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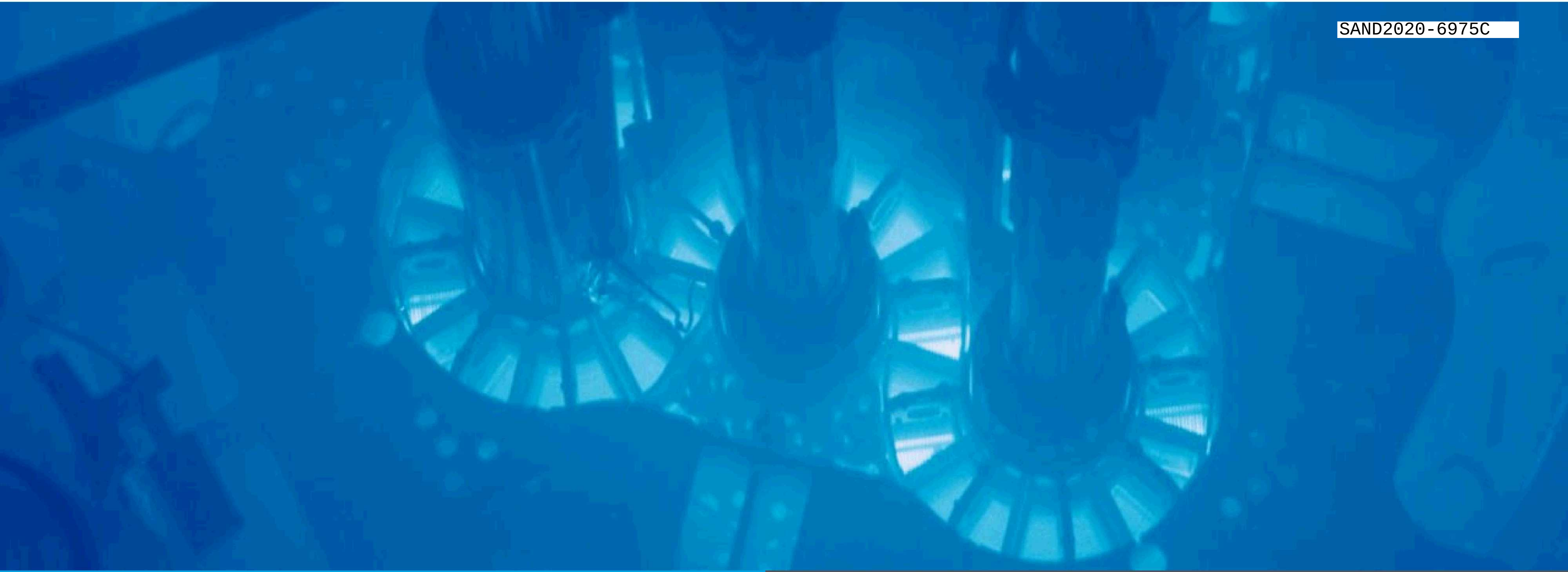

Analysis of Water Retention in Vacuum Drying Tests

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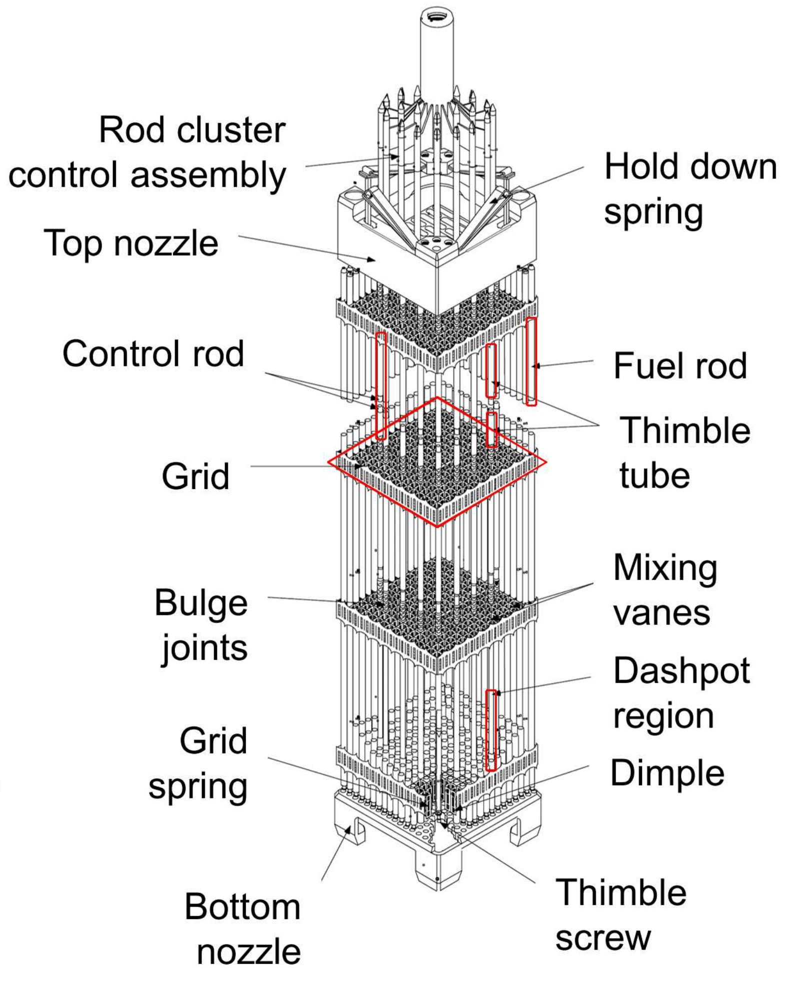
Background

- As part of commercial dry storage operations at nuclear power plants, drying procedures are employed to remove water from canisters of spent nuclear fuel (SNF).
- Numerous water retention sites exist within the internal volume of a multi-assembly dry storage system that require a specialized approach to the removal of residual water.
- Residual water may impact fuel, cladding, and other components in the system and lead to fuel degradation and cladding corrosion, embrittlement, and breaching.



PWR assembly components.

Figure 3.1-16 in Nuclear Regulatory Commission (2002). Westinghouse Tec Manual (ML023040131). Washington, D.C.

Objective

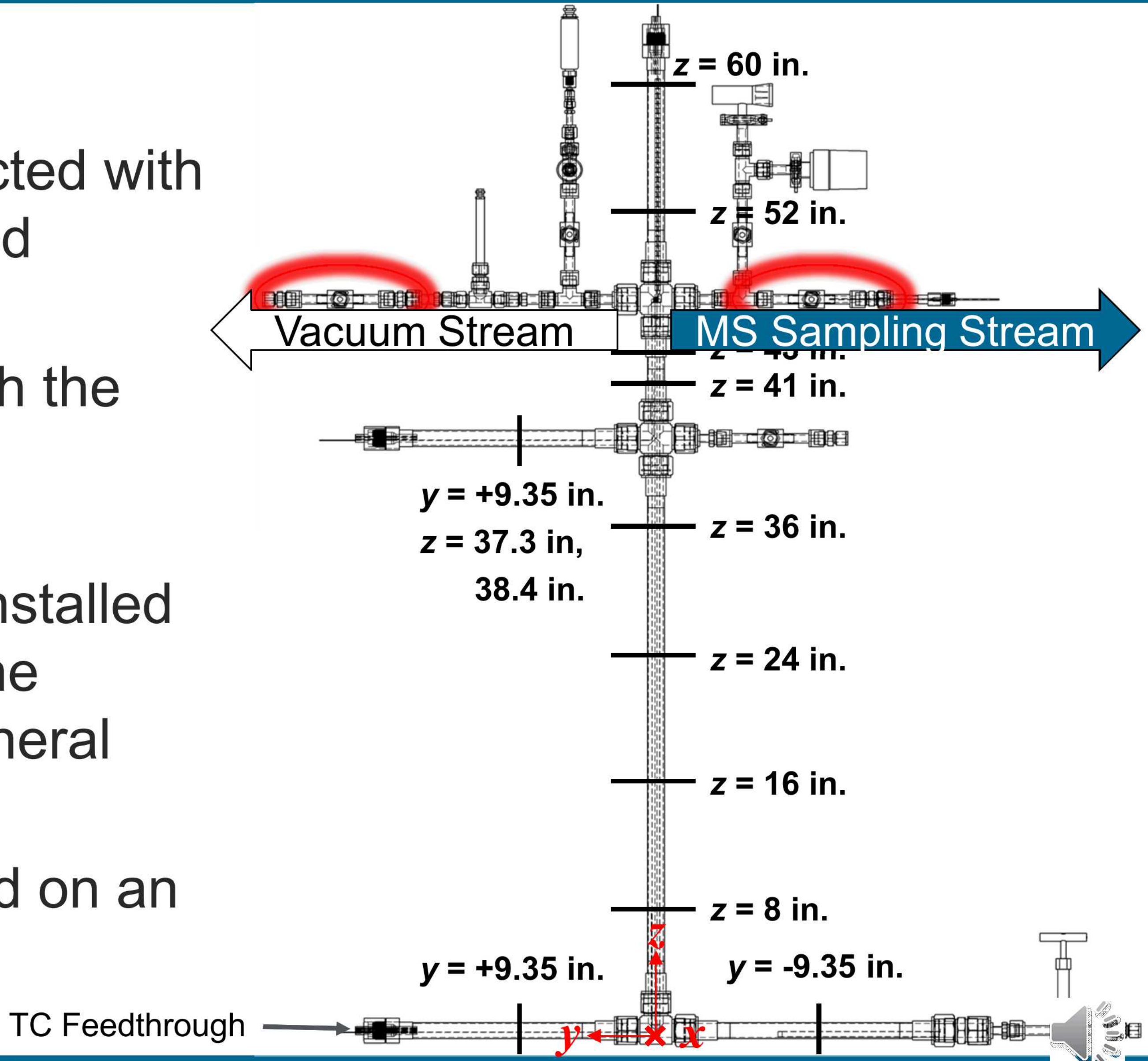
- There is a need for validation-quality data for commercial drying processes.
- A scaled experiment incorporating well-controlled boundary conditions and relevant physical processes can supplement existing field data.
- An exploratory small-scale test was designed to generate time-dependent data on temperature, pressure, and moisture content during a simulated commercial vacuum drying process for SNF canisters.
- Moisture monitoring instrumentation were incorporated to address knowledge gaps from previous studies.
  - Will augment existing data from High Burnup Demo.

Vertical above grade dry cask storage system at Maine Yankee.

Figure 1-3(a) in Freeze, G. *et al.* (2019). Comparative Cost Analysis of Spent Nuclear Fuel Management Alternatives (SAND2019-6999 rev. 1). Sandia National Laboratories, Albuquerque, NM.

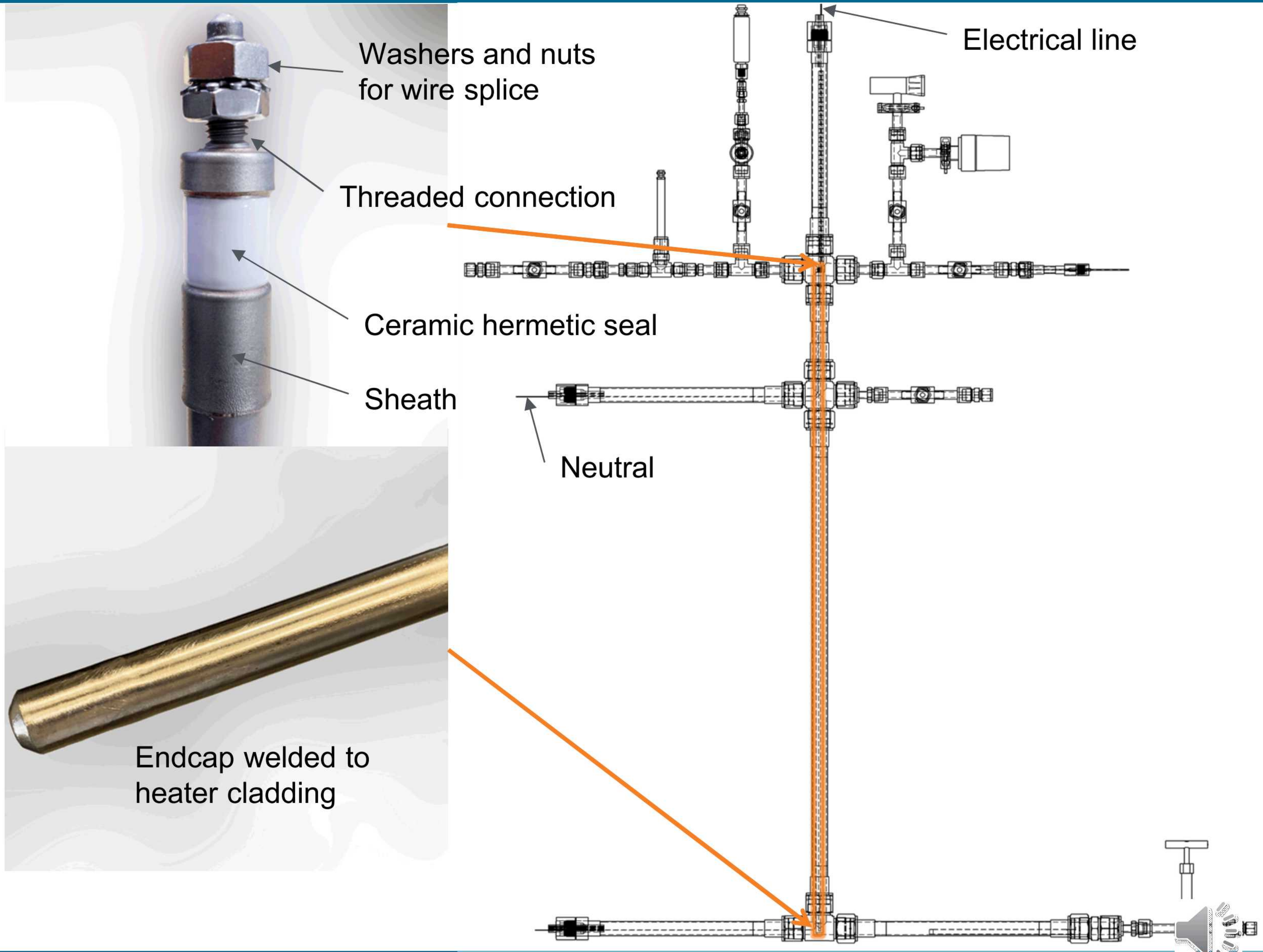
Test Apparatus

- A pressure vessel (PV) was constructed with 316 stainless-steel tubing and welded vacuum coupling radiation fittings.
- Bellows-sealed valves interfaced with the vacuum pump system and mass spectrometer (MS) sample inlet.
- Type-K thermocouples (TCs) were installed externally along the axial length of the pressure vessel as well as the peripheral standoffs.
- Axial TCs aligned with those installed on an internal heater rod.



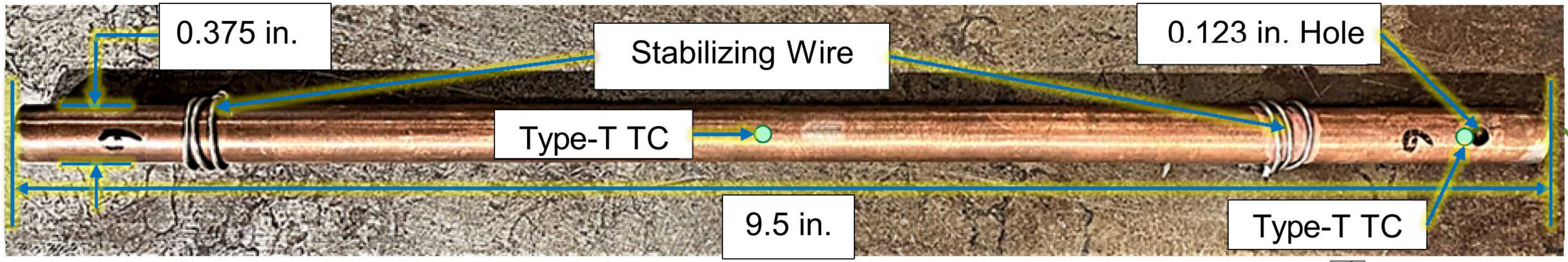
Heater Rod

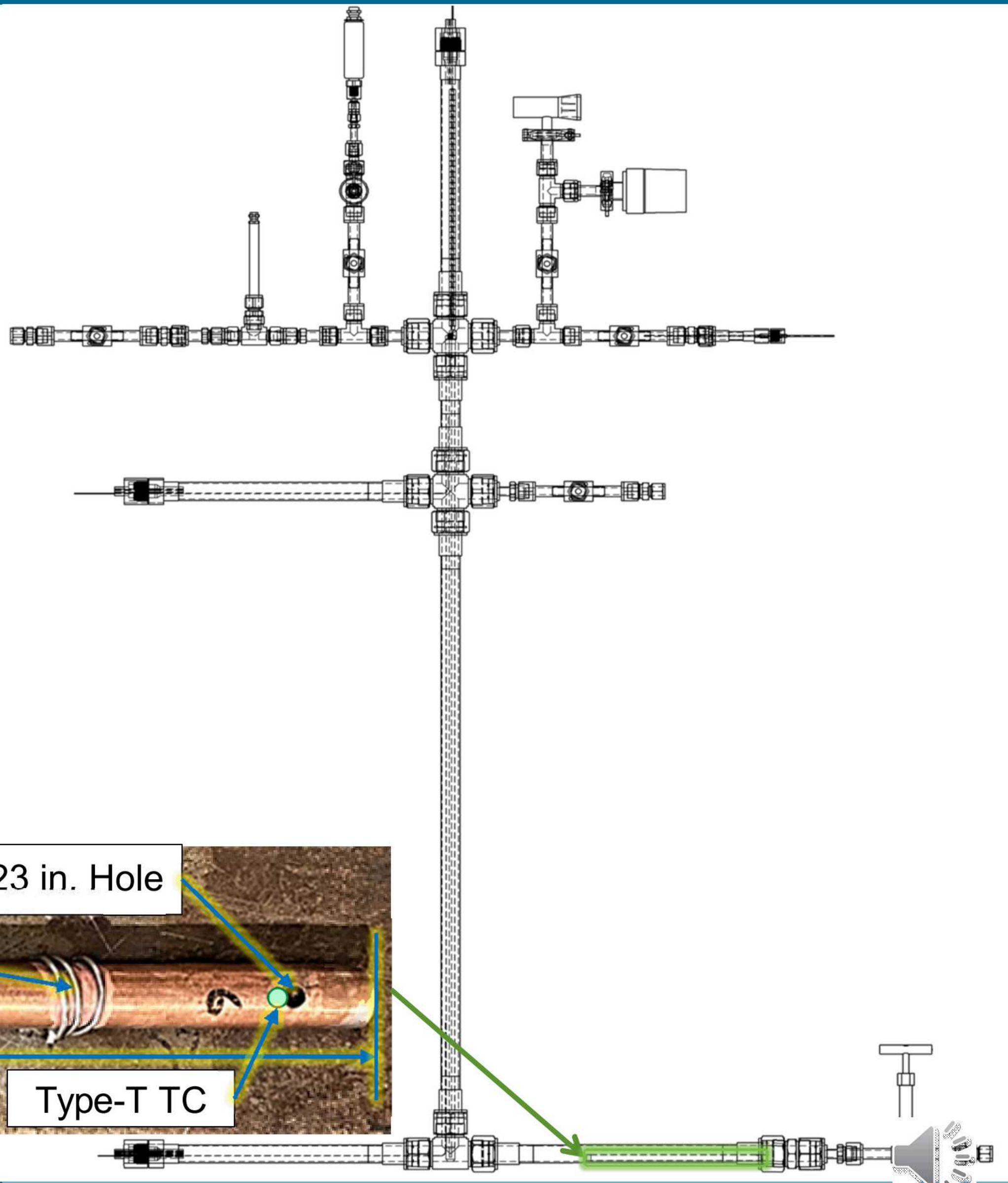
- A partially submersible heater was constructed for operation under moist conditions as a fuel rod surrogate.
- Power of 150 W determined through iterative testing to impart a peak cladding temperature of ≈ 400 °C under vacuum (ISG-11, Rev. 3 criterion).



Water Introduced via Copper Ampoule

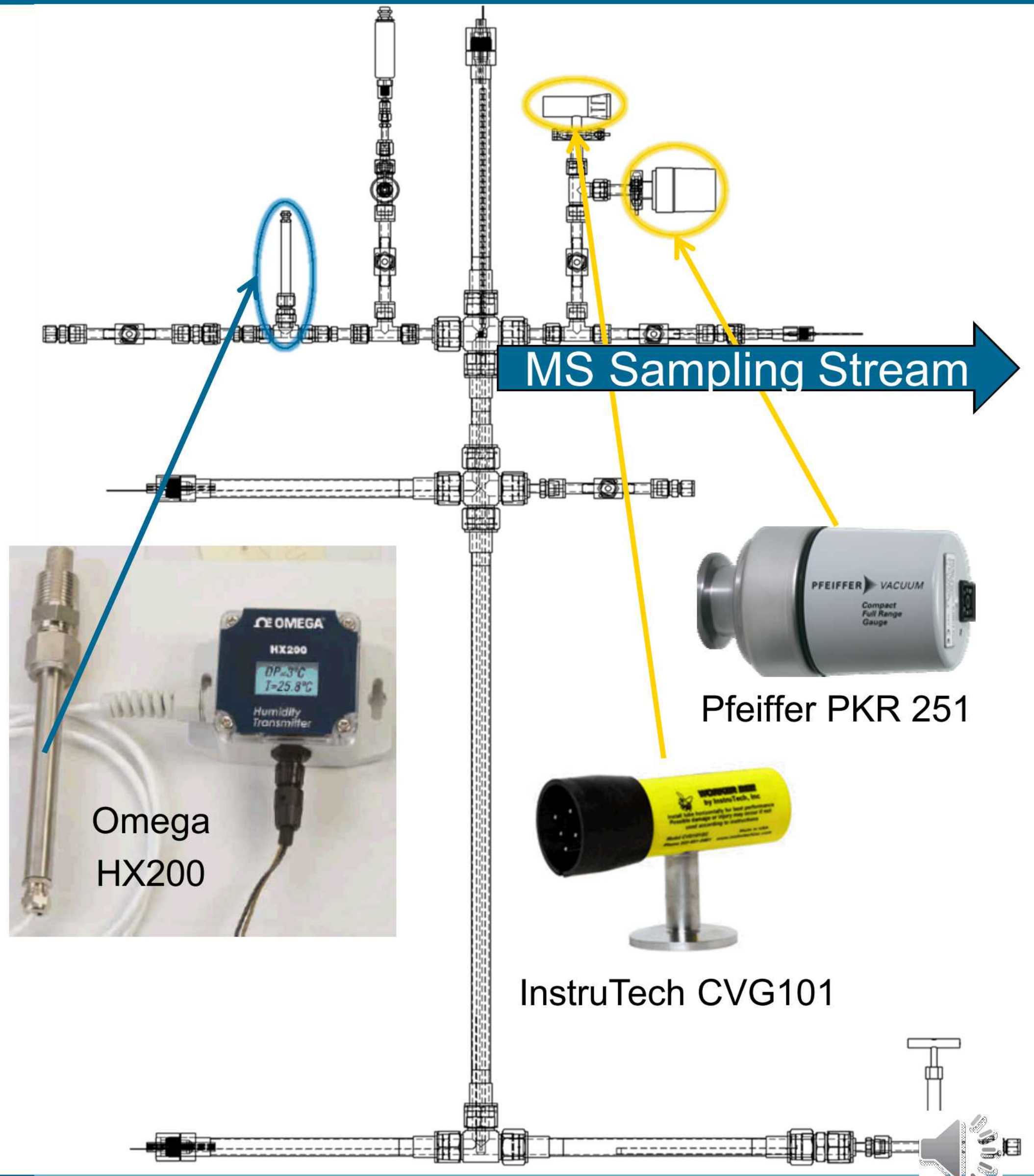
- An ampoule was created with copper tubing to install a predetermined quantity of water into the system (10.74 grams).
- A hole of 0.123 in. was included to represent a gross cladding breach.
- Ampoule mounted in lower right standoff opposite of vacuum pump inlet and included Type-T thermocouples on body and orifice.





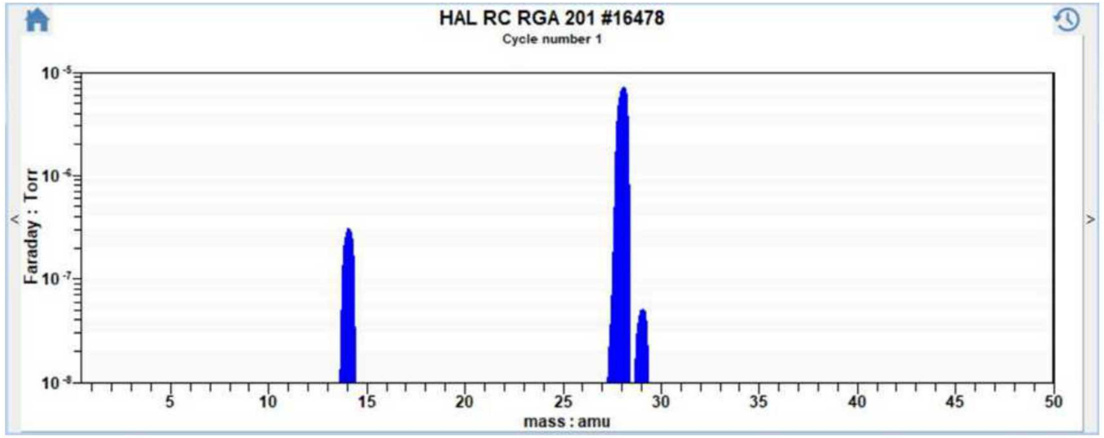
Moisture Monitoring

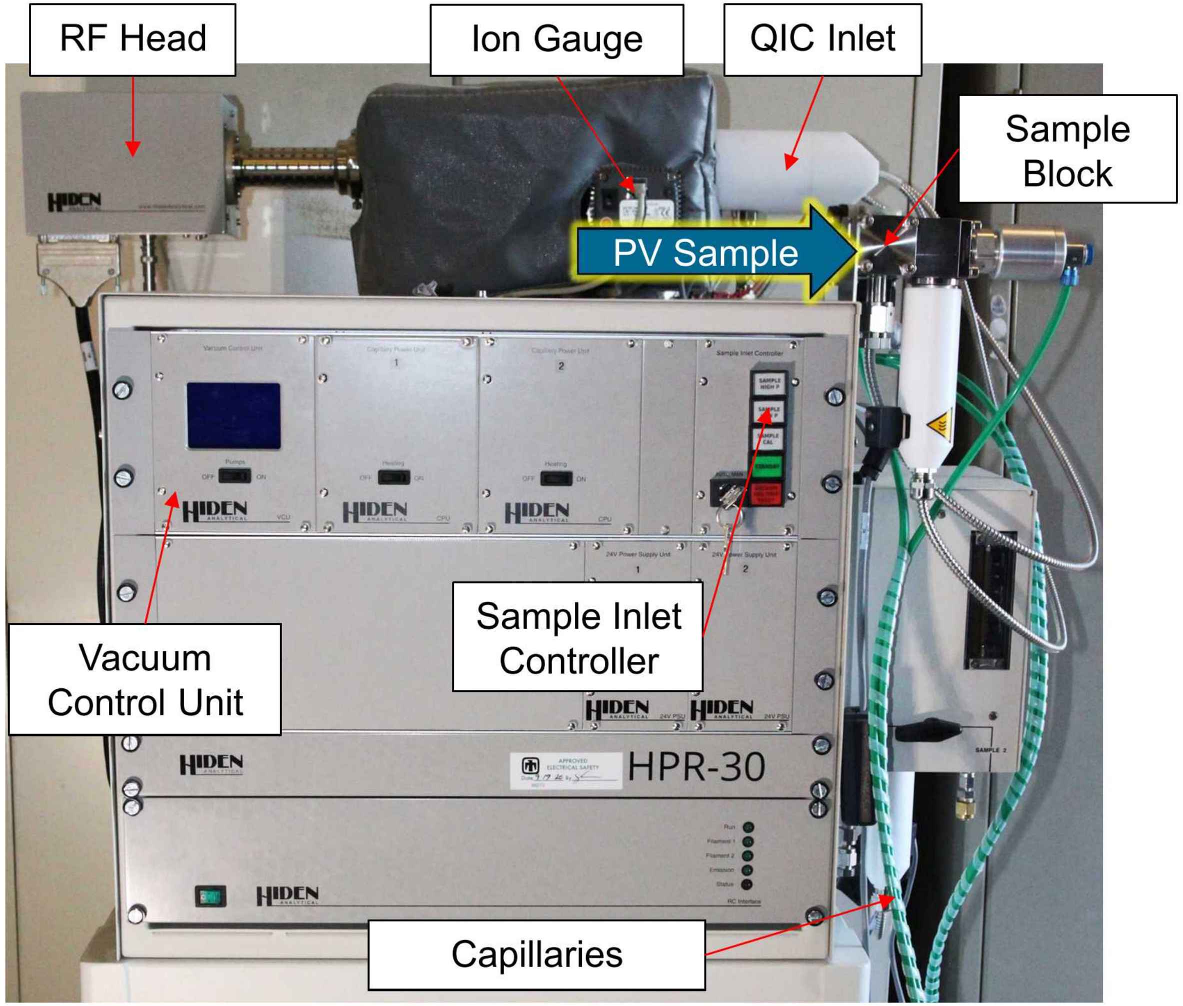
- An Omega HX200 solid-state capacitance dew point (DP) sensor was used to continuously monitor moisture in the pressure vessel.
- Sensor mounted on branch opposite to MS sampling stream and inline with vacuum pump.
- Pressure was measured with two redundant Pirani-type gauges.



Mass Spectrometer

- A Hiden Analytical HPR-30 quadrupole mass spectrometer was used to evaluate the composition of PV gas samples for pressures < 3.75 torr.
- Relative concentration of given molecule determined by fraction of raw counts in sample.





Vacuum Drying Procedure

Figure 6: Varian V-301 turbo mini pumping station. Capable of evacuating system down to 16 mtorr (1 mtorr nominal).

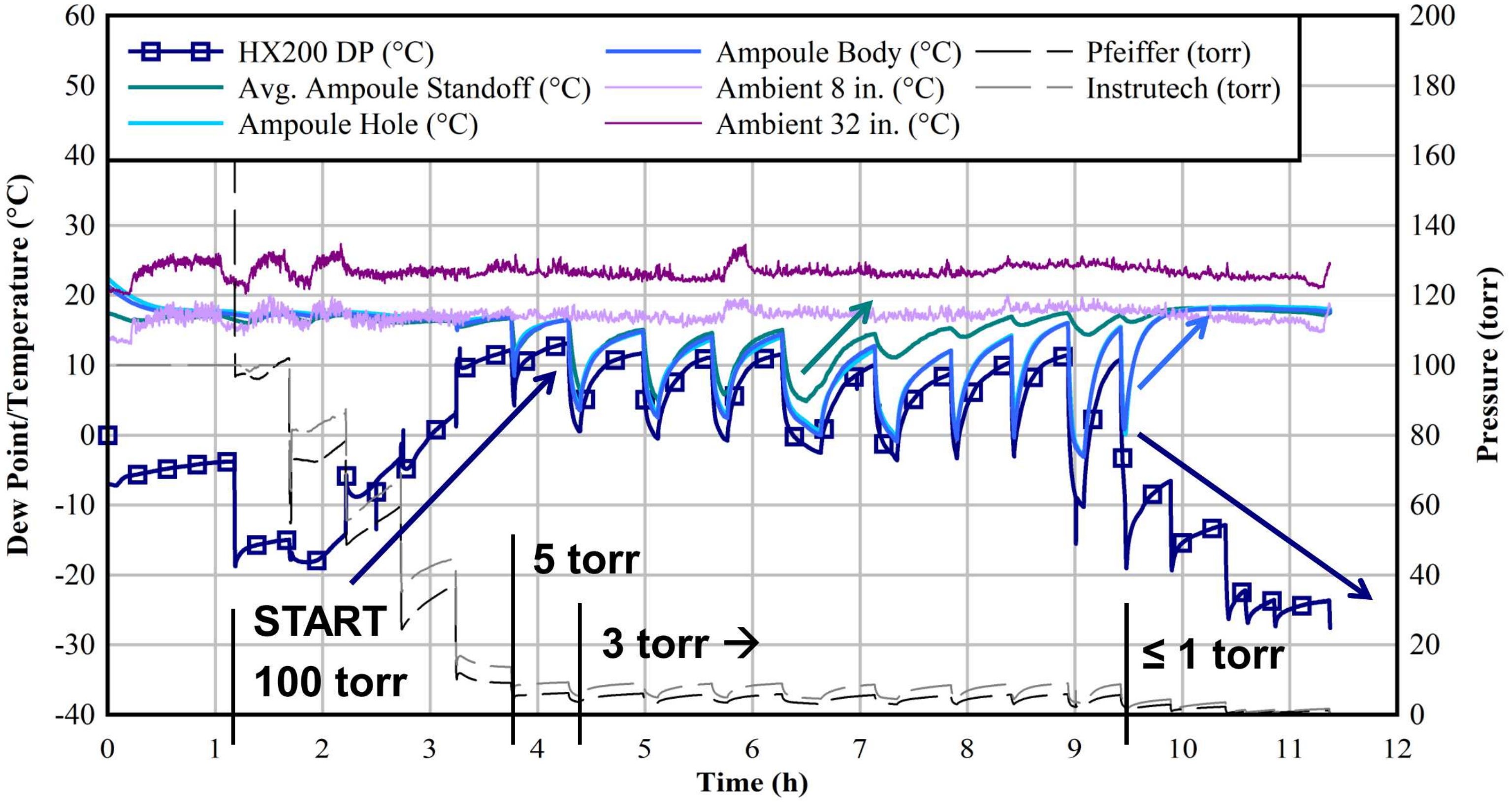
Table 1: Hold points for vacuum drying procedure

#	Target Pressure (torr)	Rebound Threshold (torr)
1	100	150
2	75	100
3	50	75
4	25	50
5	10	25
6	5	10
7	3	5
8	1	3
9	0.5	1

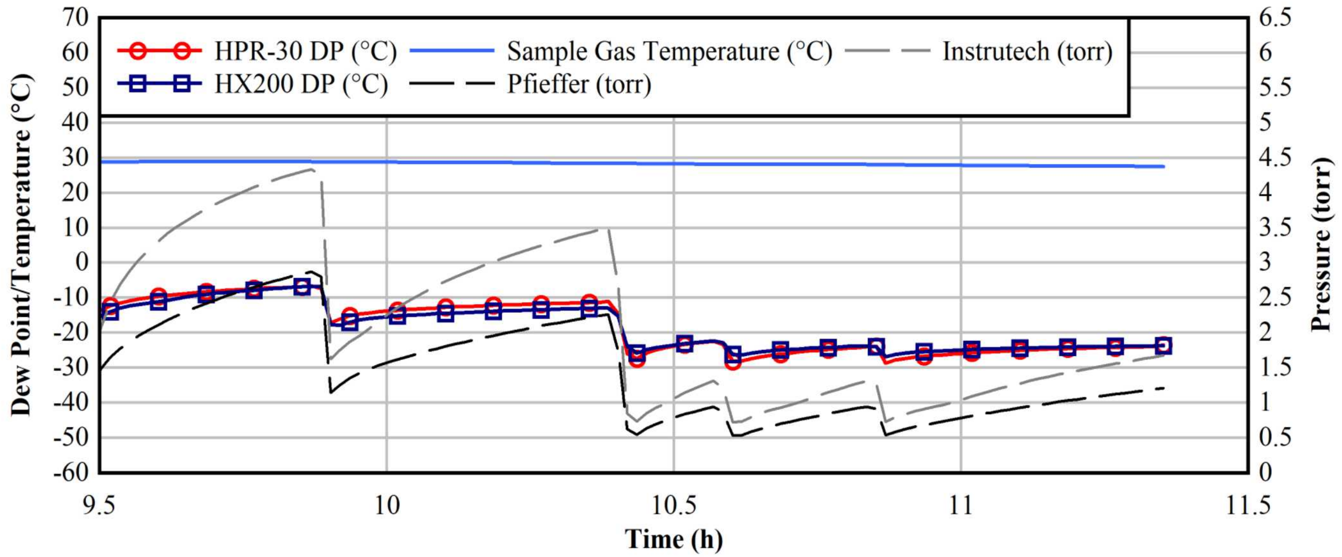
- The pressure vessel was evacuated to incrementally lower subatmospheric target pressures and held for 30 minutes each.
- Pressure rebound was monitored after isolating the system from the turbo pump.
- If rebound exceeded a certain threshold, PV was evacuated to target pressure again for an additional hold.
- Test is successful if final hold does not rebound above 3 torr (NUREG-1536).

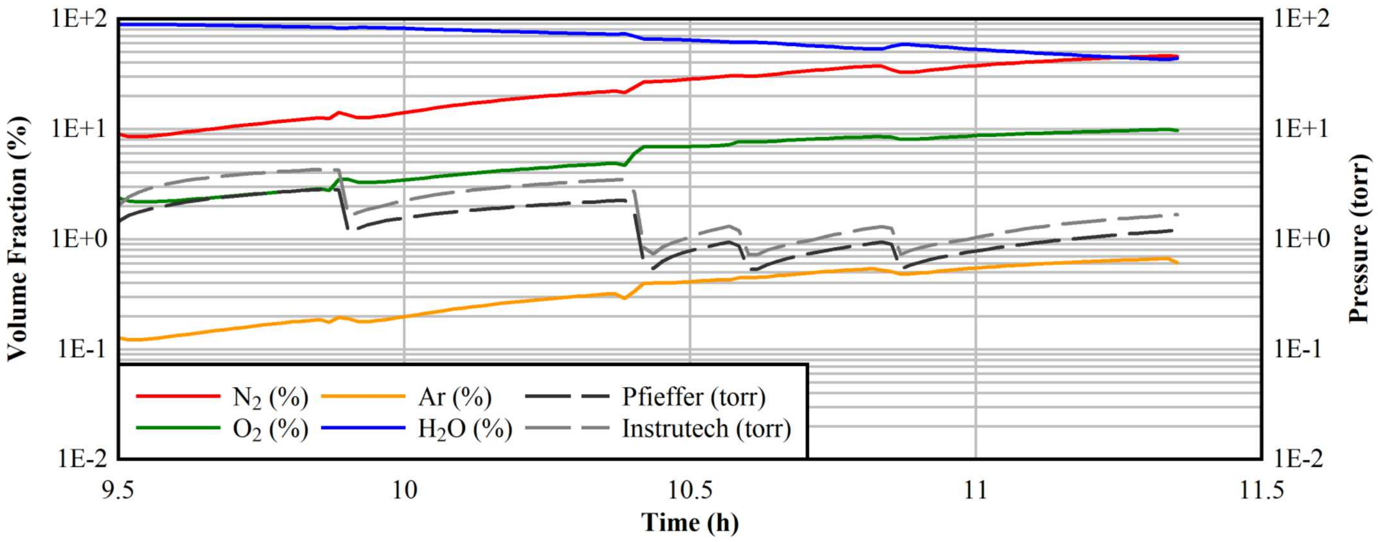
Dew Point & Temperature Behavior

- As pressure is reduced, dew point begins to increase, reaching peak levels in the 5 torr hold.
- Several evacuations to 3 torr are needed, during which the ampoule and standoff temperatures decrease in concert.
- After the last 3 torr hold, ampoule and standoff temperatures return to ambient, and DP decreases below background levels.



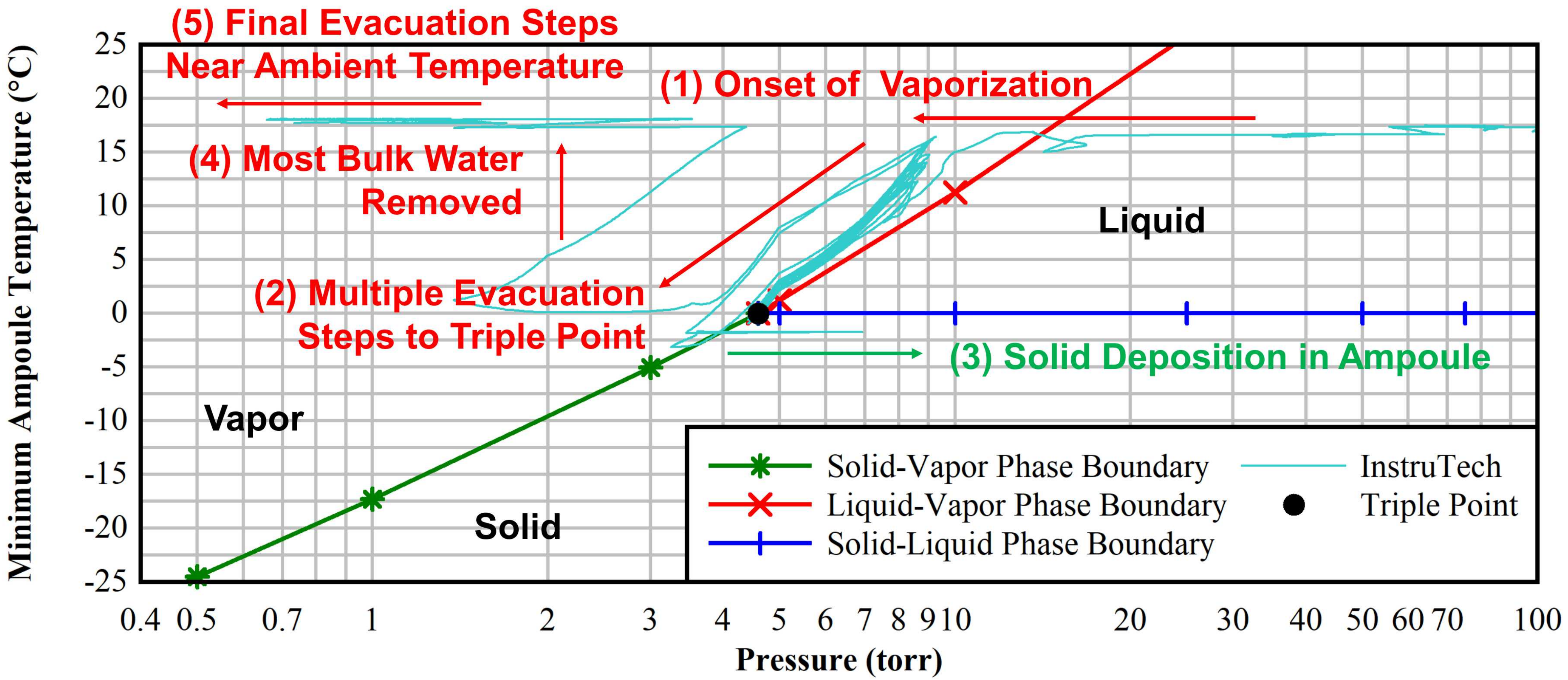
Mass Spectrometer Data





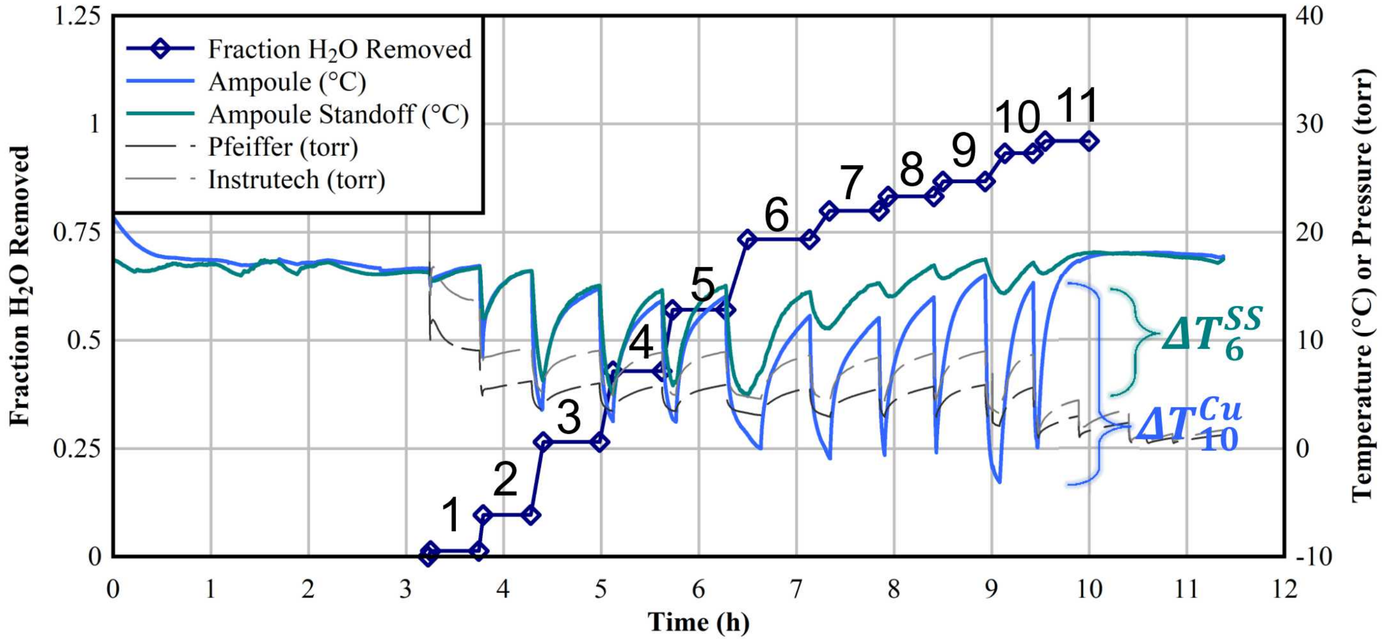
- For the holds at 1 torr and below, the mass spectrometer dew point data align very closely with the HX200 sensor.
- DP remains below temperature of sample gas, indicating no condensation in sample line.
- Composition data shows that the relative content of water in air decreases over time.

Phase Transitions



Energy Balance

- The temperatures of the copper ampoule and surrounding stainless-steel standoff were shown to change during 11 hold periods.
- These ΔT measurements were used to evaluate the energy expended in vaporizing the original 10.74 g of water.
- Estimated water mass balance within $\pm$4 wt% from simple analysis.



$$\Delta M_i^{H_2O} = \Delta E_i / \Delta H_{vap}$$
$$= \left(M_{SS} C_p^{SS} \Delta T_i^{SS} + M_{Cu} C_p^{Cu} \Delta T_i^{Cu}\right) / \Delta H_{vap}, \; i = 1, 2, \ldots 11$$

$C_p^{H_2O}$ = 4.180 J/g-K, M_{H_2O} = 10.74 g, ΔH_{vap} = 2,477 J/g (10 °C)

C_p^{Cu} = 0.385 J/g-K, M_{Cu} = 56.6 g

C_p^{SS} = 0.500 J/g-K, M_{SS} = 727 g

Discussion

- The removal of water using a vacuum drying procedure has been demonstrated in a small-scale pressure vessel with a partially submersible fuel rod surrogate.
- Time-dependent results cumulatively verify the removal of most water from an ampoule representing a water retention site.
- Instrumentation was demonstrated to be viable for quantifying conditions simulating vacuum drying.
- Next evolution of experiments are planned for a prototypic-length scale with multiple surrogate rods in an assembly.
  - Assembly would feature partially submersible heater rods and specialized diagnostic rods to introduce cladding breach effects and internal rod pressure monitoring.
- More information available in SAND2020-5341 R.
  - OSTI: https://www.osti.gov/servlets/purl/1631218

Questions?

Clean. **Reliable. Nuclear.**

References

- Nuclear Regulatory Commission (2003). Spent Fuel Project Office Interim Staff Guidance-11, Revision 3: Cladding Considerations for the Transportation and Storage of Spent Fuel. Washington, D.C.
- Nuclear Regulatory Commission (2010). Standard Review Plan for Spent Fuel Dry Storage Systems at a General License Facility (NUREG-1536). Washington, D.C.
- Salazar, A., Lindgren, E. R., Fasano, R. E., Pulido, R. J. M., & Durbin, S. G. (2020). Development of Mockups and Instrumentation for Spent Fuel Drying Tests (SAND2020-5341 R). Sandia National Laboratories. Albuquerque, NM.