Molten Salt Reactor PROGRAM

Overview of the Technology Development and Demonstration Supporting MSRs

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April 23, 2025

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Argonne NATIONAL LABORATORY · INL Idaho National Laboratory · Los Alamos NATIONAL LABORATORY · OAK RIDGE National Laboratory · Pacific Northwest NATIONAL LABORATORY · Sandia National Laboratories · U.S. DEPARTMENT of ENERGY Office of Nuclear Energy

FY25 PICS milestones (M2 + completed M3) relevant to off-gas and radionuclide transport (MSR RD 1.15.06, ARR 2.04.07)

Milestone Number	Description	Status as of 03-31-2025 (end of Q2)
M2RD-25OR0602014	**Complete mobile LIBS analysis of the off-gas from small and large sparging salt vessel.**	**Due 9-26-2025**
M3RD-25OR0602012	Complete aerosol analysis.	Complete 12-20-2024
M3AT-25IN0702051	Complete report on final as-constructed design of the Molten Salt Tritium Transport Experiment facility.	Complete 12-22-2024
M3AT-25AN0702041	Complete system component integration plan and preliminary designs for engineering scale test facility	Complete 1-24-2025
M3AT-25AN0702042	Complete initial construction activities for automated salt transfer device	Due 3-28-2025

FY25 PICS milestones (upcoming M3) relevant to off-gas and radionuclide transport (MSR RD 1.15.06, ARR 2.04.07)

Milestone Number	Description	Status as of 03-31-2025 (end of Q2)
M3RD-25OR0602018	Complete bubble visualization tests in molten salt systems	Due 6-27-2025
M3AT-25AN0702043	Complete demonstration of aerosol sensor sensitivity to aerosol formation mechanism	Due 9-19-2025
M3AT-25OR0702021	Complete molten salt loop collaborative test campaign with novel sensors	Due 9-30-2025
M3AT-25AN0702031	Installation of Molten Salt Flow Loop with Chemistry Monitoring and Control System	Due 9-30-2025
M3AT-25AN0702043	Complete demonstration of aerosol sensor sensitivity to aerosol formation mechanism	Due 9-19-2025

FY24-25 PICS milestones from Sandia National Laboratories

Milestone Number	Description	Status as of 03-31-2025 (end of Q2)
M3RD-24SN0602071	Produce MSR Safety Roadmap	Completed 9-30-2024
M3RD-24SN0602072	MELCOR-SAM Code-to-Code Crosswalk: Liquid Salt Test Loop	Completed 9-25-2024
M3RD-24SN0602073	Molten Salt Tritium Transport Experiment (MSTTE) MELCOR Model	Completed 9-15-2025
M3RD-25SN0602032	Complete Deposition Modeling of Metals and Safeguard Materials in MSRs	Due 9-30-2025

The Molten Salt Transport Experiment Loop (MSTTE) has been built and is being commissioned at INL

- Loop will be used to understand tritium transport through molten salt
- Copenhagen Atomics loop being commissioned at INL
- Features include a hydrogen injection system and a permeation test section

Tommy Fuerst, thomas.fuerst@inl.gov

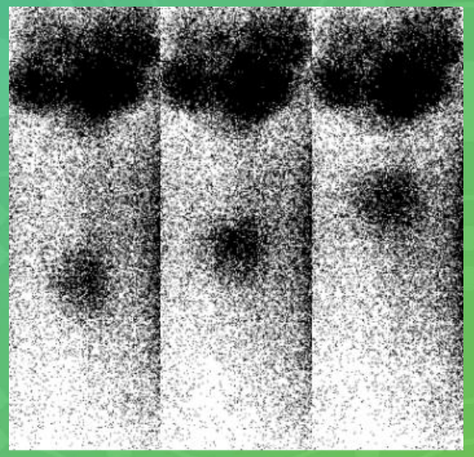
INL/RPT-23-74691

Leveraging MARS Capabilities: Using Neutrons to Image Gas Bubbles in Molten Salt

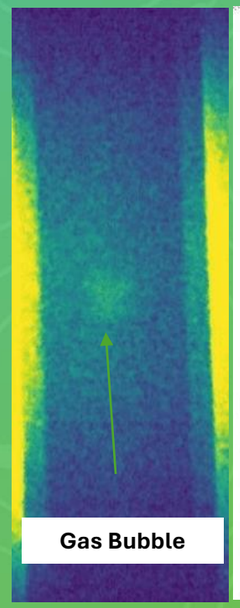
- **Successfully demonstrated the ability to detect and track argon and helium gas bubbles in molten FLiNaK up to 700 °C using HFIR MARS CG1D Instrument**
  - Max Image Acquisition Rate of 71 fps, 56 µm effective pixel size
- **Other applications:**
  - Expand to other salts systems (actinides, fluorides, beryllium-containing)
  - Insoluble particle transport
  - General two-phase flow systems
- **Summary paper submitted to ANS Annual Conference 2025**
  - Orea, D., et al. "Optical and Neutron Imaging Measurements of Gas Bubble Rise Velocity in Molten Salt" Transactions of the American Nuclear Society 2025
- **NEFCD staff:** Daniel Orea, Kevin Robb, Joanna McFarlane
- **Instrument Team:** James Torres, Yuxuan Zhang, Roger Hobbs, Bekki Mills, Doug Kyle,

Joanna McFarlane holding flow cell replica for H2O/D2O initial beam test

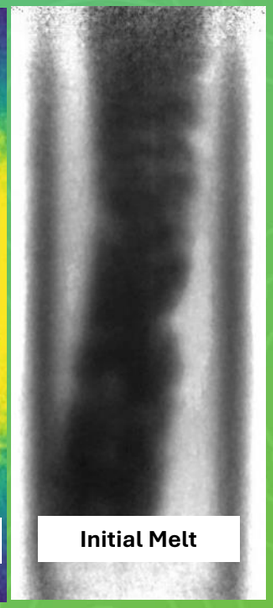
Flow cells staged with FLiNaK inside glovebox for final testing



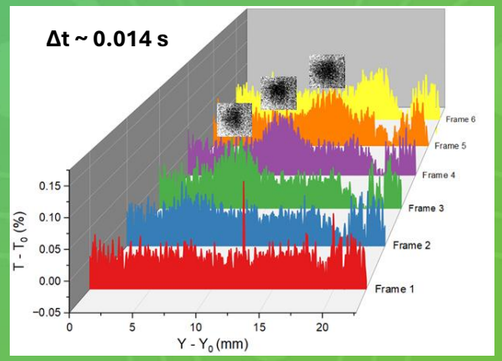
In beam flow cell and open furnace alignments

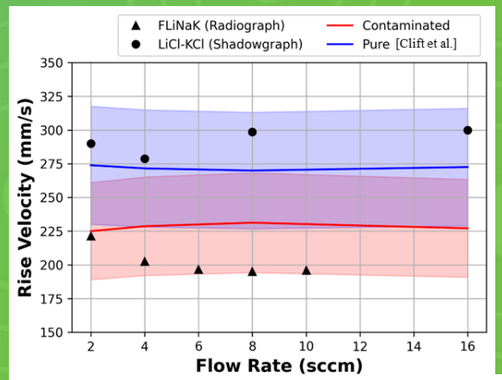


Gas Bubble



Initial Melt

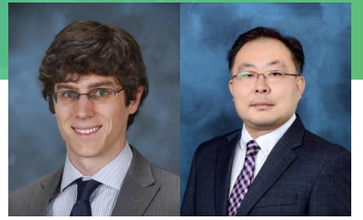


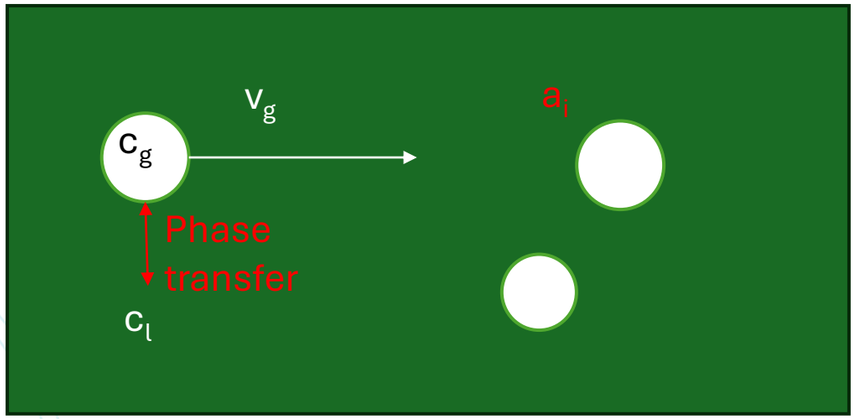


Comparing against existing correlations

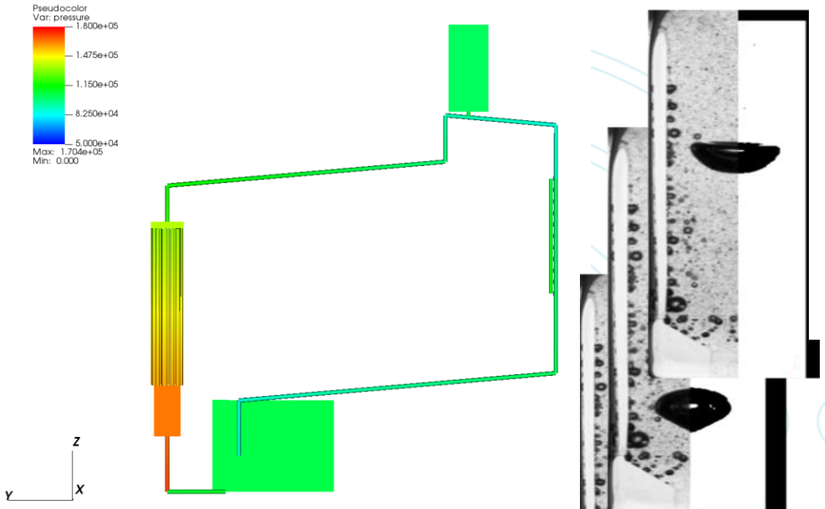
Point-of-contact: Daniel Orea oread@ornl.gov
Sponsor: DOE Office of Nuclear Energy

Development of modeling tools for MSR fission gas behavior

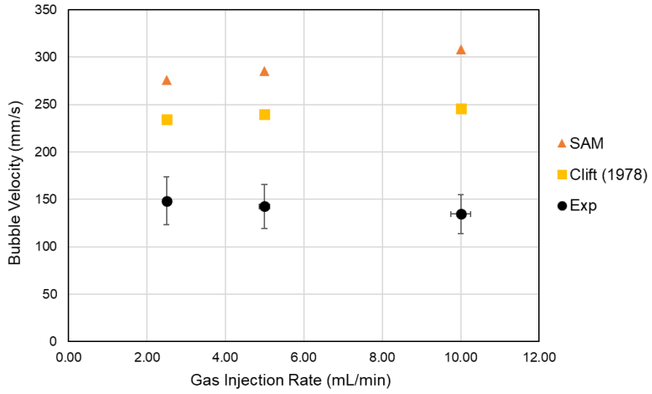




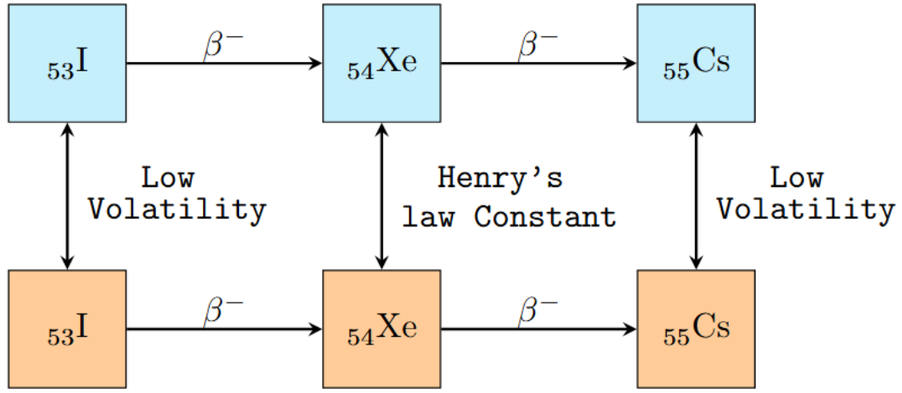
Development and coupling of SAM and Mole for modeling of gas and species transport, phase transfer, isotope decay, and fission gas release



Modeling of LSTL pressure distribution



Modeling of bubble rise experiments shows impact of wall effect



The Gibbs Energy Minimizer (GEM) predicts gas phase behavior and solubility using temperature, pressure, and composition inputs. It applies Gibbs energy minimization to model equilibrium states, focusing on low-volatility gases like iodine in molten salts, using tools such as FactSage and Thermochimica.

- **Application:** GEM is applied to estimate iodine and cesium solubility in molten salts.
- **Model Features:** Incorporates dependencies on temperature, pressure, and mole fraction to enhance accuracy and applicability in predicting gas phase behavior and solubility dynamics.

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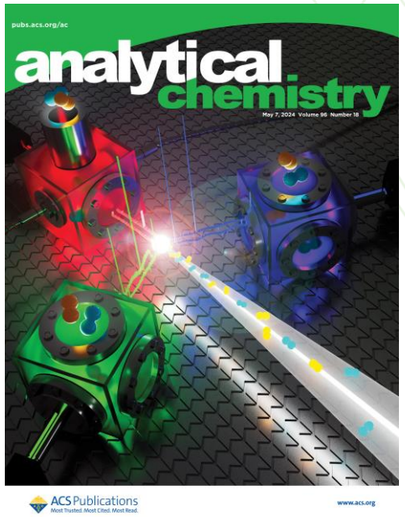
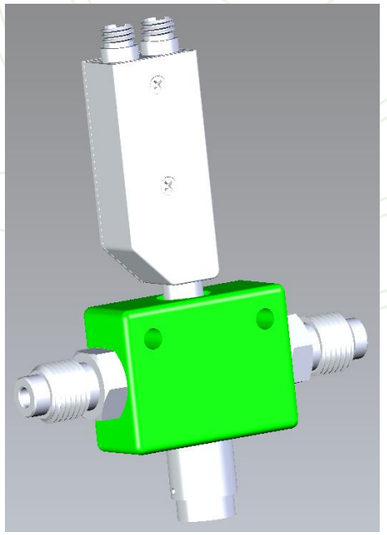
PNNL - Online Monitoring: Molecular Approach

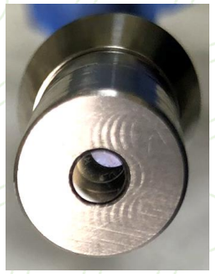
- Goal of using optical spectroscopy for identification and quantification of key analytes in an off-gas treatment system
  - Development of sensors and instrumentation specific to gas-phase measurements
    - Sensors tested at ORNL salt loops
    - Improving measurement cells and instrumentation for improved signal and limits of detection (LOD)
      - New gas flow cell on order
      - Received and currently testing new Raman instrument
  - Building quantification/chemometric analysis tools for application across instrumentation and sensors
  - Papers, Presentations, Reports:
    - 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, 96 (18), 7220-7230. DOI: 10.1021/acs.analchem.4c00802.
    - Felmy H.M., R.M. Cox, A.F. Espley, E.L. Campbell, B.R. Kersten, H.E. Lackey, and S.D. Branch, et al. 06/24/2024. "Raman spectroscopic quantification of hydrogen isotopes using chemometric models applied across multiple systems." Presented by H.M. Felmy at ACS NORM, Pullman, Washington.
    - Felmy H.M., R.M. Cox, A.M. Lines, and S.A. Bryan. 2024. Demonstration of optical spectroscopic online monitoring for MSR off-gas treatment. PNNL-36645. Richland, WA: Pacific Northwest National Laboratory.



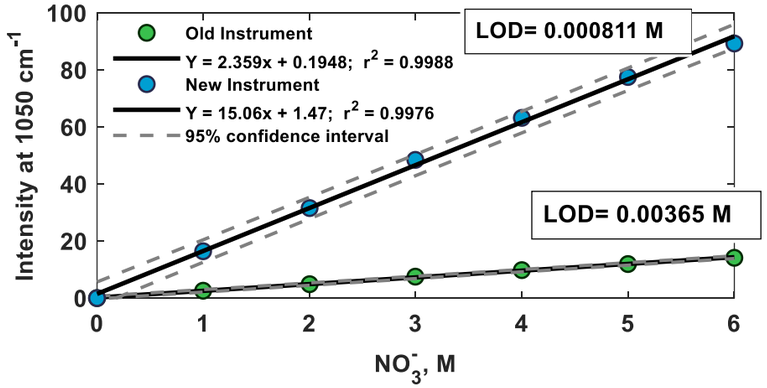
Improving Gas Cell Design



Sensor Testing at ORNL



Improving Instrumentation



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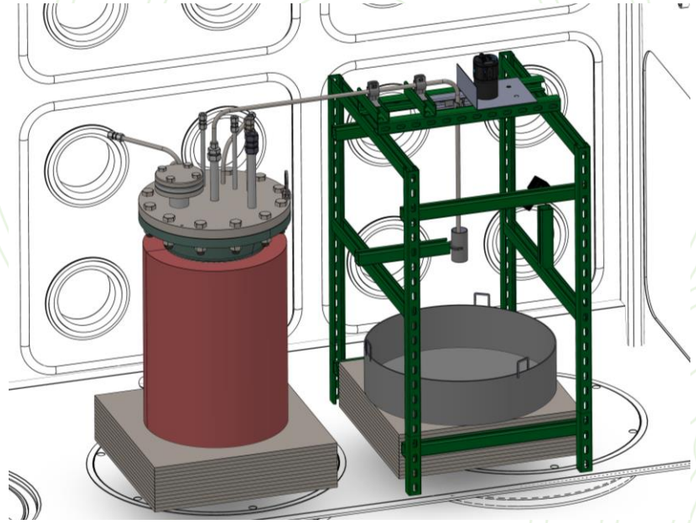
Argonne highlights

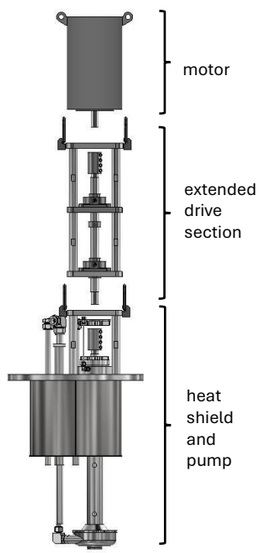
Salt Accident Analysis Facility

- Engineering-scale experimental test system for simulating molten salt release accidents
- Will provide data to support development and validation of MSR safety analysis models
- Status of facility and measurement development activities:
  - Completed preliminary facility design and initiated construction of molten salt transfer system
  - Developing method to measure real-time salt aerosol size distribution and concentration



Actinide Salt Loop

- Pumped, non-isothermal molten salt loop designed to enable practical testing of corrosion monitoring and control technologies using actinide-bearing fuel salts
- Status of facility and measurement development activities:
  - Pump has arrived on-site and assembly in radiological glovebox is proceeding as planned
  - Additional corrosion monitoring and control approaches have been developed at small scales for deployment in pumped loop

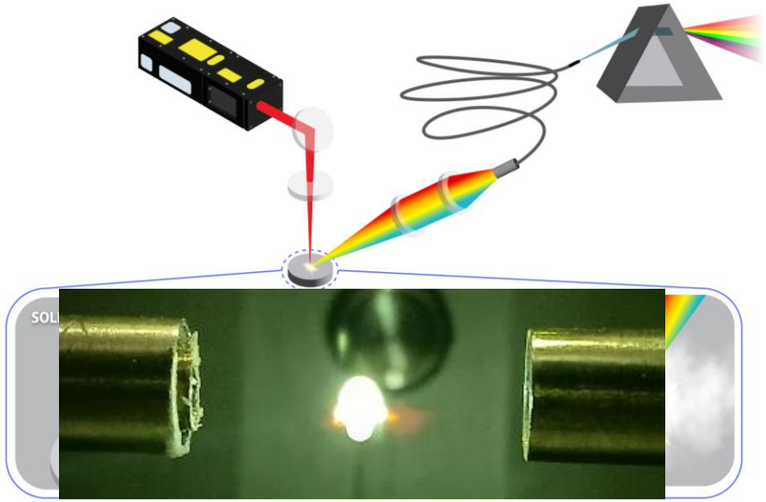


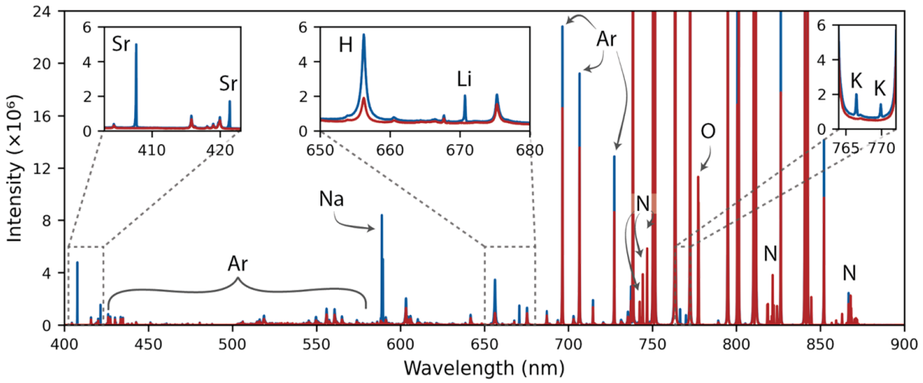
Contributors: Sara Thomas, Nora Shaheen, Nathaniel Hoyt

Sara Thomas, sathomas@anl.gov

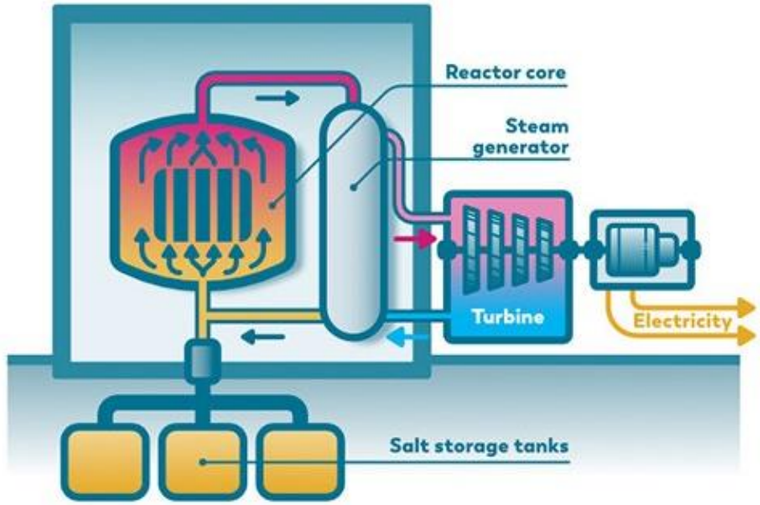
Using Lasers to Monitor Next-Gen Nuclear Reactors with Aerosol Sampling

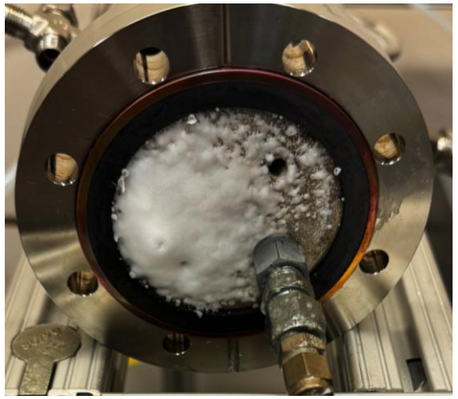
Laser-Induced Breakdown Spectroscopy (LIBS)



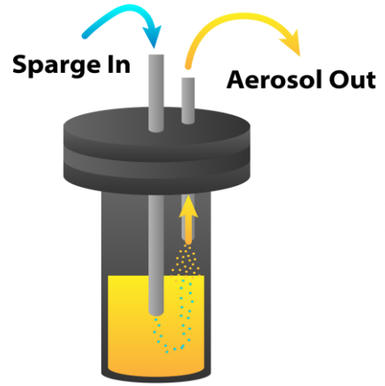


Molten Salt Reactors (MSR)

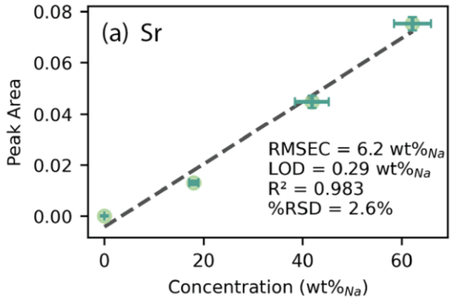




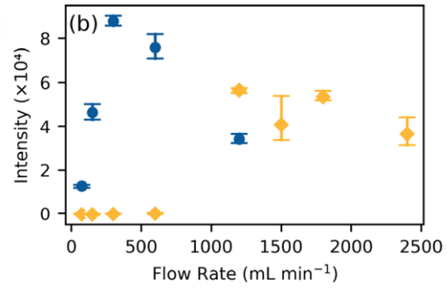
Aerosol Sampling



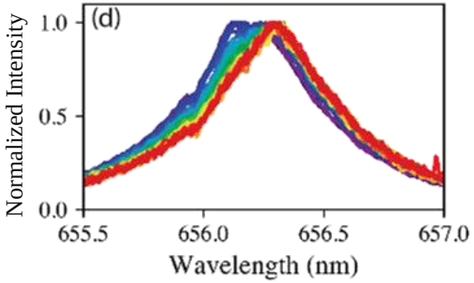
Low Detection Limits



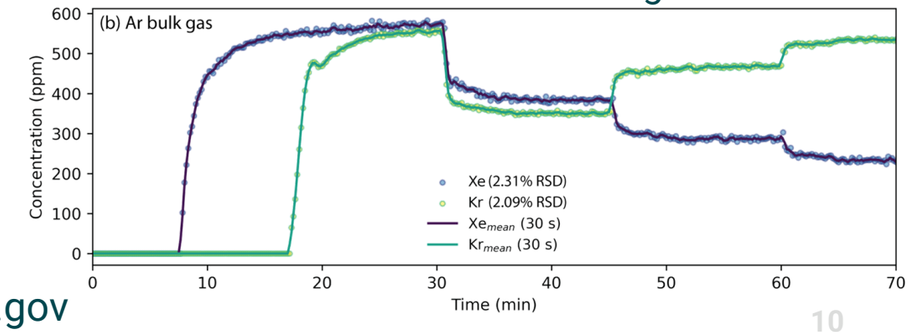
Low Flow = Less Sample



Isotope Shifts



Real-time Monitoring

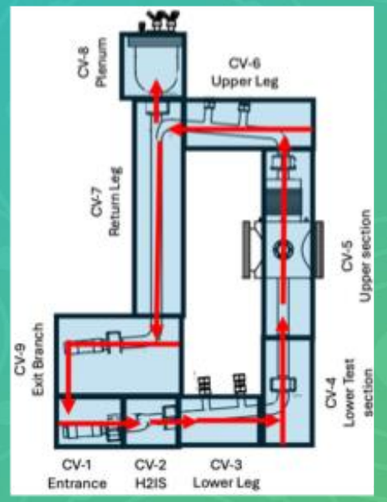


OAK RIDGE National Laboratory

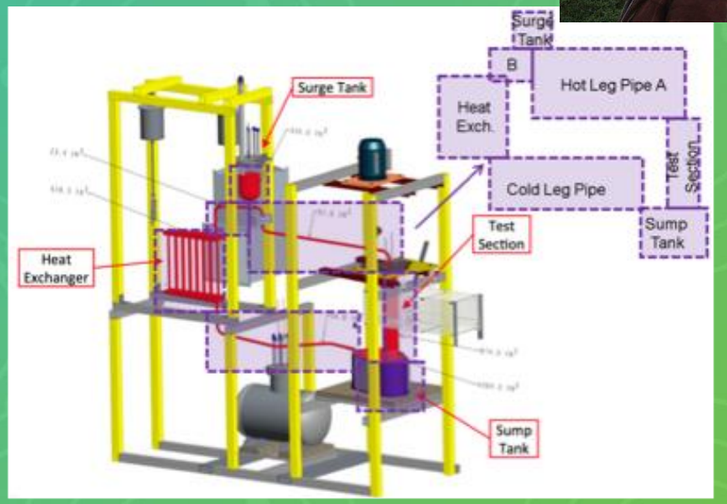
Z. Kitzhaber, kitzhaberzb@ornl.gov & H. Andrews, andrewshb@ornl.gov

MELCOR: Powerful Reactor Licensing Simulations on a Laptop

- **MELCOR can model multiple scales at the front and back end of the nuclear enterprise**
  - MSTTE (small test units)
  - LSTL (large test units)
  - MSRE (reactor plants)
  - SNF Pyroprocessing
  - SNF Canisters and transportation

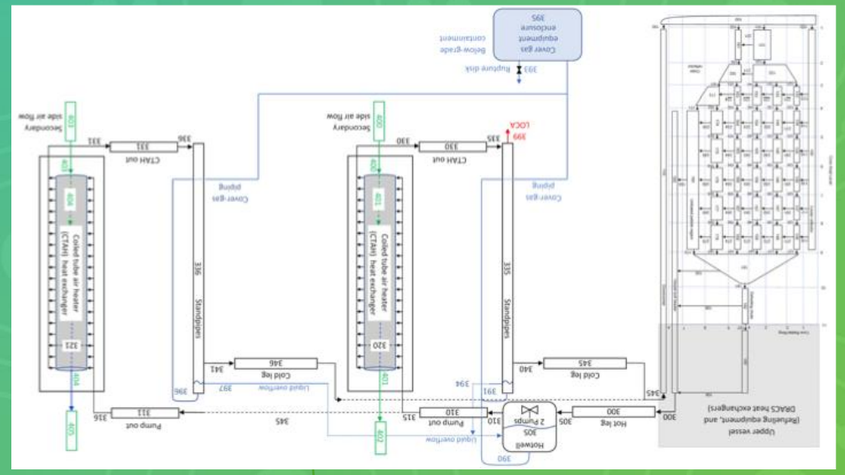


MSTTE MELCOR Model

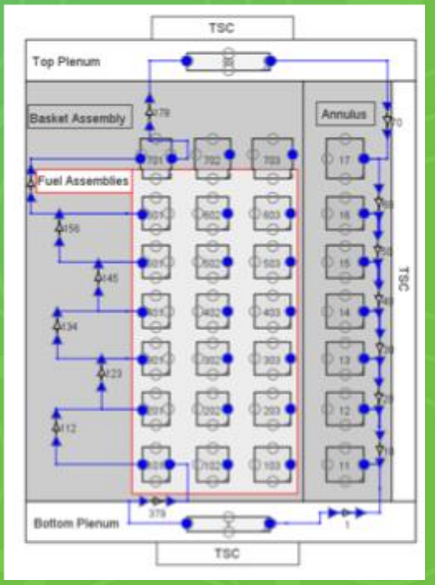


LSTL MELCOR Model

- **Software Architecture Modernization Effort**
  - Generalized models provide
    - Faster model implementation
    - Shared models between different applications
    - Applicability to non-nuclear processes
  - Future Python interface will allow users to use MELCOR data with external programs



MSRE MELCOR Model



SNF Canister

- **MSR Campaign is driving development for new approaches to chemistry and radionuclide transport**

Matthew Christian, mschris@sandia.gov, SNL
SAND-2024-13135

Reports and publications – INL, SNL, PNNL

INL

S. Thomas et al., “Method for Real-Time Salt Aerosol Concentration and Size Measurements for Molten Salt Reactor Safety Assessments”, ANL/CFCT-24/15, 09-17-2024 (2024).

T. Fuerst et al., “Experimental Design and Details of the Molten Salt Tritium Transport Experiment”, submitted Annals of Nuclear Energy (2025)

SNL

M. Christian et al., “A Road Map to Determine Chemical Phenomenology Required for Molten Salt Reactor Accident Modeling”, SAND-2024-13135 (2024)

PNNL

B.J. Riley et al., “Analytical capabilities for iodine detection: Review of possibilities for different applications”, AIP Advances, 14(8), (2024) 10.1063/5.0208591.

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, 96 (18), 7220-7230. DOI: 10.1021/acs.analchem.4c00802.

Felmy H.M., R.M. Cox, A.F. Espley, E.L. Campbell, B.R. Kersten, H.E. Lackey, and S.D. Branch, et al. 06/24/2024. "Raman spectroscopic quantification of hydrogen isotopes using chemometric models applied across multiple systems." Presented by H.M. Felmy at ACS NORM, Pullman, Washington.

Felmy H.M., R.M. Cox, A.M. Lines, and S.A. Bryan. 2024. Demonstration of optical spectroscopic online monitoring for MSR off-gas treatment. PNNL-36645. Richland, WA: Pacific Northwest National Laboratory.

Publications continued - ANL

S. Thomas (2025) “Preliminary Design of Engineering-Scale Salt Accident Analysis Facility to Support Molten Salt Reactor Licensing.” Argonne National Laboratory Report ANL/CFCT-25/1.

S. Thomas (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.

N. A. Shaheen, J. Guo, and N. C. Hoyt (2024) “Quantitative Correction of Ohmic Effects on Square Wave Voltammetry for High-Concentration Soluble-Soluble Redox Reactions in Molten Salts.” *J. Electrochem. Soc.*, 171,126502.

N. A. Shaheen, J. Guo, and N. C. Hoyt (2024) “Development and Assessment of Deployed Sensors and Technologies to Support Molten Salt Loop Operations.” Argonne National Laboratory Report ANL/CFCT-24/28.

N. A. Shaheen, J. Guo, and N. C. Hoyt (2024) “Quantification and correction of impedance effects on square wave voltammetry for high concentration soluble-soluble reactions.” ECS PRiME.

This work was conducted for US DOE Office of Nuclear Energy Advanced Reactor Technologies Molten Salt Reactors Campaign.

Work at Argonne National Laboratory is supported by the U.S. Department of Energy Office of Science under contract DE-AC02-06CH11357.

Publications continued - ORNL

D. Orea et al., “Optical measurements of gas bubble rise velocity in molten LiCl-KCl”, submitted to Nucl. Eng. & Design (2025)

H. Andrews, “Real-time monitoring of trace noble gases using LIBS- An investigation on the impact of bulk gas on plasma properties and sensitivity (2025), submitted to Spectrochimica Acta Part B: Atomic Spectroscopy.

Z. Kitzhaber, “Sparge sampling of molten salts for online monitoring via laser-induced breakdown spectroscopy”, submitted to Analytical Chemistry (2025)

K. Robb et al., “ Measurement of aerosols in the LSTL and FASTR off-gas systems”, ORNL/TM-2024/3728 (2024).

H. Andrews et al., “Real-time elemental and isotopic measurements of molten salt systems through laser induced breakdown spectroscopy, JACS, 147(1), 910-917, 2025, 10.1021/jacs.4c13684

J. Moon et al. “Density measurements of molten LiF-BeF_2 and LiF-BeF_2-LaF_3 salt mixtures by neutron radiography”, ACS Omega 6, (2024) 10.1021/acsomega.4c01446

Speaker line up for off-gas and radionuclide transport

Time	Title	Speaker/Lab
8:20-8:45	Salt Loop and Capability for Testing Sensors and Off Gas components	Kevin Robb/ORNL
8:45-9:10	Bubble Behavior in Molten Salts Relevant to MSRs	Daniel Orea/ORNL
9:10-9:35	Actinide Salt Loop and Sensors Development at ANL	Nathaniel Hoyt/ANL
9:35-10:00	On-line Monitoring for MSR Off-Gas Treatment: Molecular approach	Heather Felmy/PNNL
10:00-10:30	NETWORKING – MSR and the Fuel Cycle	Melissa Rose/ANL
10:30-10:55	Laser Induced Breakdown Spectroscopy (LIBS) for elemental monitoring of MSR off-gas streams	Hunter Andrews/ORNL
10:55-11:20	Update on Radiation Exposure Measurements of Metal Organic Framework at PNNL	Praveen Thallapally & Mark Murphy/PNNL
11:20-11:45	Experiment and Modeling Liquid Salt Test Loop LSTL	Kyoung Lee/Bob Salko /ORNL
11:45-12:10	Tritium Transport	Thomas Fuerst/INL
12:10-12:35	Argonne Engineering Scale Salt Accident Analysis Facility	Sara Thomas/ANL

Thank you

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Funding provided by the DOE-NE-5 Advanced Reactor Technology, Molten Salt Reactor Campaign