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Modeling of Liquid Hydrogen No-Vent-Fill Tests Using Thermal Desktop

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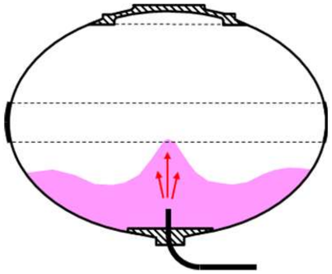
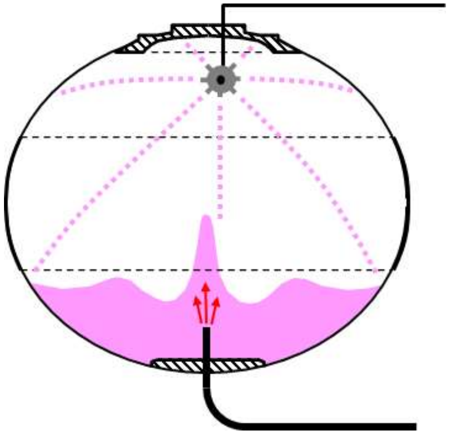
Introduction

- On-orbit/low-g cryogenic propellant transfers and tank fills are critical operations enabling NASA's planned deep space crewed exploration missions. No-vent transfers and fills are a particularly valuable approach since the propellant location in the receiver tank isn't always certain and a venting transfer/fill may eject both vapor and liquid propellant.

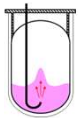
- Towards exploring and optimizing the no-vent-fill process for LH2, NASA conducted a series of jet and spray fill-based tanking experiments at the NASA Lewis facilities of CCL-7 and K-Site in the early 1990s:



NASA Lewis K-Site 2000 Liter



NASA Lewis K-Site 5000 Liter



NASA Lewis CCL-7 34 Liter

- In the present effort, we are developing a nodal analysis approach to model similar jet-based LH2 no-vent-fill processes anchored by datasets from the 3 indicated experiments and Thermal Desktop (TD). The TD twin-tank compartment models feature a conductive finite element wall of variable thickness surrounding a three-lump representation of the ullage and pool separated by an interface. Conjugate heat transfer between the wall and tank fluid interior is represented as well as attendant heat and mass transfer across the interface. The effects of nucleate, film, and transition boiling are also included.

Liquid-Vapor Interface HTC

- Key to our effort is a better simulation of the bulk energy and mass transfer occurring across the liquid-vapor interface throughout the tank filling phase of the process. An improved representation of the heat and mass transfer occurring in the highly convective and turbulent environment of an LH2 jet/spray tank fill can be obtained by replacing the TD default values of interfacial heat transfer coefficient (IHTC) with those provided by Shumway for interfaces formed from jets and submerged jets. ‡

- During the jet portion of the fill:

$$IHTC = 0.02\,\rho\,C_p\,v\sqrt{\frac{d}{l}}$$

ρ, C_p: density, specific heat of inflowing LH2

v, d, l: liquid jet velocity, diameter, and length

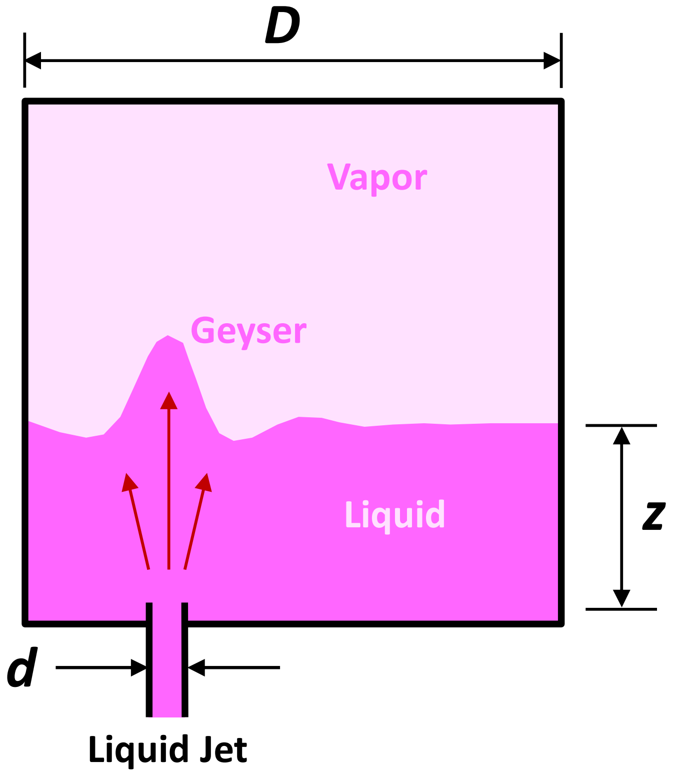
- And after the jet submerges:

$$IHTC = 0.02\,\rho\,C_p\,v\,Pr^{-0.33}\left(2.39-\frac{0.645\,z}{D}\right)\frac{d}{D}\left(1-\frac{Ja}{2}\right)$$

In this expression "*Ja*" is the Jakob number = $C_p\,\frac{(T_s - T_f)}{h_{fg}}$.

z, D: liquid-vapor interface height above jet exit, and tank diameter

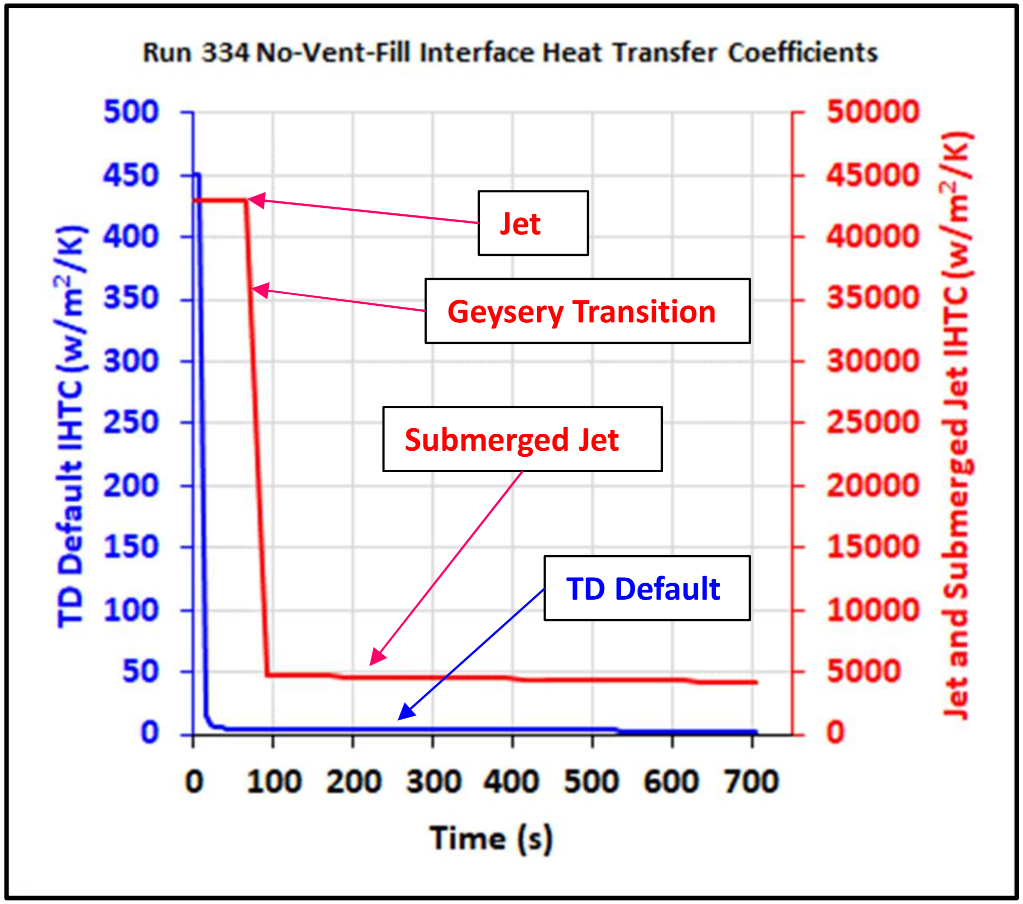
Pr, T_s, T_f, h_{fg} : Prandtl number, saturation T, liquid T, and phase change enthalpy of inflowing LH2



‡ Shumway, R. W., "*Condensation Enhancement on a Pool Surface Caused by a Submerged Liquid Jet*," INEL Conference Report 97-00261, June 1997.

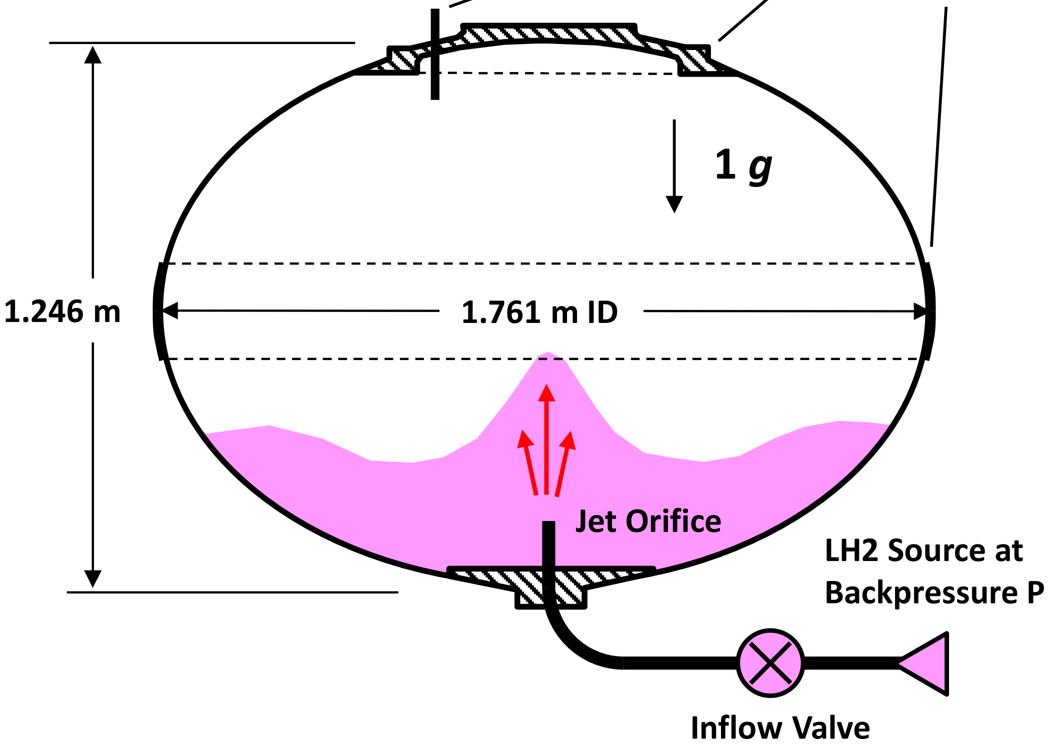
Liquid-Vapor Interface HTC (cont.)

- The substituted IHTC magnitudes are particularly sensitive to jet velocity and can be as many as three orders of magnitude higher than TD default values. The chart below compares the TD default value of the liquid-side IHTC with the jet and submerged jet IHTC prediction using inflow conditions for the K-Site 2K liter tank. In this case, a factor of 100 separates the magnitudes represented by blue and red:



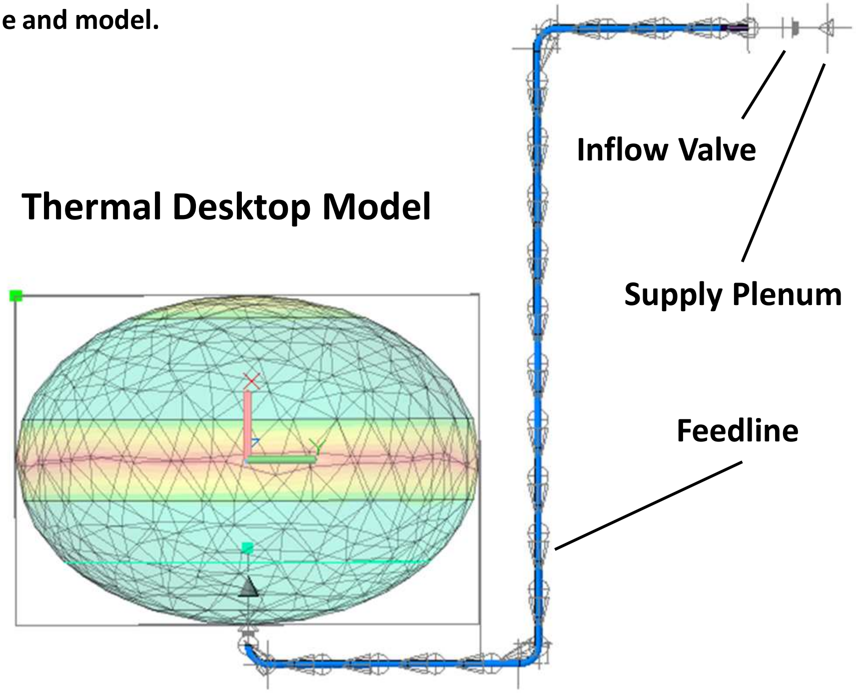
NVF Test 1, Hardware, Model (K-Site 2K Liter)

Vacuum Chamber-Enclosed Test Article



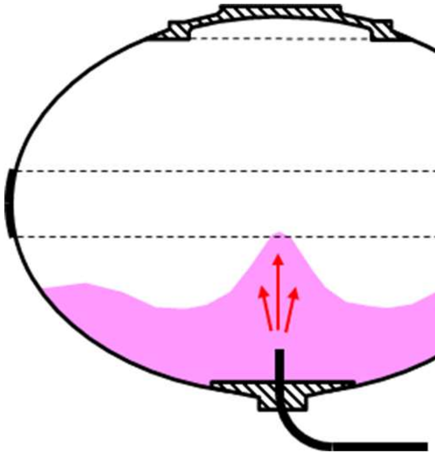
Tank wall nominal thickness = 1.6 mm, enhanced at top, bottom, and mid-sections of test article and model.

Thermal Desktop Model

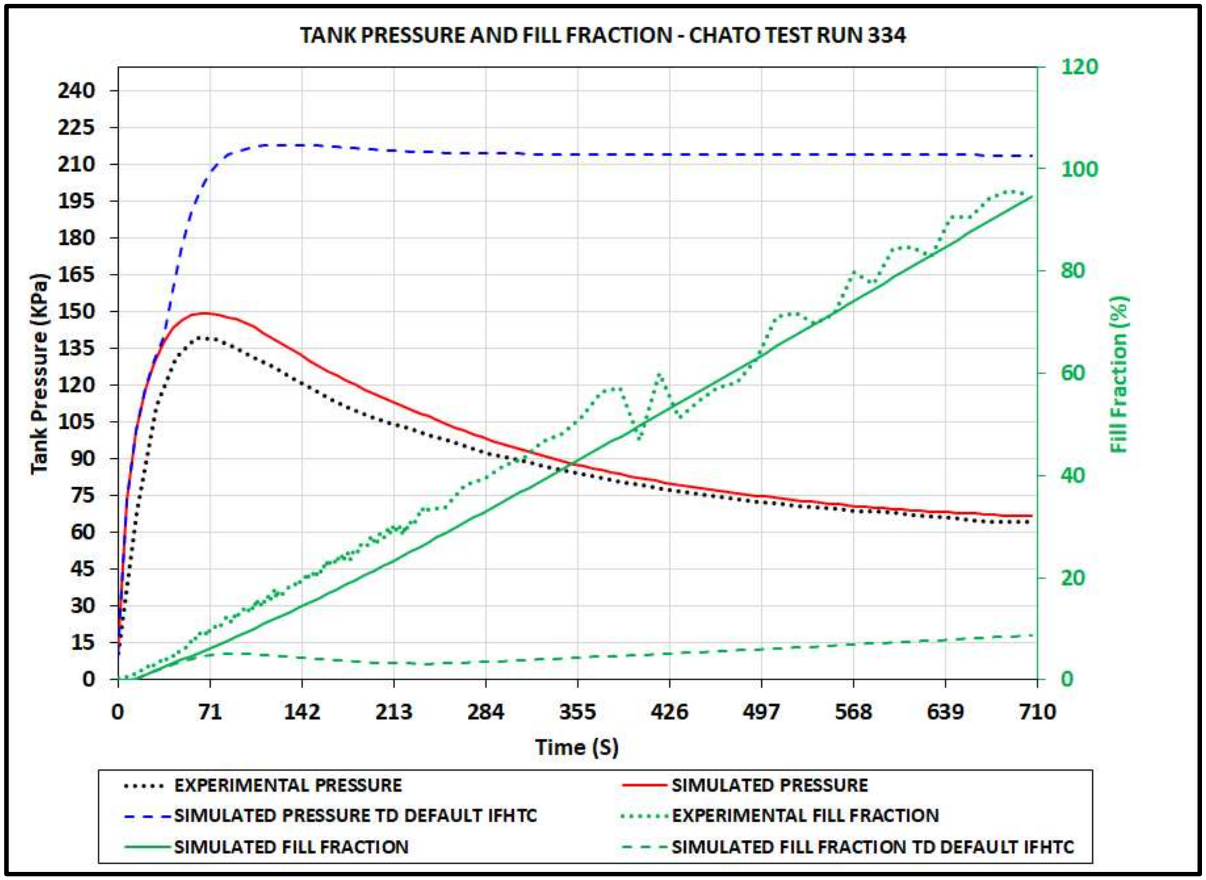


- Elliptical aluminum tank of variable wall thickness initially cooled and evacuated to a preset pressure, temperature via charge-hold-vent process.
- At test start tank vent closes, inlet valve opens, and LH2 flows in from source tank at constant backpressure P via jet bottom-located in tank. Test concludes when tank pressure exceeds source backpressure or fill level reaches predetermined limit.
- Tank instrumented with pressure, wall temperature, and rake-mounted internal temperature sensors.

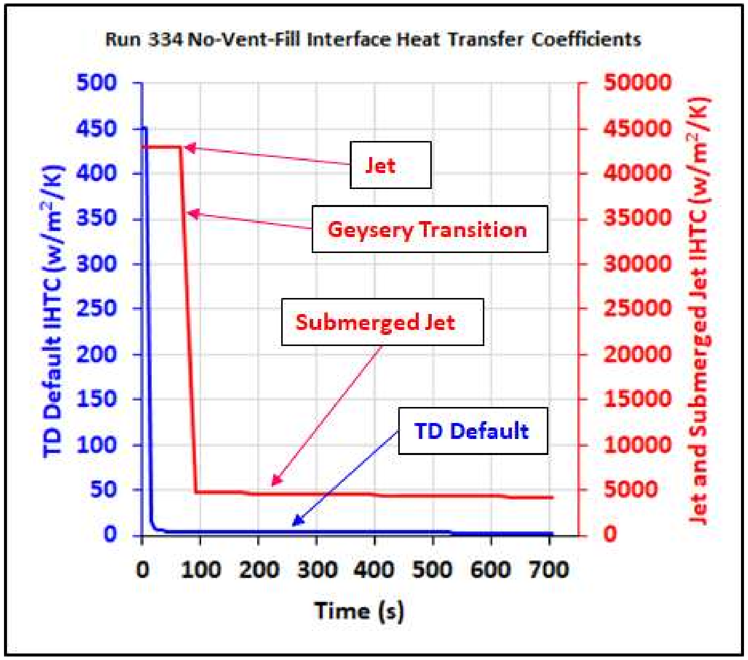
Pressure and Fill Comparison – K-Site 2K Liter Run 334



LH2 inflow temperature = 17.1 K, averaged initial wall temperature = 94.8 K, inlet mass flow rate = 0.191 kg/s.

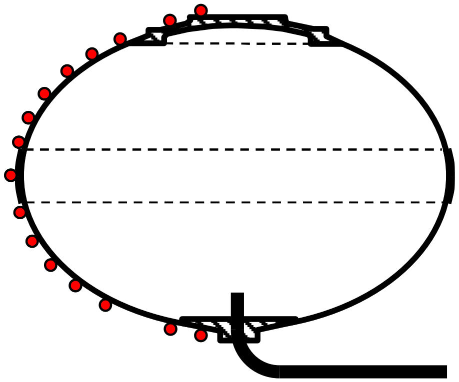


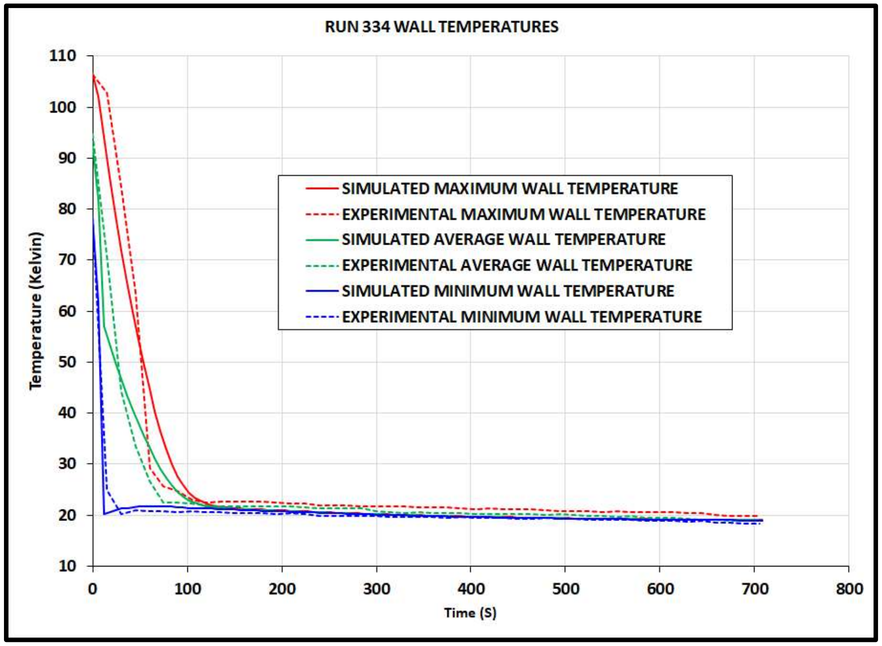
Experimental final fill = 94%.



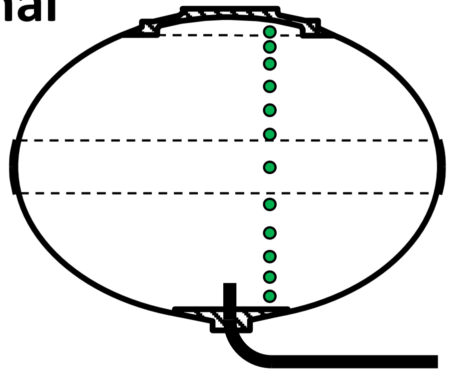
Temperature Comparison – K-Site 2K Liter Run 334

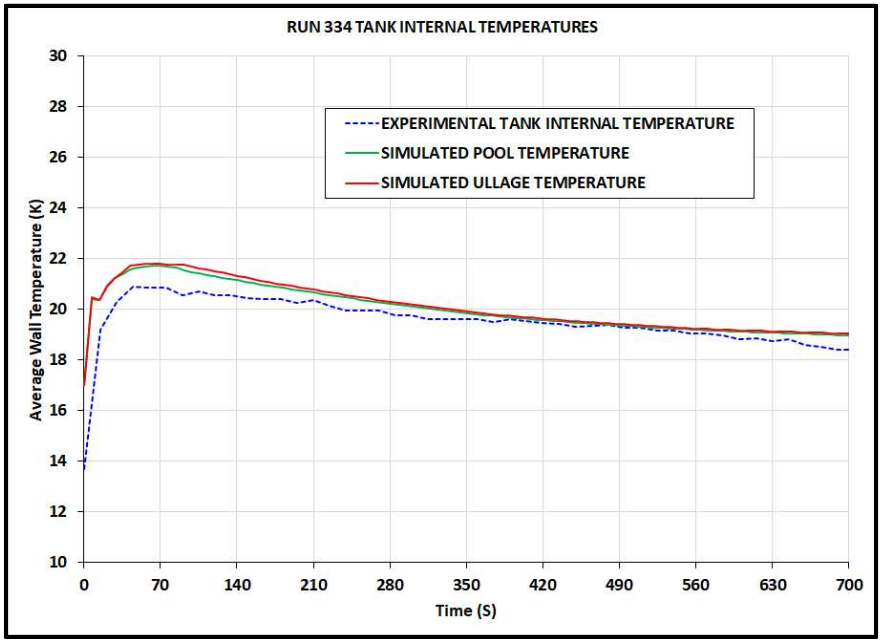
Wall





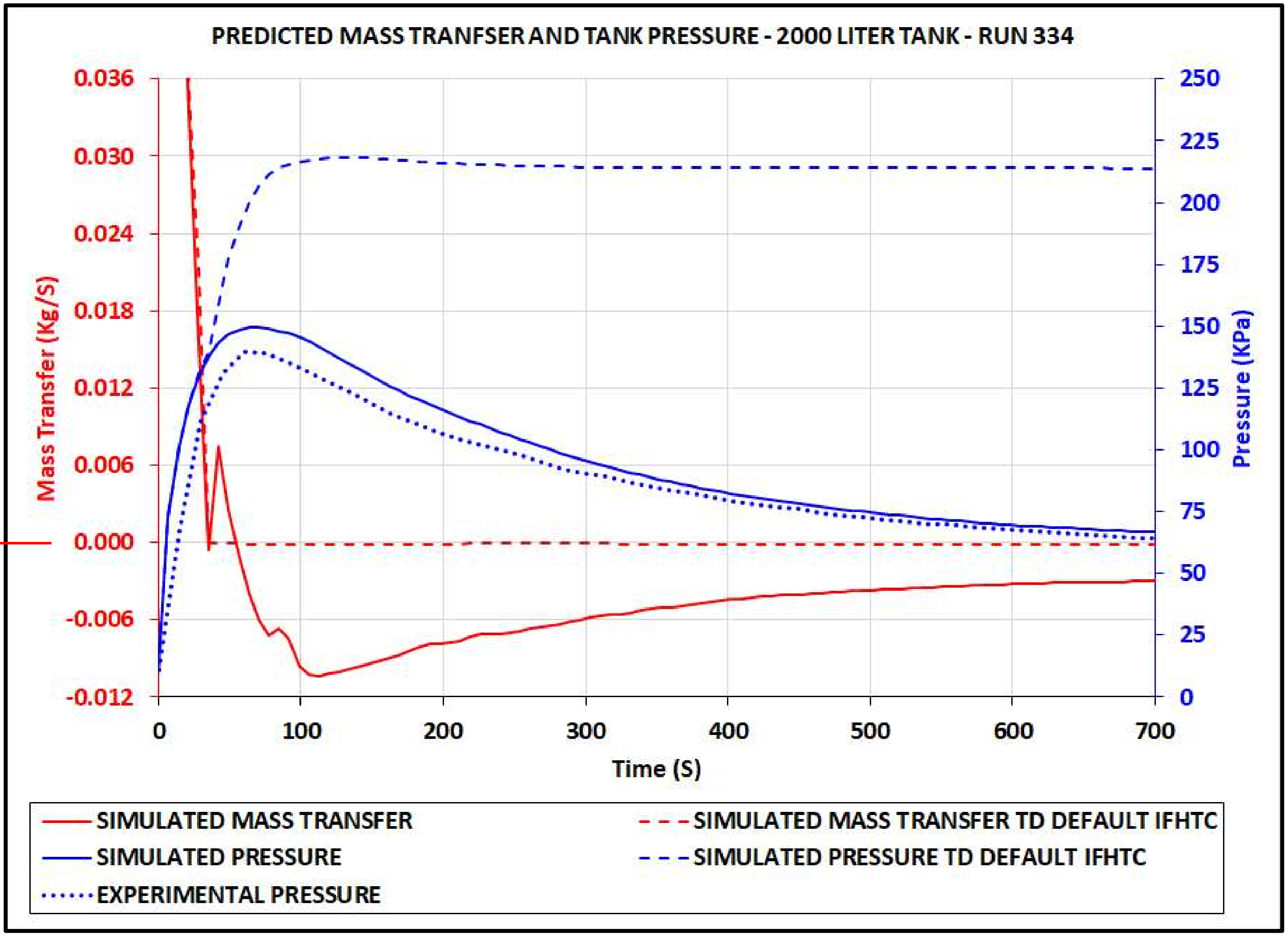
Internal





In the experiment, recorded temperature differences between tank internal rake sensors were negligible so the averaged response is shown.

Mass Transfer Prediction – 2K Liter Tank Run 334



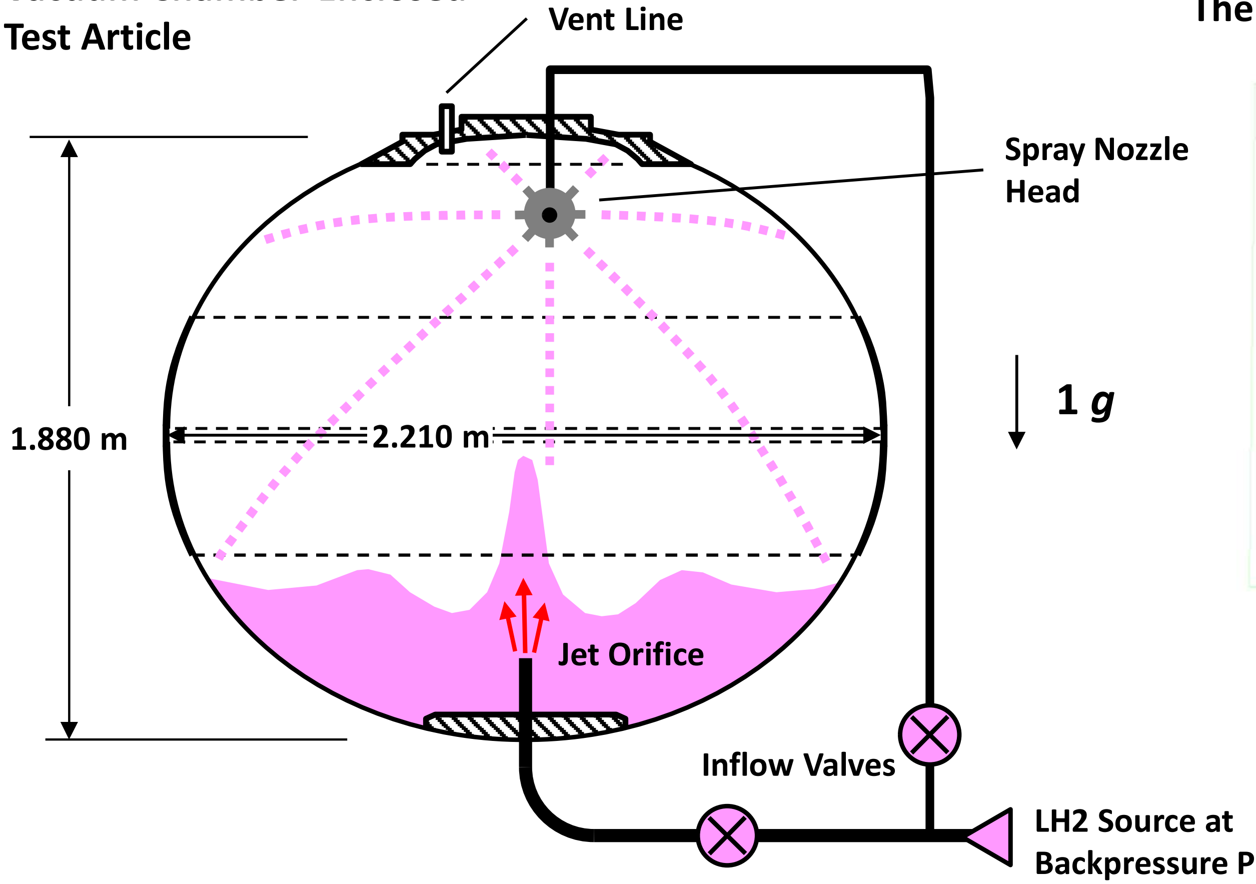
Evaporation

Condensation

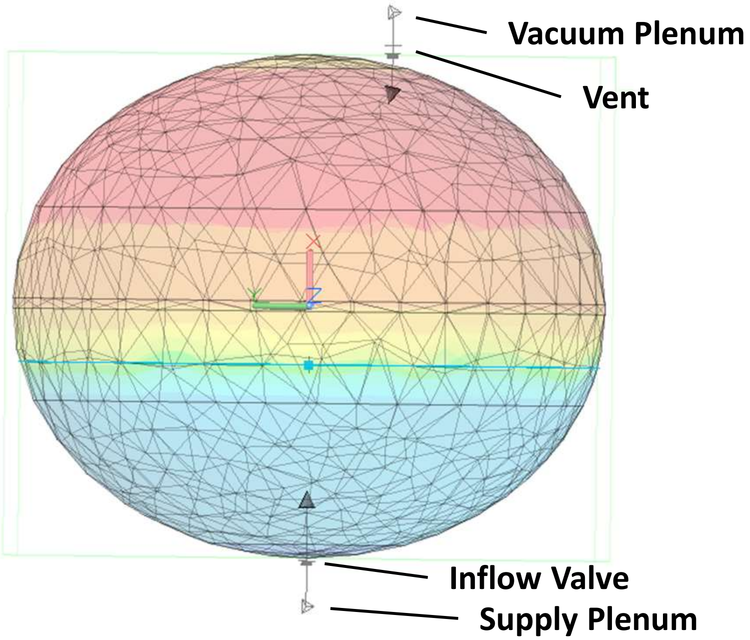
Replacement of the TD default IHTCs with the jet and submerged jet versions promotes condensation and a better comparison to experimental results.

NVF Test 2, Hardware, Model (K-Site 5K Liter)

Vacuum Chamber-Enclosed Test Article



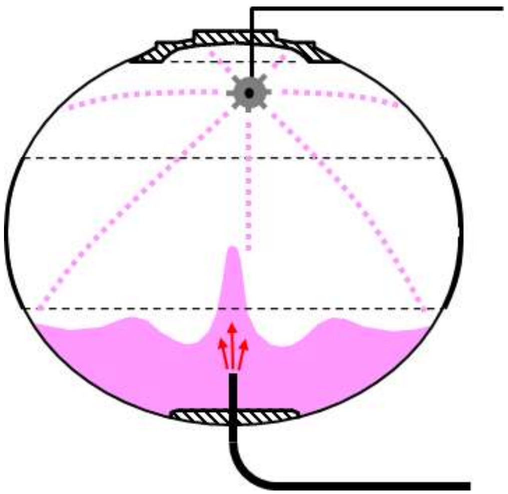
Thermal Desktop Model



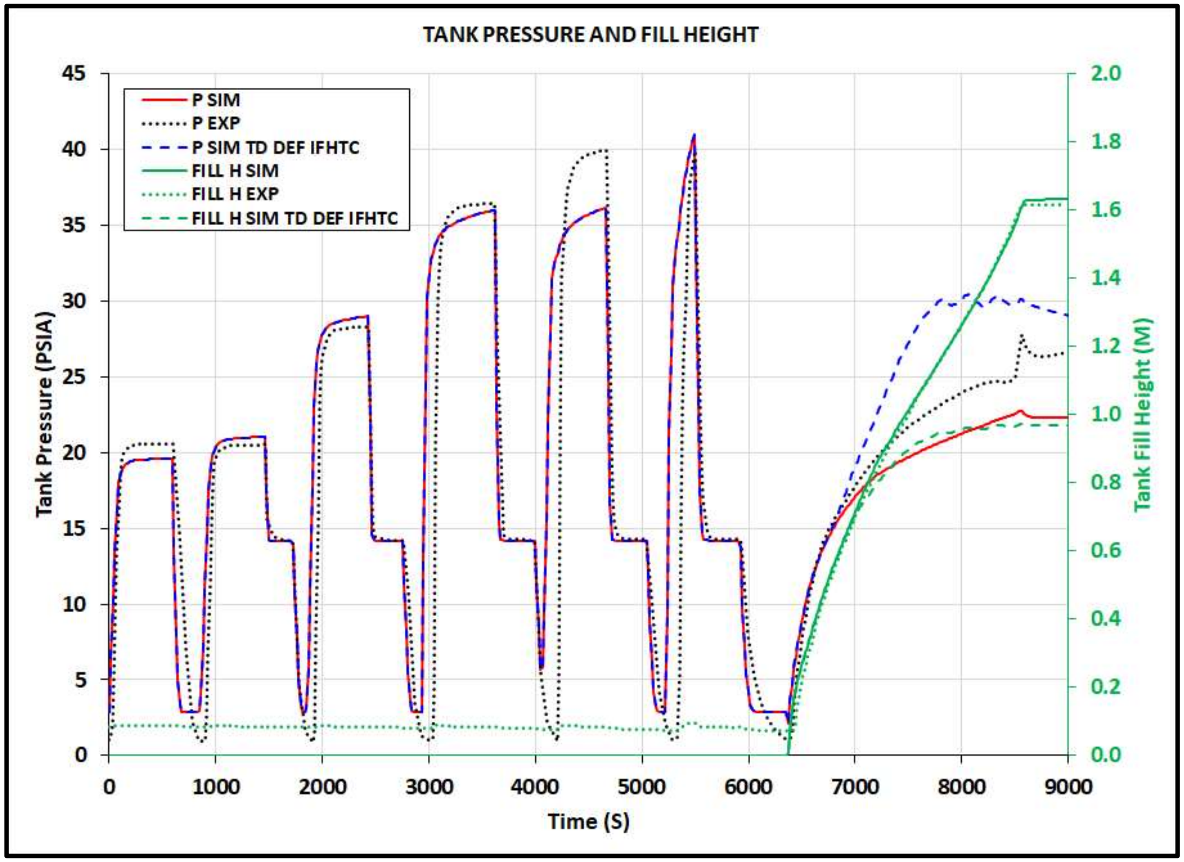
Tank wall nominal thickness = 2.2 mm, enhanced at top, bottom, and mid-sections of test article and model.

- **At test start, elliptical aluminum tank of variable wall thickness cooled and evacuated to preset pressure, temperature via charge-hold-vent process running for 6 cycles. Both bottom-located jet and top spray nozzle cluster are used.**
- **After last chill cycle tank vent closes, inlet valve opens, and LH2 flows in from source tank at constant backpressure P via jet and spray nozzles. Test concludes when fill level reaches predetermined limit.**
- **Tank instrumented with pressure, wall temperature, and rake-mounted internal temperature sensors.**

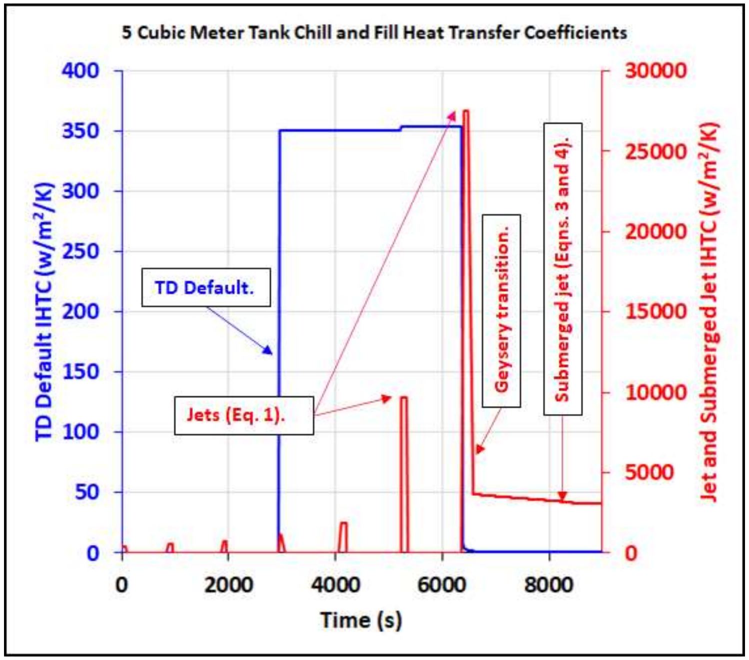
NVF Test 2 Pressure and Fill Comparison – K-Site 5K Liter



LH2 inflow temperature = 21.3 K, averaged initial wall temperature = 244 K, inlet mass flow rate (fill) = 0.143 kg/s.

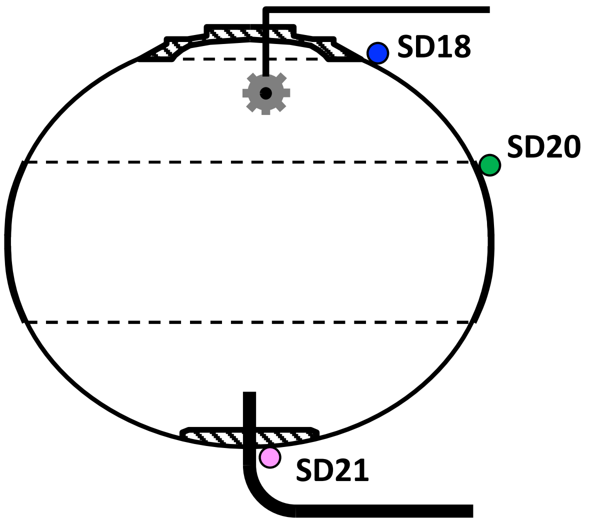

TANK PRESSURE AND FILL HEIGHT

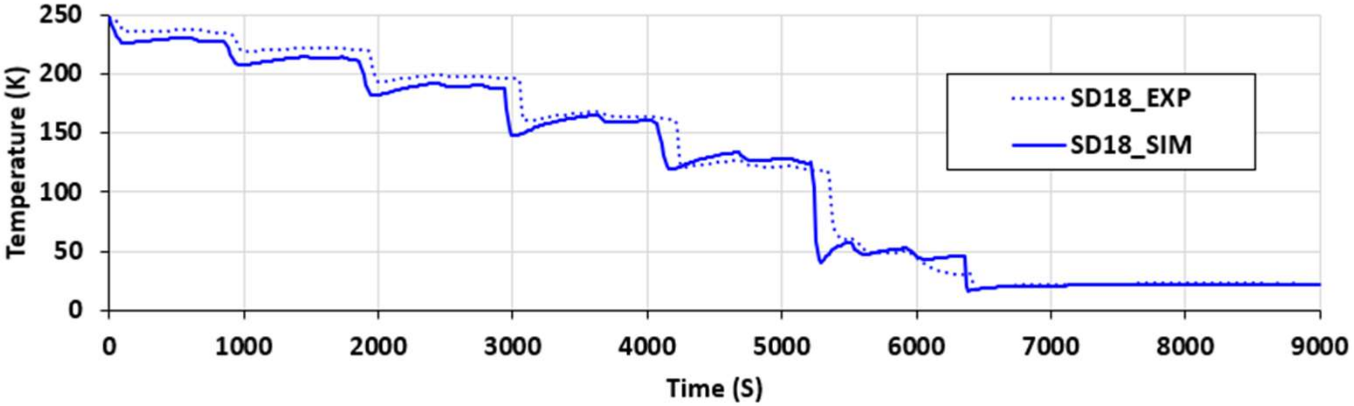
Experimental final fill = 94%.

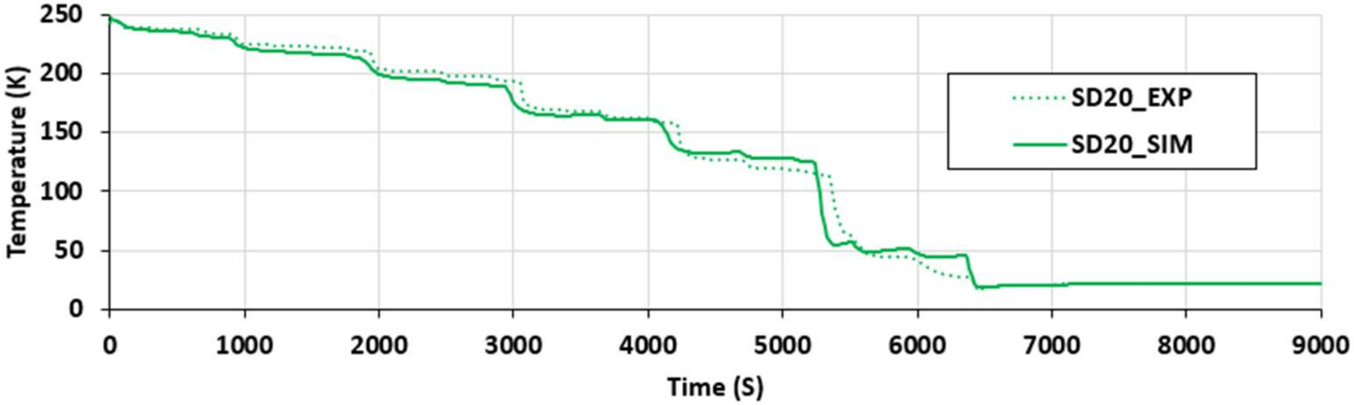

5 Cubic Meter Tank Chill and Fill Heat Transfer Coefficients

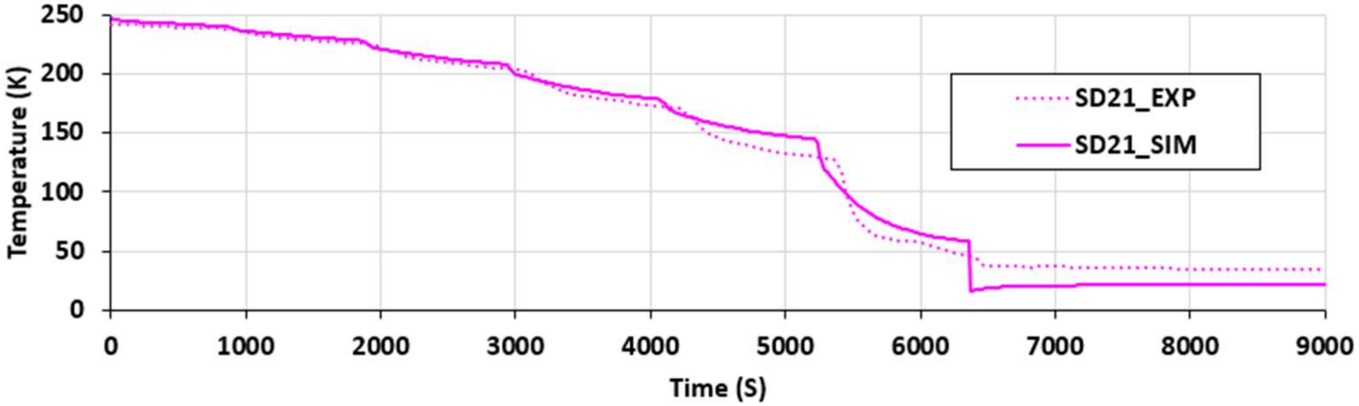
NVF Test 2 Temperature Comparison – K-Site 5K Liter

Wall Temperatures

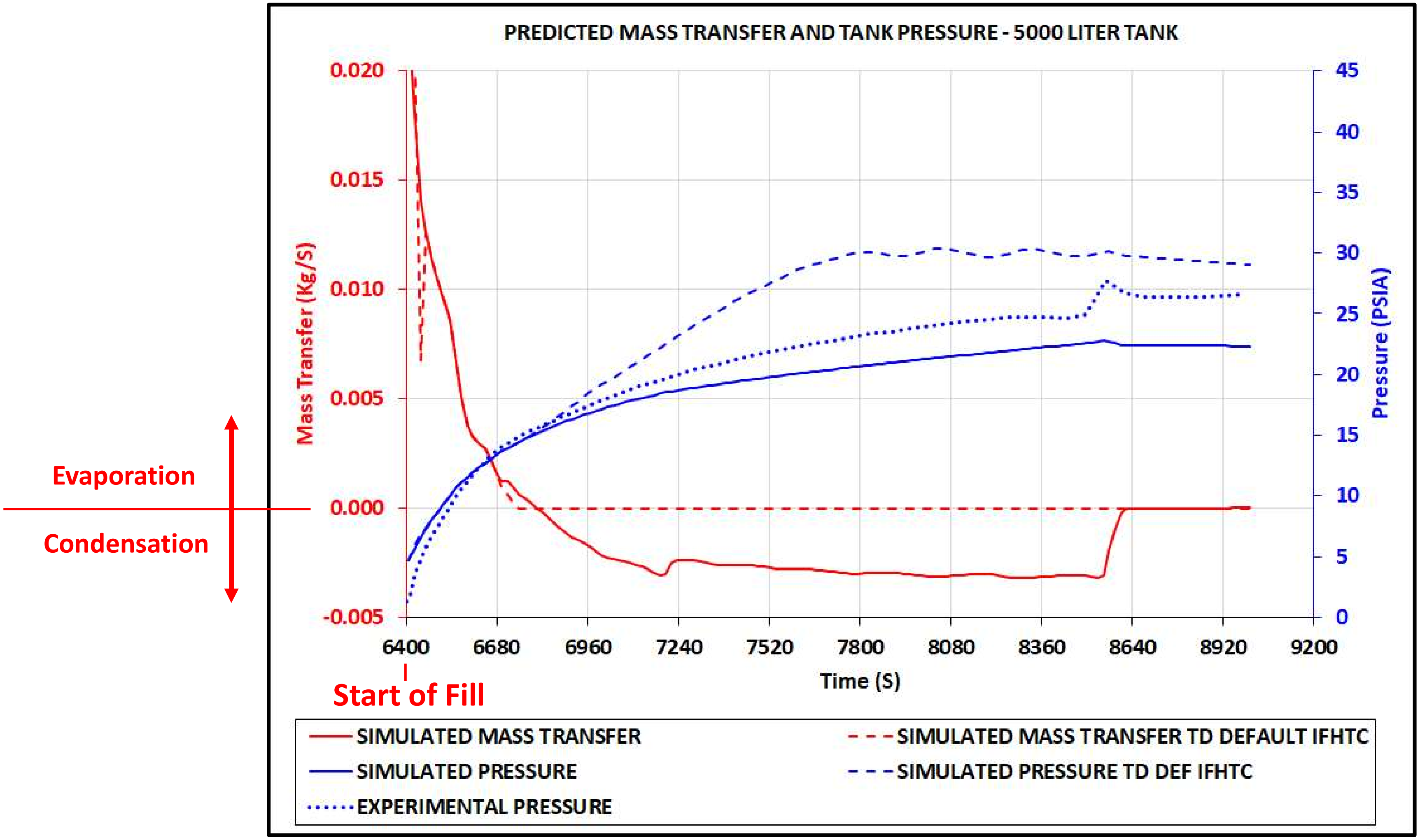








NVF Test 2 Mass Transfer Prediction – 5K Liter Tank



Evaporation

Condensation

Start of Fill

Summary

- Thermal Desktop twin-tank compartment models of 3 NASA LH2 no-vent-fill experiments and associated tank test articles were developed.

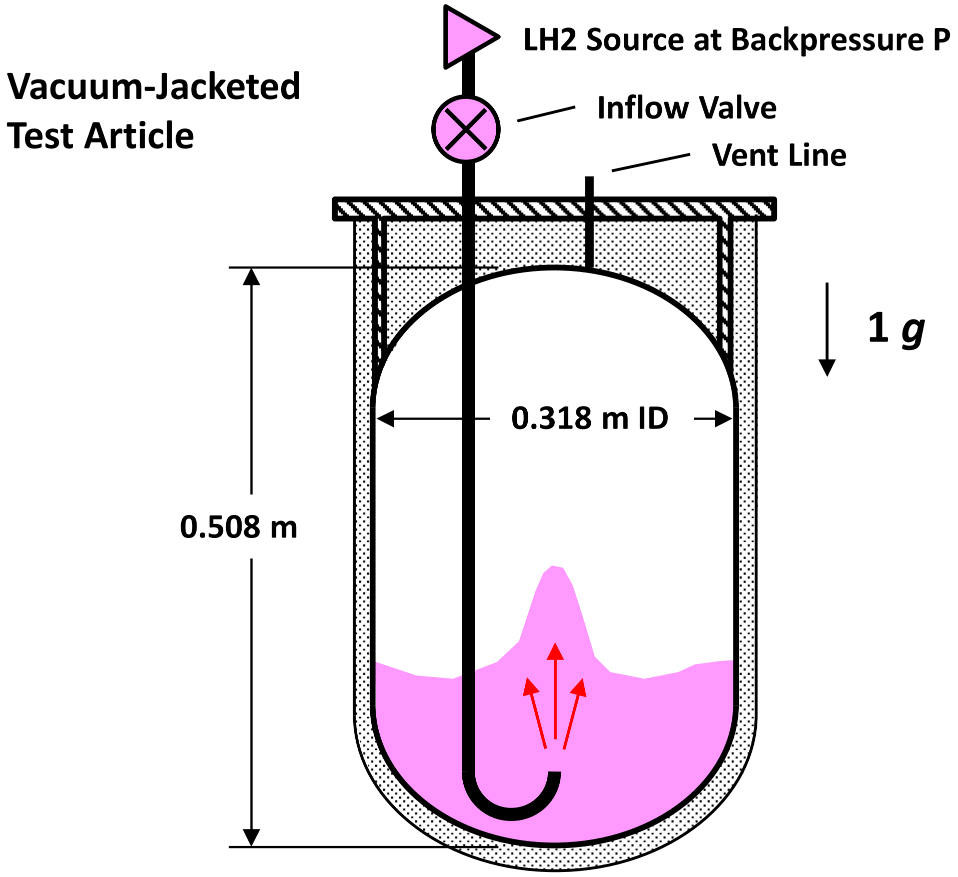
- The models featured variable wall thickness and temperature-dependent wall thermal properties.

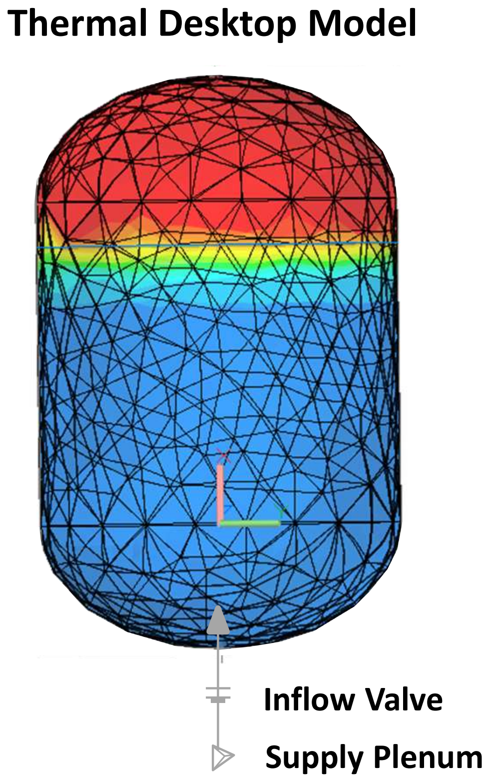
- Key to improving pressure and temperature comparisons to experimental data is the replacement of TD default interface heat transfer coefficients with relationships derived from literature better matched to the inflow fluidic and near-saturation conditions encountered in the no-vent-fill testing. Evidence from the simulations indicate these relationships promote the levels of condensation required to better compare to experimental pressure and fill data.

- Improvements in the comparisons of pressure, temperature, and tank fill history are substantial with this modeling approach.

Backup Slides

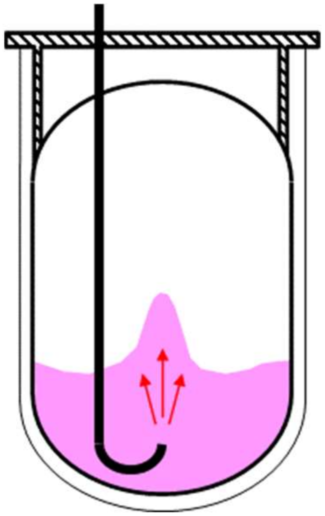
NVF Test 3, Hardware, Model (CCL-7 34 Liter)



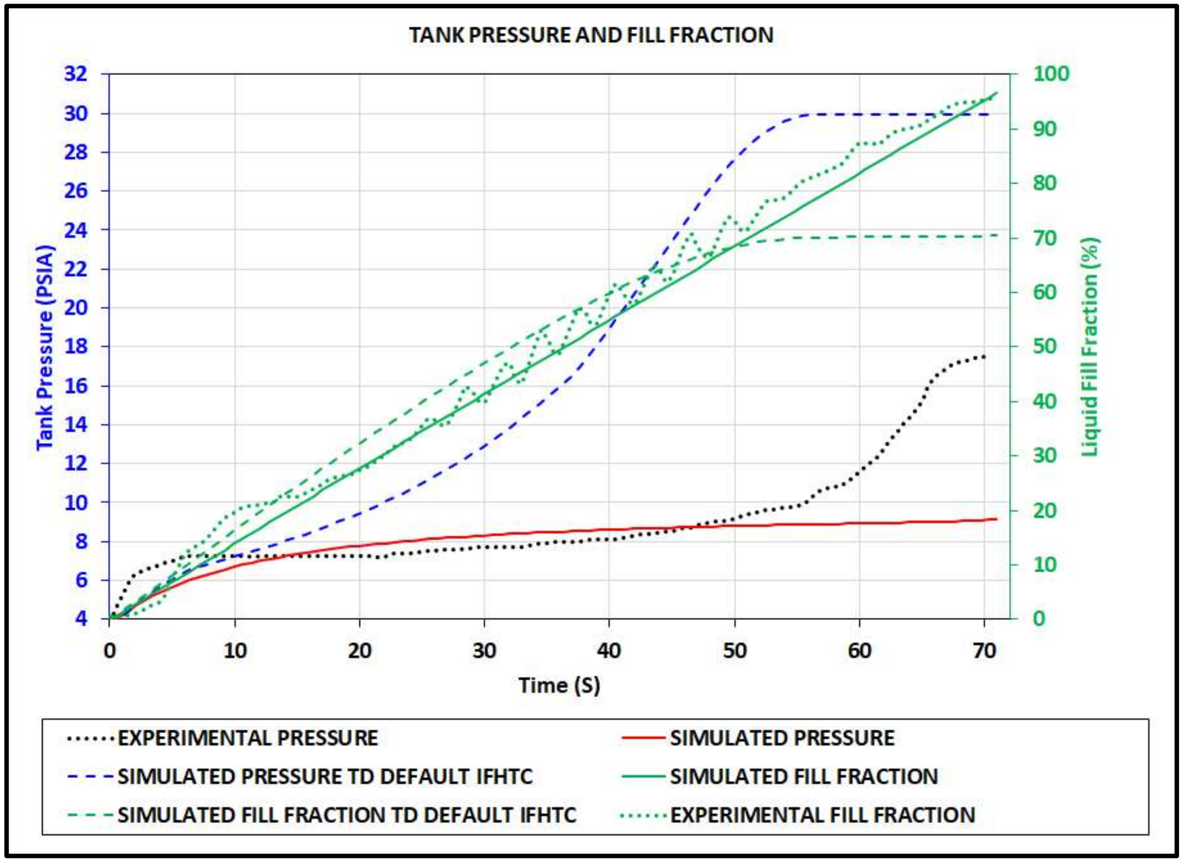


- Stainless steel tank of uniform 0.8 mm wall thickness initially cooled and evacuated to a preset pressure, temperature via charge-hold-vent process.
- At test start tank vent closes, inlet valve opens, and LH2 flows in from source tank at constant backpressure P. Test concludes when tank pressure or fill level reaches predetermined limit.
- Filling occurred from a jet issuing from an upward-facing pipe bend located at tank bottom.
- Tank instrumented with pressure, wall temperature, and rake-mounted internal temperature sensors.

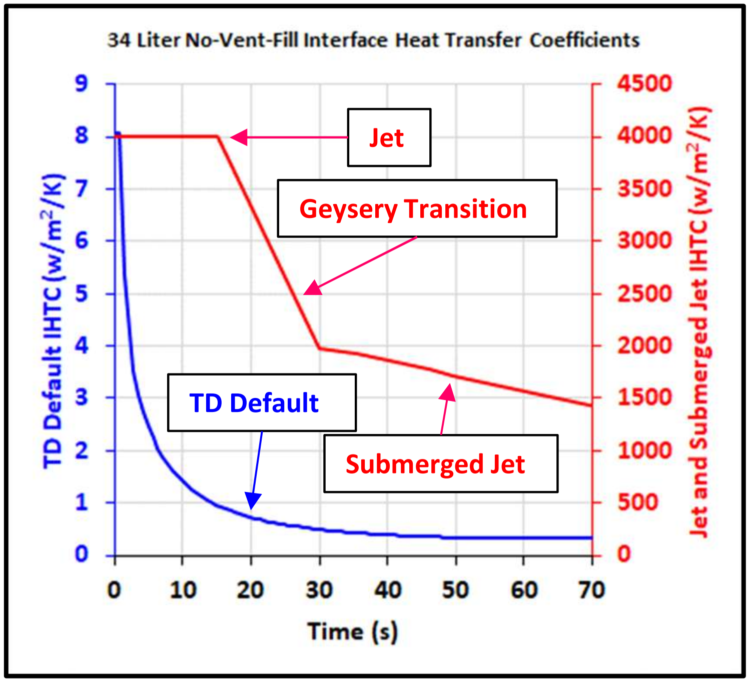
NVF Test 3 Pressure and Fill Comparison – CCL-7 34 Liter



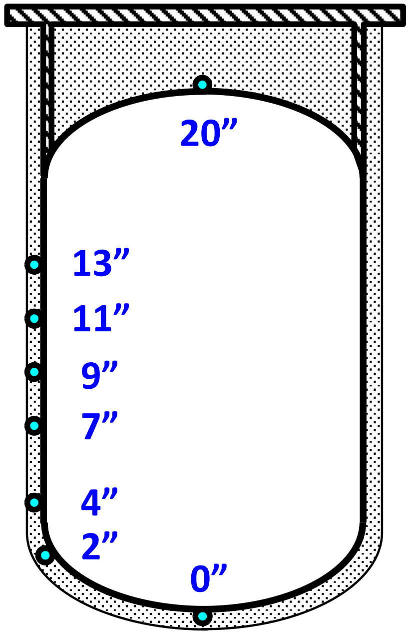
LH2 inflow temperature = 18.2 K, averaged initial wall temperature = 44.4 K, inlet mass flow rate = 0.034 kg/s.

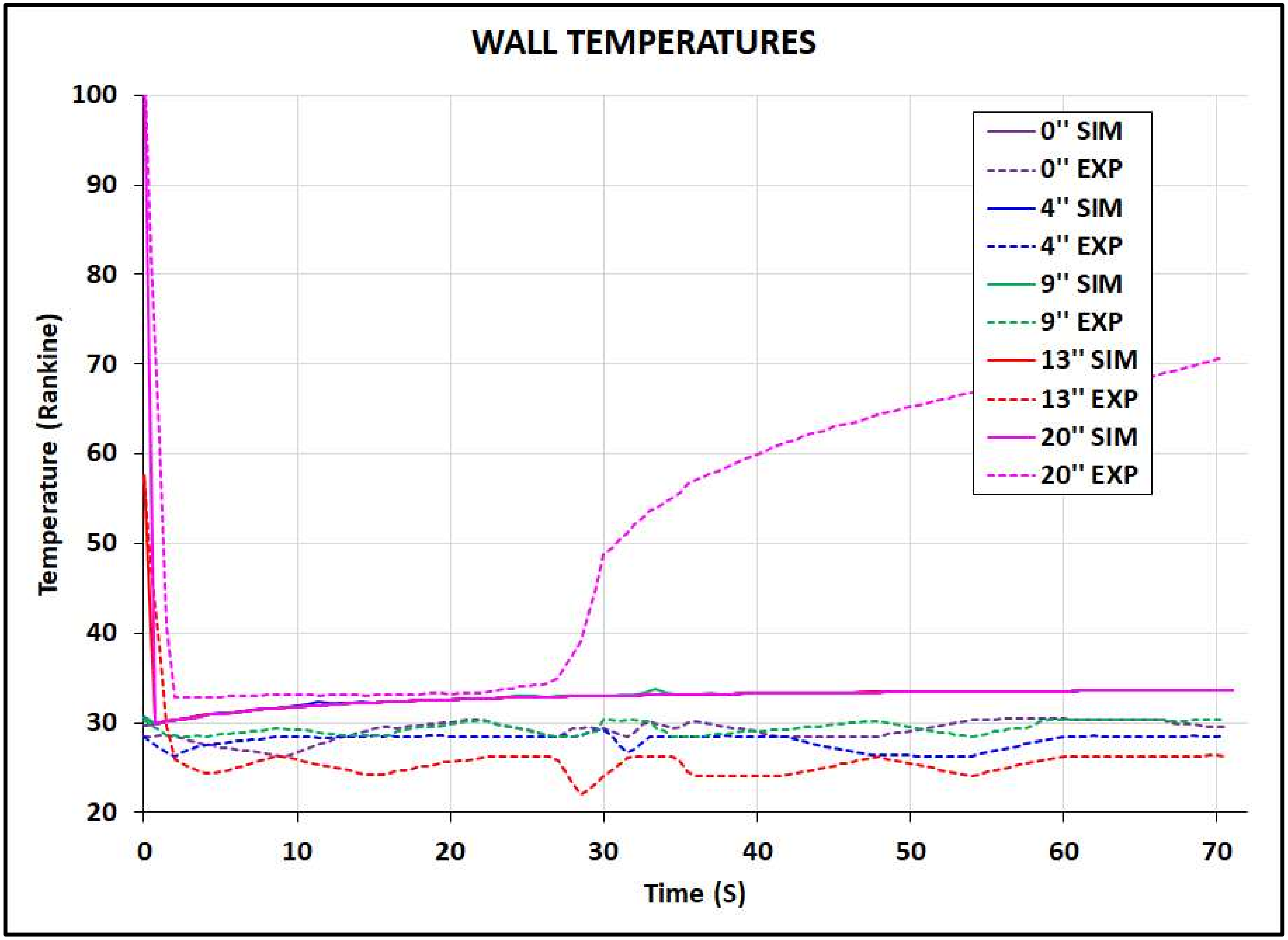


Experimental final fill = 96%.

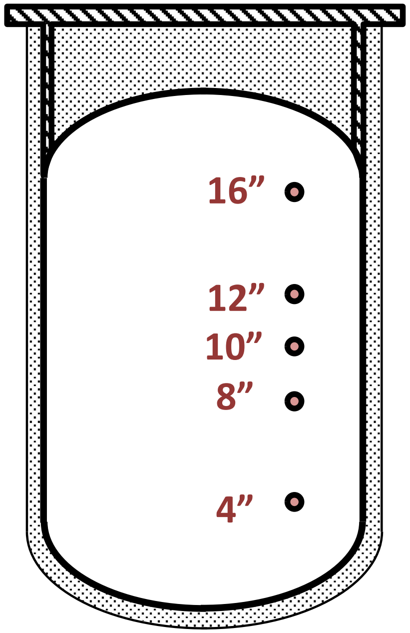


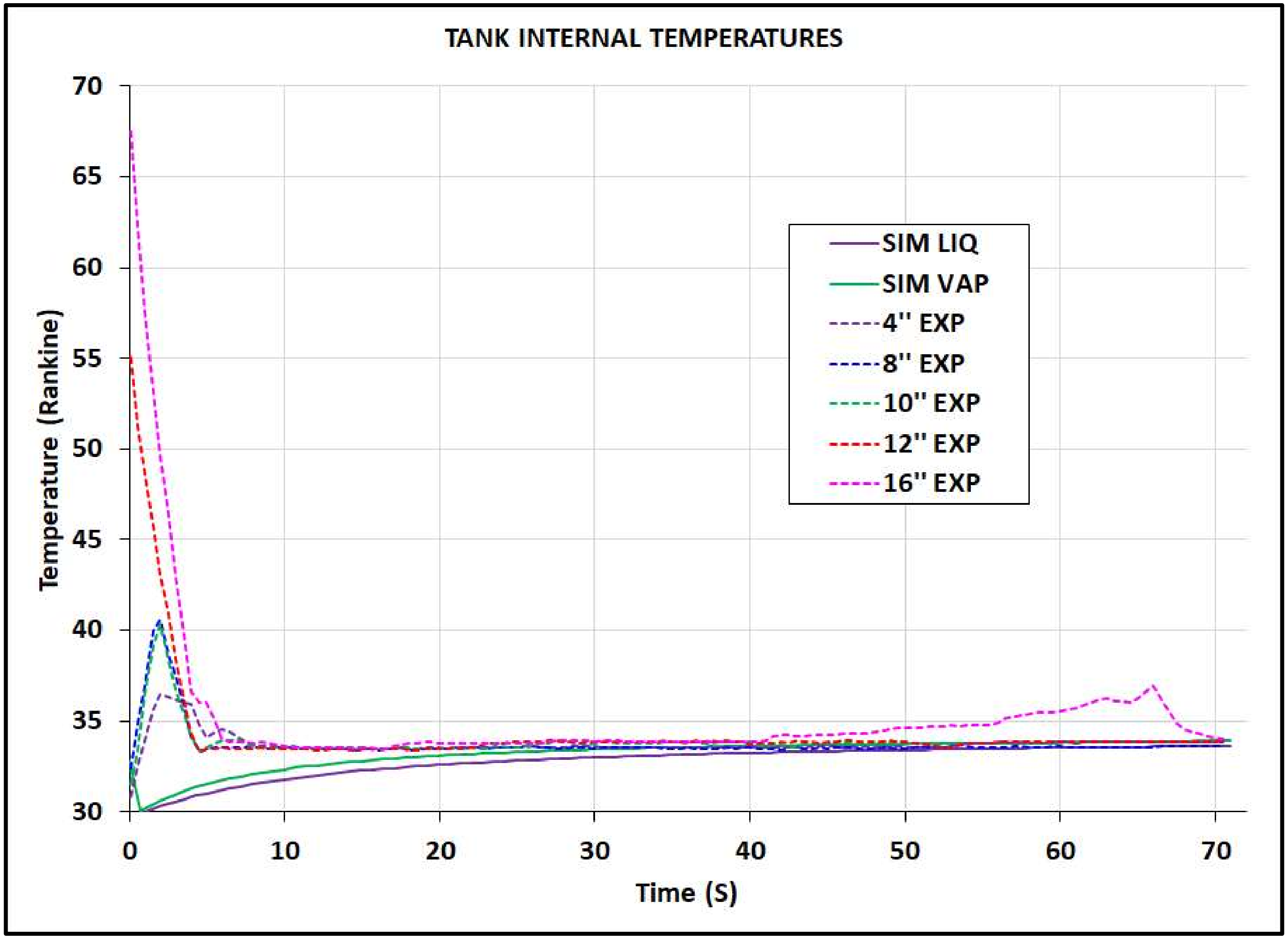
NVF Test 3 Temperature Comparison – CCL-7 34 Liter



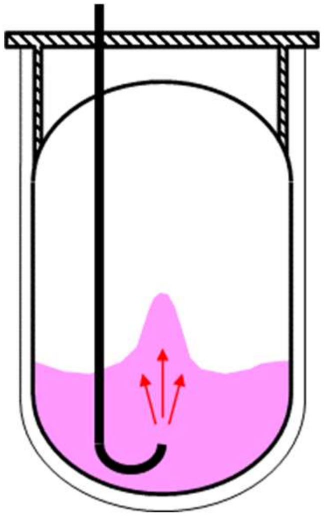


NVF Test 3 Temperature Comparisons – CCL-7 34 Liter (cont.)



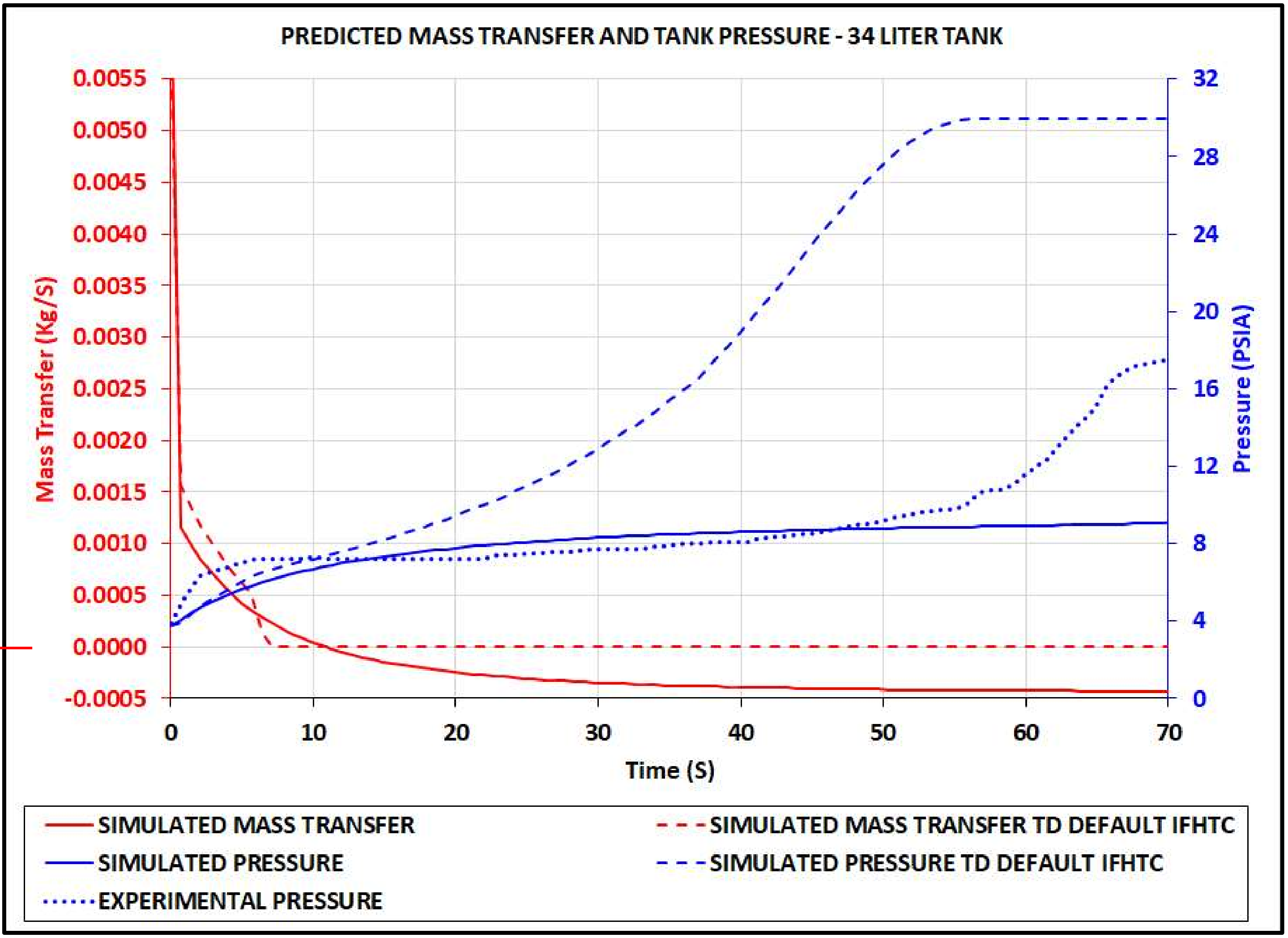


NVF Test 3 Mass Transfer Predictions - CCL-7 34 Liter

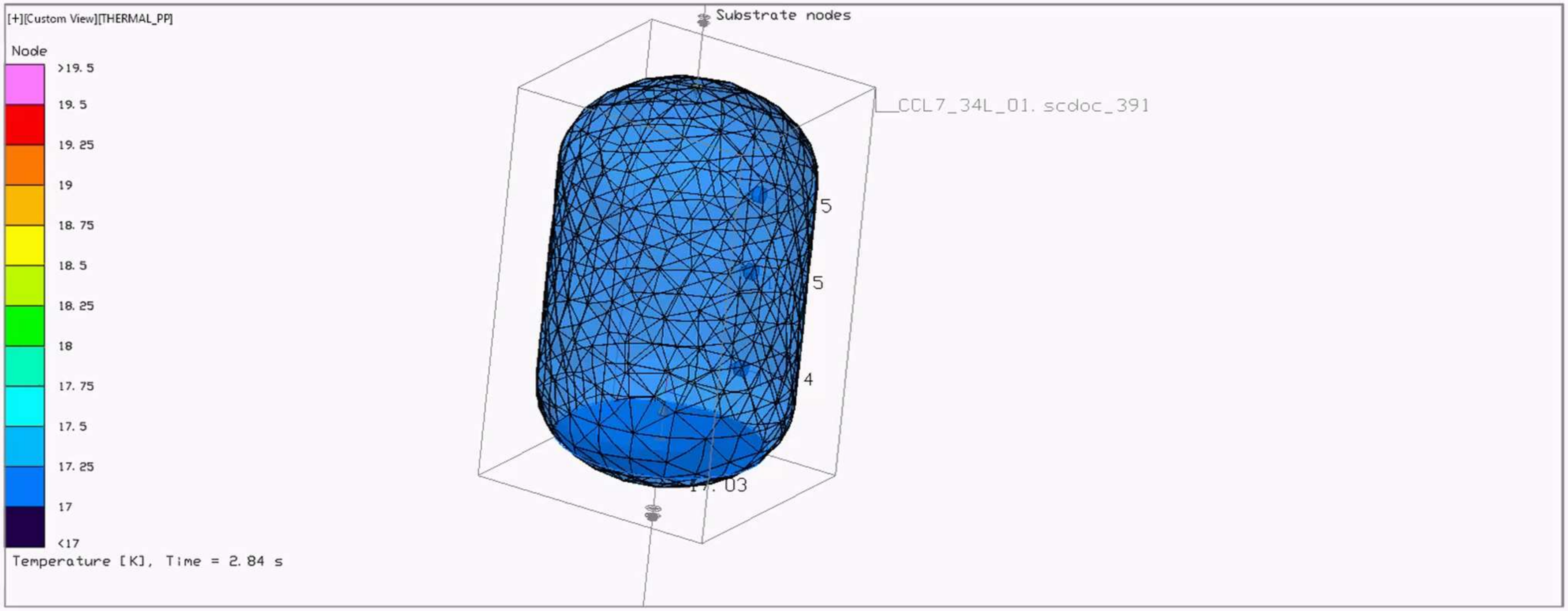


Evaporation

Condensation

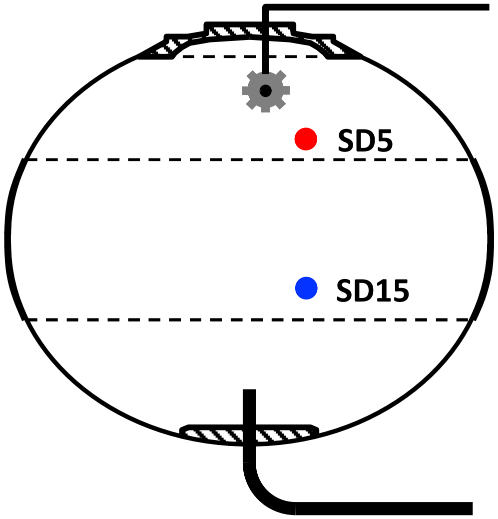


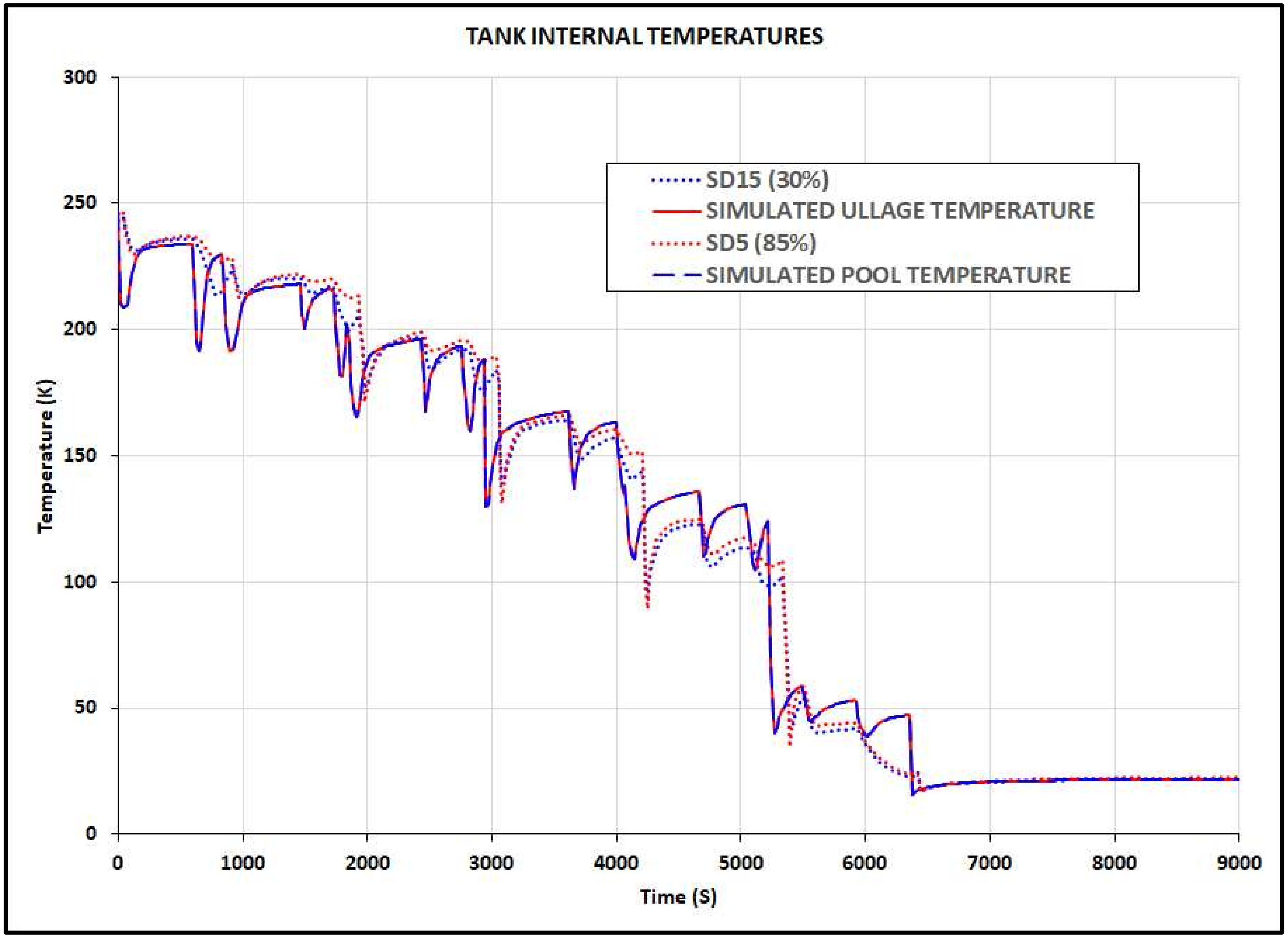
Filling Animation – CCL-7 34 Liter



Test 2 NVF Temperature Comparison – K-Site 5K Liter

Internal Temperatures





K-Site 2K Liter Tank Test Configuration

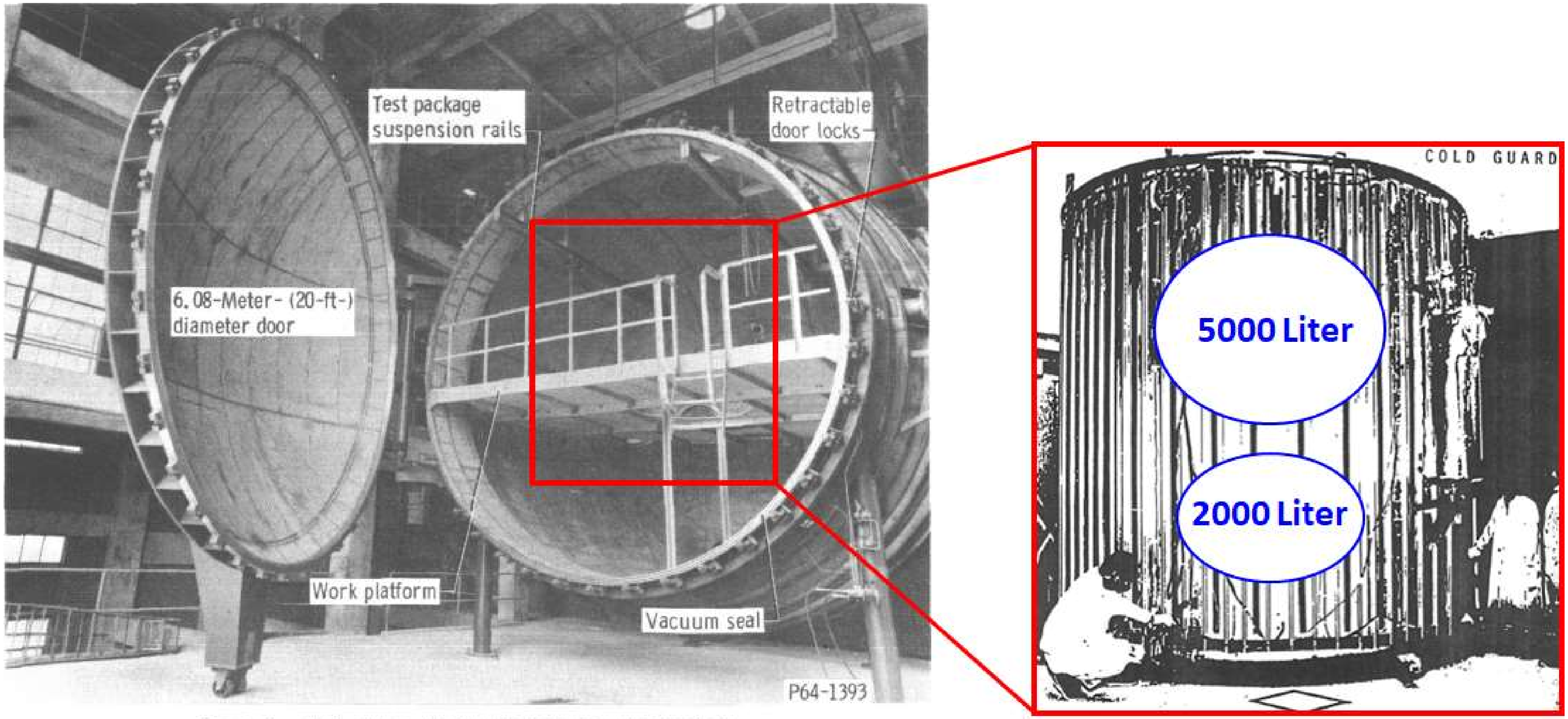


Figure 1. - 7.61-Meter- (25-ft-) diameter vacuum chamber.