Thermal Desktop Modeling of the RRM3 On-Orbit Cryogenic Methane Storage and Active Cooling Experiment

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Presented at The 30th Space Cryogenics Workshop

July 18, 2023

Outline

- Introduction & Background
- Thermal Desktop Model Set Up
- Previous CFD Modeling Results
- Current Zero G Modeling Results
- Conclusions & Future Work

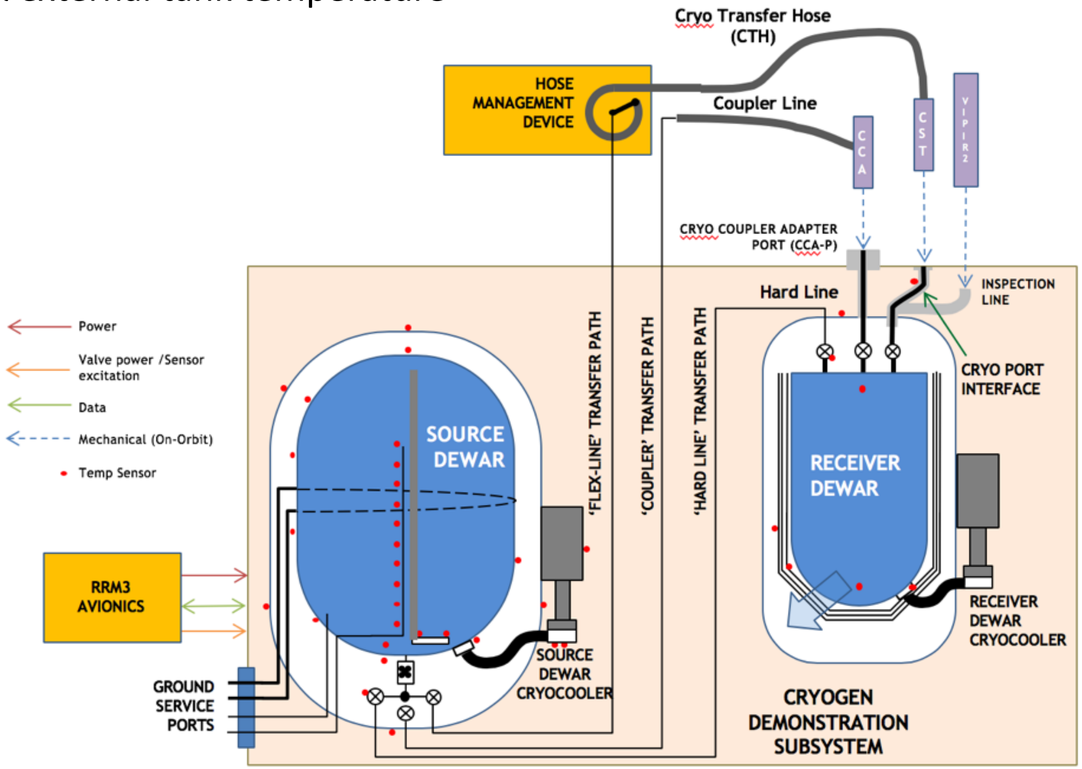
Introduction & Background

- Cryogenic fluid storage & transfer systems are critical to future space missions in LEO and beyond
- Creating accurate models of these systems anchored to existing data is essential to developing predictive tools for future missions
- Several experiments have already been conducted on orbit to collect data on cryogenic fluid systems
- Robotic Refueling Mission – 3 (RRM3) microgravity experiment is one such dataset that can be used to create these models
  - Collected 4+ months worth of LEO cryogenic storage & transfer data

RRM3 Fuel Transfer Module on the ISS from Breon et al (2020)

Introduction & Background Cont'd

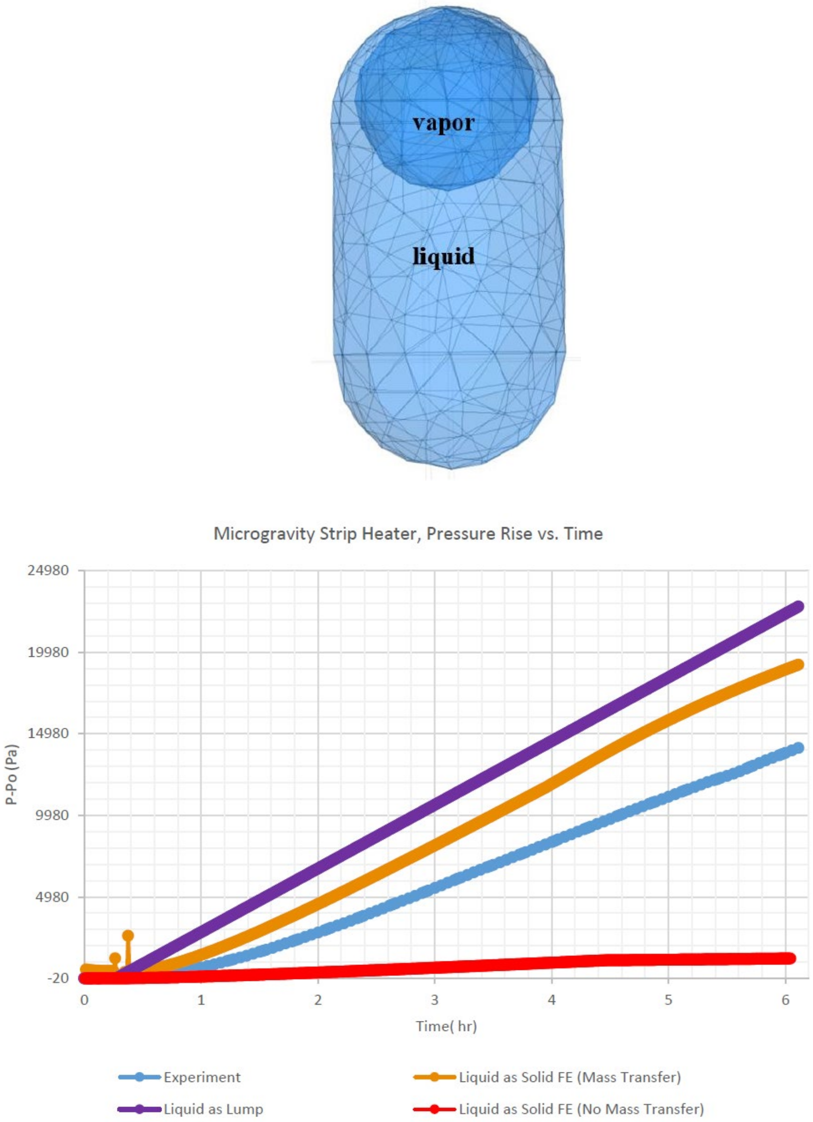
- Current study: Self pressurization of the RRM3 source dewar
- 50-liter Aluminum 2219 tank
  - Fluid: Liquid Methane
  - Duration: 7 hour Cool to Reboost period
  - Thermal Desktop model created to measure:
    - Tank pressurization
    - Internal & external tank temperature



RRM3 Cryogen Demonstration System Block Diagram from Kassemi et al. (2022)

Previous 0g Self-Pressurization Model in Thermal Desktop

- A previous modeling study[1] focused on creating a Thermal Desktop model of the Zero Boil-Off Tank Experiment (ZBOT) conducted onboard the ISS in 2017
- Pressurization of tank containing two-phase fluid in microgravity
  - Conduction (not convection) through fluid is the primary heat transfer method in microgravity
  - Liquid is modeled as a solid finite element nodes in TD
  - Vapor modeled as a single lump
  - Mass transfer across liquid-vapor interface (LVI) governed by Schrage Equation
  - Pressure rise using this method matches data within 25%



TD Model of ZBOT Fluid and resultant Pressure Rise in Tank from Tesny and Hauser (2019)

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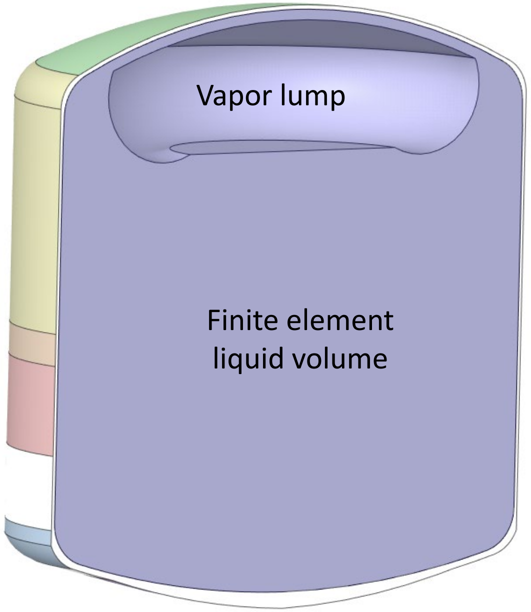
[1] Tesny, E and Hauser, D (2019)

0g Thermal Desktop Model Setup

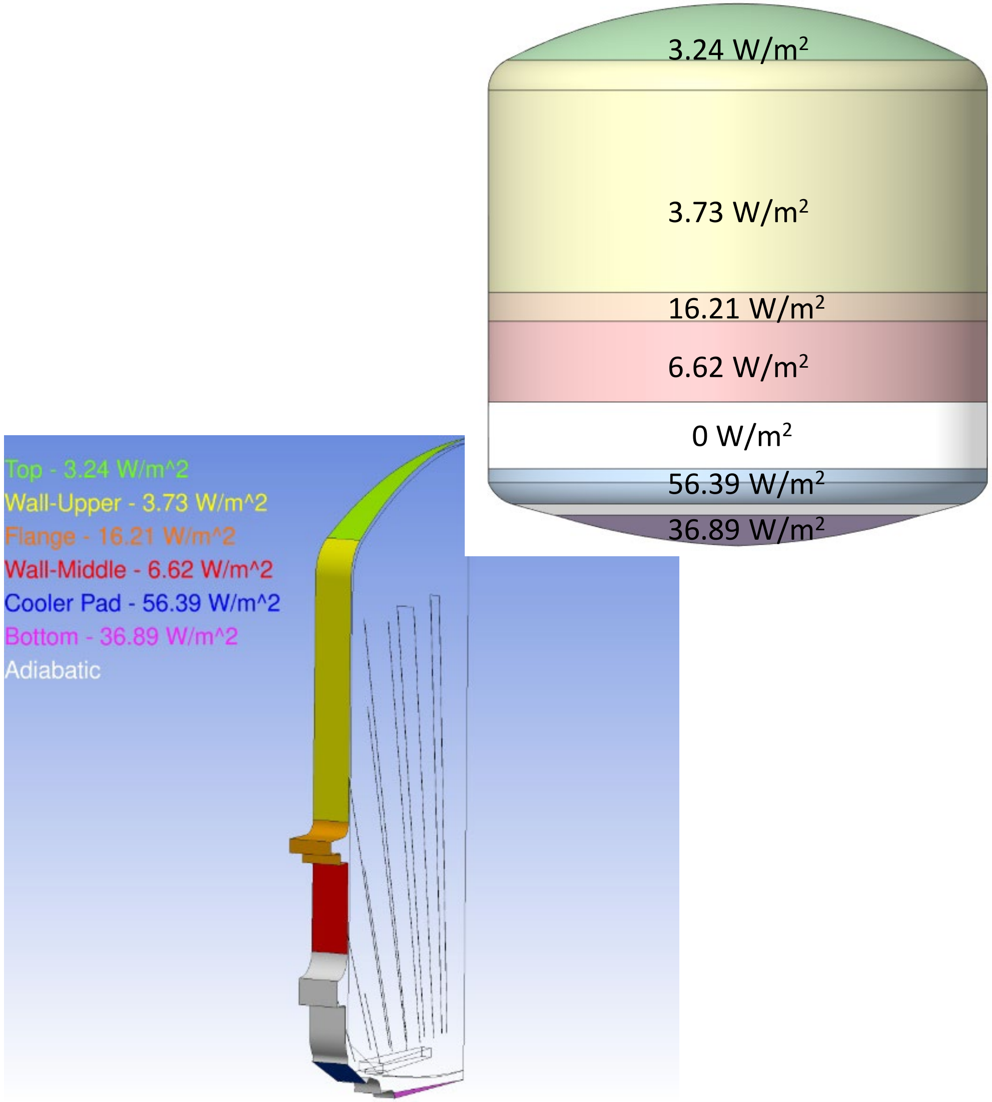
- Method used for ZBOT adapted for RMM3 Source Dewar
- Tank Wall simplified in SpaceClaim and imported into Thermal Desktop
- Tank Wall represented as a series of solid finite element nodes
  - All internal tank geometry removed from interior
- Liquid volume modeled as a finite element solid
- Ullage modeled as a single vapor lump
- Ullage shape and location approximated from CFD work that modeled the self-pressurization of the source dewar



Source Dewar Thermal Desktop Model Cross-section

0g Thermal Desktop Model Setup

- Variable heat flux applied to outer tank wall to simulate heat loads on outside of source dewar
    - Finite elements split into different horizontal surfaces based on original tank geometry
- Conduction Coefficient of 10,000 W/m^2/K between Tank Wall and Liquid Volume submodels
- Initial Temperature: 104.0 K
- Initial Pressure: 7.437 psia
- Test Duration: 7.0 hrs (Cool to Reboost period)



Heat Load Distribution from Kassemi et al. (2022)

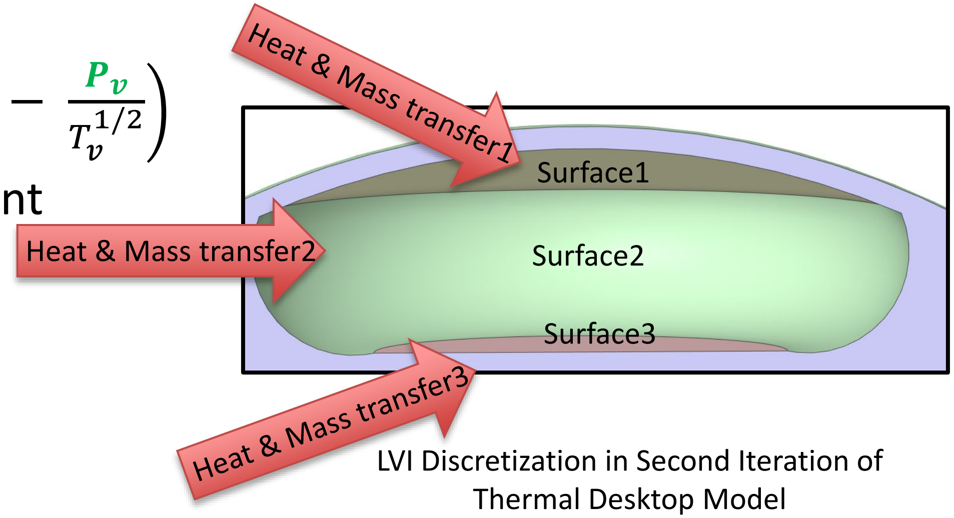
0g Thermal Desktop Model Setup

- A similar method as in the previous ZBOT study was used to calculate heat and mass transfer across the Liquid-Vapor interface (LVI) Mass Transfer across LI:
  - Schrage Equation

$$|\dot{m}| = \left(\frac{2\sigma}{2-\sigma}\right)\left(\frac{M_v}{2\pi R_u}\right)^{1/2}\left(\frac{P_i}{T_i^{1/2}} - \frac{P_v}{T_v^{1/2}}\right)$$

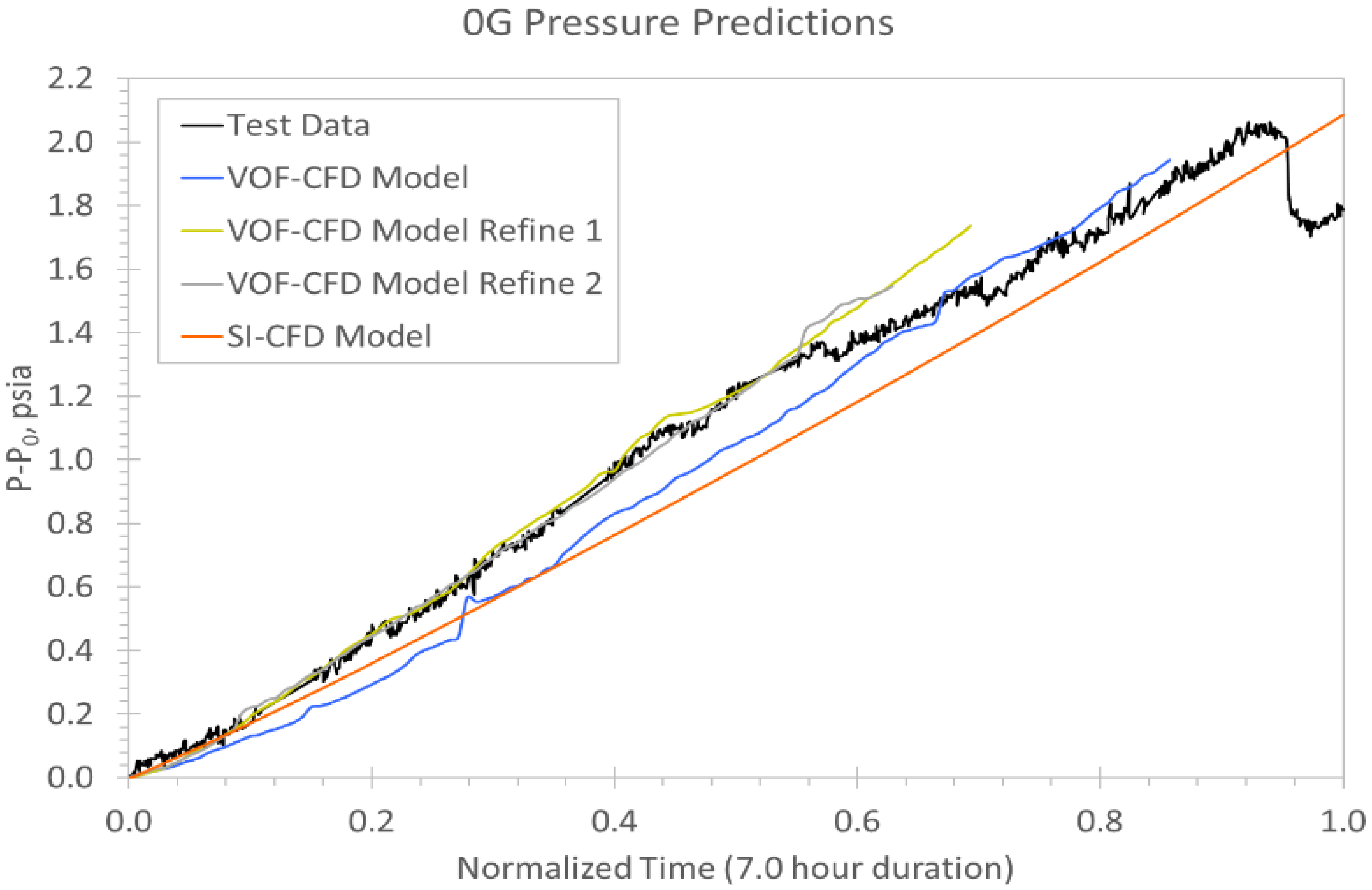
σ = accommodation coefficient

- ➢ Antoine Equation
  - ▪ $P = 10^{A+\frac{B}{T}}$
- ➢ Heat Transfer Across LVI
  - ▪ $\dot{Q} = \dot{m} h_{vap}$
- Results presented for:
  - Single Model: only 1 heat and mass transfer path across LVI surfaces
  - Split Model: Heat and Mass transfer split up across 3 outer LVI surfaces (shown at left)

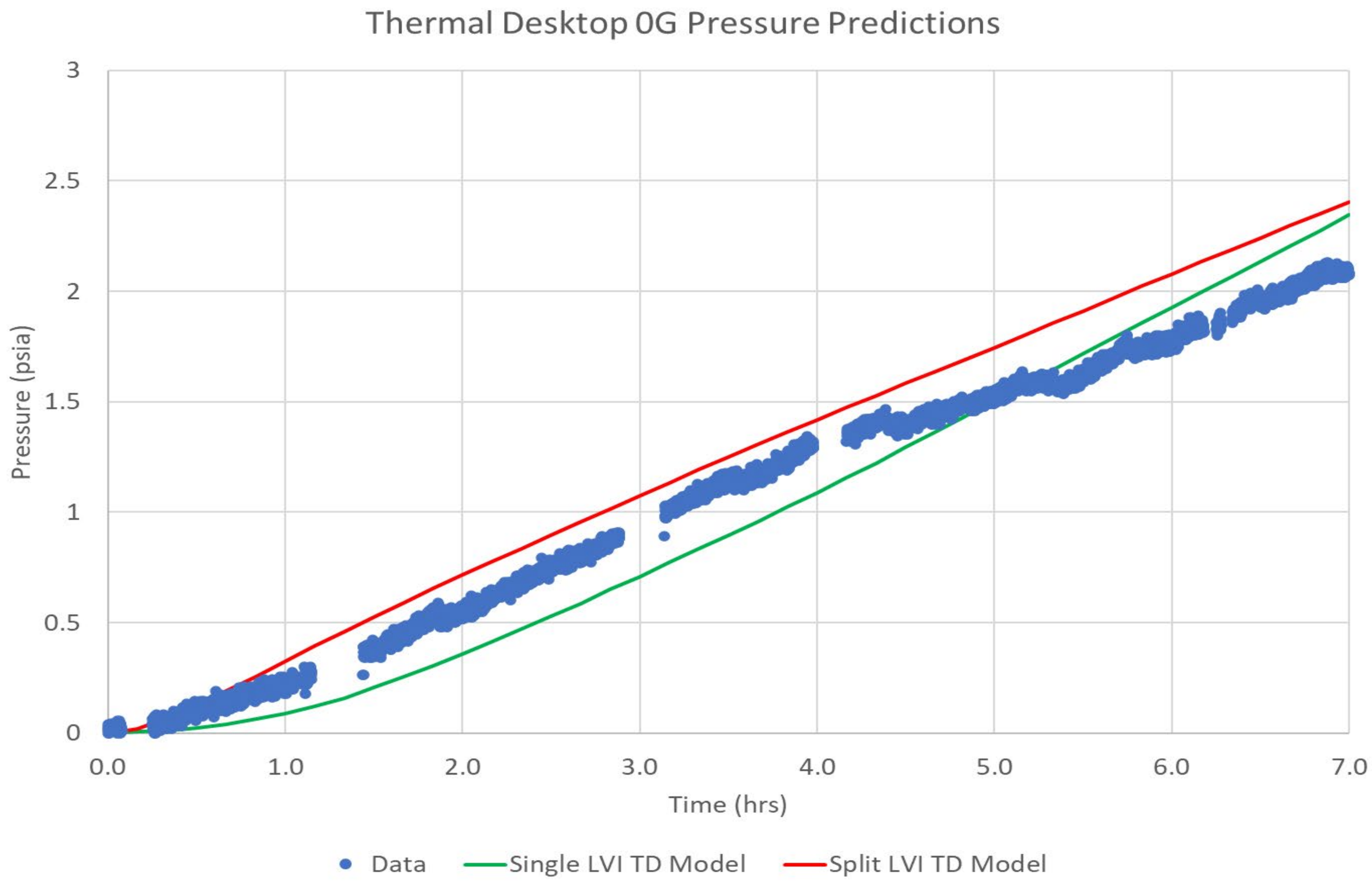


LVI Discretization in Second Iteration of Thermal Desktop Model

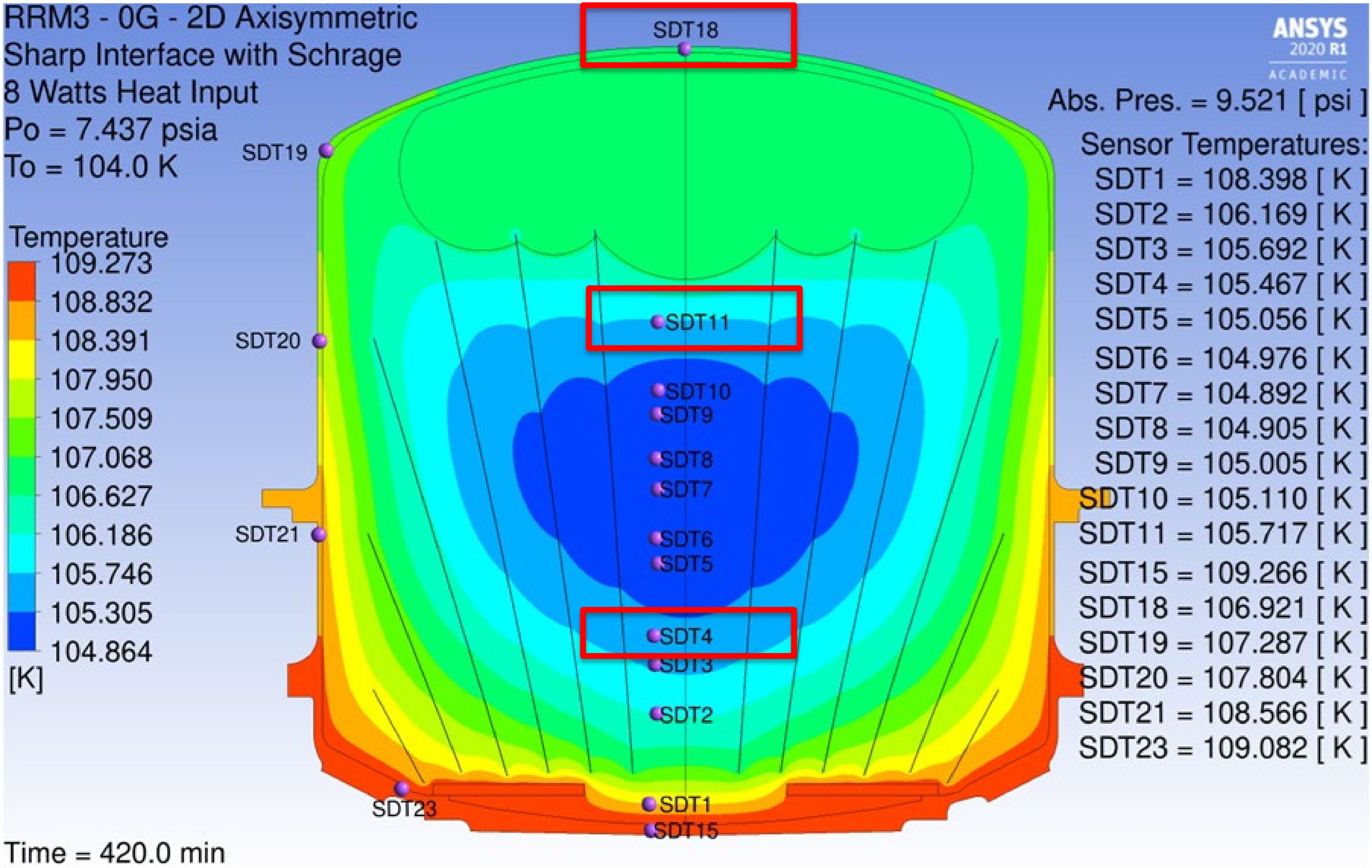
Previous CFD Modeling



Thermal Desktop Model



Previous 0g CFD Model Temperature Contours



RRM3 - 0G - 2D Axisymmetric
Sharp Interface with Schrage
8 Watts Heat Input
Po = 7.437 psia
To = 104.0 K

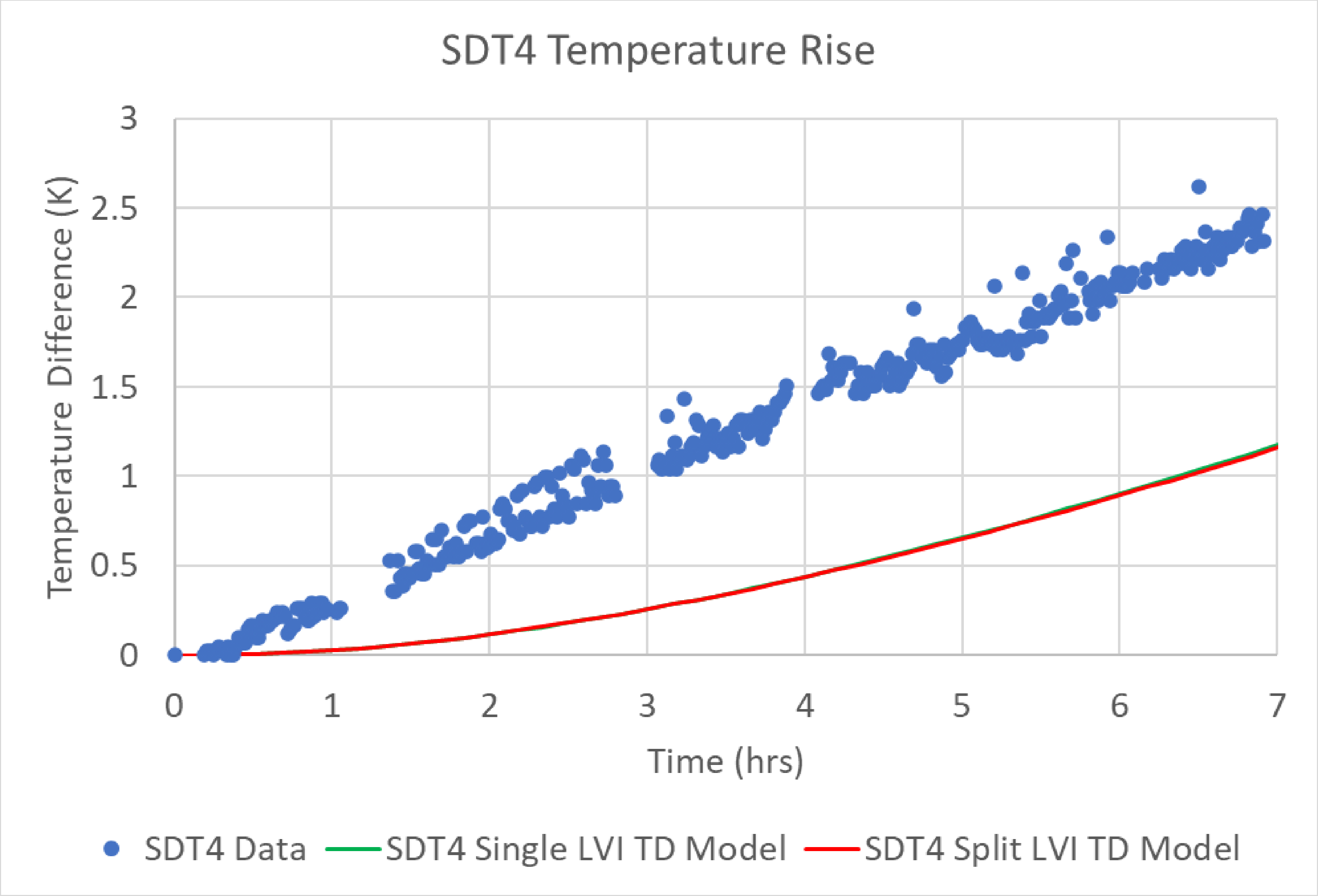
Abs. Pres. = 9.521 [psi]

Sensor Temperatures:
SDT1 = 108.398 [K]
SDT2 = 106.169 [K]
SDT3 = 105.692 [K]
SDT4 = 105.467 [K]
SDT5 = 105.056 [K]
SDT6 = 104.976 [K]
SDT7 = 104.892 [K]
SDT8 = 104.905 [K]
SDT9 = 105.005 [K]
SDT10 = 105.110 [K]
SDT11 = 105.717 [K]
SDT15 = 109.266 [K]
SDT18 = 106.921 [K]
SDT19 = 107.287 [K]
SDT20 = 107.804 [K]
SDT21 = 108.566 [K]
SDT23 = 109.082 [K]

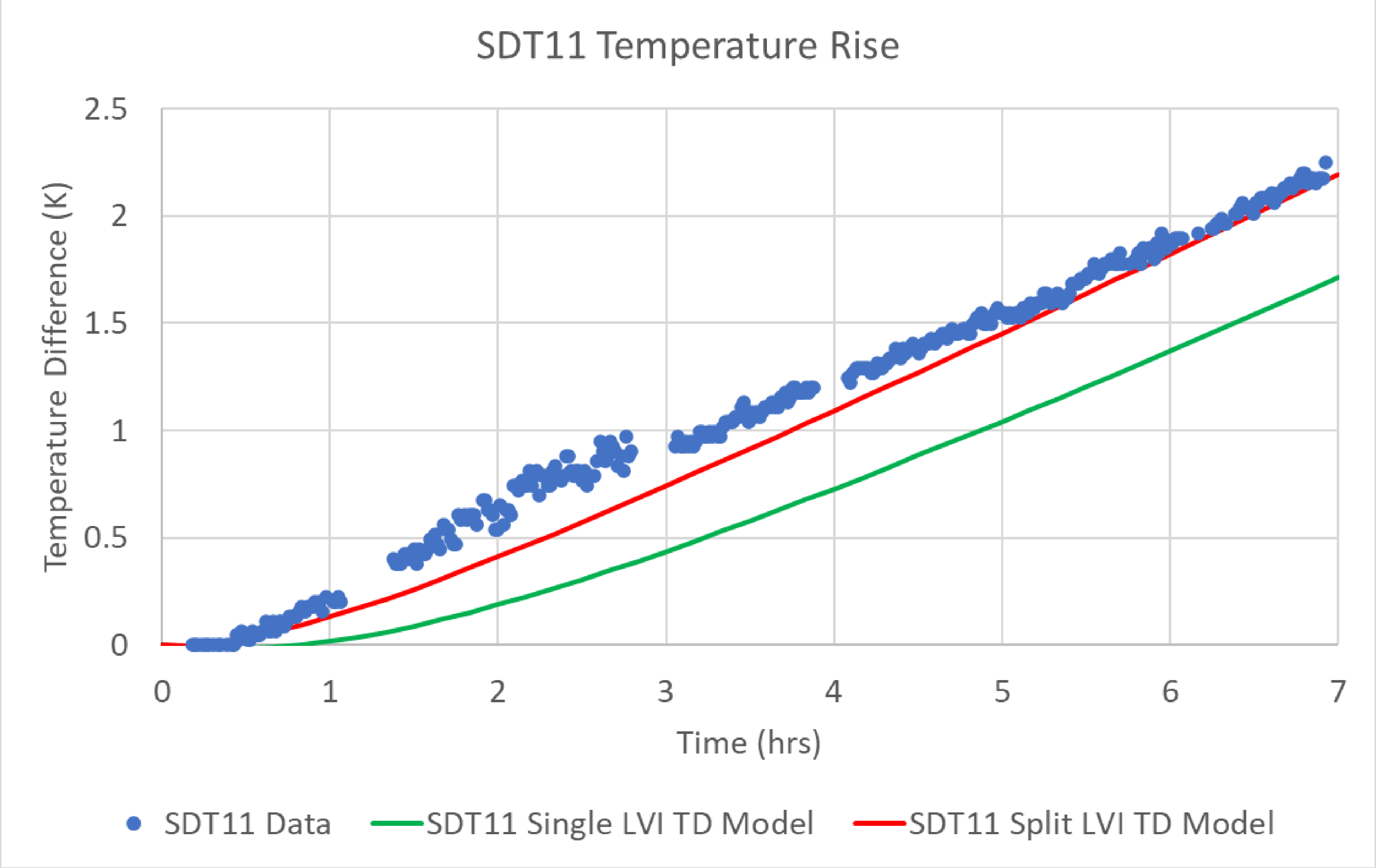
Time = 420.0 min

SDT Locations and Internal Temperature Distribution from Kassemi et al. (2022)

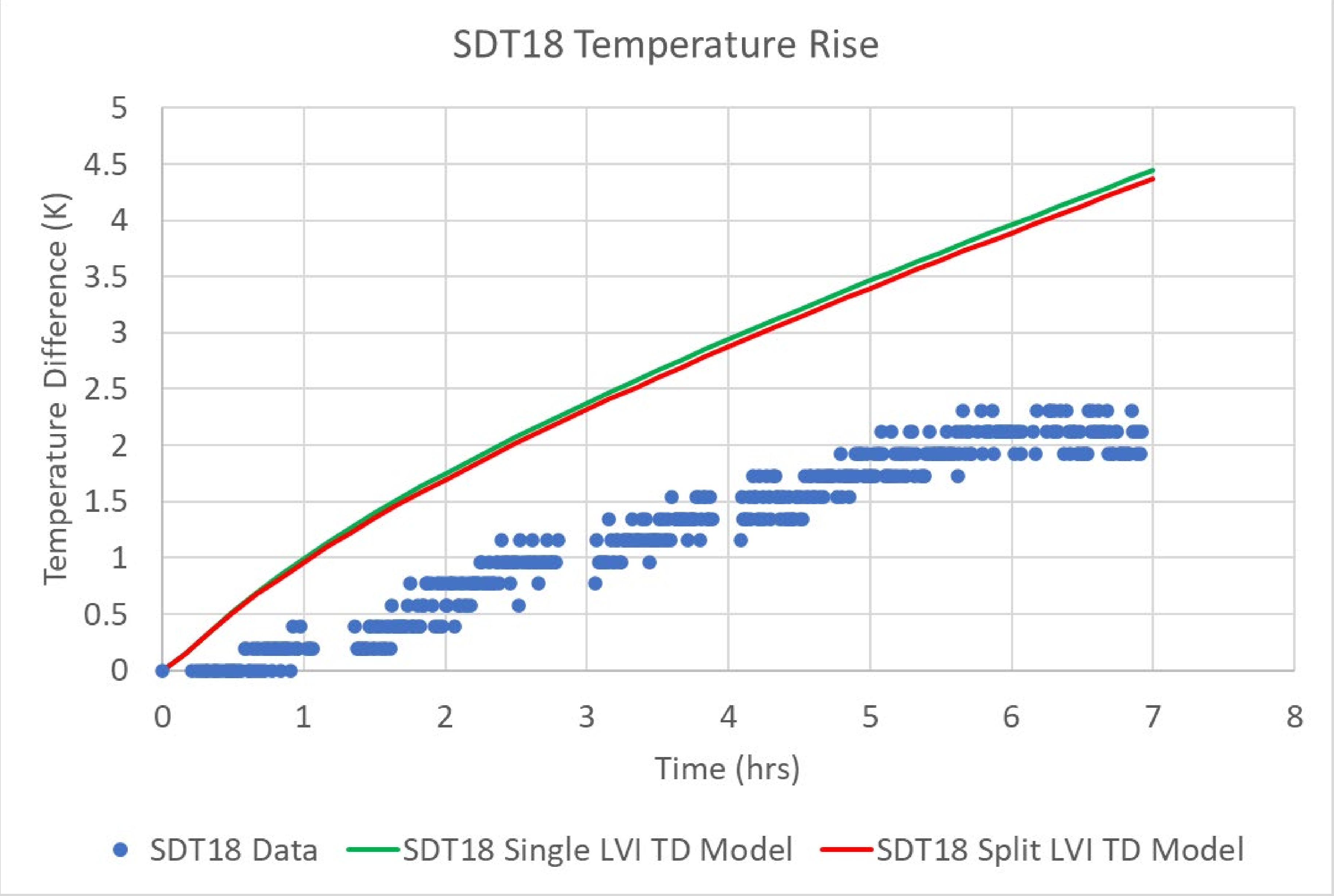
Internal Fluid Temperature (SDT, Tank Bottom)



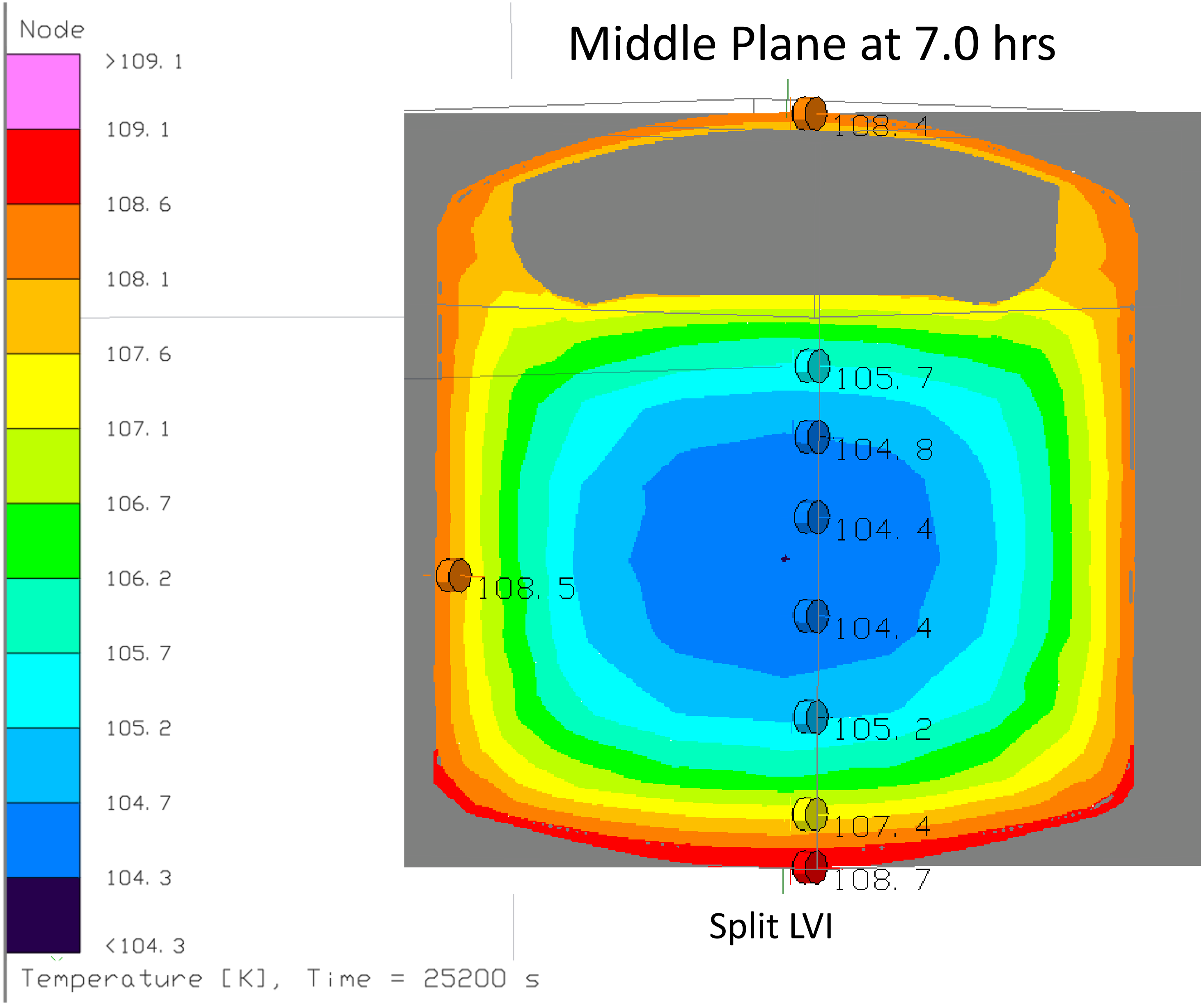
Internal Fluid Temperature (SDT11, near LVI)



External Tank Temperature



0g Thermal Desktop Model Temperature Contours



Conclusions

- Split LVI Thermal Desktop Model was able to more accurately predict the pressure rise inside the ullage and the liquid and wall temperatures over the Single LVI model
  - Split LVI model predicts pressure rise within ~15%, whereas Single LVI predicts within ~25%
- Split model also gives better agreement with data temperature rise close to interface due to refined heat & mass transfer prediction
  - Split LVI predicts temperature rise within ~15%, whereas Single LVI predicts within ~50%
  - Difference between models less apparent farther away from the interface
- Both models do similarly well predicting outside wall temperatures and overpredict the temperature rise by ~90%
- The Split LVI model can be used to inform design of future tank self-pressurization in microgravity

Questions?

References

1. Tesny, E and Hauser D. “Thermal Modeling of Zero Boil off Tank Experiment.” AIAA Propulsion and Energy 2019 Forum, 2019, https://doi.org/10.2514/6.2019-4280.
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6. Tesny E and Hauser D. Validation of ZBOT Experiment Using SINDA/FLUINT Multi-node Analysis Tool. eCryo-RPT-0161. 2019