Molten Salt Reactor
PROGRAM

Optical Measurements of Gas Bubble Rise Velocity in Molten LiCl-KCl

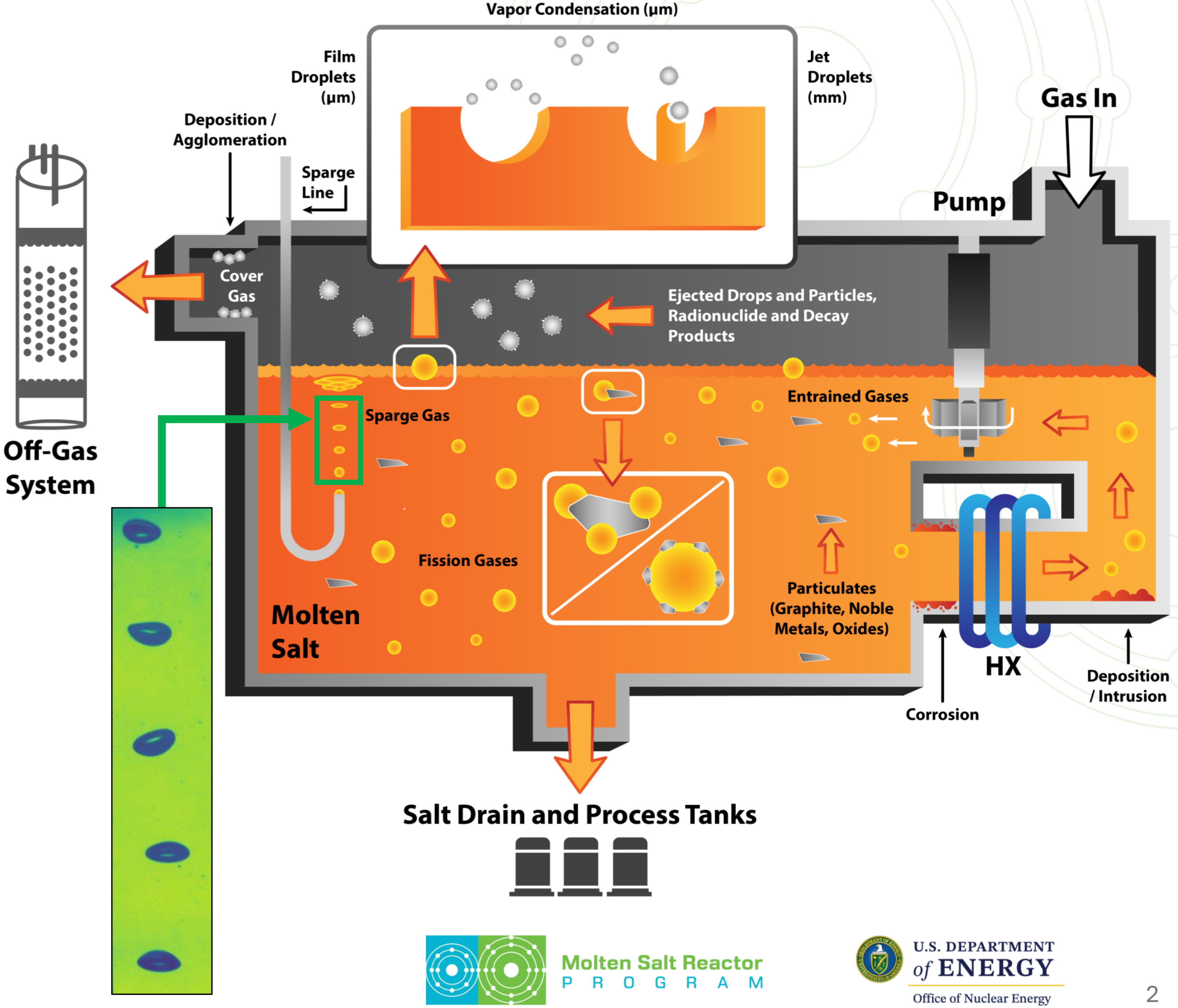
Daniel Orea, Kevin Robb, Joanna McFarlane

MSR Annual Program Review April 22-25, 2025

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

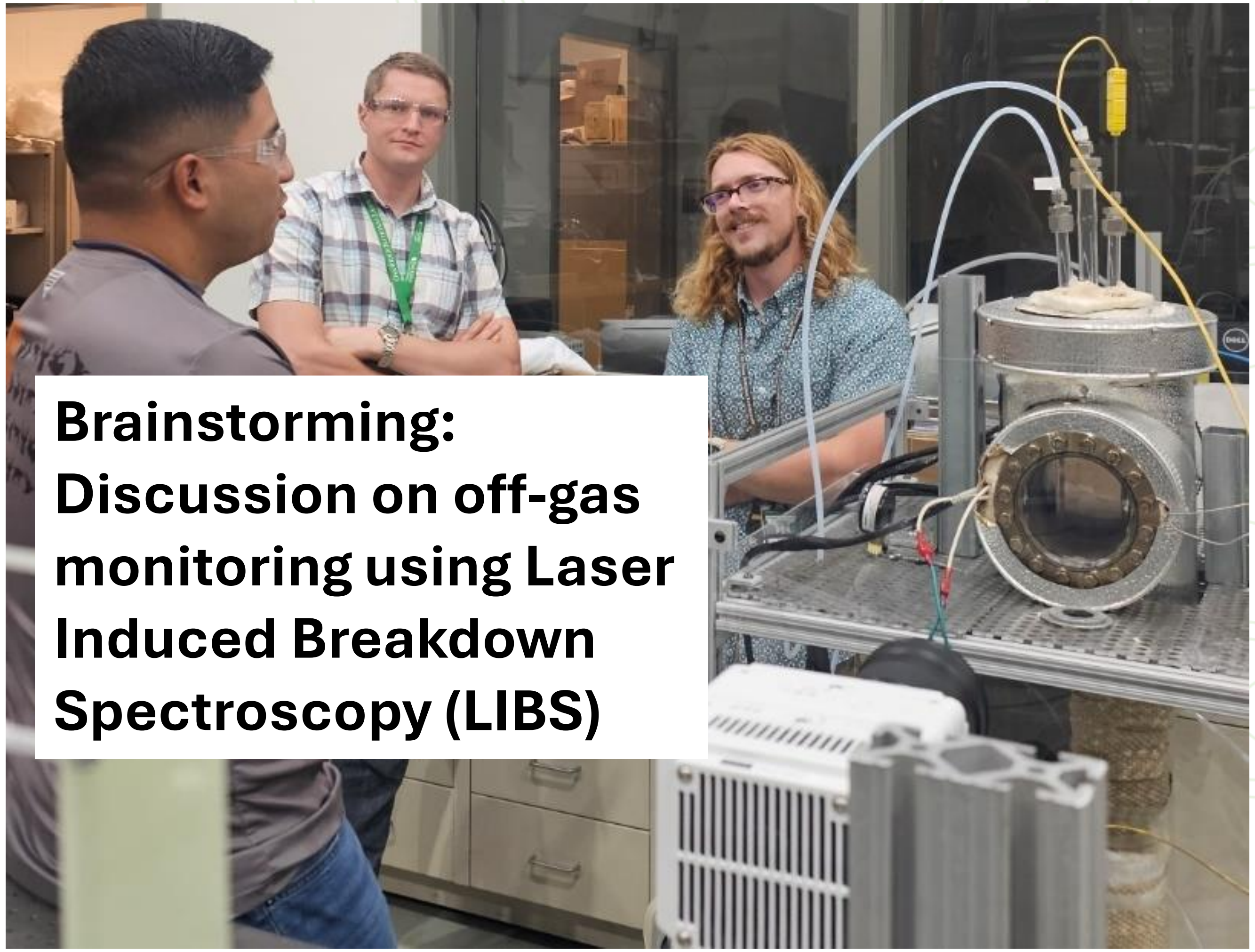
MSR Gas and Particle Transport Phenomena

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



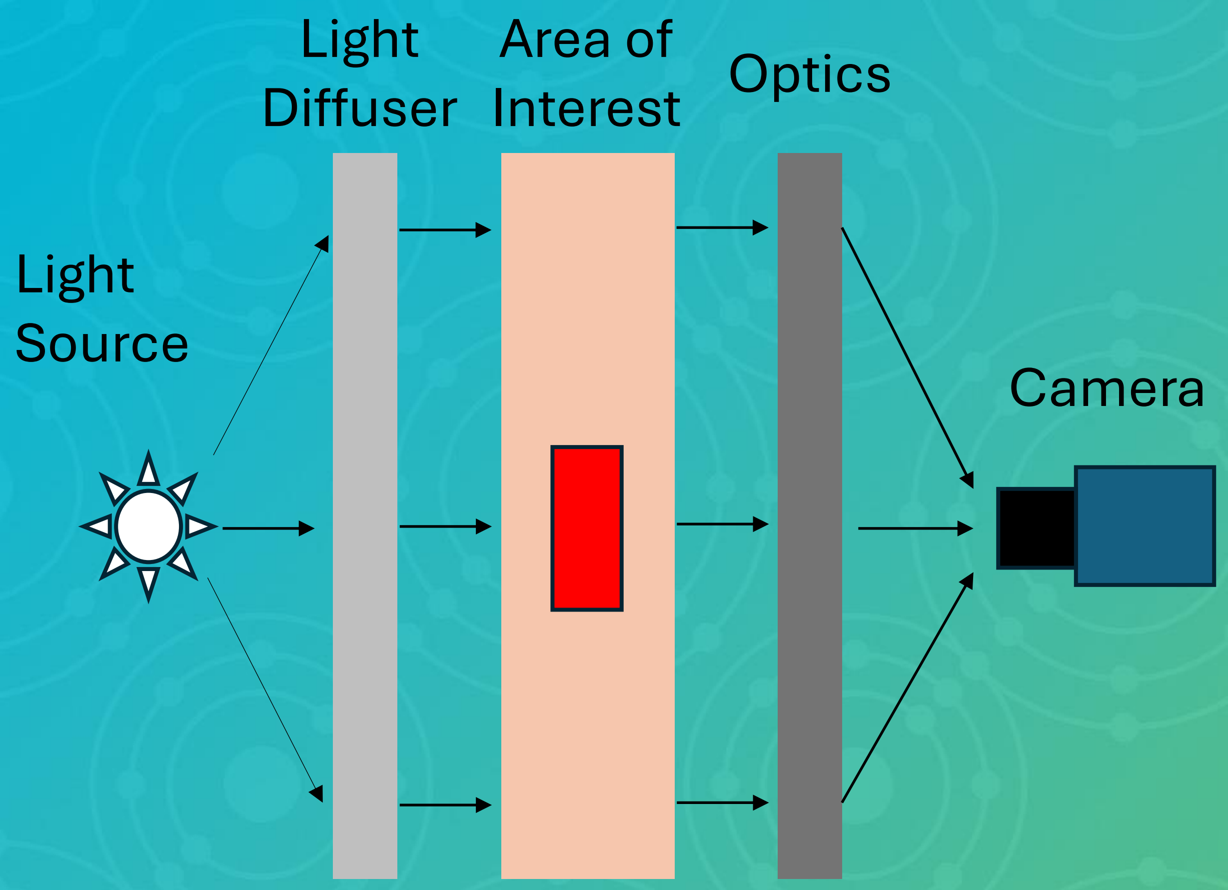
Importance of Gas Transport

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



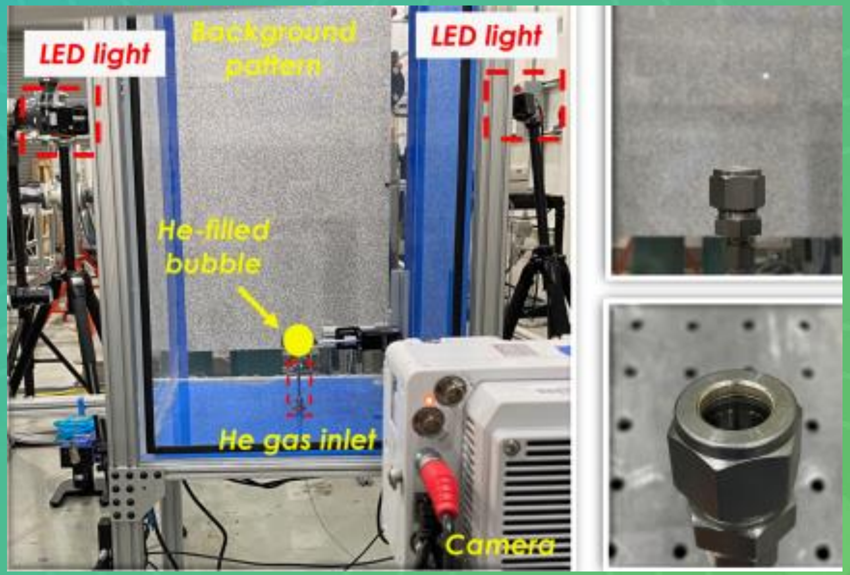
Left to Right) Daniel Orea, Zechariah Kitzhaber, Hunter Andrews

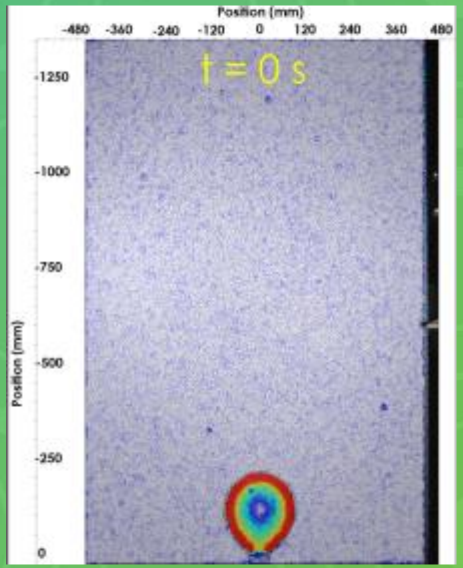
Optical Measurement Techniques

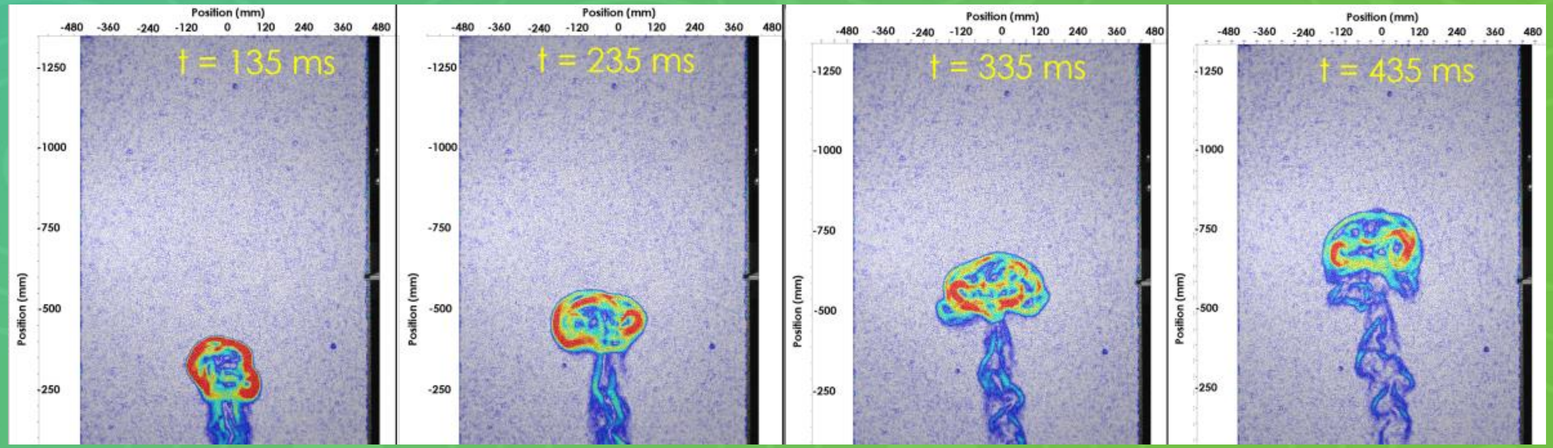


Schematic Diagram of Shadowgraph

Application of Advance Shadowgraph (Schlieren)

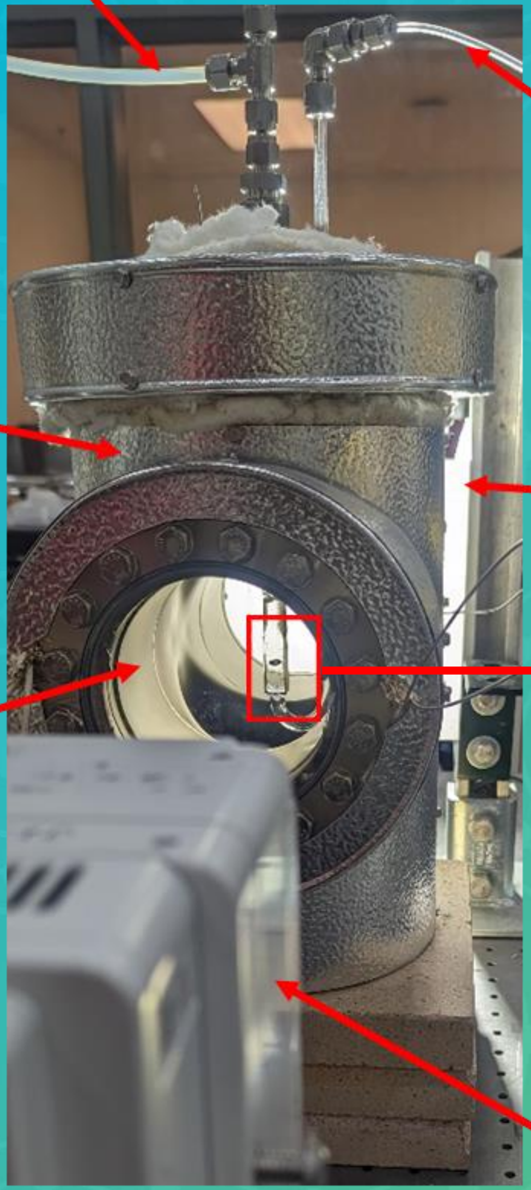




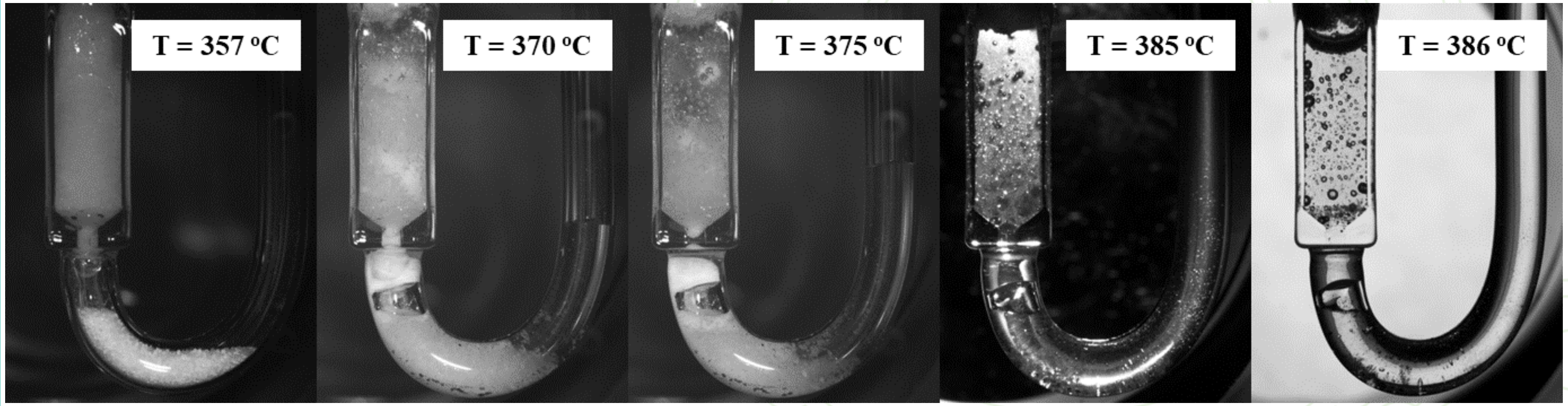


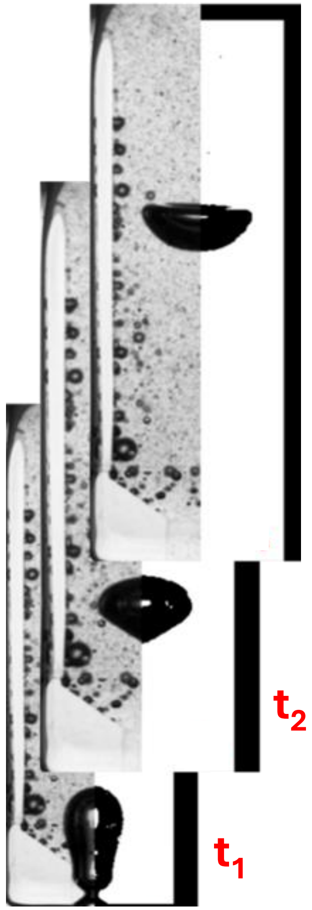
T. D. Nguyen, N. Goth, P. Moresco, V. Jodoin and V. Rao, "Preliminary experimental and numerical studies of light-core vortex rings," in *American Nuclear Society Annual* , 2024.

Initial Experiments

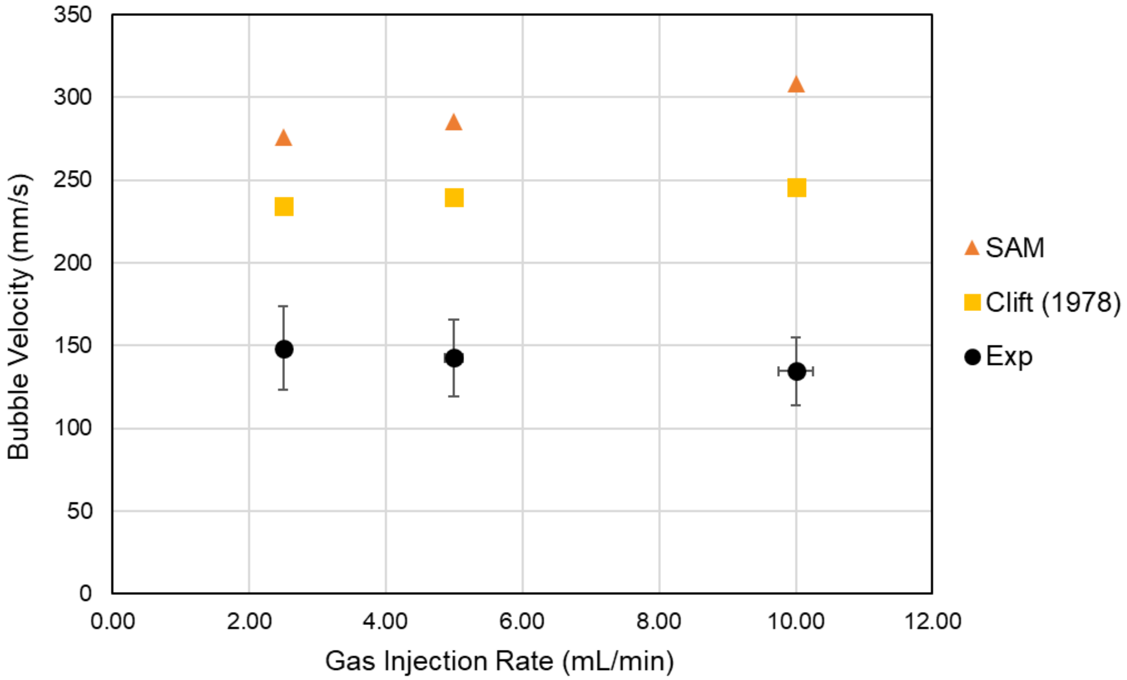


0.6 LiCl / 0.4 KCl [mol%]





Helium Bubbles



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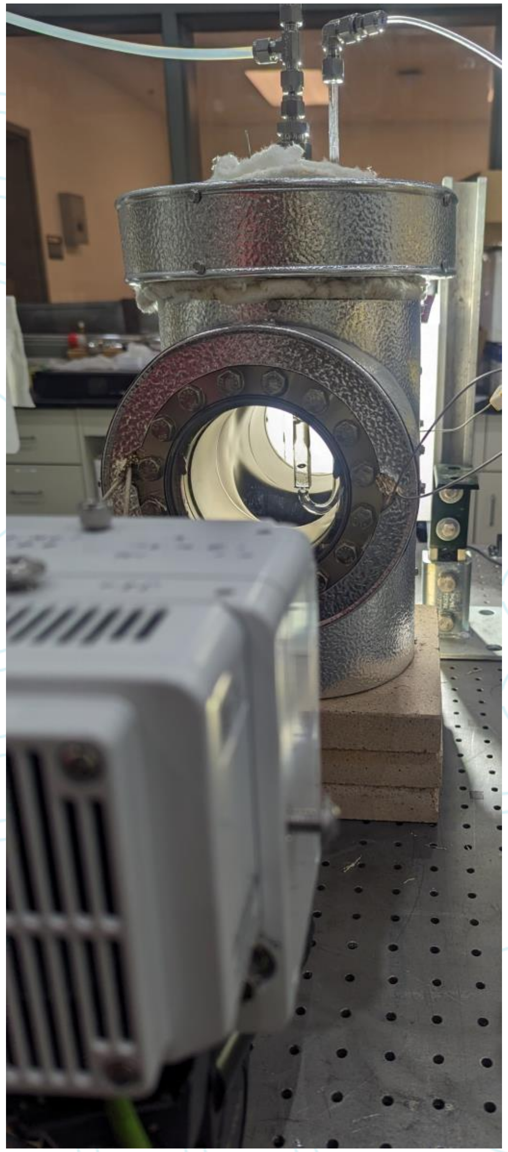
Molten Salt Visualization Progress

Where we started

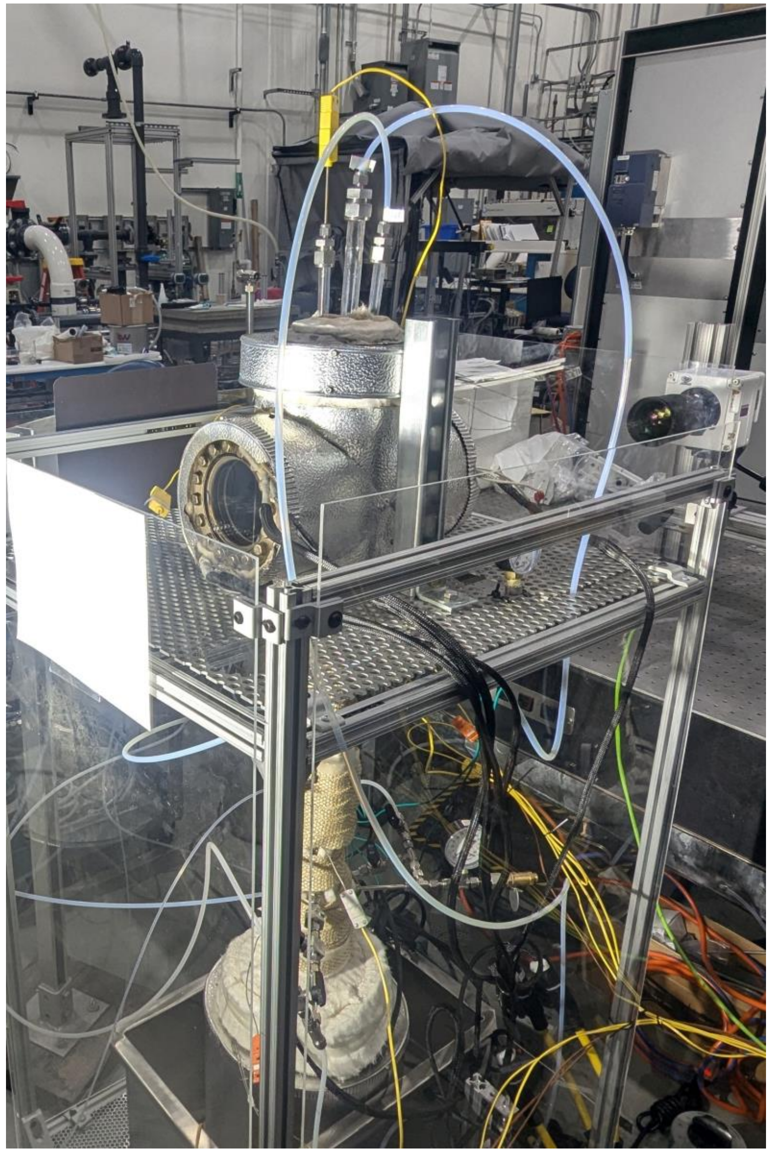


Flow Cell Improvements

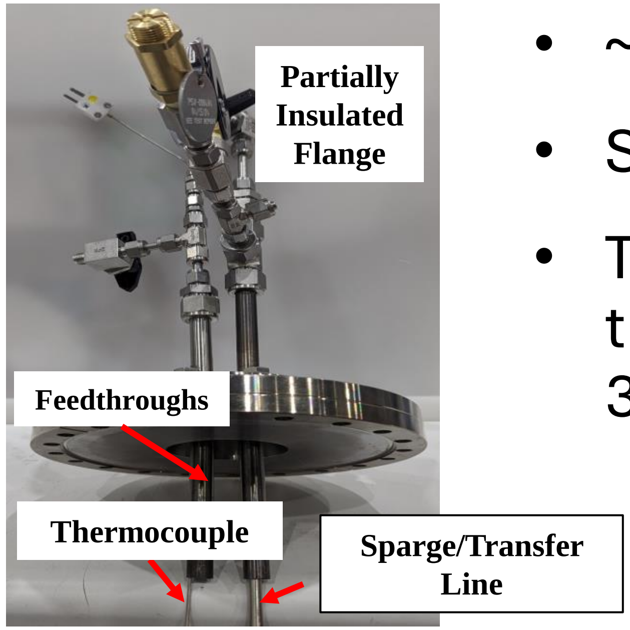
ORNL Scientific Glassblower: Carlos Rodriguez Flores

10 mL to 1,000 mL

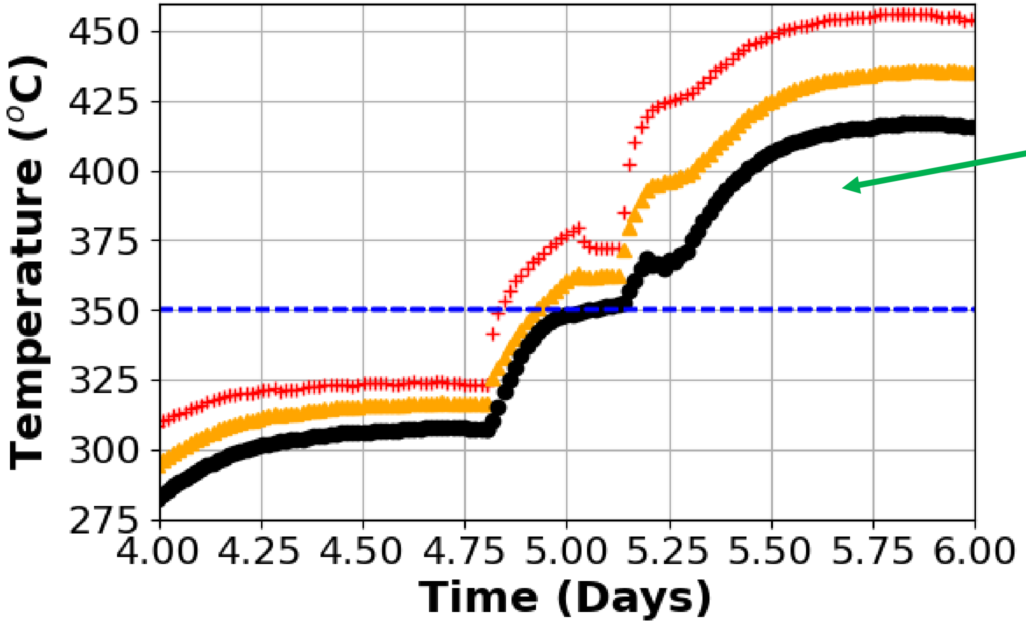
Current status

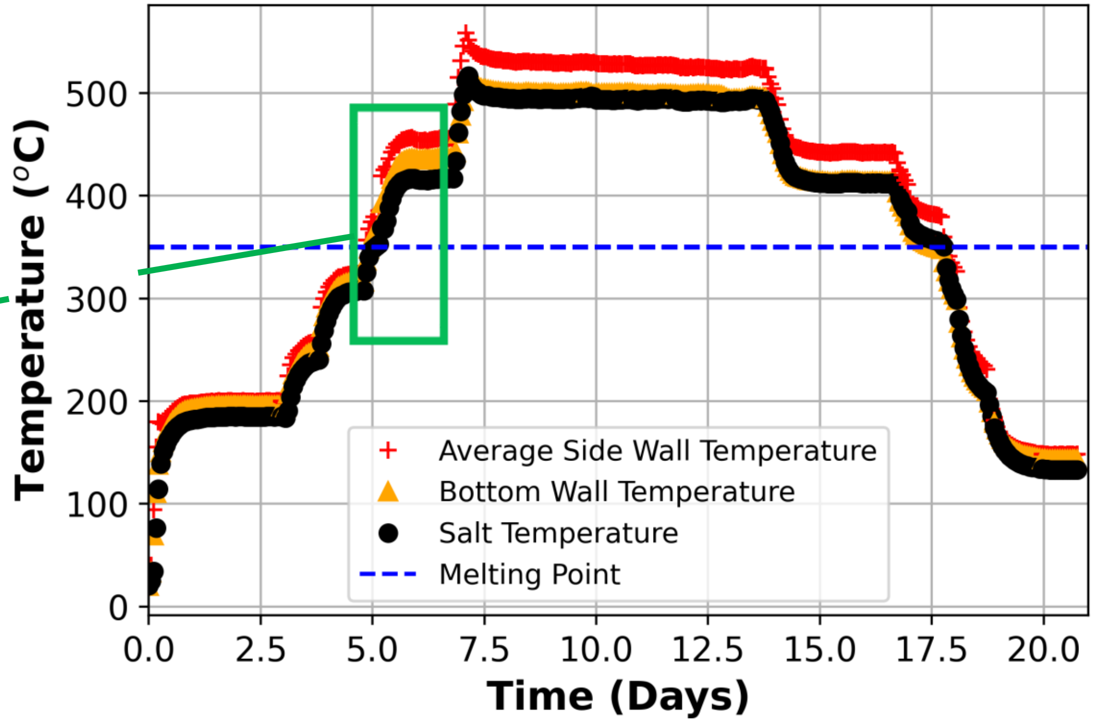


Secondary Vessel Commissioning



- ~2 kg of LiCl / KCl 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





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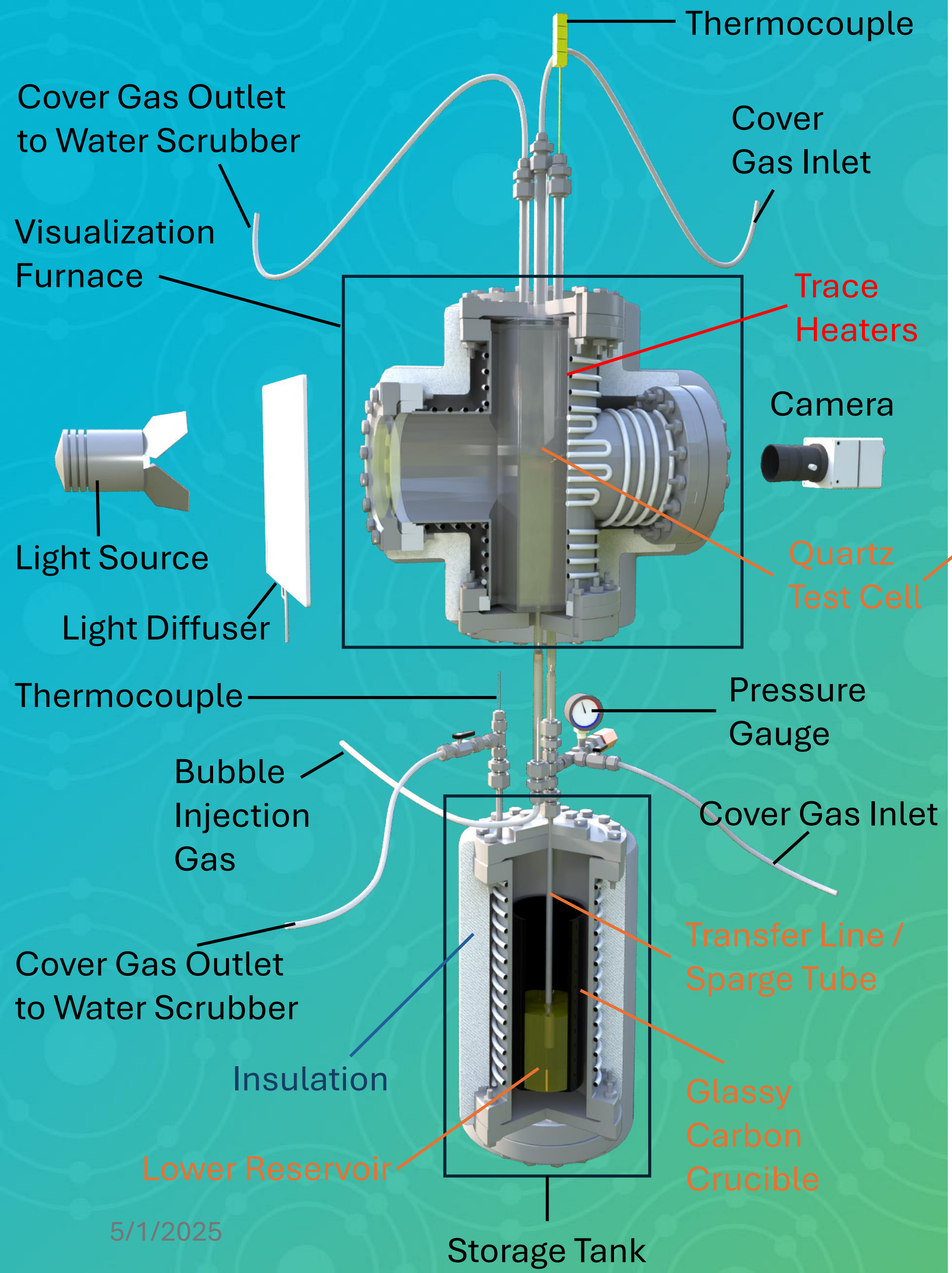
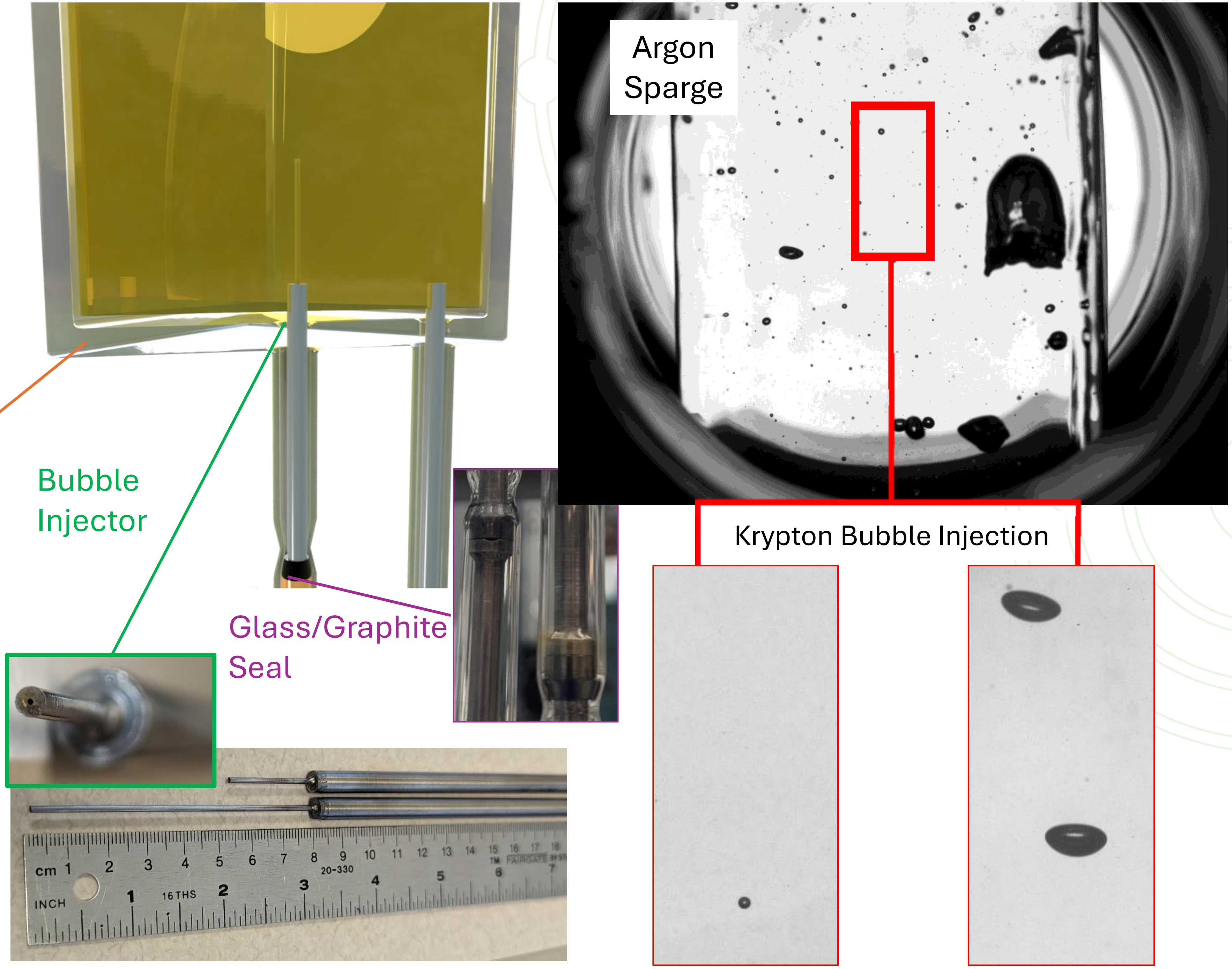
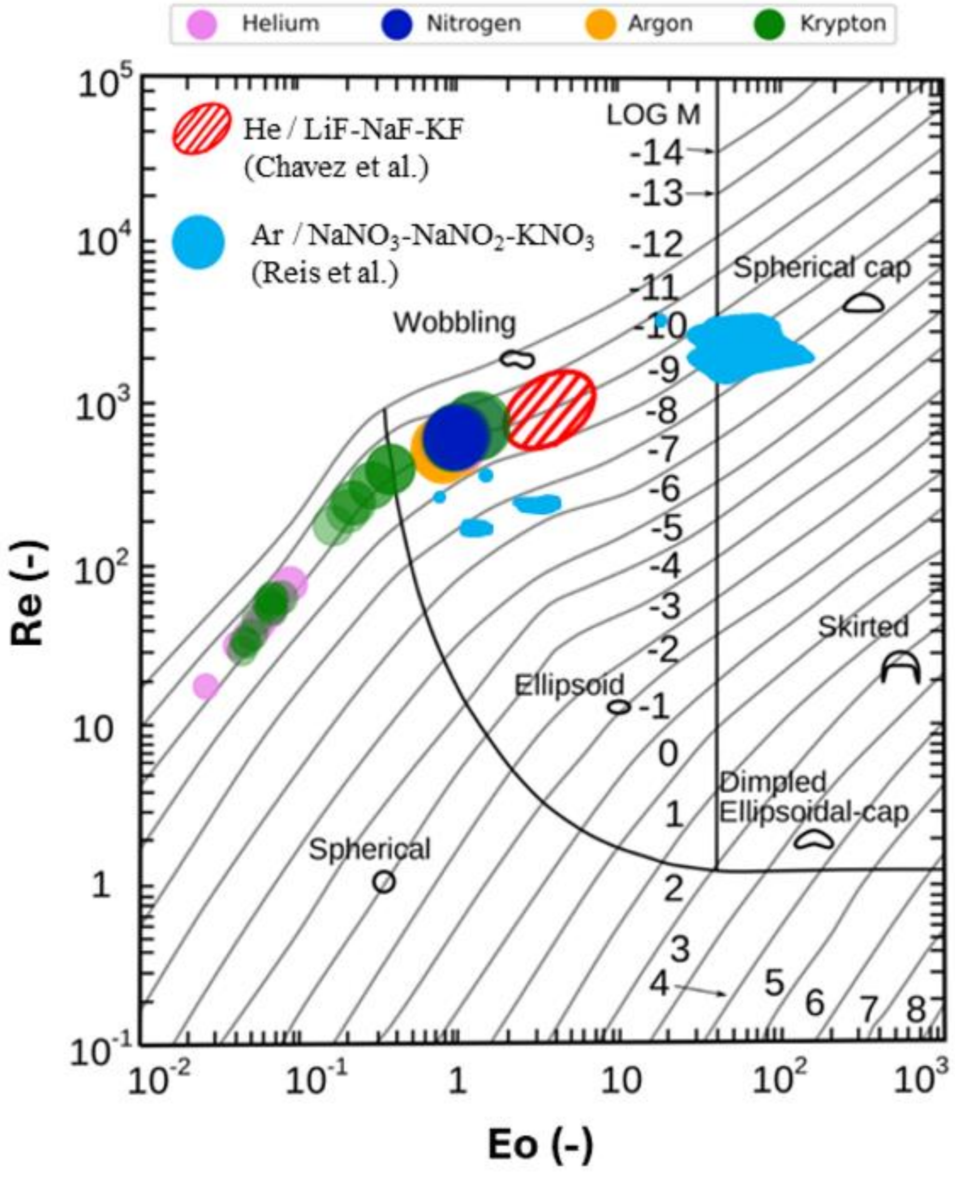
Molten Salt Visualization Apparatus





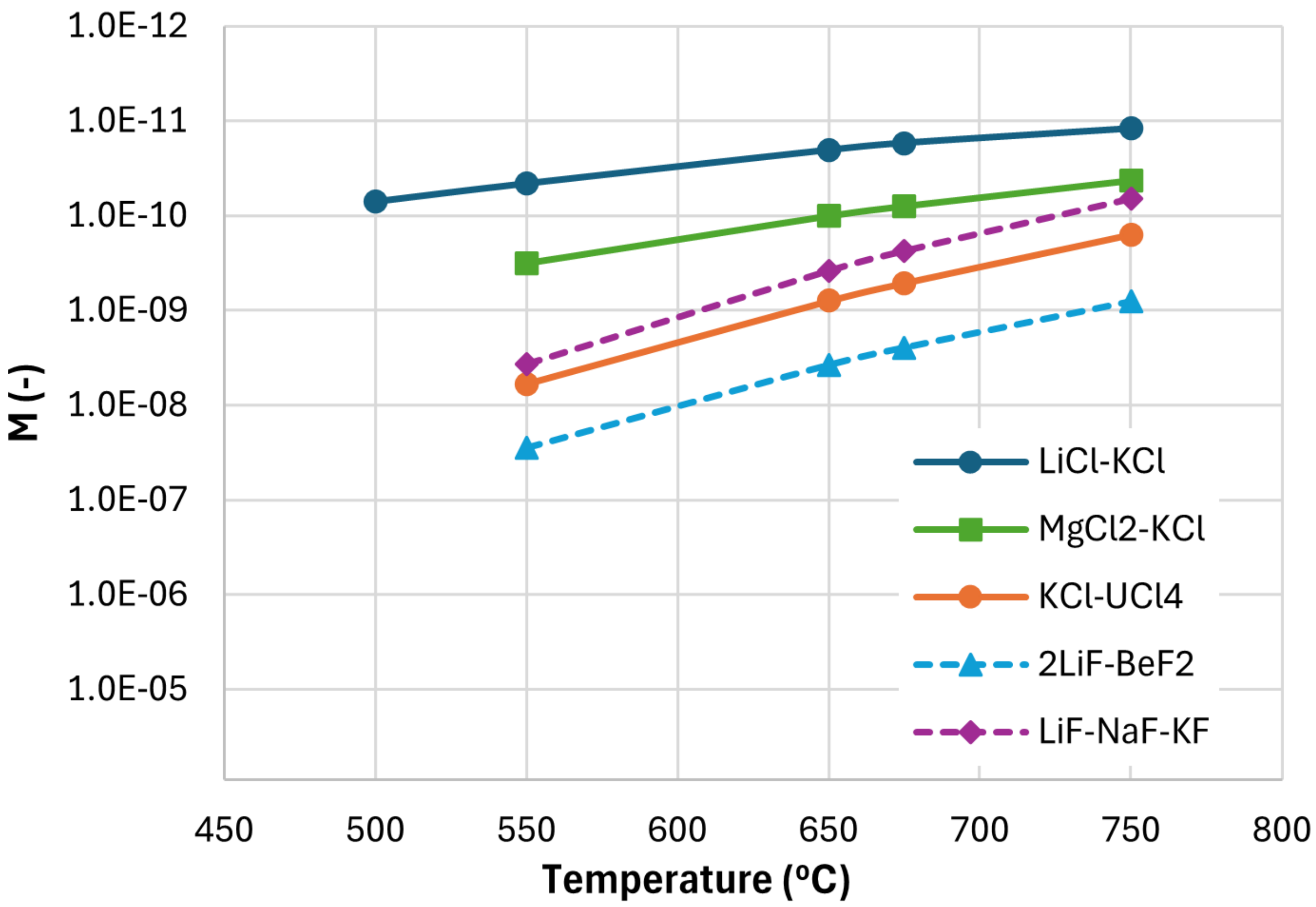
Bubble Behavior in Molten Salt



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

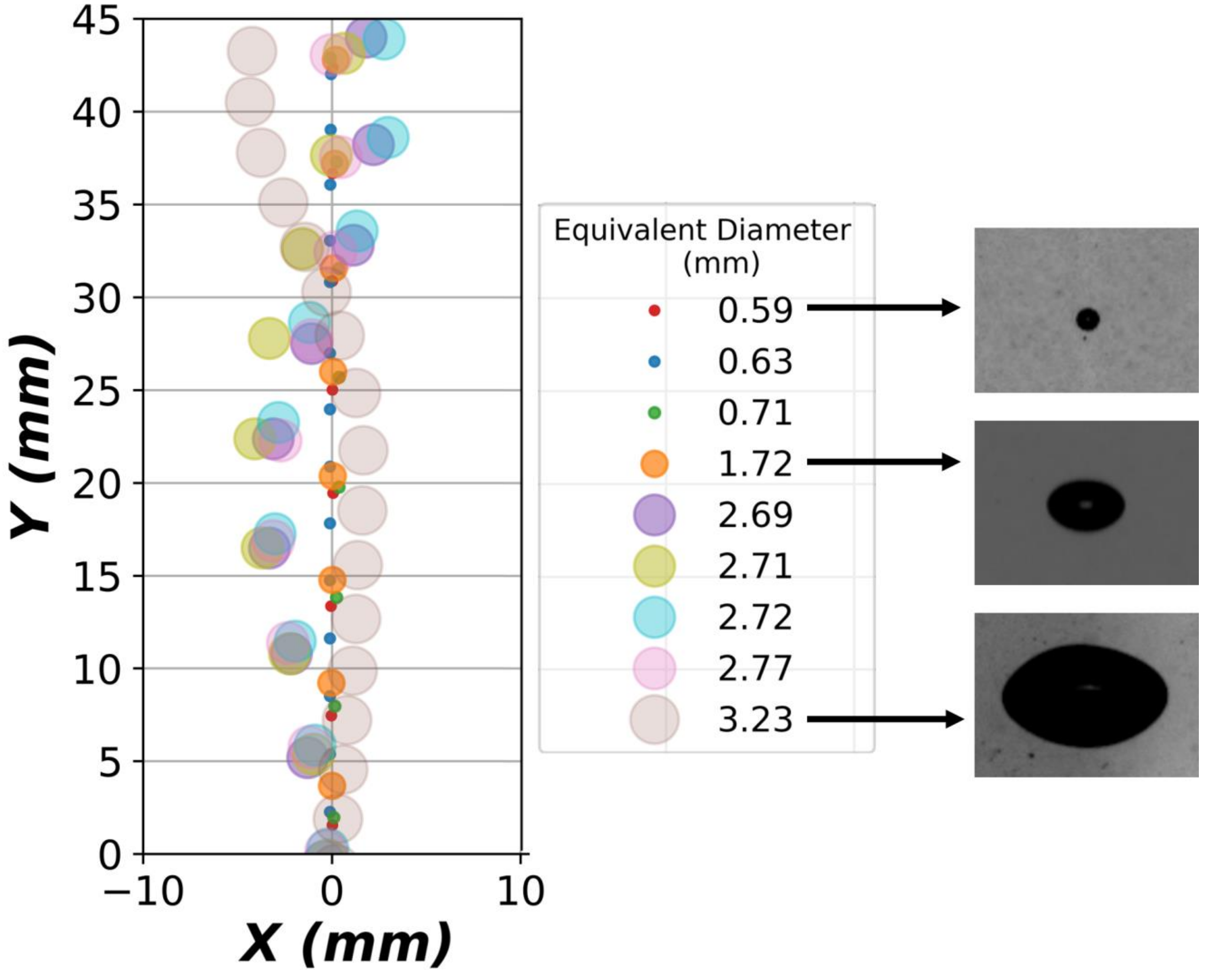
$$Re = \frac{\rho_l V D}{\mu_l}$$

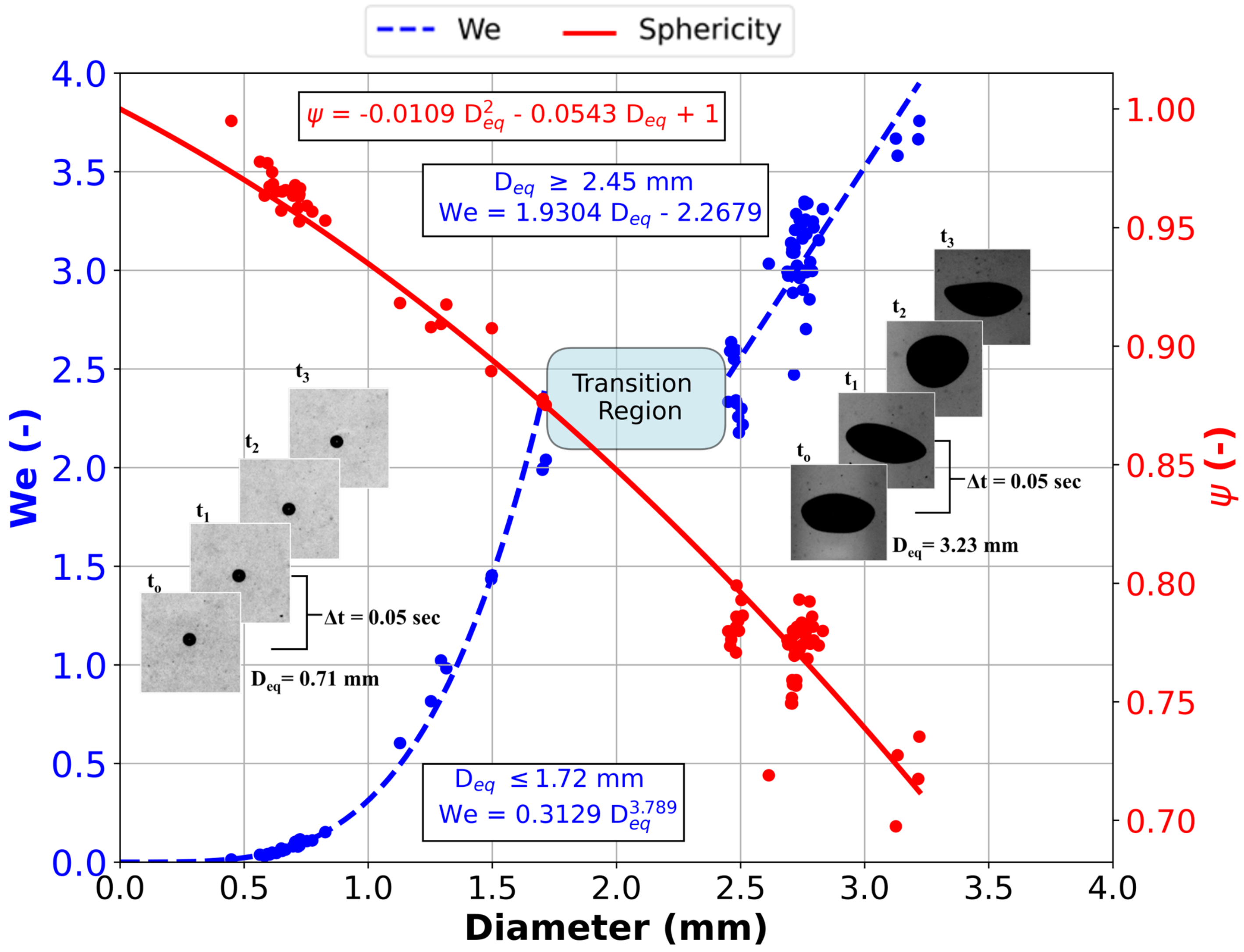
$$Mo = \frac{\Delta \rho g \mu^4}{{\rho_l}^2 {\sigma_l}^3}$$



D. Orea, K. Robb and J. McFarlane, "Optical Measurements of Gas Bubble Rise Velocity in Molten LiCl-KCl," Nuclear Engineering and Design, 2025. (in review)

Bubble Behavior in Molten Salt (cont'd)





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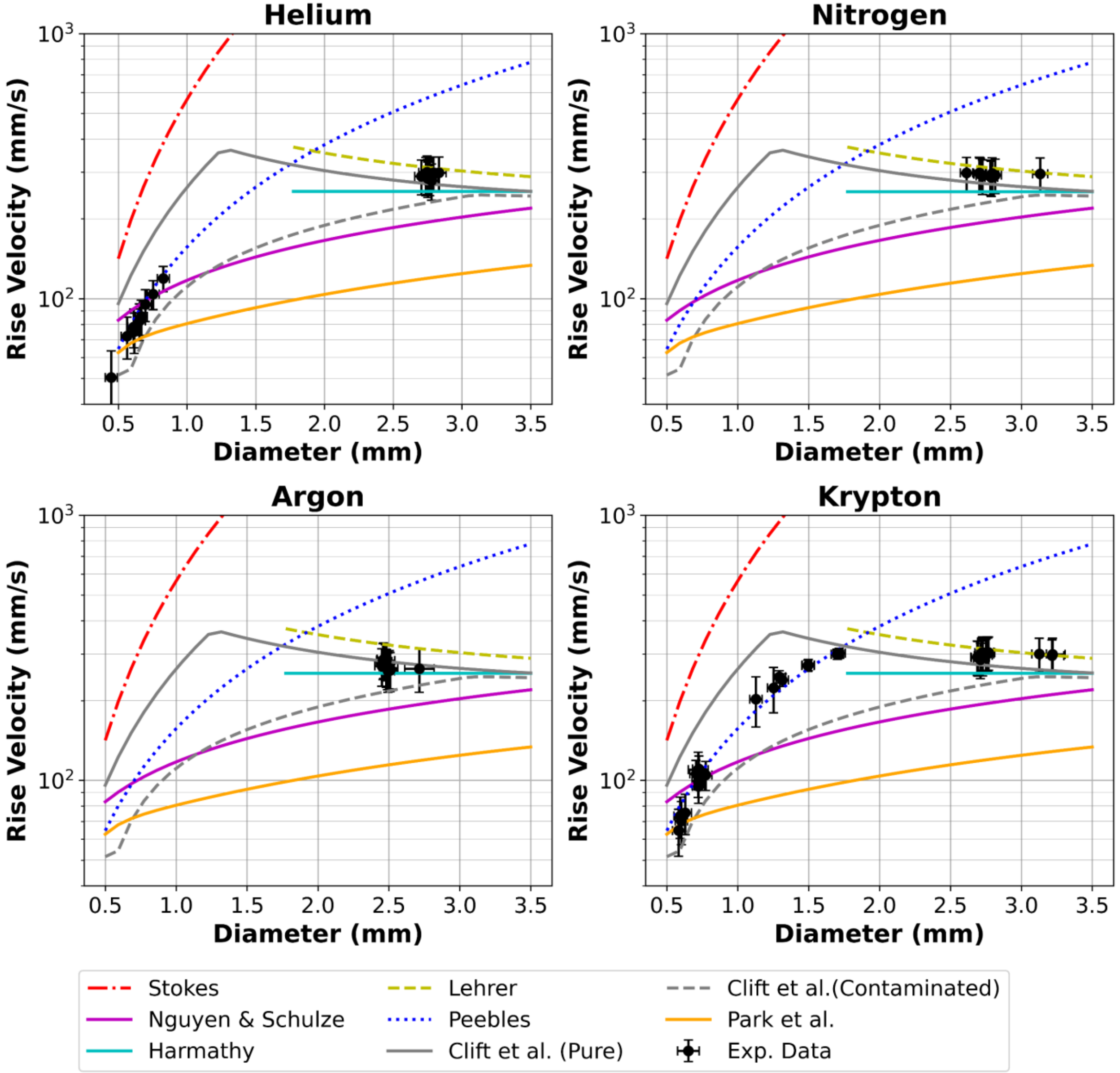
Bubble Rise Velocity

Reference	Model	Notes
Stokes [22]	$V_T = {}^{2\rho_l g R_{eq}^2}/_{9\mu_l}$	Assumes a rigid sphere
Nguyen & Schulze [23]	$V_T = 18V_{stk}\left(\frac{4a^2 Ar^{2b-1} Mo^{0.46b}}{3k}\right)^{1/2-2b}$	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]	$V_T = 1/\sqrt{{}^1/_{V_{vis}^2} + {}^1/_{V_{in}^2} + {}^1/_{V_{spheroid}^2}}$	$V_{vis} = {}^{g\rho_l D_{eq}^2}/_{12\mu_l}$ $V_{in} = 0.14425g^{5/6}(\rho_l/\mu_l)^{2/3} D_{eq}^{3/2}$ $V_{spheroid} = \sqrt{{}^{2.14\mu_l}/_{\rho_l D_{eq}} + 0.505gD_{eq}}$



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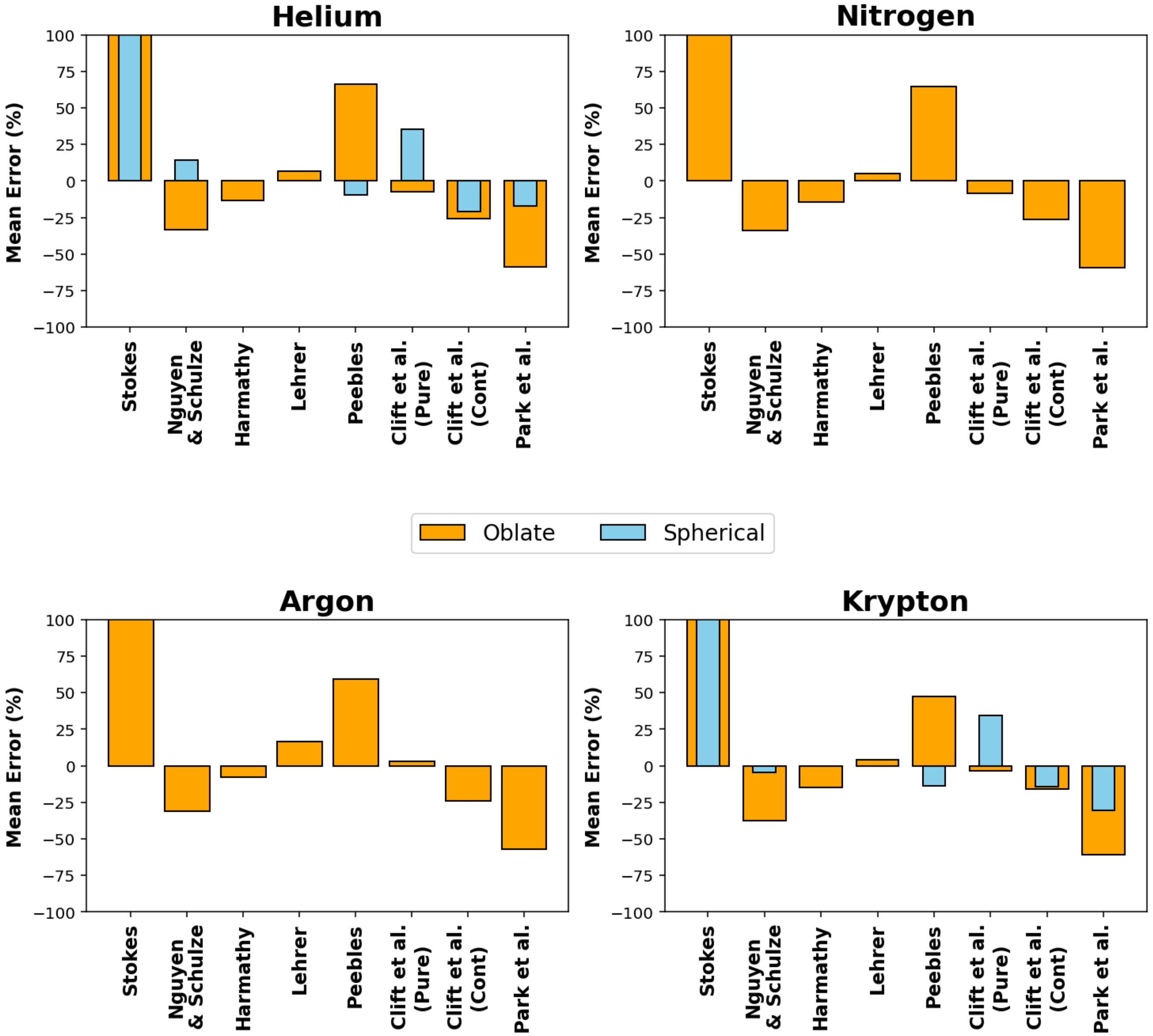
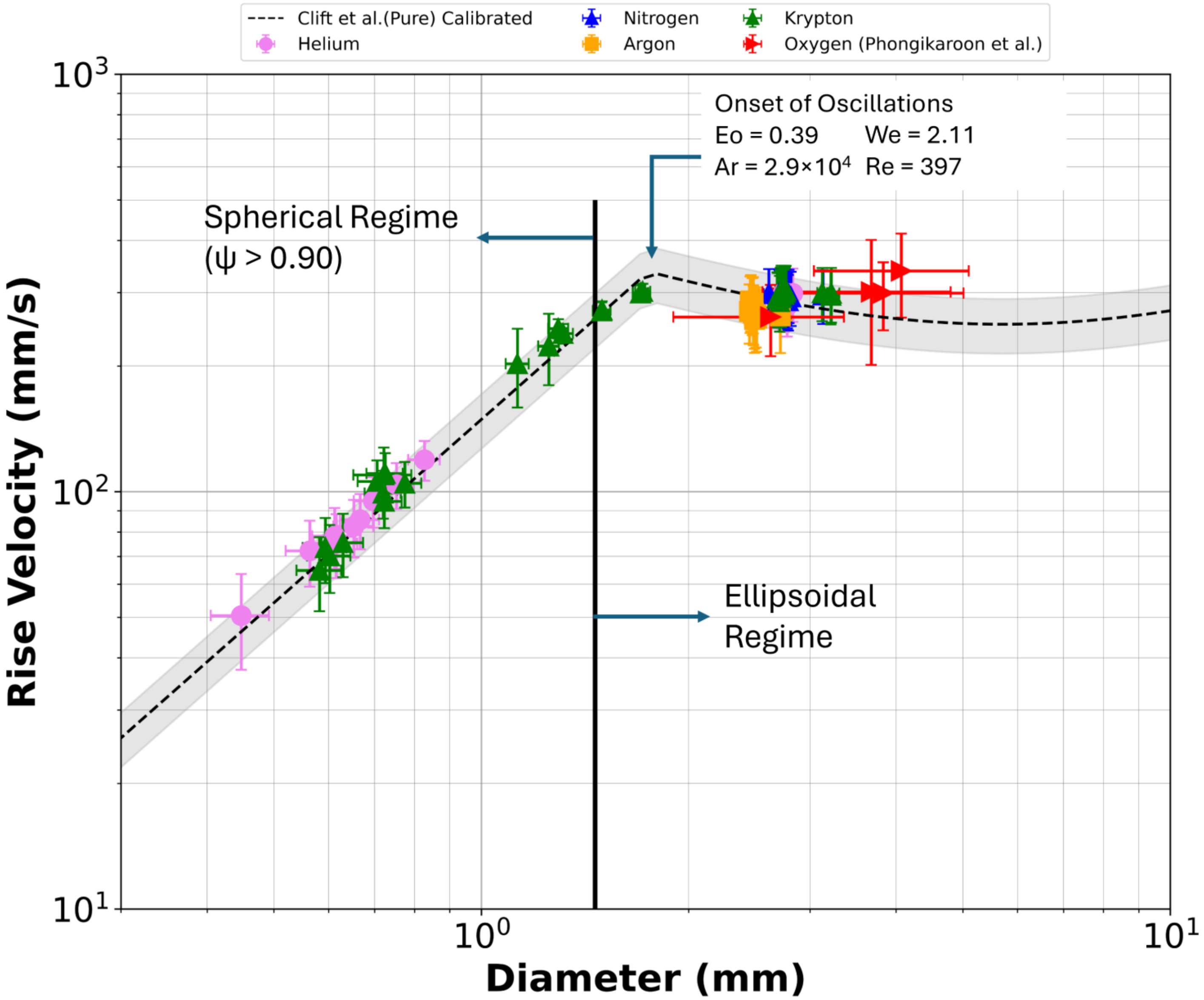
Bubble Rise Velocity (cont'd)





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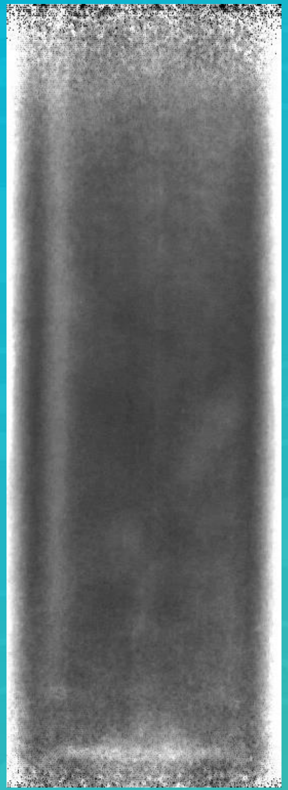

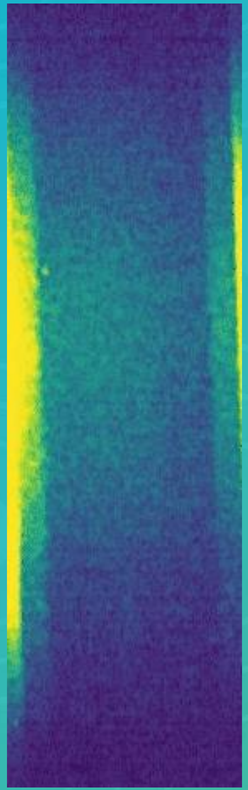

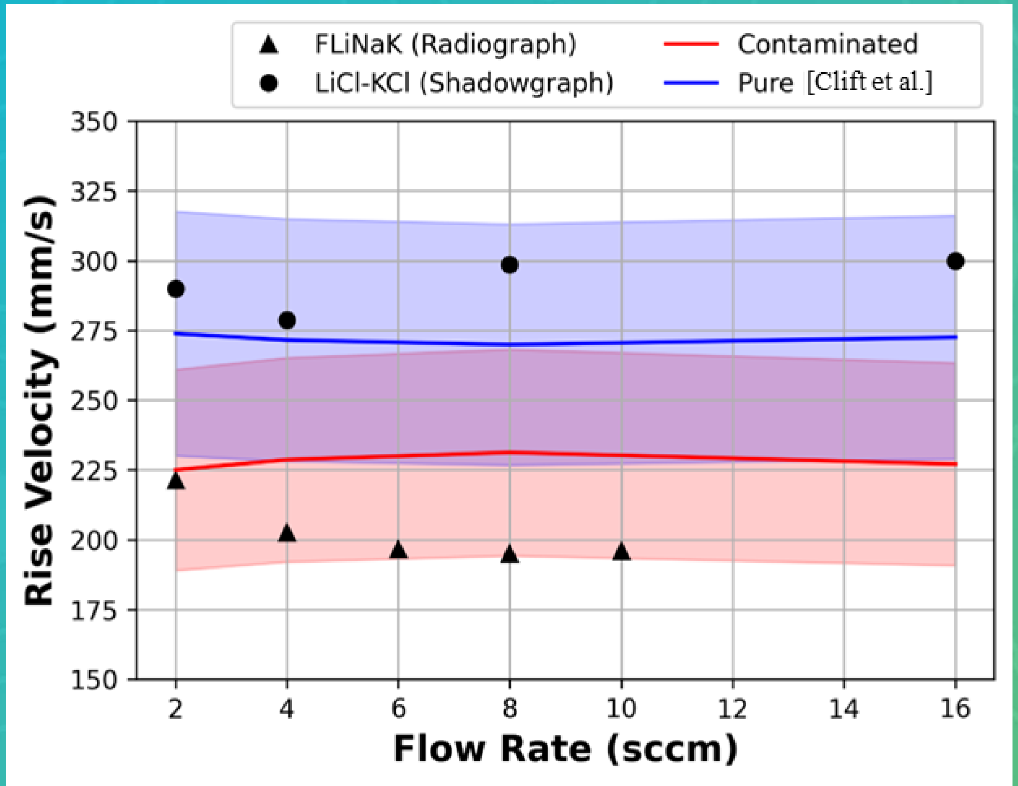

Expanding Data to Other Salts

- Successfully demonstrated the ability to detect and track gas bubbles in molten LiF-NaF-NaK
- ORNL HFIR MARS CG1D Instrument
  - Max Image Acquisition Rate of 71 fps, 56 μm effective pixel size
- Other salts systems (actinides, fluorides, beryllium-containing)
- 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

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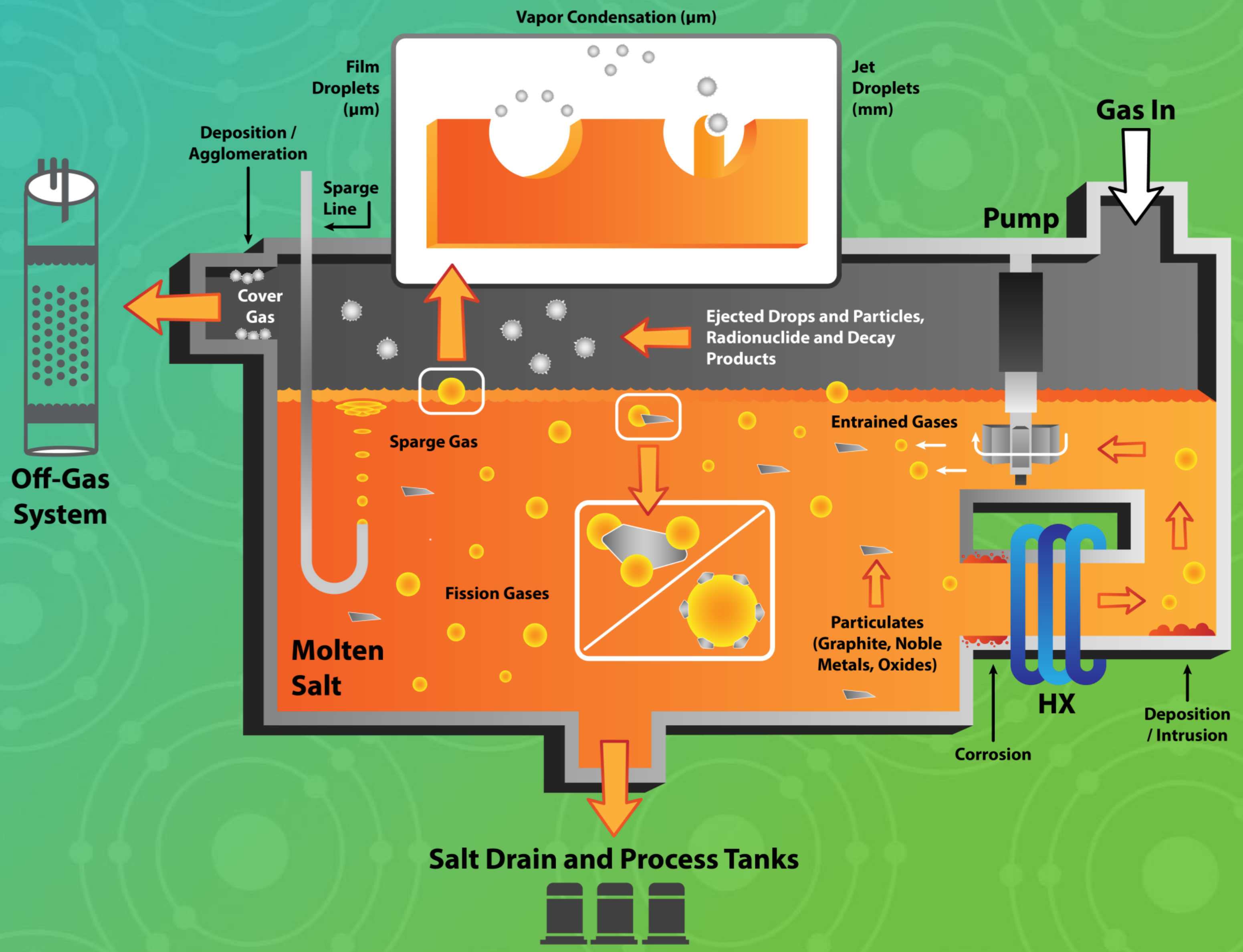
Looking Ahead

- Custom furnace upgrades to allow additional measurements techniques
  - o Particle Image Velocimetry (PIV)
  - o Schlieren Technique
  - o Ultrasonic Sensors – Void fraction measurements
- Investigate other phenomena
  - o Particle/gas behavior, bubble burst, aerosol generation, etc.
- Transition from stagnant to flowing salt
  - o Perform flowing salt measurements



Thank you

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