Oak Ridge National Laboratory

Molten Salt Reactor PROGRAM

Molten Salt Reactor Campaign at ORNL

Joanna McFarlane, mcfarlanej@ornl.gov

ORNL Molten Salt Workshop

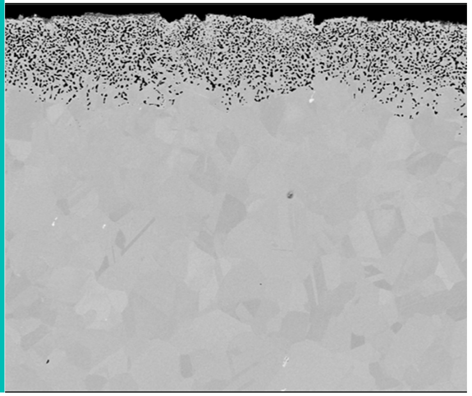
November 5-7, 2024

We are addressing the big questions for licensing MSRs

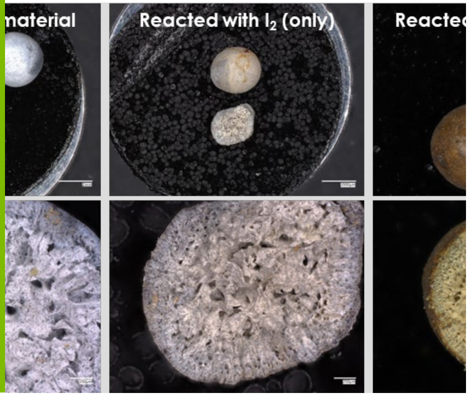
Radionuclide Transport

Safeguards and Security

Materials and Corrosion



Waste and fuel cycle



ORNL's role in the MSR campaign: Providing critical data and validated predictive models to evaluate structural materials compatibility and lifetime in molten halide salts

Oak Ridge National Laboratory

Pacific Northwest NATIONAL LABORATORY

INL Idaho National Laboratory

Mission

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

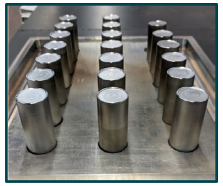
Argonne NATIONAL LABORATORY

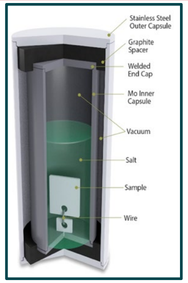
Los Alamos NATIONAL LABORATORY

Sandia National Laboratories

Purification + testing

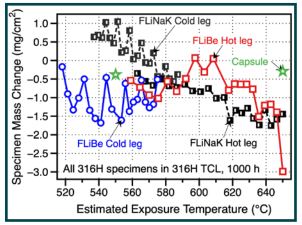
- Salt chemistry
- Fuel salt vs Coolant salt
- Allowable impurities
- Redox control

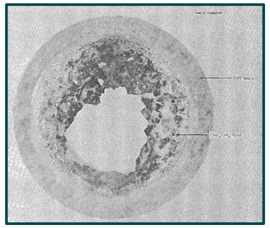




Mass Transfer

- Corrosion
- Deposition
- Temperature dependence
- Sensor Technology

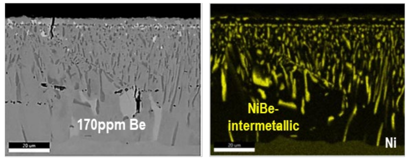


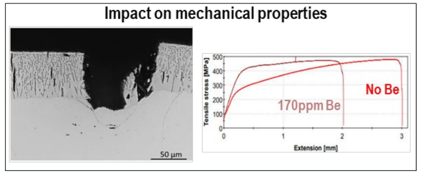


Hastelloy N, $NaBF_4$-NaF-$KBF_4$8760 h, TCL, 605-460 °C, - J. Koger, Corrosion, 1974

Long-term operation

- Transmutation performance
- Salt chemistry changes
- Redox control (how much?)
- Useful predictive models





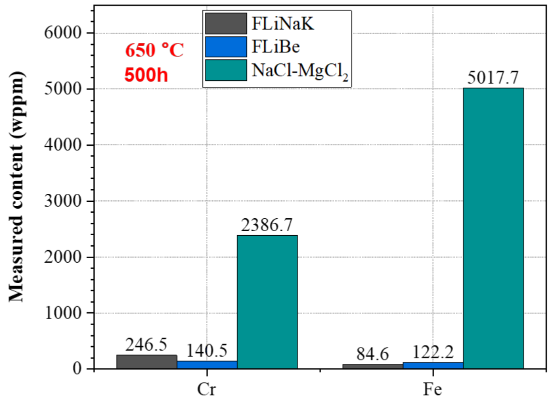
316H, FLiBe, 1000h capsule test, 650 °C - Keiser et al., JNM, 2022

AMMT Oak Ridge National Laboratory

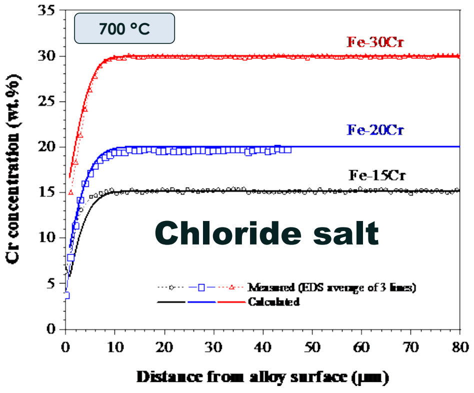
U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

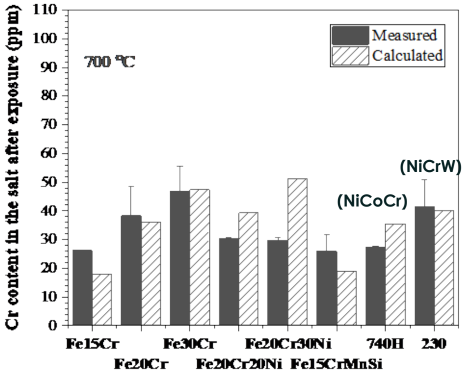
Generated key data to enable a design strategy for corrosion resistant structural materials for MSRs

Completed Cr and Fe dissolution studies in fluoride and chloride salts between 550-850°C



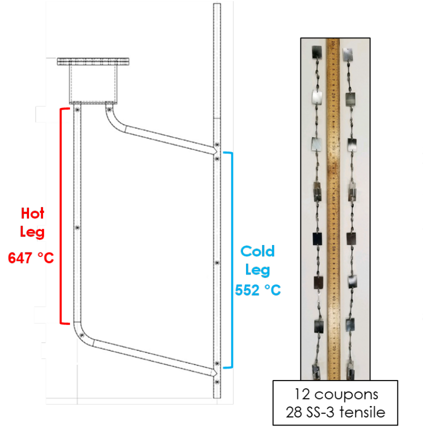
Excellent agreement between observed and calculated microstructural evolution and salt chemistries



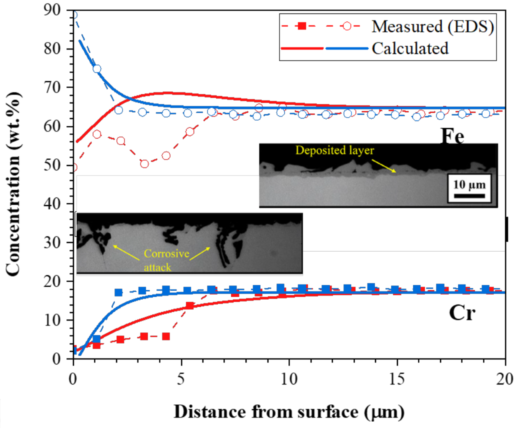


*Pillai et al., JNM 2021, JOM 2023

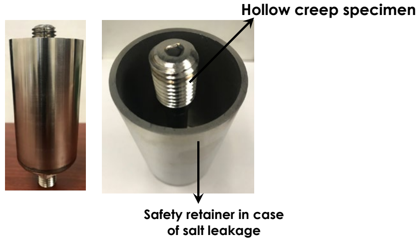
Leveraged the success of predicting corrosion behavior in static tests to describe corrosion behavior under flowing conditions



Alloy	Fe	Ni	Cr	Mo	Mn	Si	C
316H	64.5	13.3	17.2	2.3	1.9	0.5	0.06

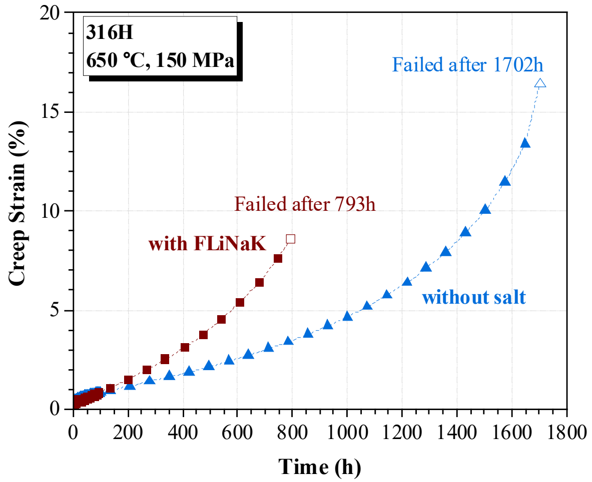


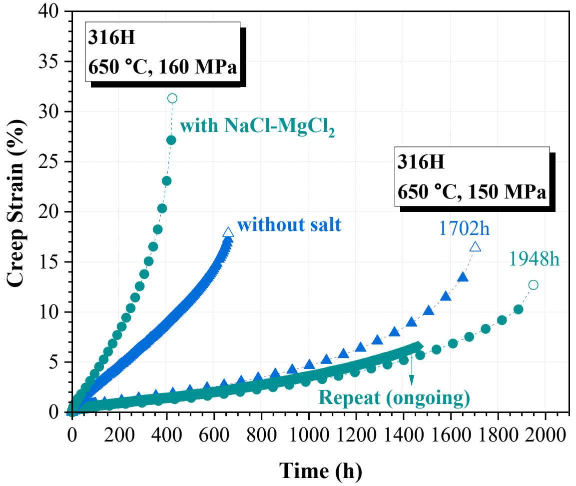
FY24 Milestone: Measure the effect of molten halide salt exposure on creep rupture lifetime

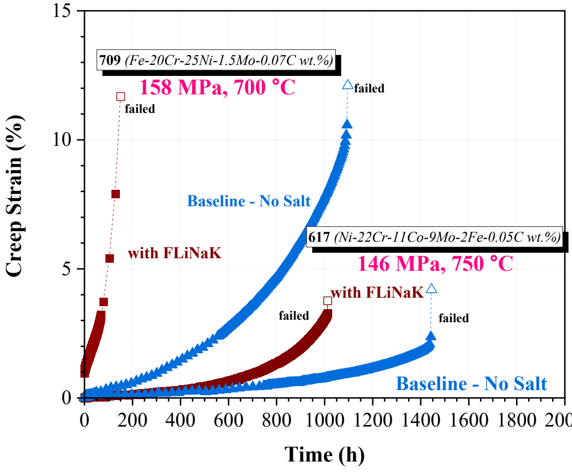


	316H 650°C, 150 MPa	709 700°C, 158 MPa	617 750°C, 146 MPa
Empty (no salt)	completed	completed	completed
FLiNaK	completed	completed	completed
$MgCl_2$-NaCl	completed		

Significant impact of molten salt environment on creep behavior of 316H*, 617 and 709







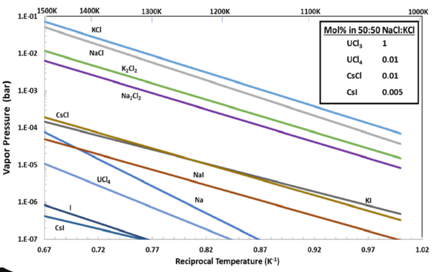
*Potential stress and salt chemistry dependence observed for 316H in NaCl-$MgCl_2$

Oak Ridge National Laboratory
Rishi Pillai pillairr@ornl.gov, Severine Cambier

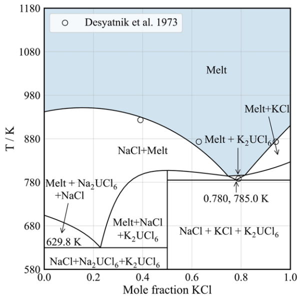
Administer the Molten Salt Thermal Properties Database-Thermochemical (*MSTDB-TC*): (Ted Besmann, besmann@usc.edu)

- Library of Gibbs energy functions and models compatible with equilibrium solver FactSage™ and open-source codes
- **mstdb.ornl.gov**

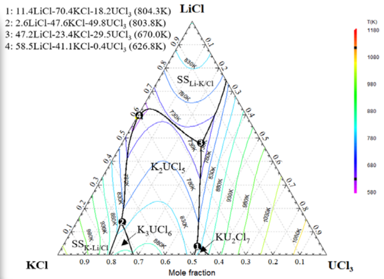
Computed Vapor Pressures



Phase Equilibria



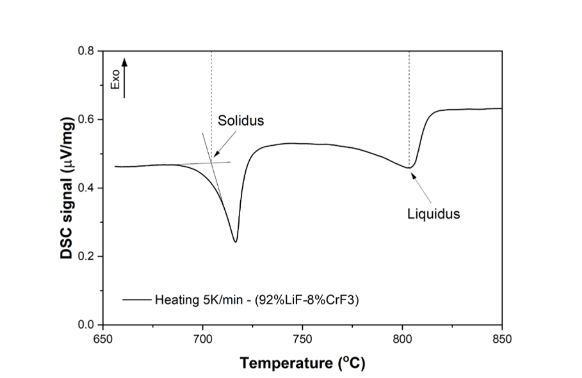
Liquidus Projections



- Organize Component Data

Compound	$\Delta_f H^o(298)$ J/mol	$S^o(298)$ J/mol K	C_p J/mol K	Temp. Range K
CsF (l)	-535,041	108.1938	70.56	298-1400
LiF (l)	-598,653.75	42.956	64.45	298-2000
NaF (l)	-557,859.5	52.583	73.036	298-2000
KF (l)	-551,944	71.144	70.485	298-2000

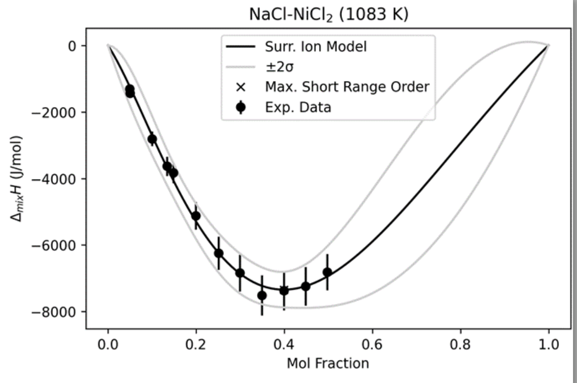
- Review Measurements



- Modeling

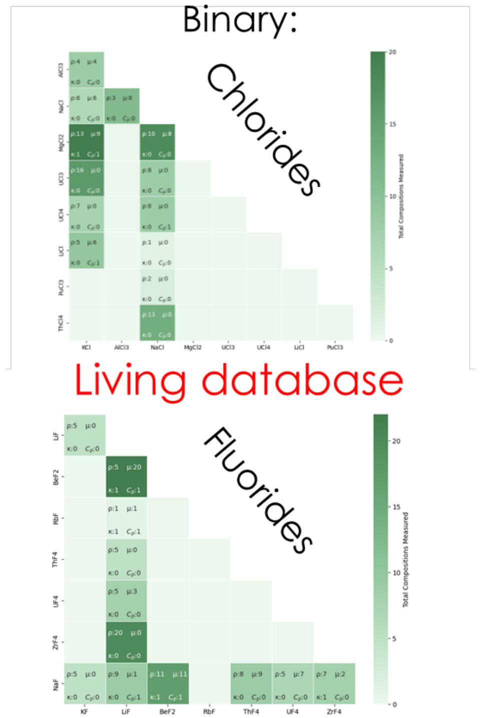
Gibbs Energy Functions

- Compounds
- Vapor Species
- Salt Melt
- Solid Solutions

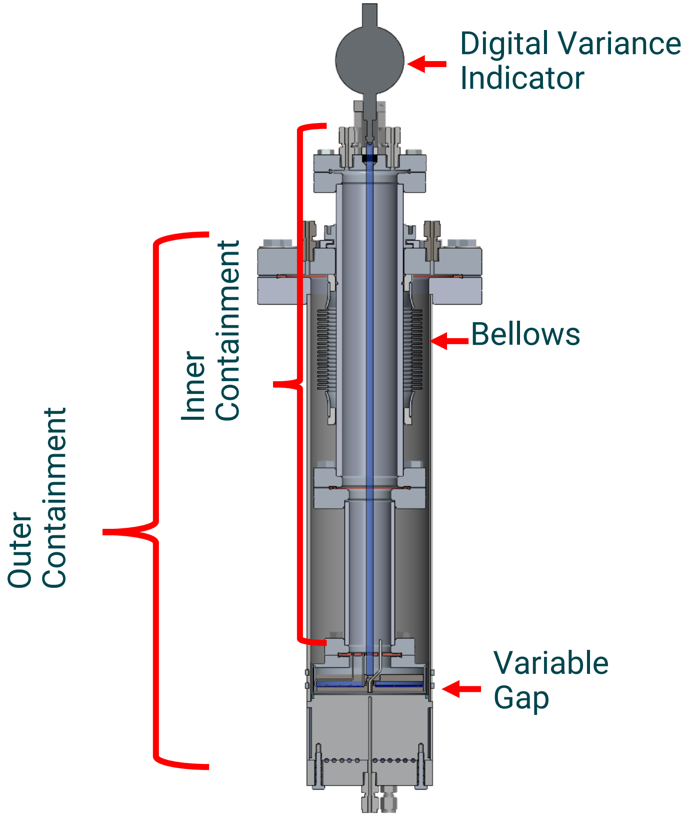


Provide support for MSTDB-TP (thermophysical properties) and lead measurements of thermal conductivity and viscosity

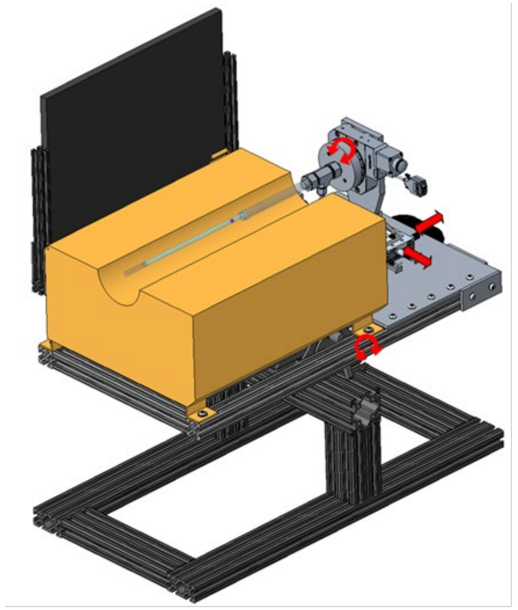
MSTDB-TP

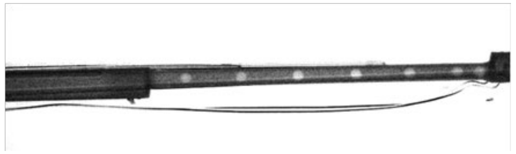


Thermal Conductivity



Viscosity

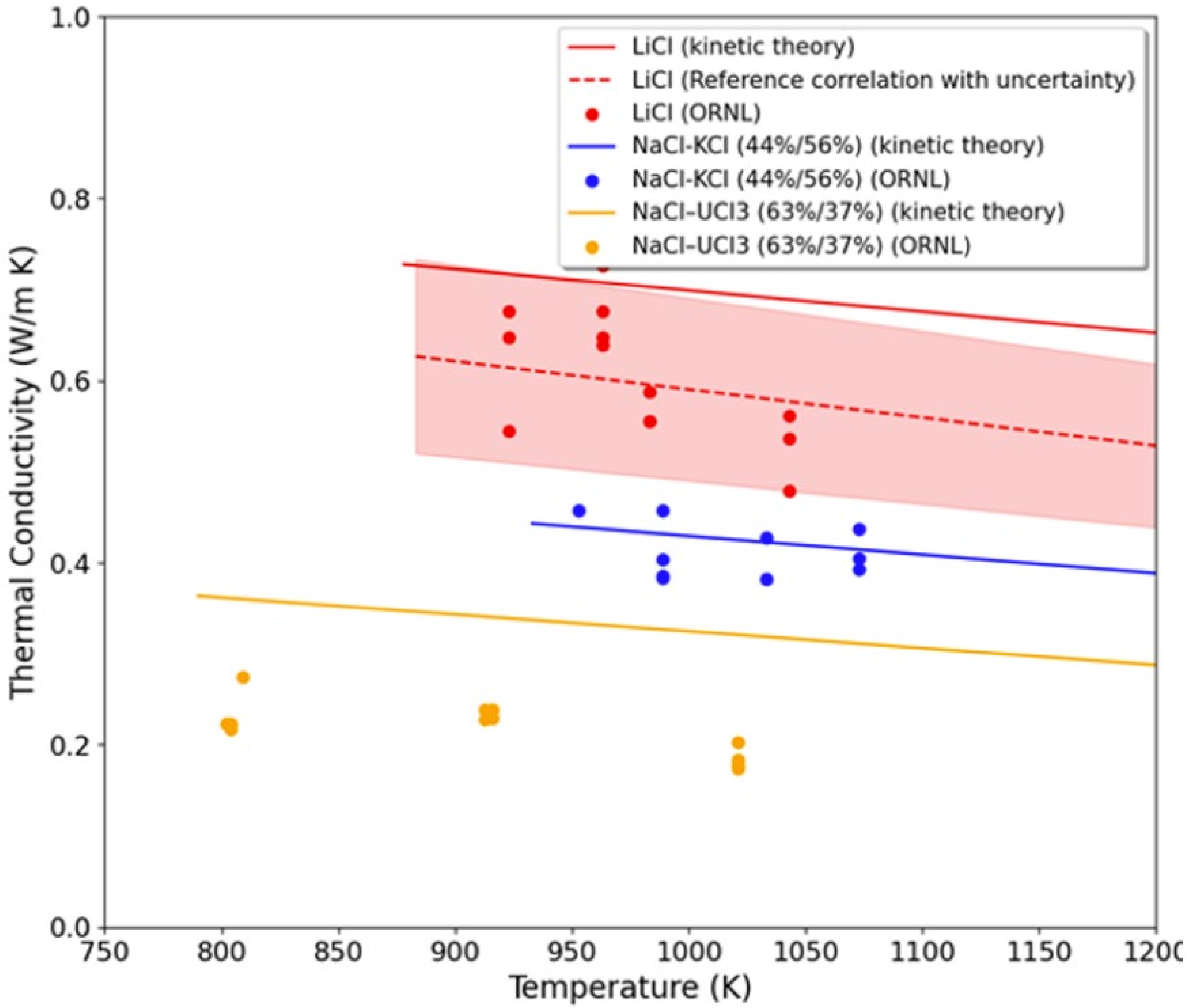




Tony Birri birriah@ornl.gov, Nick Termini, Ryan Chesser

Measurements being taken on coolant and fuel salt mixtures

Tony Birri birriah@ornl.gov, Nick Termini, Ryan Chesser



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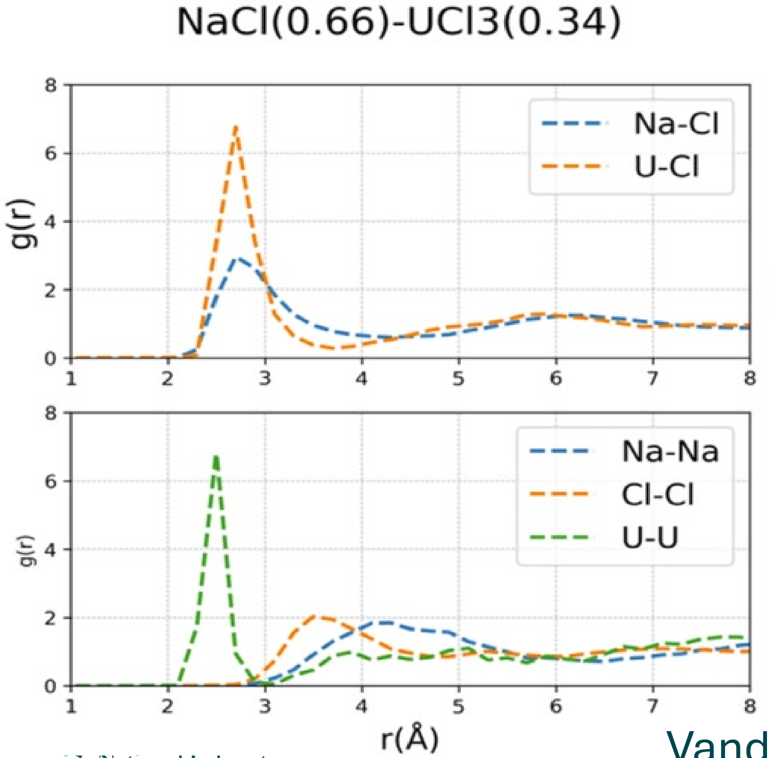
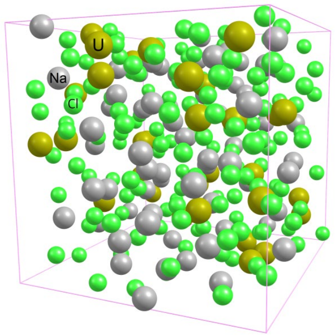
Atomistic simulations to assess local structure, thermophysical and transport properties (V.-A. Glezakou, B. Smith)

UCl-NaCl

- Well-separated U atoms which diffuse slower than Na/Cl; fairly stable U-Cl associations

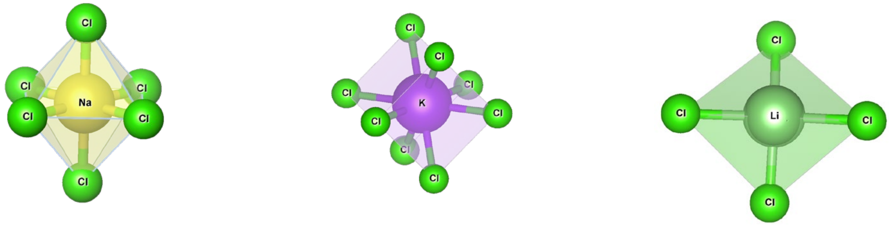
D_{Na} (10^{-5} cm^2s^{-1})	D_U (10^{-5} cm^2s^{-1})	D_{Cl} (10^{-5} cm^2s^{-1})
5.08	3.2	5.3





Transport Properties of Pseudo-ternary Chlorides Na/K/Li-Cl

- Four different mixtures; complementary studies to experimental work by Birri and coworkers
- Self Diffusion coefficients appear to decrease with the conc. of KCl, and increase with conc. of LiCl. (coordination number holds the inverse of that trend)
- Na+ and K+ primarily exhibit hexahedral and octahedral coordination where as Li+ exhibits distorted tetrahedral.



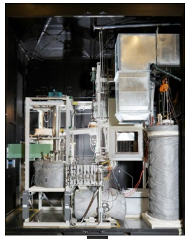
Mix #	D_{Na}	D_K	D_{Li}	D_{Cl}	T	Comp (cP)	Exp (cP)
10	3.32	6.57	7.96	5.07	968	1.08	
11	6.09	6.73	7.95	5.59	1058	1.17	1.28
12	5.39	4.74	6.41	4.18	1058	1.42	
13	9.01	10.60	12.61	8.46	1058	0.90	1.06

Vanda Glezakou glezakouva@ornl.gov

Facility to Alleviate Salt Technology Risks (FASTR)

Largest Cl salt loop in DOE

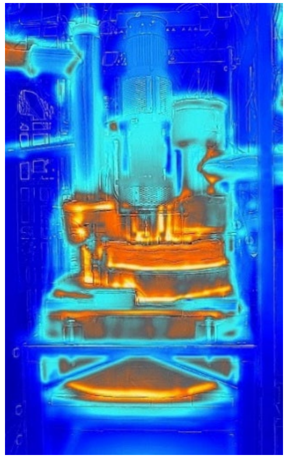
Salt	NaCl-KCl-$MgCl_2$
Operating Temp.	725°C
Flow rate	≤7.0 kg/s (228 lpm)
Operating pressure	Near atmospheric
Primary Materials	C-276 & Inconel 600
Loop volume	154 liters
Power	400 kW Main Heater ~71 kW trace
Primary piping ID	5.20 cm (2.05 in.)
Initial operation	December 2022

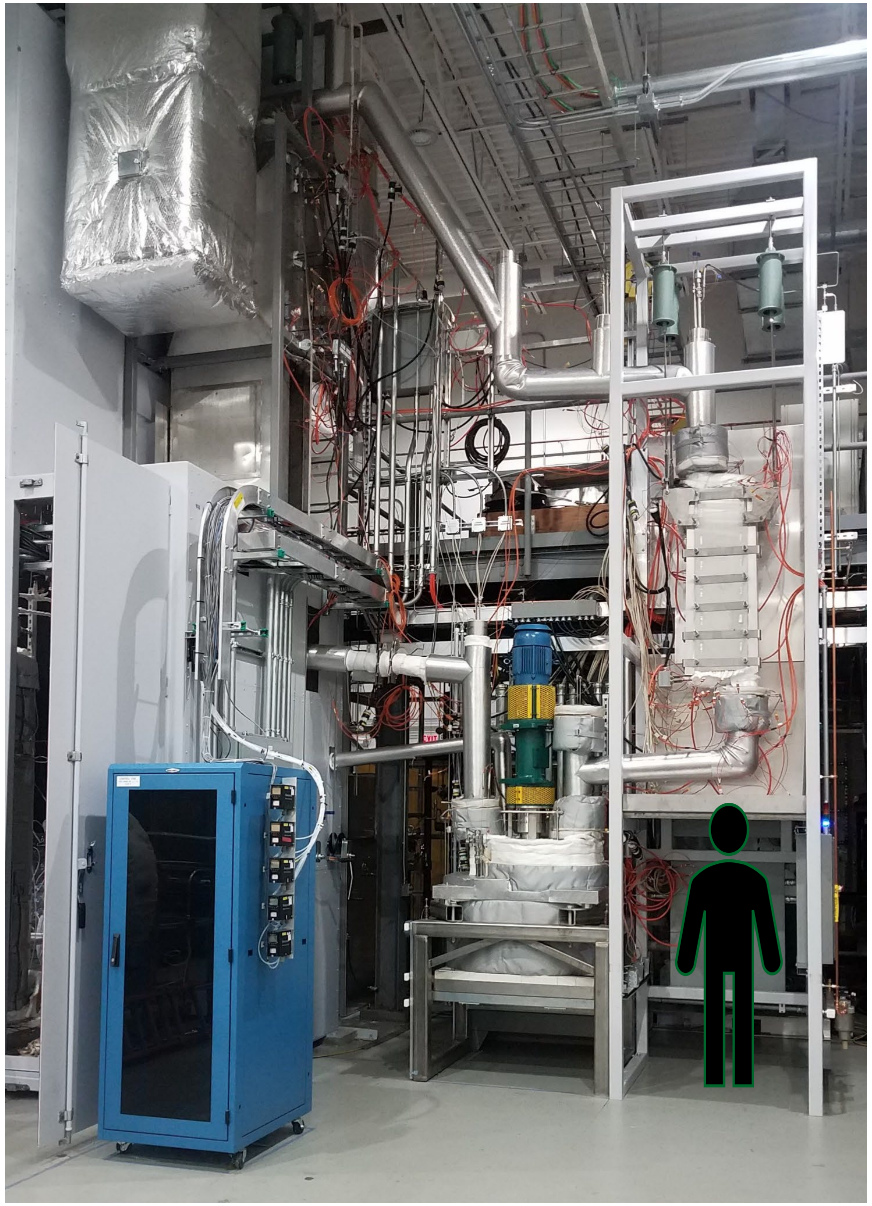


Kevin Robb
robbkr@ornl.gov

Compared to LSTL, FASTR is:

- 2x higher capacity pump
- 2x larger salt volume
- 2x larger pipe
- 2x thermocouples
- 2x main heating capacity
- 3x trace heating capacity
- 4x number of salt flanges



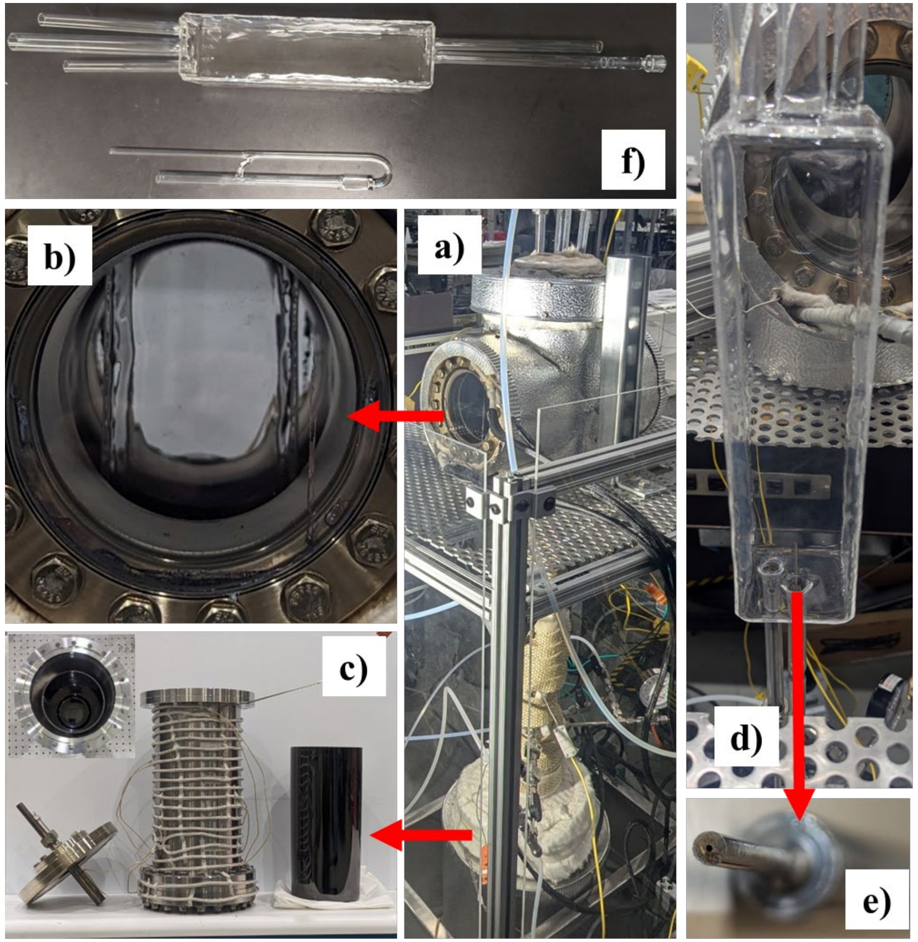


Original development support by DOE-EERE SETO CPS 33875

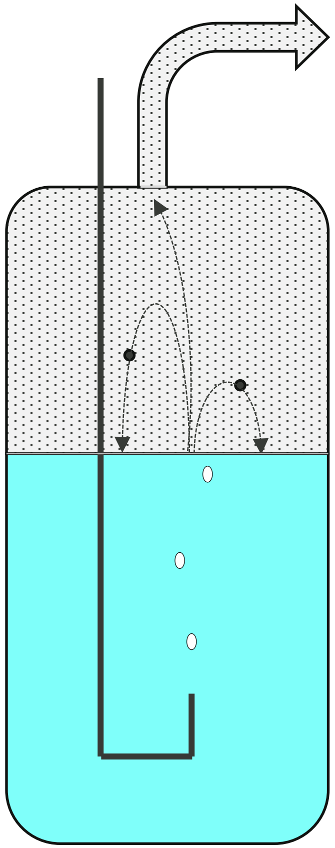
Robb, Kevin, and Kappes, Ethan. *Facility to Alleviate Salt Technology Risks (FASTR): Commissioning Update.* United States: **ORNL/TM-2023/2846**, 2023. Web. doi:10.2172/1960689.
Robb, Kevin, Kappes, Ethan, and Mulligan, Padhraic L. *Facility to Alleviate Salt Technology Risks (FASTR): Design Report.* United States: **ORNL/TM-2022/2803**, 2022. Web. doi:10.2172/1906574.

Visualization can be used to examine two-phase flow at high resolution (10 micron)

a) Complete system
b) Internal visualization cell
c) Auxiliary preheater
d) Molten salt vessel with internal gas capilliary bubbler and transfer tube
e) Capillary bubbler
f) 10 mL versus 1 L cell

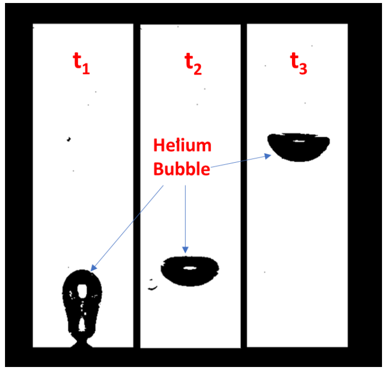


Measure fission gas and aerosol transport into salt off-gas

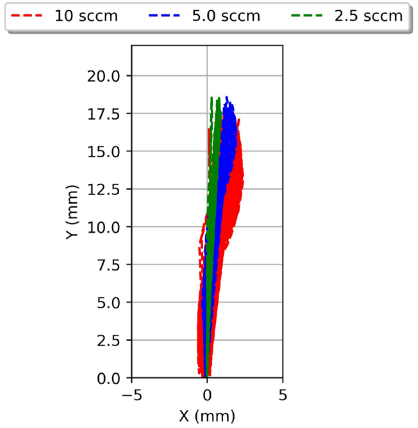


- Aerosol transport
- Droplet formation
- Bubble/species transport
- Gas solubility and retention dynamics

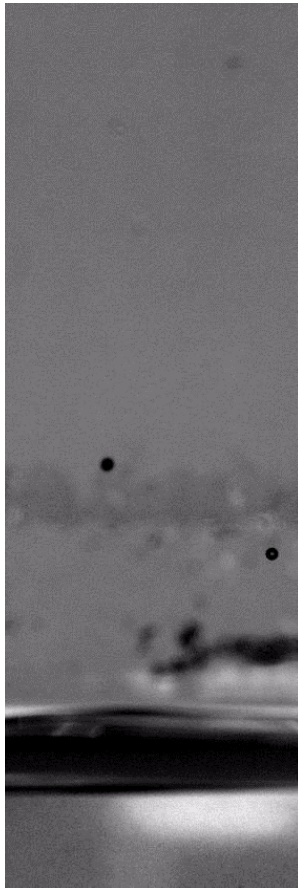
Bubble Flow through LiCl-KCl



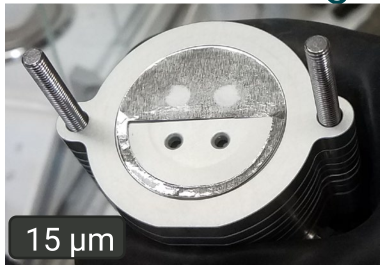
Bubble Path inside LiCl-KCl

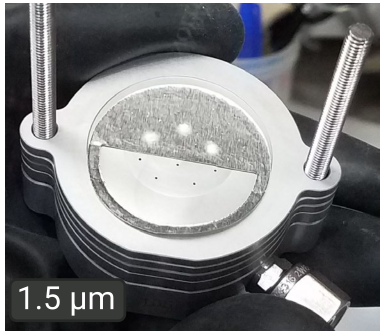


Jet Drops above LiCl-KCl

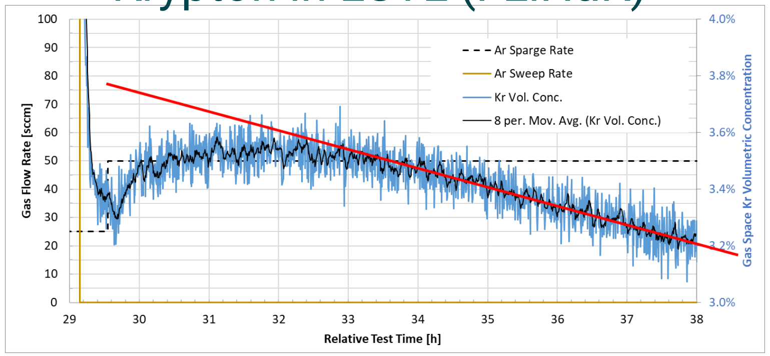


Aerosols in LSTL & FASTR FLiNaK & NaKMgCl





Krypton in LSTL (FLiNaK)



ORNL/TM-2024/3579

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Daniel Orea, Hunter Andrews, Brandon Hunter, Kevin Robb

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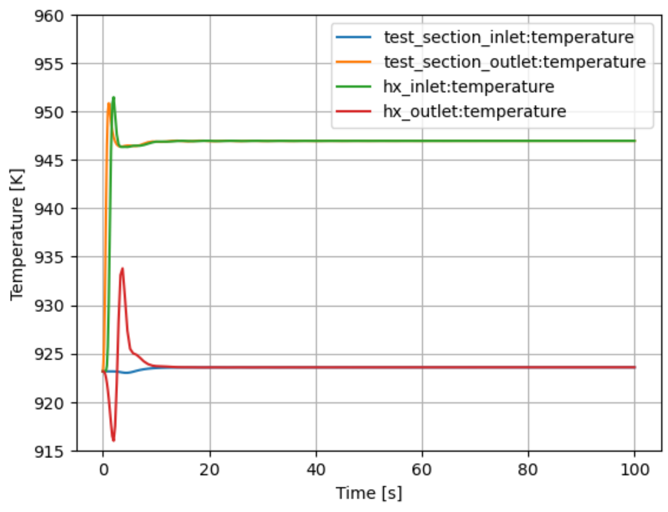
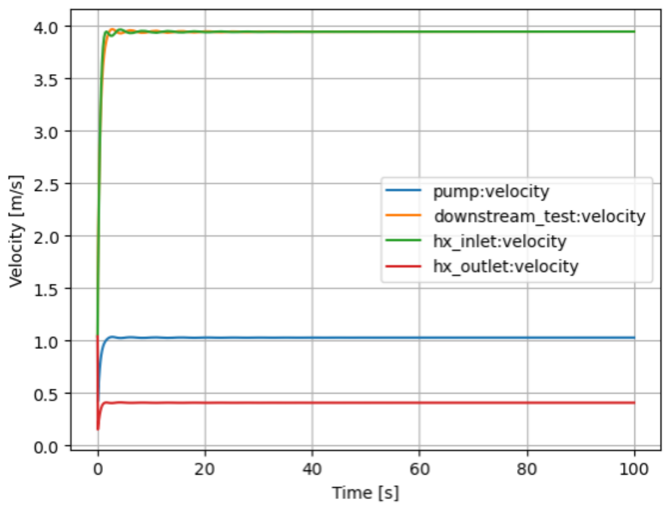
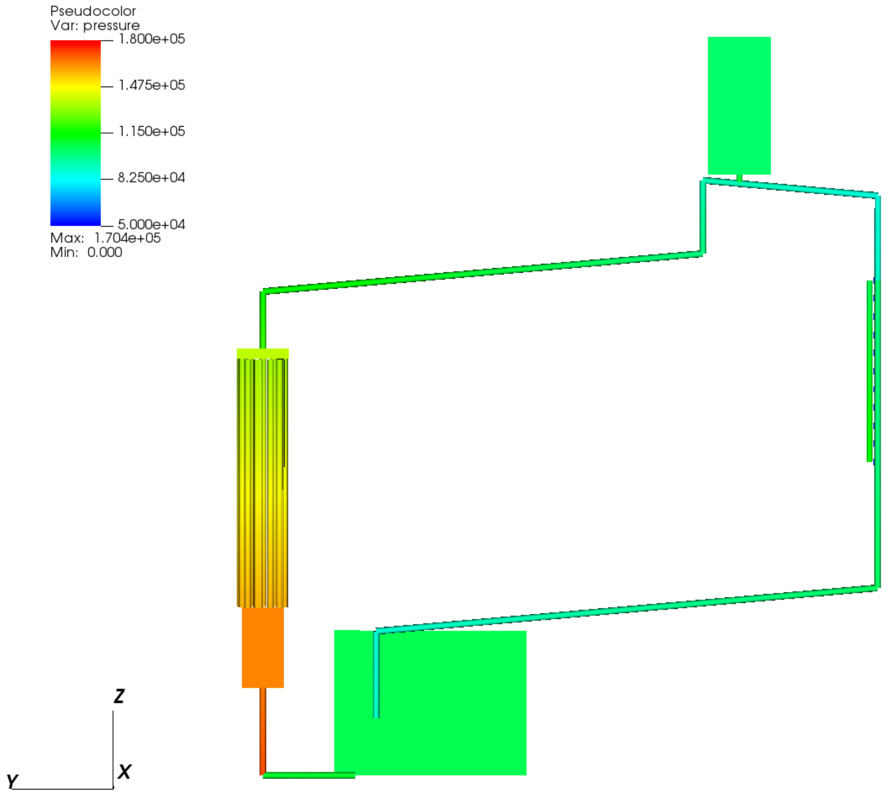
Loop model developed for the LSTL (Bob Salko, salkork@ornl.gov)

- A model was created in the NEAMS system T/H code, SAM
- Modeling options tuned to obtain steady-state heat balance with reasonable mass flow rate and system temperature



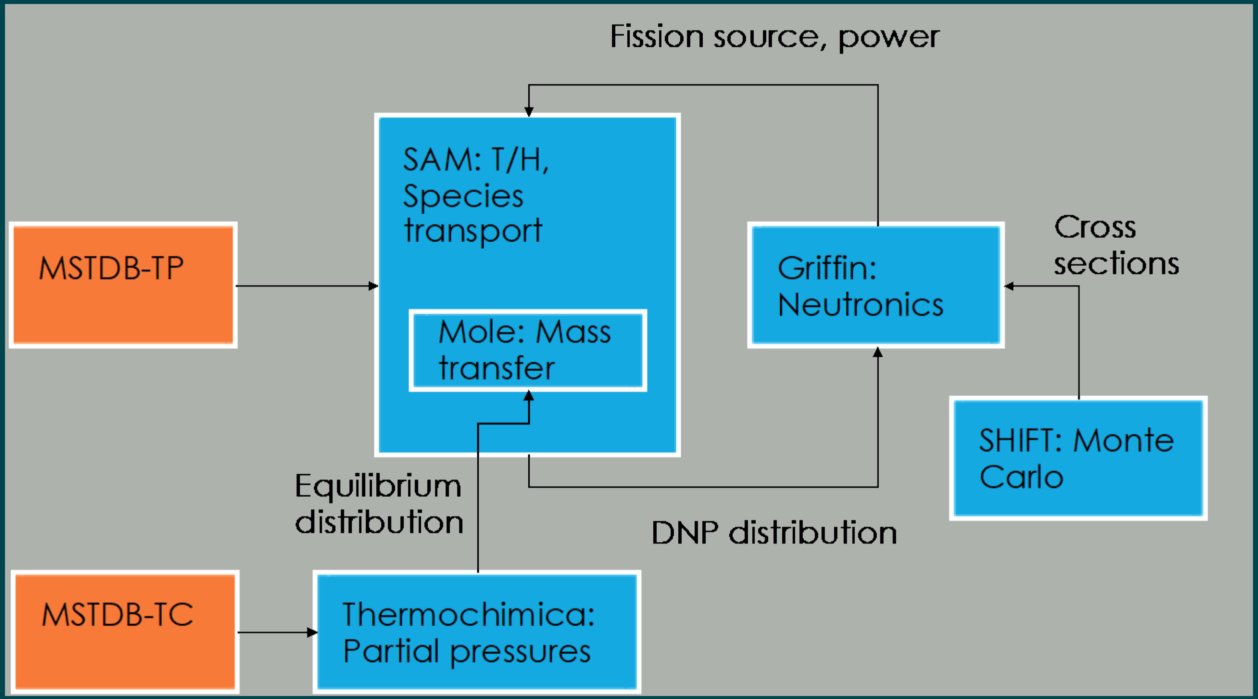


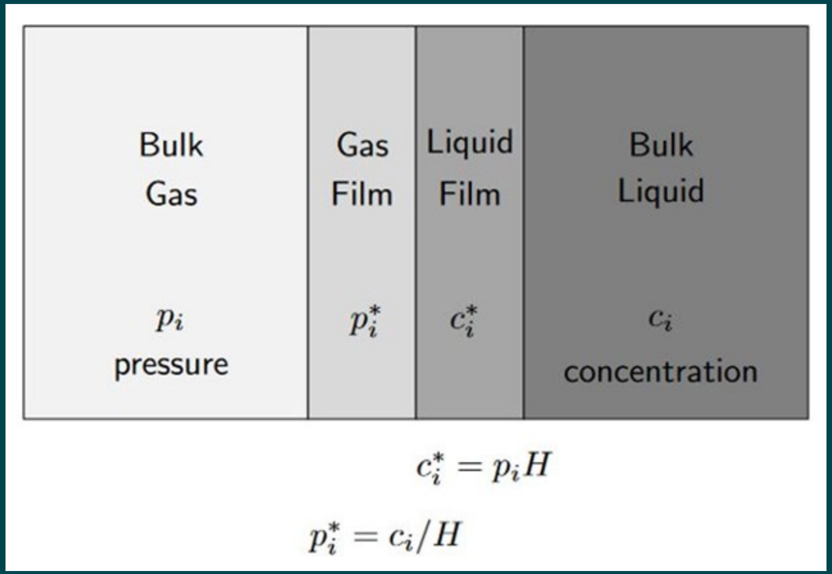
SAM temperature and velocity distribution prediction in LSTL

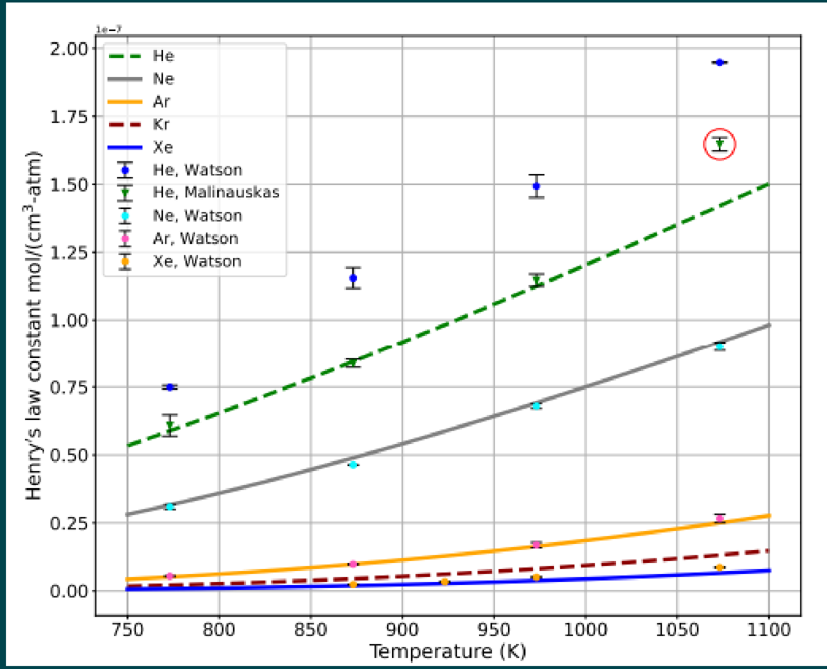


SAM pressure distribution visualization

Use multiphysics mod/sim in combination with MSTDB-TC to predict radionuclide transport.



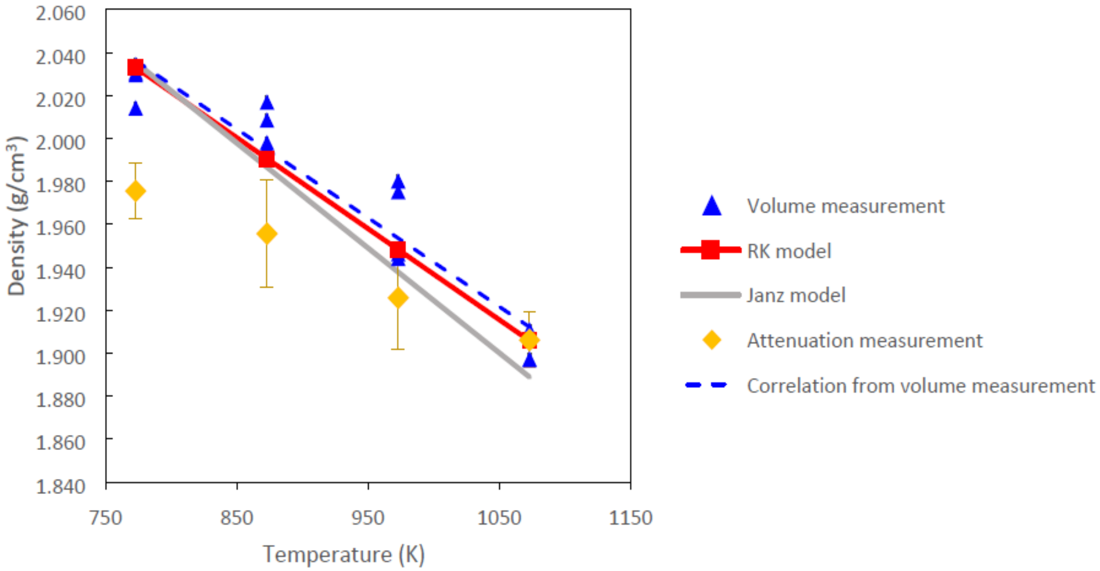


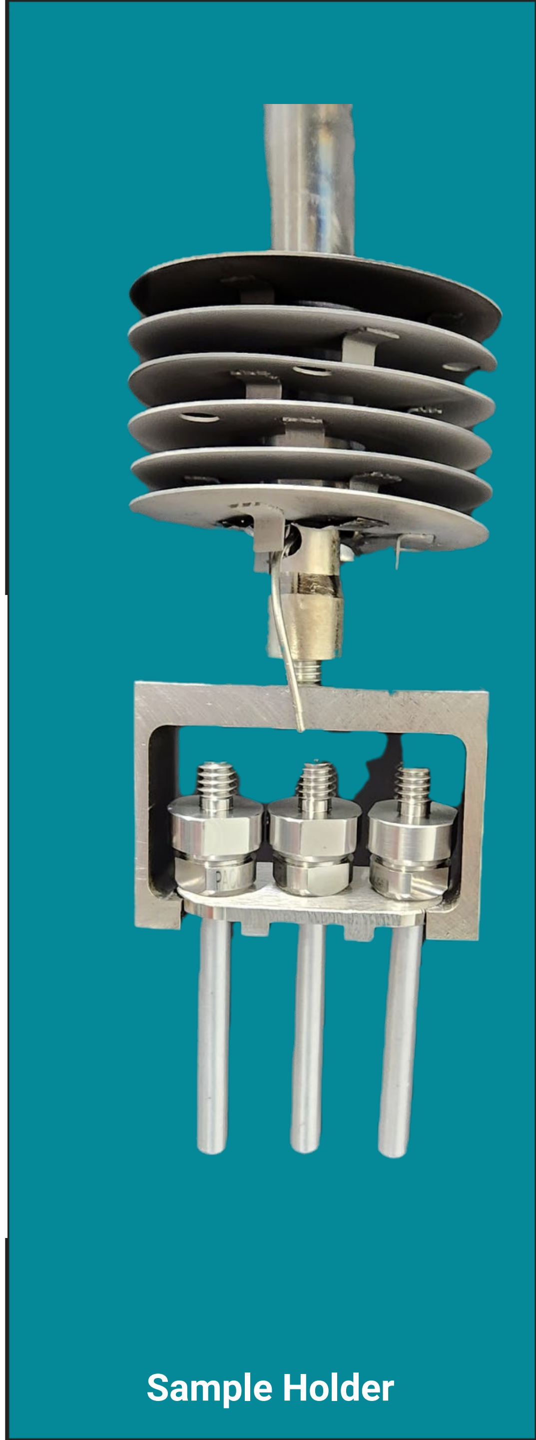


Bob Salko, Kyoung Lee leeko@ornl.gov

Molten salt properties and structure can be studied in situ at high temperatures by neutron radiography and neutron scattering

- **Successful molten salt tests completed at HFIR MARS & SNS NOMAD DOE Office of Science beamlines.**
- **Collaboration with university on NEUP, NSUF, and RTE experiments**
- **PIE by gamma radiography, CT, and LIBS**
- **Collaboration with U South Carolina liquid salt thermodynamic calculations using MSTDB-TC**





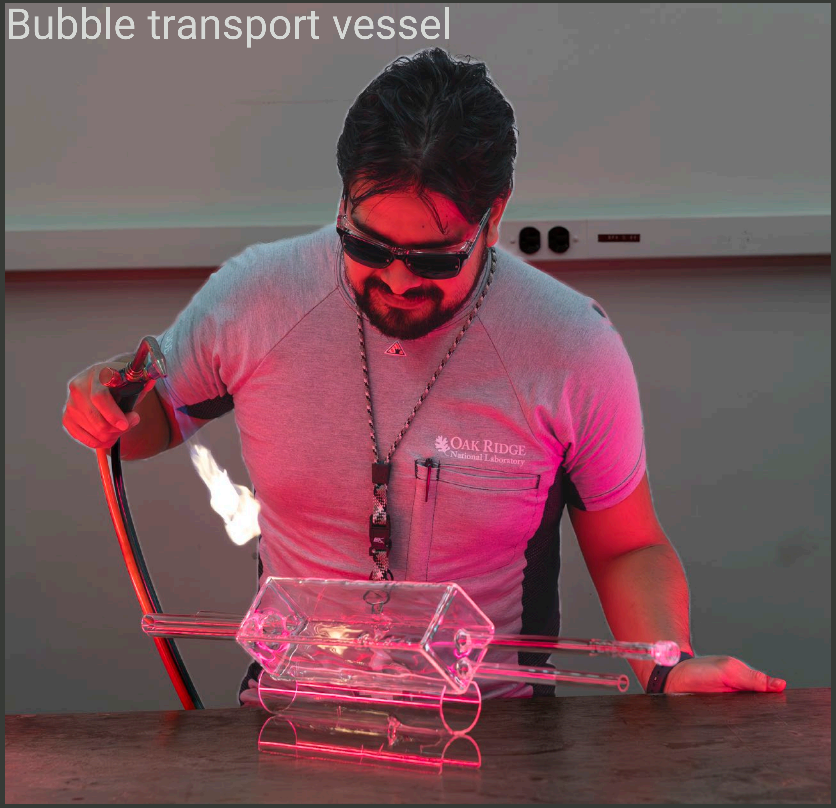
DOE Office of Science User Facility operated by ORNL at HFIR

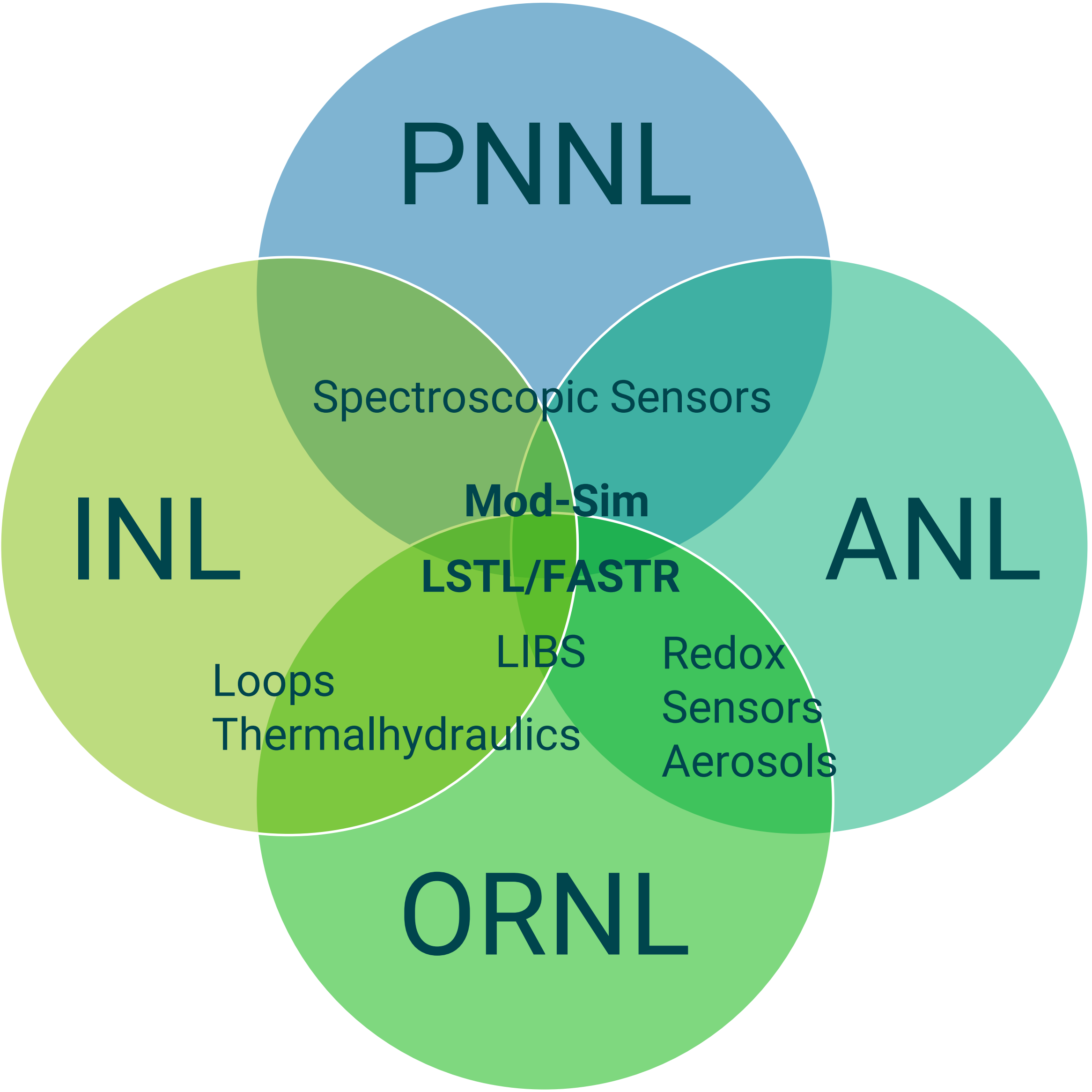
J. Moon et al., ACS Omega, 6, https://doi/10.1021/acsomega.4c01446.

Points-of-contact: Joanna McFarlane, Kevin Robb, Daniel Orea, Molly Ross

Sponsor: DOE Office of Nuclear Energy, DOE Office of Science

Inter-lab collaboration


Bubble transport vessel



ORNL Directory

1. Salt synthesis, purification, characterization – Richard Mayes mayesrt@ornl.gov, Severine Cambier
2. Thermochemistry – Ted Besmann besmann@usc.edu
3. Fundamental thermophysical properties – Tony Birri birriah@ornl.gov, Nick Termini termininc@ornll.gov, Vanda Glezakou glezakouva@ornl.gov, Brett Smith, Ryan Chesser
4. Corrosion– Rishi Pillai pillairr@ornl.gov, Be_2C – Anne Campbell campbellaa@ornl.gov,
5. Graphite/salt interactions – Nidia Gallego gallegonc@ornl.gov
6. Fission gas and aerosol generation and transport – small scale and large-scale facilities – Kevin Robb robbkrr@ornl.gov, Daniel Orea oread@ornl.gov, Molly Ross rossmc@ornl.gov, Hunter Andrews andrewshb@ornl.gov
7. Sensor development – need to monitor reactor & off-gas during operation and after operation – Hunter Andrews, Daniel Orea, Zechariah Kitzhaber, Peggy Milota, Brandon Hunter)
8. NEAMS modeling – SAM, MOLE, MELCOR – Bob Salko salkork@ornl.gov, Kyoung Lee leeko@ornl.gov
9. Cross-cutting technical issues with other programs (e.g., Fusion materials – Rishi Pillai, HALEU- Leigh Martin martinlr@ornl.gov, safety – Be handling Nidia Gallego, isotope separation – Kristian Myhre myhrekg@ornl.gov, Nonpro – Karen Hogue hoguekk@ornl.gov, Nuclear Security – Prashant Jain jainpk@ornl.gov, Iodine capture – NE43 – Katie Johnson johnsonkr@ornl.gov, NSRD – Thien Nguyen nguyend@ornl.gov)
10. Office of Science facilities at ORNL – SNS, HFIR, neutrons.ornl.gov, HPC Frontier https://www.olcf.ornl.gov/tag/hpc/
11. New initiatives MPEX, MDF, gamma irradiation

Posters and presentations at the workshop

Presentation & poster: Nidia Gallego – Molten Salt and Graphite

Presentation: Hunter Andrews – Off-gas and waste forms

Posters on Salt Chemistry and Properties

- Nick Termini
- Ryan Chesser
- Alex Ivanov
- Zechariah Kitzhaber

Posters on Materials Science

- Nidia Gallego
- Rishi Pillai
- Peggy Milota

Thank you

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Honoring Jim Keiser (1942-2024) & Bruce Pint (retired Oct 18, 2024)

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