MSR Accident Testing Activities at Argonne

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MSR Campaign Review Meeting
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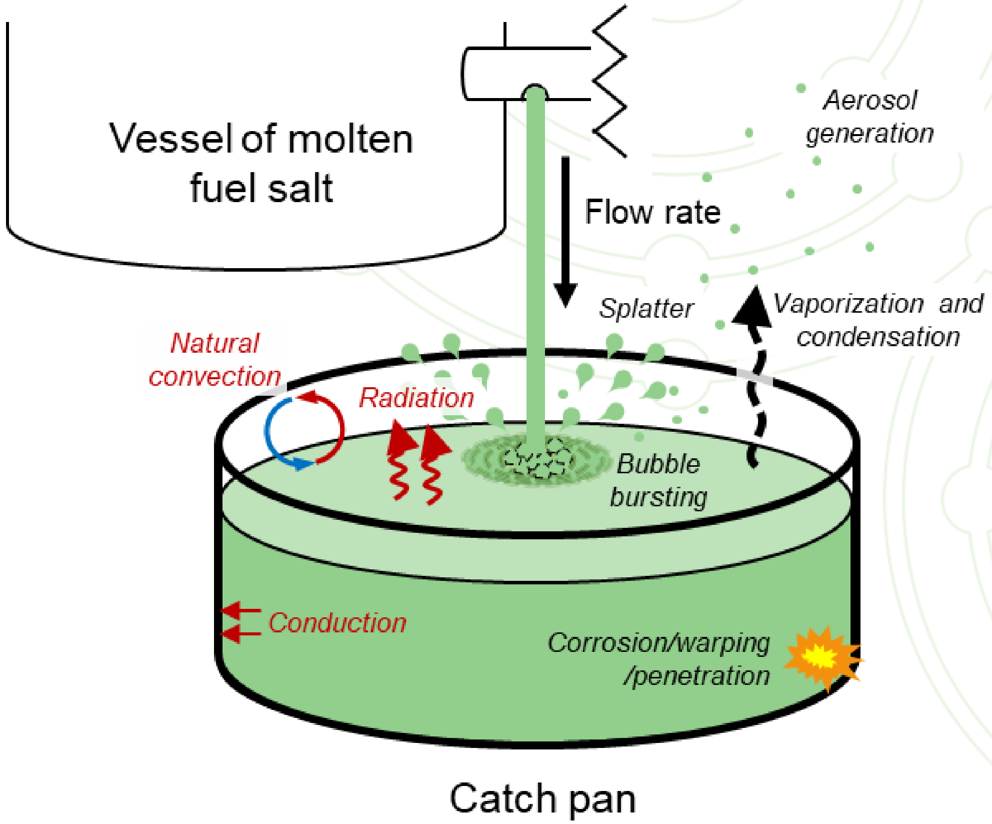
Advanced reactor licensing and accident analysis

- 10 CFR Part 53 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 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



OBJECTIVE

Generate experimental data that quantify the consequences of fuel salt release accidents to support the development and validation of MSR accident analysis models

Argonne approach to MSR accident testing

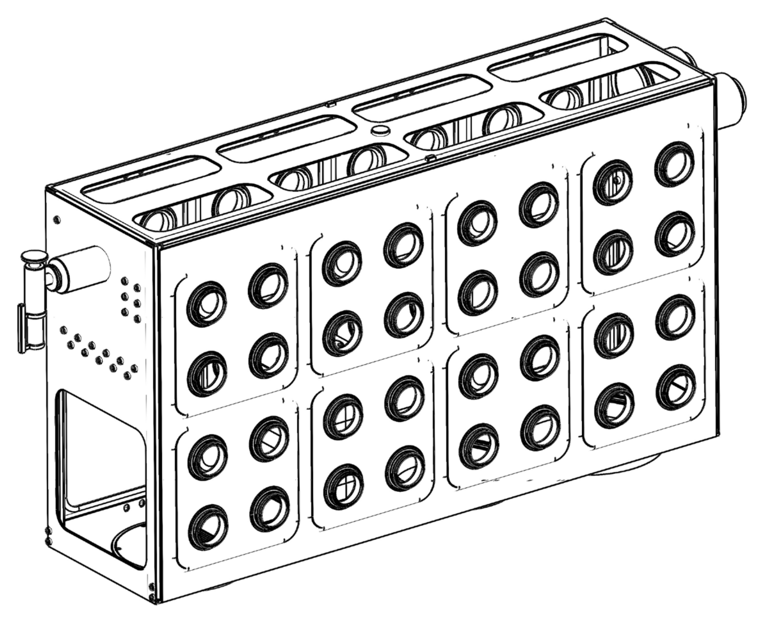
Laboratory-scale testing and development

Phase 1 → Conduct separate effects tests
- Develop methods to simulate processes
- Develop measurement techniques
- Fill data gaps in process models

Phase 2 → Conduct integral effects tests
- Gain experience with surrogate fuel salt and measuring processes simultaneously
- Fill data gaps in process models

Phase 3 → Design and construct engineering-scale test system

Engineering-scale testing



Argonne approach to MSR accident testing

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Past and current activities

- Developed methods to simulate:
  - Molten salt spill into catch pan[1,3,6]
  - Salt aerosol formation by different mechanisms[7,8]
- Developed techniques to quantify:
  - Molten salt spreading[1-4]
  - Heat transfer of spilled molten salt pools[3,5]
  - Salt aerosol particle characteristics[6,7,8]
- Initiated design and construction of engineering-scale test system[9]

Note: citations are listed on bibliography slide at end of presentation

Argonne approach to MSR accident testing

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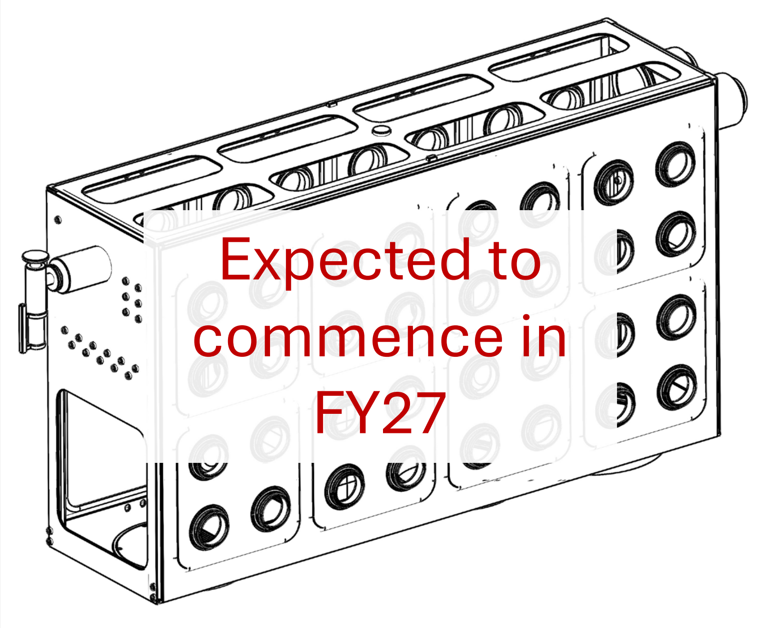
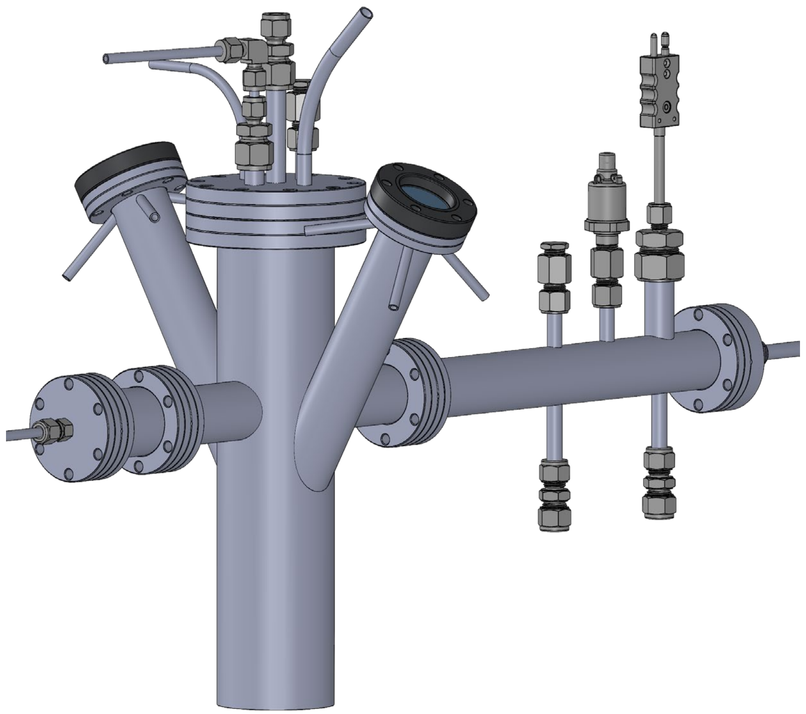
Engineering-scale testing



Overview of FY26 work scope

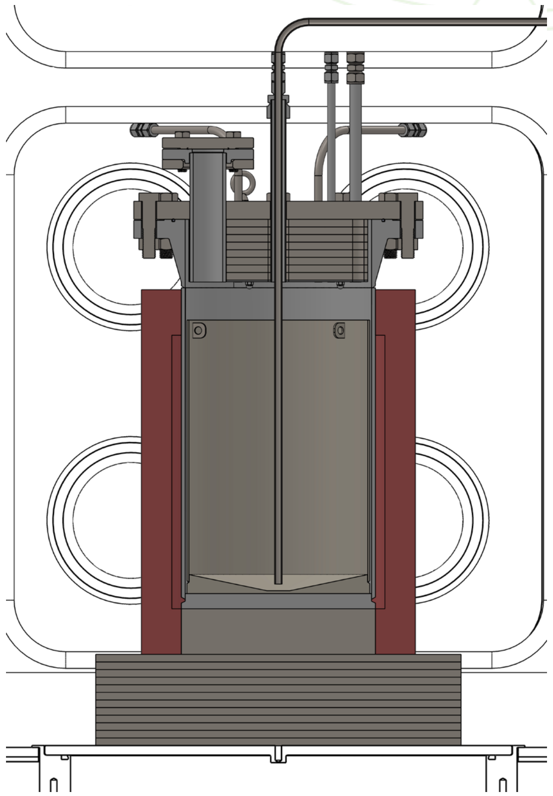
1 Salt aerosol separate effects testing

Scope: Quantify the effects of molten salt temperature, composition, and formation mechanism on salt aerosol characteristics



2 Engineering-scale test system

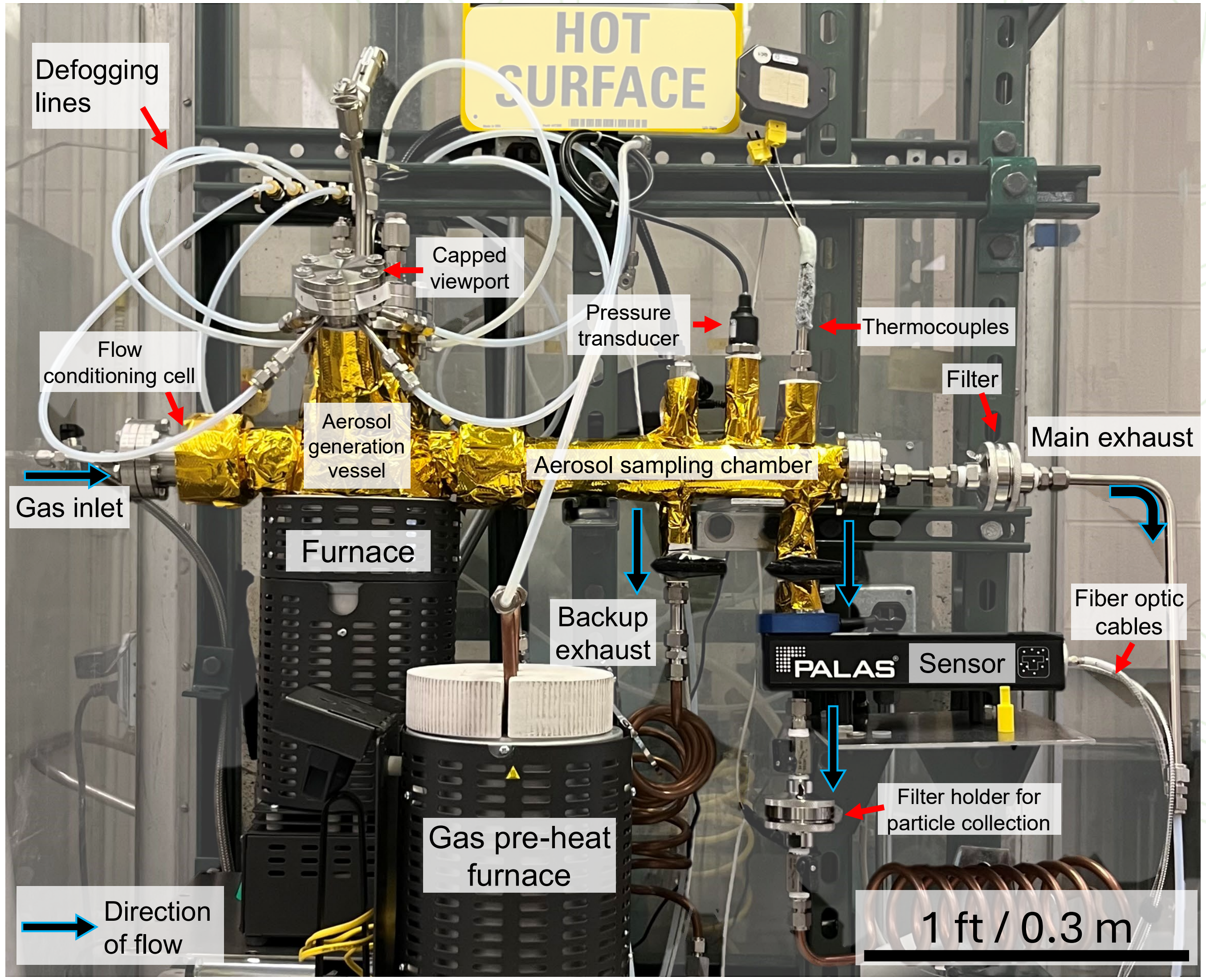
Scope: Procure and demonstrate components of the Salt Accident Analysis Facility



Argonne test stand for real-time salt aerosol characterization

Aerosol definition: solid or liquid suspended in a gas

- Addresses key data gaps, enables systematic and controlled testing, and enables method validation prior to use in engineering-scale tests
- Generates and characterizes salt aerosols in real-time
  - Real-time size distribution and concentration
  - Bulk elemental composition of particles collected on filters
  - Elemental composition of single particles
- Withstands corrosive and high temperature gas streams and maintains measurement accuracy over a range of gas compositions and temperatures



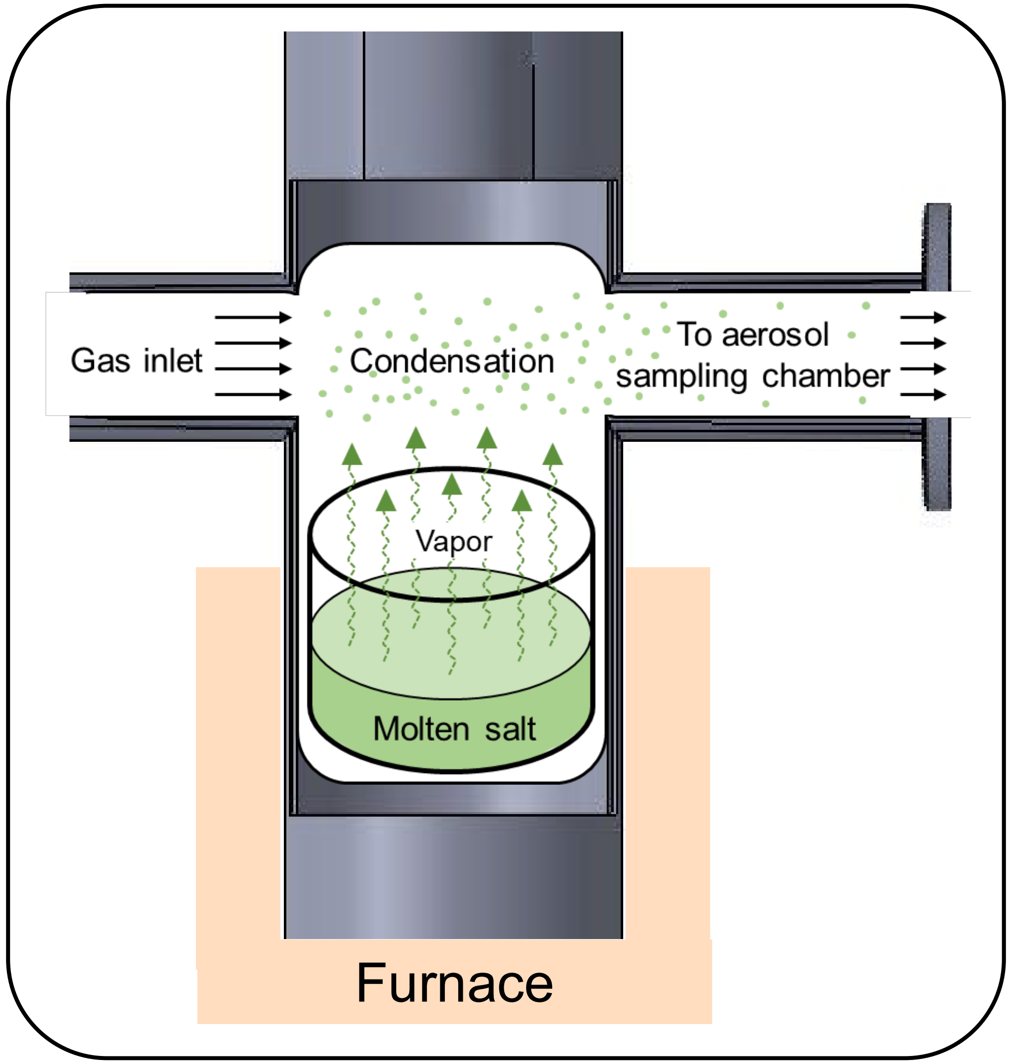
Thomas, S. (2024) "Method for Real-Time Salt Aerosol Concentration and Size Measurements for Molten Salt Reactor Safety Assessments." Argonne National Laboratory Report ANL/CFCT-24/25.

Thomas, S. and O'Brien, A. (2025) "Real-Time Characterization of Salt Aerosols Generated from Static and Sparged Molten Salts." Argonne National Laboratory Report ANL/CFCT-25/18.

Salt aerosol formation in test stand by different mechanisms

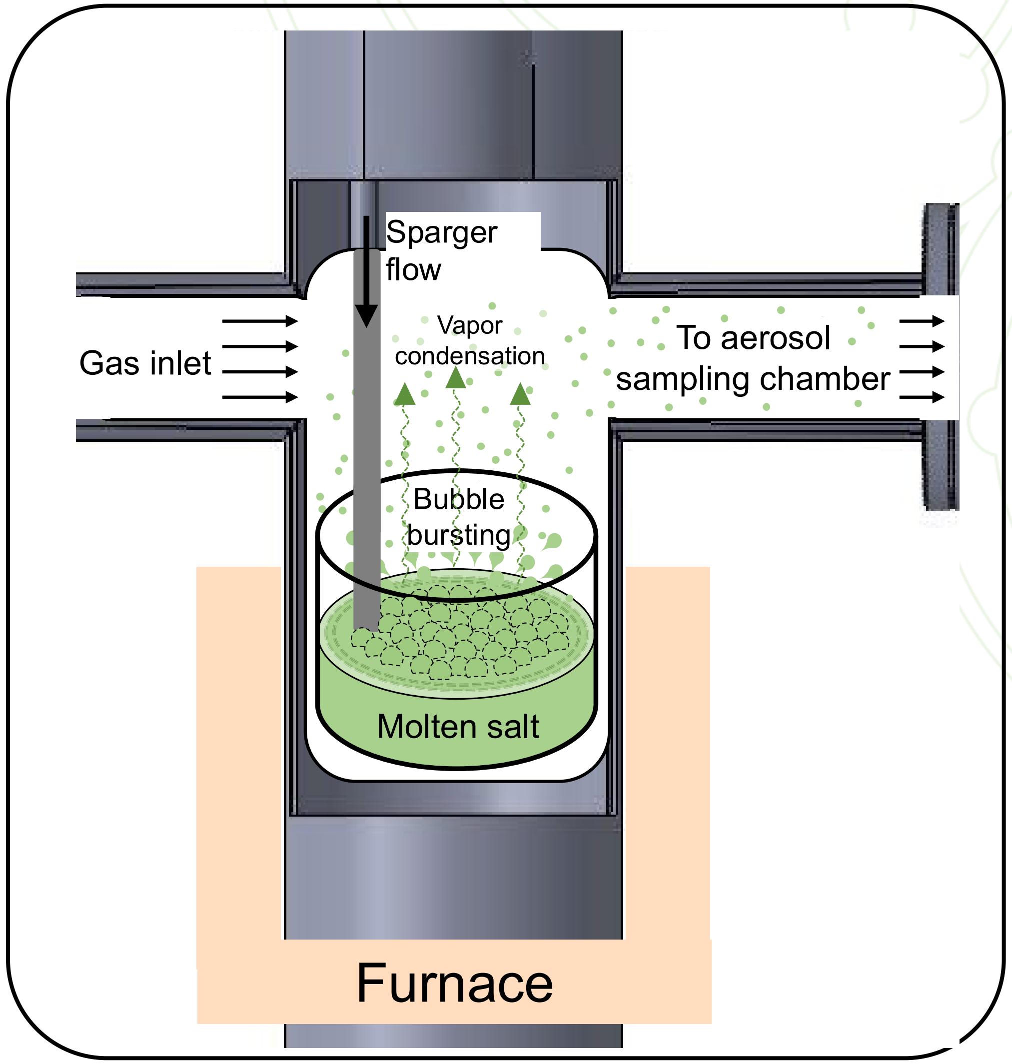
Aerosol formation from static salt

✓ Vapor condensation



Aerosol formation from sparged salt

✓ Vapor condensation ✓ Bubble bursting



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Overview of FY25 results

Objective: To quantify the size and concentration of salt aerosol particles generated from static and sparged molten salt

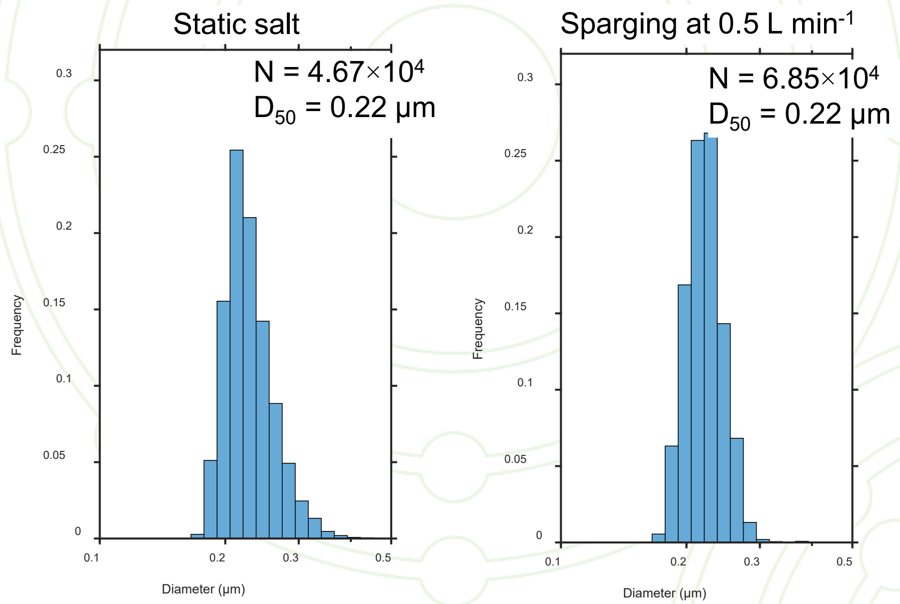
Salt composition: eutectic LiCl-KCl (melting point: 352 °C)

Sparge gas: pre-heated ultra-high purity argon

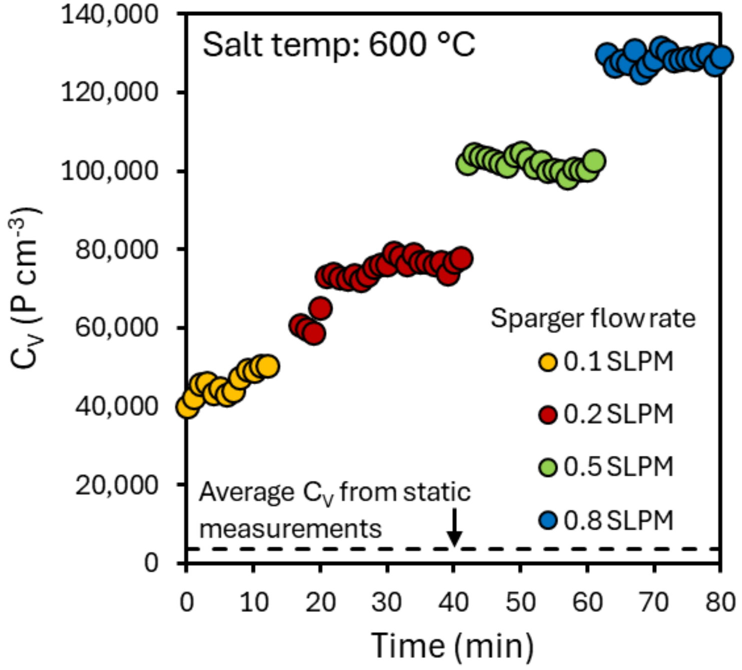
Main findings:

- Sparging had no effect on measured salt aerosol particle size distributions
- Particles with effective diameters greater than 0.5 μm were not detected by sensor
- Sparging yielded significantly higher aerosol concentration

Particle size distribution (salt temp: 600 °C)



Particle concentration



Views of molten salt surface through viewport

Static salt

Sparging salt at 0.5 L min^{-1}

FY26 salt aerosol experimental plan

Objective: To quantify the real-time size and concentration and post-test elemental composition of salt aerosol particles generated from static and sparged molten salt doped with surrogate fission products

Salt composition: eutectic LiCl-KCl doped with surrogate fission products

Sparge gas: pre-heated ultra-high purity argon

Test matrix:

	Gas sparge rate (L min^{-1})			
Temperature	0 (static)	0.2	0.5	0.8
500 °C	✓	✓	✓	✓
600 °C	✓	✓	✓	✓

Measurements:

Salt aerosols

Real-time particle size distribution and concentration using optical light scattering sensor

Post-test analyses of particles collected downstream:

- Bulk elemental composition (ICP-MS)
- Elemental composition of select particles (SEM-EDS)

Salt

Bulk elemental composition of salt samples before and after testing (ICP-MS)

Gas

Temperature and pressure of gas in aerosol sampling chamber just upstream of aerosol sensor

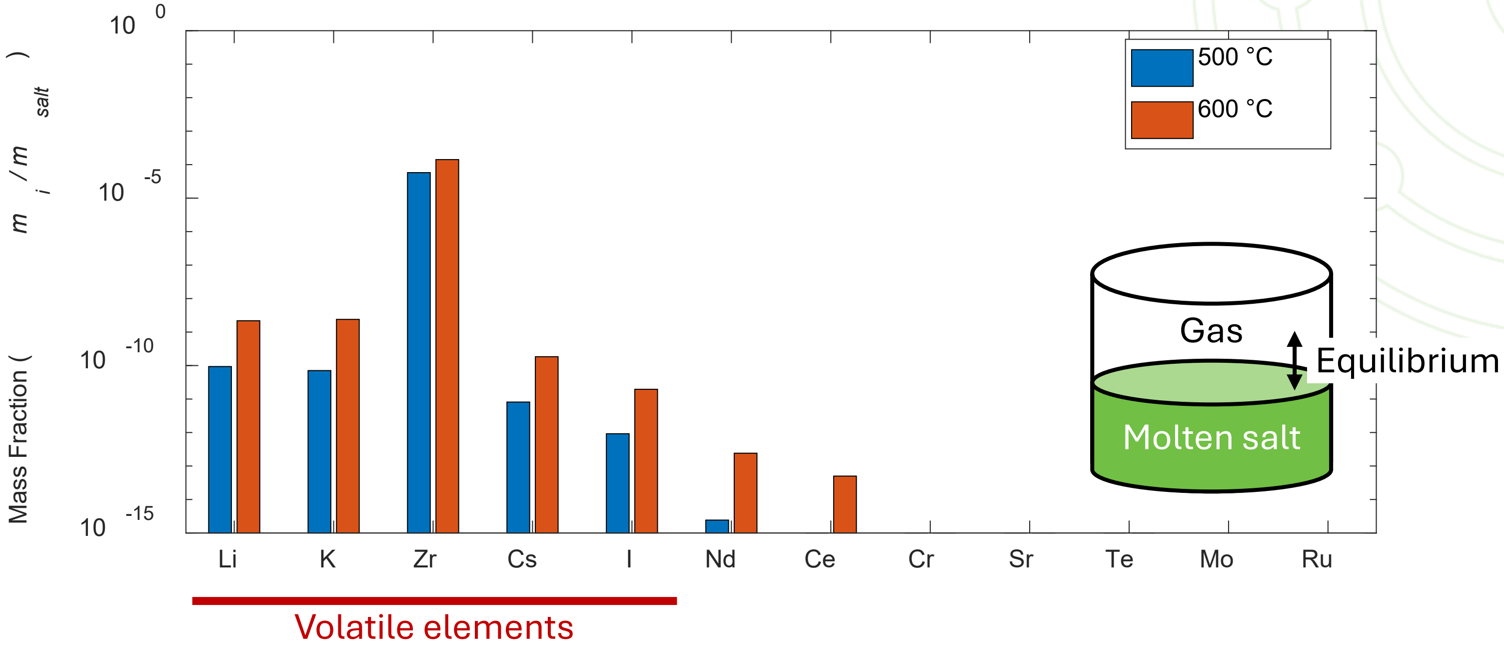
Salt composition

- Compositions were inspired by depletion calculations for MSRs (McMurray et al., 2021), selected to provide insight on aerosol formation mechanism, and simplified by selecting surrogate fission products to represent those with similar expected behavior
- Salt aerosol particle composition will indicate chemical versus mechanical formation pathways
  - Vapor pressure correlation → vapor condensation mechanism
  - Bulk salt composition correlation → bubble bursting mechanism
- Thermodynamic calculations were performed to evaluate partitioning of elements among gas, liquid, and solid phases

Component	Concentration (mole %)
$(LiCl\text{-}KCl)_{eut}$	99.08
$NdCl_3$	0.1
$CeCl_3$	0.1
CsCl	0.1
CsI	0.01
$SrCl_2$	0.1
$CrCl_2$	0.1
Mo[a]	0.1
Ru[a]	0.1
Te[a]	0.01
Zr[b]	0.2

[a] added as metallic powder. [b] added as thin wire

Calculated mass fraction of gas species per initial mass of salt in system



McMurray, J. et al., (2021) "Roadmap for Thermal Property Measurements of Molten Salt Reactor Systems." Oak Ridge National Laboratory Report ORNL/SPR-2020/1865.

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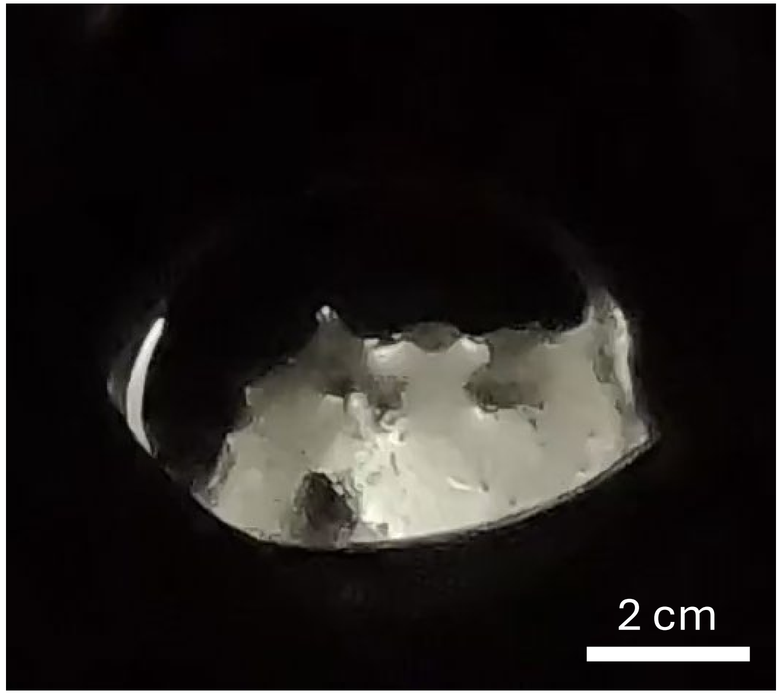
Results – static salt

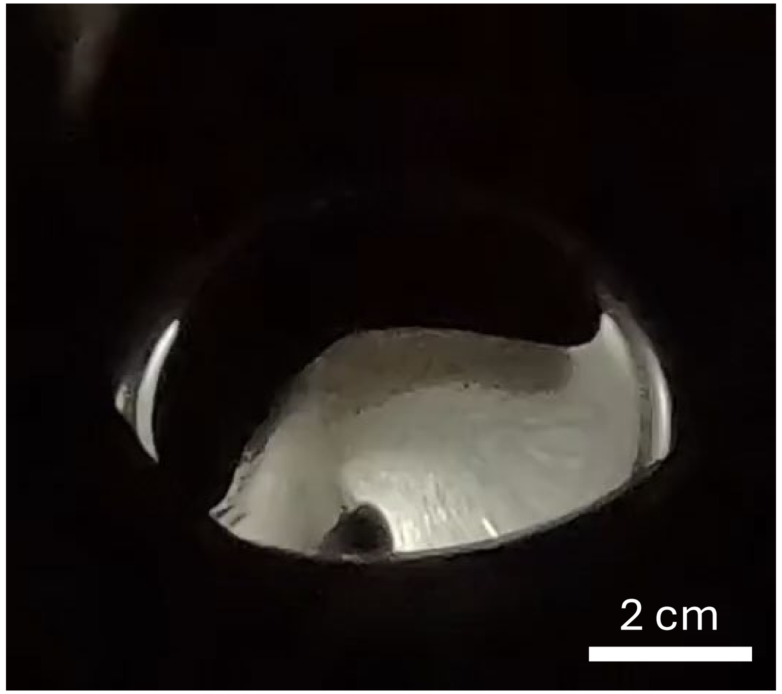
- Observed thin layer of material floating on salt surface at 500 °C
- Particles were not detected by aerosol sensor from static salt at either temperature
- Particles on downstream collection filter were detected by SEM and analyzed for elemental composition using EDS

Views of molten salt surface through viewport

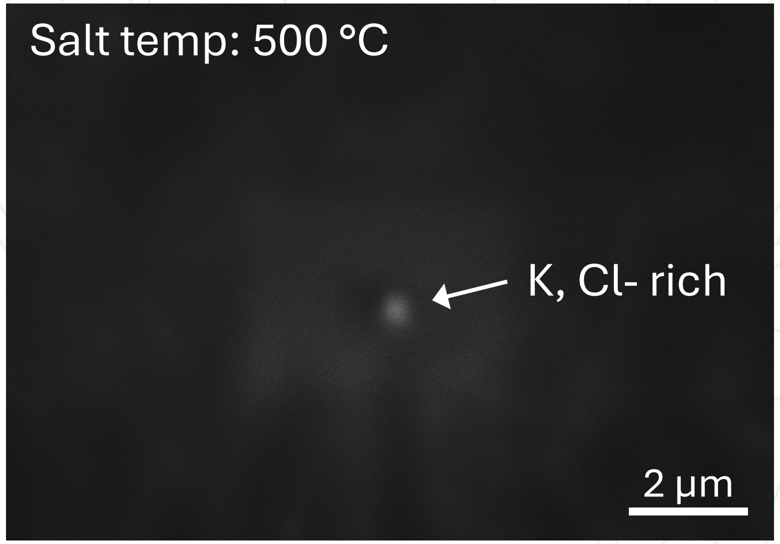
Salt temp: 500 °C

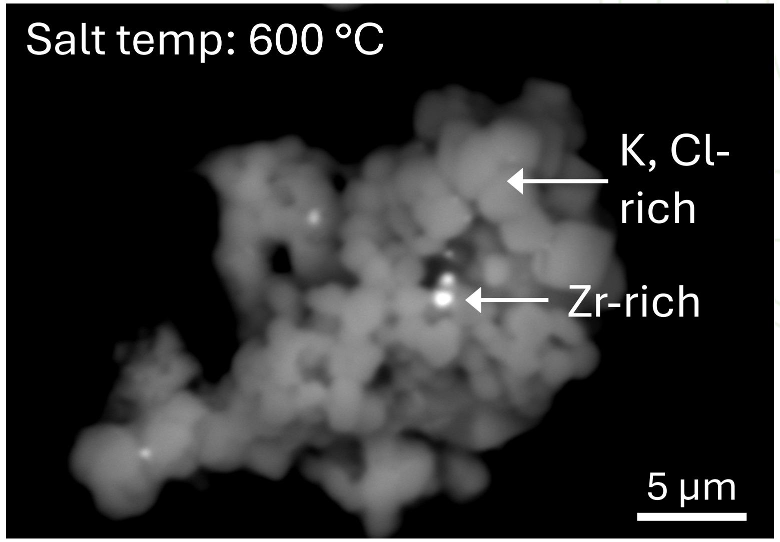


Salt temp: 600 °C



Backscattered electron micrographs of collected particles*





*Particle clustering and growth may occur during sampling and may not be representative of airborne characteristics

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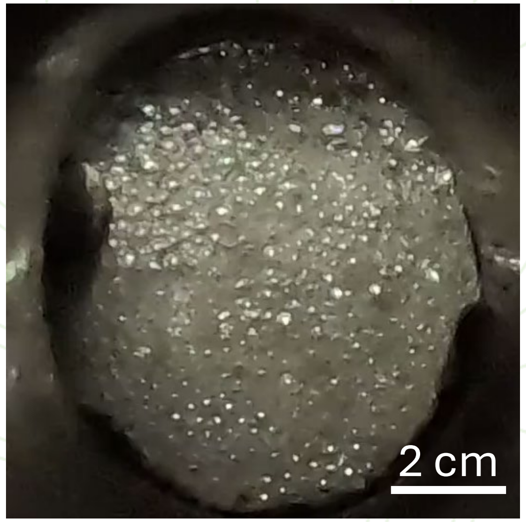
Results – sparged salt at 500 °C

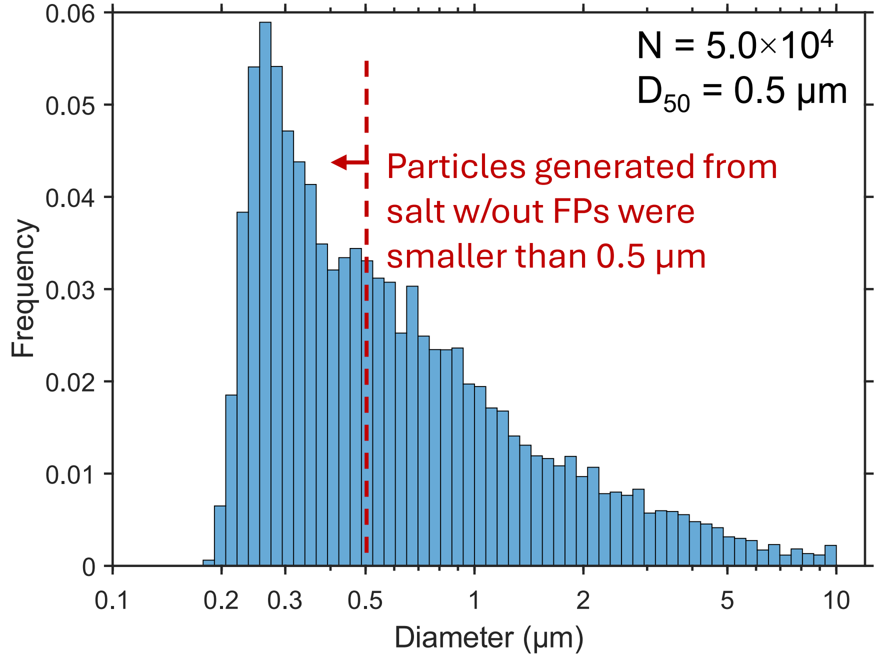
- Sparging salt at 500 °C produced foam at salt surface
  - Surrogate fission products act as surfactant to lower surface tension and stabilize bubbles (longer lifetime, smaller size)
  - Testing at 0.5 L min^{-1} and 0.8 L min^{-1} was not possible due to significant amount of foam
- Particle size distributions were markedly different compared to salt without surrogate fission products (FPs) under same conditions
- Particles on downstream collection filter appear as spherical clusters in SEM micrographs
- Significant quantity of Zr-rich regions detected with EDS

View of molten salt surface through viewport

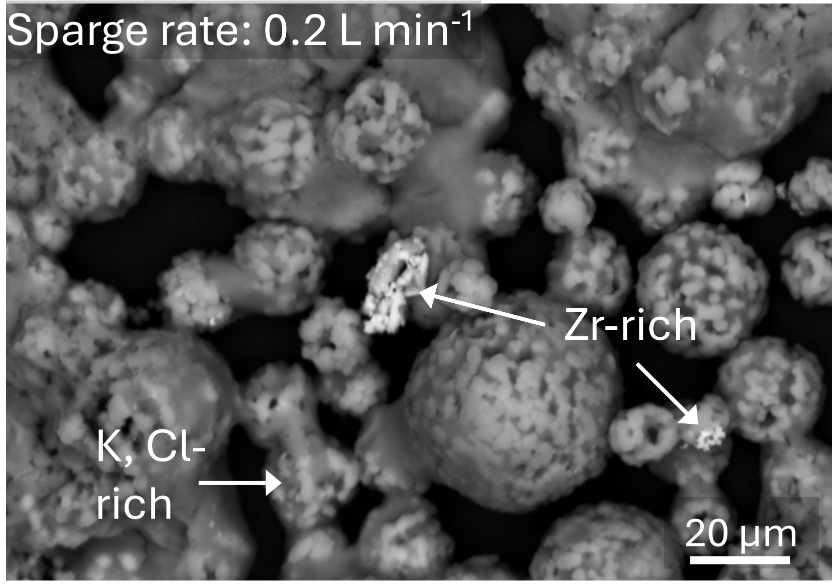
Sparging salt at 0.2 L min^{-1}



Particle size distribution



Backscattered electron micrograph of collected particles



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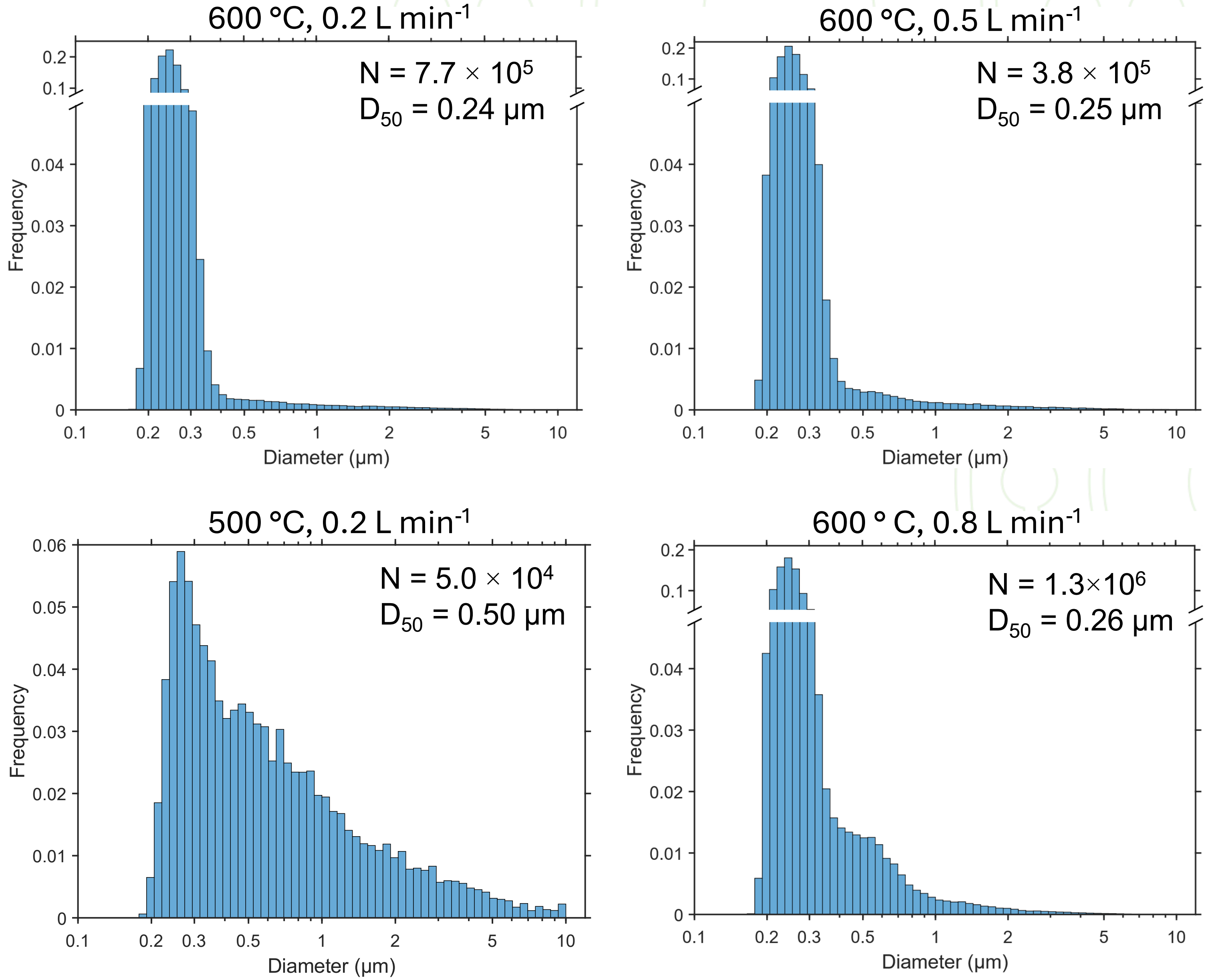
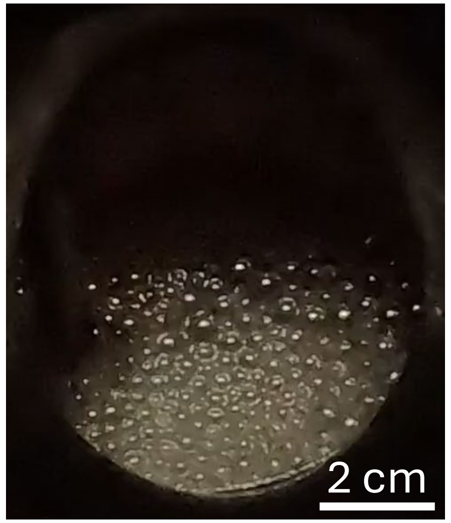
Results – sparged salt at 600 °C

- Sparging at 600 °C produced larger, shorter-lived bubbles than at 500 °C (no foam)
- Particle size distributions were bimodal
  - Median diameter (D_{50}) comparable to that measured in tests without surrogate FPs under same conditions
  - Higher sparge flow rates produced larger salt aerosol particles
- Particle clusters observed in SEM micrographs are not spherical like those from salt sparged at 0.2 L min^{-1}

Particle size distributions



Sparging salt at 0.2 L min^{-1}



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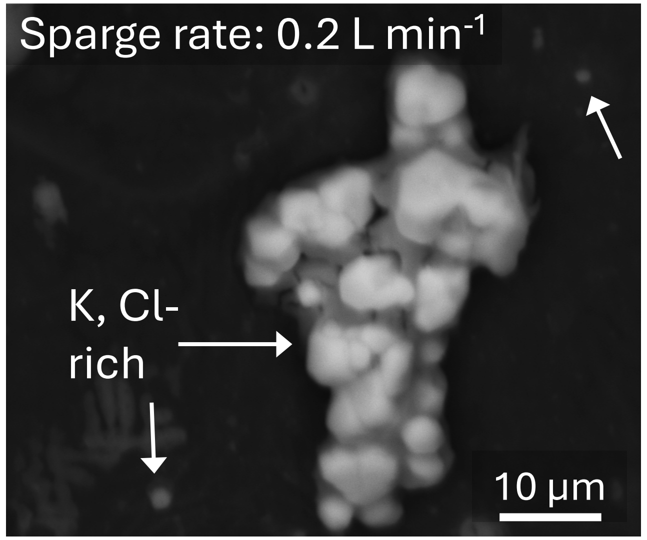


Salt aerosol testing: FY26 accomplishments, milestones, and future work

Accomplishments		Status
1	Conduct salt aerosol testing using salt doped with surrogate fission products	Complete
2	Analyze collected samples and measured data from salt aerosol testing	In progress

Milestone Number	Title	Due
M3AT-26AN0702034	Complete tests on salt aerosol formation from molten salts bearing surrogate fission products	6/30/26 *on schedule*

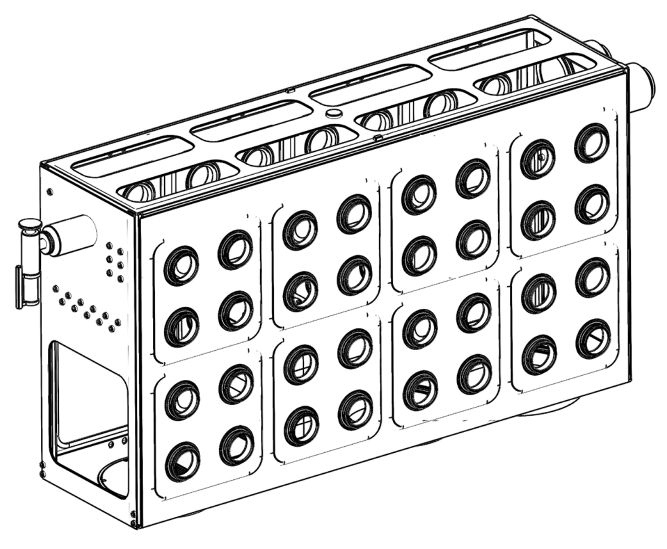
Future work

- Conduct additional separate effects tests on aerosol formation to generate experimental data that can be used to parameterize process models on aerosol formation, e.g.:
  - Characterize material observed to be floating on surface of eutectic LiCl-KCl at 500 °C (i.e., the surfactant)
  - Test fluoride salt compositions
  - Test effect of presence of humidity and oxygen in atmosphere
- Advance particle characterization capabilities
  - Combine optical light scattering sensor with LIBS to obtain size, concentration, and composition in real-time
  - Assess improved particle collection and preparation methods, enhanced imaging techniques, and approaches for determining speciation (μ-XANES)

Need for engineering-scale MSR accident simulation and analysis capability

- Accident analysis models must be validated using experimental data generated at relevant scales
- Some safety-affecting behaviors associated with fuel salt release accidents may only manifest at large scales

Engineering-scale test facility design criteria



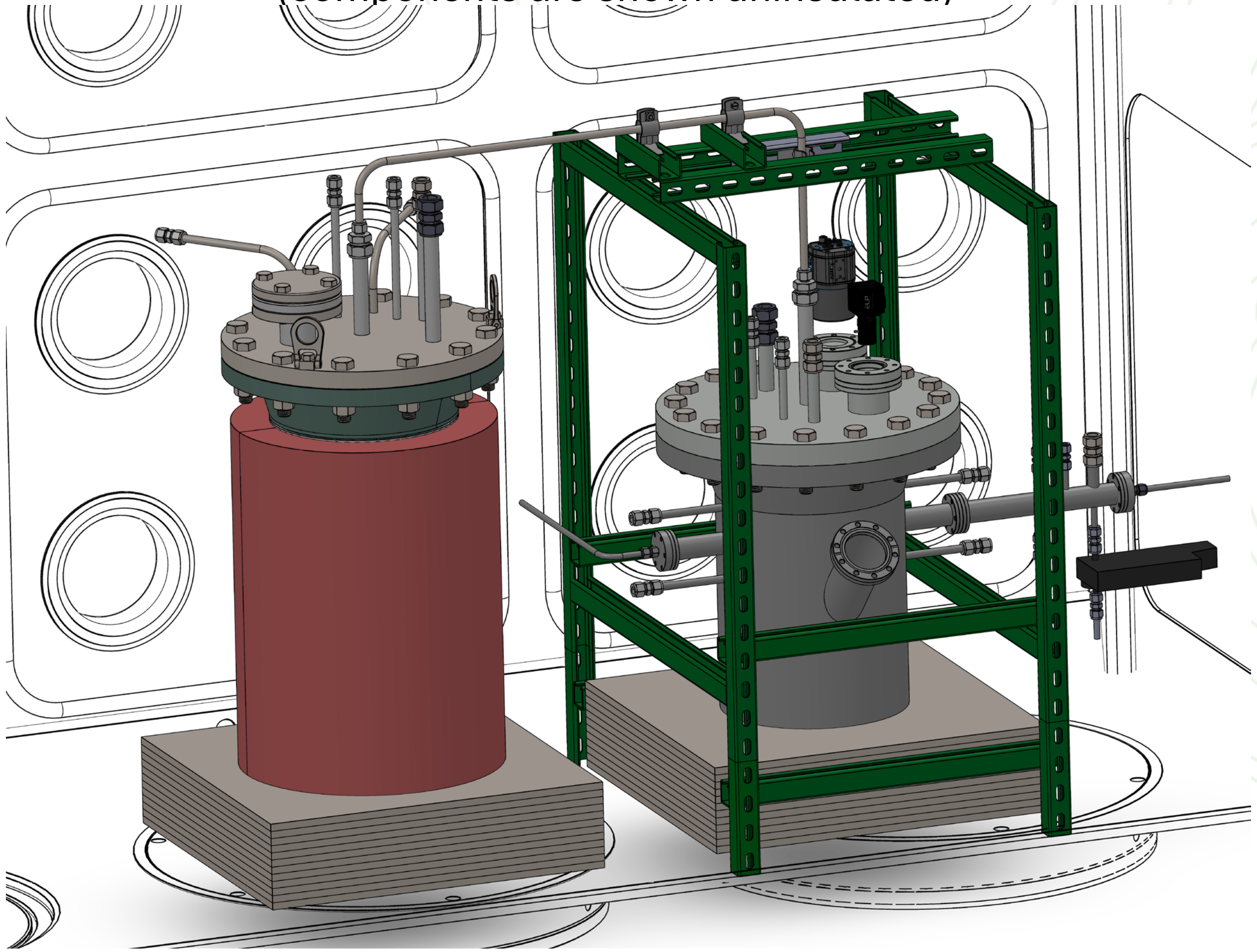
- Optimal scale
  - Large enough to represent key behaviors
  - Small enough to fit in existing glovebox facilities (minimize cost) and to minimize waste generation
- Versatile
  - Able to test a range of accident scenarios
  - Compatible with chloride and fluoride salts
- Real-time measurement of processes

Overview of Salt Accident Analysis Facility

- The Salt Accident Analysis Facility (SAAF, pronounced "safe") is an engineering-scale experimental test system for simulating molten salt release accidents
- Located within an argon atmosphere glovebox
- Consists of two subsystems:

Molten salt transfer system	Salt containment system
• Consists of vessel, heaters, and molten salt transfer line • Heats salt to desired temperature • Transfers molten salt through tubing by pressurizing vessel headspace	• Adaptable • Stakeholders and target accident scenario dictate design, e.g.: – Catch pan open to glovebox atmosphere – Closed vessel isolated from glovebox atmosphere

SAAF configuration with **closed containment vessel**
(components are shown uninsulated)



Molten salt transfer system	Salt containment system

Test variables and measurement capabilities

Test variables

- Salt composition
  - Chloride and fluoride salts bearing actinides and surrogate fission products
- Composition of atmosphere
  - Inert atmosphere
  - Air atmosphere (isolated from glovebox atmosphere)
- Salt release conditions, e.g.,
  - Rapid release of large salt volume
  - Slow release of salt (i.e., drips)
  - Salt release as a spray through a small orifice
- Containment configuration and materials, e.g.,
  - Size, geometry, and material of catch pan
  - Type, thickness, and location of insulation
- Additional variables can be considered, e.g.,
  - Entrained gas bubbles in salt prior to release
  - Salt leaking through insulation

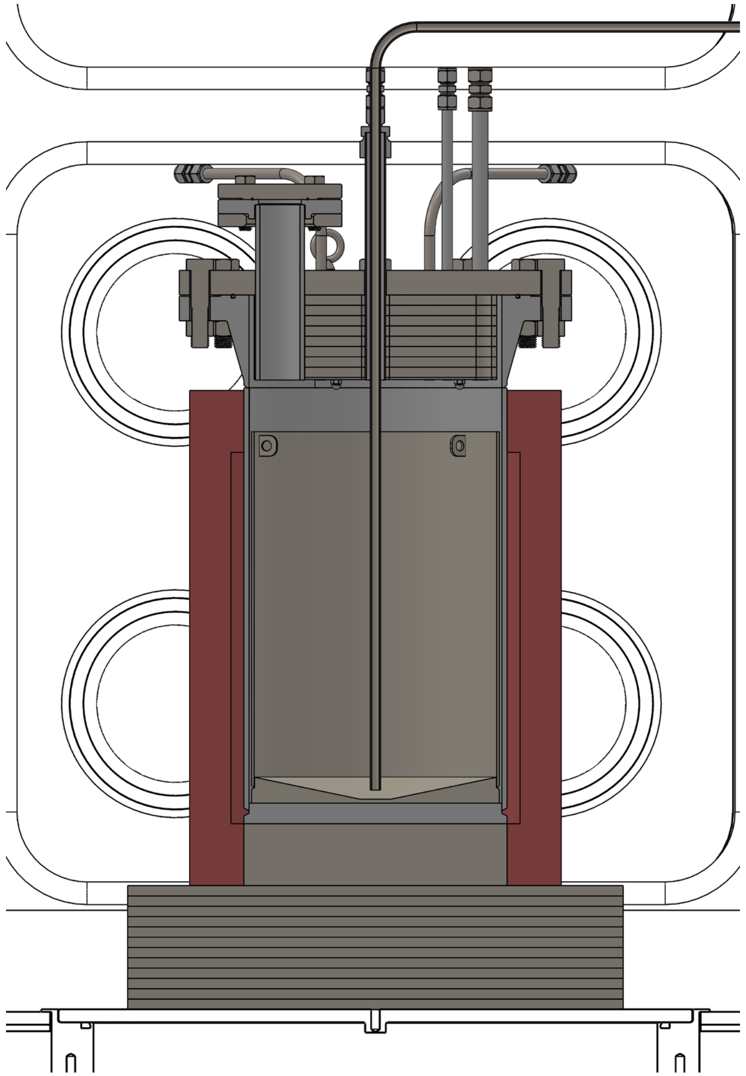
Measurement capabilities

- ✔ Leading edge and area measurements to quantify molten salt spreading by using an infrared camera
- ✔ Temperature measurements to quantify heat transfer
- ✔ Size distribution and composition of salt splatter collected on coupons
- ✔ Elemental composition and distribution in bulk salt from samples collected after testing
- ⟳ Real-time salt aerosol measurements
- ✖ Real-time composition of gas headspace

Legend: ✔ Developed; ⟳ Under development; ✖ Requires development

Molten salt transfer system

Section view
(components are shown uninsulated)

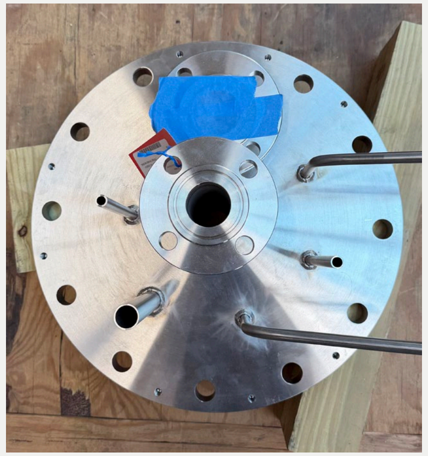


DESIGN SPECIFICATIONS

ASME-stamped pressure vessel
Material: 316 stainless steel
Salt volume capacity: 15 L
Maximum operating temp.: 800 °C
Nickel 201 liner

- Velocity and flow rate at transfer line outlet determined by:
  - Initial headspace pressure
  - Initial salt level in vessel
  - Transfer tube inner diameter
  - Vertical position of transfer line outlet
- Expect to receive vessel May 2026

Photos of vessel base and lid at machine shop (April 2026)



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SAAF: FY26 accomplishments, milestones, and future work

Accomplishments		Status
1	Receive molten salt transfer vessel from vendor	In progress *May 2026*
2	Receive custom crucibles and insulation and build controller for heaters	In progress
3	Demonstrate molten salt transfer mechanism using standard fluid	In progress

Milestone Number	Title	Due
M3AT-26AN0702032	Complete procurement of key components and demonstration of molten salt transfer vessel	9/25/26 *on schedule*

Future work

- Install molten salt transfer system in glovebox
- Prioritize accident scenarios to simulate in facility
- Identify surrogate fuel salt compositions to test
- Design and construct initial variation of salt containment system
- Simulate and assess accident scenarios using facility (install additional variations of salt containment system as needed)

Thank you

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