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Idaho National Laboratory

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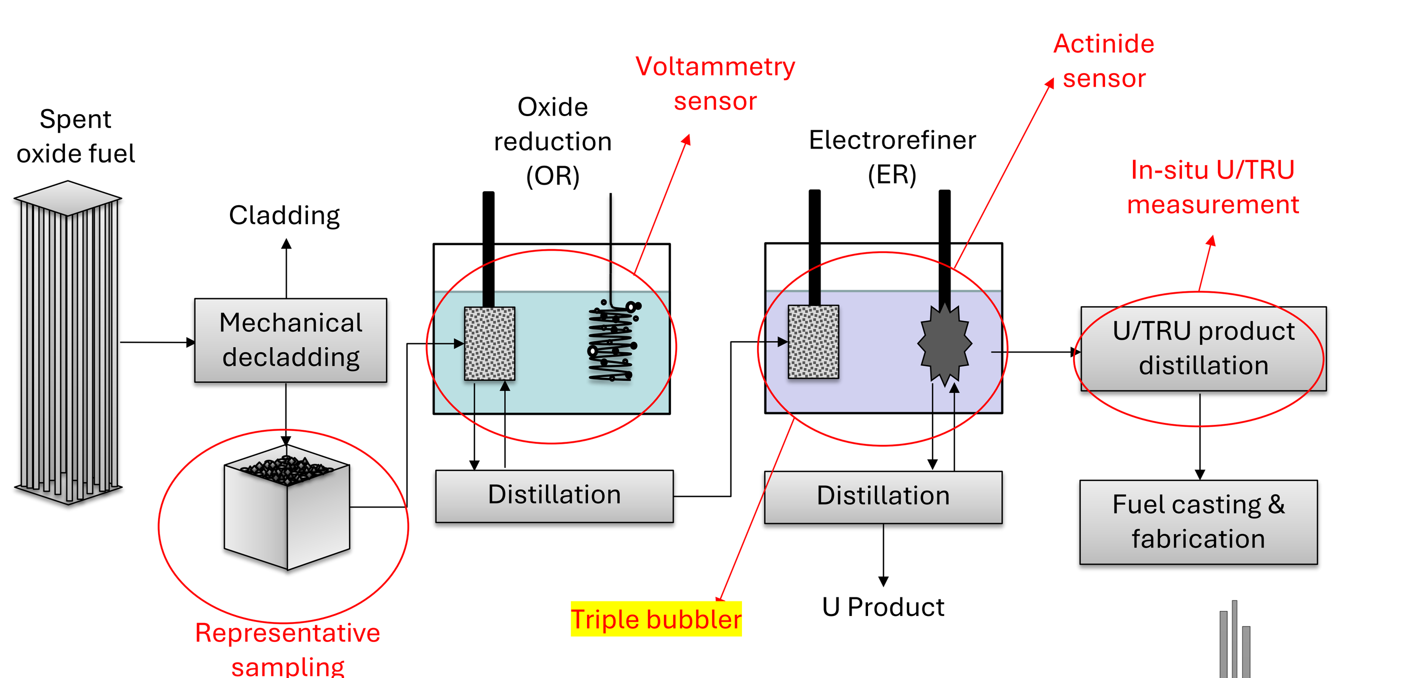
D230 Material Minimization, Security & International Safeguards

Introduction & Purpose

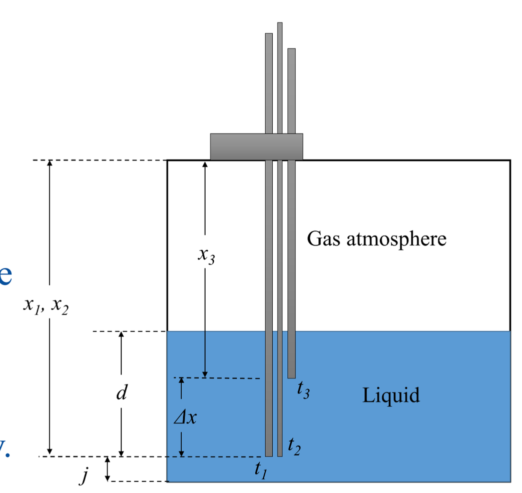
Brief Introduction Into Pyroprocessing:

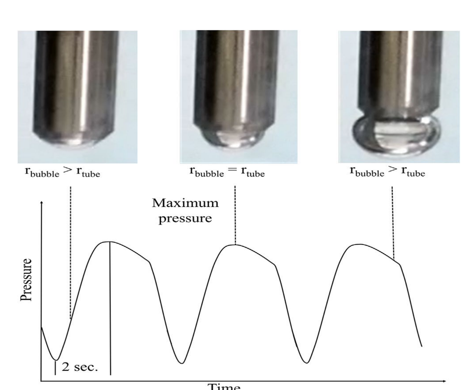
The emerging field of molten salt applications in the nuclear industry is driving innovation and necessitating the development of advanced monitoring technologies. Central to this progression is the construction of a new, enhanced bubbler system designed to improve the accuracy and reliability of molten salt measurements—critical for nuclear material tracking and accounting in commercial processes. Idaho National Laboratory (INL) is at the forefront of these developments. The recent focus has been refining a triple bubbler capable of precisely monitoring molten salt density and level within a vessel, thereby enabling the calculation of total salt volume and mass of special nuclear material.



How the Tripple Bubbler Works:

The Tripple Bubbler utilizes three dip tubes strategically placed throughout a fluid. Tubes one and two are placed approximately the same depth in the fluid, and tube three is places ~10 cm higher. At the outlet, dip tubes one and three have the same diameter while tube two has a smaller radius. With this setup the fluid density ρ, surface tension γ, and the depth d_1 can be calculated simultaneously.

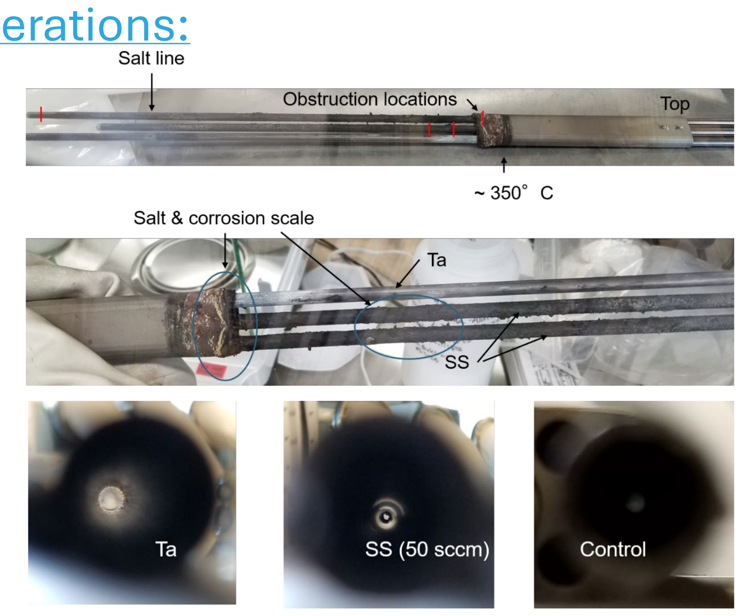




- Bubble pressure fluctuates as a function of development.
  - In the beginning stages, the bubble radius is larger than the tube and the pressure is low.
  - The pressure reaches a peak when the radius of the bubble is exactly equal to the radius of the tube.
  - When the radius of the bubble expands past the tube the pressure drops until separation.

Corrosion and Plugging in Previous Iterations:

Previous iterations of the triple bubbler experienced significant troubles with the development of scale and dip tube plugging problems. This is likely due to the Maroni Effect. The high surface tension of molten salt combined with the temperature gradient from the molten salts to the dip tubes. This allows the liquid to climb the tube. This combined with insufficient gas flow (0-6 cm³ per min) allowed for corrosion and plugging in the stainless-steel lines. The risk of plugging can be mitigated by changing the material to tantalum, expanding the diameter of the tubes, and increasing the gas flow rate.



Methods & Materials

Governing Equations:

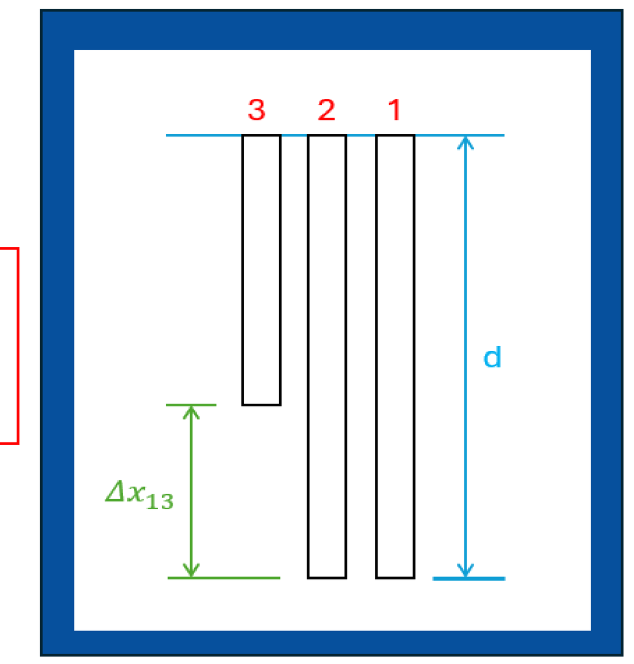
The equations that govern the pressure of the submerged bubble and relate it to the fluid density are given below.

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

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

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

Previous iterations didn't include this term. However, the buoyancy term must be included for tube two due to the expanded geometry.



When these equations are solved algebraically for d_1, γ, and ρ:

$$d_1 = \frac{-P_1c_1r_1r_2^2+P_1c_1r_1r_3^2+P_1\Delta x_{12}r_1r_2-P_1\Delta x_{13}r_1r_3+P_2c_1r_1^2r_2-P_2c_1r_2r_3^2+P_2\Delta x_{13}r_1r_3-P_3c_1r_1^2r_3+P_3c_1r_2^2r_3-P_3\Delta x_{12}r_2r_3}{P_1r_1r_2-P_1r_1r_3-P_2r_1r_2+P_2r_2r_3+P_3r_1r_3-P_3r_2r_3}$$

$$\gamma = \frac{-r_1r_2r_3(-P_1c_1r_2+P_1c_1r_3+P_1\Delta x_{12}-P_1\Delta x_{13}+P_2c_1r_1-P_2c_1r_3+P_2\Delta x_{13}-P_3c_1r_1+P_3c_1r_2-P_3\Delta x_{12})}{c_2(c_1r_1^2r_2-c_1r_1^2r_3-c_1r_1r_2^2+c_1r_1r_3^2+c_1r_2^2r_3-c_1r_2r_3^2+\Delta x_{12}r_1r_2-\Delta x_{12}r_2r_3-\Delta x_{13}r_1r_3+\Delta x_{13}r_2r_3)}$$

$$\rho = \frac{P_1r_1r_2-P_1r_1r_3-P_2r_1r_2+P_2r_2r_3+P_3r_1r_3-P_3r_2r_3}{g(c_1r_1^2r_2-c_1r_1^2r_3-c_1r_1r_2^2+c_1r_1r_3^2+c_1r_2^2r_3-c_1r_2r_3^2+\Delta x_{12}r_1r_2-\Delta x_{12}r_2r_3-\Delta x_{13}r_1r_3+\Delta x_{13}r_2r_3)}$$

The constants c_1 and c_2 are then calibrated in DI water using the following equations:

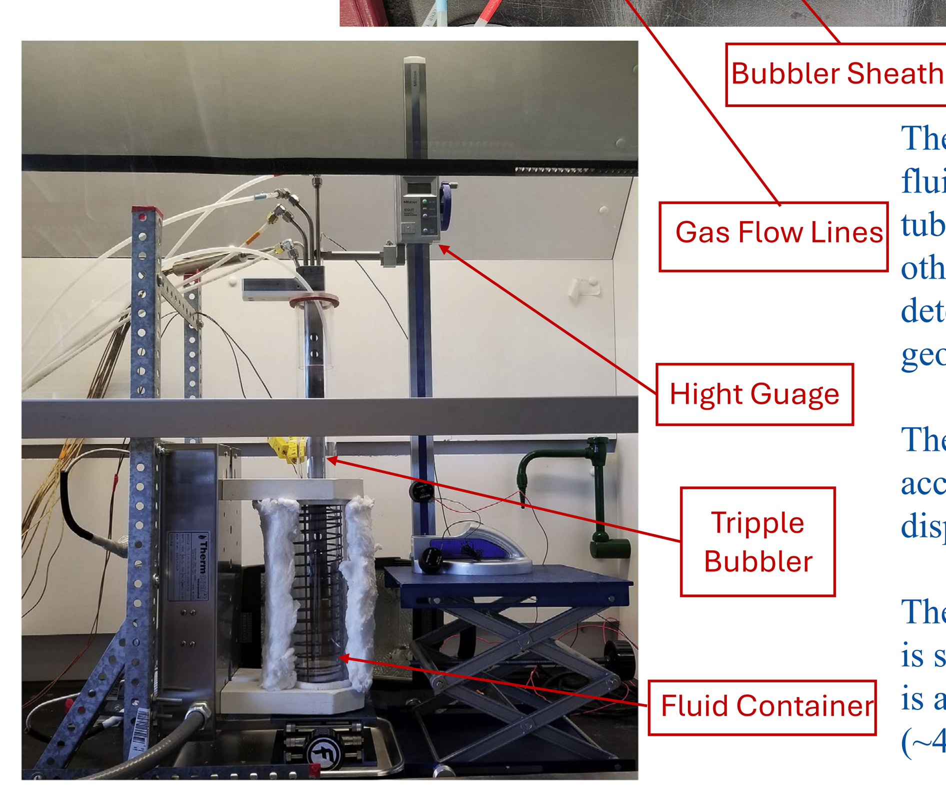
$$c_1 = \frac{P_1d_1r_1r_2 - P_1d_1r_1r_3 - P_1\Delta x_{12}r_1r_2 + P_1\Delta x_{13}r_1r_3 - P_2d_1r_1r_2 + P_2d_1r_2r_3 - P_2\Delta x_{13}r_2r_3 + P_3d_1r_1r_3 - P_3d_1r_2r_3 + P_3\Delta x_{12}r_2r_3}{-P_1r_1r_2^2 + P_1r_1r_3^2 + P_2r_1^2r_2 - P_2r_2r_3^2 - P_3r_1^2r_3 + P_3r_2^2r_3}$$

$$c_2 = \frac{-r_1r_2r_3(-P_1d_1r_2 + P_1d_1r_3 - P_1\Delta x_{12}r_3 + P_1\Delta x_{13}r_2 + P_2d_1r_1 - P_2d_1r_3 - P_2\Delta x_{13}r_1 - P_3d_1r_1 + P_3d_1r_2 + P_3\Delta x_{12}r_1)}{\gamma(d_1r_1^2r_2 - d_1r_1^2r_3 - d_1r_1r_2^2 + d_1r_1r_3^2 + d_1r_2^2r_3 - d_1r_2r_3^2 - \Delta x_{12}r_1^2r_2 + \Delta x_{12}r_2r_3^2 + \Delta x_{13}r_1^2r_3 - \Delta x_{13}r_2^2r_3)}$$

Experimental Scope and Setup:

Once the constants have been calibrated the bubblers A and B will be tested in these fluids:

- NaCl 10 wt%
- NaCl 22.5 wt%
- $CaCl_2$ 21 wt%
- $CaCl_2$ 35 wt%
- Mineral Oil



The bubbler is then inserted into the fluid at an exact known depth for tube one. The exact depths of the other dip-tubes can then be determined using predetermined geometric factors.

The exact depth is then corrected to account for the depth due to displacement.

The mass flow rate of the argon gas is set so the rise time of the bubble is approximately two seconds. (~4sccm)

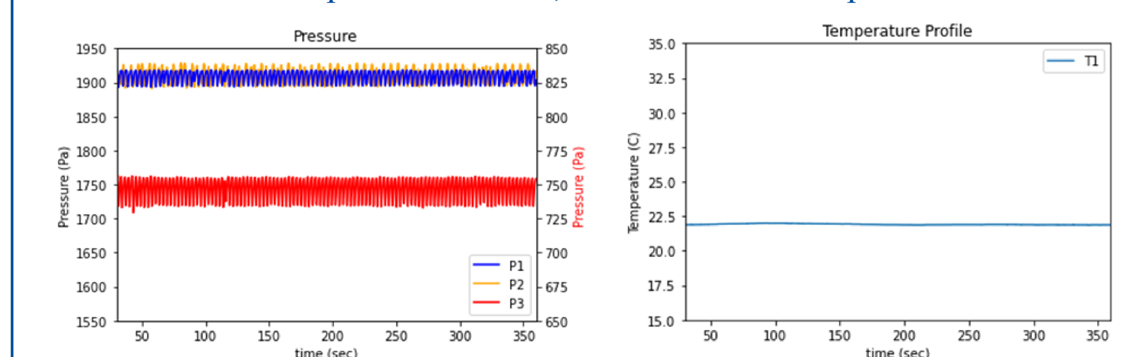
A measurement is then taken for a period of 360 seconds. Average pressures from each dip-tube are combined with the measured geometric factors to calculate the fluid density. This calculated density is then averaged over three runs per liquid tested.

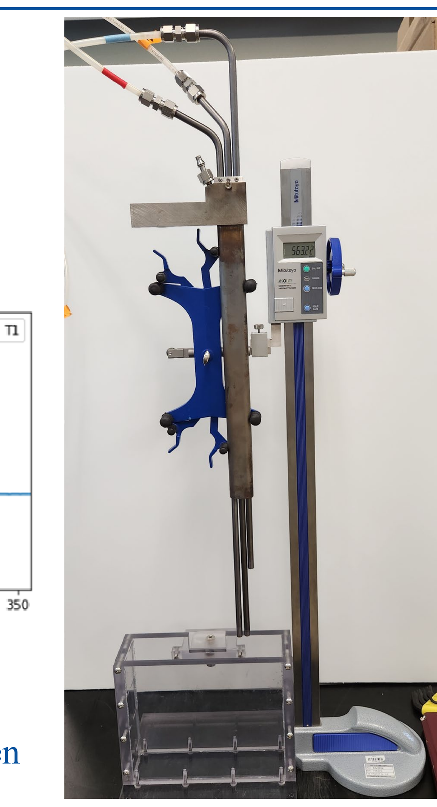
Results & Conclusion

Pressure Results:

Working Fluid $CaCl_2$ 21 wt%

- Tube one: Depth of 14.000 cm, Flow Rate of 4.0 cm³ per min.
- Tube two: Depth of 13.960 cm, Flow Rate 3.2 cm³ per min.
- Tube three: Depth of 3.971 cm, Flow Rate 4.0 cm³ per min.





As shown above, the pressure readings from dip-tube one and dip-tube two are similar. This is to be expected as both dip-tubes are placed at nearly the same height in the fluid. The differences in pressures between these two tubes is a result of the differences in tube inside radii.

Density Results:

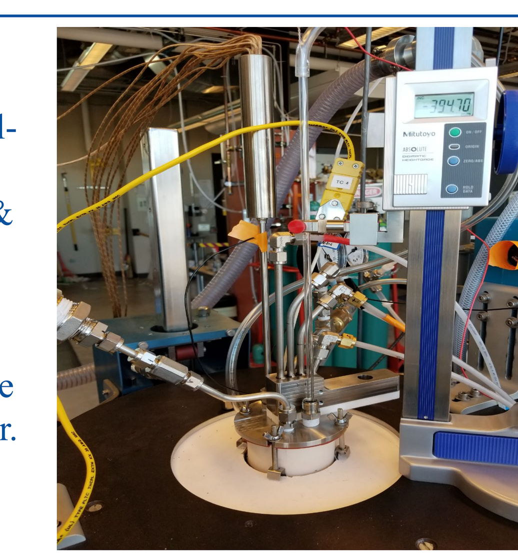
Working Fluid	Average Density Bubbler A (kg/m³)	Average Density Bubbler B (kg/m³)	Actual Density (kg/m³)	Percent Error A (%)	Percent Error B (%)
DI water	998	995	998.08	-0.0476	-0.0793
10 wt% NaCl	1070	1060	1070.14	0.120	-0.609
22.5 wt% NaCl	1160	1160	1161.47	0.0869	-0.0354
21 wt% $CaCl_2$	1180	1180	1183.19	0.113	-0.04731
35 wt% $CaCl_2$	1330	1330	1331.10	-0.164	-0.218
Mineral Oil	842	841	843.88	-0.161	-0.347

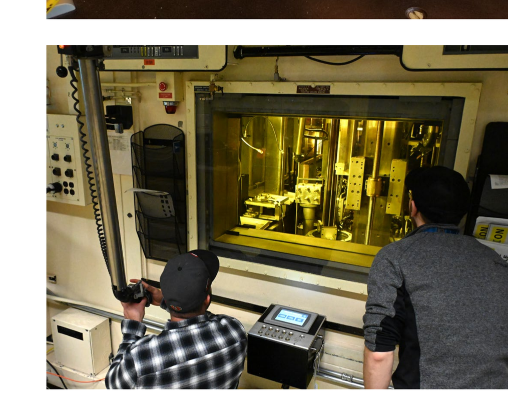
It can be observed that both bubblers, A and B, can be used to determine the density of the fluid with an accuracy of less than 1%. However, it is important to note that bubbler A had a higher degree of accuracy. The measurements from Bubbler B consistently led to a fluid density calculation that is lower than the actual value. This difference could likely be remedied by changing the c_1 constant from a mathematically calculated formula to an experimentally derived constant.

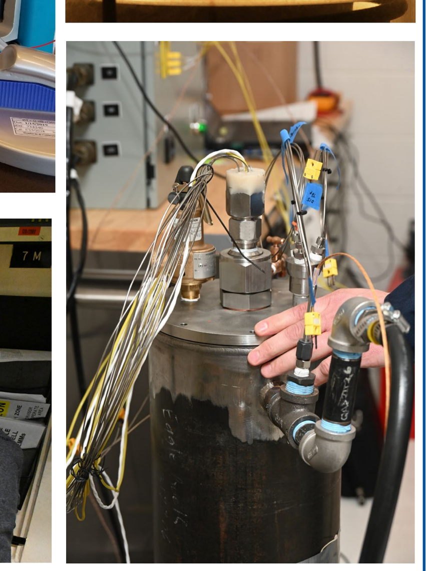
Future Work

Continued Testing:

- 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 electro-refiner.







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