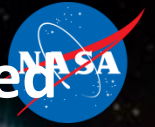


SINDA/FLUINT and Thermal Desktop Multi-Node Settled and Unsettled Propellant Tank Modeling of Zero Boil Off Test



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AIAA Propulsion and Energy Forum
August 19 through 22, 2019**

- Cryogenic propellant storage tank self-pressurization involves complex physical phenomena which are usually analytically modelled via complex multidimensional CFD codes
- Unfortunately these codes, even when modelling axisymmetric domains, may takes weeks or longer to obtain transient pressure and temperature information for relatively short periods of time (several seconds to several hours).
- Propellant tank storage end-to-end mission simulations can last a duration of days to weeks to months.
- Multi-node modelling of propellant tanks is a viable alternative to traditional CFD modelling and presents the advantage of greatly reduced run times on the order of hours and days compared to the weeks or longer for CFD

- SOLUTION: A multi-node model represents the fluid within the storage tank, as well as the storage tank itself, as a fluid-thermal network
 - This type of setup is not necessarily geometrically based. This can be accomplished using a commercial generalized fluid-thermal network code, such as SINDA/FLUINT (SF)
 - The advantage of using a fluid-thermal network code like SF lies in its extensive ability to model the external environment of the storage tank through the graphical user interface, Thermal Desktop (TD)

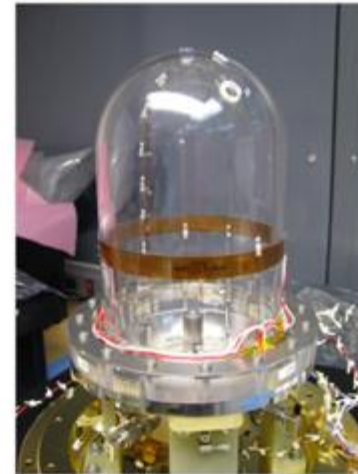
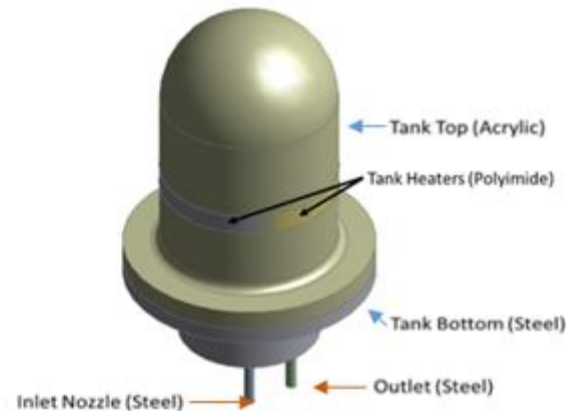
- A general purpose SF stratified tank model was created to simulate self-pressurization of cryogenic storage tanks
 - The model can be set up as a multi-nodal representation (one, two, or three dimensional)
 - The state of the fluid in the tank can be settled under conditions of normal gravity or unsettled in a microgravity environment
 - Furthermore, the tank wall and its exterior environment can also be modelled in TD with full geometric detail
 - An interface with TD was created so that detailed geometric tank wall modelling and complex radiative thermal environments could be included

- This model was validated with Zero-Boil-Off Test (ZBOT) data
 - Self-pressurization under 1g and microgravity with a strip heater and a surrounding vacuum jacket
 - SF multi-nodal representation of the tank wall and its exterior environment as well as a detailed TD geometric representation of the tank wall and its external radiative environment
 - Jet mixing under microgravity

Zero-Boil-Off-Test Set Up



- The ZBOT tests were conducted in microgravity (approximately $5\text{E-}6 \text{ m/s}^2$) and a 1g environment
- The heater supplied 0.5 W in microgravity and 1.0 W in the 1g environment



A stainless steel nozzle injects liquid into the tank, and a stainless steel outlet tube removes liquid from the tank.

FIGURE 1: ZBOT TANK

Zero-Boil-Off-Test Set Up



- A vacuum jacket was used to isolate the tank from the environment
- The vacuum jacket was comprised of aluminum and the windows are glass
- The area-averaged temperature of the vacuum jacket was controlled in order to control the radiative environment and thus the heat transfer into the tank

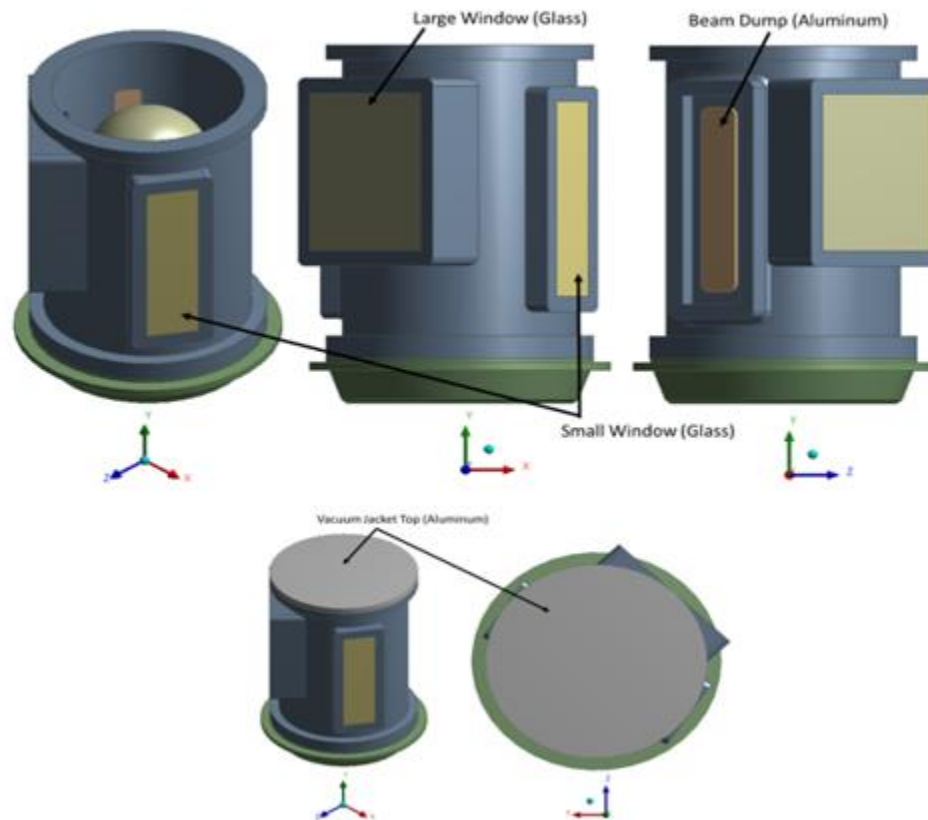


FIGURE 2: ZBOT Vacuum Jacket Assembly

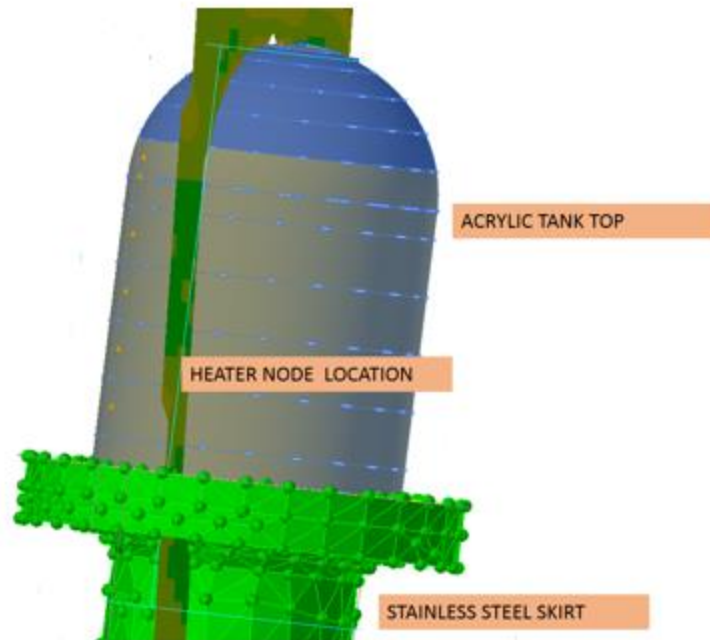


FIGURE 3: Thermal Desktop Geometric Representation of Tank

Thermal Desktop and SINDA/FLUINT Modelling

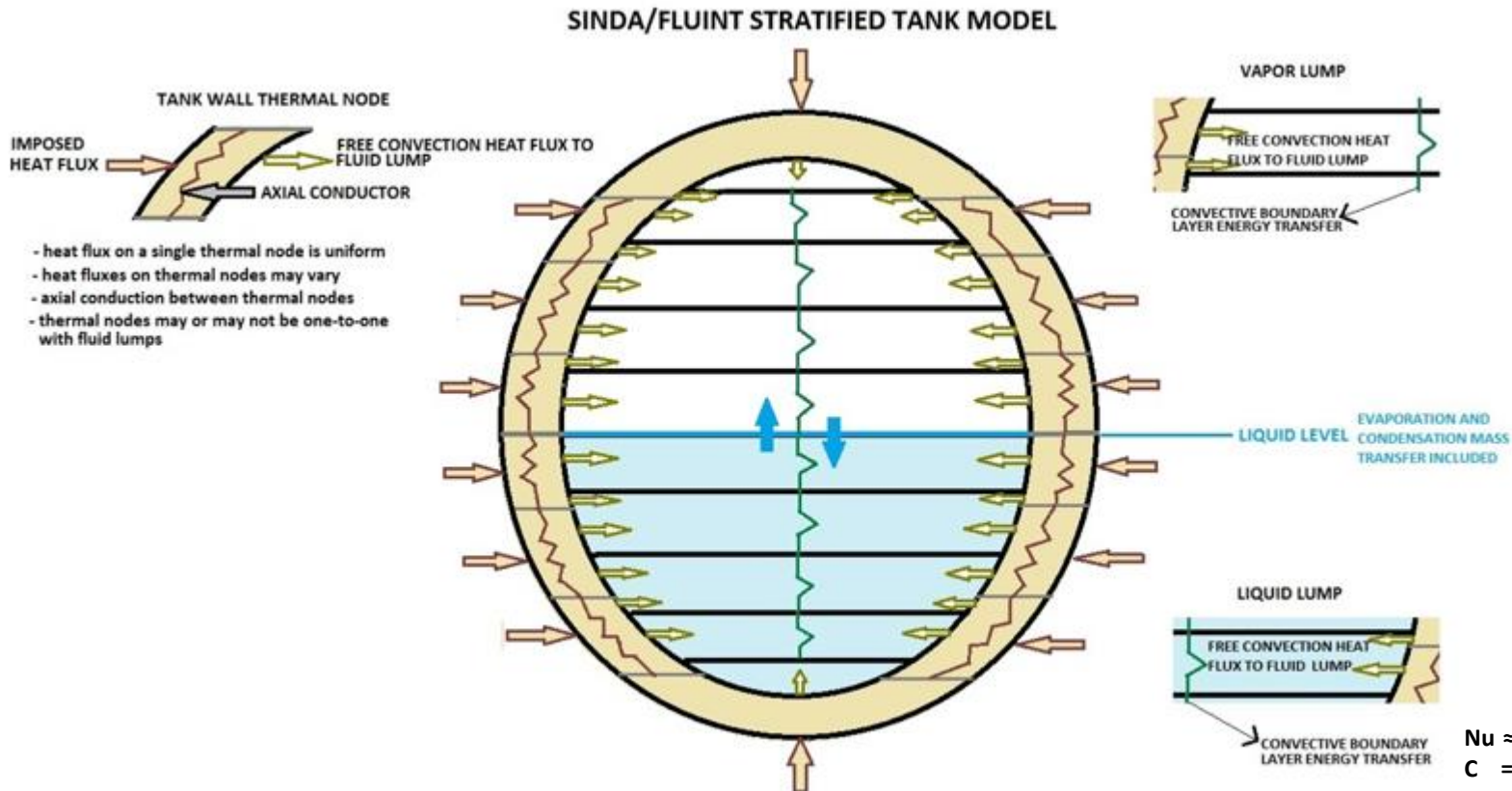


FIGURE 4: SINDA/FLUINT Stratified Tank Showing Liquid/Vapor Interface, Tank Wall with Thermal Conductors, Free Convective Heat Transfer and Associated Boundary Layer Energy Transfer

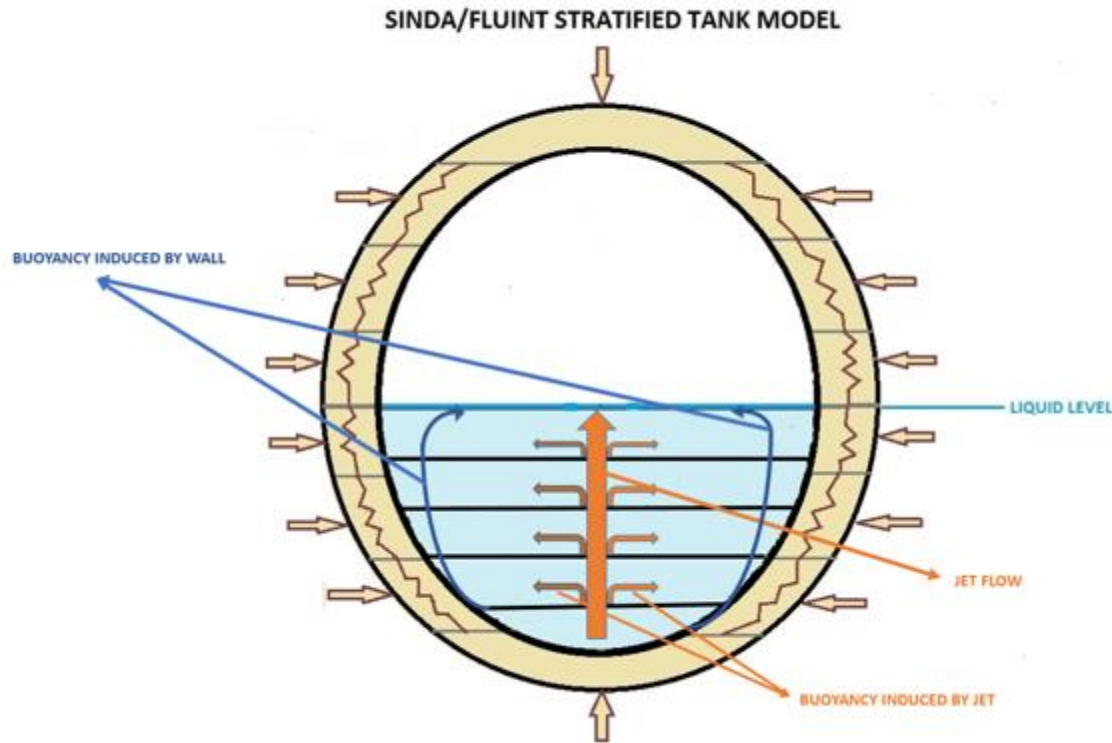


FIGURE 5: SINDA/FLUINT Stratified Tank Showing Liquid/Vapor Interface, Tank Wall with Thermal Conductors, Jet Flow, and Buoyancy Induced by Jet and Wall

Radiation

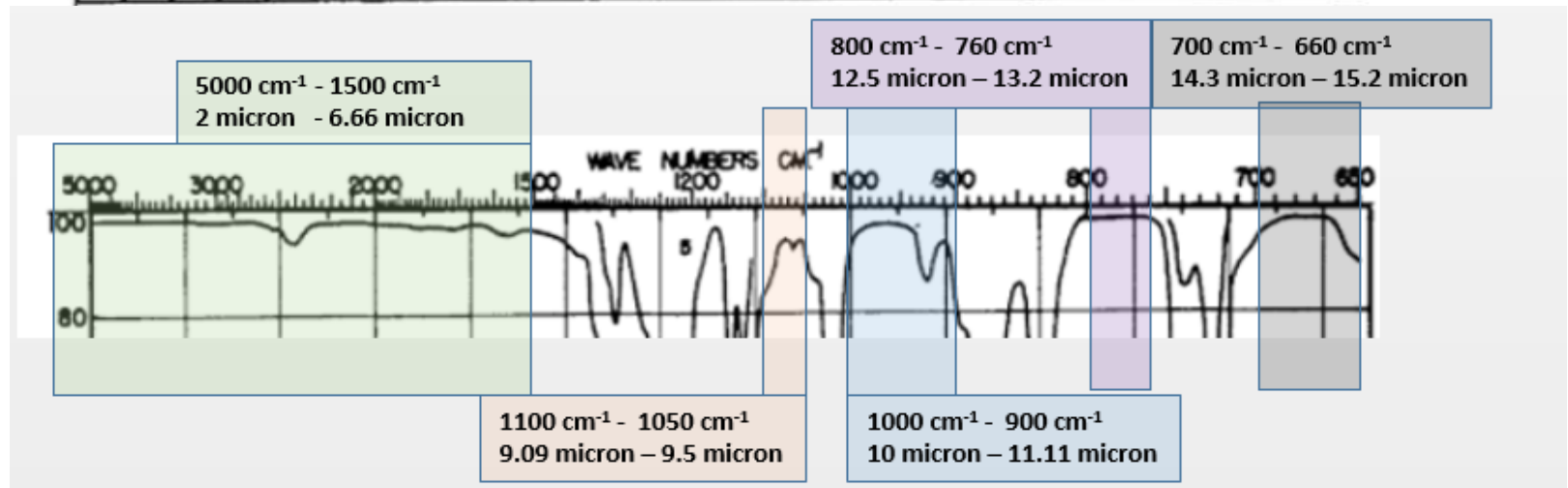
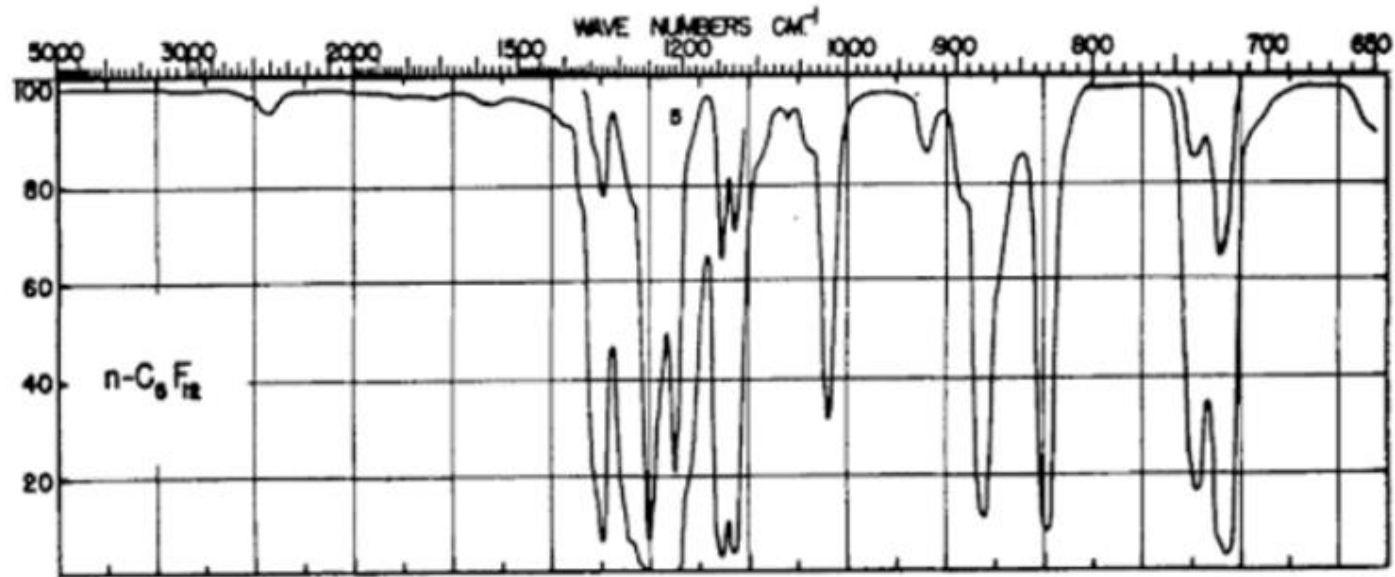


FIGURE 6: Perfluoropentane Transmittance Versus Wave Number
Total Transmittance Approximately 25%

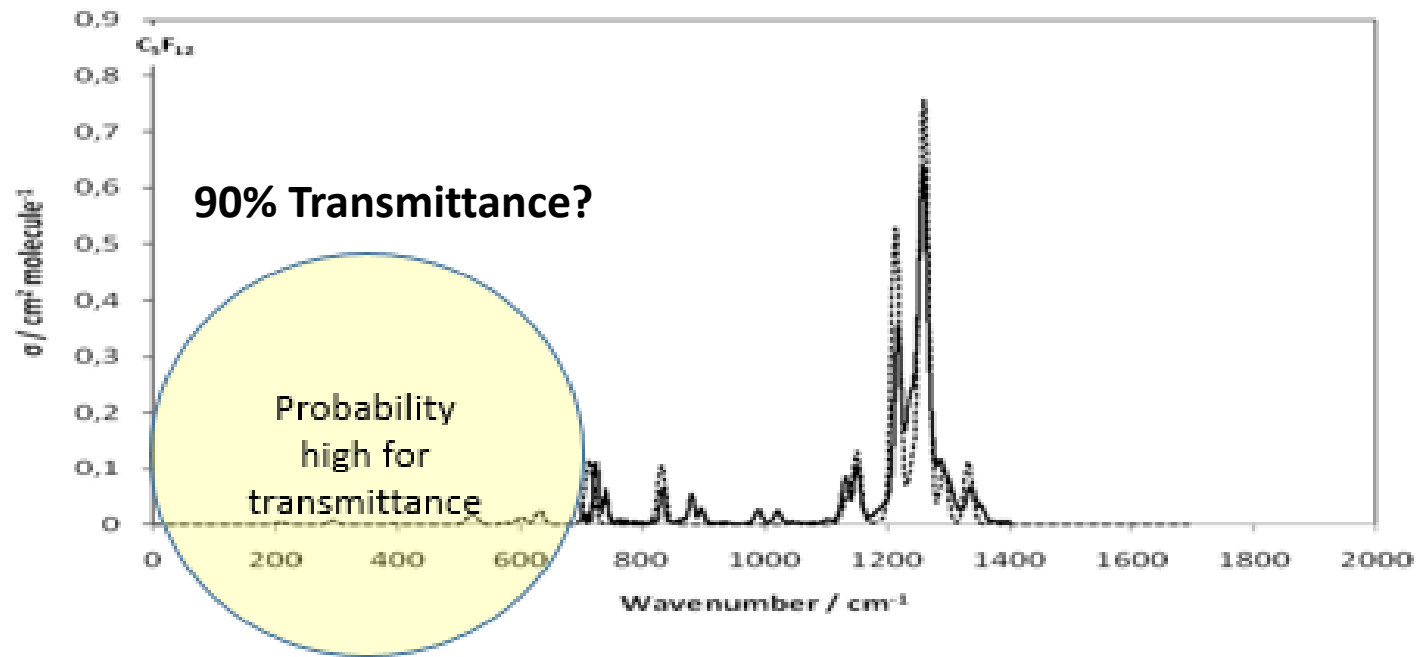


FIGURE 7: Perfluoropentane Probable Transmittance Versus Wave Number

Total Transmittance Approximately 13%

Results: ZBOT Self-Pressurization Case, 90% Fill Level, 1.0 W Strip Heater, 1g

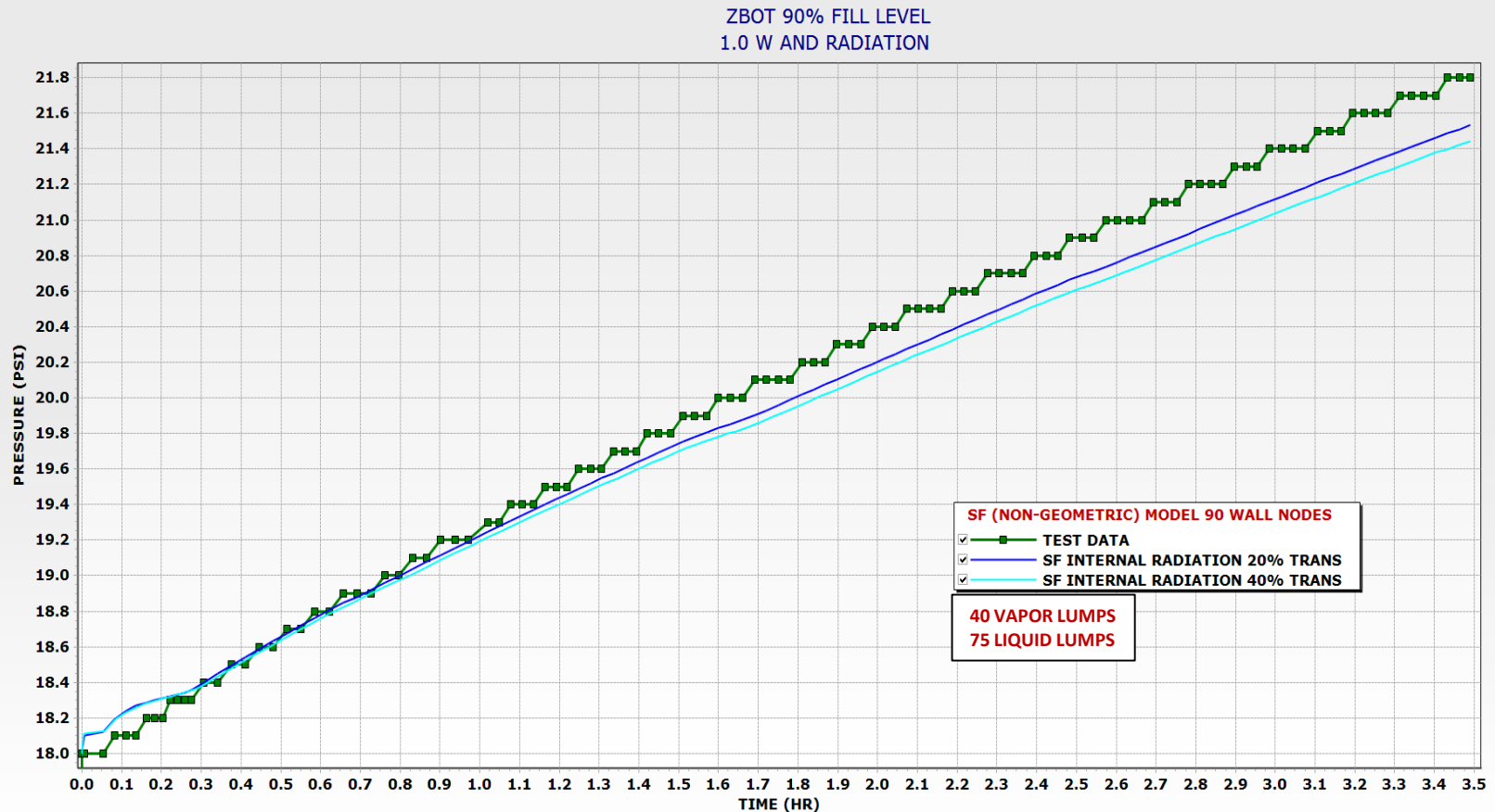


FIGURE 9: ZBOT Self-Pressurization Case Pressure Versus Time for 20% and 40% Rates of Radiation Transmission through Perfluoropentane for SF Model

Results: ZBOT Self-Pressurization Case, 80.82 % Fill Level, 0.5 Watts Strip Heater, Microgravity

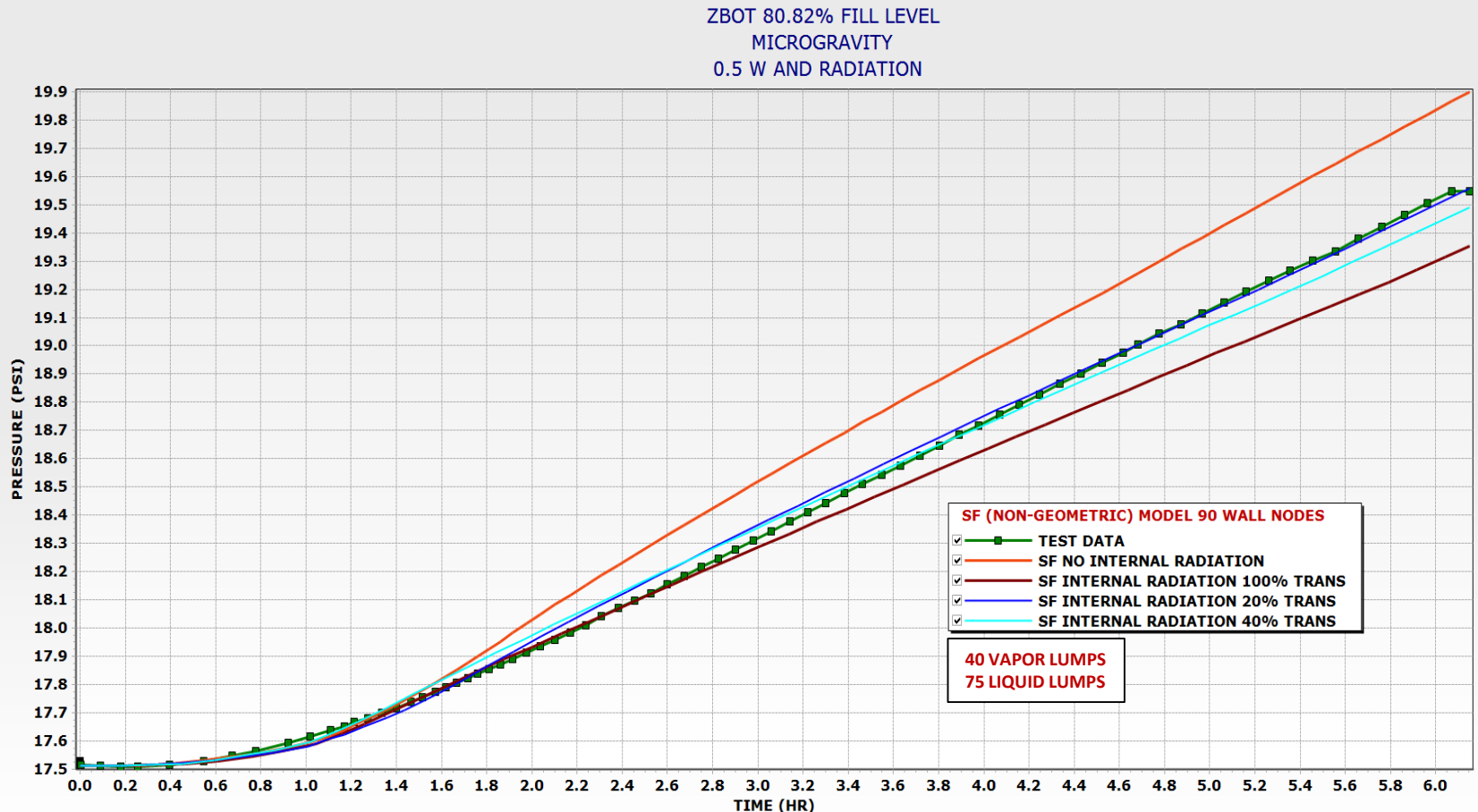


FIGURE 10: ZBOT Self-Pressurization Case Pressure Versus Time for Various Rates of Radiation Transmission through Perfluoropentane for SF Model

Results: ZBOT Self-Pressurization Case, 80.82 % Fill Level, 0.5 Watts Strip Heater, Microgravity

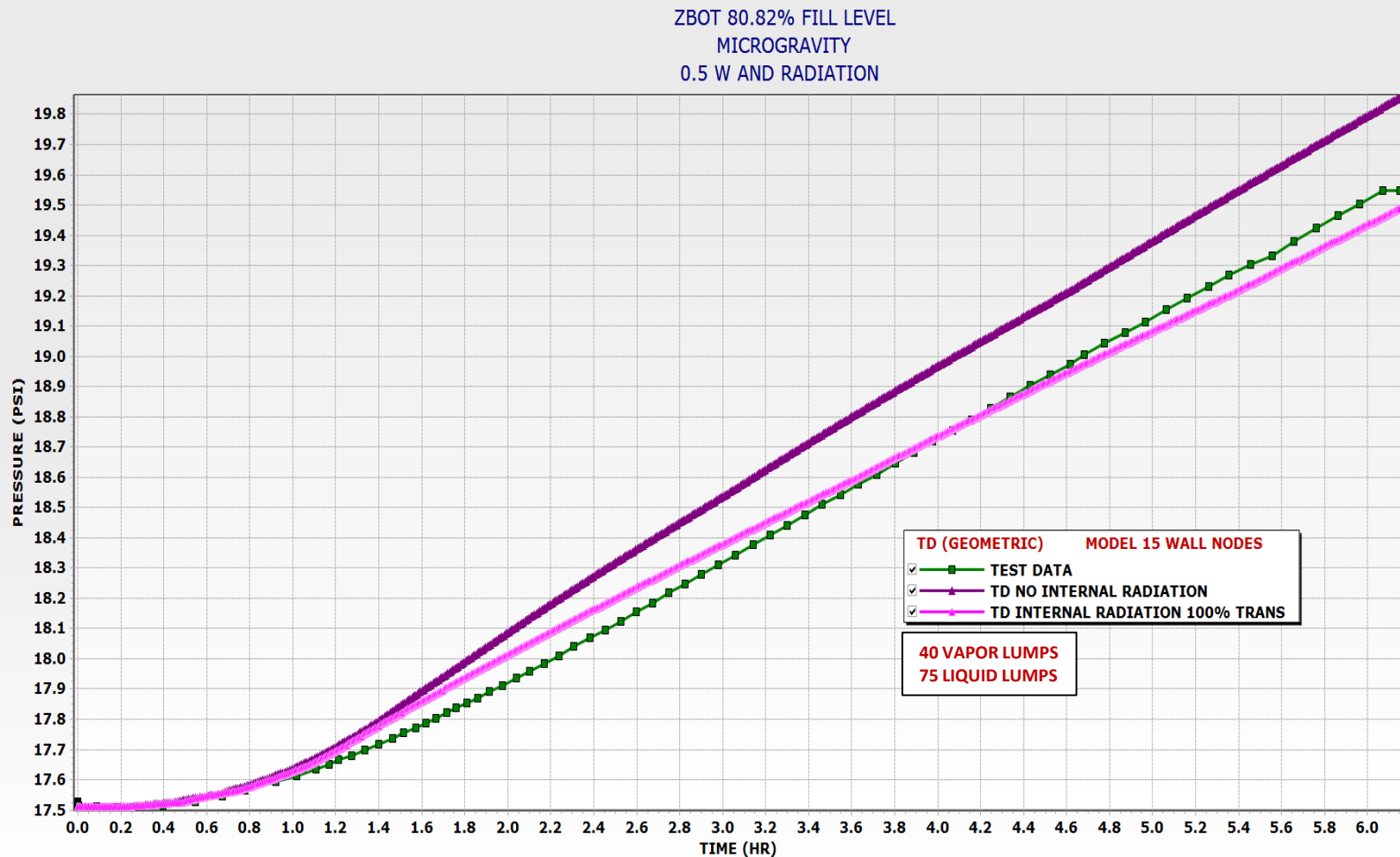


FIGURE 11: ZBOT Self-Pressurization Case Pressure Versus Time for Various Rates of Radiation Transmission through Perfluoropentane for TD Model

Results: ZBOT Self-Pressurization Case, 80.82 % Fill Level, 0.5 Watts Strip Heater, Microgravity

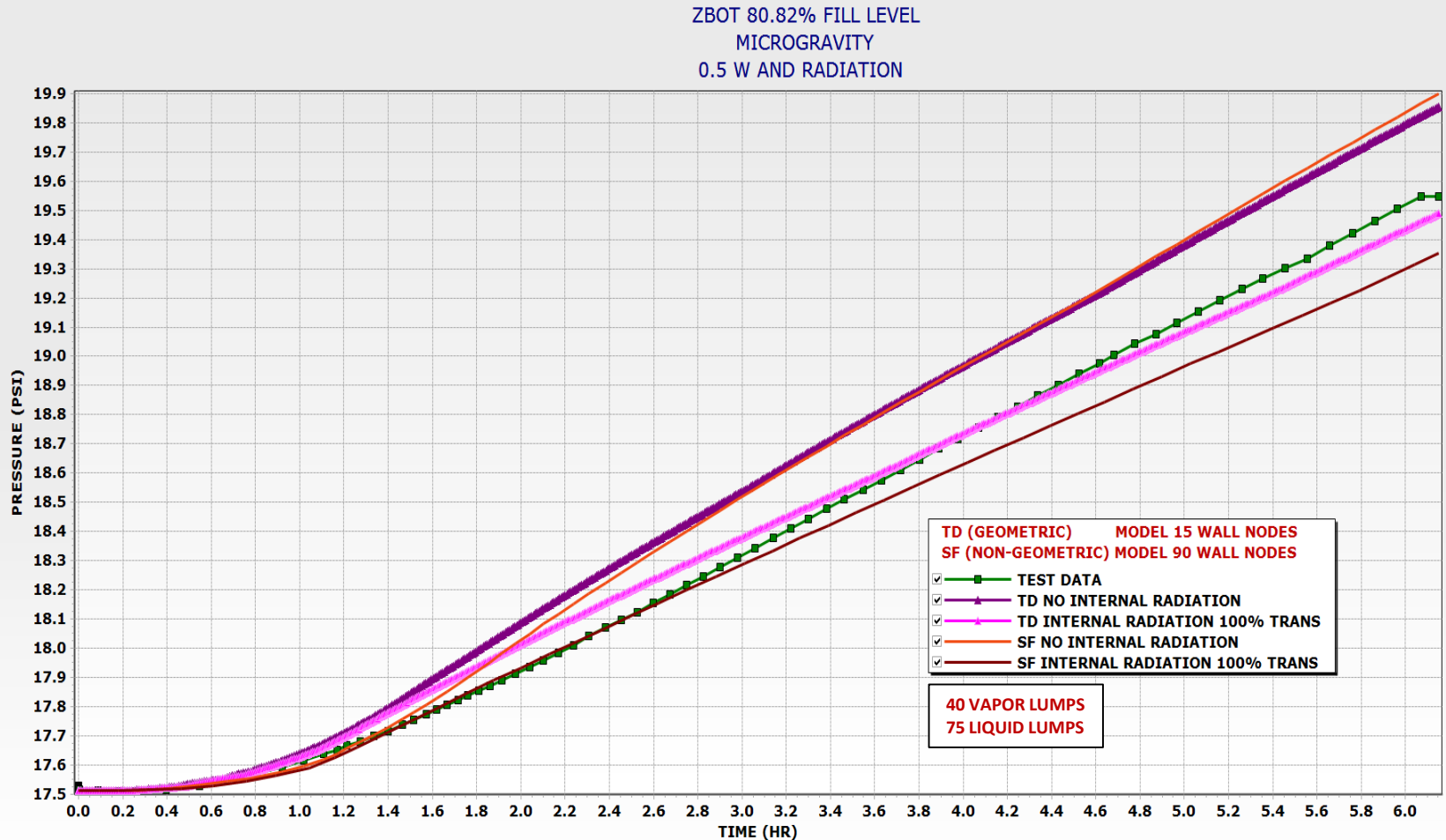


FIGURE 12: ZBOT Self-Pressurization Case Pressure Versus Time for 0% and 100% Rates of Radiation Transmission through Perfluoropentane for TD Model and SF Model

Results: ZBOT Self-Pressurization Case, 80.82 % Fill Level, 0.5 Watts Strip Heater, Microgravity

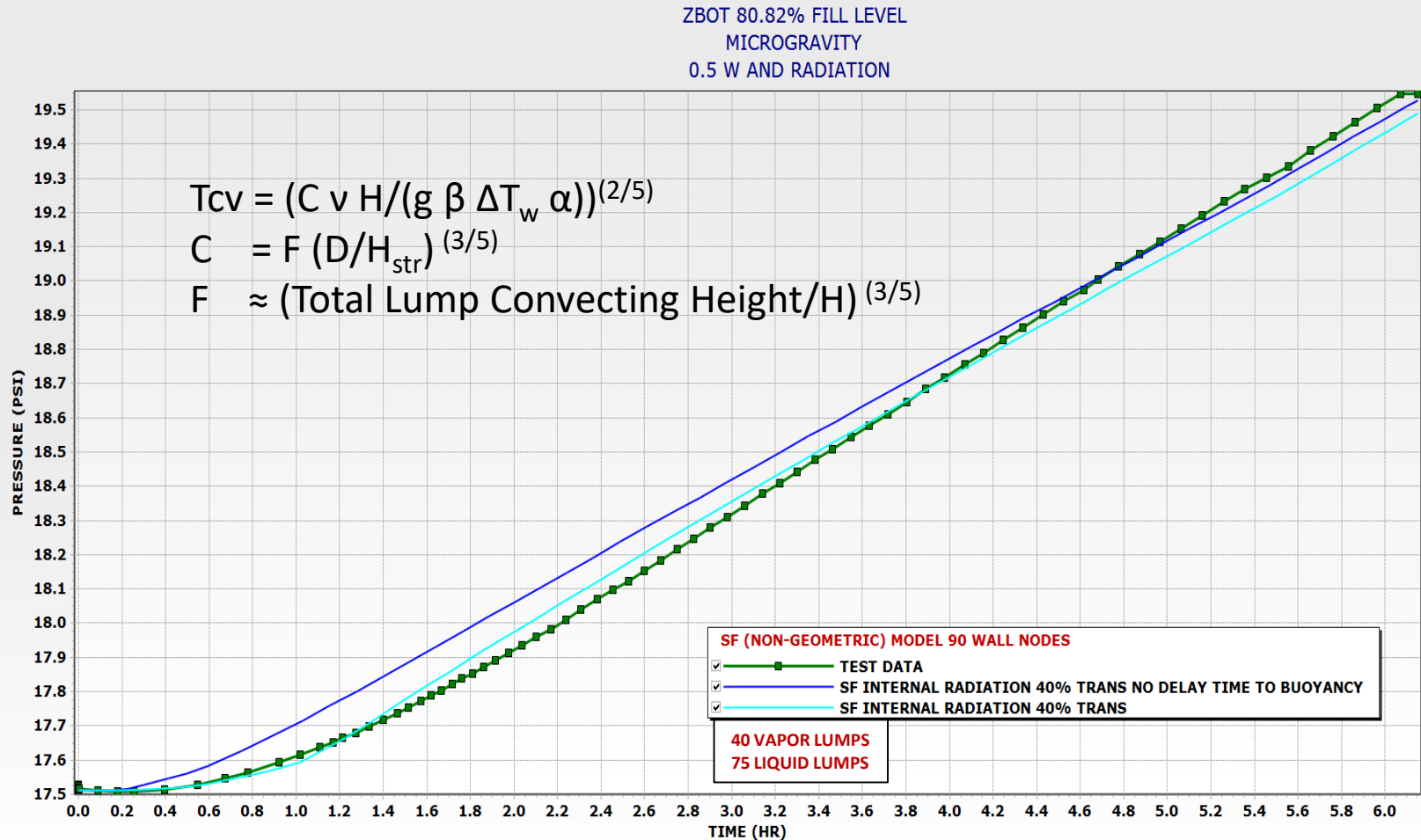


FIGURE 13: ZBOT Self-Pressurization Case Pressure Versus Time with and without Delay Time to Buoyancy for SF Model

Results: ZBOT Self-Pressurization Case, 80.82 % Fill Level, 0.5 Watts Strip Heater, Microgravity

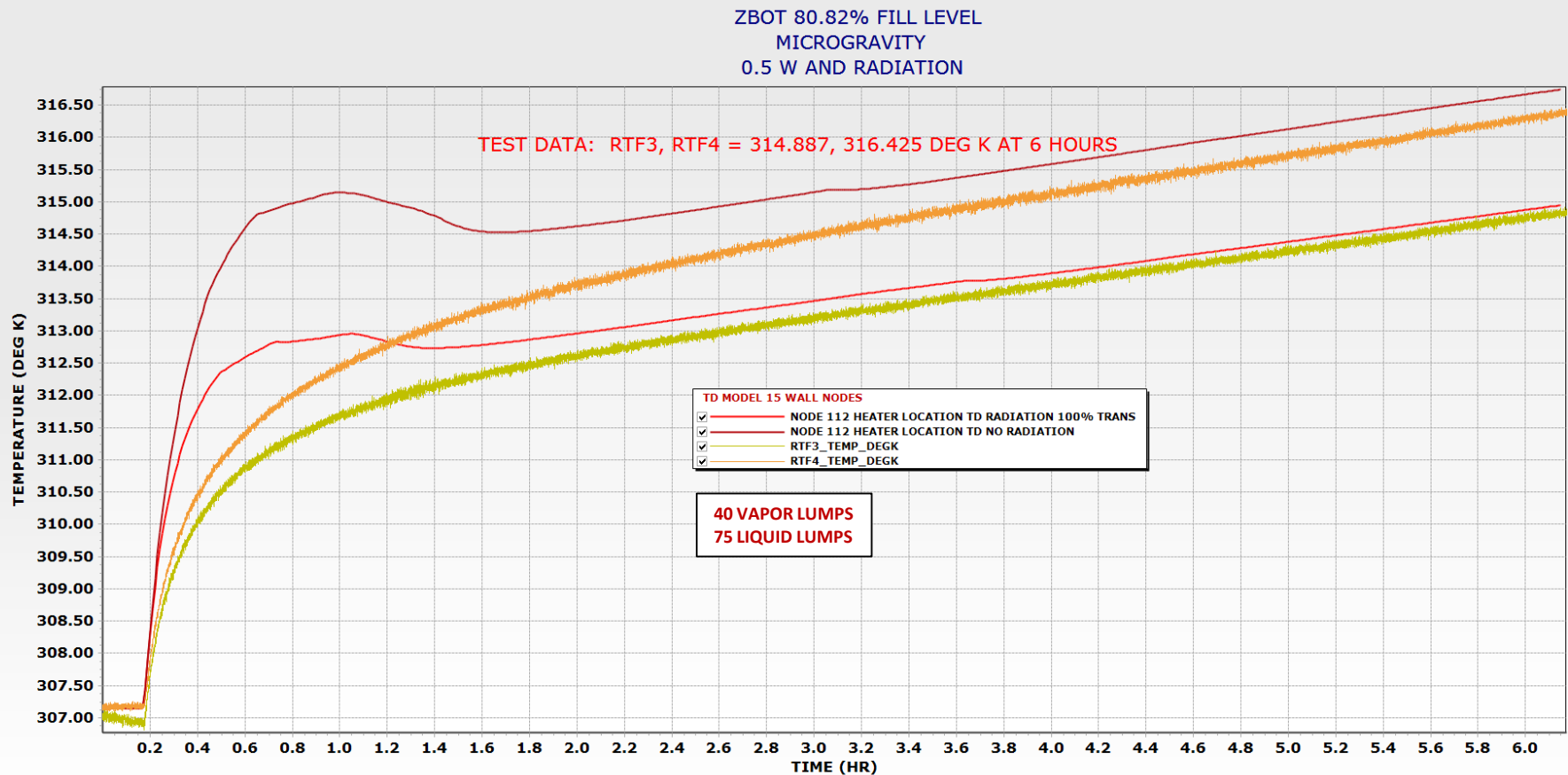


FIGURE 14: ZBOT Self-Pressurization Case Wall Temperature at Heater Location Versus Time for 0% and 100% Rates of Radiation Transmission through Perfluoropentane for TD Model

Results: ZBOT Self-Pressurization Case, 80.82 % Fill Level, 0.5 Watts Strip Heater, Microgravity

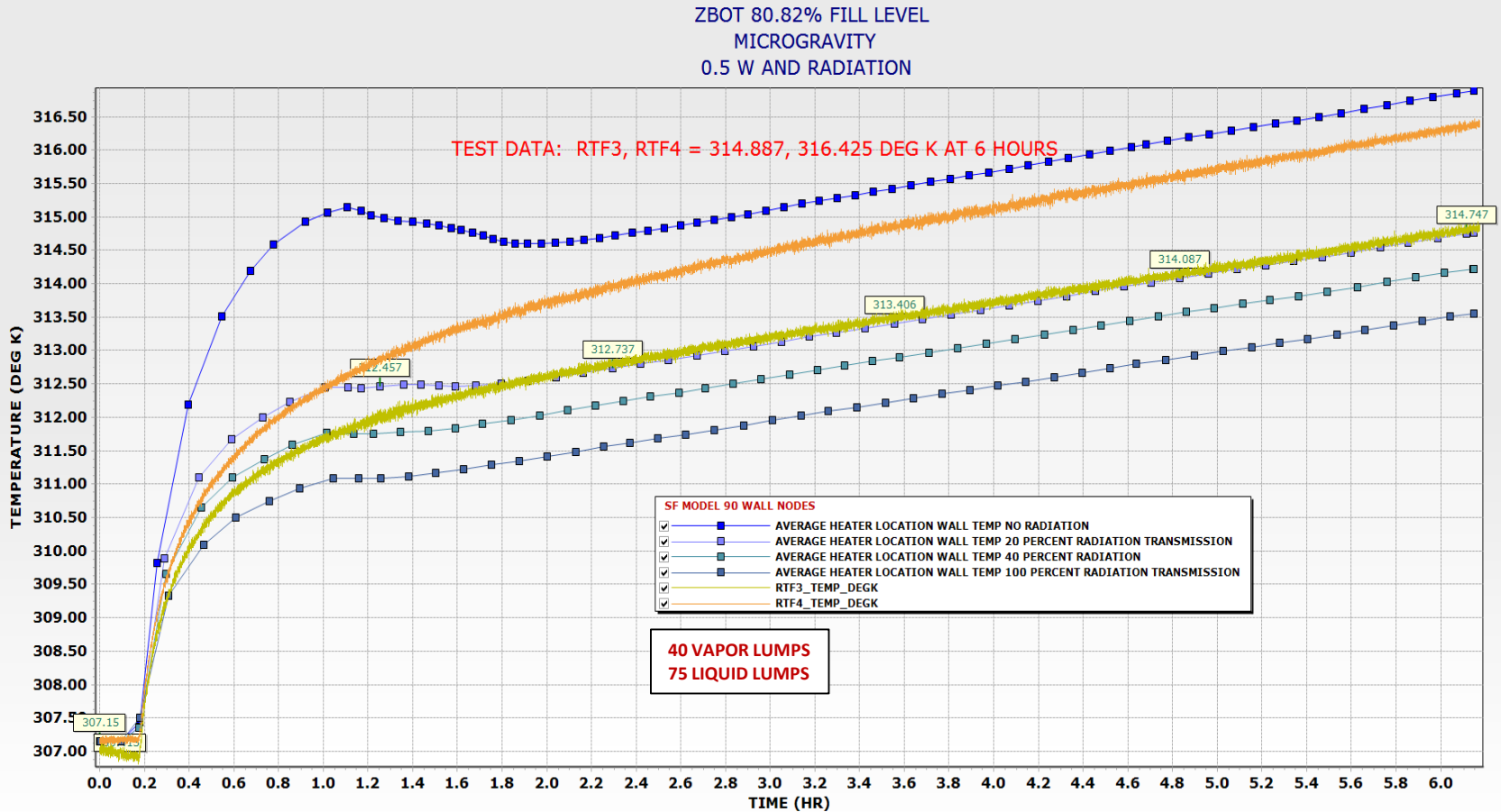


FIGURE 15: ZBOT Self-Pressurization Case Wall Temperature at Heater Location Versus Time for Various Rates of Radiation Transmission through Perfluoropentane for SF Model

Results: ZBOT Jet Mixing Case 905, 90% Fill Level, 1g

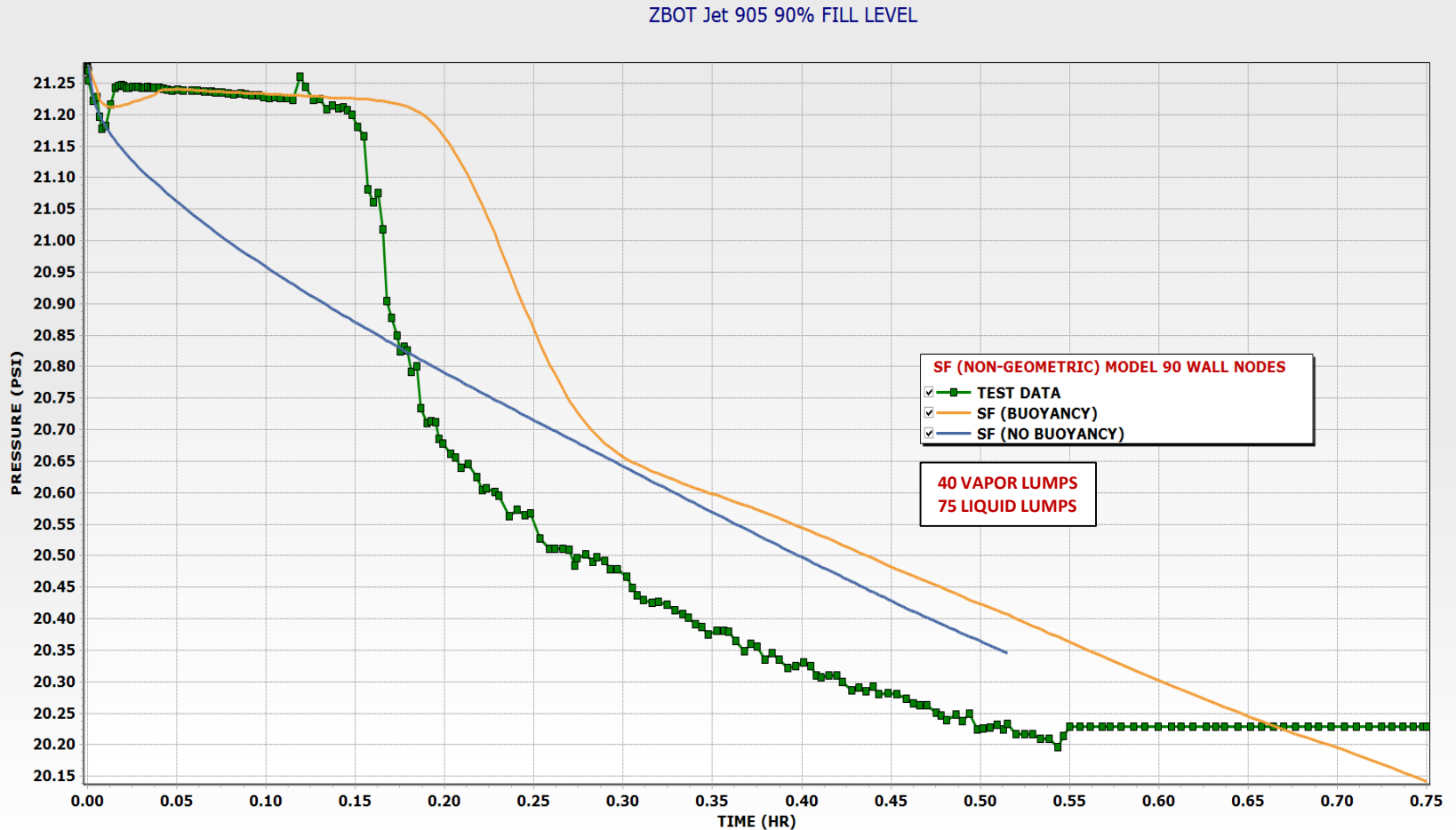


FIGURE 16: ZBOT Jet Mixing Case 905 1g Pressure Versus Time for Test Data, SF Jet Buoyancy Model, SF Jet with No Buoyancy Model

Results: ZBOT Jet Mixing Case 905, 90% Fill Level, 1g

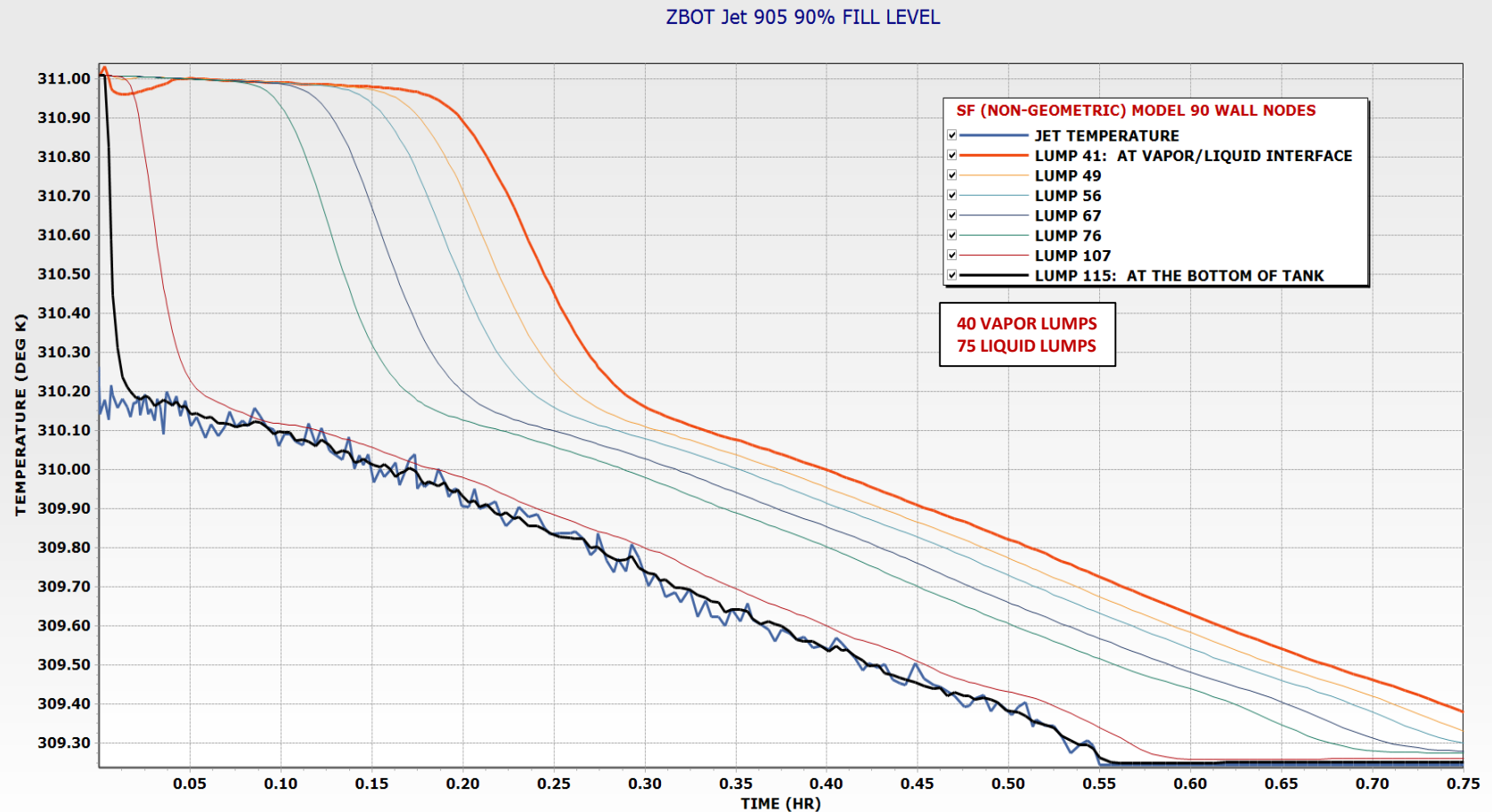


FIGURE 17: ZBOT Jet Mixing Case 905 1g Temperature Versus Time for SF Jet Buoyancy Model

Results: ZBOT Jet Mixing Case 905, 90% Fill Level, 1g



ZBOT Jet 905 90% FILL LEVEL

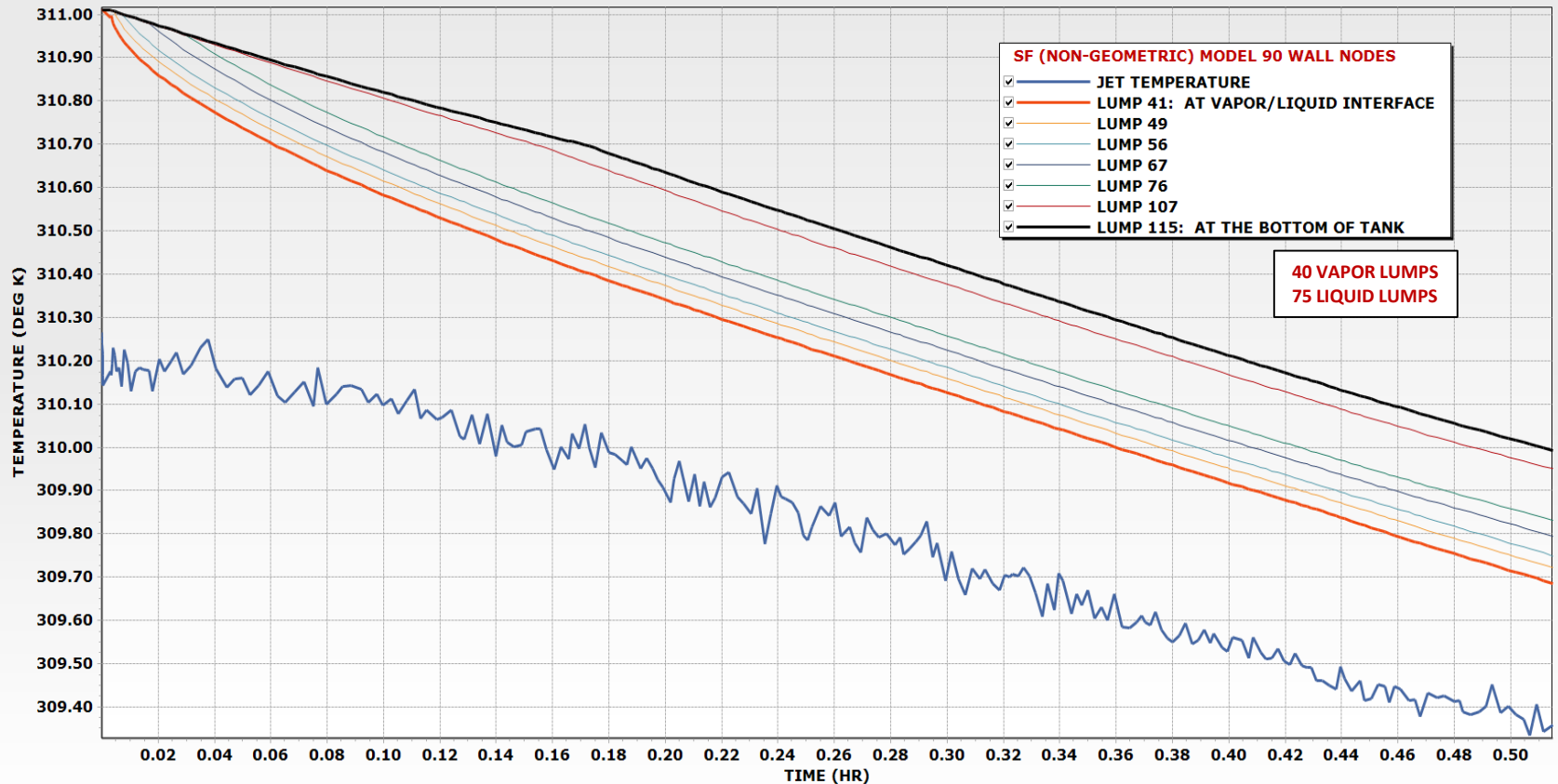


FIGURE 18: ZBOT Jet Mixing Case 905 1g Pressure Versus Time for SF Jet with No Buoyancy Model

Results: ZBOT Jet Mixing Cases 205, 206, 207

Microgravity



ZBOT Jet Mixing Cases Microgravity	Jet Flow Rate (g/s)
205 76.4% Fill	3.85
206 76.64% Fill	3.86
207 76.82% Fill	3.84

Table 1: ZBOT Jet Mixing Cases

The heat transfer that occurs at the vapor/liquid interface due to the jet impingement:

$$\begin{aligned} \text{Nu} &= (\rho c_p U_j X_a \text{St}) D / k \\ \text{St} &= 0.0198 \text{Pr}^{(-0.33)} (1.0 - 0.5\text{Ja}) \\ X_a &= 1.0 + (D_{\text{int}}/D_j)^{2.0} 0.0198 \text{Pr}^{(-0.33)} (V_{\text{int}}/U_j) \\ V_{\text{int}} &= U_j D_j/D_{\text{int}} (10.04 (0.24) - X_b \text{djet}/D_{\text{int}}) \\ X_b &= 7.14(0.24) - 3.06(0.34) \end{aligned}$$

NOTE!! Not Tracking the Vapor Bubble Movement

Results: ZBOT Jet Mixing Cases 205, 206, 207

Microgravity

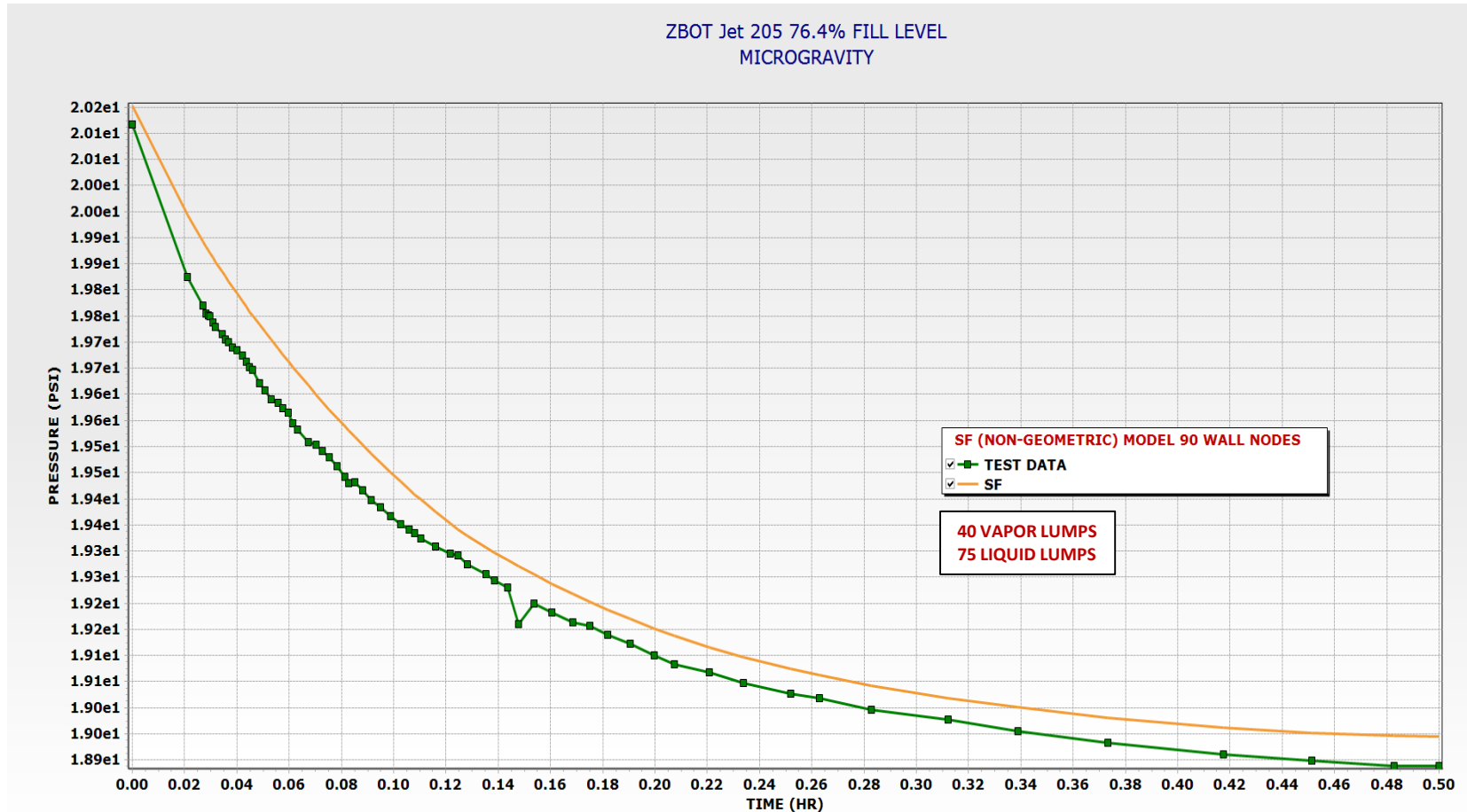


FIGURE 19: ZBOT Jet Mixing Case 205 Microgravity Pressure Versus Time for SF Model

Results: ZBOT Jet Mixing Cases 205, 206, 207

Microgravity



ZBOT Jet 206 76.64% FILL LEVEL
MICROGRAVITY

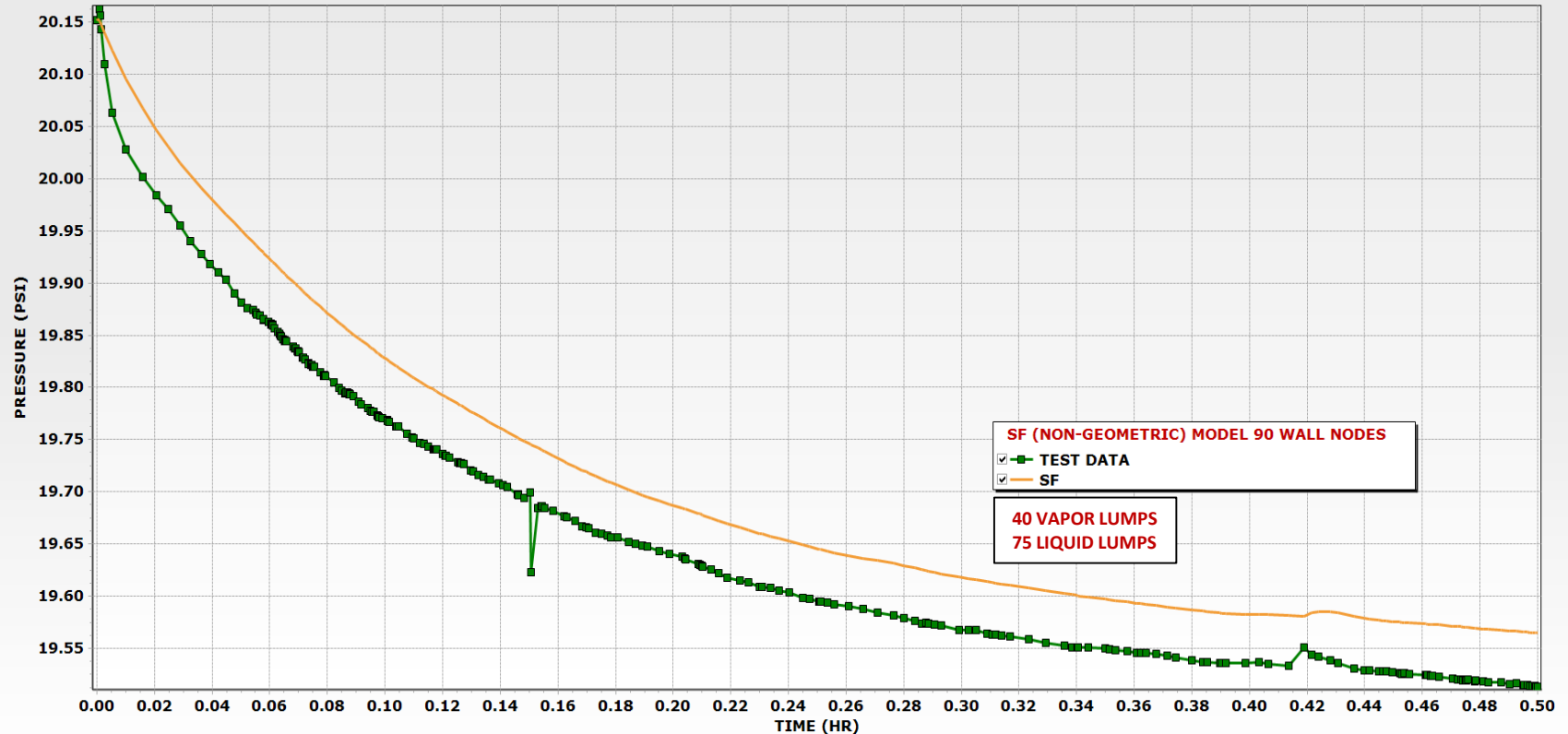


FIGURE 20: ZBOT Jet Mixing Case 206 Microgravity Pressure Versus Time for SF Model

Results: ZBOT Jet Mixing Cases 205, 206, 207

Microgravity

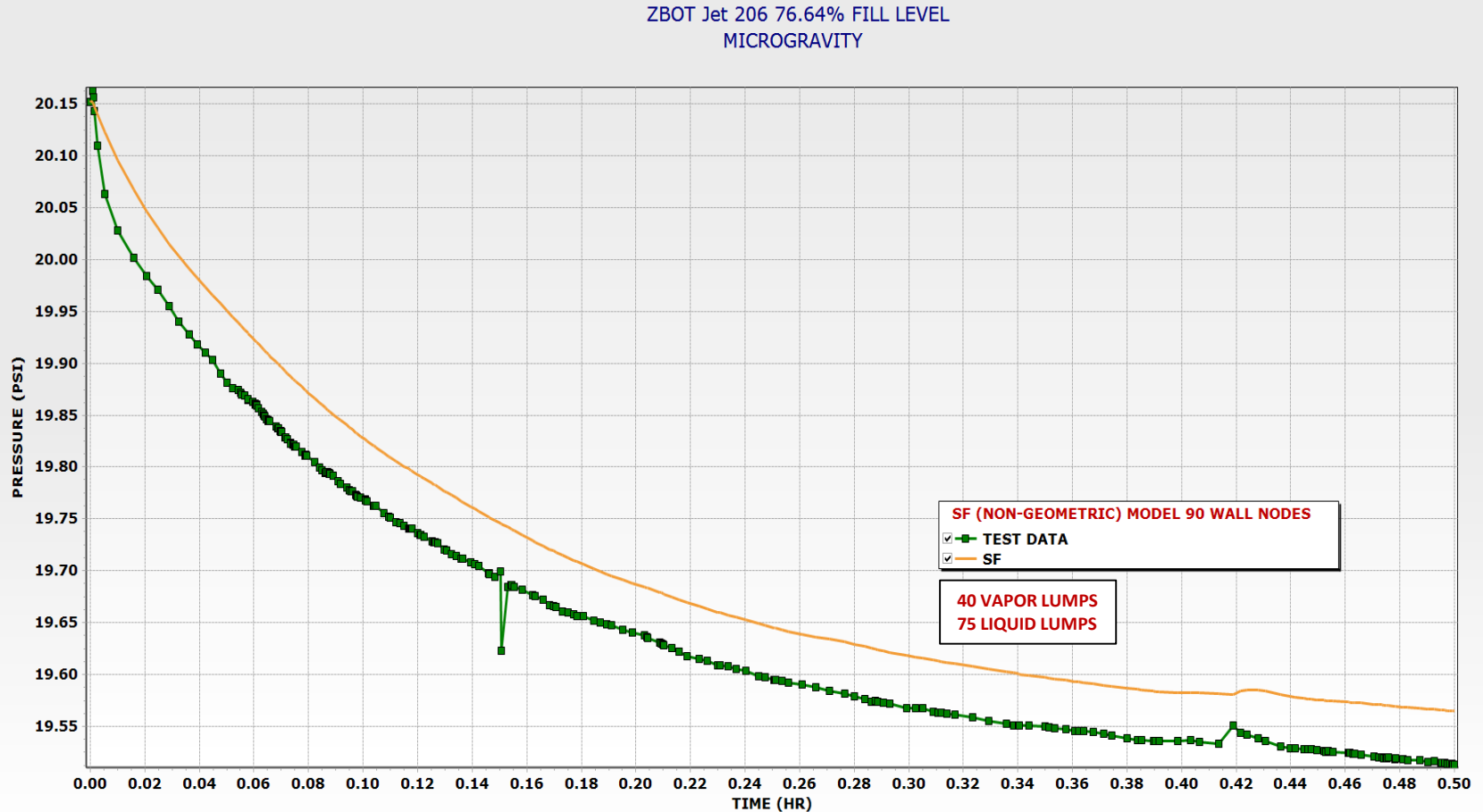


FIGURE 20: ZBOT Jet Mixing Case 207 Microgravity Pressure Versus Time for SF Model

- It was demonstrated that a one-dimensional multi-nodal approach to modelling self-pressurization in microgravity and 1g is very effective
- The one-dimensional multi-nodal model also is effective in modelling jet mixing in microgravity and 1g
- Run times for the SF models averages at about a couple of hours for the self-pressurization and jet mixing. The models using the TD interface take approximately 12 hours.
- The SF and TD models compare favorably to each other in terms of calculating radiation heat rates internally in the tank and externally to a given environment
- Temperature and Pressure results between the SF and TD models are also comparable.

- It was found that in microgravity there was a delay time before free convective heat transfer dominates over pure conduction heat transfer within the tank
- It was found that perfluoropentane was not completely opaque in the IR range, thereby allowing some radiation transmission within the tank, which not surprisingly affected the microgravity cases more than the 1g cases
- Finally a working interface to link the tank stratification model in SINDA/FLUINT to Thermal Desktop was developed so that more complex tanks and their environments could be modelled.