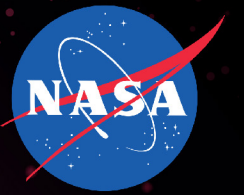




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Numerical Modeling of No Vent Filling of a Cryogenic Tank with Thermo-dynamic Vent System Assisted Injector

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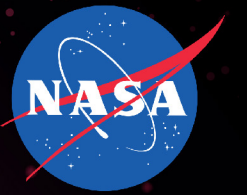
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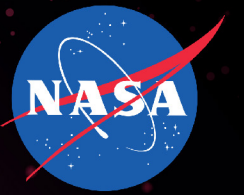


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Topics

1. Introduction
2. No Vent Fill Experiment
3. GFSSP Model
4. Boiling Model
5. Condensation Model
6. Comparison of Numerical & Test Data
7. Conclusions
8. Acknowledgement
9. References

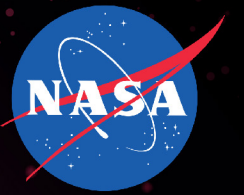


Introduction

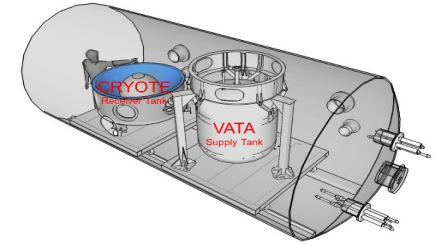
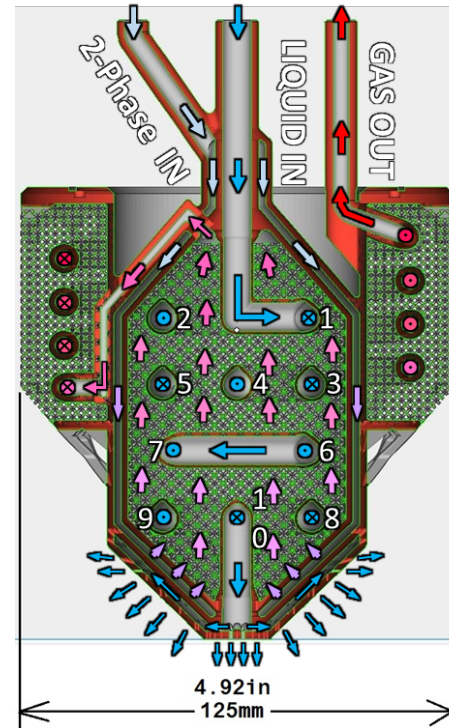
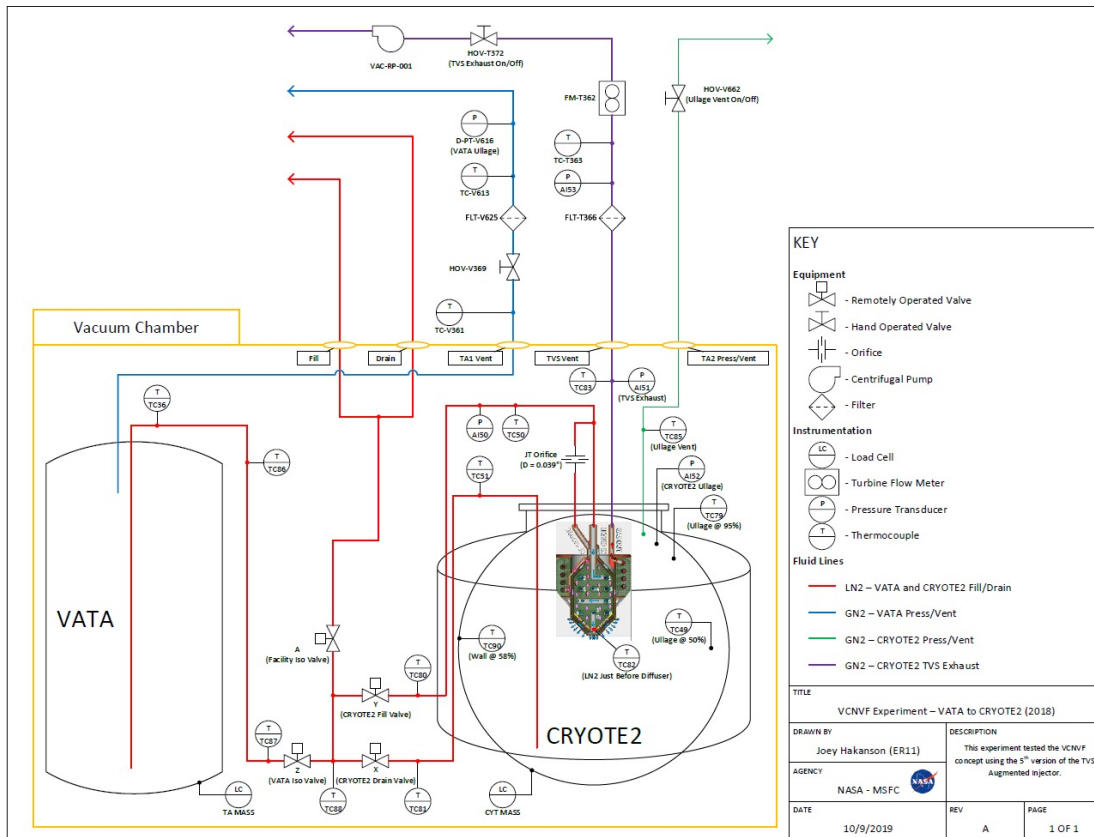
- Filling a cryogenic tank in deep space is challenging because liquid propellant may not settle at the tank bottom causing loss of propellant due to venting
- There are several No Vent Fill Methods to reduce or eliminate loss of propellant in space
 - Charge – Hold – Vent [Chato (1991)]
 - Vented Chill & No Vent Fill [Rhys (2014)]
 - No Vent Fill using TVS assisted injector [Hartwig (2021)]
- TVS assisted No Vent Fill is advantageous for its operational simplicity compared to other methods
- TVS assisted No Vent Fill method was tested in a Flight Tank (CRYOTE) at NASA/MSFC and will be extensively tested in Reduced Gravity Cryogenic Transfer (RGCT) Project
- This paper presents Numerical Simulation of Experimental Test of Chilling and Filling of CRYOTE tank with a TVS assisted Injector



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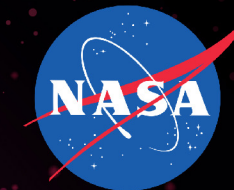


No Vent Fill Testing with TVS Assisted Injector



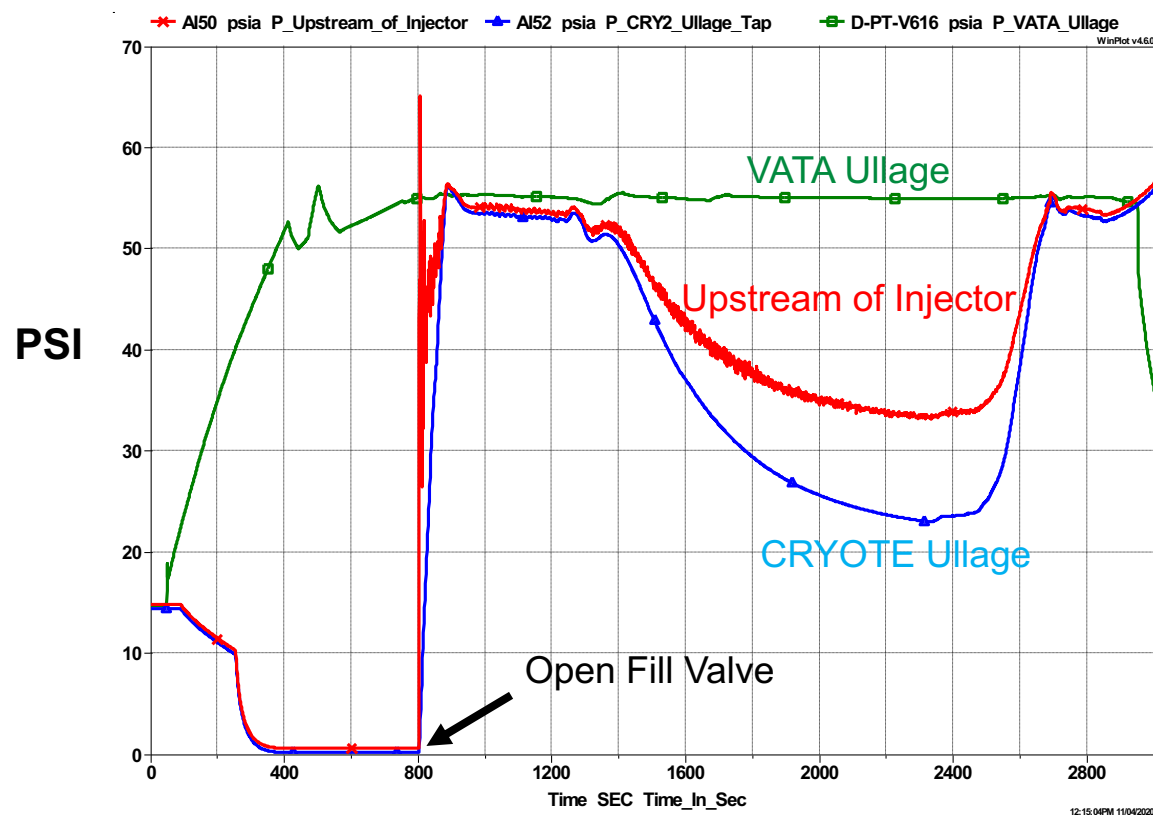


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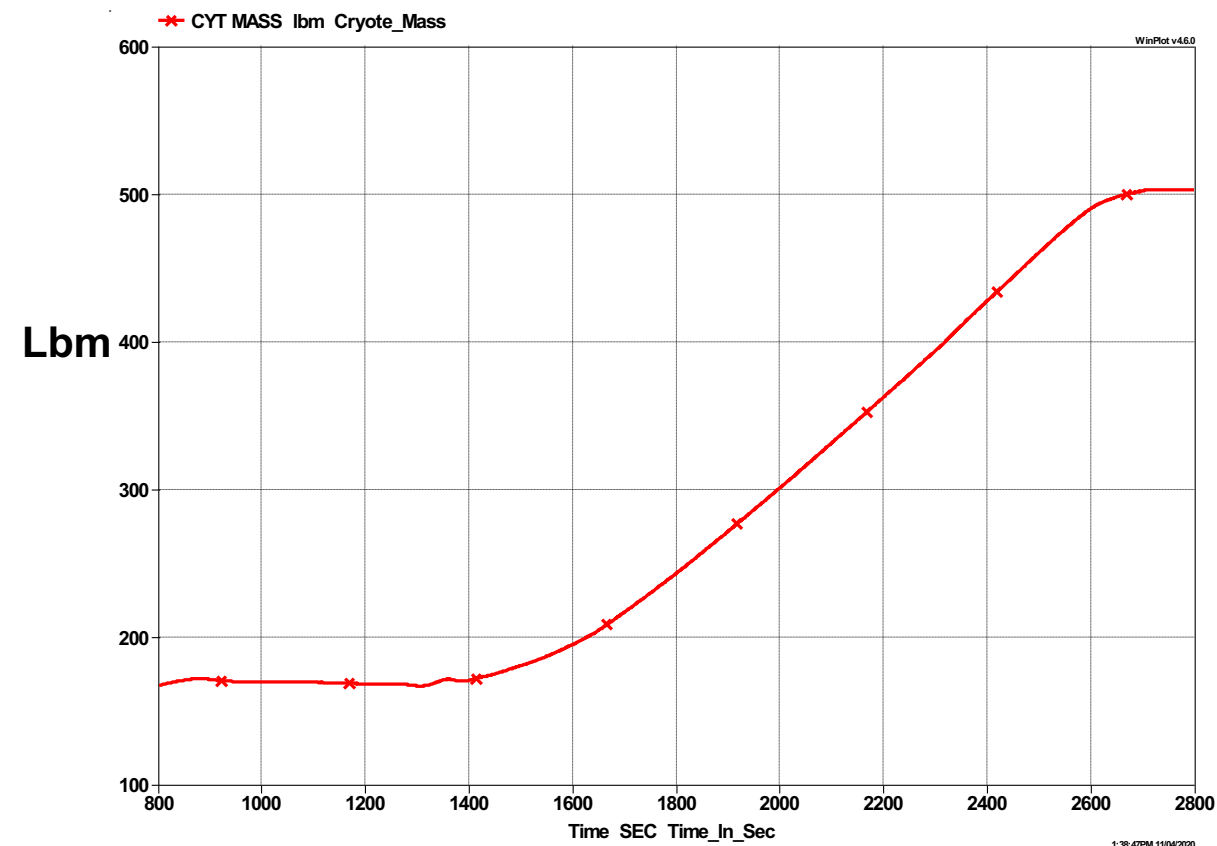


Test Results for Pressure and Tank Filling

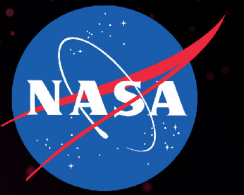
Pressure



Resident Mass



- Liquid accumulation appears to begin at $t \approx 1300$ sec.
- Pressure plot shows evidence of condensation at 1300 sec.

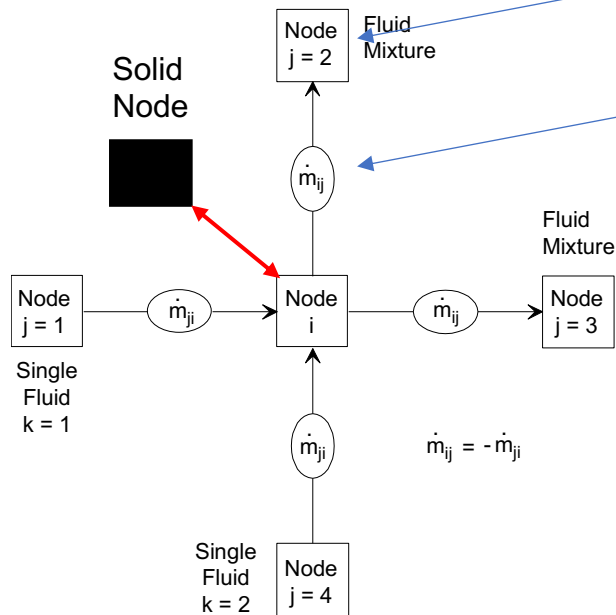


Introduction to GFSSP

Mass and Energy Conservation Equations are solved at nodes

Momentum Conservation Equations are solved at branches

Mathematical Closure



Unknown Variables

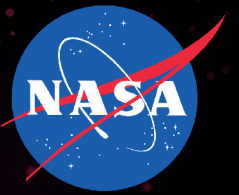
1. Pressure
2. Flowrate
3. Fluid Temperature
4. Solid Temperature
5. Species Concentration
6. Mass

Available Equations to Solve

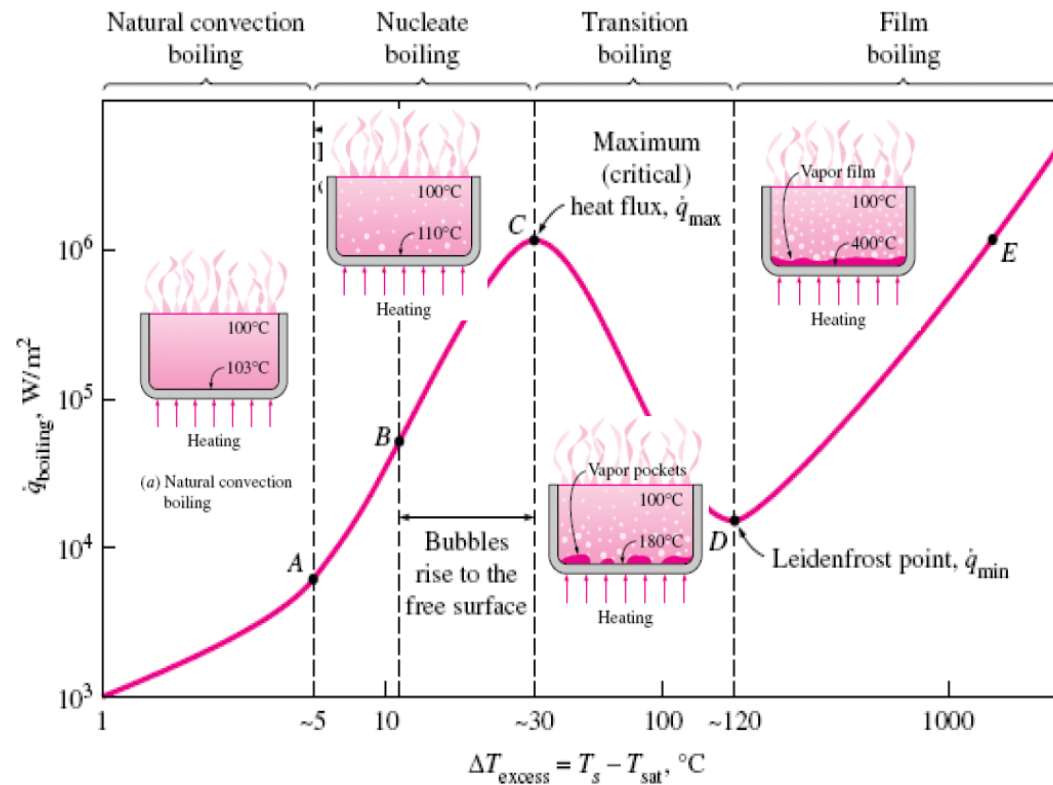
1. Mass Conservation Equation
2. Momentum Conservation Equation
3. Energy Conservation Equation of Fluid
4. Energy Conservation Equation of Solid
5. Conservation Equations for Mass Fraction of Species
6. Thermodynamic Equation of State

Schematic of GFSSP Nodes and Branches





Pool Boiling Correlations

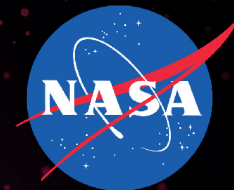


Film Boiling – Wang (2020)
Leidenfrost Point – Baumeister (1973)
Critical Heat Flux – Leinhard (1973)
Nucleate Boiling – Minchenko (1961)
Natural Convection – Shirai (2010)

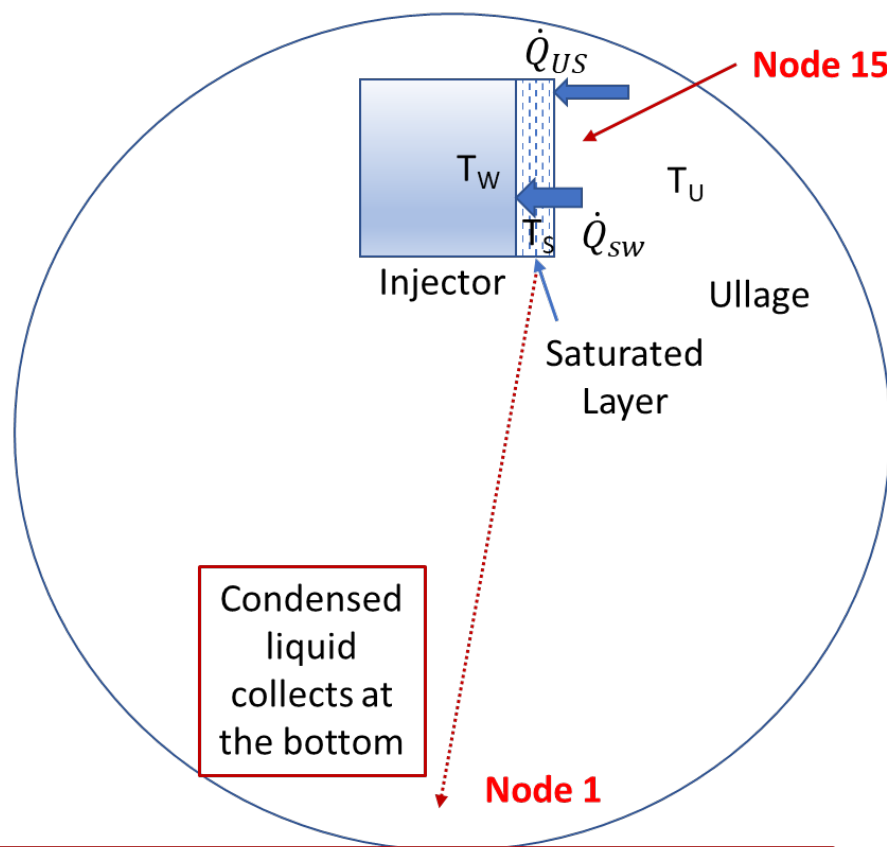
If $0 < \Delta T \leq \Delta T_{\text{ONB}}$
Use H_{NC}
Else if $\Delta T_{\text{ONB}} < \Delta T \leq \Delta T_{\text{CHF}}$
Use H_{NB}
Else if $\Delta T_{\text{CHF}} < \Delta T \leq \Delta T_{\text{LFP}}$
Use H_{TB}
Else if $\Delta T_{\text{LFP}} < \Delta T$
Use H_{FB}



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Condensation Model at Injector-Ullage Interface



- Mass sink at Node 15 will reduce its thermal capacitance and therefore will cool faster
- As T_U approaches T_S condensation rate increases

$$T_U > T_S > T_W$$

$$\dot{Q}_{US} = h_{US} A_{eff} (T_U - T_S)$$

Heat Transfer from Node 15 to saturated layer

$$\dot{Q}_{SW} = h_{SW} A_{eff} (T_S - T_W)$$

Heat Transfer from saturated layer to wall

$$\dot{Q}_{SW} - \dot{Q}_{US} = \dot{m}_{cond} h_{fg}$$

Mass sink at Node 15
Mass source at Node 1 until filled

Estimation of h_{US} :

$$Nu_{US} = \frac{h_{US} D'}{k_g} = 0.565 Ra_D^{1/2}$$

$$Ra_D = \frac{K g \beta |T_U - T_S| D'}{\alpha_g \nu_g}$$

$$D' = D_{tube} + \delta_L$$

$$K = \frac{\epsilon D_H^2}{32}$$

Estimation of h_{US} :

$$h_{SW} = \frac{\epsilon k_L + (1 - \epsilon) k_W}{\delta_L}$$

$$\epsilon = \frac{V_f}{V}$$

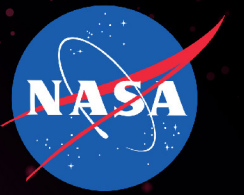
$$D_H = \frac{4V_f}{A} = \frac{4\epsilon V}{A}$$

$$\delta_L = \alpha D_H$$

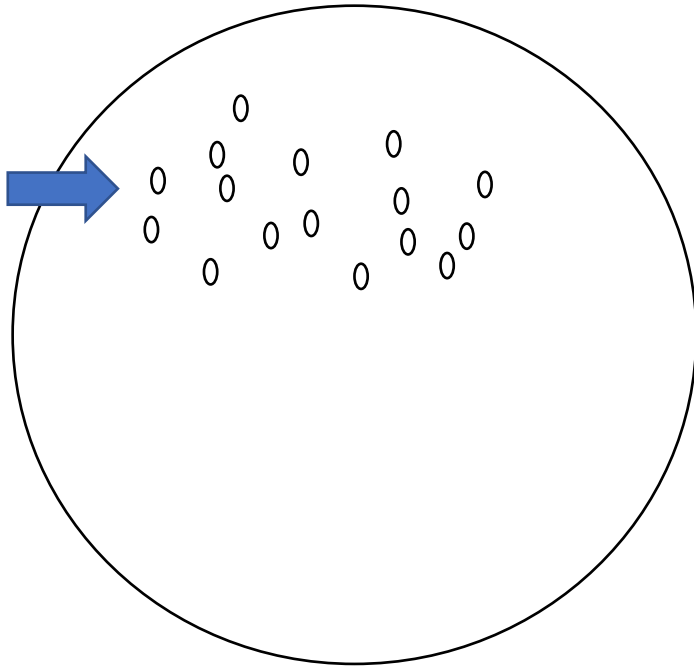
α has been adjusted

k_L = Liq. Conductivity at T_S

k_W = Liq. Conductivity at T_W



Spray Droplet Condensation Model



$$N_i = \frac{\dot{m}_i \Delta \tau_{res}}{\frac{\pi d^3}{6} \rho_L} \quad \leftarrow \text{Number of Droplets} = \text{Resident Mass/Droplet Mass}$$

$$\Delta \tau = \frac{\Delta H}{V_i} \quad \leftarrow \text{Residence Time} = \text{Characteristic Length/Spray Velocity}$$

$$\dot{q} = HA(T_{sat} - T_L) \quad \leftarrow \text{Condensation Heat Transfer}$$

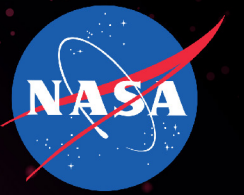
$$A = N_i \pi d^2 \quad \leftarrow \text{Heat Transfer Area}$$

$$H = \frac{k_L}{d} Nu_{D,in} \quad \leftarrow \text{Heat Transfer Coefficient}$$

According to Kronig and Brink (1950) $Nu_{D,in} = 17.9$.

Assumptions:

- Bubble Diameter = 1.5 mm
- Characteristic Length Scale = 50% Tank Diameter
- Heat Transfer Multiplying Factor (η_c) = 1.5

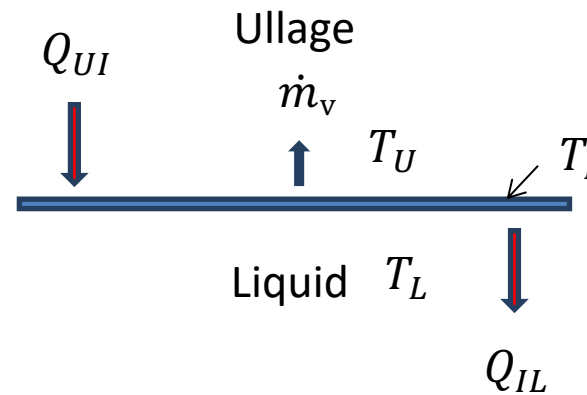


Condensation at Liquid-Vapor Interface

$$Q_{UI} = h_{UI}A(T_U - T_I),$$

$$Q_{IL} = h_{IL}A(T_I - T_L)$$

$$\dot{m} = \frac{Q_{UI} - Q_{IL}}{h_{fg}},$$



$$h_{UI} = K_H C \frac{k_f}{L_s} Ra^n = h_{IL}$$

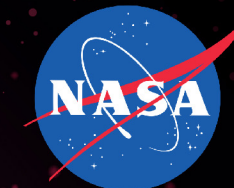
$$Ra = Gr Pr$$

where $K_H = 0.5$, $C = 0.27$, and $n = 0.25$

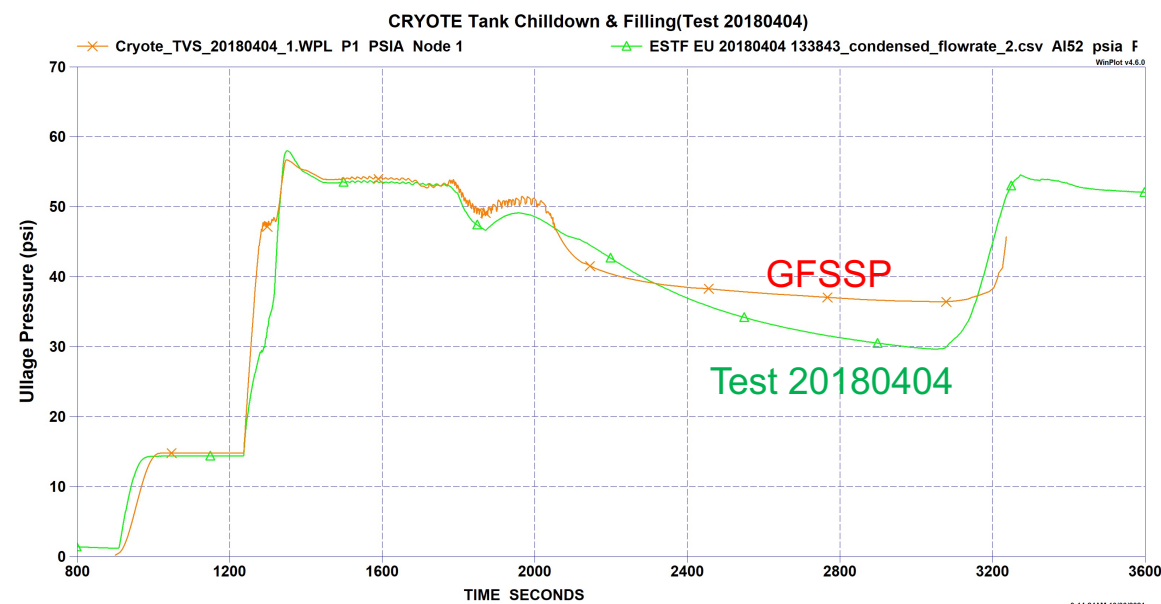
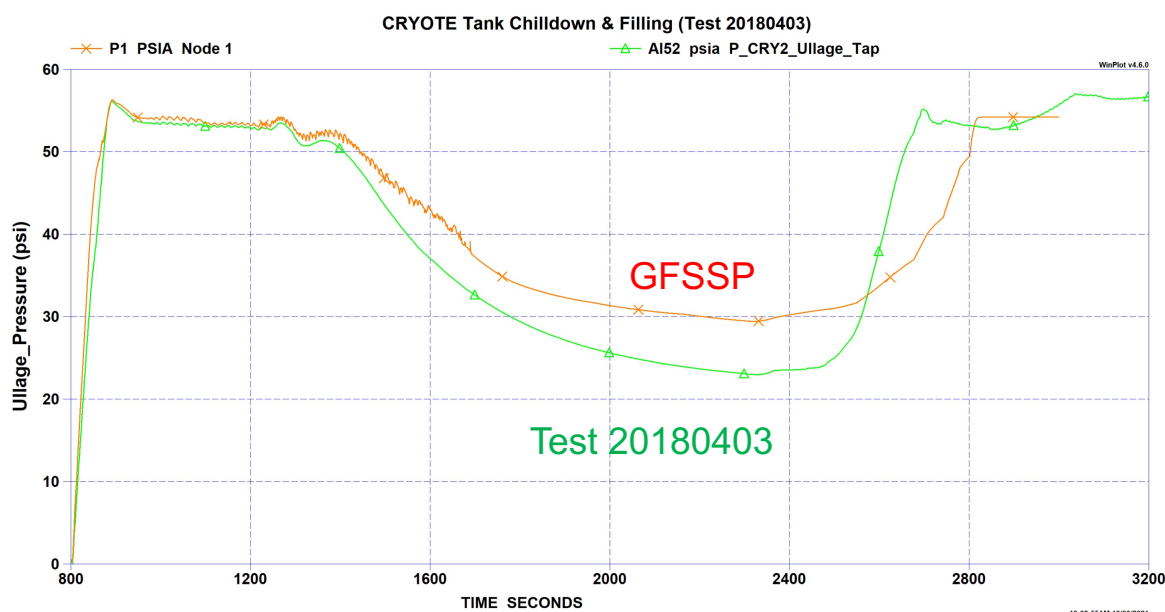
h_{UI} is based on vapor property
and h_{IL} is based on liquid
property



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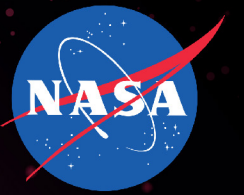


Comparison with Test Data : Tank Pressure

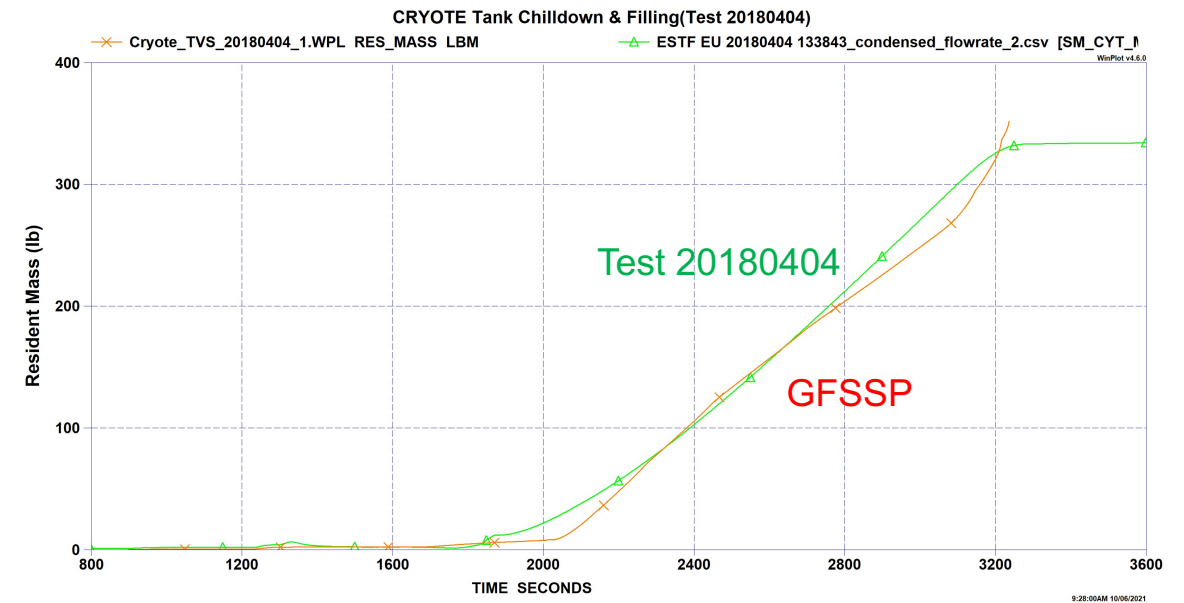
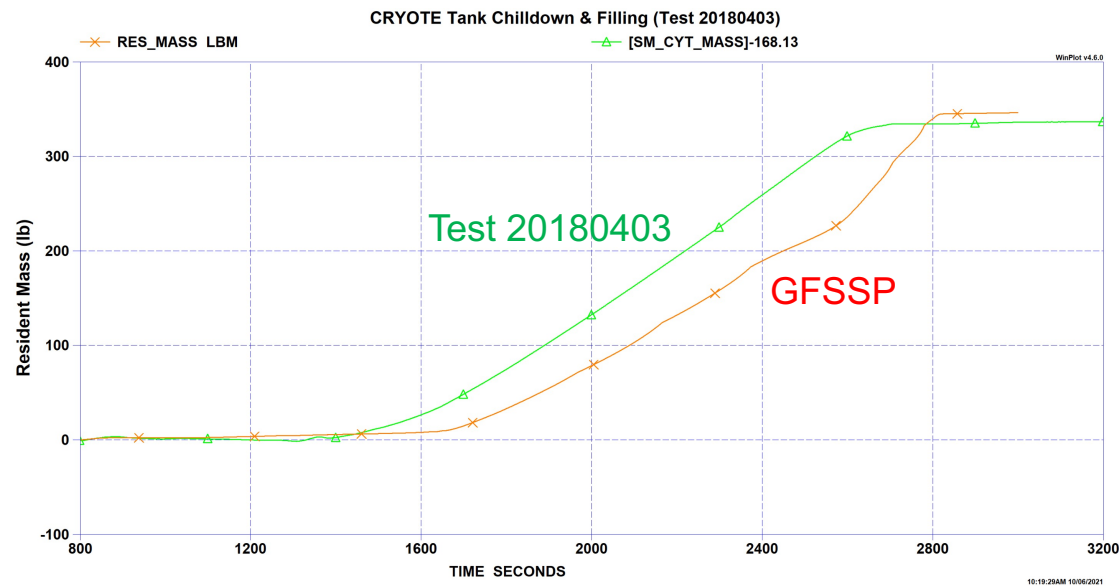




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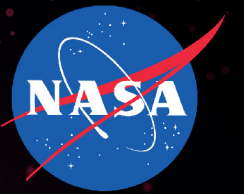


Comparison with Test Data : Resident Mass in Tank



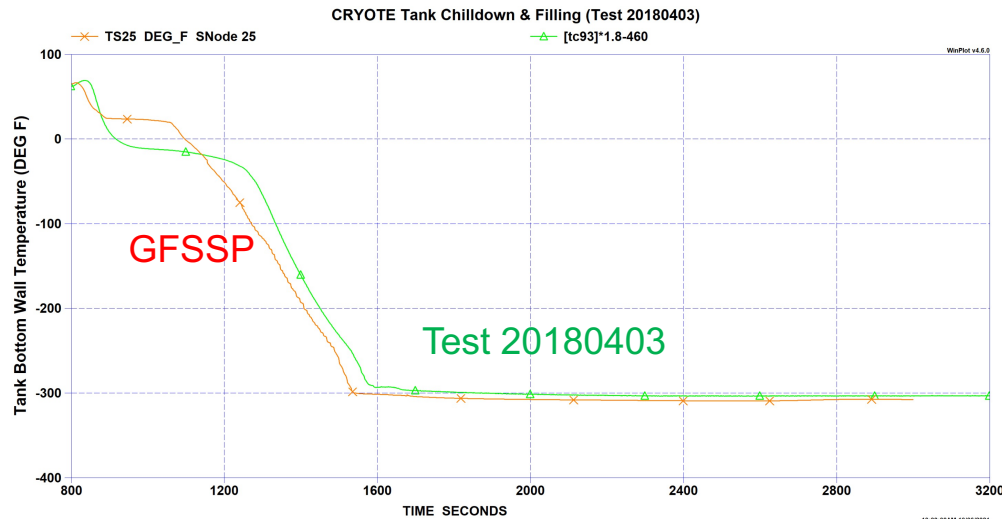


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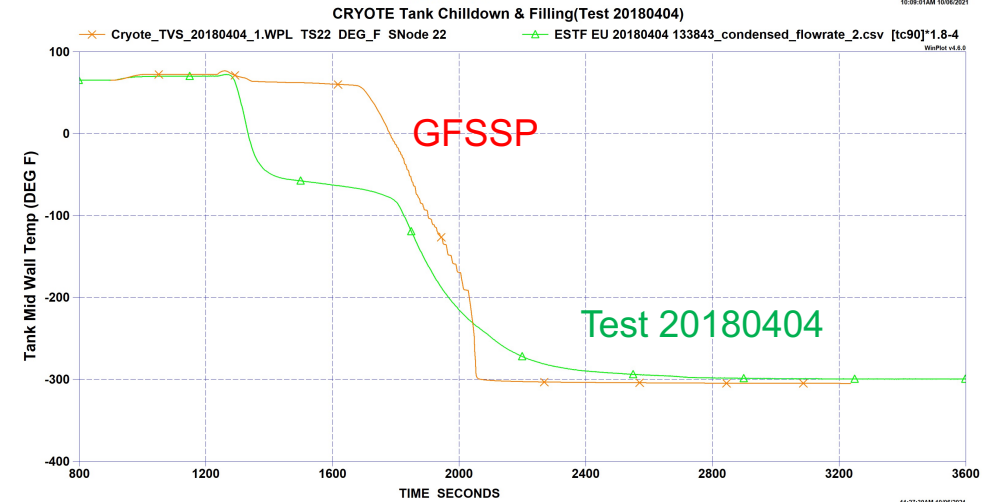
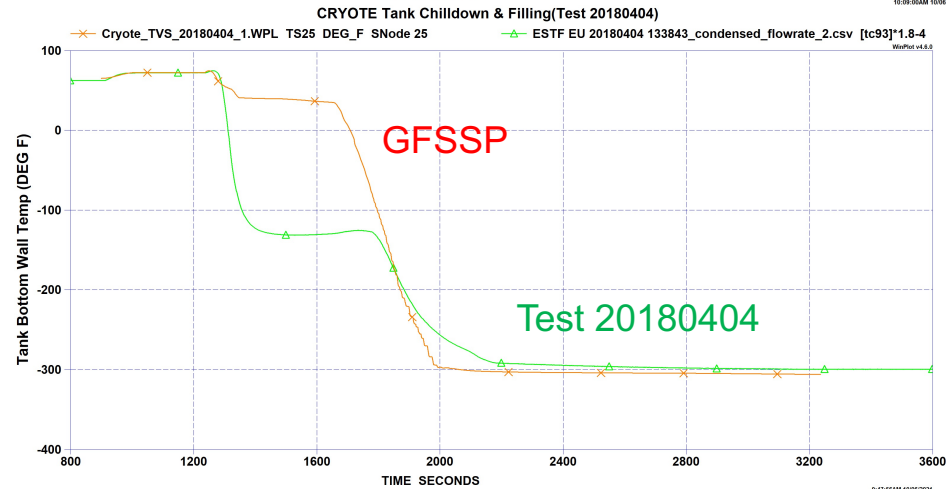
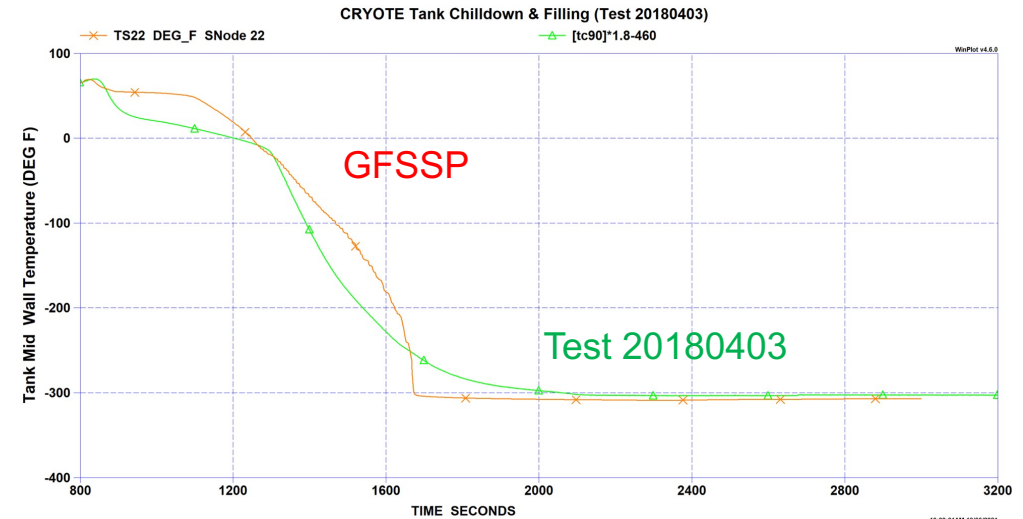


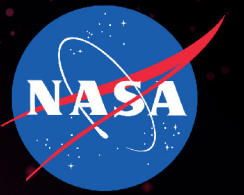
Comparison with Test Data : Wall Temperatures

Tank Bottom



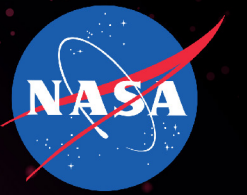
Mid Section





Concluding Remarks

- TVS assisted Injector is a promising candidate for No Vent Filling of a Cryogenic Tank in Space
- Numerical Modeling of No Vent Filling of a Cryogenic Tank is a challenging task for several reasons
 - Fluid undergoes phase change multiple times; both boiling and condensation occurs during the process
 - There is no established method of modeling condensation
 - In absence of an Exit Boundary (No Vent), elimination of numerical error becomes difficult
- In this paper, “Adhoc” condensation models were developed to simulate a No Vent Fill experiment using a One-Dimensional Flow Network Model
- Future work will attempt to model recirculating flow in the tank by developing an axisymmetric network flow model

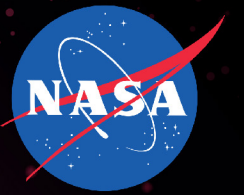


Acknowledgement

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- Authors wish to acknowledge Mr. Joey Hackerson for providing critical information of TVS Injector for modeling condensation heat transfer



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