INL/CON-24-76276-Revision-1

Bubbler Design Updates for Nuclear Safeguards Applications

July 2024

Changing the World's Energy Future

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Idaho National Laboratory

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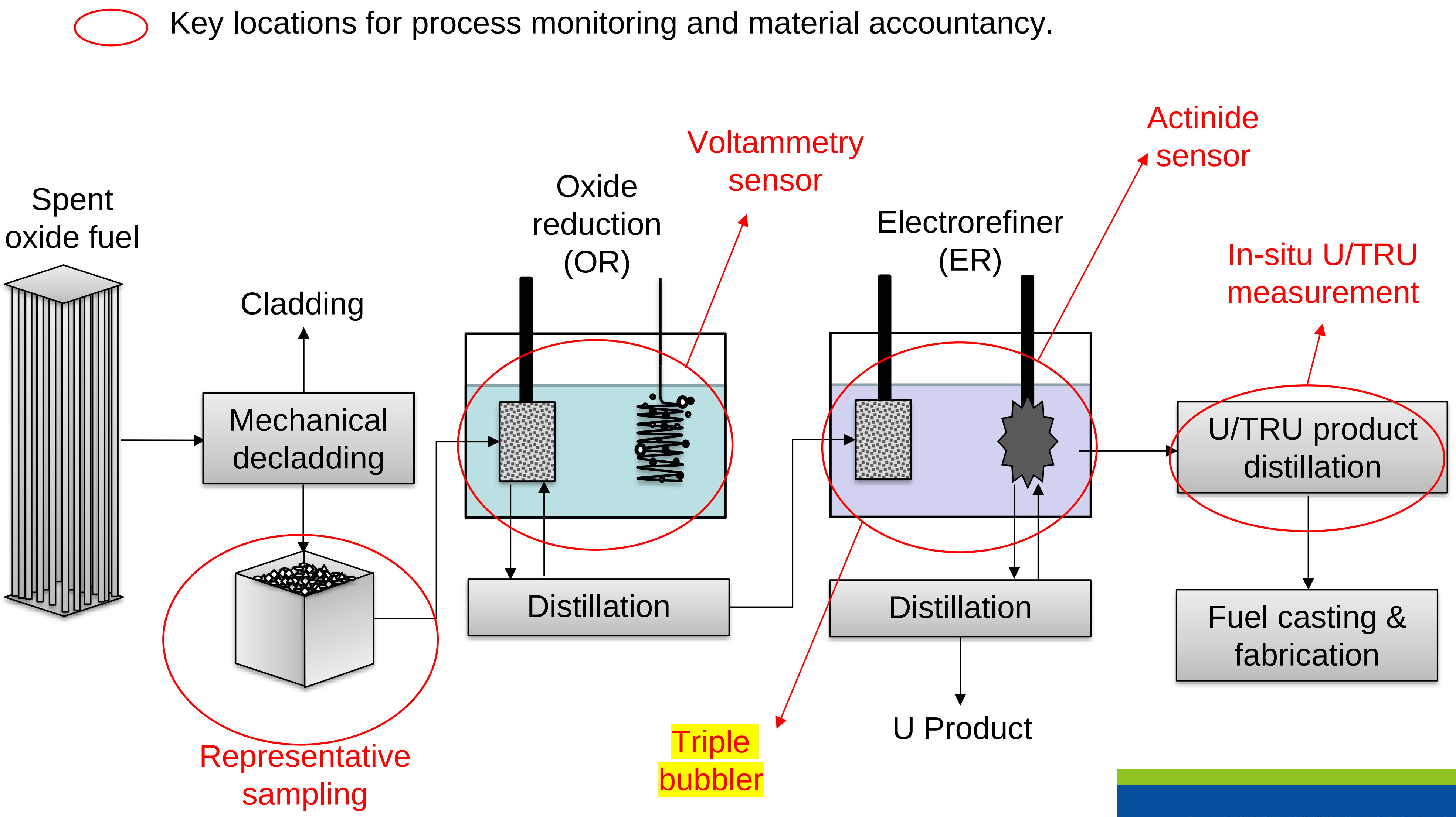
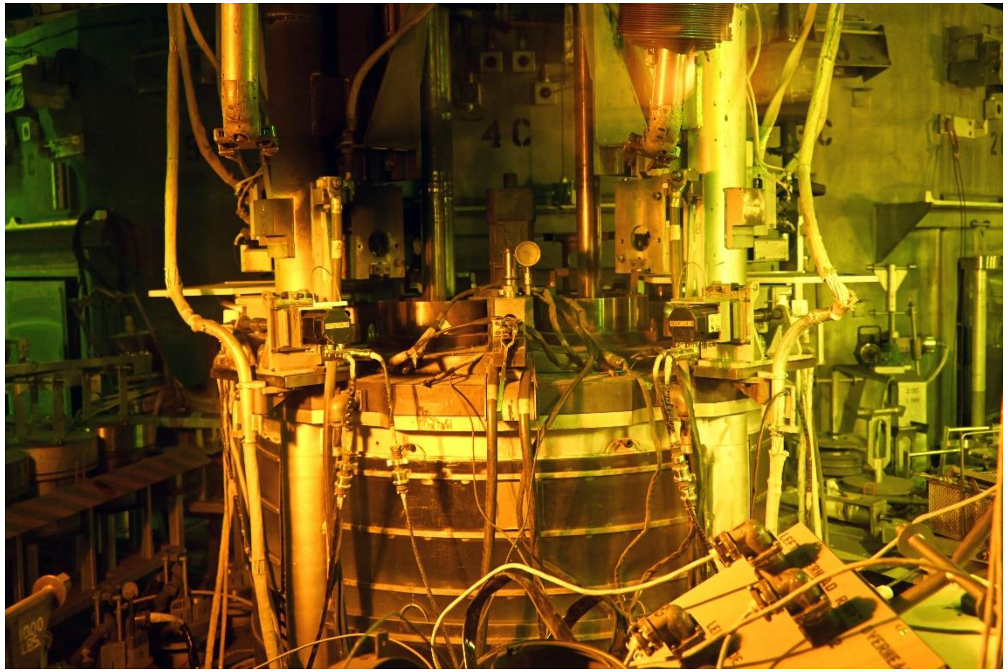
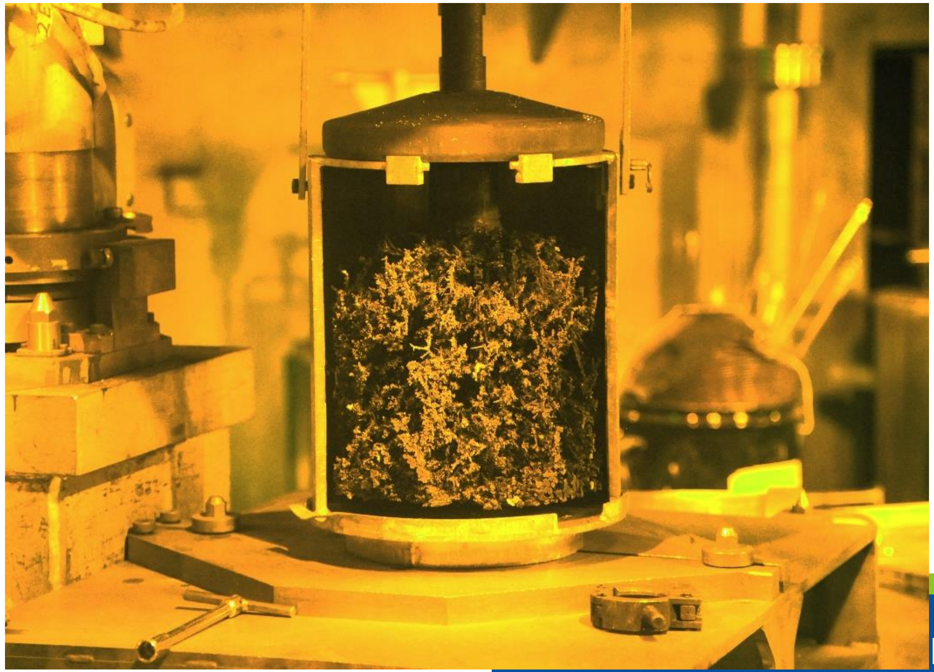
Pyroprocessing & Safeguards Efforts



Material Accountancy

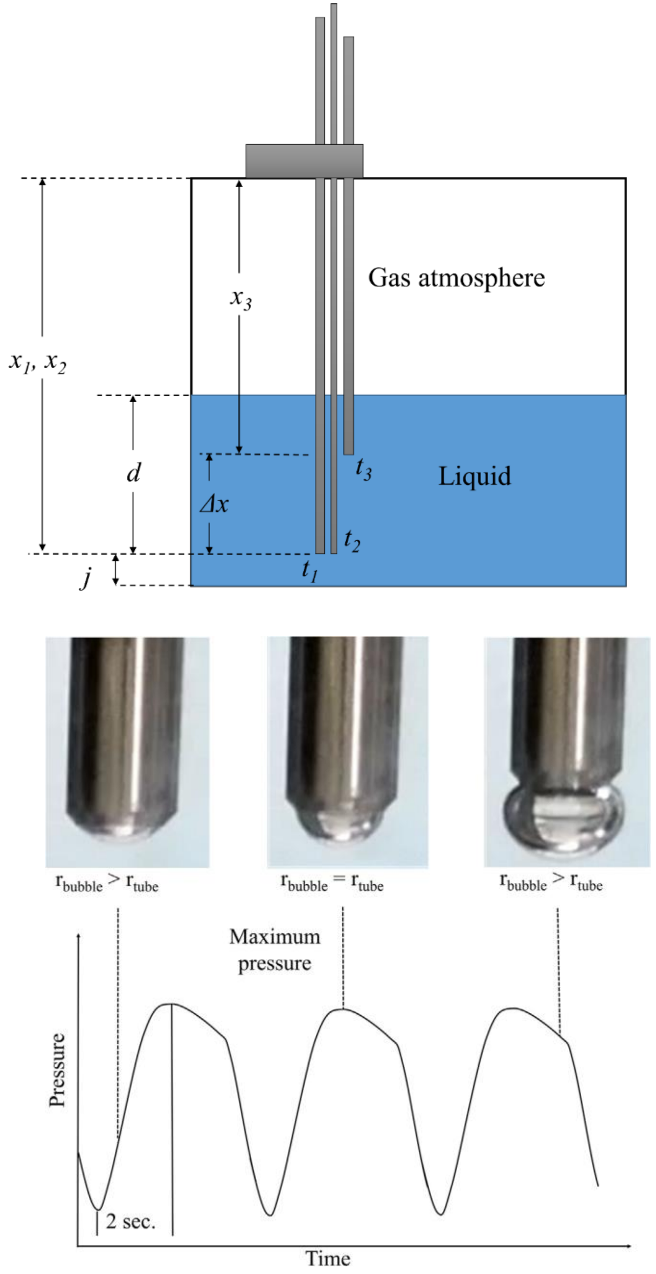
- Motivation:
  - Nuclear Material Accountancy (NMA): Direct measurement of salt density and depth necessary to determine total mass of salt and special nuclear material in electrorefining systems.
  - Process monitoring (PM): Online measurement of salt characteristic, including depth, surface tension and density, allow verification of operational activates and process control.

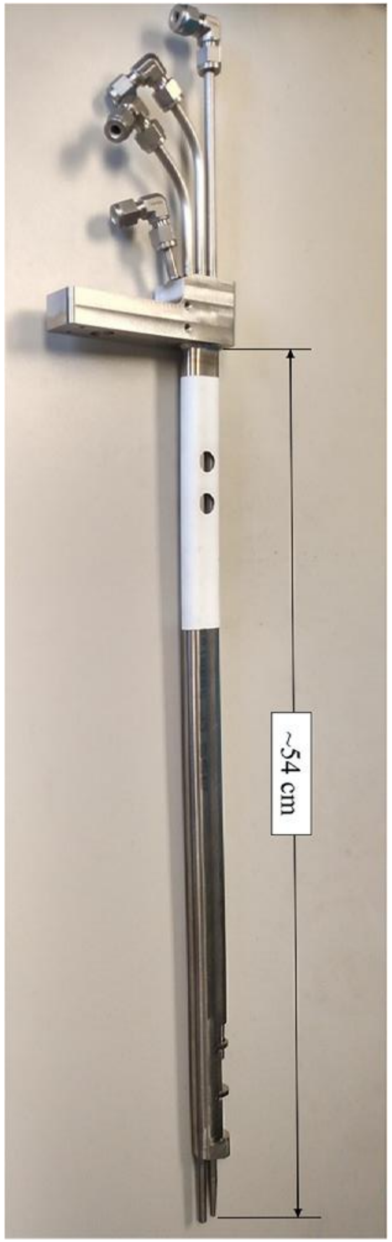




Bubble Shape and Development

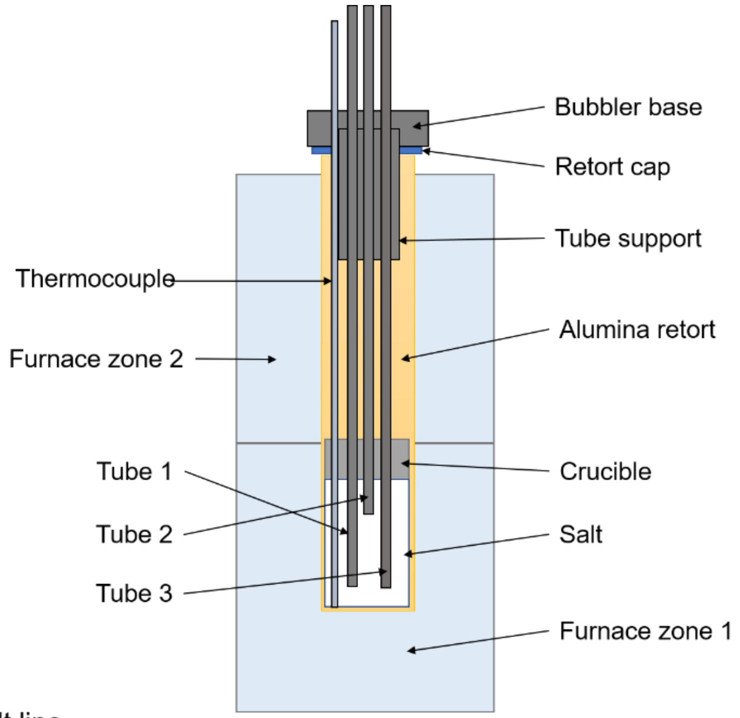
- The techniques for using bubble pressure to determine the density of a fluid has been well researched.
- Bubble pressure fluctuates as a function of development.
  - In the beginning stages, the bubble radius is larger than the tube and the pressure is low.
  - The pressure reaches a peak when the radius of the bubble is exactly equal to the radius of the tube.
  - When the radius of the bubble expands past the tube the pressure drops until separation.

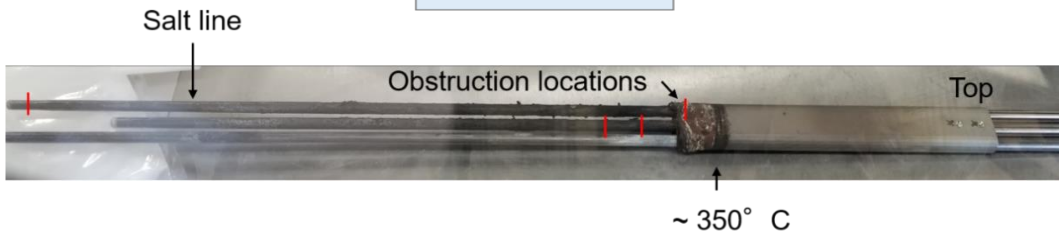


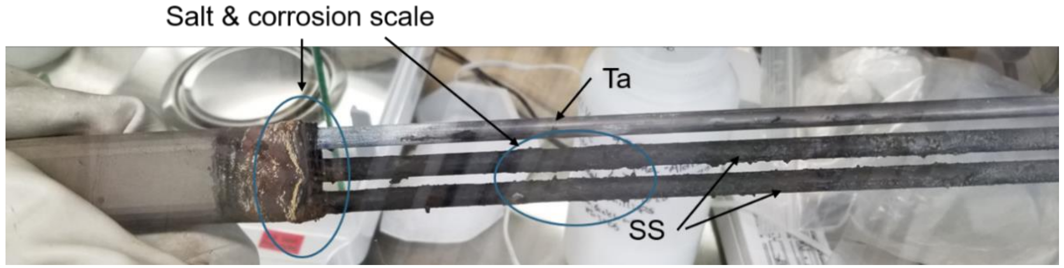


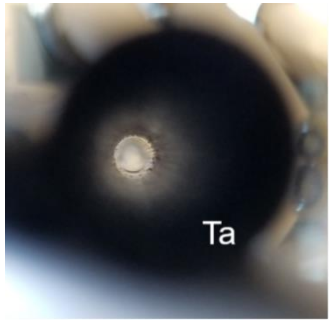
Background Information

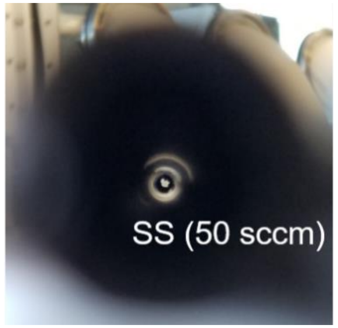
- Previous designs were prone to plugging due to:
  - Insufficient gas flow (0-6 cm^3/min range)
  - Corrosion (O_2 in gas lines?)
  - Small tube diameter
- Corrosion developed on dip tube surfaces:
  - Resistant to washes and soaks in DI water
  - Removable only by vigorous scrubbing and scraping

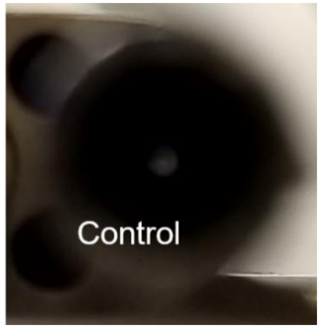












Triple Bubbler Updates

- Installed new MFCs on the gas panel
  - Range of 4-200 cm3/min
  - Still updating software interface to control them
- Tested O_2 absorbers in line with HFEF gas lines
- Redesigned bubbler with larger tubes!
  - 0.312” (7.93 mm) OD vs 0.25” (6.35 mm) OD
  - ID are 0.242” (6.16 mm) vs 0.15” (3.81 mm)
  - How do larger tubes effect accuracy?

Geometric Changes

- The tubes were arranged so that tube three is placed on the edge to minimize interactions with rising bubbles.
- The governing equations to relate pressure to density are:

$$P_1 = \rho g d_1 + c_1 \rho g r_1 + \frac{c_2 \gamma}{r_1}$$

$$P_2 = \rho g d_2 + c_1 \rho g r_2 + \frac{c_2 \gamma}{r_2}$$

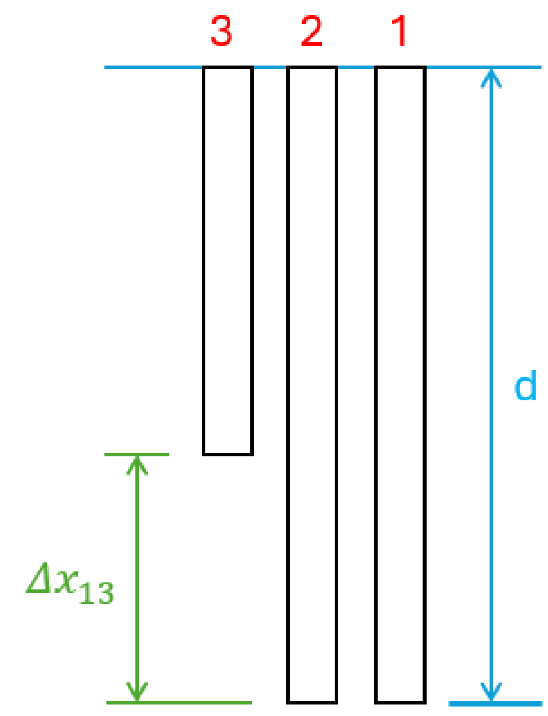
$$P_3 = \rho g d_3 + c_1 \rho g r_3 + \frac{c_2 \gamma}{r_3}$$

- When solved algebraically for d_1, γ, and ρ:

$$d_1 = \frac{-P_1 c_1 r_1 r_2^2 + P_1 c_1 r_1 r_3^2 + P_1 \Delta x_{12} r_1 r_2 - P_1 \Delta x_{13} r_1 r_3 + P_2 c_1 r_1^2 r_2 - P_2 c_1 r_2 r_3^2 + P_2 \Delta x_{13} r_1 r_3 - P_3 c_1 r_1^2 r_3 + P_3 c_1 r_2^2 r_3 - P_3 \Delta x_{12} r_2 r_3}{P_1 r_1 r_2 - P_1 r_1 r_3 - P_2 r_1 r_2 + P_2 r_2 r_3 + P_3 r_1 r_3 - P_3 r_2 r_3}$$

$$\gamma = \frac{-r_1 r_2 r_3 (-P_1 c_1 r_2 + P_1 c_1 r_3 + P_1 \Delta x_{12} - P_1 \Delta x_{13} + P_2 c_1 r_1 - P_2 c_1 r_3 + P_2 \Delta x_{13} - P_3 c_1 r_1 + P_3 c_1 r_2 - P_3 \Delta x_{12})}{c_2 (c_1 r_1^2 r_2 - c_1 r_1^2 r_3 - c_1 r_1 r_2^2 + c_1 r_1 r_3^2 + c_1 r_2^2 r_3 - c_1 r_2 r_3^2 + \Delta x_{12} r_1 r_2 - \Delta x_{12} r_2 r_3 - \Delta x_{13} r_1 r_3 + \Delta x_{13} r_2 r_3)}$$

$$\rho = \frac{P_1 r_1 r_2 - P_1 r_1 r_3 - P_2 r_1 r_2 + P_2 r_2 r_3 + P_3 r_1 r_3 - P_3 r_2 r_3}{g (c_1 r_1^2 r_2 - c_1 r_1^2 r_3 - c_1 r_1 r_2^2 + c_1 r_1 r_3^2 + c_1 r_2^2 r_3 - c_1 r_2 r_3^2 + \Delta x_{12} r_1 r_2 - \Delta x_{12} r_2 r_3 - \Delta x_{13} r_1 r_3 + \Delta x_{13} r_2 r_3)}$$



Scope of Testing

- Calibration in DI water by calculating values of c_1 and c_2

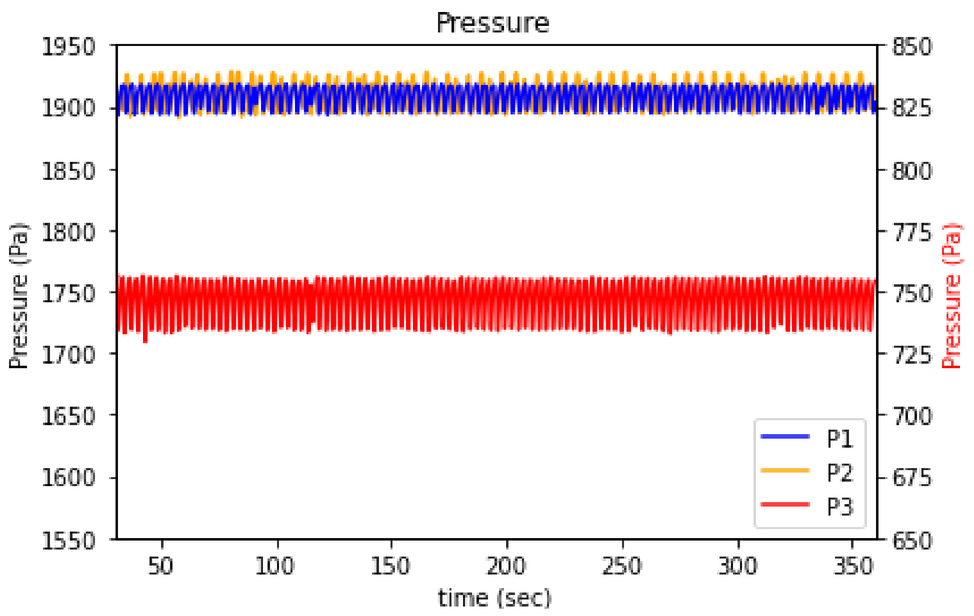
$$c_1 = \frac{P_1 d_1 r_1 r_2 - P_1 d_1 r_1 r_3 - P_1 \Delta x_{12} r_1 r_2 + P_1 \Delta x_{13} r_1 r_3 - P_2 d_1 r_1 r_2 + P_2 d_1 r_2 r_3 - P_2 \Delta x_{13} r_2 r_3 + P_3 d_1 r_1 r_3 - P_3 d_1 r_2 r_3 + P_3 \Delta x_{12} r_2 r_3}{-P_1 r_1 r_2^2 + P_1 r_1 r_3^2 + P_2 r_1^2 r_2 - P_2 r_2 r_3^2 - P_3 r_1^2 r_3 + P_3 r_2^2 r_3}$$

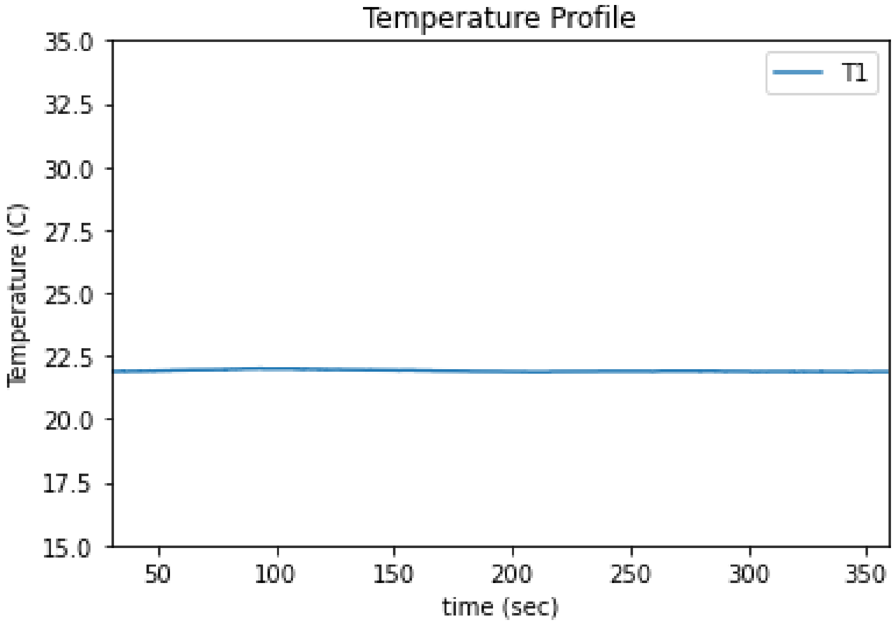
$$c_2 = \frac{-r_1 r_2 r_3 (-P_1 d_1 r_2 + P_1 d_1 r_3 - P_1 \Delta x_{12} r_3 + P_1 \Delta x_{13} r_2 + P_2 d_1 r_1 - P_2 d_1 r_3 - P_2 \Delta x_{13} r_1 - P_3 d_1 r_1 + P_3 d_1 r_2 + P_3 \Delta x_{12} r_1)}{\gamma (d_1 r_1^2 r_2 - d_1 r_1^2 r_3 - d_1 r_1 r_2^2 + d_1 r_1 r_3^2 + d_1 r_2^2 r_3 - d_1 r_2 r_3^2 - \Delta x_{12} r_1^2 r_2 + \Delta x_{12} r_2 r_3^2 + \Delta x_{13} r_1^2 r_3 - \Delta x_{13} r_2^2 r_3)}$$

- Measured the accuracy against these liquids:
  - NaCl 10 wt%
  - NaCl 22.5 wt%
  - $CaCl_2$ 21 wt%
  - Ca Cl_2 35 wt%
  - Mineral Oil

Pressure Results

- Working Fluid $CaCl_2$ 21 wt%
- Tube one
  - Depth of 14.000 cm
  - Mass Flow Rate 4.0 cm^3 per min.
- Tube two
  - Depth of 13.960 cm
  - Mass Flow Rate 3.2 cm^3 per min.
- Tube three
  - Depth of 3.971 cm
  - Mass Flow Rate 4.0 cm^3 per min.





Working Fluid	Average Density Bubbler A (kg/m^3)	Average Density Bubbler B (kg/m^3)	Actual Density (kg/m^3)	Percent Error A (%)	Percent Error B (%)
DI water	998	995	998.08	0.0476	0.328
10 wt% NaCl	1070	1060	1070.14	0.108	0.611
22.5 wt% NaCl	1160	1160	1167.37	0.430	0.544
21 wt% $CaCl_2$	1180	1180	1183.19	0.117	0.0507
35 wt% $CaCl_2$	1330	1330	1331.10	0.0169	0.221
Mineral Oil	842	841	843.88	0.171	0.350

$$c_1 = \frac{P_1 d_1 r_1 r_2 - P_1 d_1 r_1 r_3 - P_1 \Delta x_{12} r_1 r_2 + P_1 \Delta x_{13} r_1 r_3 - P_2 d_1 r_1 r_2 + P_2 d_1 r_2 r_3 - P_2 \Delta x_{13} r_2 r_3 + P_3 d_1 r_1 r_3 - P_3 d_1 r_2 r_3 + P_3 \Delta x_{12} r_2 r_3}{-P_1 r_1 r_2^2 + P_1 r_1 r_3^2 + P_2 r_1^2 r_2 - P_2 r_2 r_3^2 - P_3 r_1^2 r_3 + P_3 r_2^2 r_3}$$

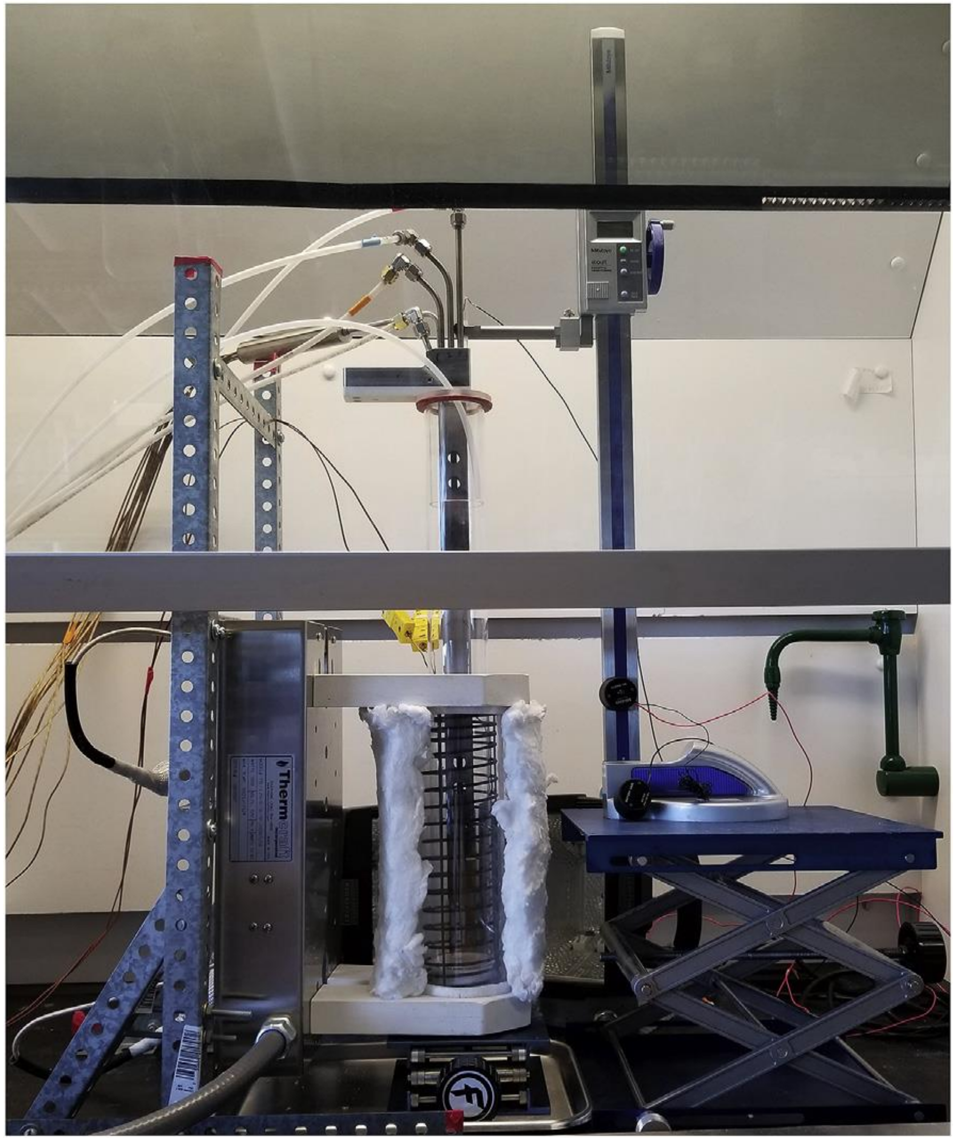
$$\rho = \frac{P_1 r_1 r_2 - P_1 r_1 r_3 - P_2 r_1 r_2 + P_2 r_2 r_3 + P_3 r_1 r_3 - P_3 r_2 r_3}{g(c_1 r_1^2 r_2 - c_1 r_1^2 r_3 - c_1 r_1 r_2^2 + c_1 r_1 r_3^2 + c_1 r_2^2 r_3 - c_1 r_2 r_3^2 + \Delta x_{12} r_1 r_2 - \Delta x_{12} r_2 r_3 - \Delta x_{13} r_1 r_3 + \Delta x_{13} r_2 r_3)}$$

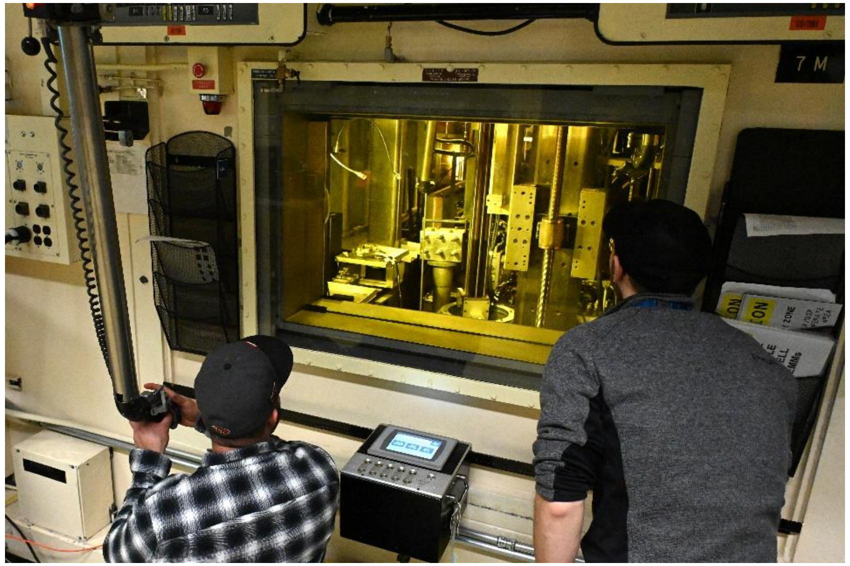
Results

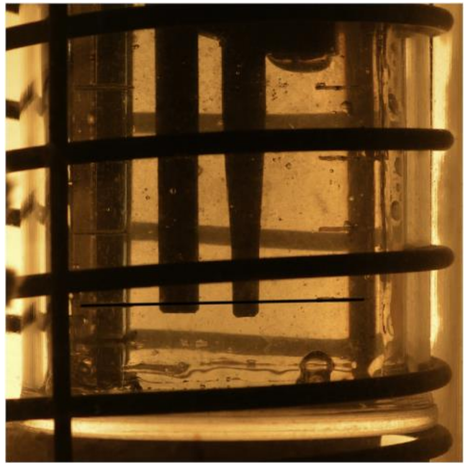
- Both Bubblers A and B are accurate within 1%
  - Bubbler B is measuring the fluid density consistently lower than the actual.
- Change the correction factor c_1 from mathematically calculated to experimentally derived.

Future Work

- High temperature (450-550°C) in LiCl-KCl salt
  - Explore effects of tube diameter & flowrate
  - Calibrate data
- Following lab testing, send one into HFEF for initial baseline testing before processing begins in the ER!







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