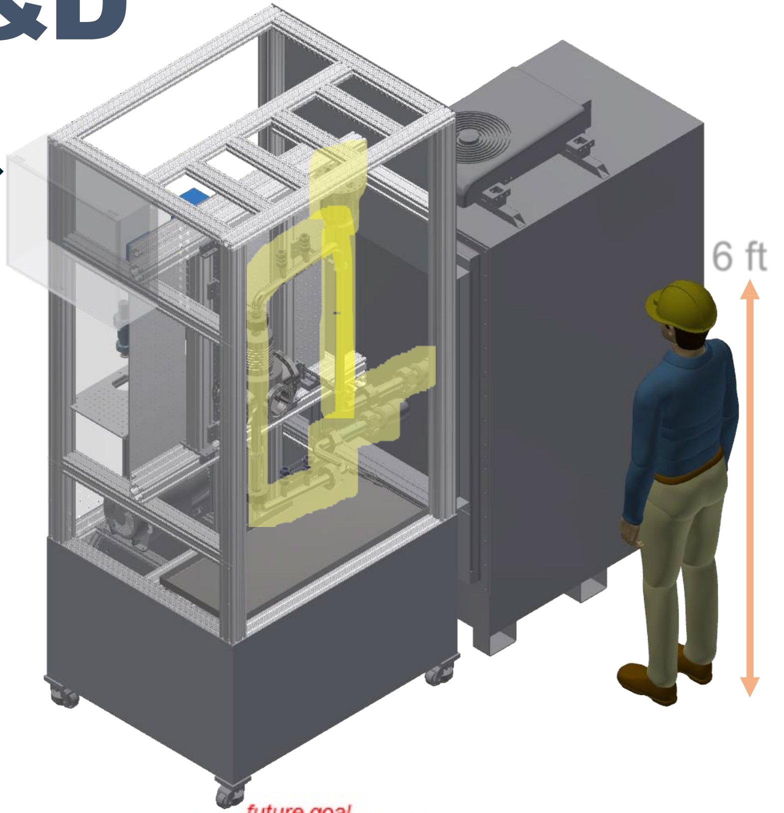
Argonne National Laboratory · INL Idaho National Laboratory · Los Alamos National Laboratory · Oak Ridge National Laboratory · Pacific Northwest National Laboratory

Molten Salt Reactor PROGRAM

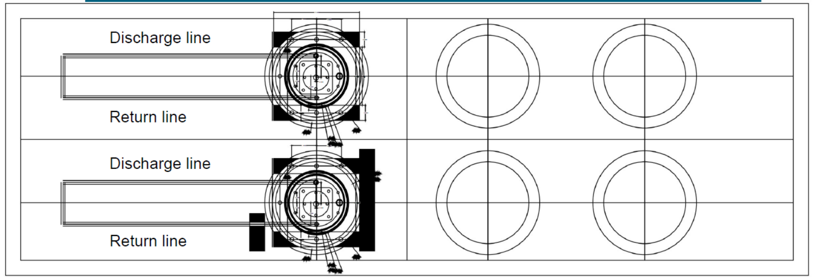
Salt Loops supporting MSR R&D

FASTR -Facility to Alleviate Salt Technology Risks – ORNL
NaCl-KCl-MgCl2
725C
154L

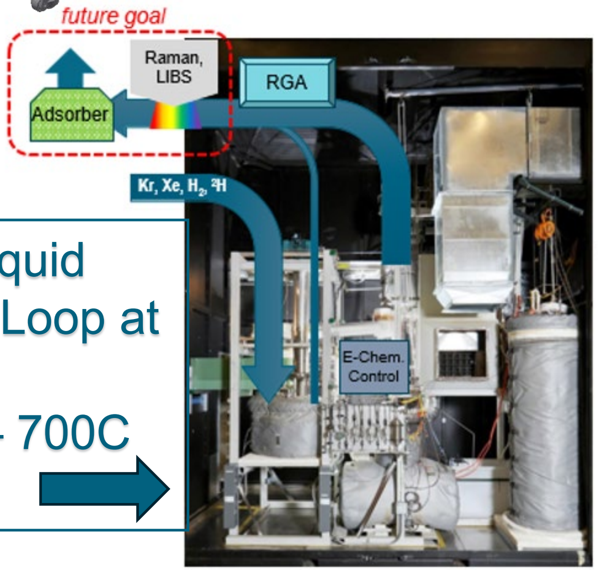
MSTTE – Molten Salt Tritium Transport at INL
FY 2025 Deuterium- FLiNaK salt



Actinide Salt Loop at ANL



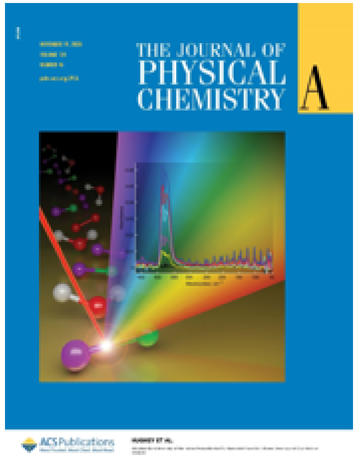
LSTL - Liquid Salt Test Loop at ORNL
FLiNaK – 700C
80L



Tandem use of Raman, LIBS, and redox probes, flow sensors demonstrated in FASTR – AUG 2025

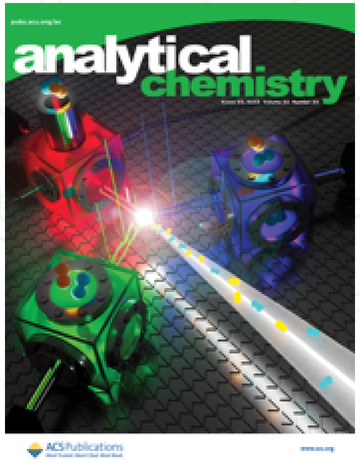
Online Monitoring: Molecular Approach through Raman

- On-line monitoring using optical spectroscopy for:
  - Identification and quantification of target species
  - Oxidation state information
  - Molecular and elemental species
- Goal to design sensors to:
  - Survive harsh conditions (high temperature, corrosive, and radioactive environments)
  - Improve sensitivity
- Making smart sensors
  - Build autonomous tool kits to identify and quantify species using spectral data
- **Building tools to support efficient development and cost-effective deployment of off-gas treatment systems**



Hughey, K. D.; Bradley, A. M.; Tonkyn, R. G.; Felmy, H. M.; Blake, T. A.; Bryan, S. A.; Johnson, T. J.; Lines, A. M., Absolute Band Intensity of the Iodine Monochloride Fundamental Mode for Infrared Sensing and Quantitative Analysis. *J Phys Chem A 2020, 124* (46), 9578-9588.

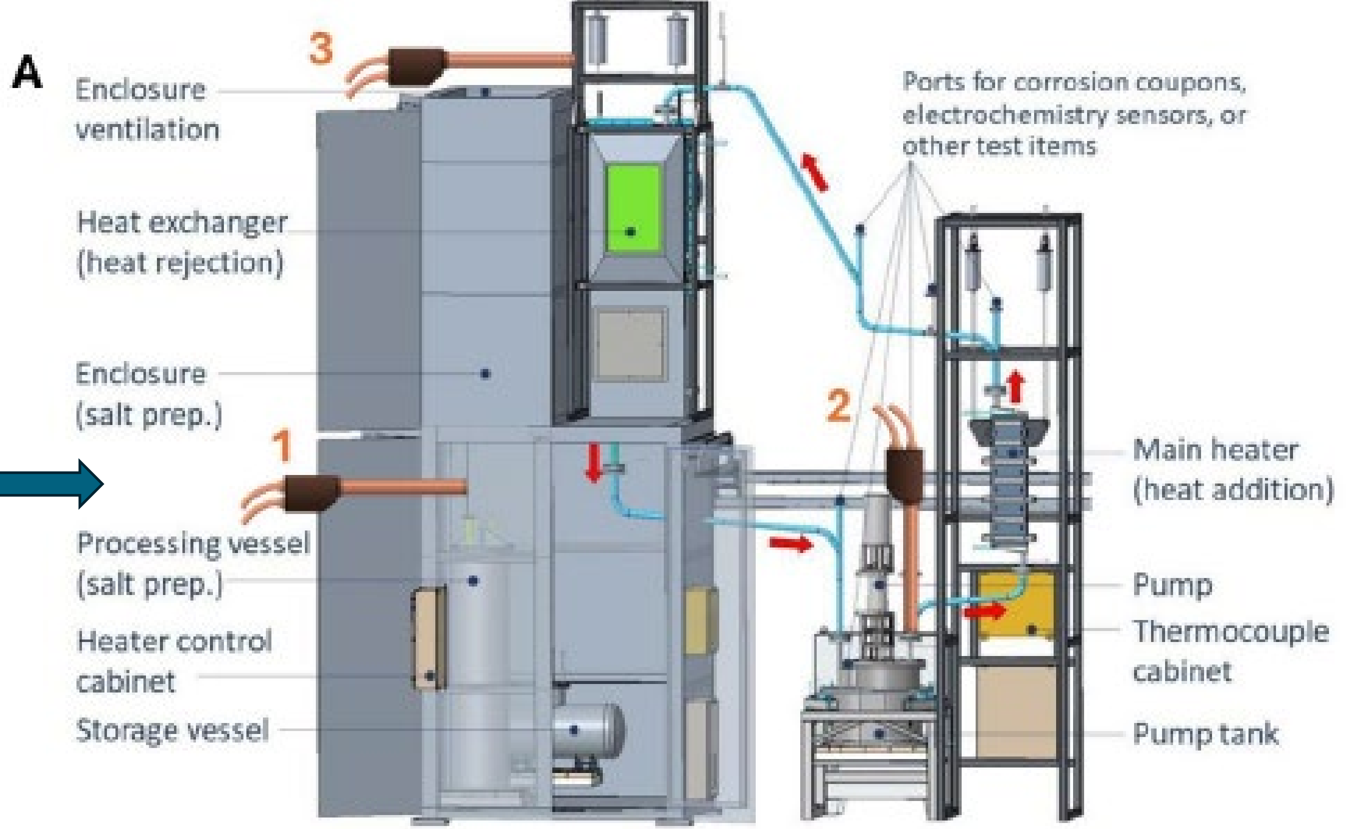
Felmy, H. M.; Clifford, A. J.; Medina, A. S.; Cox, R. M.; Wilson, J. M.; Lines, A. M.; Bryan, S. A., On-Line Monitoring of Gas-Phase Molecular Iodine Using Raman and Fluorescence Spectroscopy Paired with Chemometric Analysis. *Environ Sci Technol 2021, 55, 6, 3898–3908.*



Felmy, H. M.; Cox, R. M.; Espley, A. F.; Campbell, E. L.; Kersten, B. R.; Lackey, H. E.; Branch, S. D.; Bryan, S. A.; Lines, A. M. Quantification of Hydrogen Isotopes Utilizing Raman Spectroscopy Paired with Chemometric Analysis for Application across Multiple Systems. *Analytical Chemistry* **2024**. DOI: 10.1021/acs.analchem.4c00802.

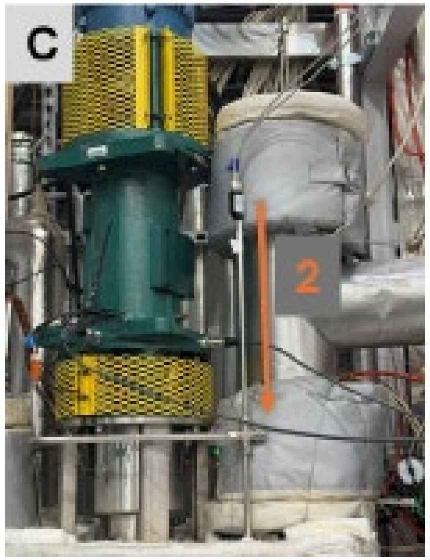
Adan Schafer Medina, Heather M. Felmy, Molly E. Vitale-Sullivan, Hope E. Lackey, Shirmir D. Branch, Samuel A. Bryan, and Amanda M. Lines ACS Omega **2022** 7 (44), 40456-40465. DOI: 10.1021/acsomega.2c05522

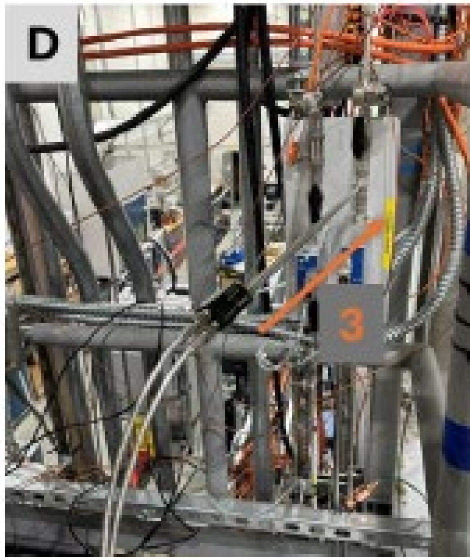
Schematic of FASTR with Raman probe locations indicated in orange (not to scale)



Photos of locations where Raman probes were incorporated into the FASTR loop are shown in

- B) Salt Storage Tank
- C) pump tank,
- D) top of the manifold

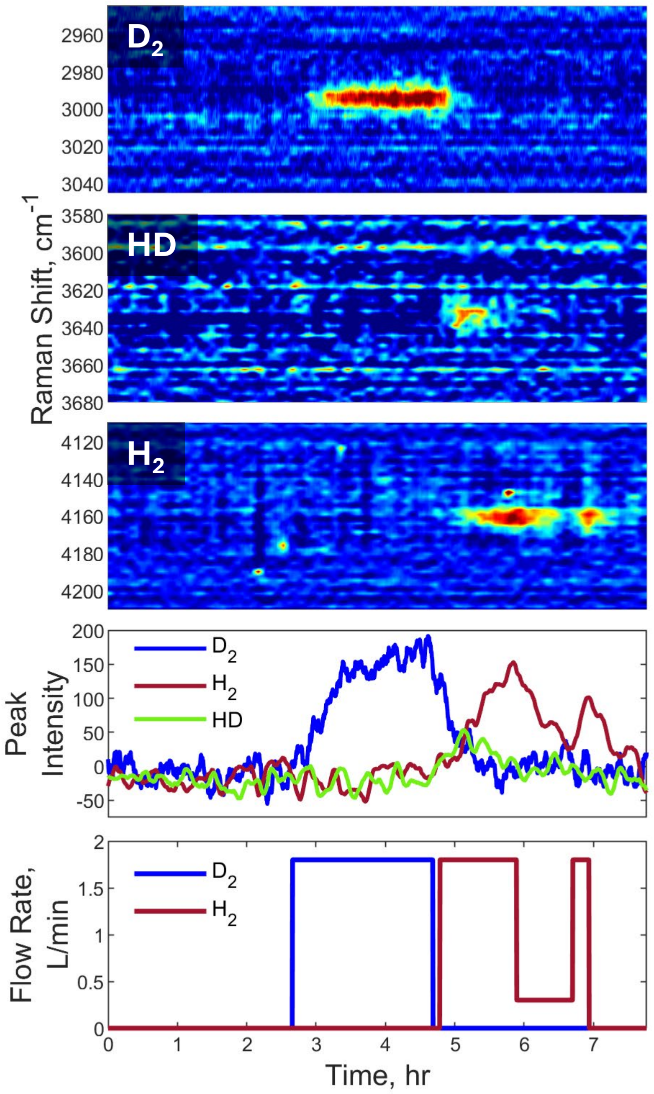




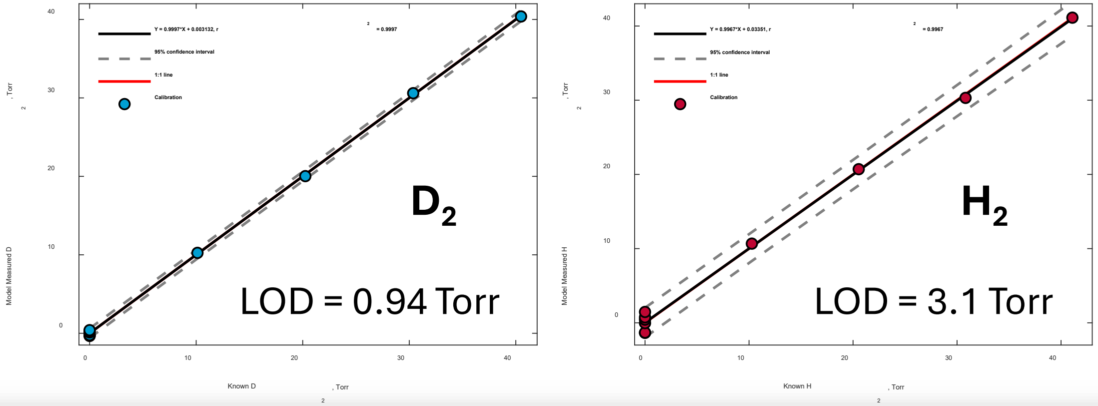
Felmy et al, PNNL-38277, SEP 2025

Onsite Demonstration of Raman at ORNL-FASTR

- **Successfully deployed Raman system at ORNL in August 2025**
- **Monitored multiple locations in FASTR loop**
- **Detected D_2, H_2, and HD in gas phase above salt storage tank**
- **In tandem with LIBS and RGA**
- **Continuing data analysis and collaboration**



Improved limits of detection (LOD)



Felmy et al, PNNL-38277, SEP 2025

Rapid Elemental Analysis using Laser Induced Breakdown Spectroscopy

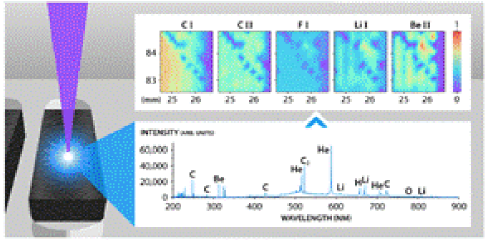
LIBS is being developed as an analytical monitoring tool for molten salt reactor (MSR) systems.

A mobile LIBS platform was configured on a small-scale salt vessel (~100 g of salt) and then transported 0.6 km to successfully monitor an engineering-scale pumped salt loop (~100 kg of salt).

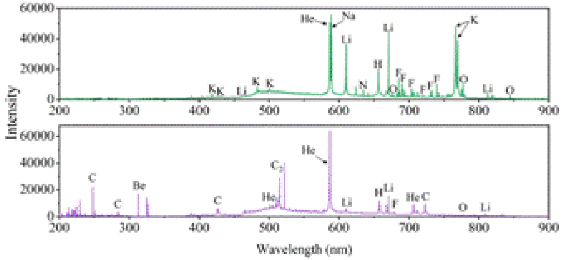
Why LIBS?

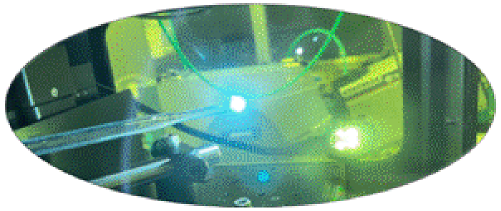
- Sensitivity across the periodic table
- Capable of remote measurements
- Rapid analysis
- Customizable to the application
- Can monitor solids, liquids, gases, and mixtures
- Elemental (occasionally isotopic) technique

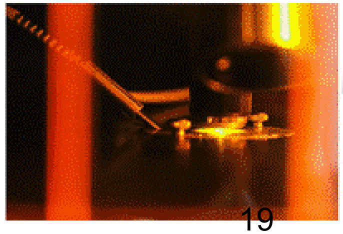
How can LIBS be used?



- Frozen salt analysis
  - As procured, purified, and post testing
- Investigating salt – material interactions
  - Graphite, structural materials
- Online monitoring
  - In-situ salt analysis, off-gas monitoring
- Real-time isotopic composition

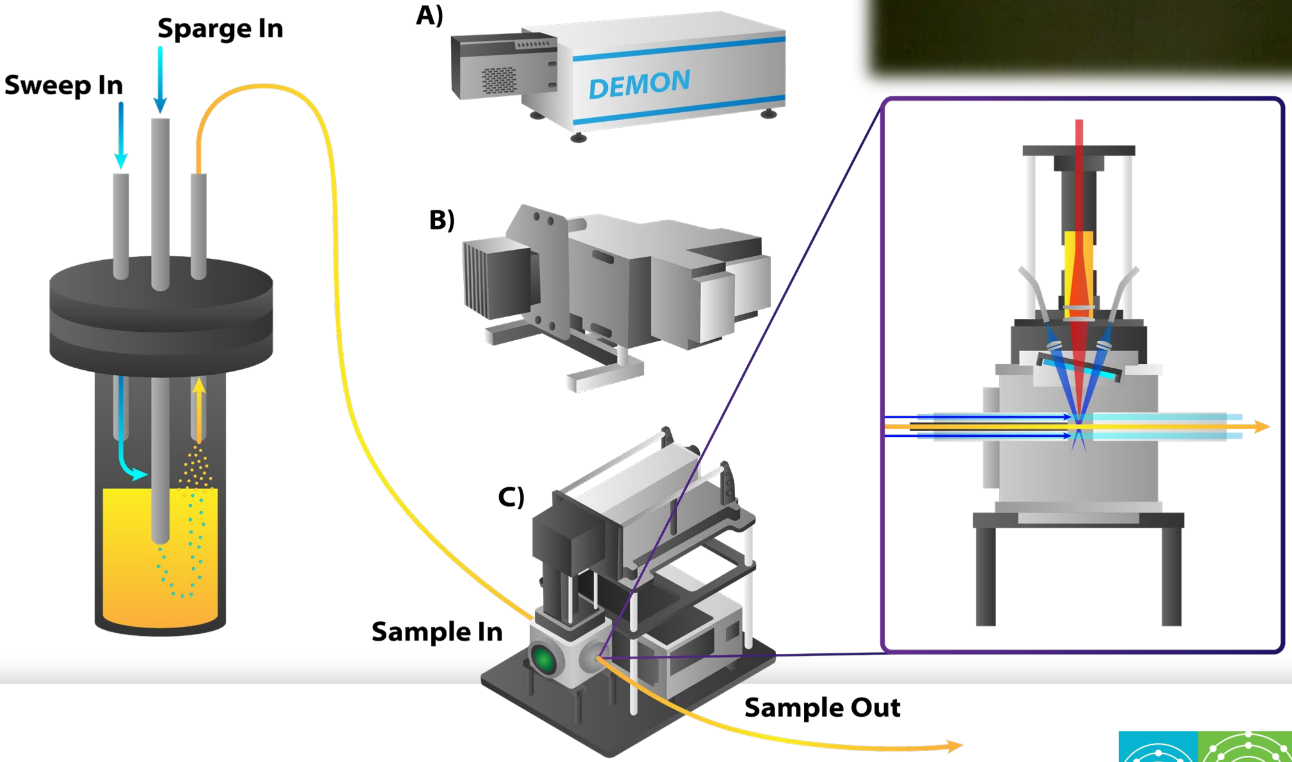


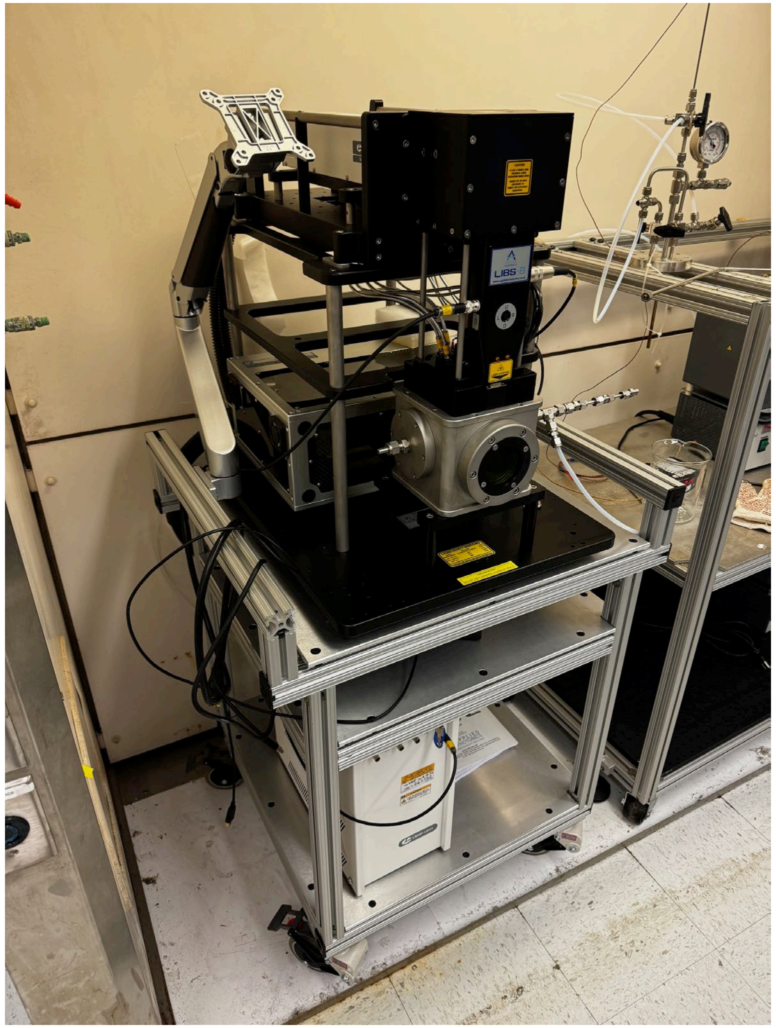




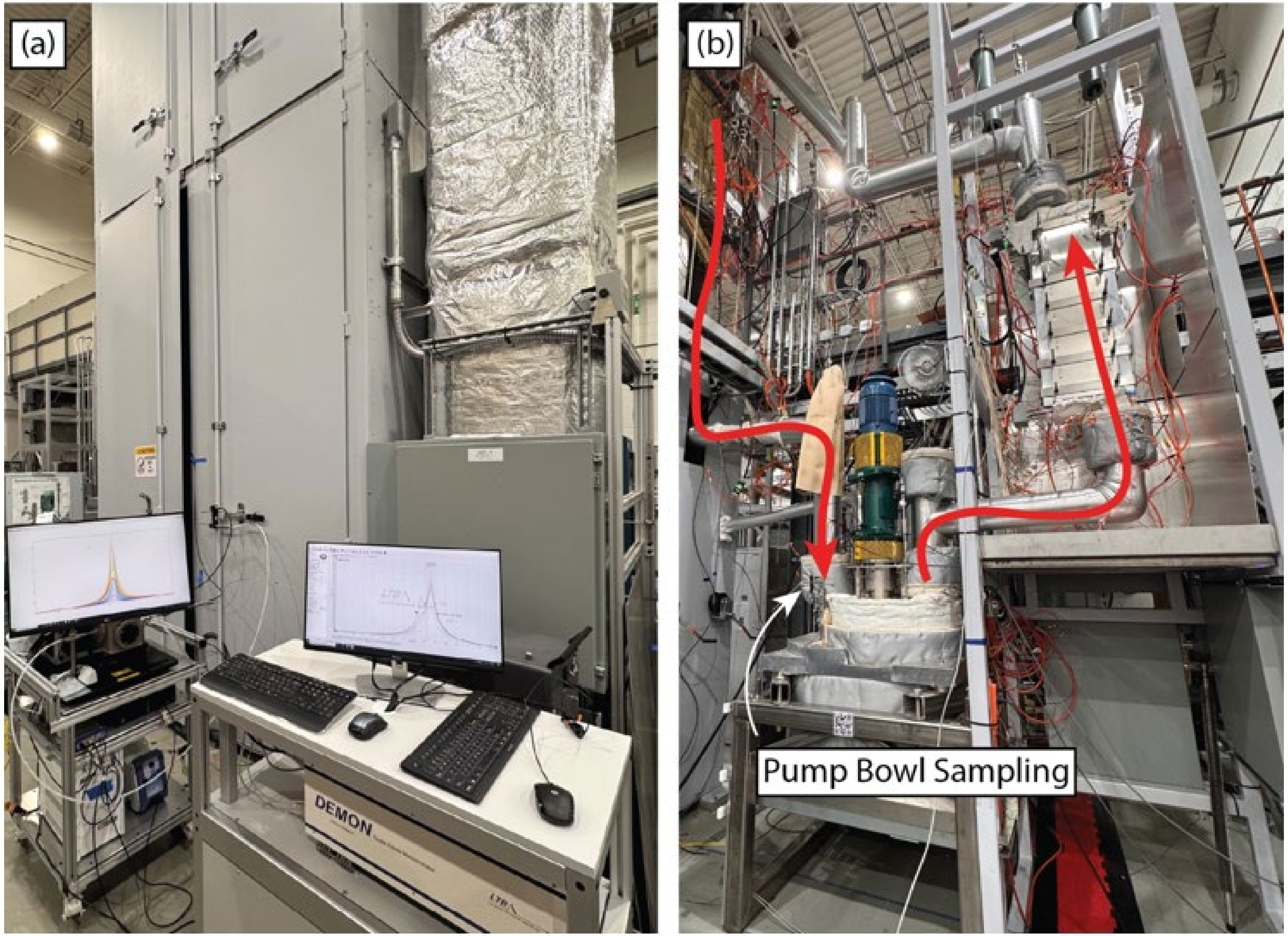
Andrews et al., ORNL/TM-2025/4115, September 2025

Mobile LIBS platform and molten salt aerosol sampling deployed at ORNL-FASTR





Hunter Andrews, andrewshb@ornl.gov



(a) FASTR storage tank with LIBS cart in the front left and DEMON spectrometer in the front right.

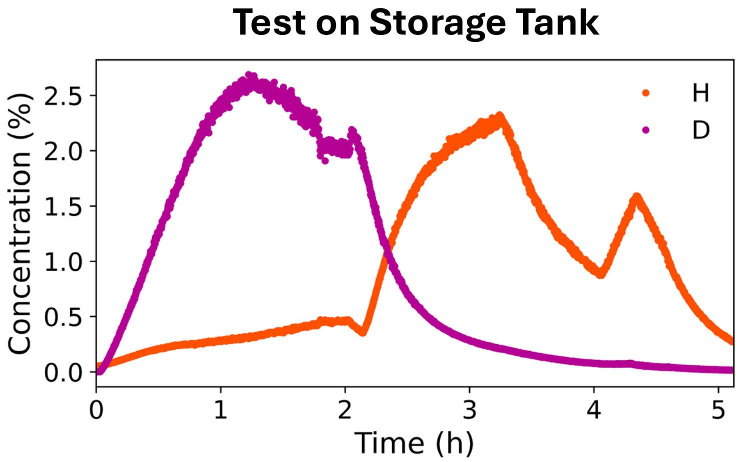
(b) FASTR loop with the salt direction shown in red and the pump bowl sampling location indicated.

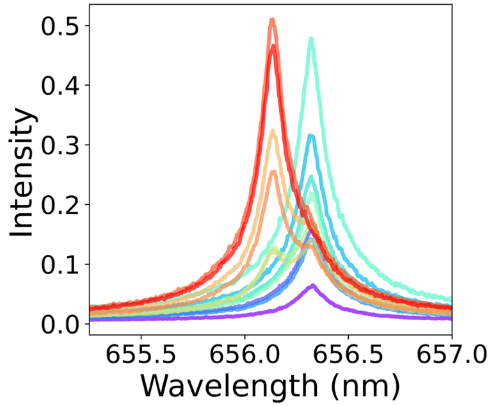
Andrews et al., ORNL/TM-2025/4115, September 2025

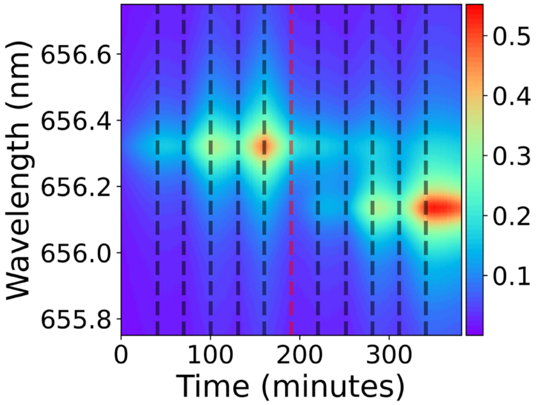
Quantification of H isotopes in FASTR with LIBS

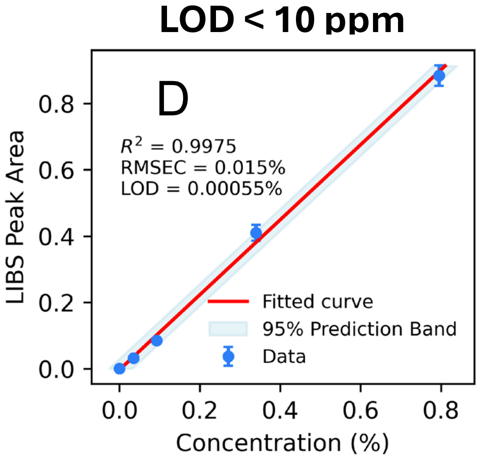
- **Mobile LIBS cart successfully deployed after 0.6 km transit**
- **Elemental detection of H and D from H_2 and D_2 gases in storage tank and pump bowl**
- **LIBS complements the molecular information from Raman with enhanced sensitivity**

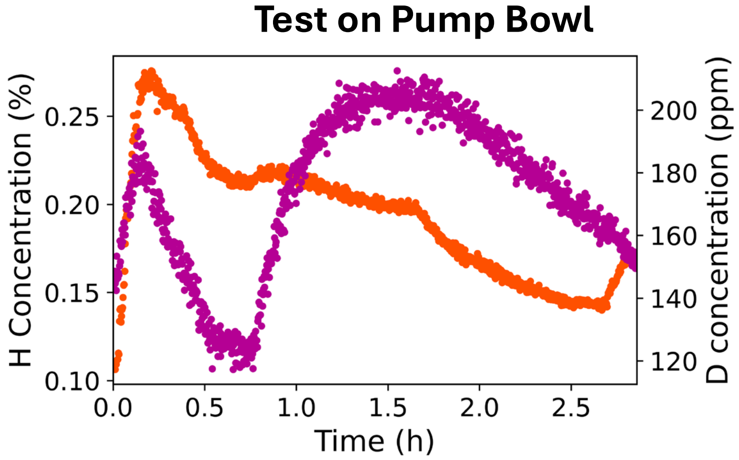
Mobile LIBS cart in transit





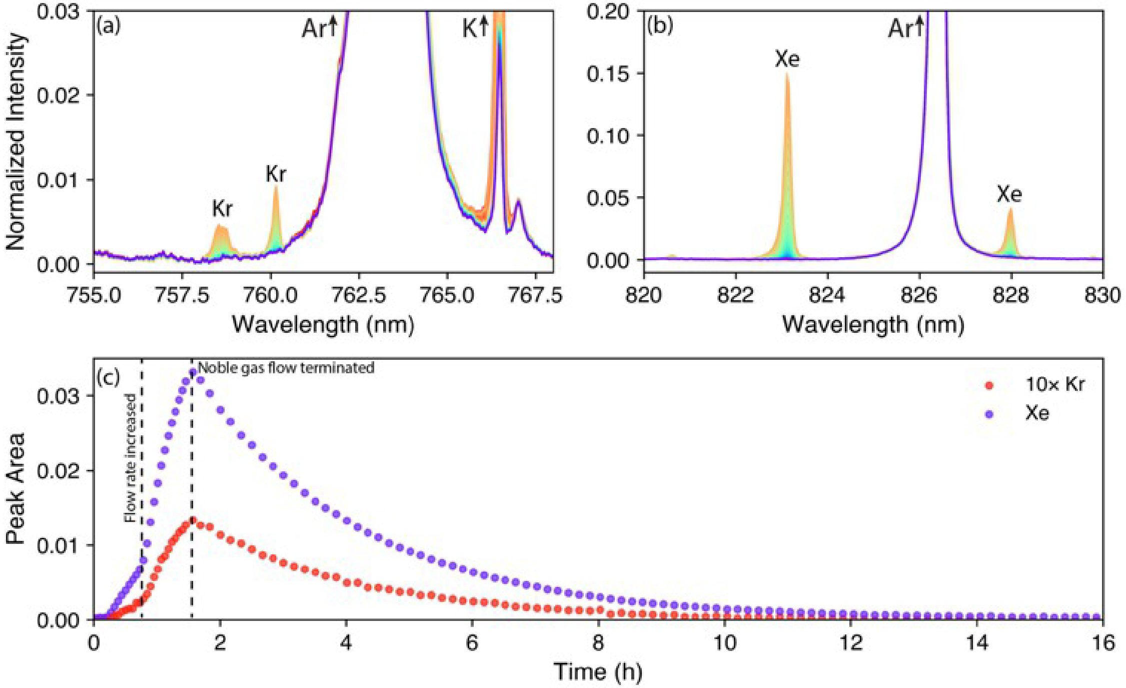






Andrews et al., ORNL/TM-2025/4115, September 2025

Time Evolution of (a) Kr and (b) Xe was recorded on the Ar-swept FASTR storage tank



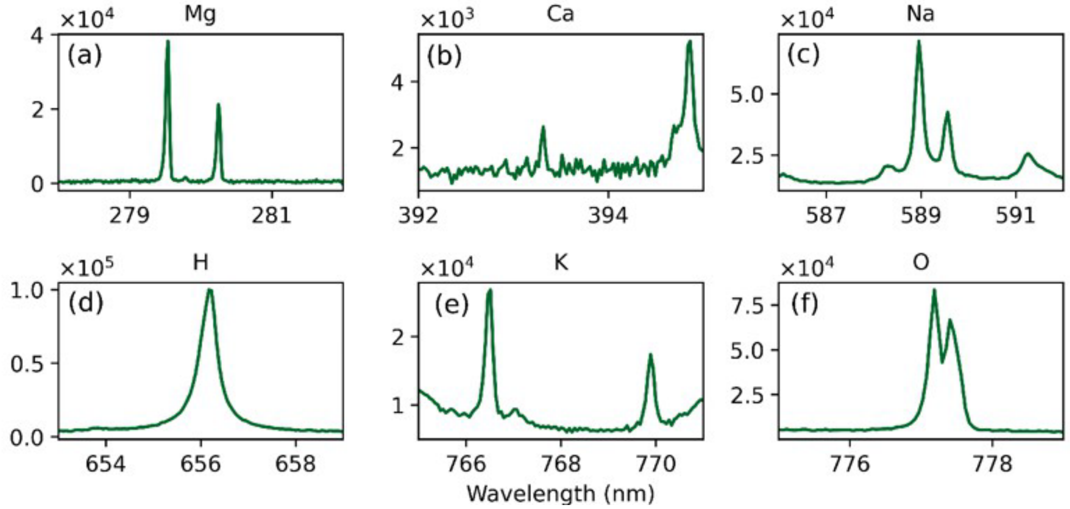
Time evolution of (a) Kr and (b) Xe recorded during the noble gas test on the FASTR storage tank as measured on the broadband MCS.

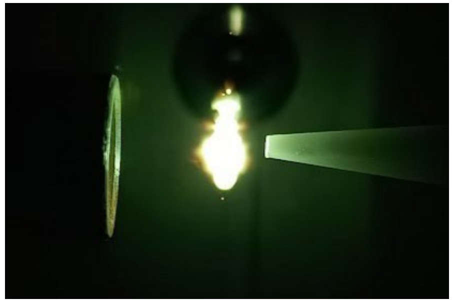
The Xe and Kr peak area trends over time are shown in (c), where the Kr peak area is multiplied by 10 to account for the magnitude of concentration difference.

Andrews et al., ORNL/TM-2025/4115, SEP 2025

Aerosols are a major pathway for radionuclide transport from MSRs

- LIBS plasma identified salt aerosols in Ar generated in FASTR under pumped flow
- Indicative of salt composition

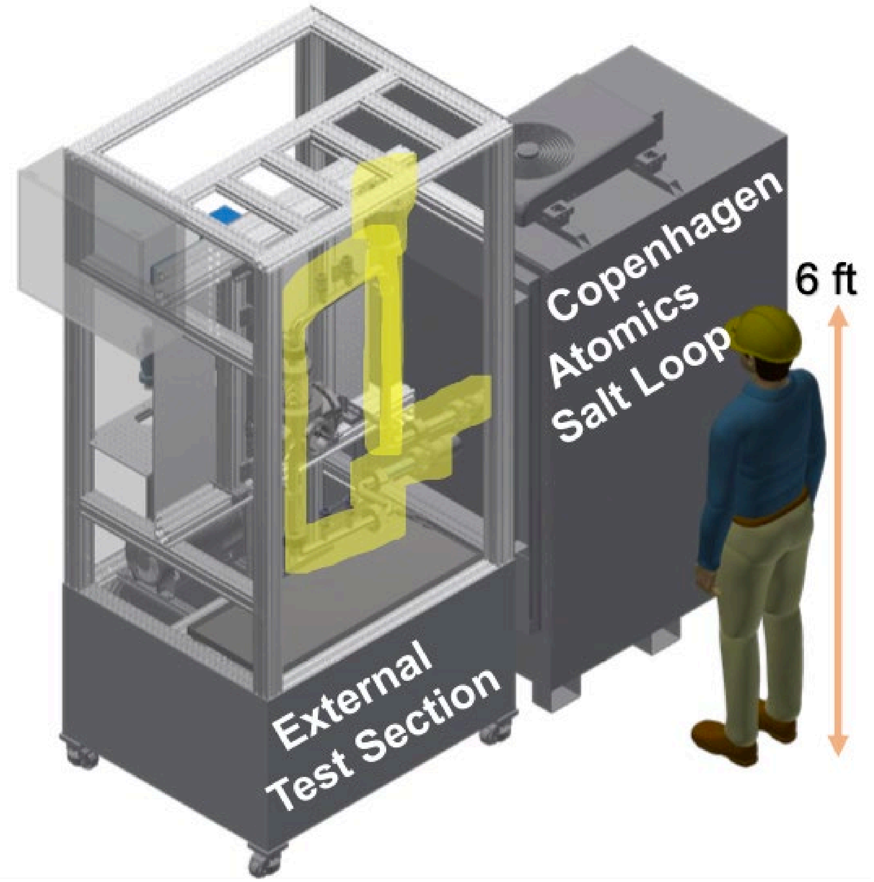




Andrews et al., ORNL/TM-2025/4115 (Sept 2025)

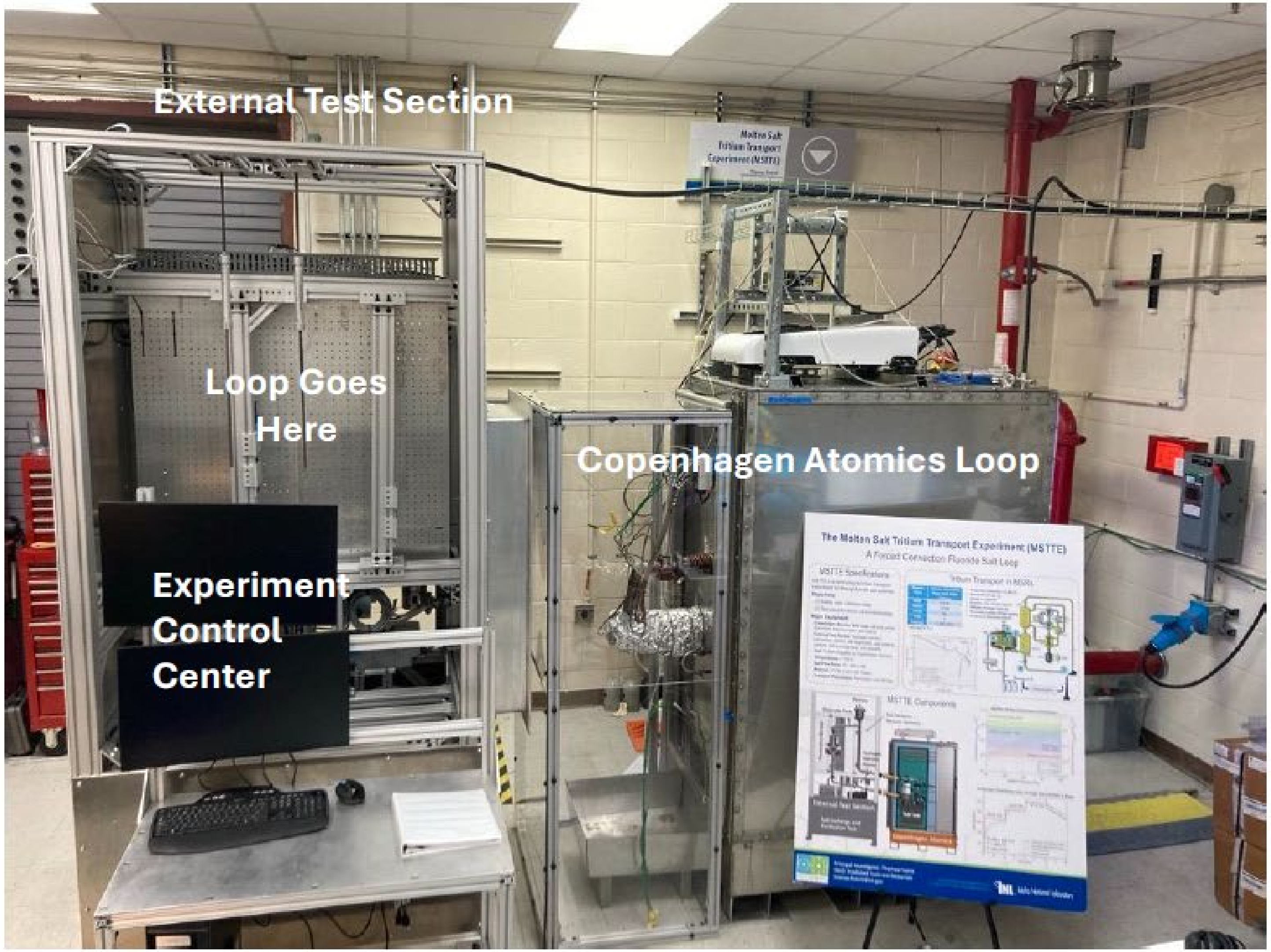
Molten Salt Tritium Transport Experiment

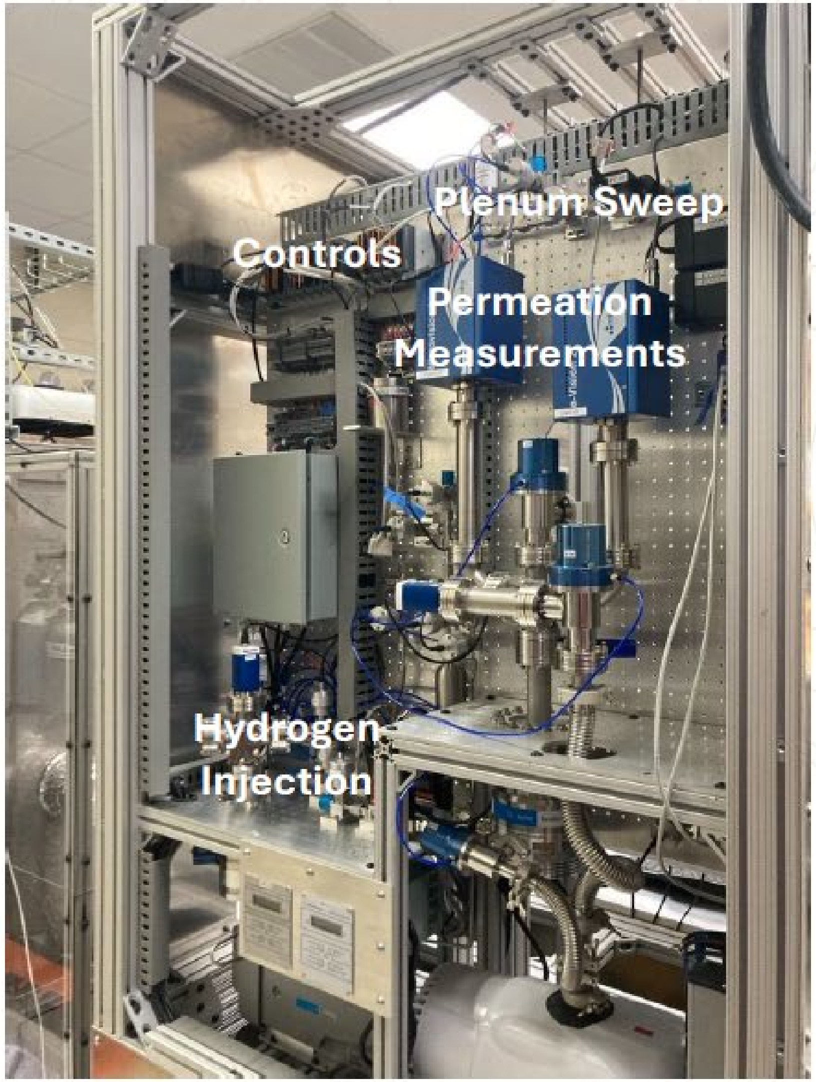
- **MSTTE is a semi-integral tritium transport experiment for flowing fluoride salt systems**
- **Location: Safety and Tritium Applied Research facility**
- **Objectives**
  - **(1) Safety code validation data**
  - **(2) Test stand for tritium control technology**
- **Major equipment**
  - **Copenhagen Atomics Salt Loop: salt tank, pump, & flow meter**
  - **External Test Section: hydrogen injection, permeation, & plenum**
- **Phased approach**
  - **Phase I: FLiNaK and D_2 – 2025/2026**
  - **Phase II: FLiBe and D_2 – 2026/2027**
  - **Phase III: FLiBe and T_2 – 2027/2028**



Courtesy Thomas Fuerst, INL

MSTTE – May 2025





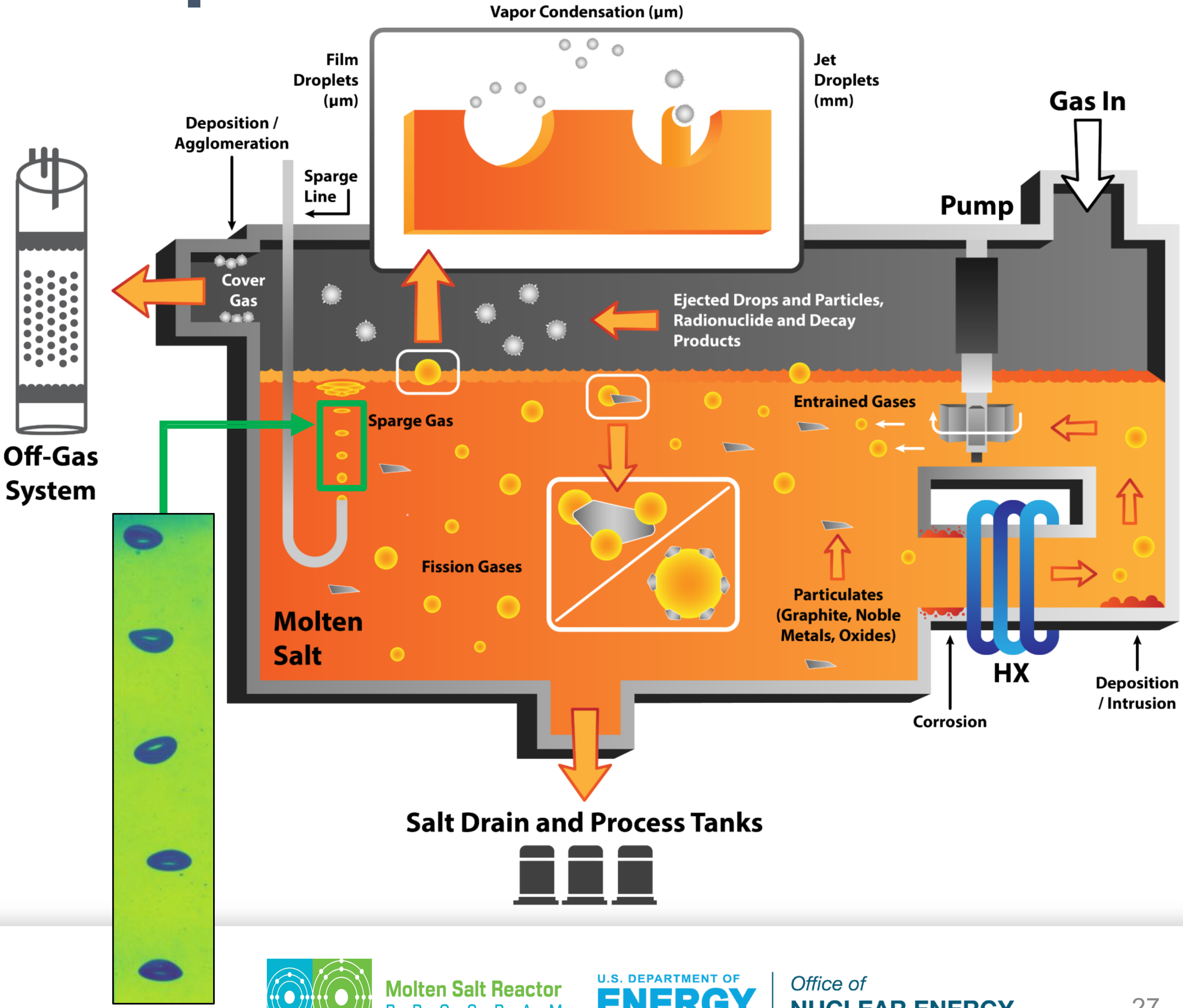
Molten Salt Reactor PROGRAM

Courtesy Thomas Fuerst, INL

MSR Gas and Particle Transport Phenomena

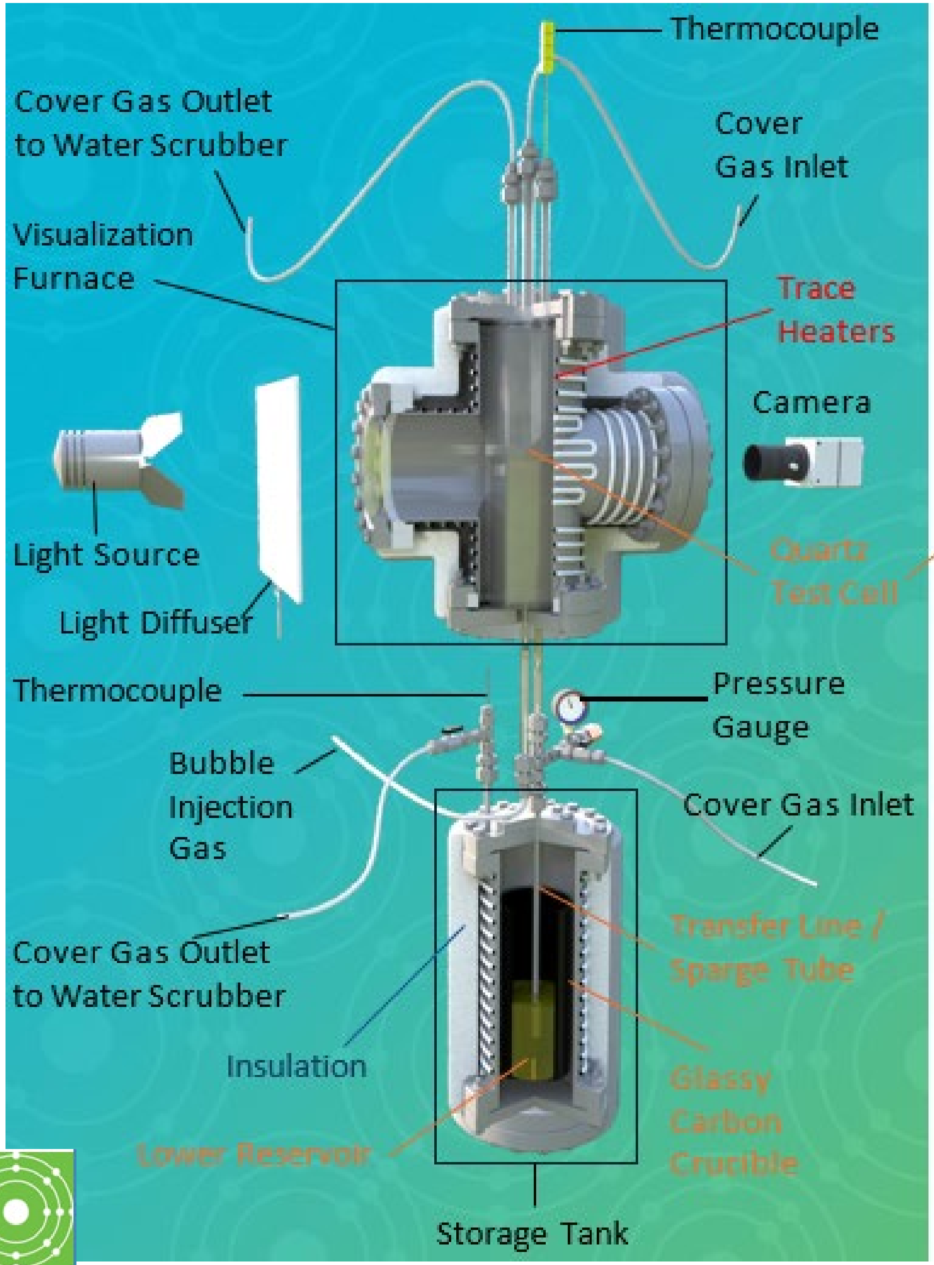
- The gas, particle behavior and gas- particle interactions are complex phenomena

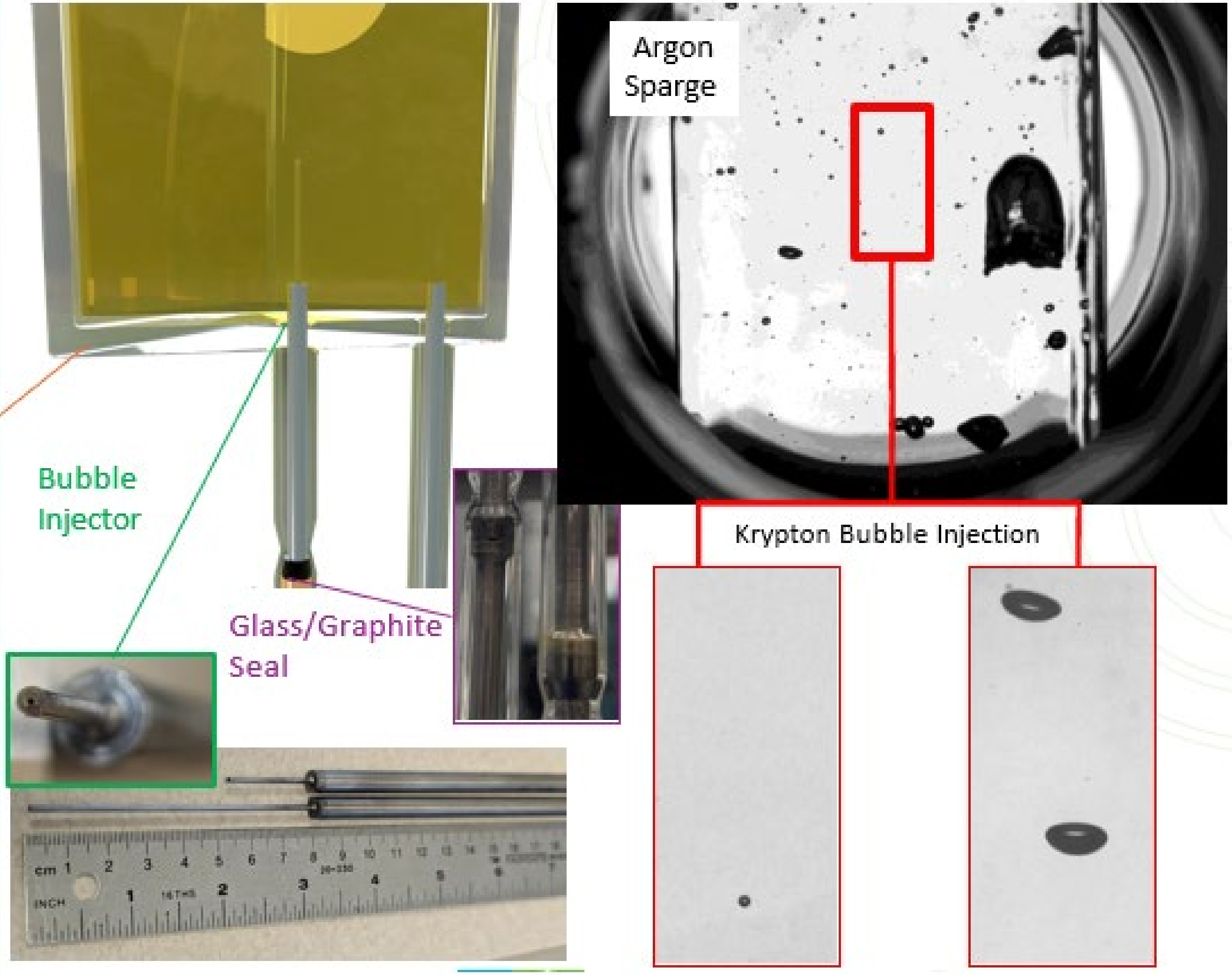
- Experimental measurements in prototypic environments requires careful planning



Courtesy Daniel Orea, ORNL

Molten Salt Visualization Apparatus

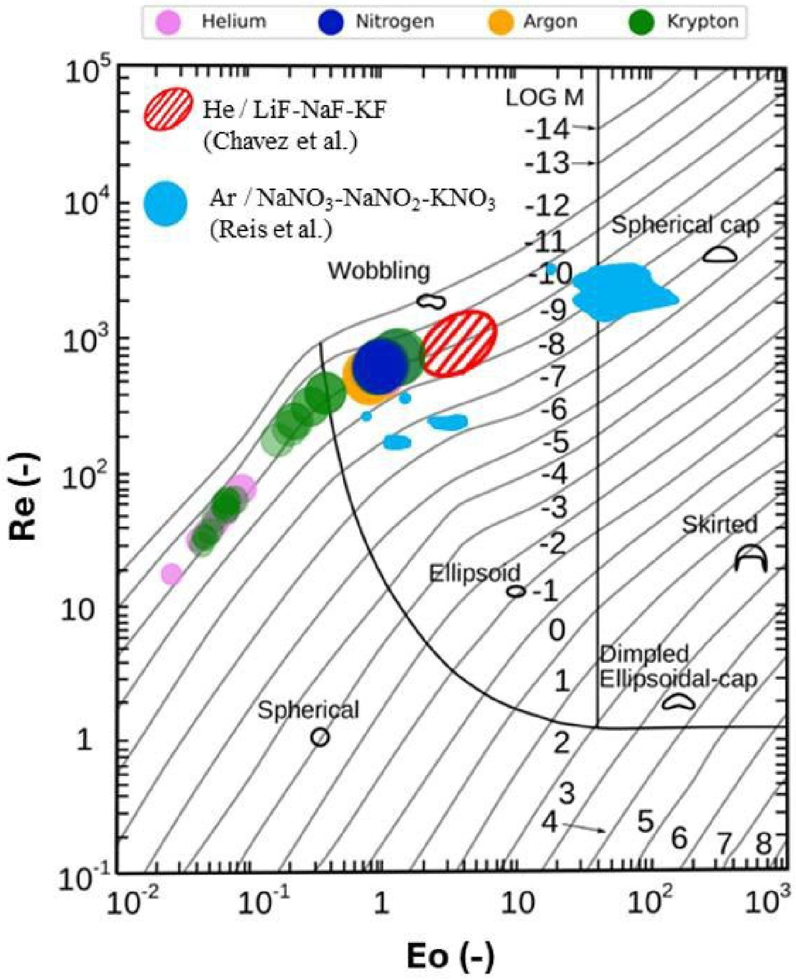




Courtesy Daniel Orea, ORNL

Molten Salt Reactor PROGRAM

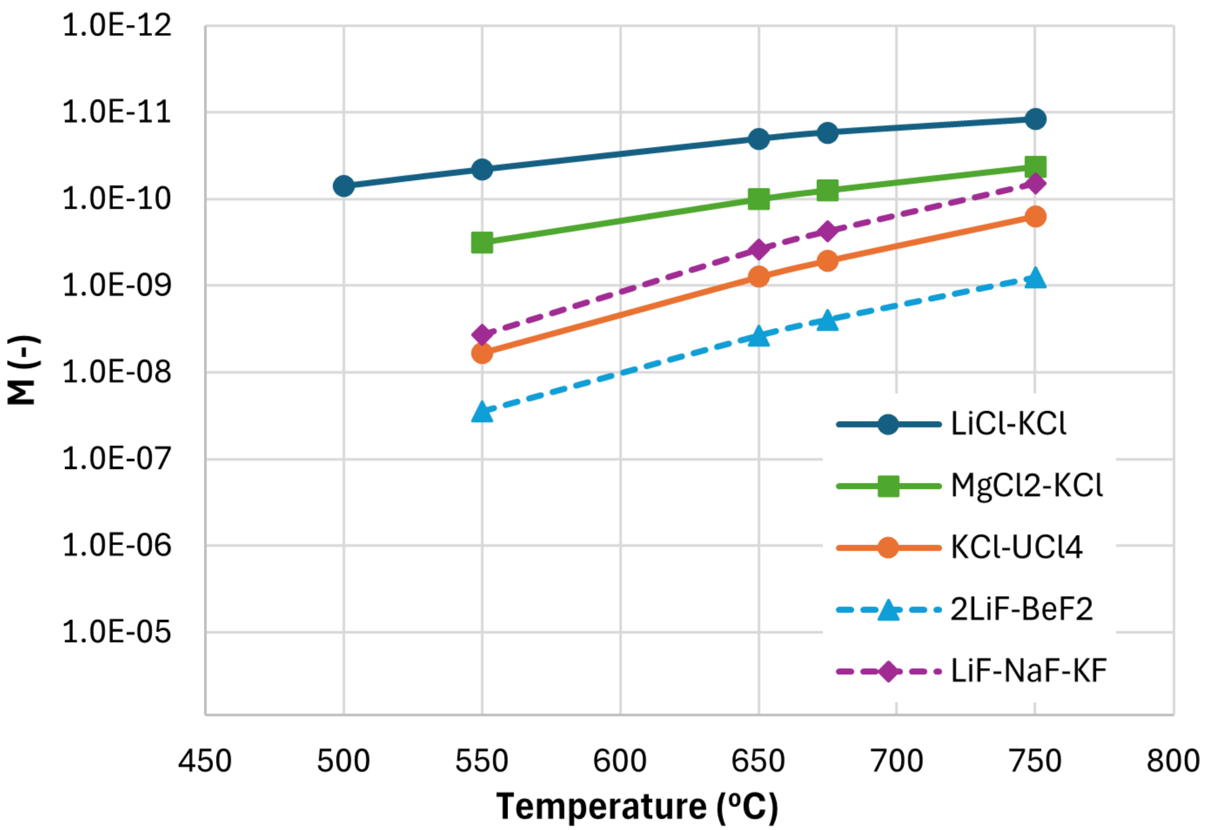
Bubble Behavior in Molten Salt



$$Eo = \frac{\Delta\rho g D^2}{\sigma_l}$$

$$Re = \frac{\rho_l V D}{\mu_l}$$

$$Mo = \frac{\Delta\rho g \mu^4}{\rho_l^2 \sigma_l^3}$$



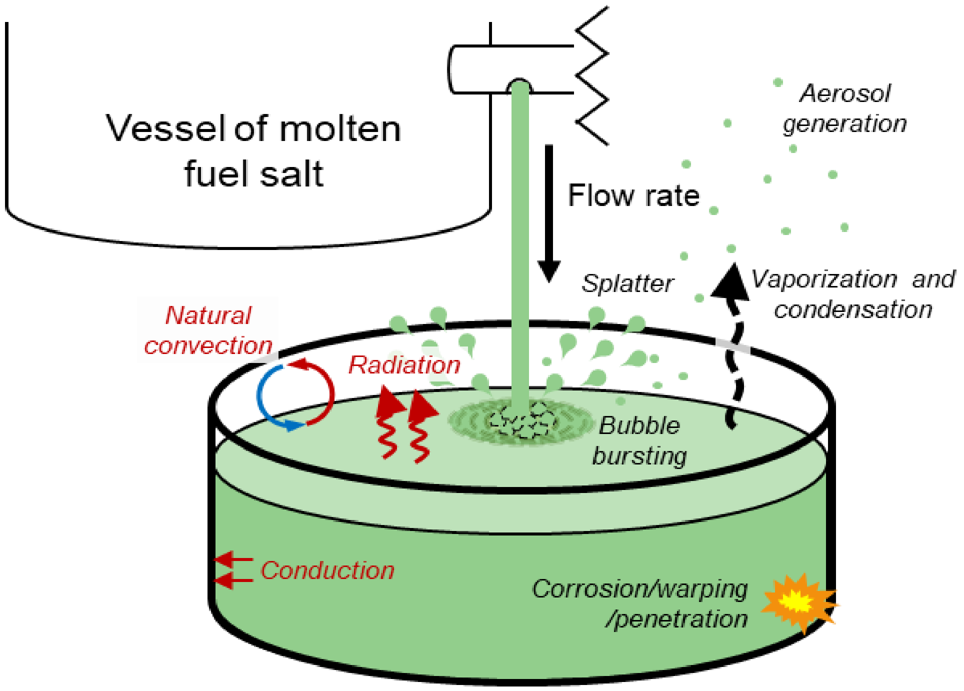
D. Orea, K. Robb, J. McFarlane, "*Comparative Study Between Experimental Measurements and Model Predictions of Bubble Rise Velocity in Molten LiCl-KCl*", Nuclear Engineering and Design (2025)

U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

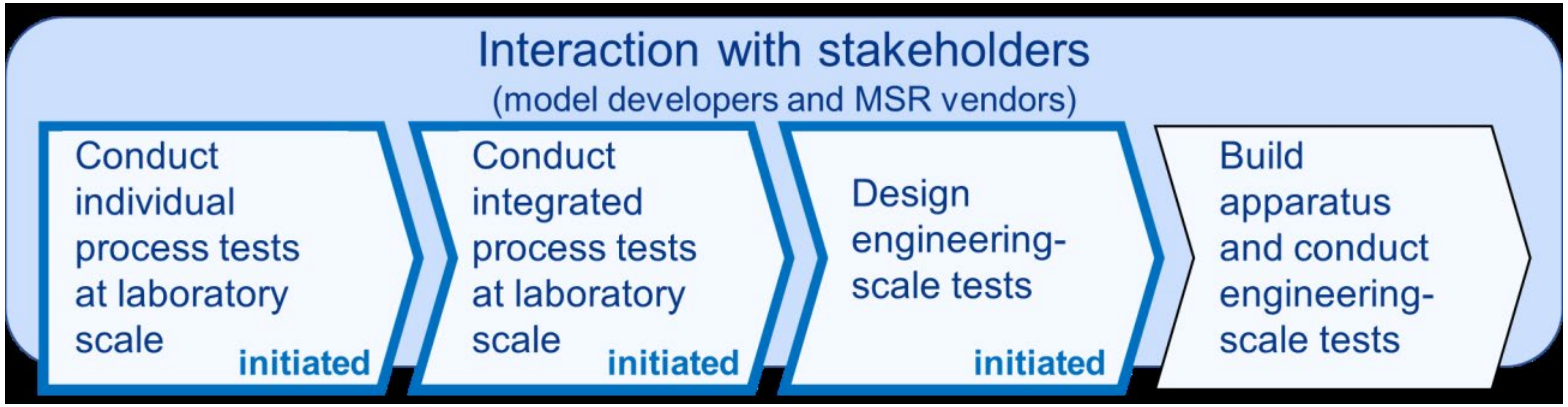
Safety and Salt Spill Test

Advanced Reactor Licensing and Accident Analysis

- U.S. Nuclear Regulatory Commission (NRC) Regulatory Guide 1.233 provides a modernized licensing framework for advanced reactors
  - Identify and evaluate the consequences of postulated accidents
  - Use validated models to predict accident progression and the mechanistic source term for expected radiological release
- All MSR developers will likely evaluate an unintended release of fuel salt
- Experimental data on the key processes that influence the safety-affecting outcomes of fuel salt release accidents are limited



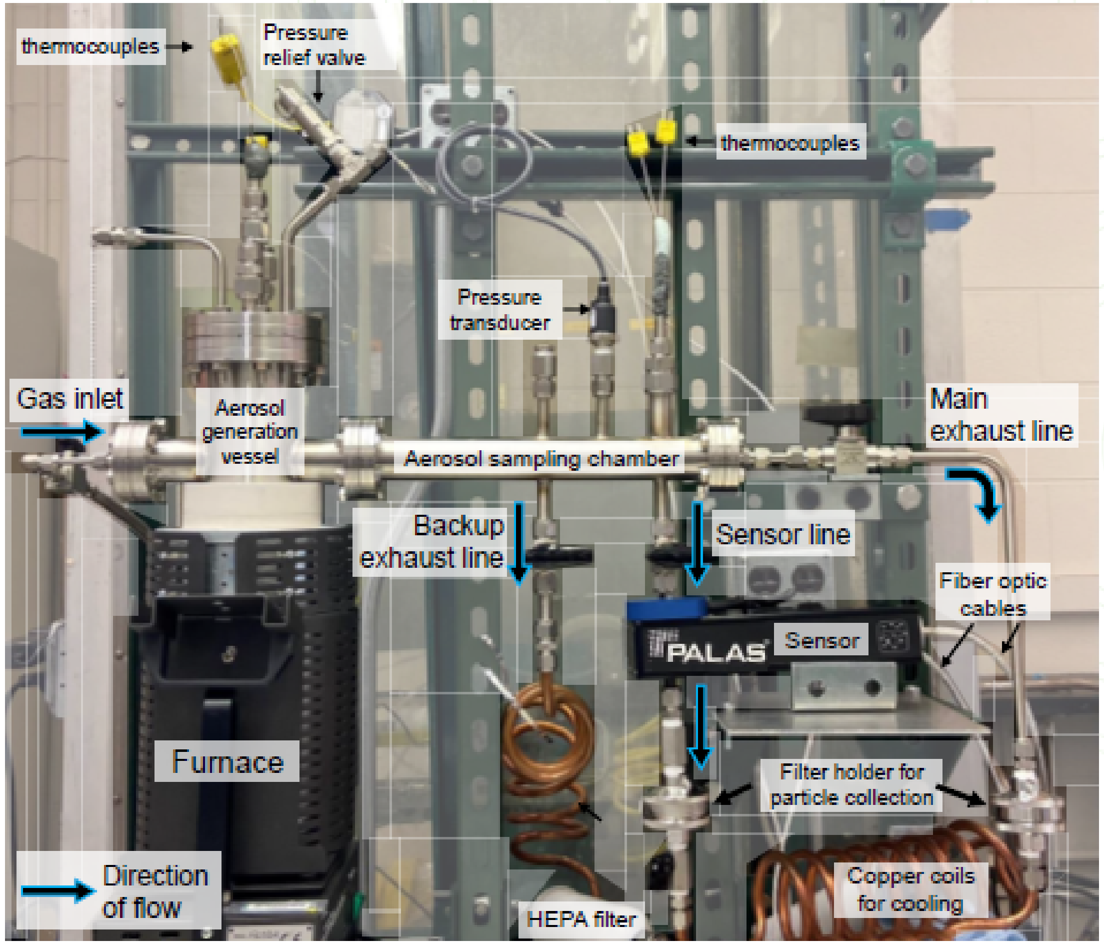
Catch pan



Courtesy S. Thomas, ANL

Argonne test stand for real-time salt aerosol characterization

- Laboratory-scale test stand to generate and characterize salt aerosols in real-time developed in FY24
  - Real-time size and concentration (optical light scattering)
  - Bulk elemental composition of particles collected on filters (ICP-MS)
  - Elemental composition of single particles (SEM-EDS)
- Motivation for developing Argonne salt aerosol test stand:
  - Addresses data gaps significant to accident consequence (formation of radionuclide-bearing aerosols)
  - Generates data on aerosol formation from molten salt systems through systematic and controlled testing
  - Provides salt aerosol measurement experience and method validation prior to use in Salt Accident Analysis Facility
- Designed for molten salt environments and a range of gas atmospheres:
  - Withstands corrosive and high temperature gas streams
  - Maintains measurement accuracy when gas composition and temperature change



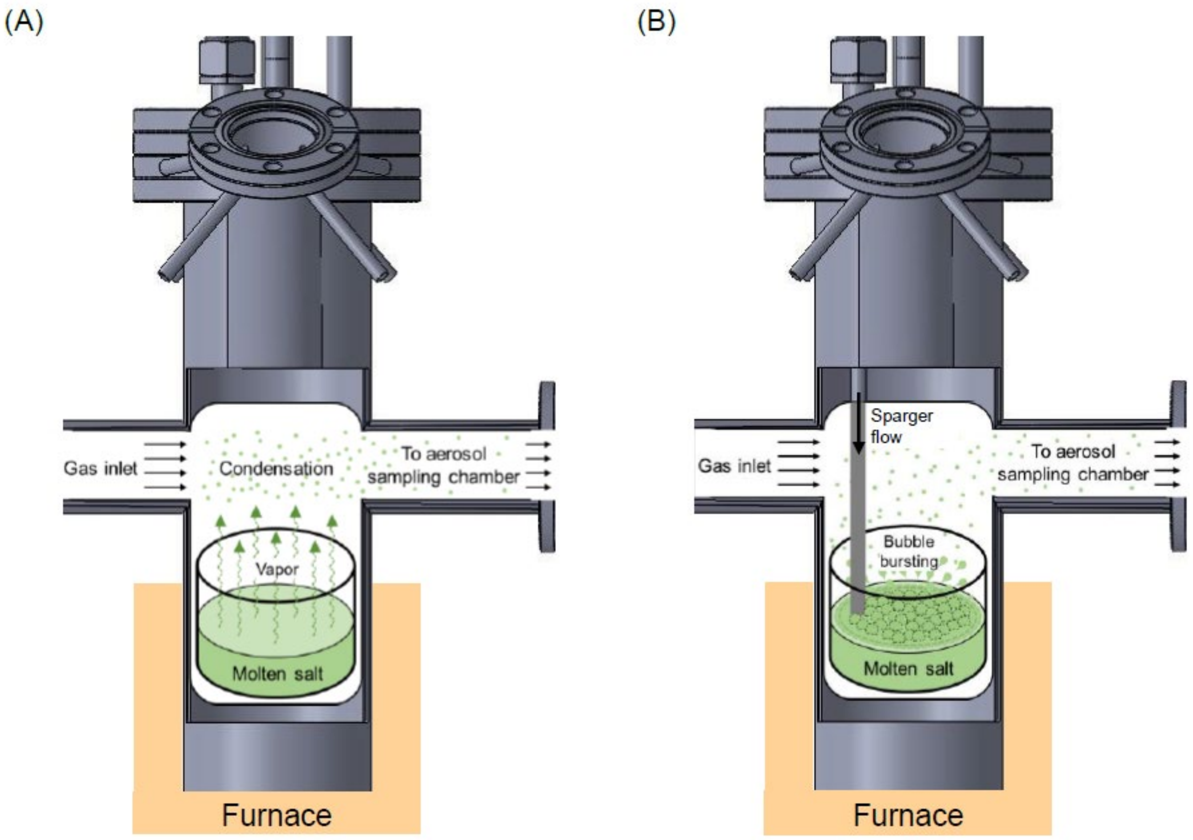
Thomas, Sara (2024) "Method for Real-Time Salt Aerosol Concentration and Size Measurements for Molten Salt Reactor Safety Assessments." Argonne National Laboratory Report ANL/CFCT-24/25.

Real-Time Characterization of Salt Aerosols Generated from Static and Sparged Molten Salt

Tests were conducted within the Argonne Salt Aerosol Test Stand to generate salt aerosols from static and sparged molten salts and measure their size and concentration in real-time.

The results provide insight into salt aerosol formation by the vapor condensation and bubble bursting mechanisms and inform the potential radiological consequences of aerosol formation from molten fuel salt.

The data will be used to develop mechanistic source term and accident progression models for MSRs.



For a static molten salt (no sparging), this system setup enables the analysis of salt aerosol formation by solely the vapor condensation mechanism

Generating salt aerosols from sparged salt is accomplished by bubbling pre-heated gas into molten salt by using a custom sparging apparatus fed through the vessel lid

S. Thomas and A. O'Brien,NL, Real-Time Characterization of Salt Aerosols Generated from Static and Sparged Molten Salt ANL/CFCT-25/18

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Modeling and Simulation

Modeling and Simulation

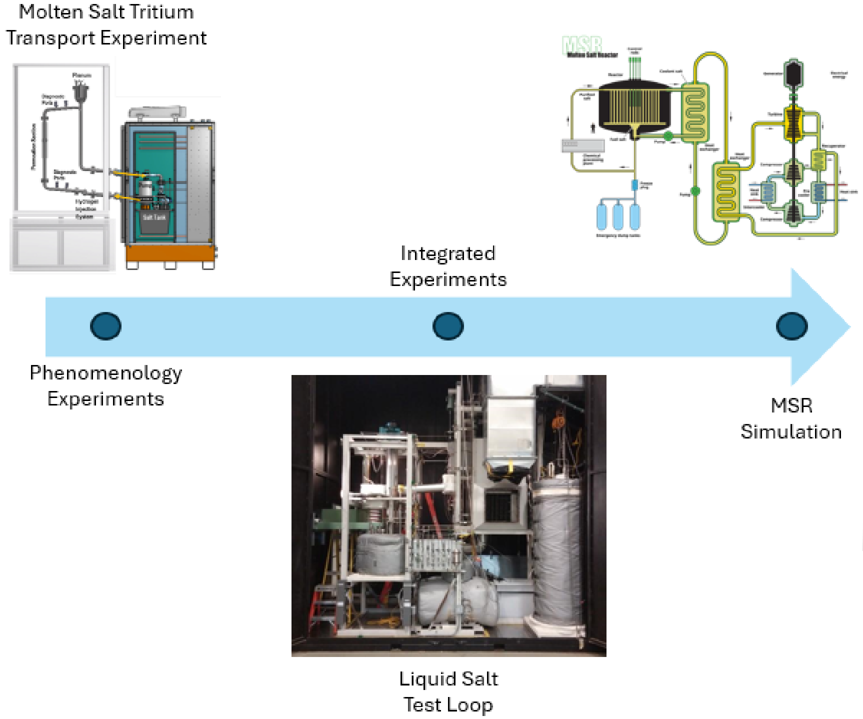
Molten Salt Reactor PROGRAM

NEAMS Nuclear Energy Advanced Modeling and Simulation

MELCOR: nuclear accident simulation code at SNL

Significant strides within the last few years to increase model accuracy for molten salt reactors (MSRs). It is the primary code developed for the

- Assessment and evaluation of safety for a broad range of reactor concepts, notably including MSRs.
- MSR model development has been focusing on improving chemistry and fission product transport mechanisms
- Working with MSR campaign to fill knowledge gaps

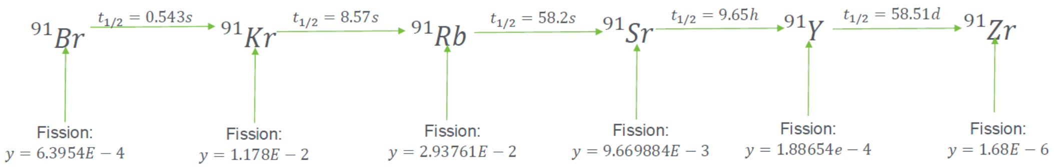


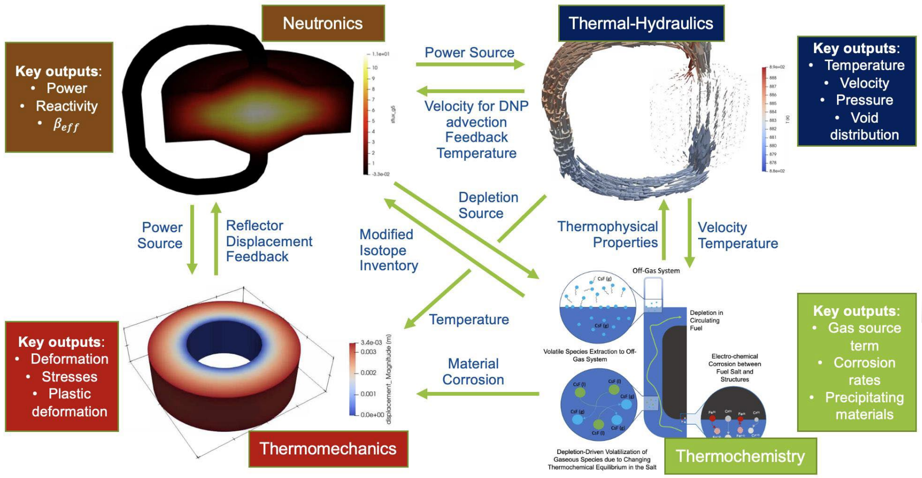
NEAMS Tools at INL

Coupling between:

- Neutronics (multi-fidelity + spatial depletion),
- Thermal-Hydraulics (coarse-mesh CFD),
- Thermomechanics (thermo-elasto-plasticity with irradiation and thermal swelling and creep),
- Thermochemistry (speciation, mass accountancy, and corrosion)

- Species tracking in MSRs
  - Tracking the depletion chain of ^{91}Br





Universities Supporting MSR development through various awards (NEUP, IRP…)

Standard Development for Oxygen Analysis in Molten Salts

ANS 20.3 Working Group

Est. May 2025

Significance to industry developments:

- *No existing standard oxygen analysis method*
- *Support MSR commercialization and licensing*
- *Need for accreditation and qualification for salt quality*

Goals:

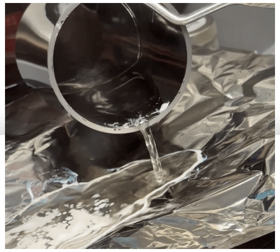
- *Develop a **standardized protocol** for measuring oxygen concentration in molten salts using inert gas fusion analysis.*
- *Establish accurate and repeatable analytical methods through **optimized sample preparation and detailed procedures**.*
- *Ensure **compatibility and reliability across different analyzers**.*
- *Create a universal guideline to enable **consistent and comparable** oxygen measurements **across different facilities**.*

Current Status:

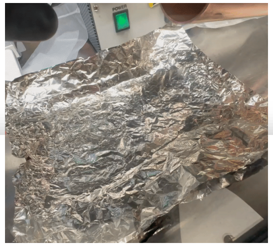
- *Protocol development*
- *Salt acquisition*

Types of salts included in the standard:

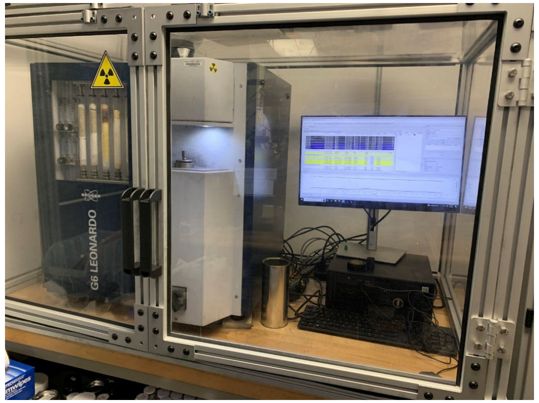
- *FLiNaK*
- *NaCl-KCl*
- *UF_4*
- *UCl_3*



FLiNaK

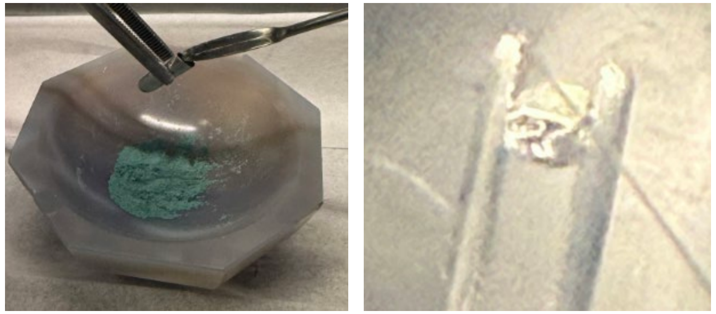


UF_4 bearing salt



Calibration

Inert Gas Fusion Analyzer



Sample Preparation

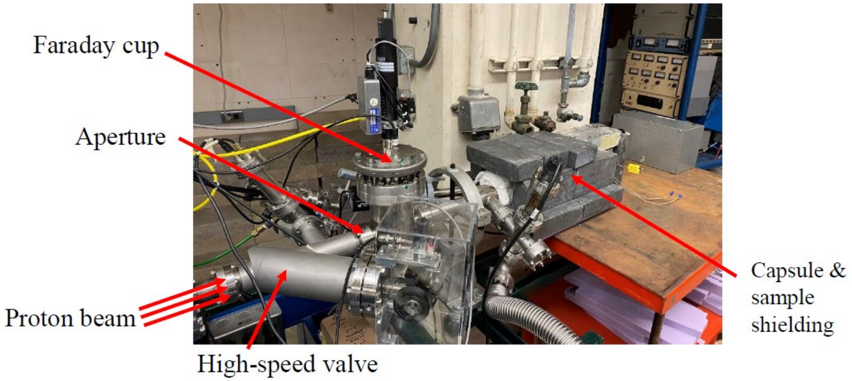
Participating institutions:

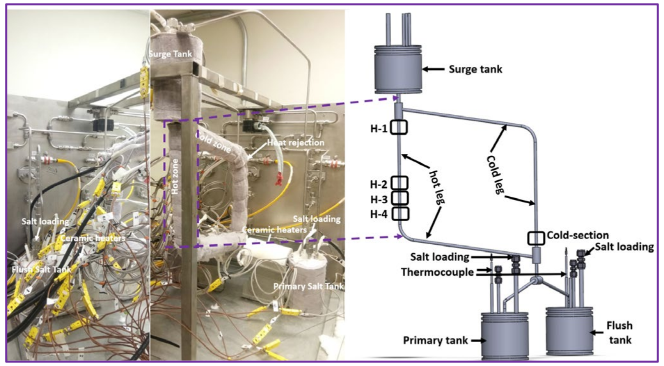
ANL, CFS, CNL, INL, MilliporeSigma, ORNL, TAMU, USC, VT

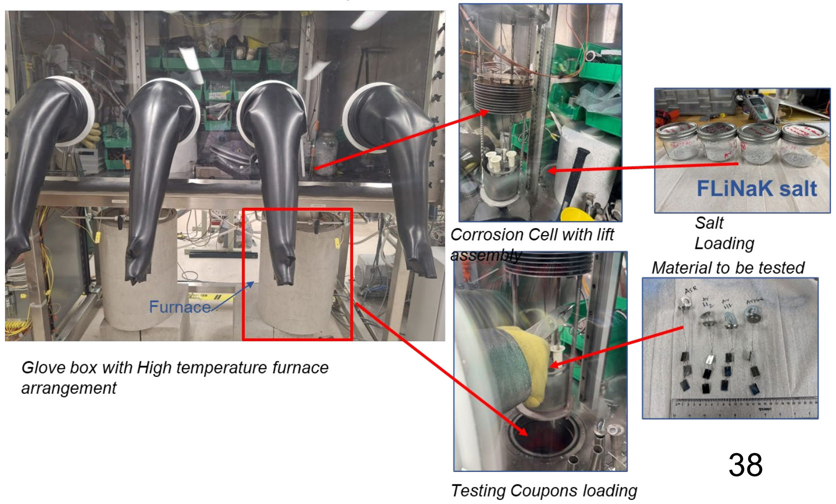
For more information, contact:
Amanda Leong aleongsw@vt.edu

Molten salt corrosion and mass transport capabilities at UW-Madison (Adrien Couet / MaDCoR) - Adrien Couet <couet@wisc.edu>

- A large suite of **chloride** & **fluoride (including FLiBe)** molten salt static corrosion capabilities
- One 1,891 sq.ft lab with 4 molten salt glovebox:
  - "Regular" long-term static corrosion test (https://doi.org/10.1016/j.apmt.2023.101850)
  - High-throughput molten salt droplet test (https://doi.org/10.1016/j.matt.2024.05.004)
  - Natural convection loop equipped with in-situ mass transport / corrosion tracers (https://doi.org/10.1038/s41467-024-47259-8 / https://doi.org/10.1016/j.corsci.2025.113383)
  - In-operando spectroscopy (in-situ UV-Vis / LIBS / surface tension / XAS)
  - In-operando electrochemistry (10.1149/1945-7111/ac7a66)
- In-situ ion irradiation effects on molten salt corrosion:
  - UW-Ion Bean Laboratory, a DOE Nuclear Science User Facility (https://doi.org/10.1016/j.corsci.2025.113385)
- One glovebox to handle uranium and minor-actinide salts for corrosion and thermophysical measurements (Characterization of Low Irradiated Materials – CLIM laboratory)

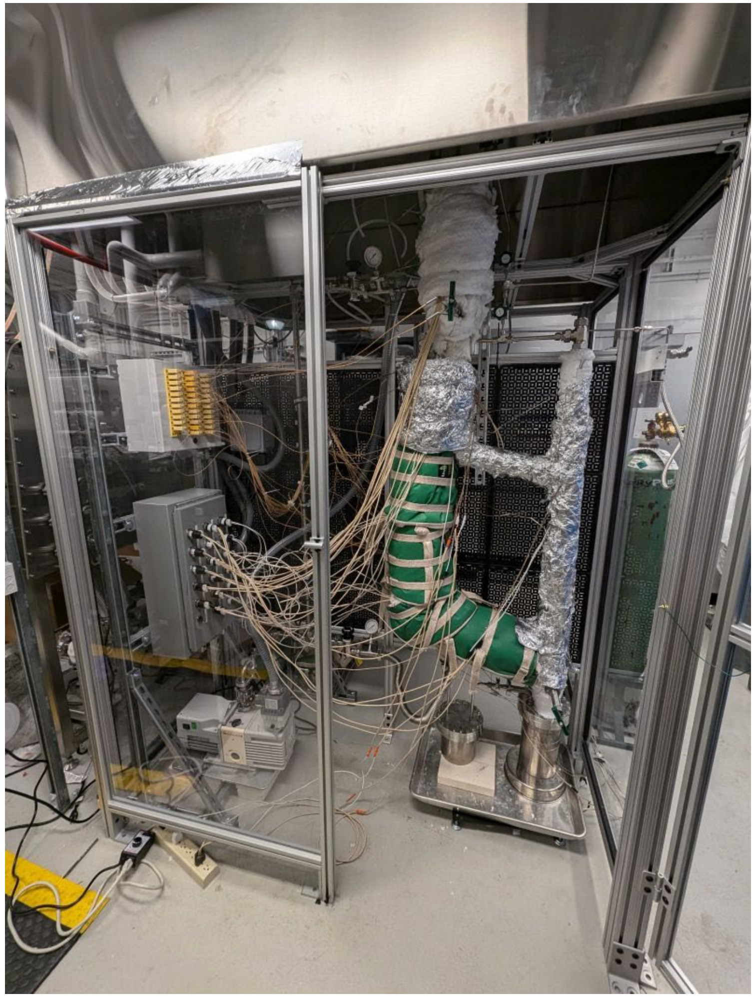




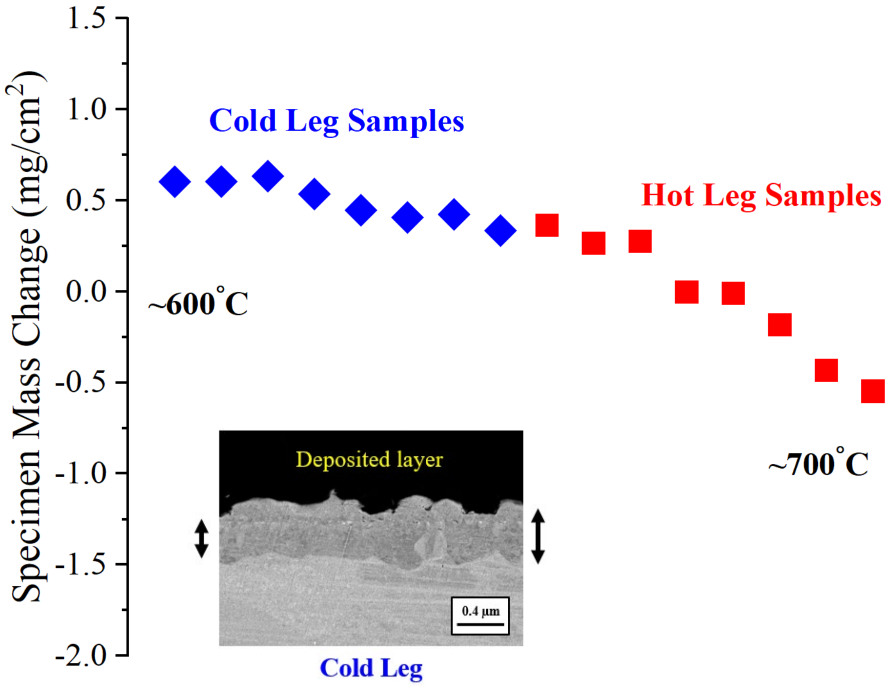


Flowing Molten Salt Corrosion Experiments at The University of Michigan – Stephen Raiman

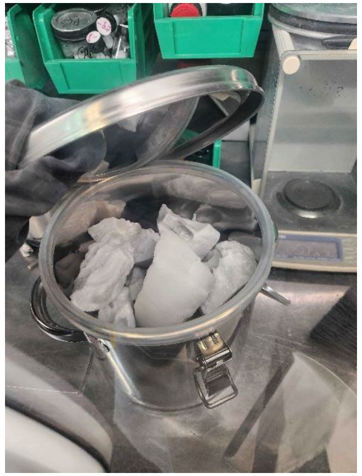
sraiman@umich.edu



- 316H Stainless loop
- 316H samples
- Hydrofluorinated FLiNaK Salt
- 500 ppm Zr redox control additive
- 700˚C Max, 600˚C Min
- 1000 hours

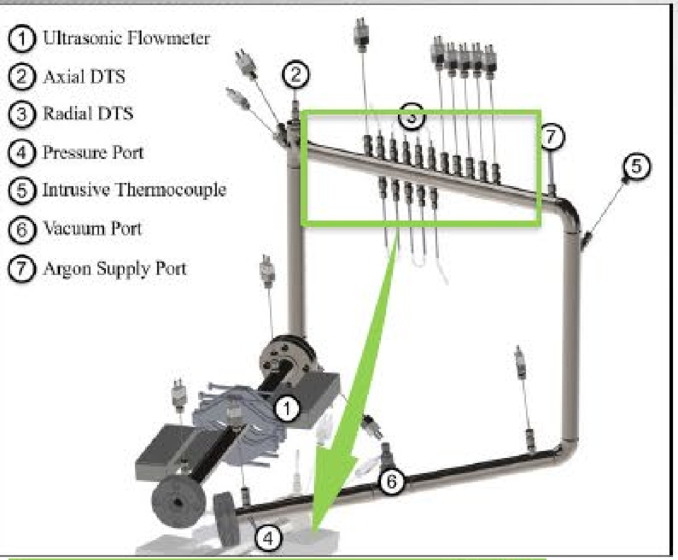


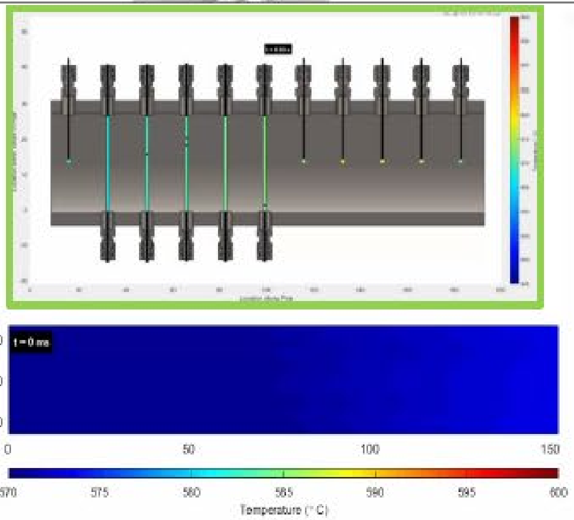
Hydrofluorination to produce minimally corrosive fluoride salts



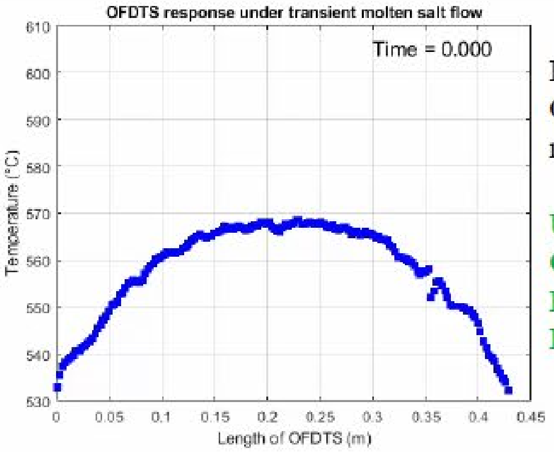
Molten Salt Research at TAMU

Forced circulation loop with HX





2D temperature field reconstruction

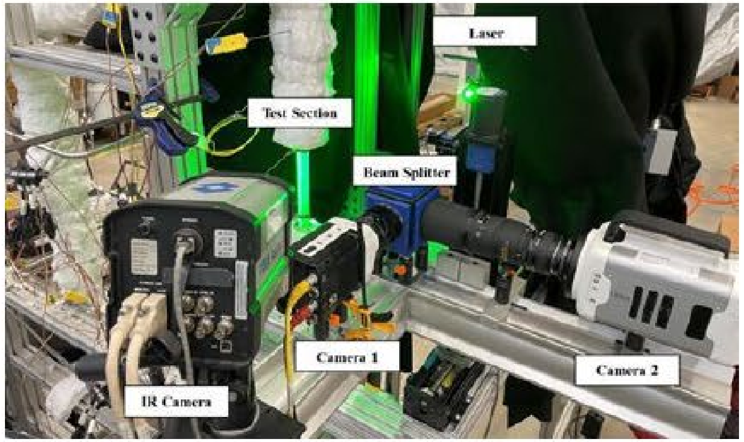


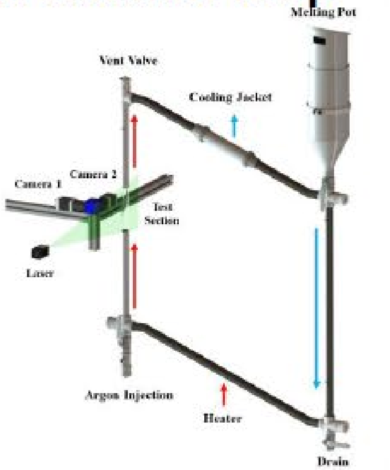
OFDTS response under transient molten salt flow

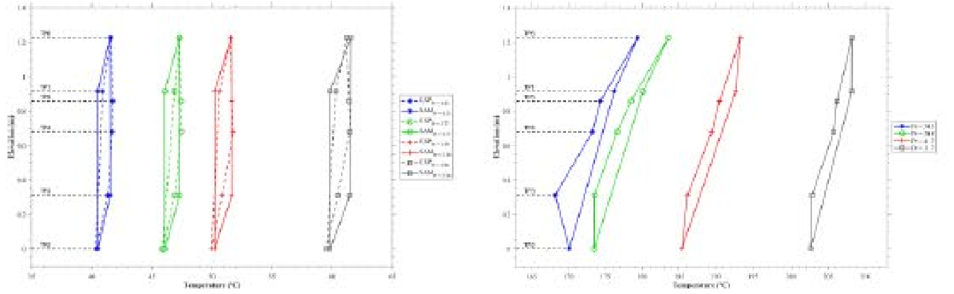
Flow spec during OFDTS measurement:

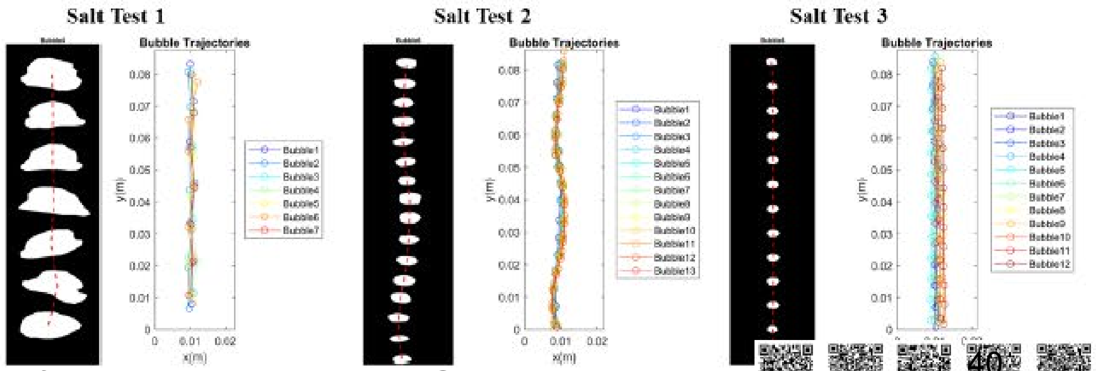
U = 2.1 m/s
Q = 68.50 L/min
Re = 25,000

Single- and two-phase natural circulation loop







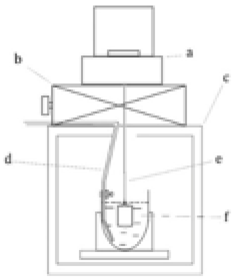


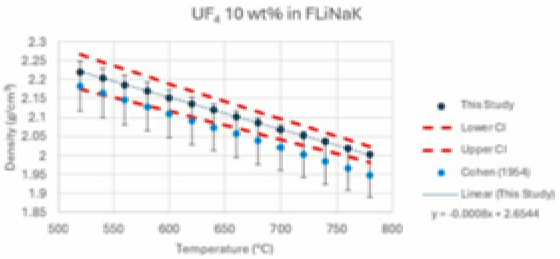
Prof. Yassin Hassan, y-Hassan@tamu.edu

Thermophysical Properties

Density

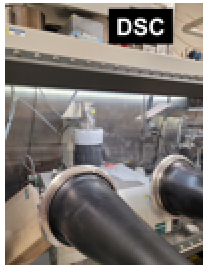
Archimedes method

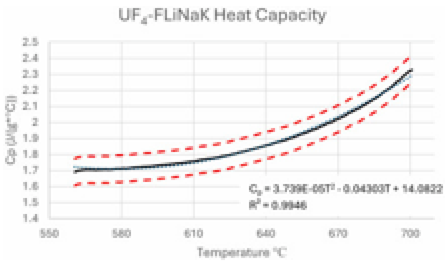




Heat Capacity

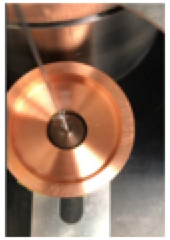
Differential scanning calorimetry

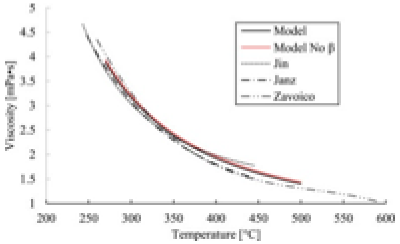




Viscosity

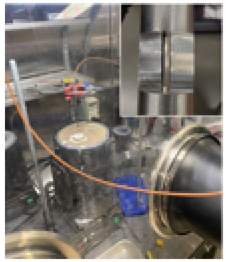
Rotating copper cup viscometer

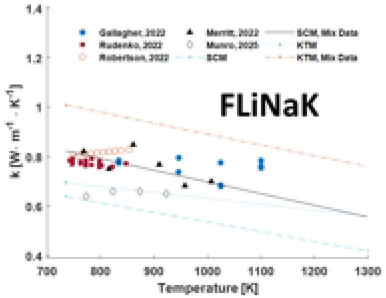




Thermal Conductivity

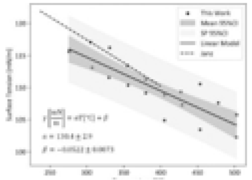
Needle probe method



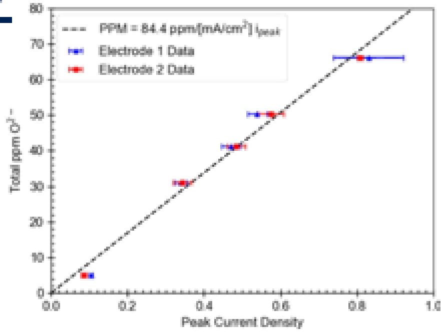


Surface Tension

Sessile drop

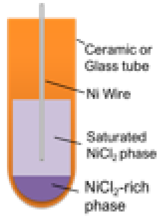


Electrochemistry



Reference Electrodes

For both Cl and F salts

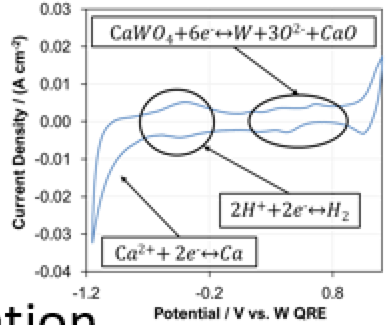


Salt Purification

Filtration and electrorefining to remove impurities, including O and H

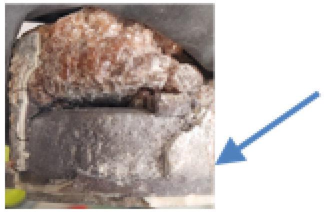
Impurity Detection

Electrochemical detection of oxygen and metallic impurities

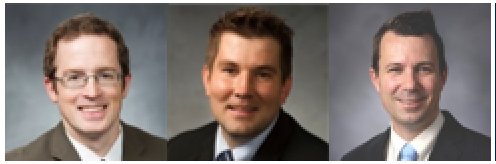


Electrorefining and Chlorination

Chlorination and chloride volatility potentially purifies rare earths and actinides with less radioactive waste (i.e., no solvent waste)



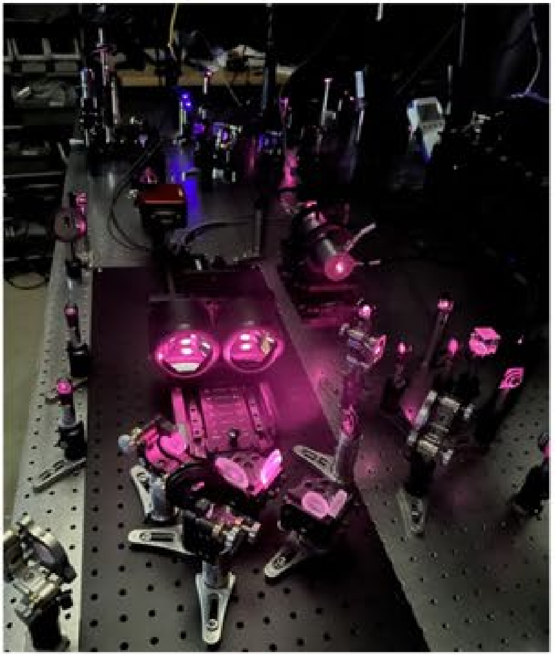
Cerium anode



BRIGHAM YOUNG UNIVERSITY

Troy Munro, Matthew Memmott, Devin Rappleye

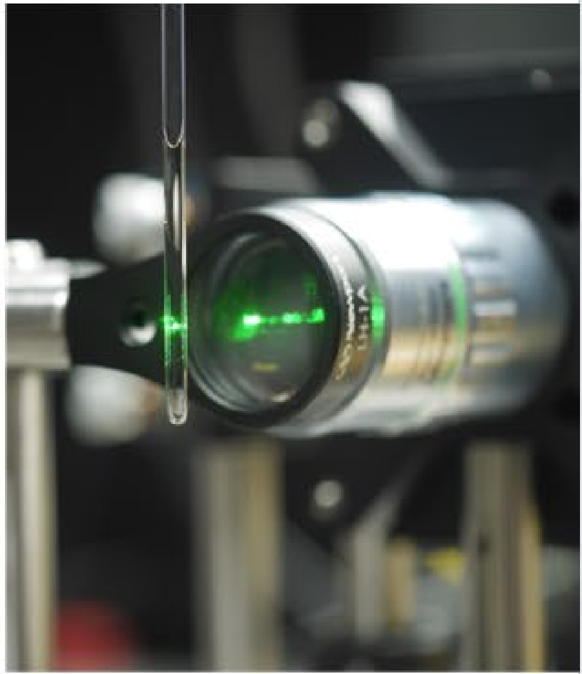
NC STATE UNIVERSITY
Department of Nuclear Engineering

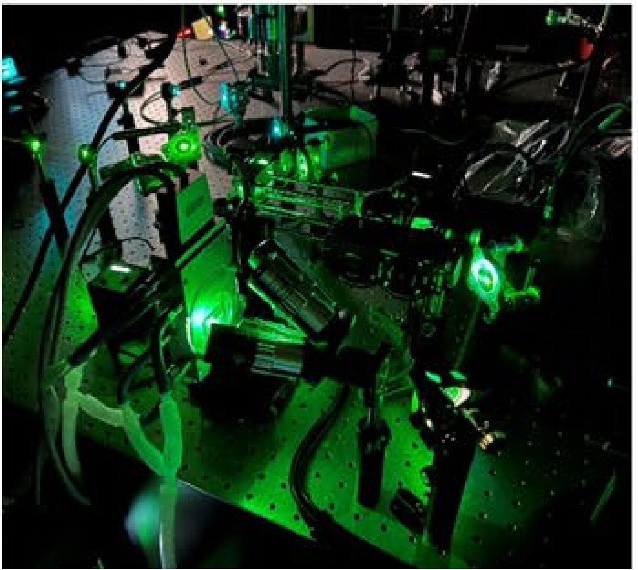


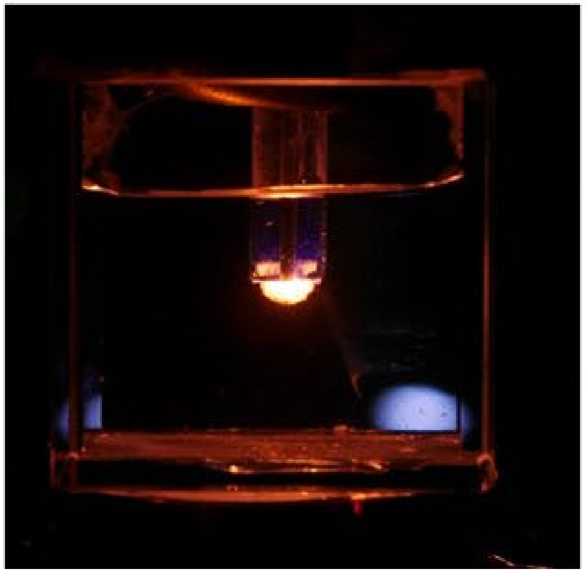
Molten salt Ultrafast Spectroscopy Characterization Laboratory
MUSCL

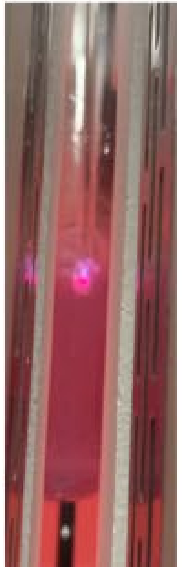
Dr. Alex Bataller, Assistant Professor
Graduate Students Extraordinaire: Kayla Hahn, Davis Bryars, Hayden Bland, Munmun Jahan, and Kyle Rizzuto

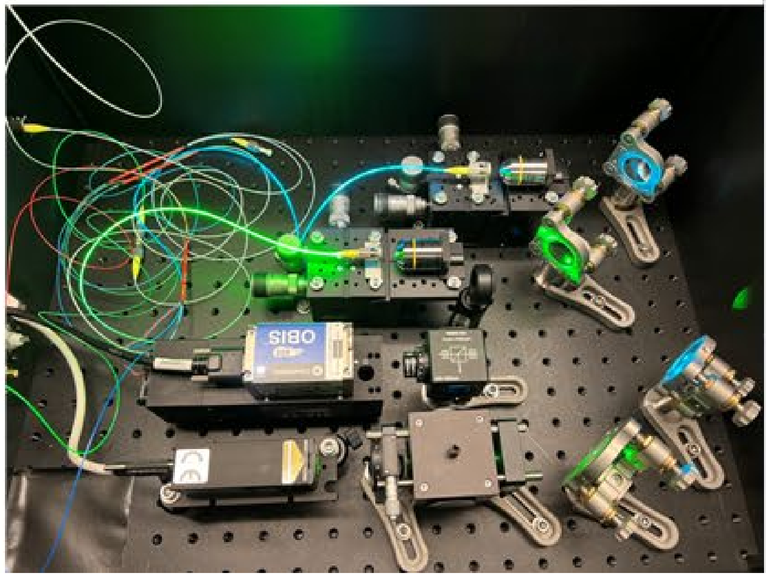
Development of optical sensors and characterization tools for extreme nuclear environments











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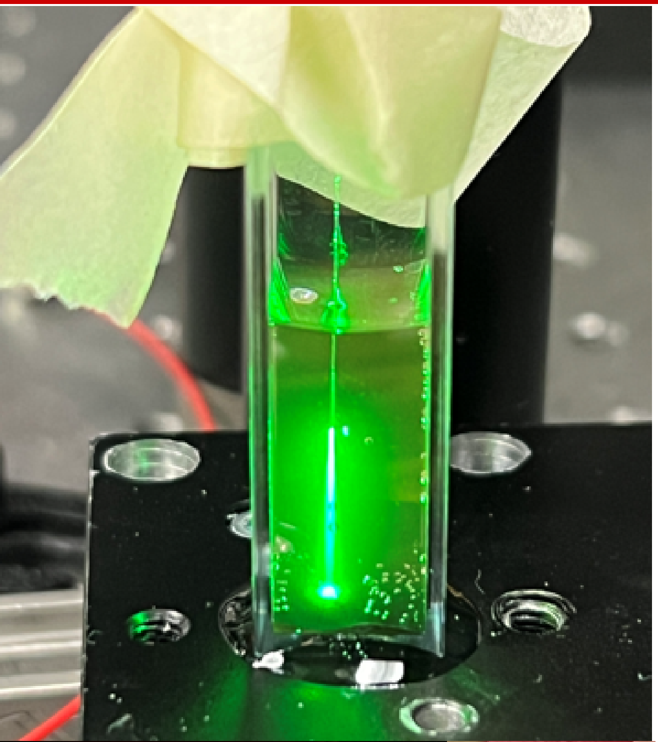
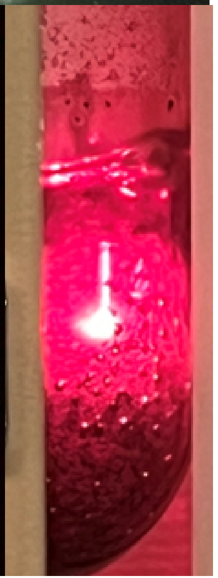




Thermophysical Property Measurements:

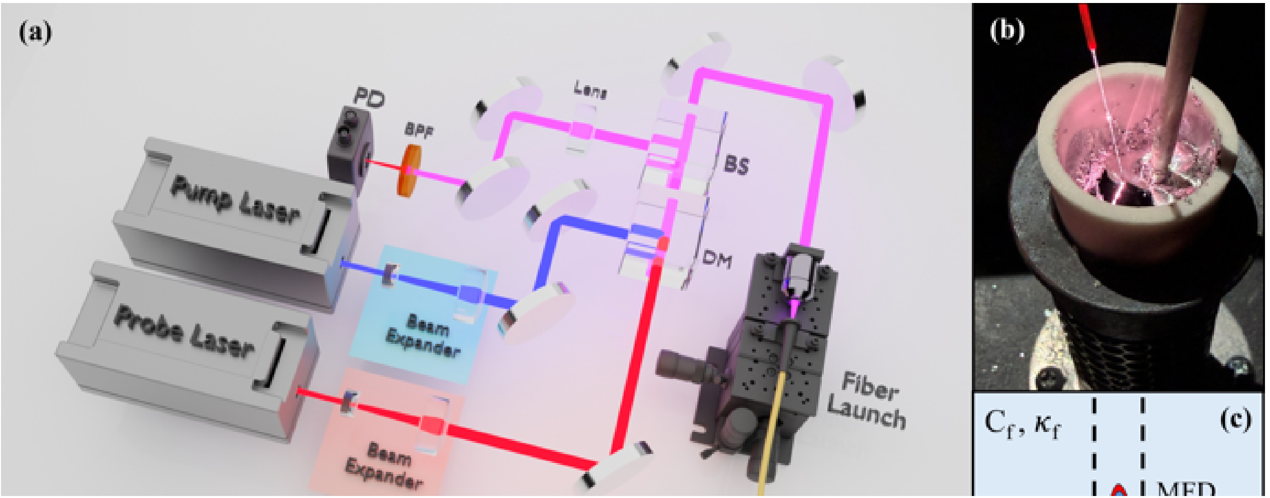
- Viscosity via Brownian motion (video tracking and DLS)
- Thermal conductivity via fiber optic frequency domain thermoreflectance

Ultrafast Molten Salt Experiments:

- The life and death of solvated electrons
- Advancing fundamental molten salt modeling using ultrafast spectroscopy (THz)

Online Material Quantification of Molten Salts:

- Submerged plasma for isotopic detection and elemental resolution (SPIDER probe)
- MiniTIG: Online material quantification of metals



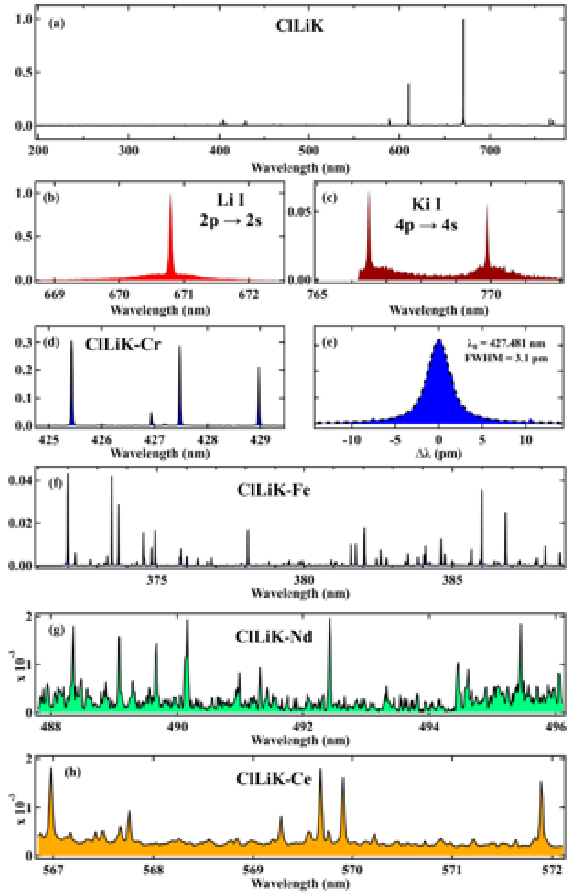


Figure 4. Molten salt spectra. (a) Full UV-VIS spectrum of ClLiK. (b), (c) Specific s → p transitions of Li and K. The Li I line at 670.79 nm dominated the emission across all salt spectra. (d) Chromium emission normalized to Li I(670.79 nm). (e) Center and FWHM of the 427.5 nm Cr I peak. Although the Echelle spectrometer limited the resolution of this line, the Fabry-Perot etalon spectrometer resolved it. (f), (g), (h) Emission spectra of Fe, Nd, and Ce. Fe emission was an order of magnitude weaker than Cr, while both rare-earth metals emitted an order of magnitude less than Fe.

Experience Building a Molten-Salt Forced-Circulation Loop at the MIT Reactor (IRP-20-22026)

C. W. Forsberg[1], D. M. Carpenter[1], A. I. Hawari[2], R. O. Scarlat[3], M. A. Borrello[3], H. Williams[3] and K. Robb[4]

[1]*Massachusetts Institute of Technology*
[2]*Texas A&M University*
[3]*University of California at Berkeley*
[4]*Oak Ridge National Laboratory*

Massachusetts Institute of Technology

NC STATE UNIVERSITY

Berkeley UNIVERSITY OF CALIFORNIA

OAK RIDGE National Laboratory

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MIT Has Designed and is Constructing a Flowing Salt Loop at MIT Reactor

- **Goal I is <u>forced circulation salt loop</u> for the MIT reactor (6 MWt)**
  - Neutron & gamma irradiation
  - Heated and cooled
  - Fully instrumented
  - Initially clean salt but capable of operating with uranium dissolved in salt
- **Goal II is to transfer lessons learned to accelerate loop construction at other university and DOE reactors**
- **Partners: U.C. Berkeley, North Carolina State University and Oak Ridge National Laboratory**

We would like to thank the U.S. Department of Energy that provided funding through the DOE Office of Nuclear Energy's Nuclear Energy University Program, **IRP-20-22026.**

Why Build Flowing Salt Test Loops?

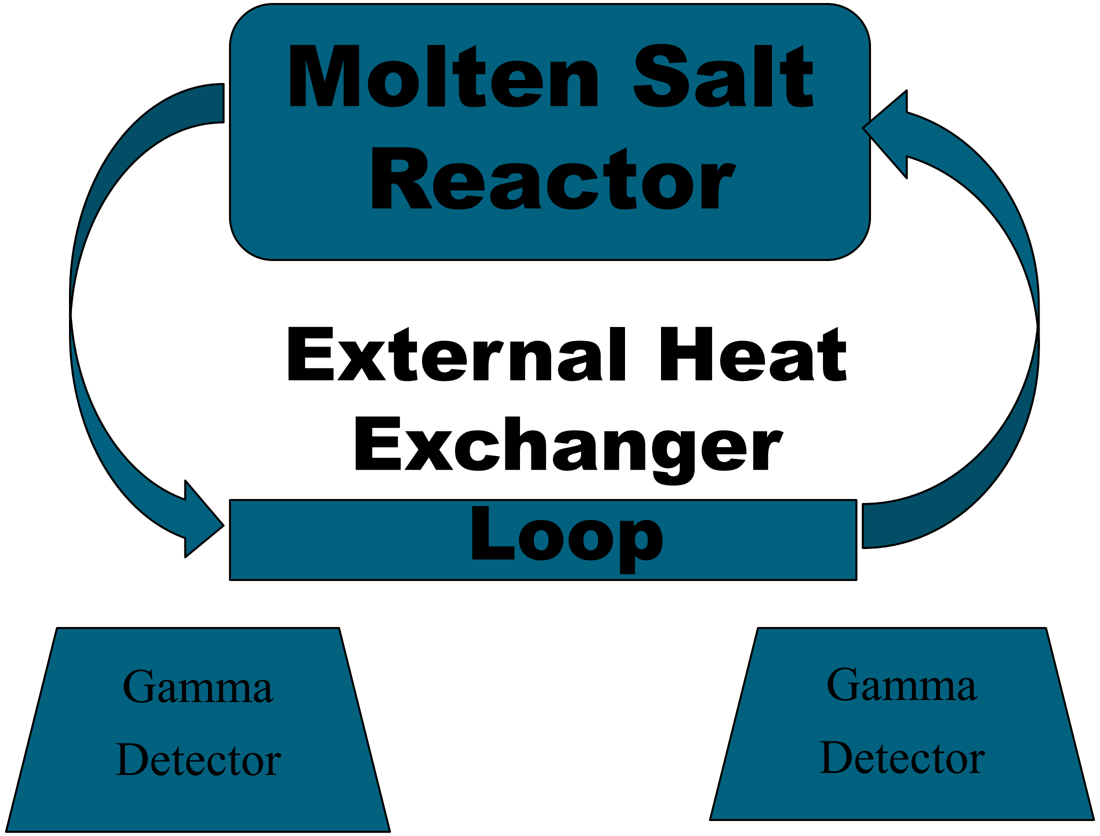
Require Development and Testing with Irradiated Flowing Salt to Provide <u>Short-lived</u> Radionuclide

- Testing instrumentation
- Understanding fission product transport and plate out
- Test tritium control systems
- Understand / Test fission gas removal
- Corrosion testing
- Measuring fissile materials production
- Safeguards

C. Forsberg, D. Carpenter, A. I. Hawari, R. O. Scarlat and K. Robb, Applications of Flowing Molten Salt Loops with Neutron Irradiation, *Transactions American Nuclear Society Winter Meeting*, Orlando, Florida, November 17-21, 2024.

Salt Reactors May Enable a Revolution in Instrumentation Using Gamma Rays to Measure Many Radionuclides

- Velocity and mass flow by decay of short-lived radionuclides
- Total burnup (^{137}Cs)
- Fissile materials production rate
  - U-238 + neutron → Np-239
  - Np-239 decays to Pu-239
- Measure Xenon in salt—efficiency of off-gas removal system

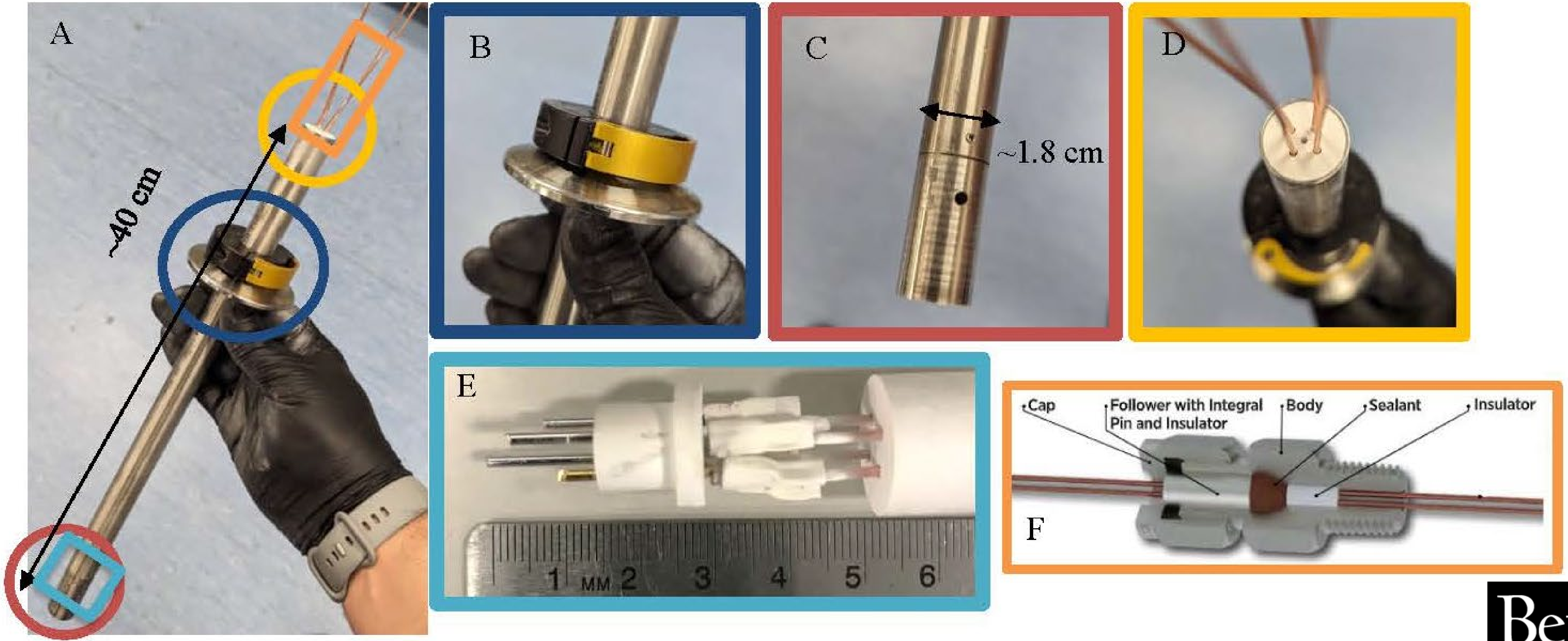


Can Measure Flow with 11 Second F-20, 1633 KeV

C. Forsberg et. al. Measuring Flow Rates and Compositions in Salt Reactors with Gamma Spectroscopy, *Transactions of the American Nuclear Society*, American Nuclear Society Annual Meeting, Las Vegas, June 16-19, 2024

Instrumentation: University of California, Berkeley Developed On-Line Redox and Chemistry Sensors for Loop

Required to know in-situ Salt Chemical Environment



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Conclusion

- Several programs in the United States are supporting MSR technology development
- The MSR program serves as the hub for efficiently and effectively addressing, in partnership with other stakeholders, the technology challenges for MSRs to enter the commercial market.
- MSR concepts are on a fast track, and we need to continue this momentum.

U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

Resources

Reports FY 2025 – MSR Program

Samuel Walker, Mauricio Tano, INL, Complete Initial Engineering Framework for Species Tracking in MSRs involving Fuel Salt and Structures

D. Zhang, T. Birri, B. Smith, M. Williamson, V. Glezakou , ORNL, Accelerating Property Prediction and Interfacial Understanding in Molten Salt Reactors Using AI and Advanced Simulations

T.M. Besmann, J. Schorne-Pinto, et al, ORNL, ORNL, Optimization of the thermochemical models for $MgCl_2$-$BaCl_2$, -$SrCl_2$; $BaCl_2$-BaI_2; $SrCl_2$-SrI_2

N. Shaheen, A. Polke, D. Johnson, N. Hoyt, ANL, Installation of Molten Salt Flow Loop with Chemistry Monitoring and Control System

K. Makovsky, M. Harris, J. Seo, K. Detrick, et al, PNNL, Proposed Strategy for Mitigation of Fluid Inclusions in Molten Salt Precursor Materials

K. Makovsky, M. Harris, J. Seo, K. Detrick, et al, PNNL, Experimental Investigation into Select Thermophysical Properties of the Potassium-Magnesium Chloride Salt System for Molten Salt Reactors

S. Thomas and A. O'Brien,NL, Real-Time Characterization of Salt Aerosols Generated from Static and Sparged Molten Salt ANL/CFCT-25/18

M. Christian, T. Haskin, D. Luxat, SNL, MELCOR Deposition Models Applied to Noble Metals

T. Karlsson, T. Trowbridge, A. Poole, et al, INL, Preliminary Report Summarizing the Initial Investigations into an Irradiated Fuel Salt and Capsule (INL/RPT-25-85239)

C. Downey, T. Karlsson, F. Gleigher, et al, INL, Initial Design of SABRE Fueled Molten Salt Experiment Irradiation Vehicle (INL/RPT-25-87142)

Reports FY 2025 – MSR Program (Cont.)

Bruce McNamara et al, PNNL, Chlorine isotope separations using thermal diffusion (PNNL-38411)
Bryn Merrill, Marisa Monreal et al., LANL, Drop Calorimetry of Actinide-Bearing Chloride Salts
Heather Felmy et al., PNNL, Demonstration of Optical Spectroscopic Flow Cell Design for Molten Salt Reactor Off-Gas Streams (PNNL-38277)
Hunter Andrews et al, ORNL, Analysis of Off-Gas Streams from Small- and Large-Scale Sparging Salt Vessels using Laser-Induced Breakdown Spectroscopy (ORNL/TM-2025/4115)
L Gardner and M Rose, ANL, Uncertainty Analyses of Molten Salt Property Measurements (ANL/CFCT-25/5)
L. Gardner, M Rose et al., ANL, Property Measurements of LiF-NaF-KF Molten Salts Doped with Corrosion Products and Oxygen (ANL/CFCT-25/22)
Manh Thuong nGuyen, PNNL, Computational investigation of thermophysical and structural properties of molten NaCl-PuCl3-AmCl3 (PNNL.38386)
Keerthana Krishnan, Praveen Thallapally et al, PNNL, Radiation Stability of MOFs for Noble Gas Capture and Separation - Gamma radiation study on CaSDB and CuBTC MOFs (PNNL-37418)
Scott Parker, Marisa Monreal et al, LANL, Analysis of Retained Voids in Molten Salts by Novel Image Processing Techniques (LAUR 25-23337)

MSR Campaign Website:

The breadth of the MSR design space presents a substantial challenge to the completeness and broad applicability of any technology development planning activity. Dozens of design concepts are currently in some state of development, nearly all have been introduced in the past decade, and it is not currently possible to reasonably evaluate which designs will eventually be successful. Nevertheless, MSRs have common characteristics and many technology development issues are broadly applicable to most MSRs

MSR Annual Campaign Review

- April 22-24, 2025
- April 16-18, 2024
- May 2-4, 2023
- April 26-27, 2022
- June 17, 2021

MSR Course

https://gain.inl.gov/doe-molten-salt-reactor-program/

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Molten Salt Reactor Reports

CHEMISTRY

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Title	Link	Report Number	Year	# of Pages
Synthesis and Thermophysical Property Determination of NaCl-PuCl3 Salts	Link	INL/RPT-22-69181	2022	34
Engineering-Scale Batch Purification of Ternary MgCl2-KCl-NaCl Salt Using Thermal and Magnesium Contact Treatment	Link	ORNL/TM-2022/2554	2022	31
An Overview of the Molten Salt Thermal Properties Database□Thermophysical, Version 2.1.1 (MSTDB-TP v.2.1.1)	Link	ORNL/TM-2023/2955	2023	25
FY23 Progress Report on Viscosity and Thermal Conductivity Measurements of Molten Salts	Link	ORNL/TM-2023/3048	2023	31
Experimental Plan for Synthesis of an Americium- and Plutonium-Containing Salt	Link	INL/RPT-24-80052	2024	18

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Thank you
Teresa Krynicki, INL

Next MSR Campaign Review in New Mexico, hosted by SNL 20-24 April 2026

IAEA MSR Structural Materials, Vienna, Austria 20-24 JUL 2026

IAEA/NAE/JRC MSR Fuel Cycle #3 June 2027

GIF WEBINARS : https://www.gen-4.org/resources/webinars

Webinar #9 https://www.gen-4.org/resources/webinars/education-and-training-series-9-molten-salt-reactors-msr
Webinar #8 https://www.gen-4.org/resources/webinars/education-and-training-series-8-fluoride-salt-cooled-high-temperature-reactors
Webinar #35 https://www.gen-4.org/resources/webinars/education-and-training-series-35-czech-experimental-program-msr-technology
Webinar #42 https://www.gen-4.org/resources/webinars/education-and-training-series-42-comparison-16-reactors-neutronic-performance
Webinar #44 https://www.gen-4.org/resources/webinars/education-and-training-series-44-molten-salt-reactor-safety-evaluation-us
Webinar #73 https://www.gen-4.org/resources/webinars/education-and-training-series-73-molten-salt-reactors-taxonomy-and-fuel-cycle
Webinar #88 https://www.gen-4.org/resources/webinars/education-and-training-series-88-multiphysics-depletion-chemical-analyses-molten
Webinar #97 https://www.gen-4.org/resources/webinars/education-and-training-series-97-overview-and-update-msr-activities-within-gif