Molten Salt Reactor
PROGRAM

Optical Measurements of Gas Bubble Rise Velocity and Aerosols in Molten Salt

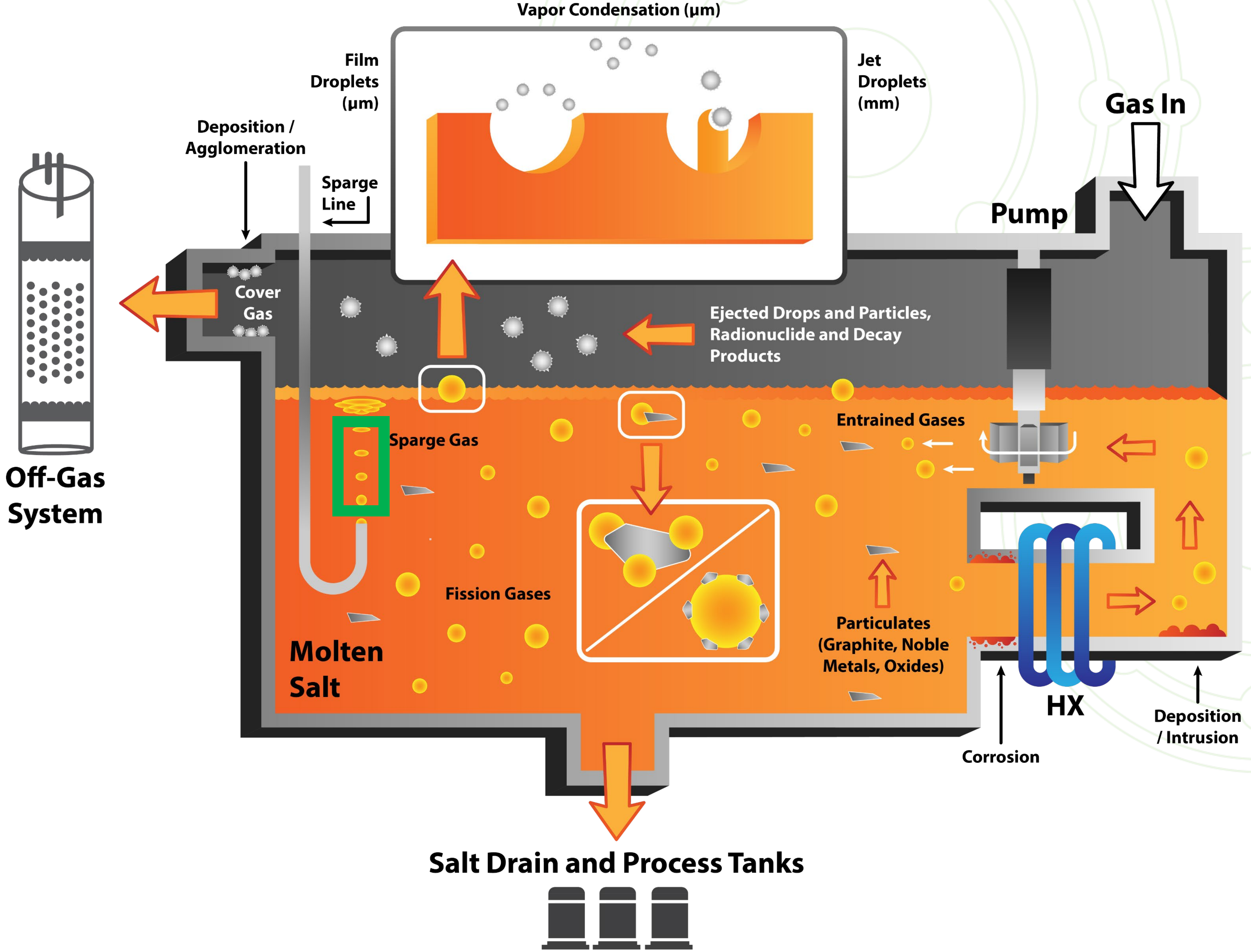
Daniel Orea, Kevin Robb, Joanna McFarlane, Hunter Andrews, Zechariah Kitzhaber

Oak Ridge National Laboratory

Argonne National Laboratory | INL Idaho National Laboratory | Lawrence Livermore 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

MSR Gas and Particle Transport Phenomena

- The gas, particle behavior and gas-particle interactions are complex phenomena
- Experimental measurements in prototypic environments require careful planning



Molten Salt Reactor PROGRAM

U.S. DEPARTMENT of ENERGY
Office of Nuclear Energy

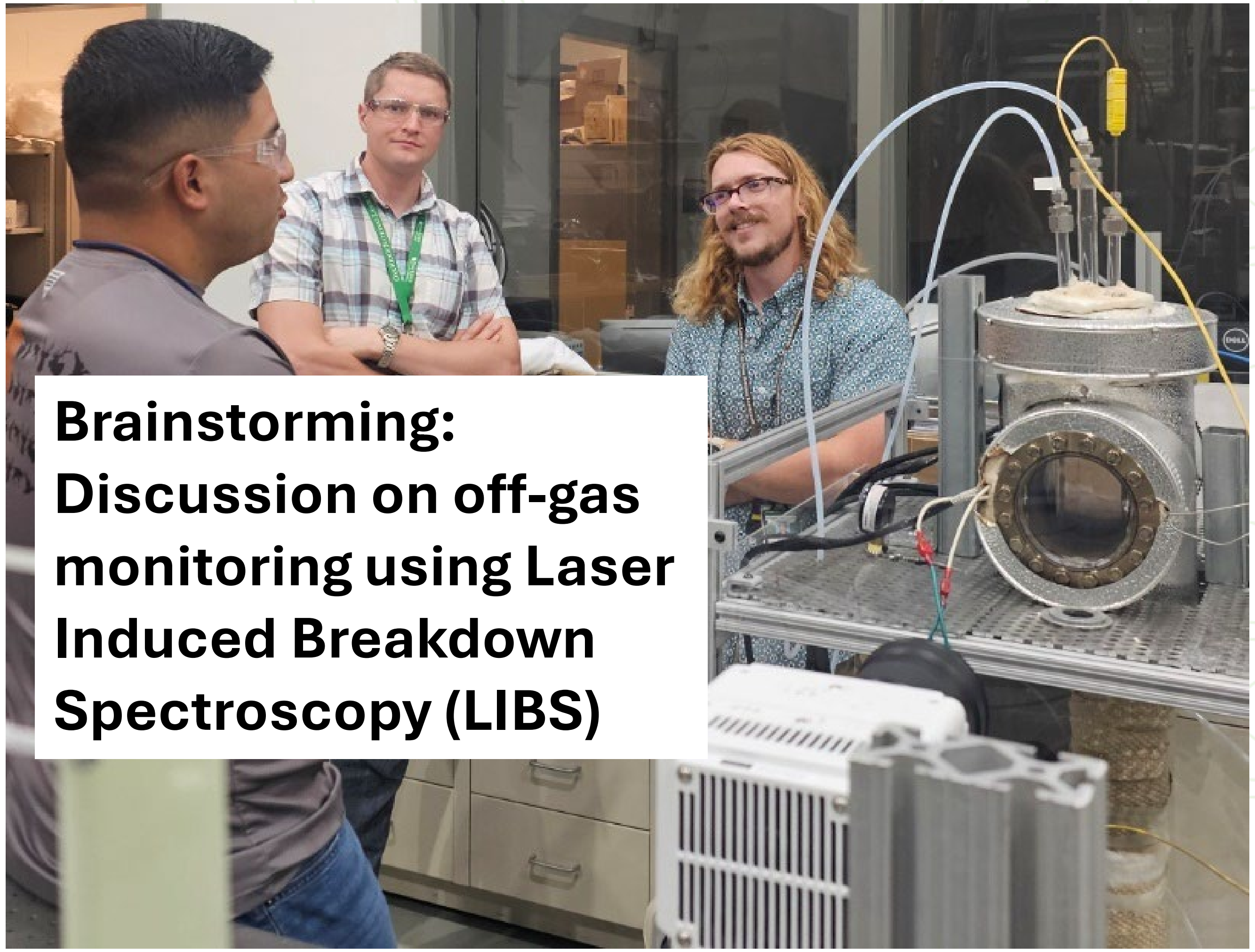
Importance of Gas Transport

- Gas transport is important for the safe operation of MSRs with regards to fission species transport and removal.

- The goal of the test series is to collect data on gas transport through molten salt, particularly, bubble size and rise velocity.

- Non-intrusive optical measurements deployed to visualize the salt.

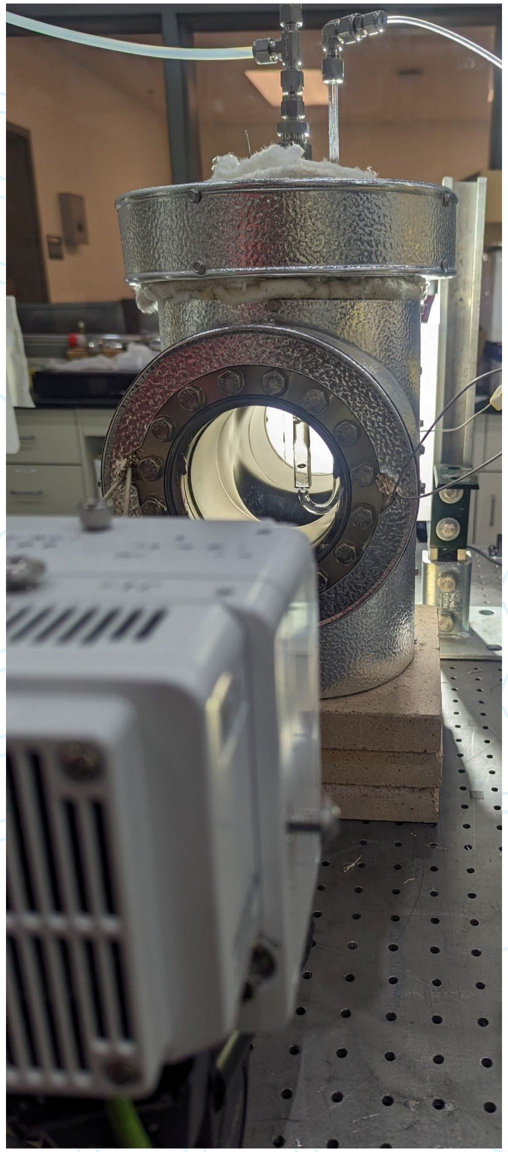
- Data will be used for model development / validation of radionuclide transport, and to provide information for licensing requirements regarding MSRs.



Left to Right) Daniel Orea, Zechariah Kitzhaber, Hunter Andrews

Molten Salt Visualization Progress

Where we started

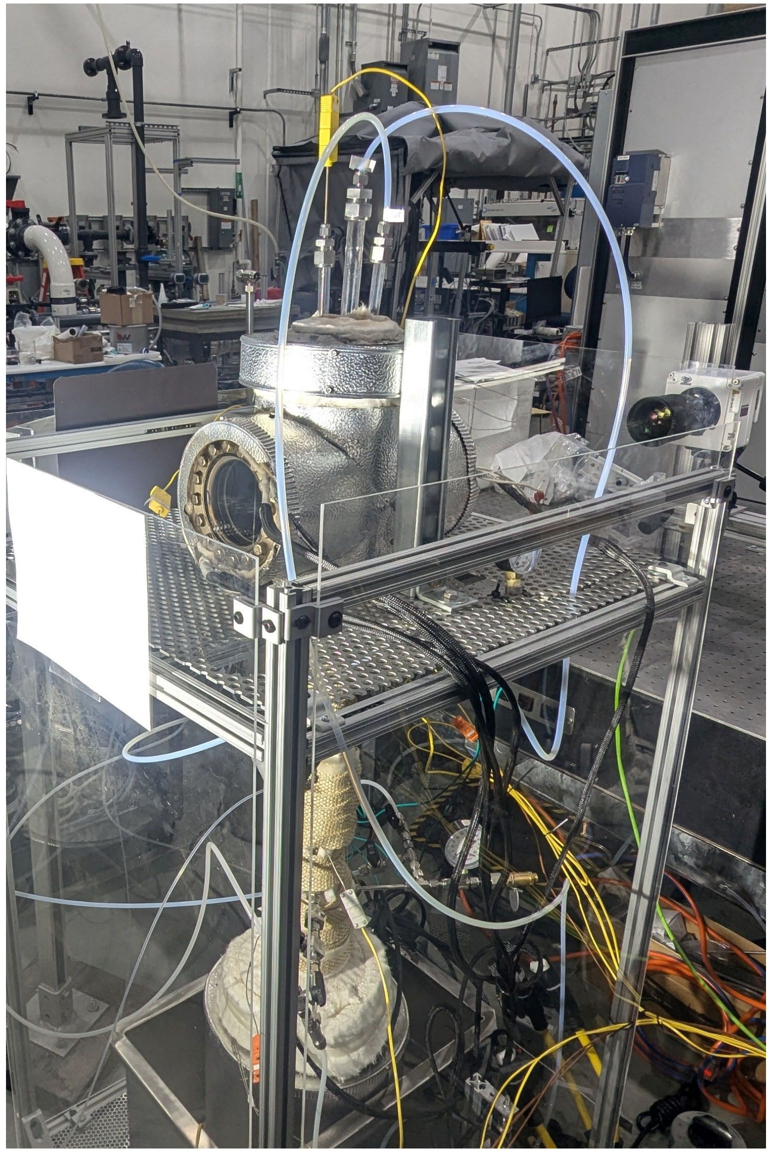


Flow Cell Improvements

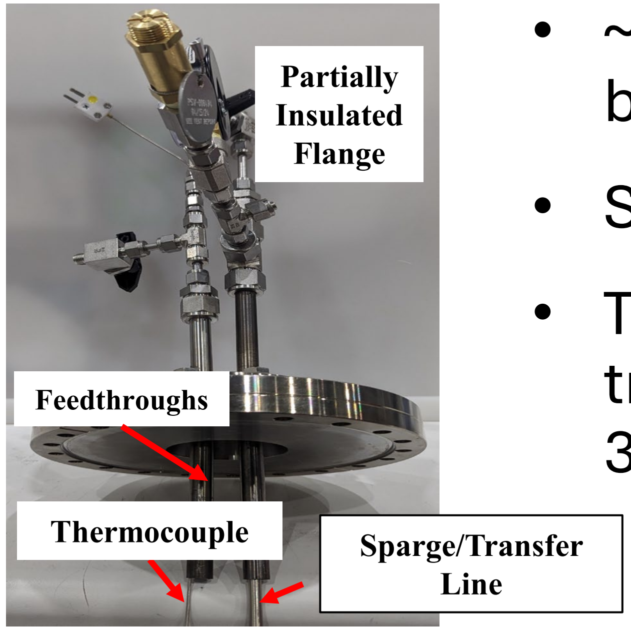
ORNL Scientific Glassblower: Carlos Rodriguez Flores

10 mL to 1,000 mL

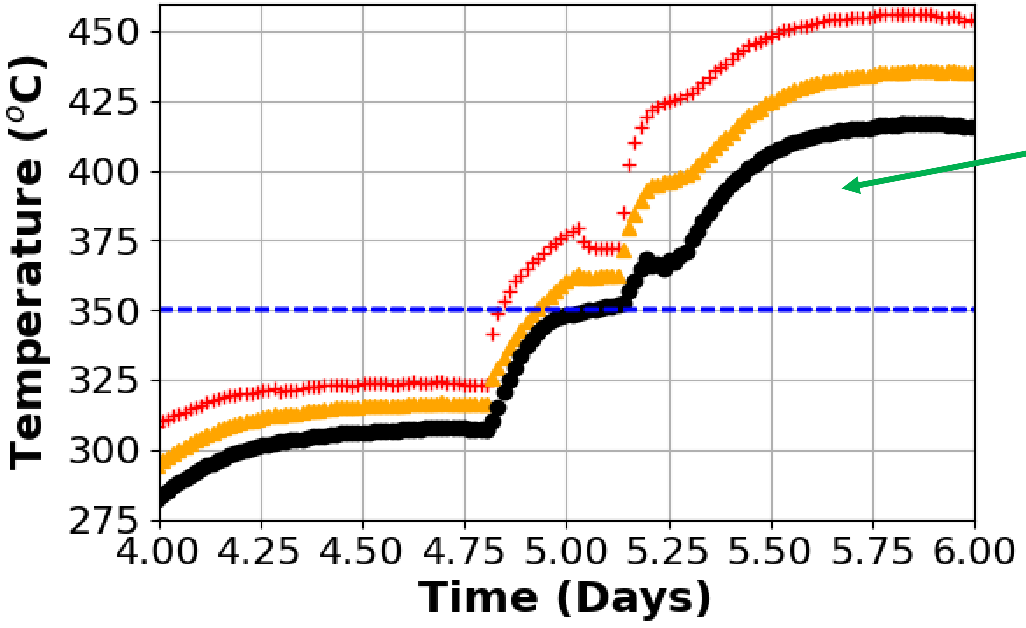
2025

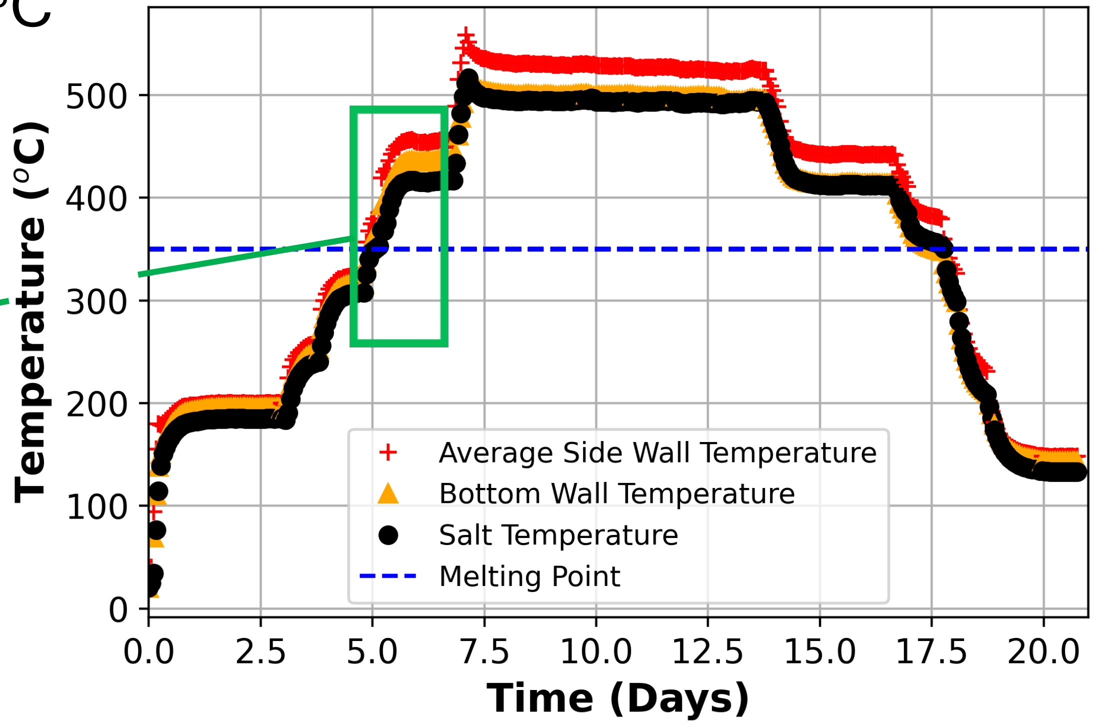


Secondary Vessel Commissioning



- ~2 kg of molten salt was mixed inside a glove box
- Salt eutectic loaded into crucible and furnace
- Temperature measurements confirmed phase-transition at expected melting temperature of 350°C

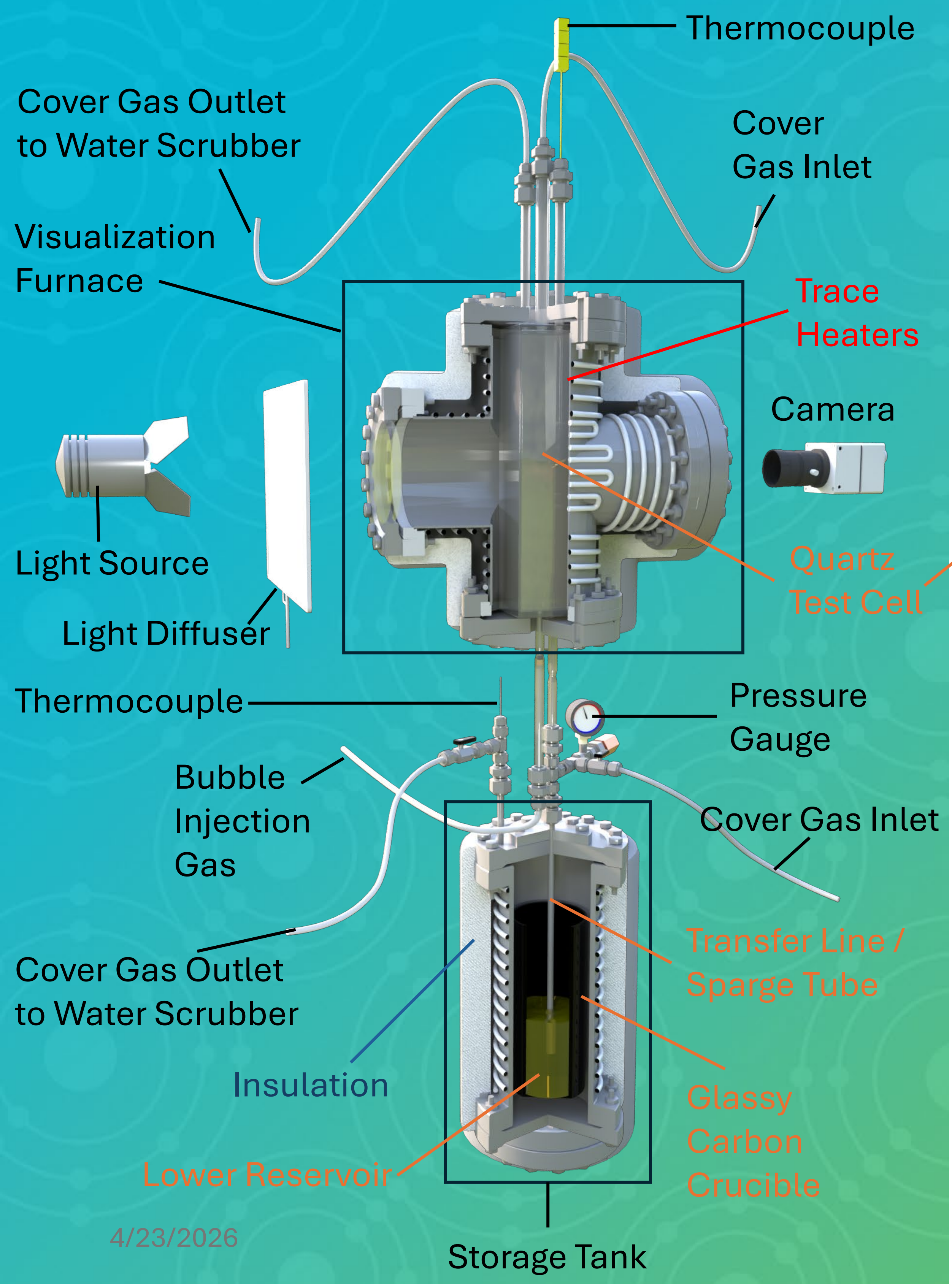


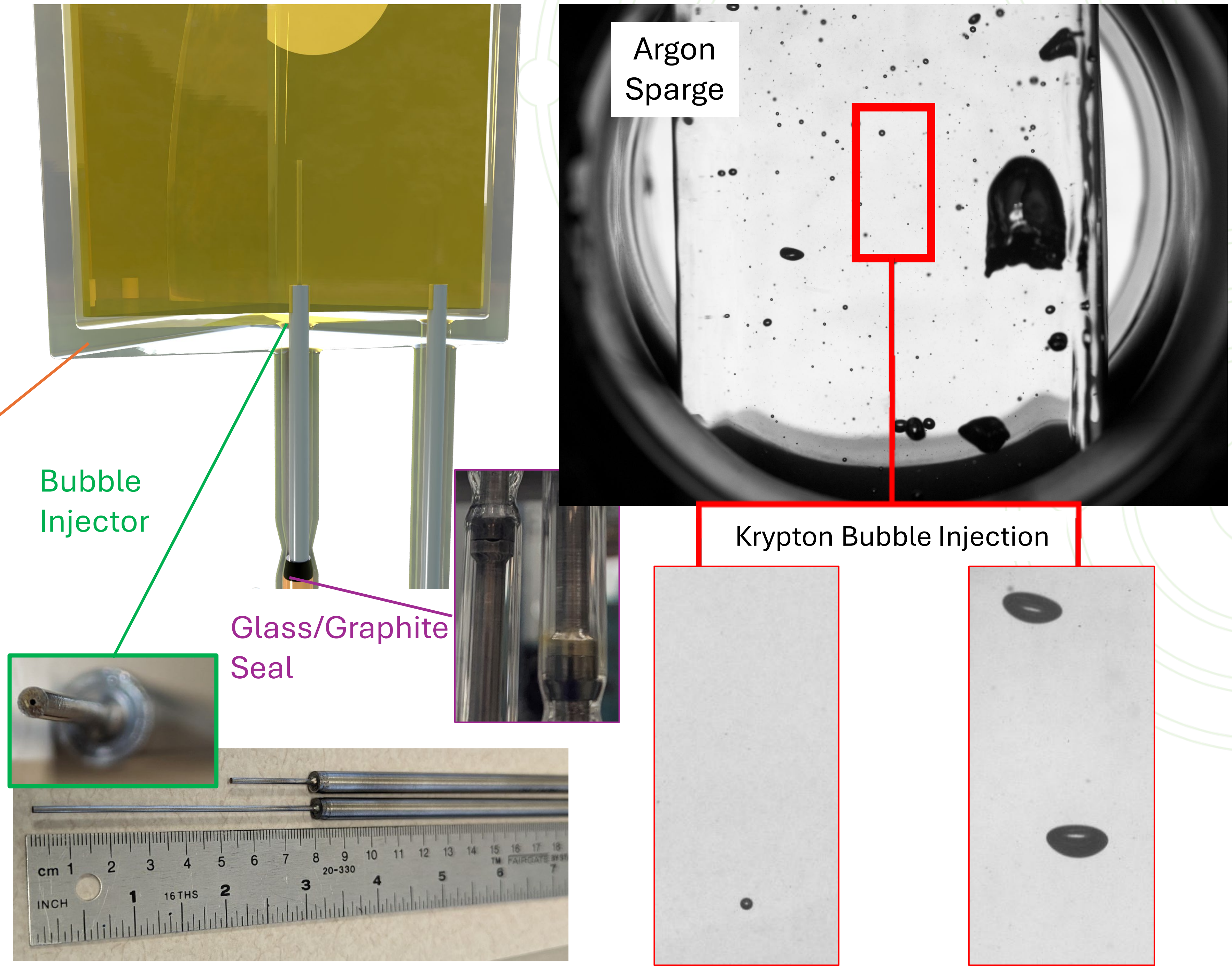


Molten Salt Reactor PROGRAM

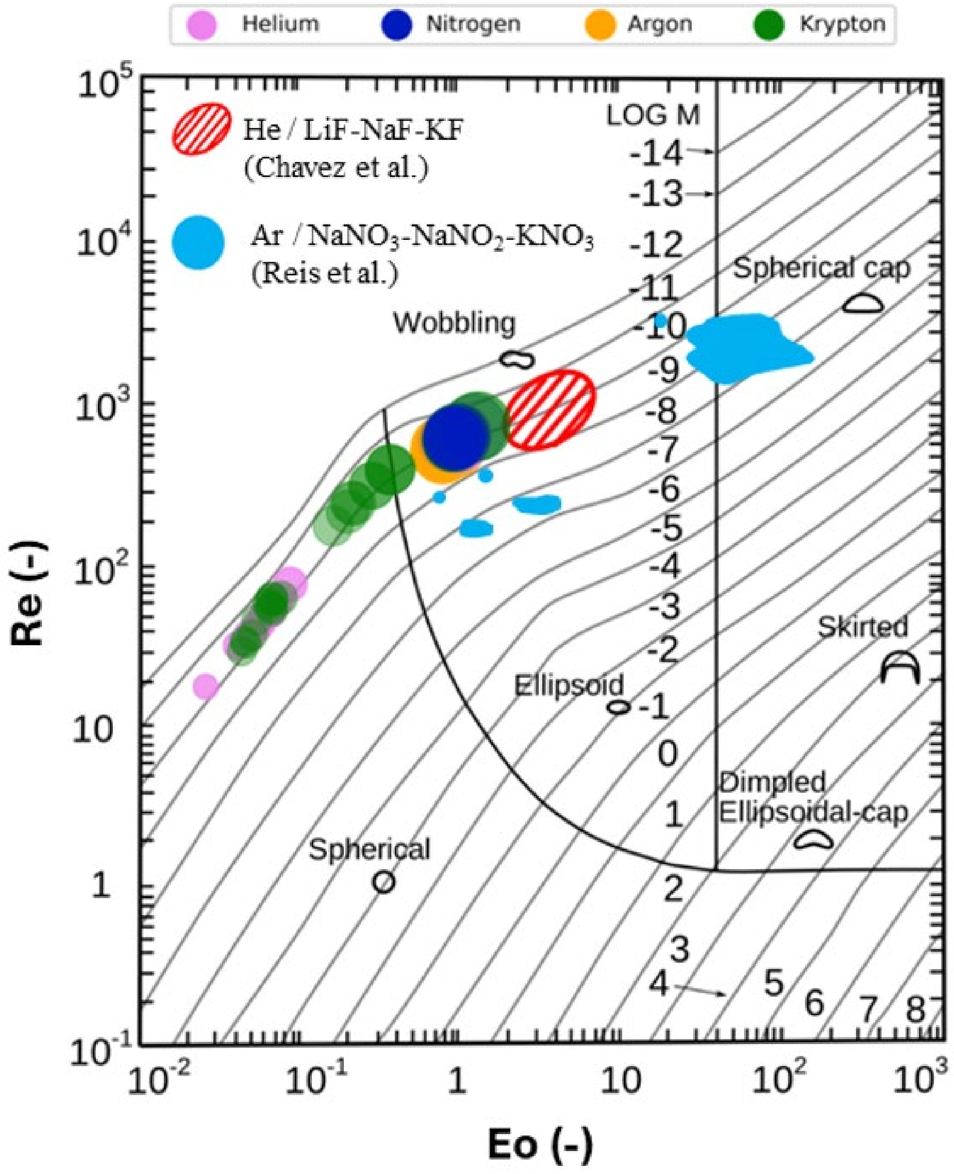
U.S. DEPARTMENT of ENERGY
Office of Nuclear Energy

Molten Salt Visualization Apparatus





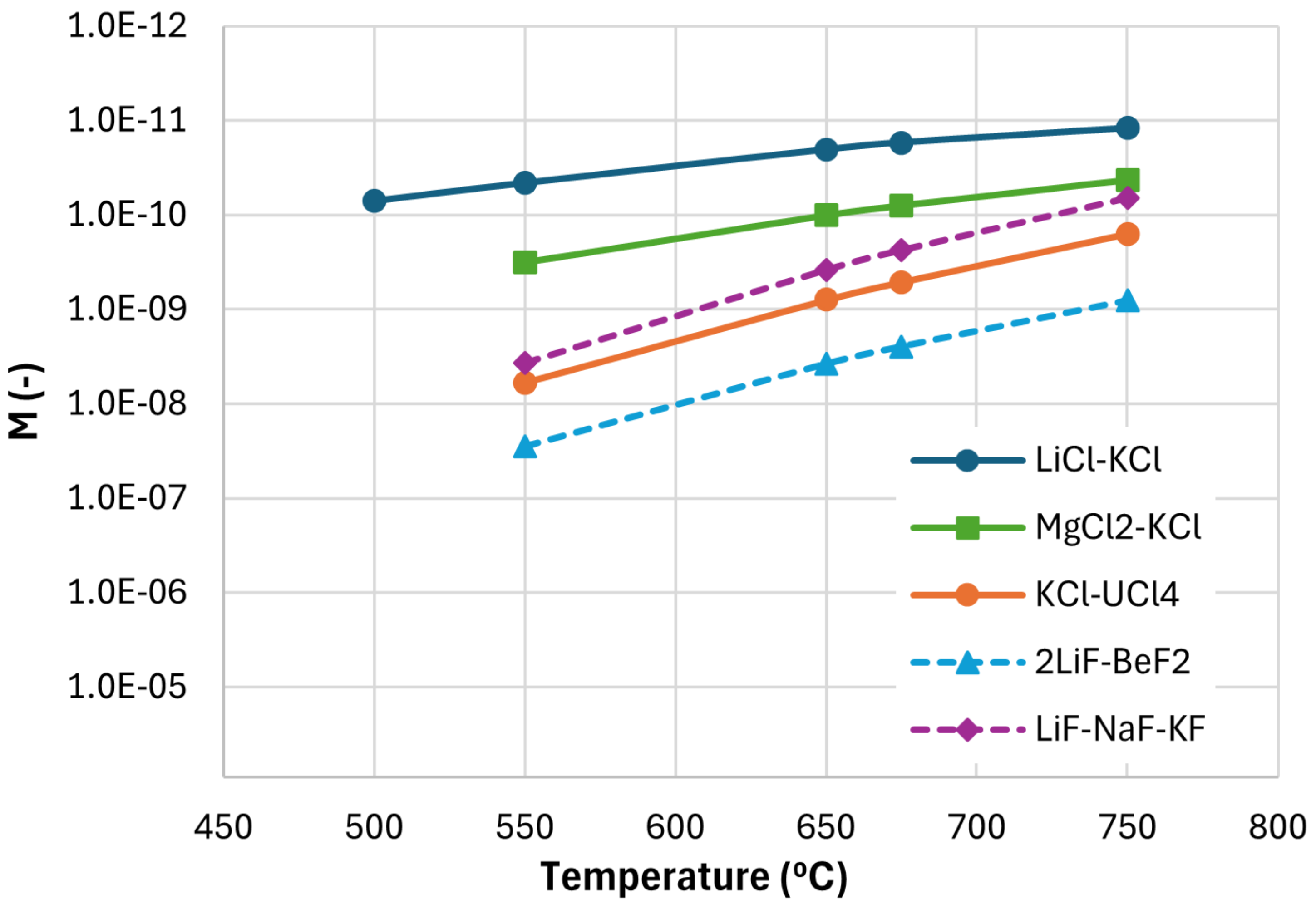
Bubble Behavior in Molten Salt



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

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

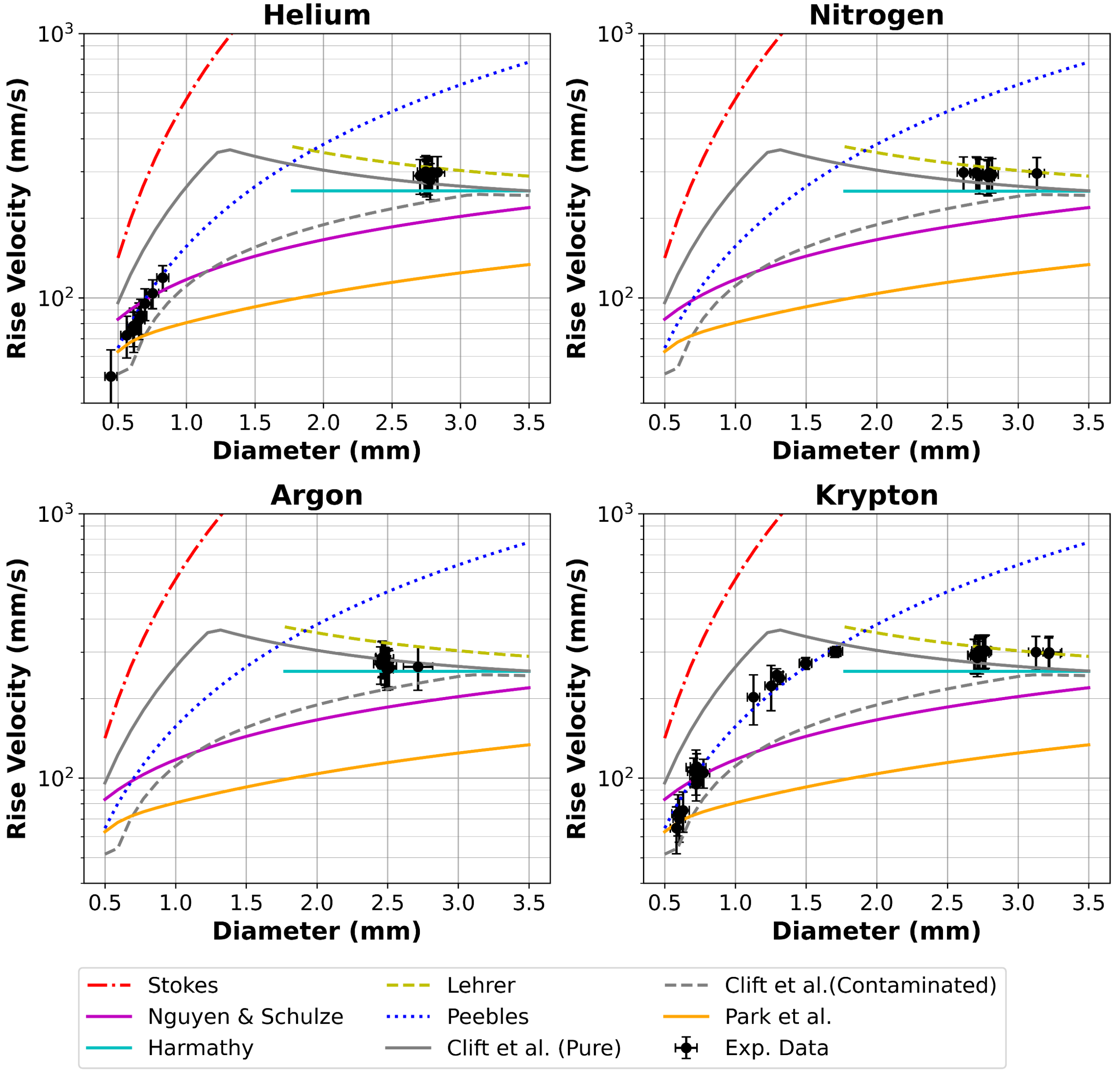
$$Mo = \frac{\Delta\rho g \mu^4}{{\rho_l}^2 {\sigma_l}^3}$$



Orea, D., Robb, K., & McFarlane, J. (2025). Comparative study between experimental measurements and model predictions of bubble rise velocity in molten LiCl-KCl. *Nuclear Engineering and Design*, *443*, 114247.

Bubble Rise Velocity

Reference	Model	Notes
Stokes [22]	$V_T = {}^{2\rho_l g R_{eq}^2}/_{9\mu_l}$	Assumes a rigid sphere
Nguyen & Schulze [23]	$V_T = 18V_{stk}\left(\frac{4a^2Ar^{2b-1}Mo^{0.46b}}{3k}\right)^{1/2-2b}$	if $12,332 \leq Ar \leq 3.158Mo^{-0.46}$; $a = 1$, $b = 0$ if $3.158Mo^{-0.46} \leq Ar \leq 29.654Mo^{-0.46}$; $a = 1.14$, $b = 0.176$ if $29.654Mo^{-0.46} \leq Ar \leq 506.719Mo^{-0.46}$; $a = 1.36$, $b = 0.280$ if $506.719Mo^{-0.46} \leq Ar$; $a = 0.62$, $b = 0$
Harmathy [24]	$V_T = 1.53\left[{}^{\Delta\rho g\sigma}/_{\rho_l^2}\right]^{1/4}$	Re > 500
Lehrer [25]	$V_T = \sqrt{{}^{3\sigma}/_{\rho_l D_{eq}} + {}^{\Delta\rho g D_{eq}}/_{2\rho_l}}$	Re > 476
Peebles [26]	$V_T = 0.136g^{0.78}\left({}^{\rho}/_{\mu}\right)^{0.52}D_{eq}^{1.28}$	$2 < Re < 1,200$
	$V_T = 1.909g^{0.5}\left(\frac{\sigma_l}{\rho_l}\right)^{0.5}D_{eq}^{-0.5}$	$Re > 1,200$
Clift et al. (pure) [20]	$V_T = 0.138g^{0.82}(\rho/\mu)^{0.639}D_{eq}^{1.459}$	$D_{eq} < 1.3$ mm
	$V_T = \sqrt{\frac{2.14\sigma_l}{\rho_l D_{eq}} + 0.505gD_{eq}}$	$D_{eq} > 1.3$ mm
Clift et al. (contaminated) [20]	$V_T = \frac{\mu}{\rho D_{eq}}Mo^{-0.149}(J - 0.857)$	$H = (4/3)EoMo^{-0.149}\left({}^{\mu_l}/_{\mu_{water}}\right)^{-0.14}$ if $H > 59.3$; $J = 3.42H^{0.441}$ if $2 < H \leq 59.3$; $J = 0.94H^{0.757}$ if $H \leq 2$; $J = ReMo^{0.149} + 0.857$
Park et al. [27]	$V_T = 1/\sqrt{{}^1/_{V_{vis}^2} + {}^1/_{V_{in}^2} + {}^1/_{V_{spheroid}^2}}$	$V_{vis} = {}^{g\rho_l D_{eq}^2}/_{12\mu_l}$ $V_{in} = 0.14425g^{5/6}(\rho_l/\mu_l)^{2/3}D_{eq}^{3/2}$ $V_{spheroid} = \sqrt{{}^{2.14\mu_l}/_{\rho_l D_{eq}} + 0.505gD_{eq}}$

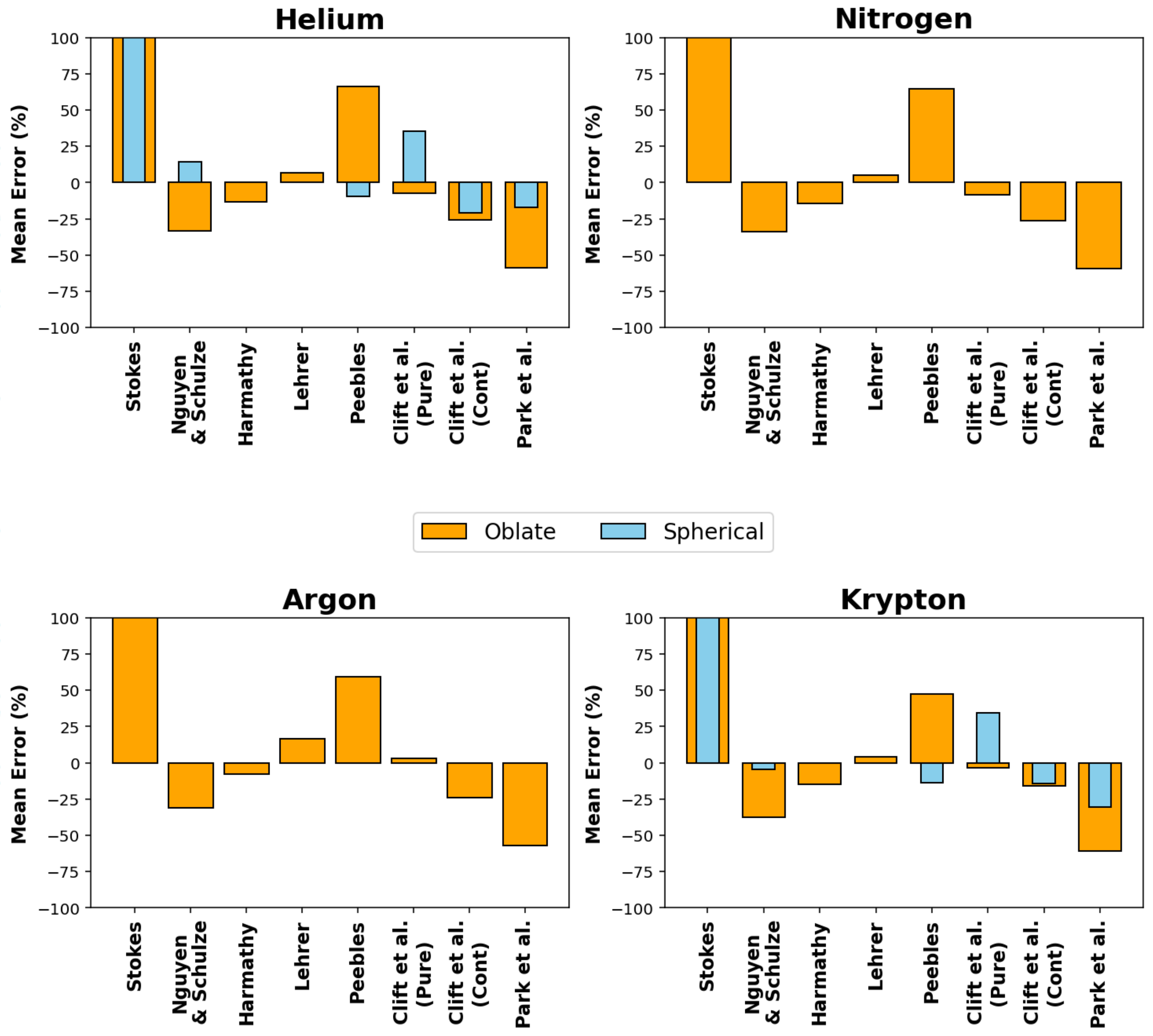


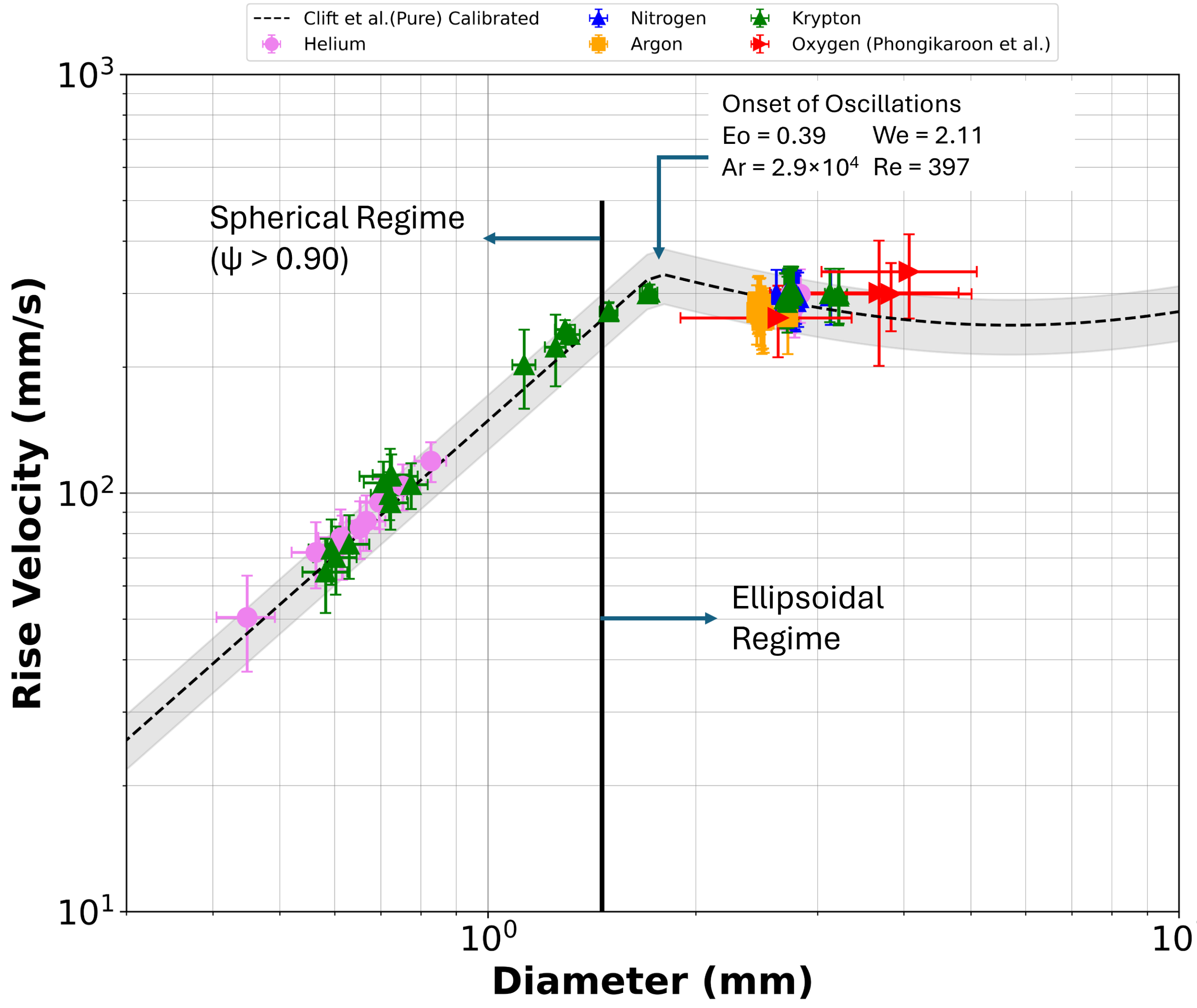
Orea, D., Robb, K., & McFarlane, J. (2025). Comparative study between experimental measurements and model predictions of bubble rise velocity in molten LiCl-KCl. *Nuclear Engineering and Design*, *443*, 114247.

Molten Salt Reactor PROGRAM

U.S. DEPARTMENT of ENERGY
Office of Nuclear Energy

Bubble Rise Velocity (cont'd)

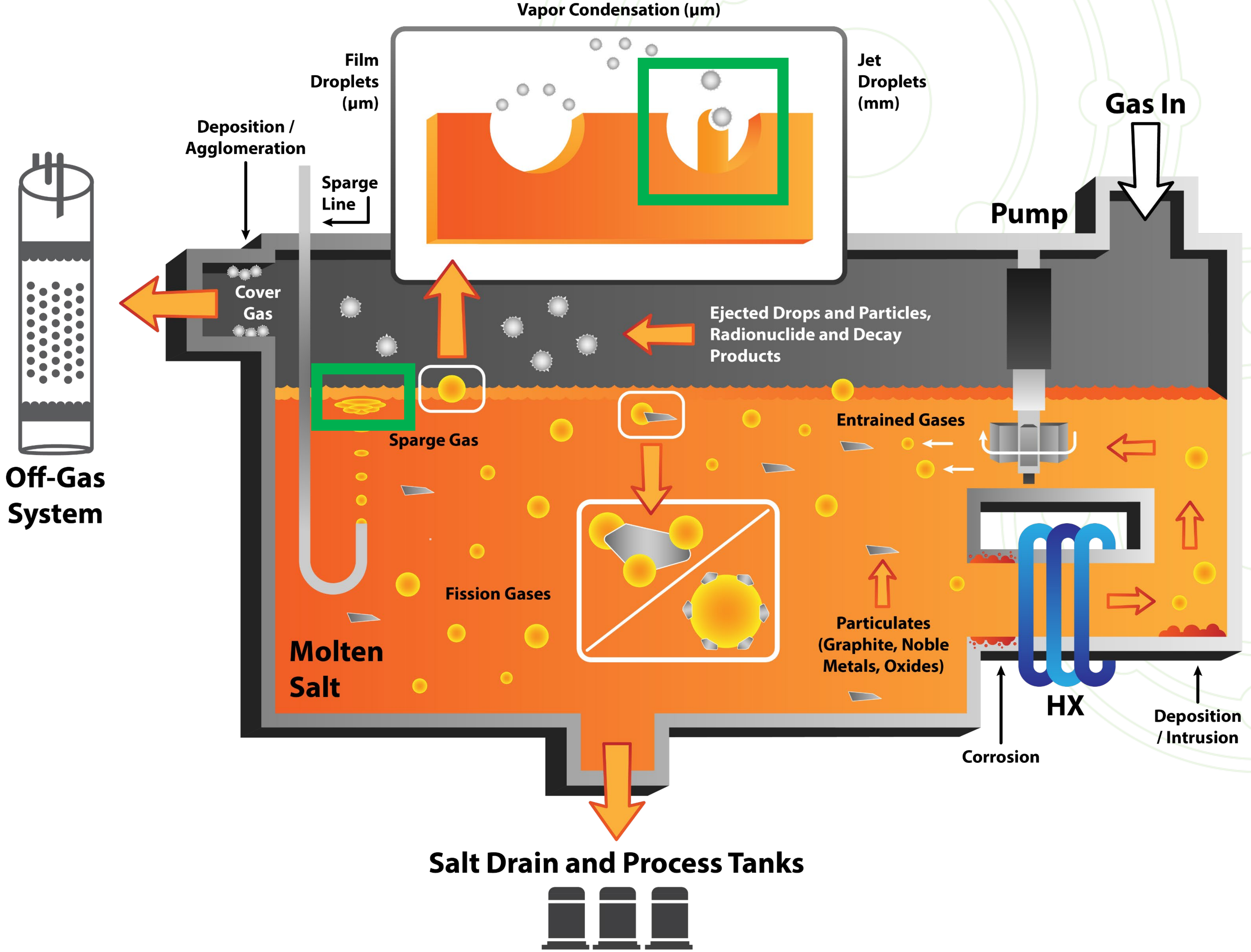




Orea, D., Robb, K., & McFarlane, J. (2025). Comparative study between experimental measurements and model predictions of bubble rise velocity in molten LiCl-KCl. *Nuclear Engineering and Design*, *443*, 114247.

MSR Gas and Particle Transport Phenomena

- Aerosol/particulate size drives entrainment and deposition in cover-gas/off-gas systems
- Bubble bursting at the free surface is a mechanical aerosol source (film and jet droplets)

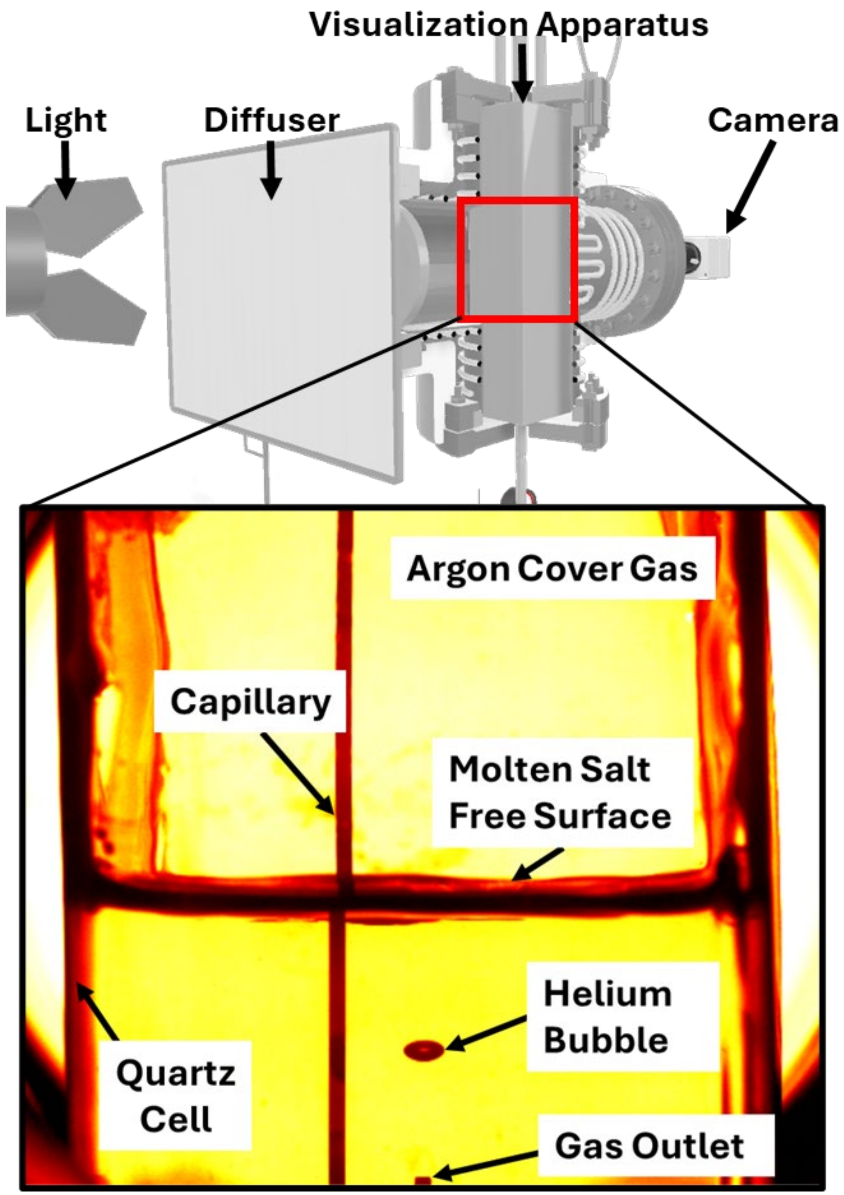


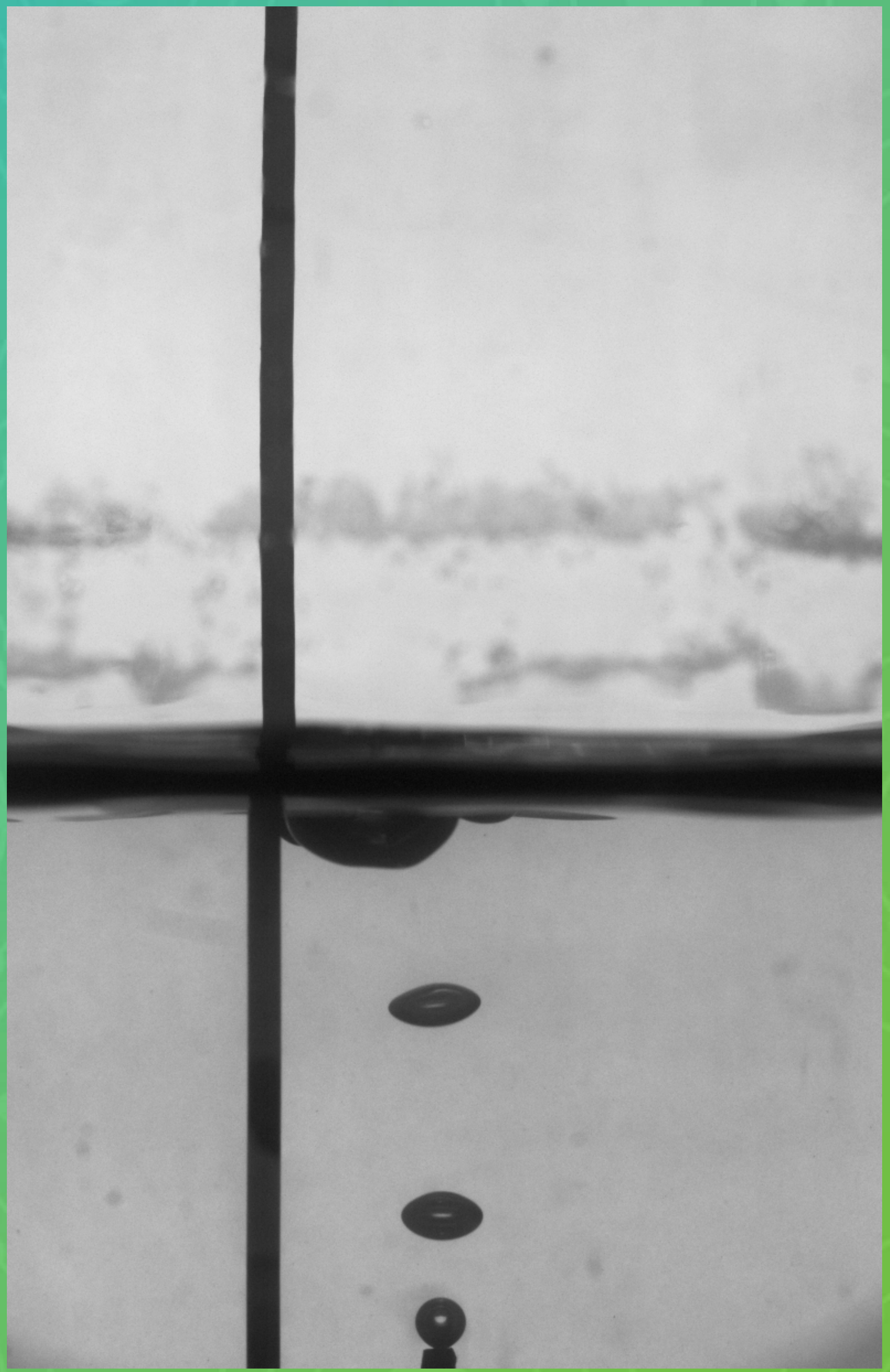
Molten Salt Reactor PROGRAM

U.S. DEPARTMENT of ENERGY
Office of Nuclear Energy

Jet Droplets Produced via Bubble Bursts

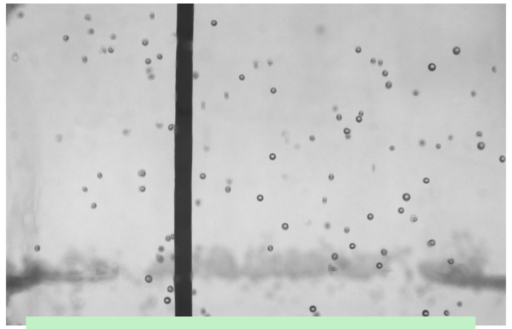
- Molten salt @ 500 °C
  - Liquid level dropped to be in frame
- Bubble injection:
  - Helium through 0.55 mm ID capillary
  - 25 mm below liquid surface
  - Gas injection rates = 2.5 / 5.0 / 10.0 sccm
- Imaging:
  - Phantom VEO 440 at 30 Hz
  - 128.9 seconds per test

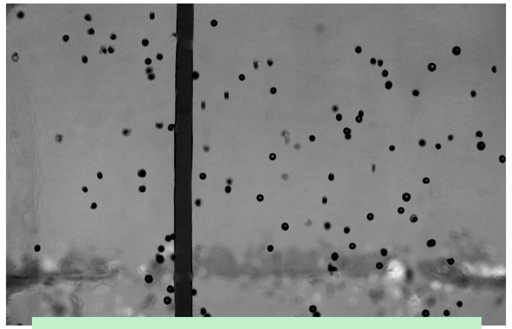


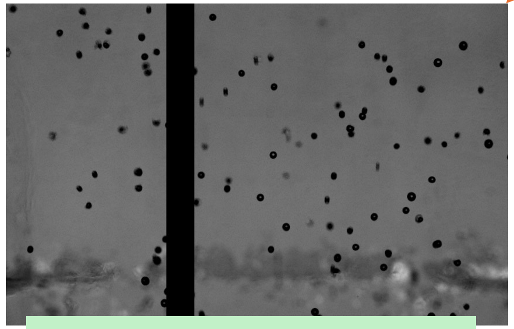


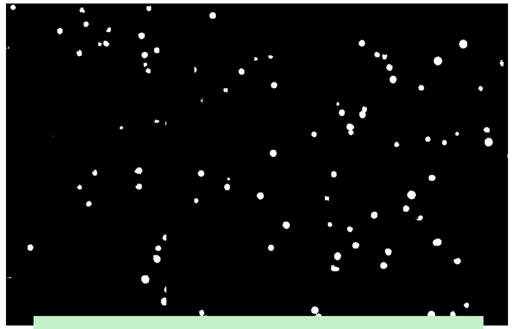
Aerosol Image Post-Processing and Tracking

Representative Post-Postprocessing


Original Image Cropped

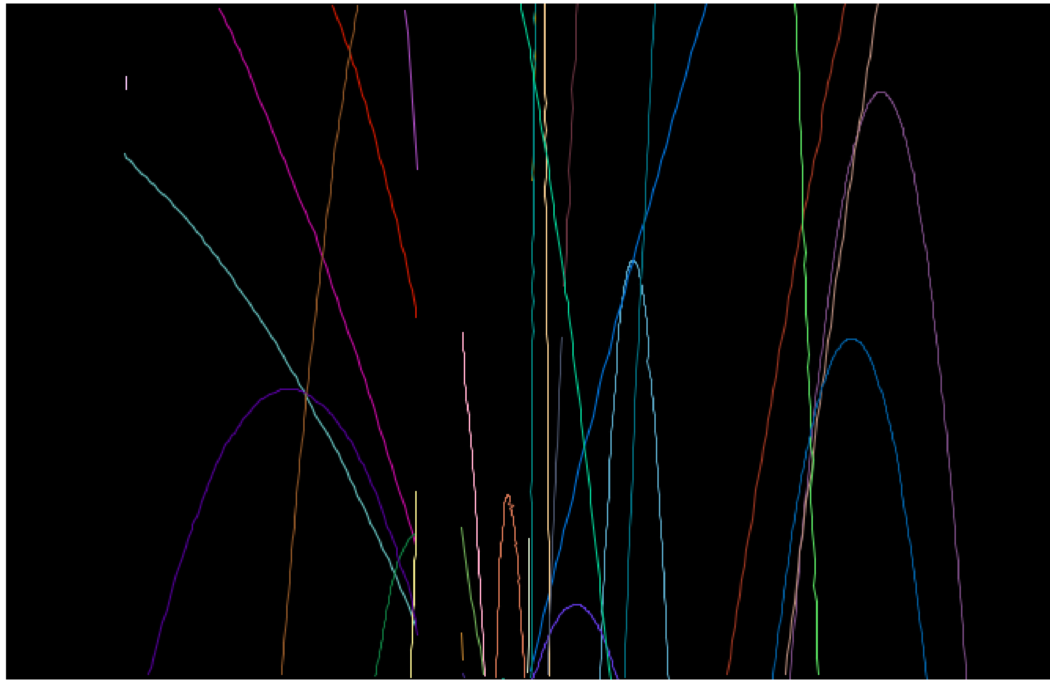

Background Subtracted


Contrast Enhanced


Threshold and Binarized

Individual Aerosol Tracking

Aerosol Tracks

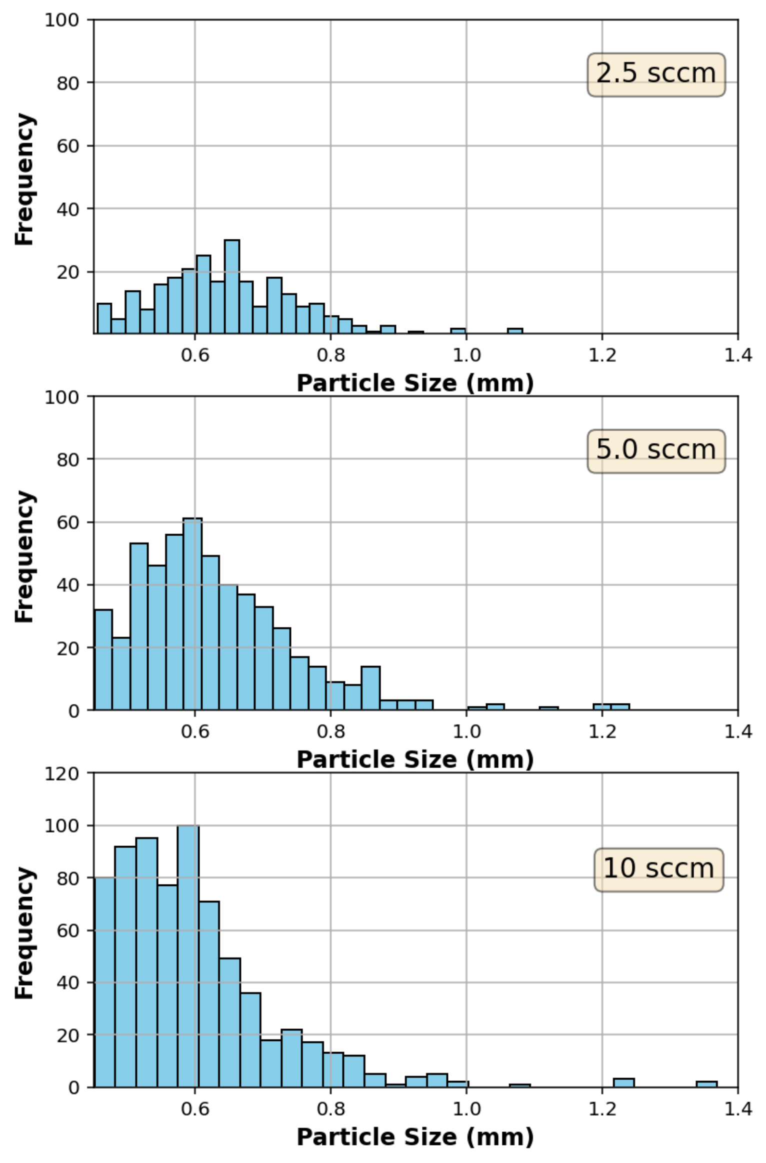


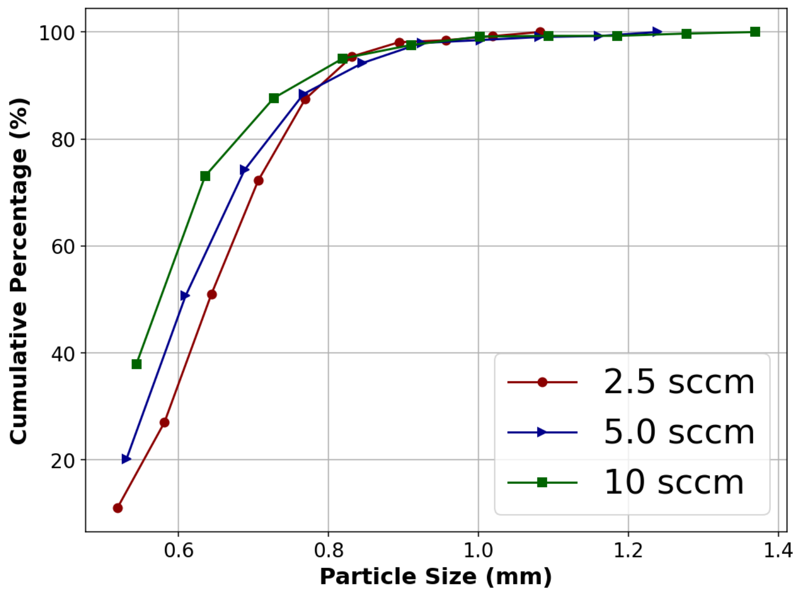
Molten Salt Reactor PROGRAM

U.S. DEPARTMENT of ENERGY
Office of Nuclear Energy

Characterization of Molten Salt Aerosols from Jet Droplets

- Flow rate drives aerosol size distribution
- Mean aerosol diameter decreases slightly with increasing sparge rate
- Bubble count scales with flow rate; bubble size does not
- Aerosol-to-bubble ratio decreases at higher sparge rates



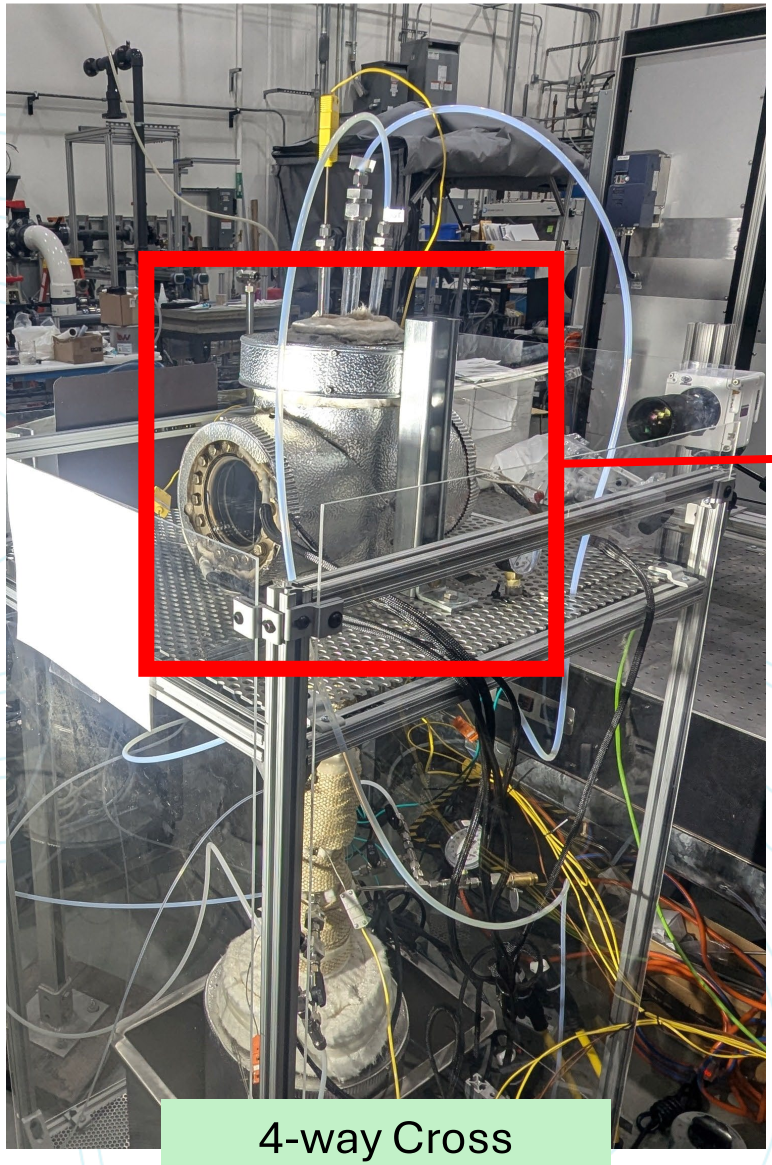


Sparge rate (sccm)	2.5	5.0	10
Bubbles Imaged	549	1,229	2,050
$D_{b,mean}$ (mm)	3.02	3.00	2.99
Aerosols Imaged	377	708	1,071
$D_{p,mean}$ (mm)	0.65	0.63	0.59
N_p / N_b	0.69	0.58	0.52

Orea, D., Robb, K., & McFarlane, J. (2026). Characteristics of Molten Salt Aerosol Droplets Produced by Bubble Bursts. Transactions of the American Nuclear Society

Visualization of Insoluble Species and Transport Apparatus (VISTA)

2025

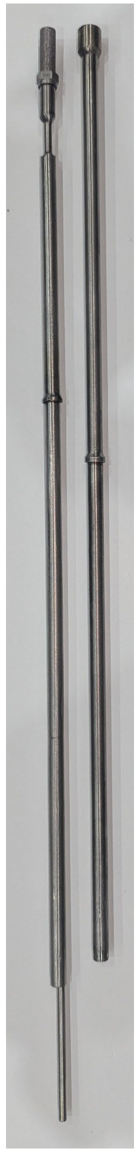


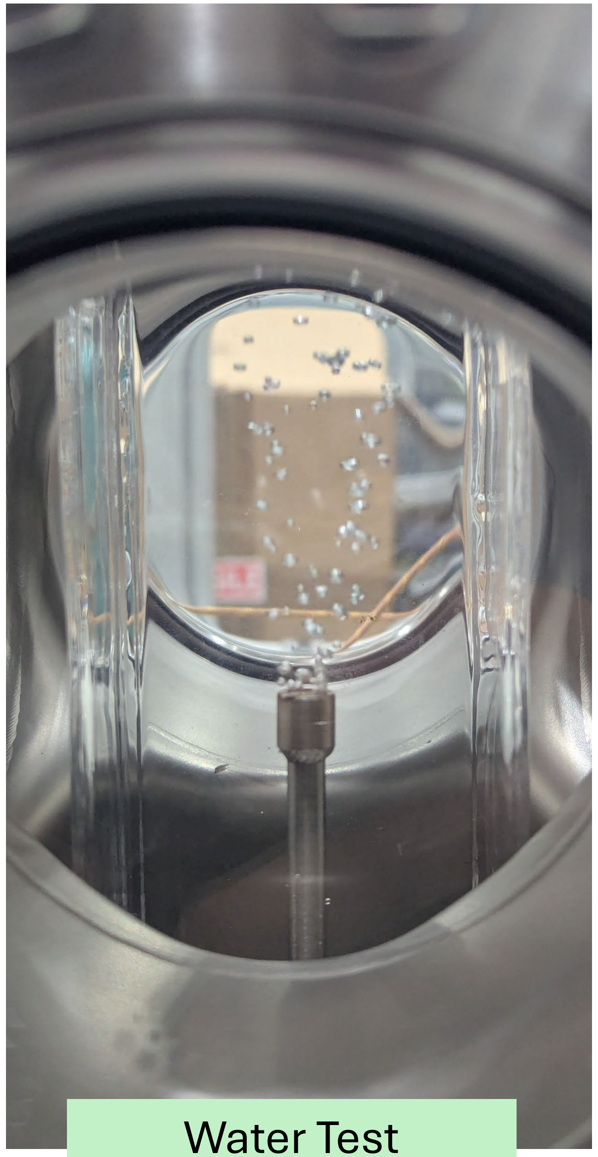
4-way Cross

Current Status

6-way Cross

New Bubblers



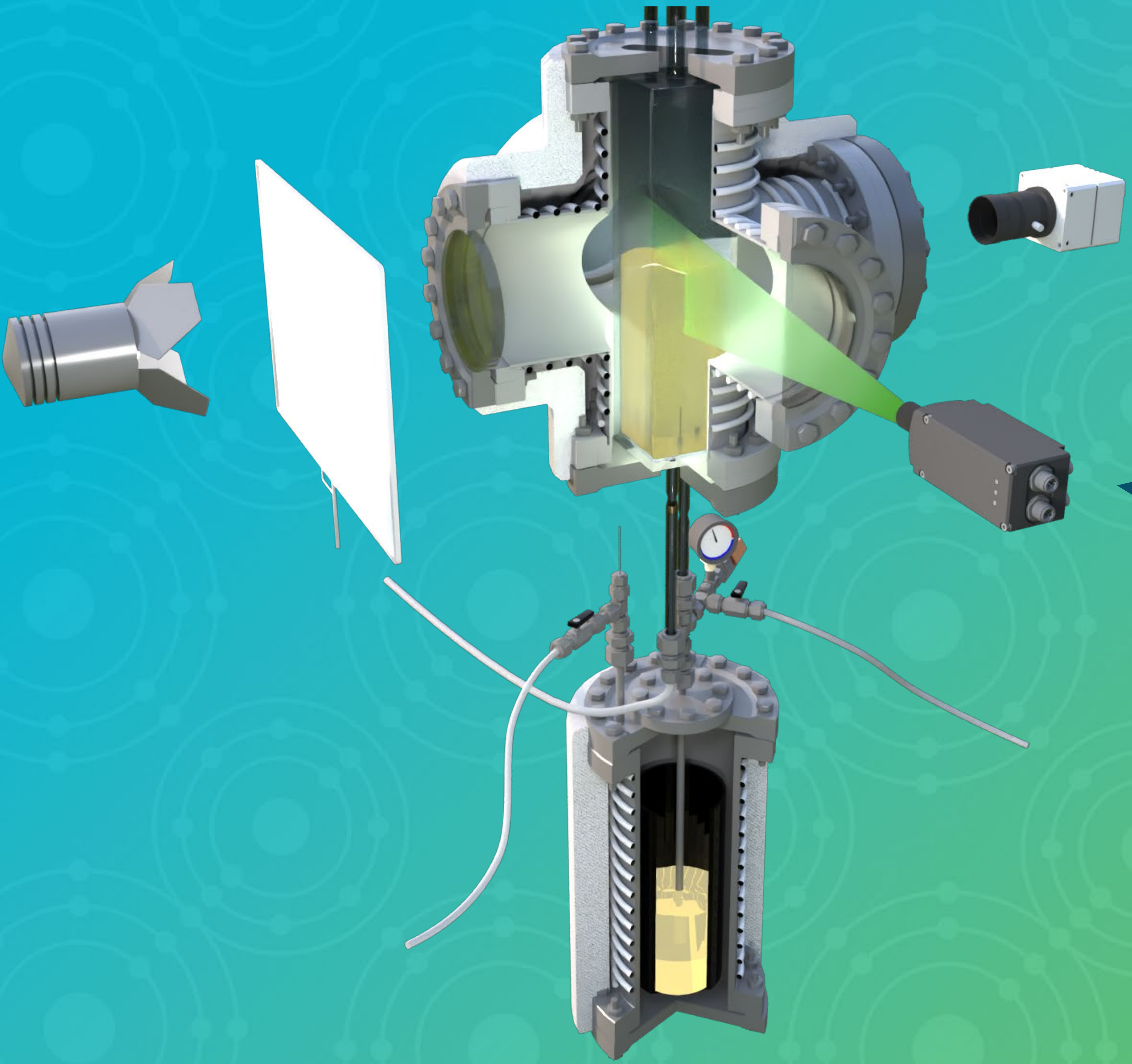


Water Test

FY26

Plans to introduce insoluble particles to molten salt

Experimental Data Collection



FY24	FY25	FY26	FY27
Established Optical Measurement Technique ✅	Bubble Rise Velocity and Jet Droplet Data ✅	Bubble and insoluble particle (micron) velocity, film and jet aerosol droplet data, off-gas composition	Bubble velocity and insoluble particle (sub-micron), film and jet aerosol droplet data, off-gas composition, stagnant and flowing salt

THANK YOU !

oread@ornl.gov

Molten Salt Reactor
PROGRAM