55th AIAA/SAE/ASEE Joint Propulsion Conference
19-21 August, 2019, Indianapolis, Indiana

# Multi-Node Modeling of Cryogenic Tank Pressurization System using Generalized Fluid System Simulation Program

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# CONTENT

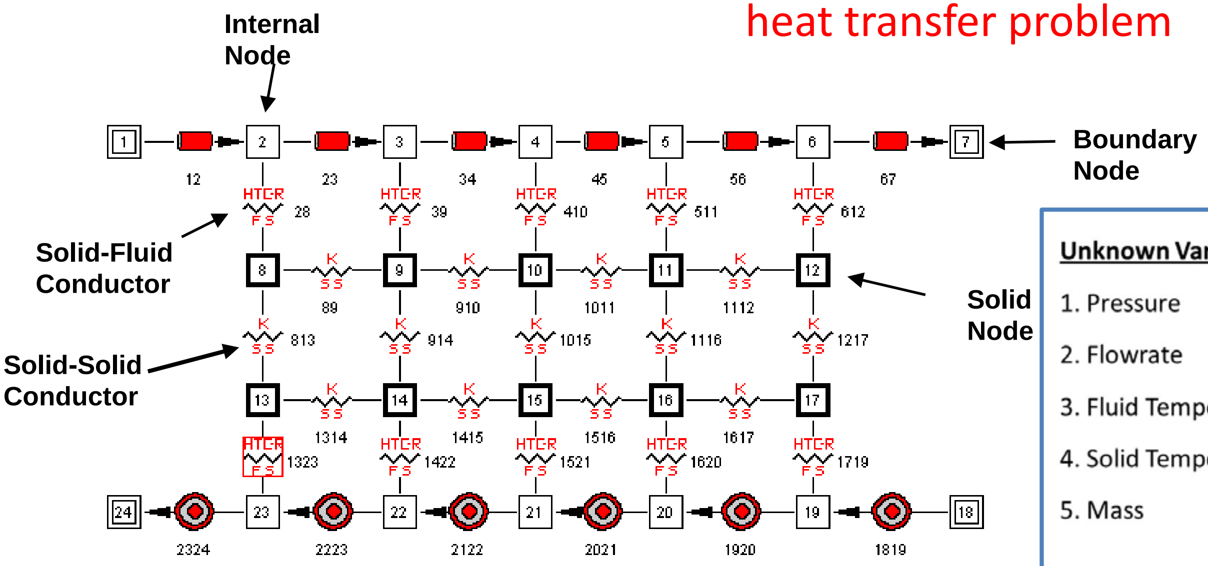
- *Purpose & Objective*
- *GFSSP Overview*
- *Review of Cryogenic Tank Pressurization Model*
- *Test Program Overview*
- *GFSSP Modeling of Tank Pressurization*
- *Comparison of Model Results with Test Data*
- *Conclusions*

# Purpose & Objective

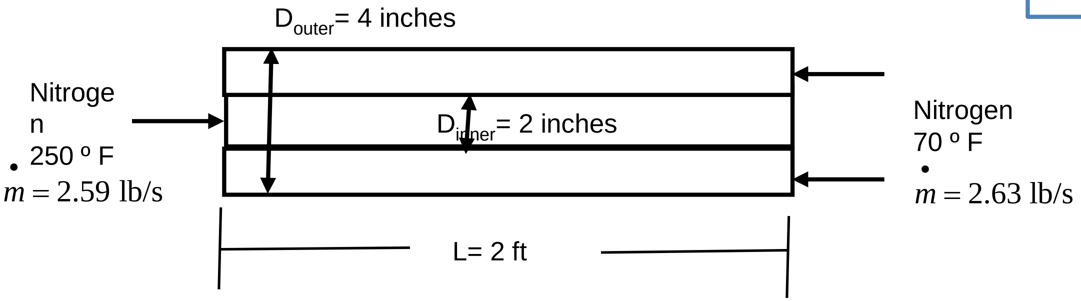
- Historically, Cryogenic Tank Pressurization is either modeled by a single node using Fluid System Code (GFSSP & ROCETS) or by high fidelity Navier-Stokes code (FLUENT or CFX).
- Use of multi-node modeling using Fluid System code has not been explored. The main purpose of this paper is to describe a multi-node system modeling of cryogenic tank pressurization in GFSSP
- In recent years, a test program has been conducted at NASA/MSFC to measure boil-off of cryogenic liquid propellant in a flight tank to support United Launch Alliance's IVF (Inter Vehicular Fluid) program where boil-off propellants are used to pressurize the tank
- The model results have been compared with test data

# GFSSP(Generalized Fluid System Simulation Program)

## Example of Heat Exchanger Model to define Network elements of a conjugate heat transfer problem

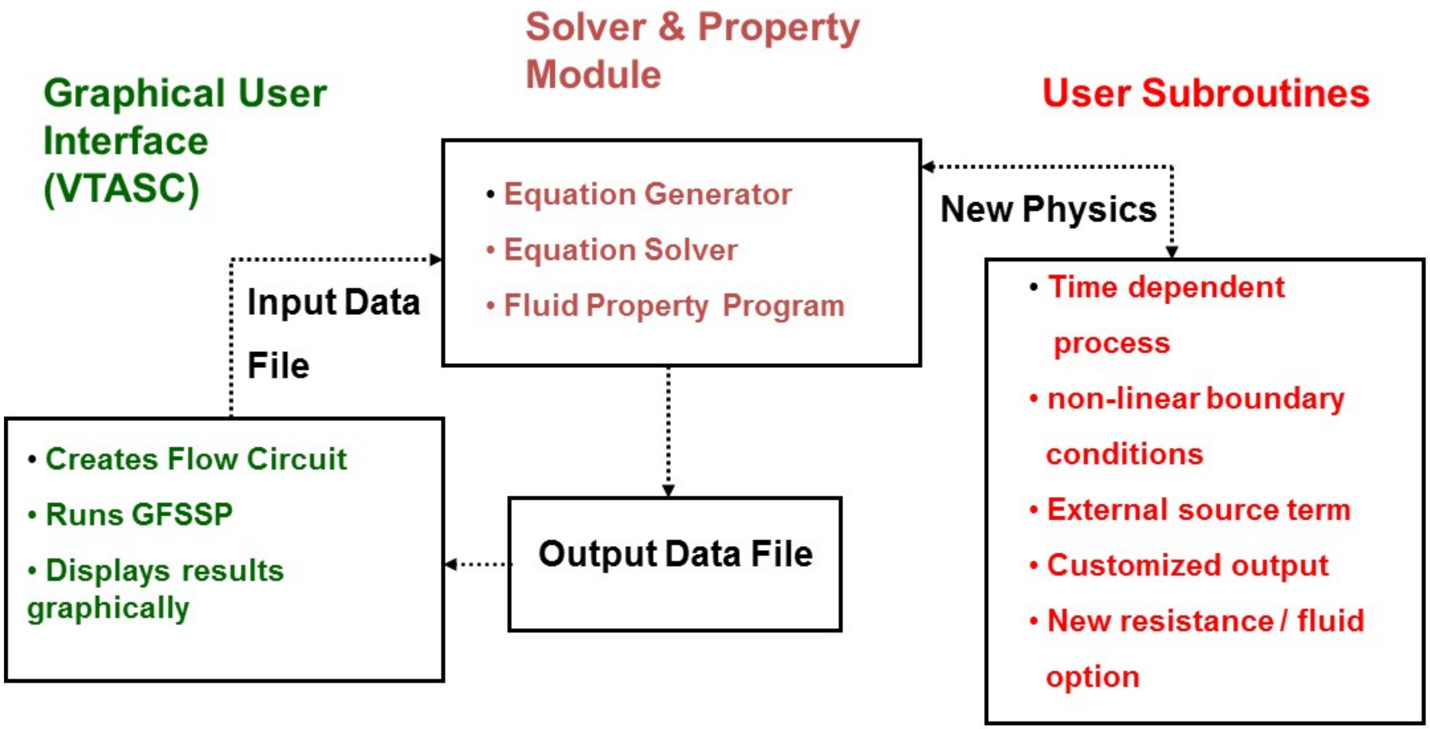


| **Unknown Variables** | **Governing Equations to Solve** |
|---|---|
| 1. Pressure | 1. Mass Conservation Equation |
| 2. Flowrate | 2. Momentum Conservation Equation |
| 3. Fluid Temperature | 3. Energy Conservation Equation of Fluid |
| 4. Solid Temperature | 4. Energy Conservation Equation of Solid |
| 5. Mass | 5. Thermodynamic Equation of State |



*Thermodynamic and Thermo-physical properties are obtained from built-in GASP and GASPAK*

# Program Structure & Numerical Scheme



**Graphical User Interface (VTASC)**

- Creates Flow Circuit
- Runs GFSSP
- Displays results graphically

Input Data File

**Solver & Property Module**

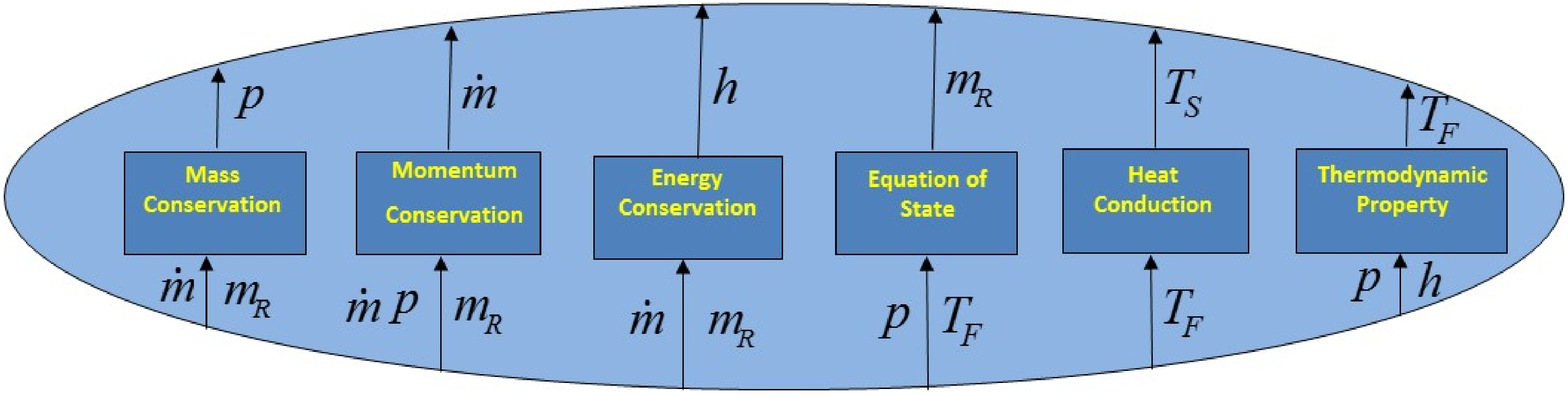
- Equation Generator
- Equation Solver
- Fluid Property Program

Output Data File

New Physics

**User Subroutines**

- Time dependent process
- non-linear boundary conditions
- External source term
- Customized output
- New resistance / fluid option



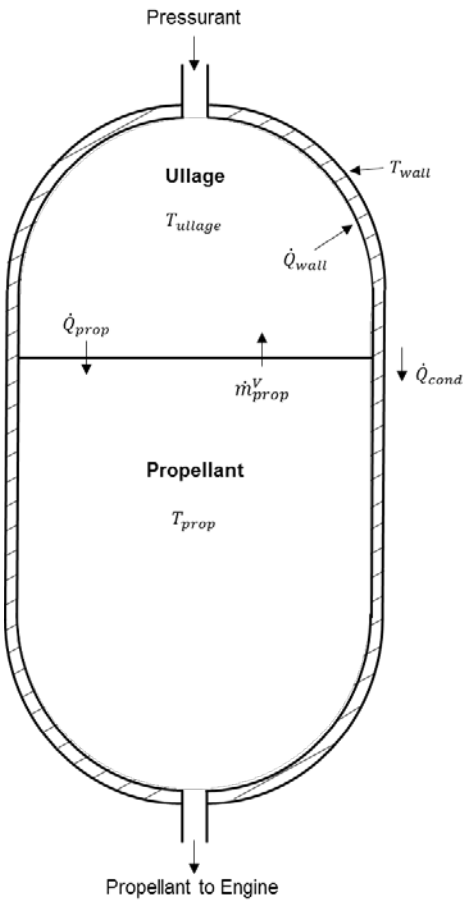
# Review of Tank Pressurization Model

- In Liquid Propulsion System, accurate modeling of Cryogenic Tank Pressurization is needed to

a) Ensure safe operation of the turbo-pump
b) Estimate amount of pressurant requirement
c) Estimate boil-off of Liquid Propellant

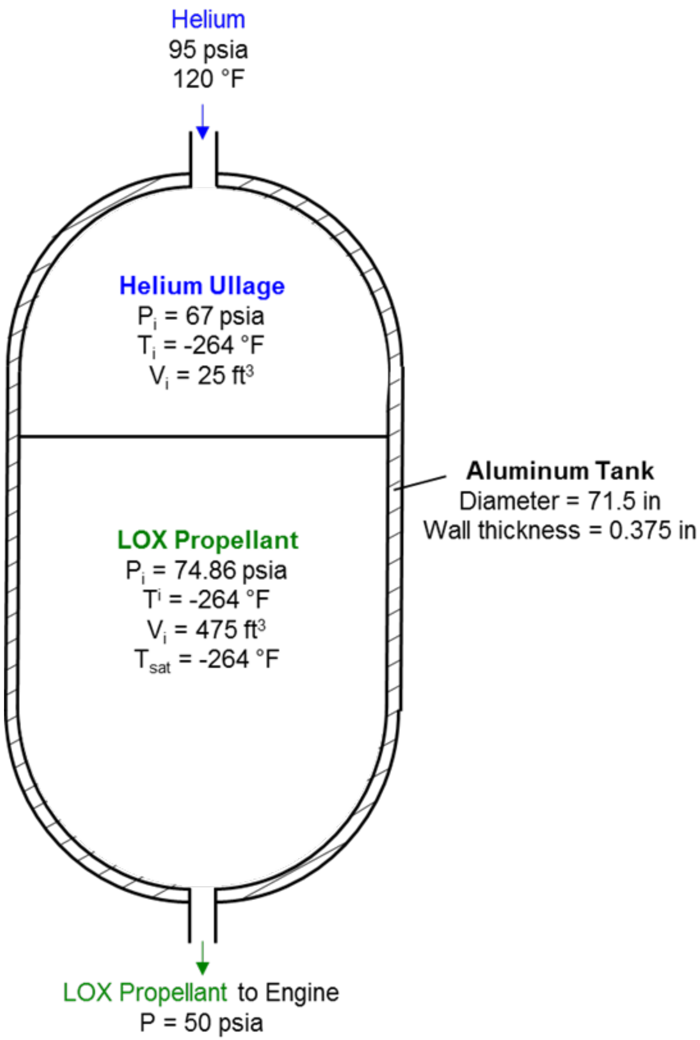
- Cryogenic Tank Pressurization model must account for

a) Heat Transfer between ullage and wall
b) Heat Transfer between ullage and liquid propellant
c) Evaporative mass transfer between liquid propellant and ullage



# Review of Tank Pressurization Model

## Zero Dimensional Model



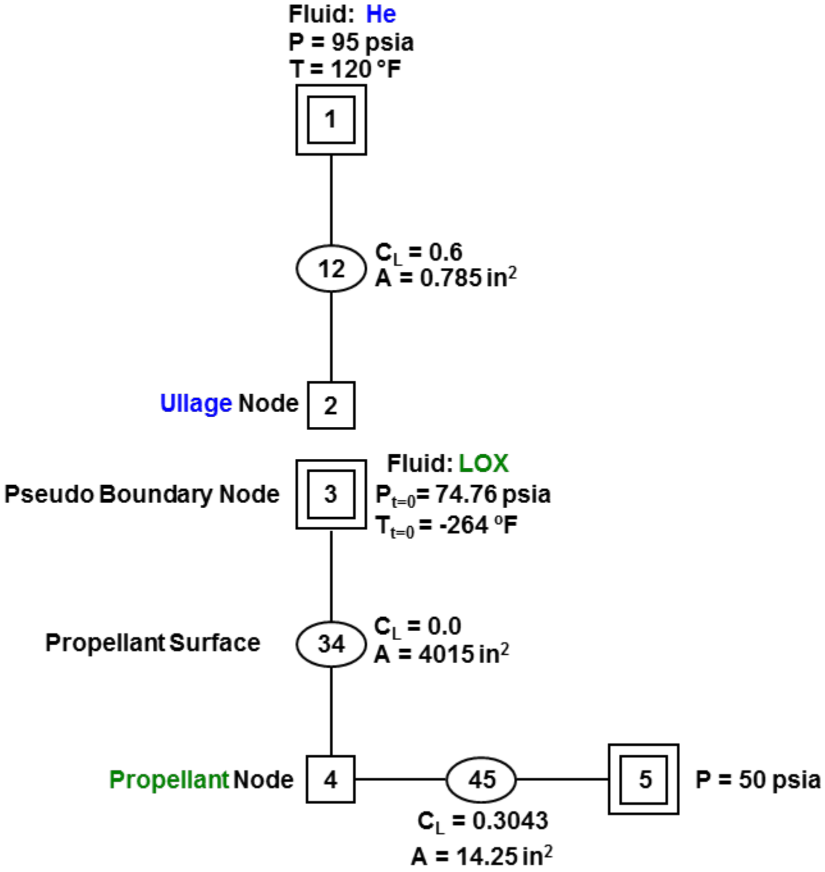
Helium
95 psia
120 °F

**Helium Ullage**
$P_i$ = 67 psia
$T_i$ = -264 °F
$V_i$ = 25 ft$^3$

**Aluminum Tank**
Diameter = 71.5 in
Wall thickness = 0.375 in

**LOX Propellant**
$P_i$ = 74.86 psia
$T^i$ = -264 °F
$V_i$ = 475 ft$^3$
$T_{sat}$ = -264 °F

LOX Propellant to Engine
P = 50 psia



**Fluid: He**
**P = 95 psia**
**T = 120 °F**

**1**

**12**
**$C_L$ = 0.6**
**A = 0.785 in$^2$**

**Ullage Node** **2**

**Pseudo Boundary Node** **3**
**Fluid: LOX**
**$P_{t=0}$= 74.76 psia**
**$T_{t=0}$ = -264 °F**

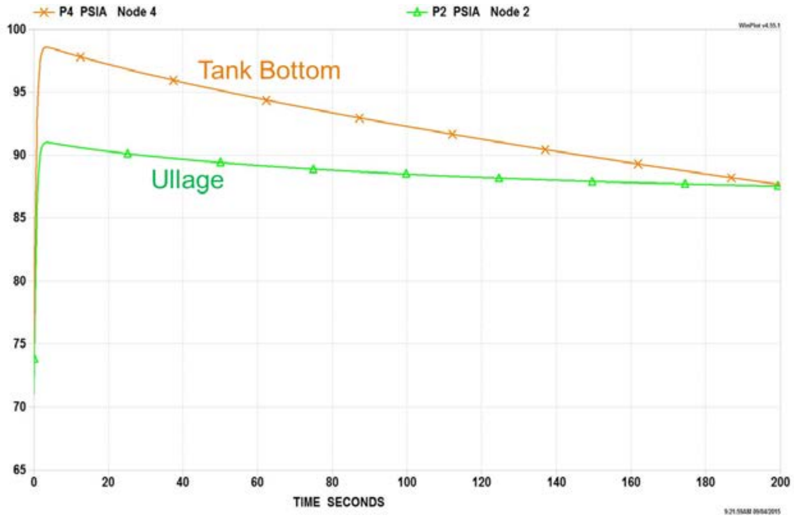
**Propellant Surface** **34**
**$C_L$ = 0.0**
**A = 4015 in$^2$**

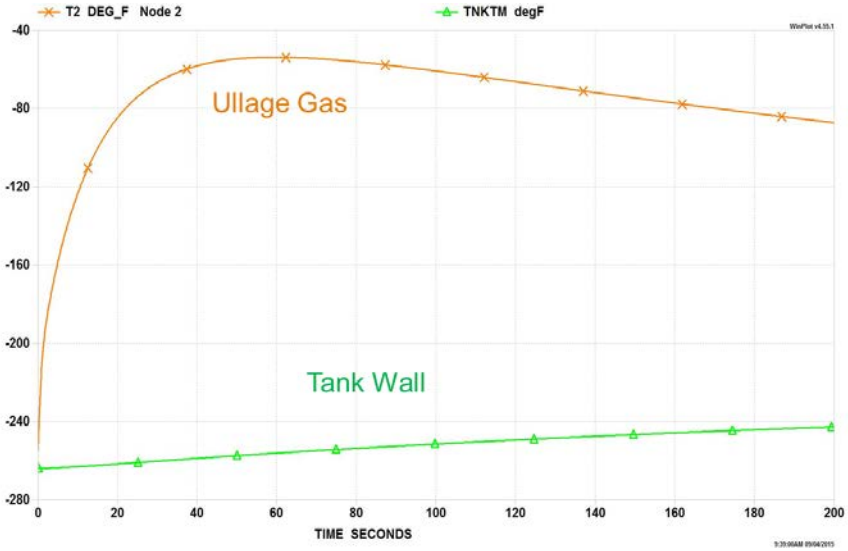
**Propellant Node** **4**

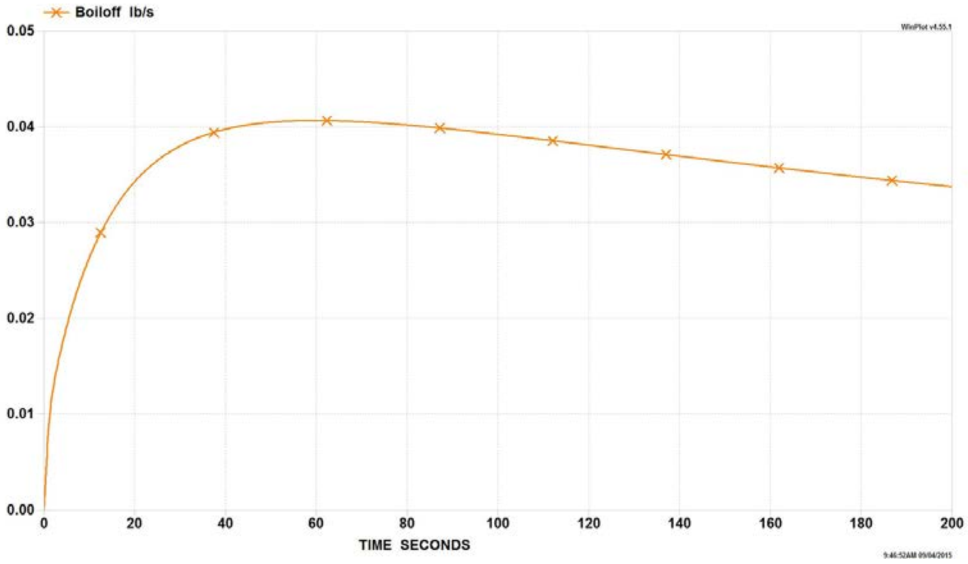
**45**
**$C_L$ = 0.3043**
**A = 14.25 in$^2$**

**5** **P = 50 psia**

# Zero Dimensional Model Results







# Zero Dimensional Model Validation

- Collapse Factor Correlation (Epstein)
  - Ratio of *actual* pressurant consumption to an *ideal* pressurant consumption which assumes **no** heat or mass transfer

$$\frac{w_p}{w_p^0} = \left\{\left(\frac{T_0}{T_s} - 1\right)\left[1 - \exp(-p_1 C^{p_2})\right] \times \left[1 - \exp(-p_3 S^{p_4})\right] + 1\right\} \times \exp\left[-p_5 \left(\frac{1}{1+C}\right)^{p_6} \left(\frac{S}{1+S}\right)^{p_7} Q^{p_8}\right]$$

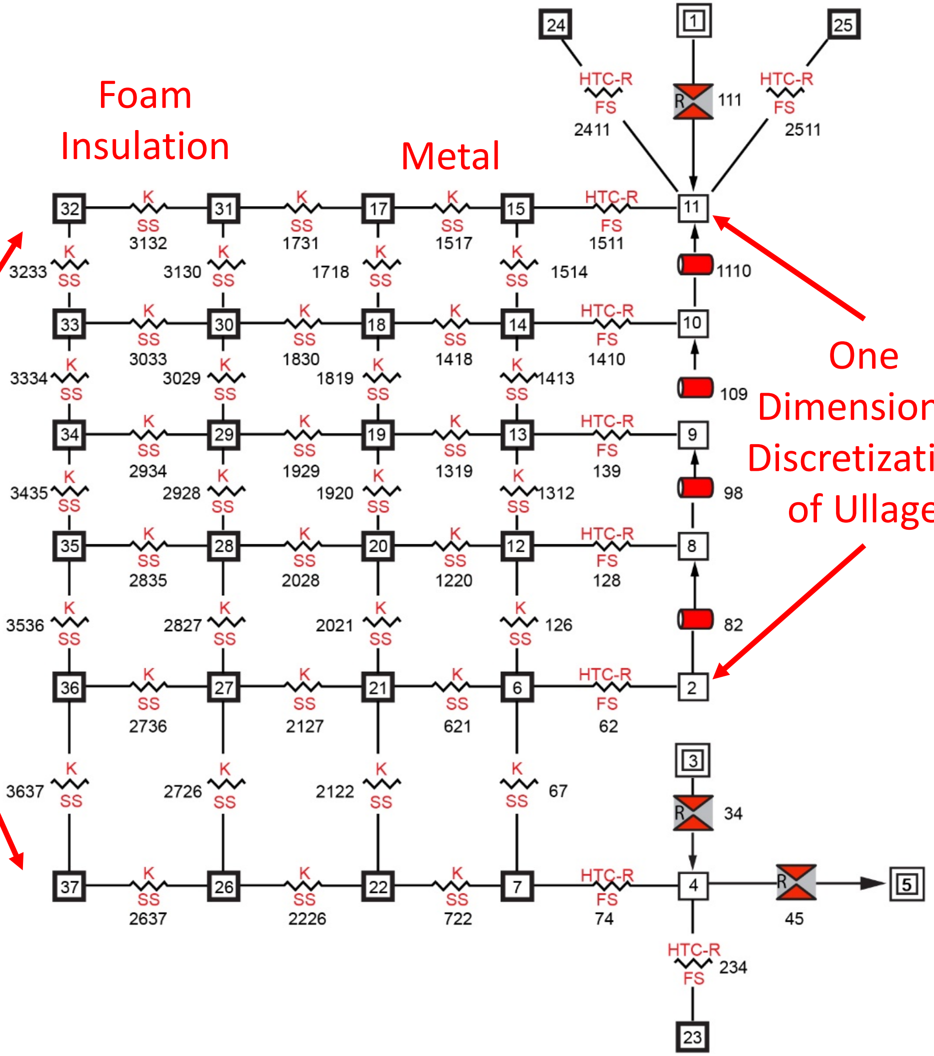
where:

$$w_p^0 = \rho_G^0 \Delta V \qquad C = \frac{\left(\rho c_p^0 t\right)_w}{\left(\rho c_p\right)_G^0 D_{eq}} \frac{T_S}{T_0} \qquad S = \frac{h_c \theta_T}{\left(\rho c_p\right)_G^0 D_{eq}} \frac{T_S}{T_0} \qquad Q = \frac{\dot{q} \theta_T}{\left(\rho c_p\right)_G^0 D_{eq} T_0}$$

| | |
|---|---|
| $C$ | ratio of wall to gas thermal capacitance |
| $p_1$ - $p_8$ | fitted constants (dependent on propellant) |
| $Q$ | ratio of ambient heat input to effective thermal capacitance of gas |
| $S$ | modified Stanton number |
| $T_0$ | pressurant inlet temperature |
| $T_s$ | propellant saturation temperature at initial tank pressure |

- Pressurization Model Validation
  - **GFSSP** Collapse Factor Prediction: **1.46**
  - Epstein Correlation Collapse Factor Prediction: **1.51**
    - **GFSSP** Prediction Discrepancy: **-3.3%**

# One Dimensional Self-Pressurization Model of Cryogenic Tank

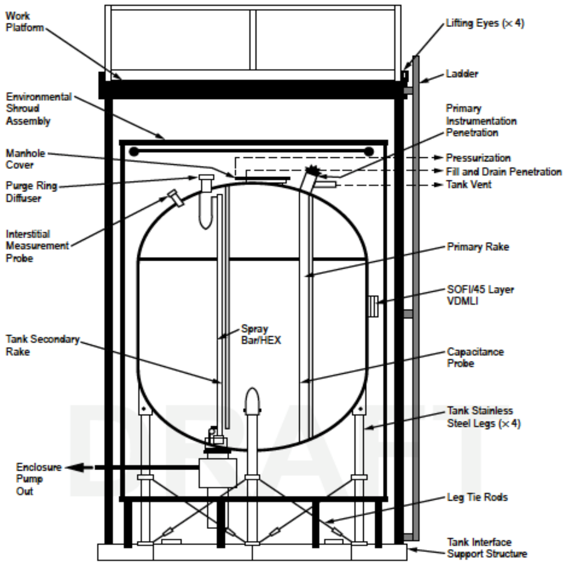


Foam Insulation

Metal

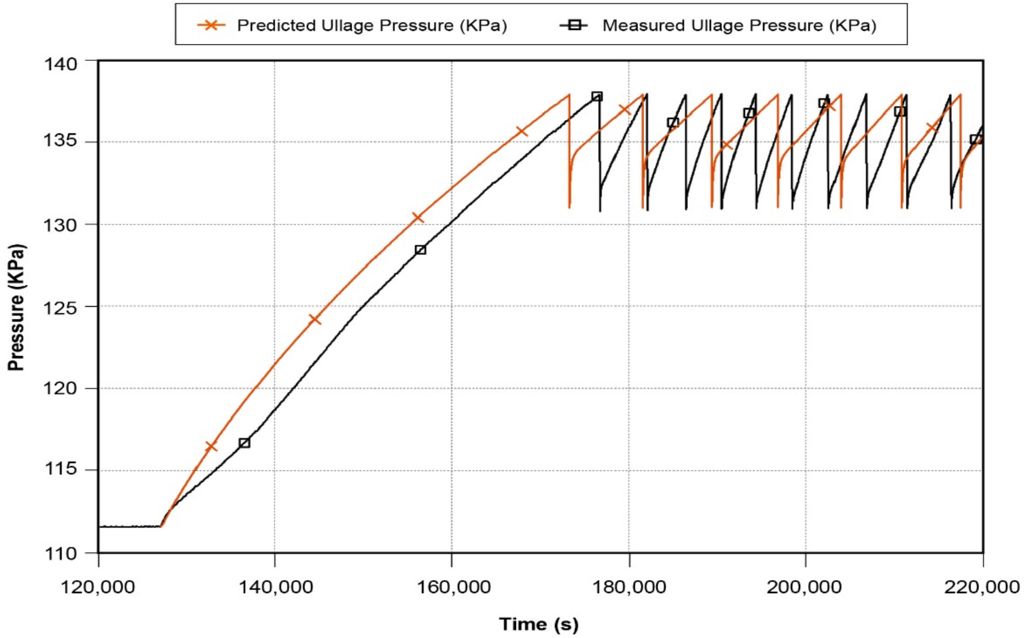
Multi Layer Insulation

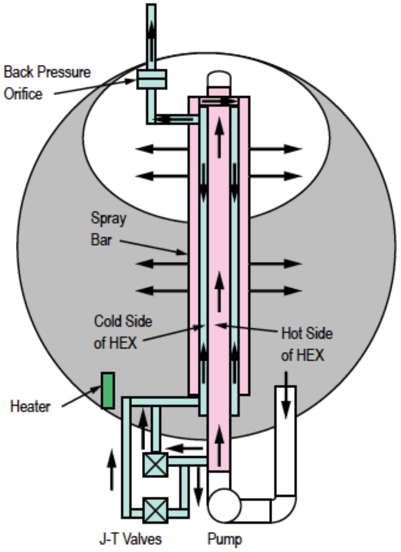
One Dimensional Discretization of Ullage

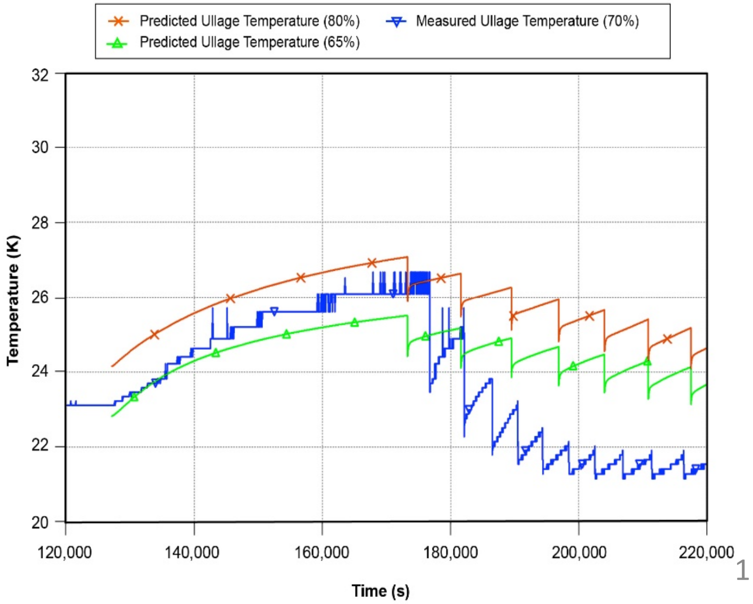


**Multi-Purpose Hydrogen Tank**

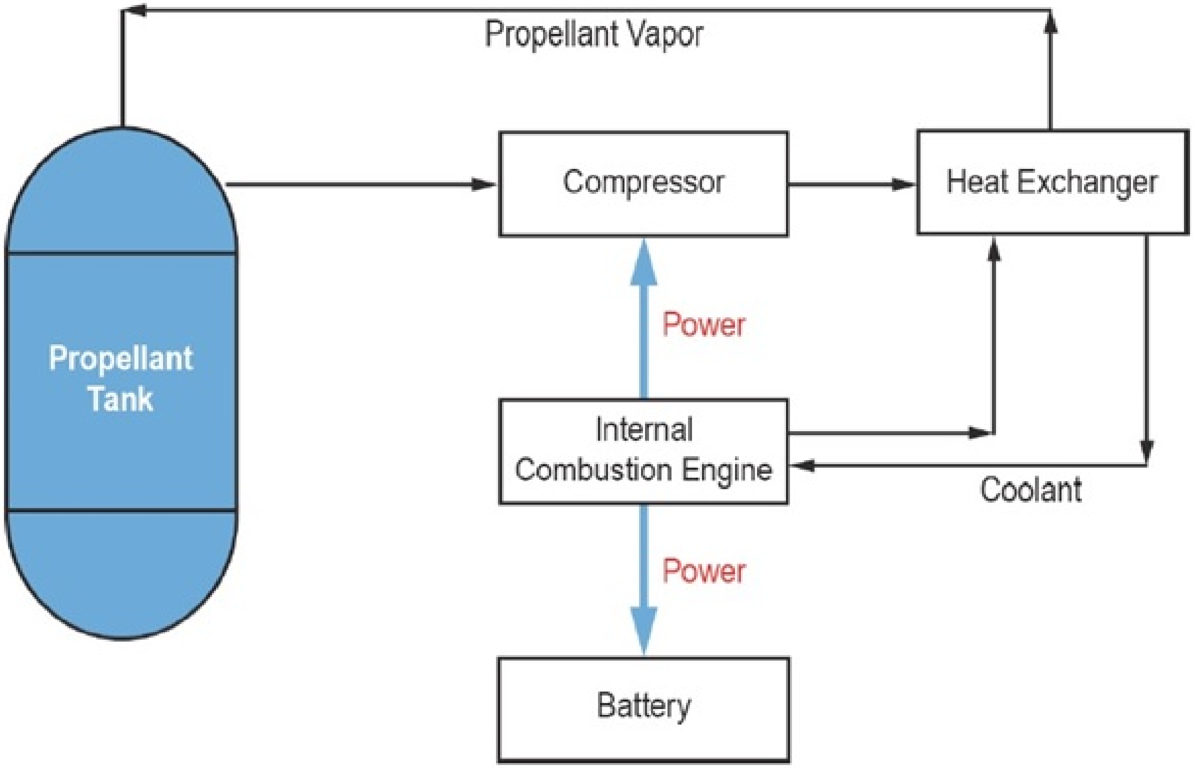
# Results of Self-Pressurization Model





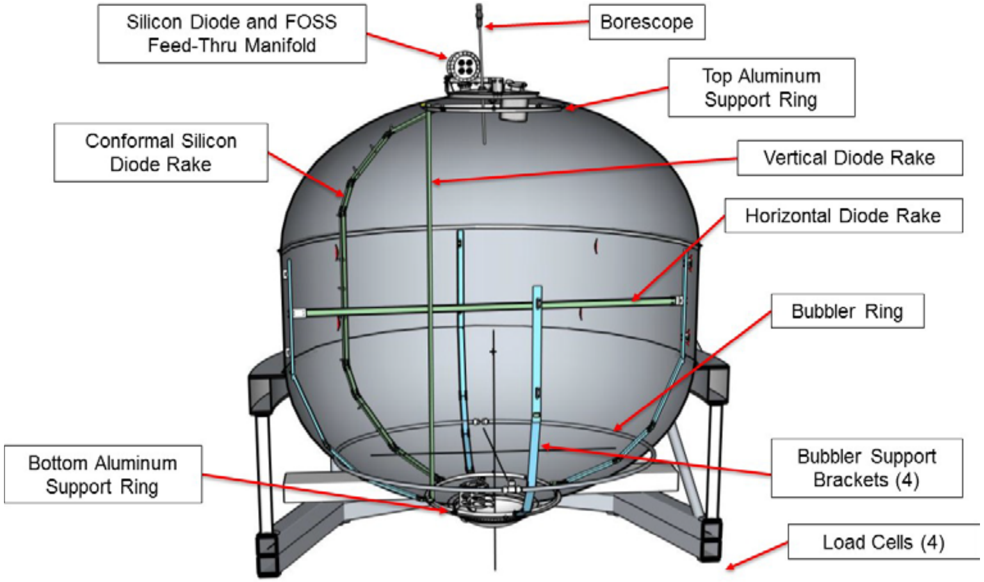


# Integrated Vehicle Fluid System Overview

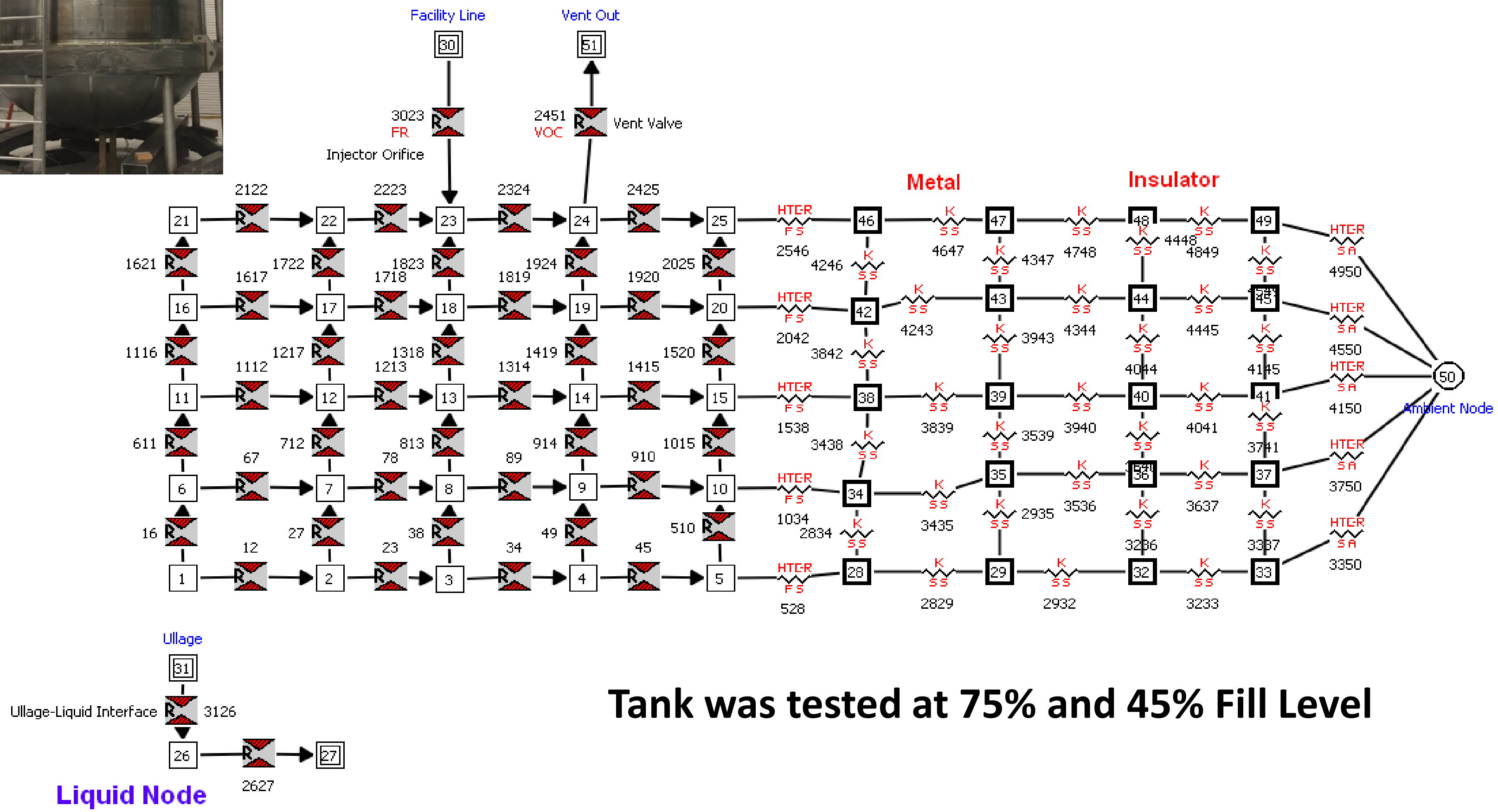


# Test Program at MSFC

## Flight Tank provided by ULA



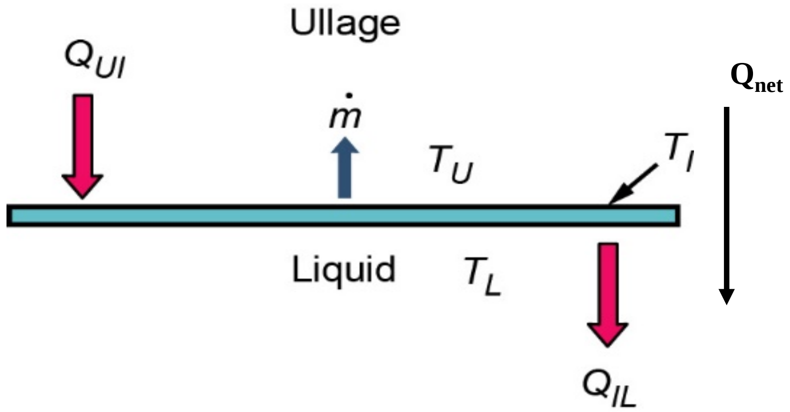
# Two Dimensional Axisymmetric Model of Tank Pressurization



## Tank was tested at 75% and 45% Fill Level

**Working Fluid**: Nitrogen, Tank Height ≈ 10 ft, Tank Dia ≈ 10 ft

# Heat and Mass Transfer Model at Liquid-Ullage Interface



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

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

Evaporative Mass Transfer:

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

Heat Transfer Coefficients using Natural Convection

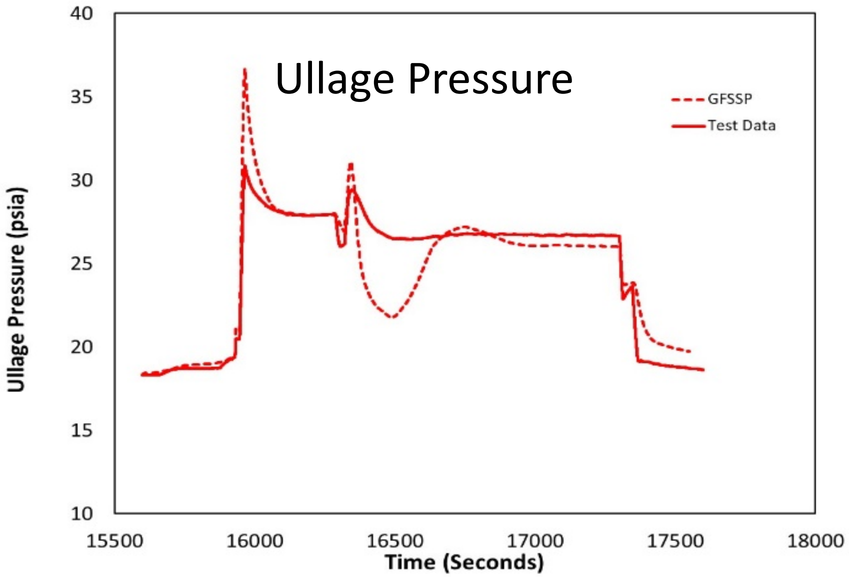
$$h_{UI} = K_H C \frac{k_f}{L_s} \mathrm{Ra}^n = h_{IL} ,$$

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

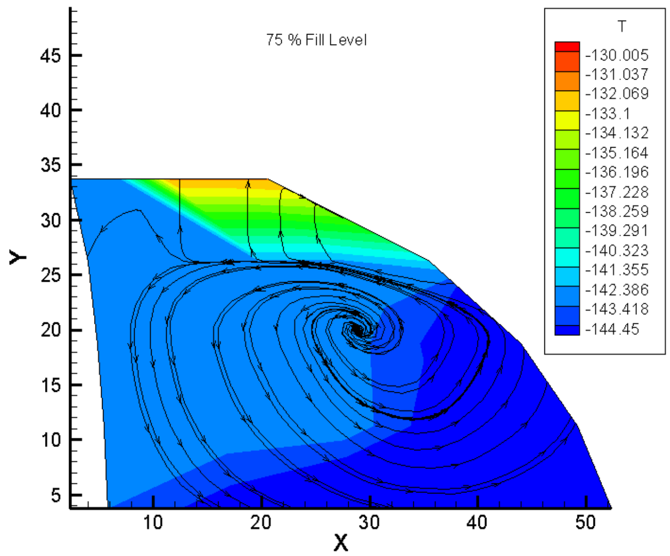
Net Heat Transfer Rate:

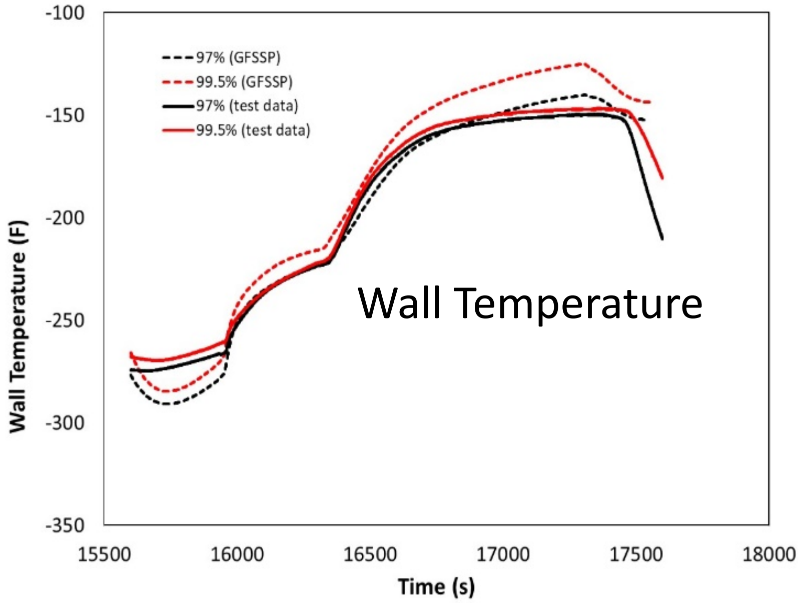
$$Q_{net} = \dot{m}[C_{P,l}(T_I - T_L) + h_{fg}]$$

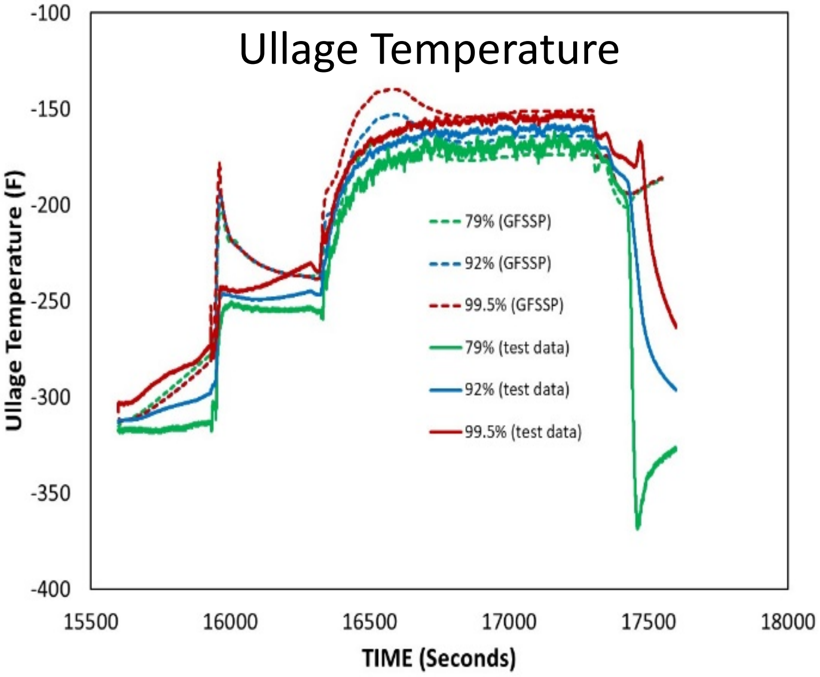
# Results for 75% Fill Level



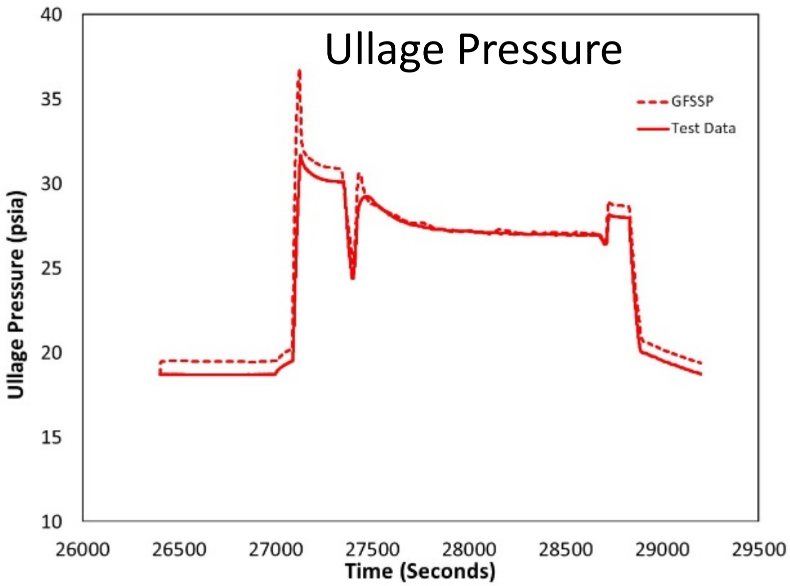
Temperature contour /stream traces



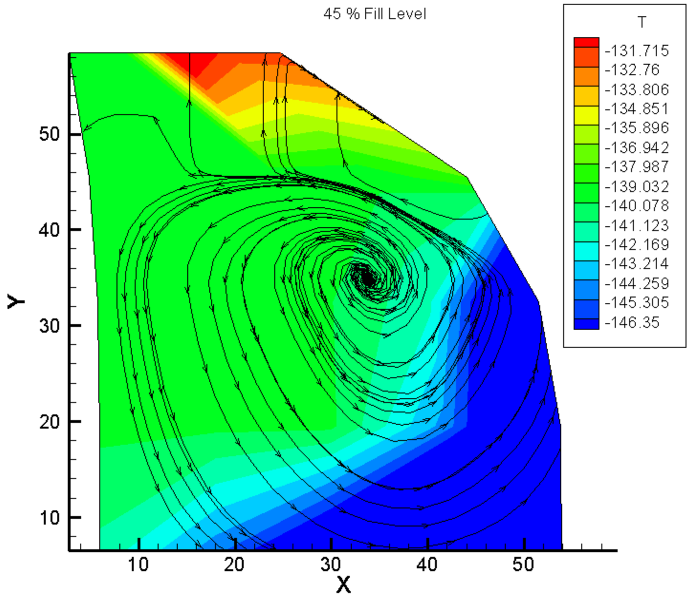


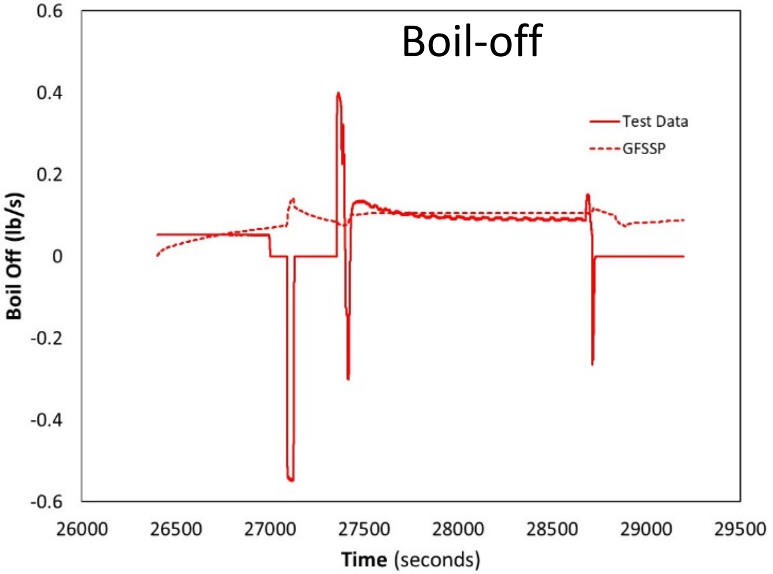


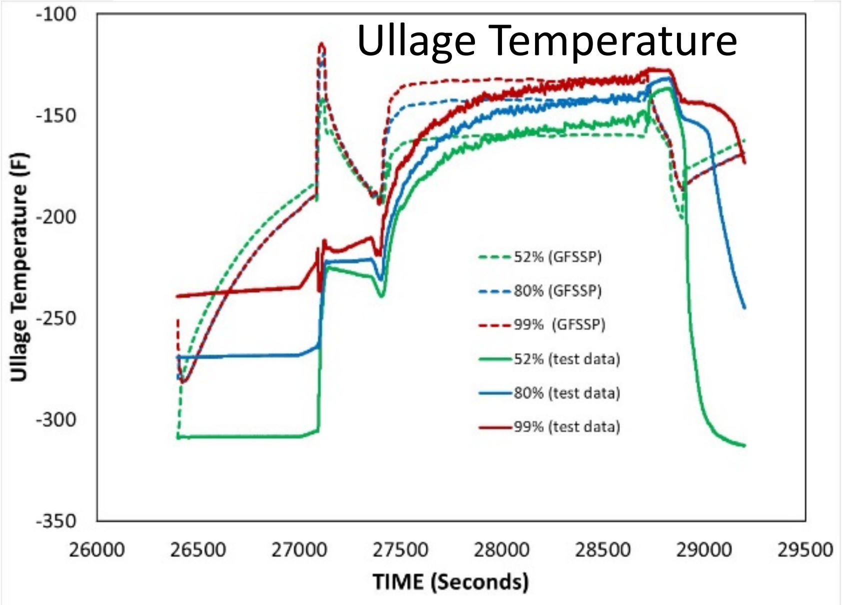
# Results for 45% Fill Level


Ullage Pressure

Temperature contour /stream traces




Boil-off


Ullage Temperature

# Conclusions

- This paper demonstrates the feasibility of system level modeling of tank pressurization using multiple nodes.
- The ullage of a flight tank has been modeled using 25 nodes and 40 branches where mass and energy conservation equations were solved at the nodes and momentum equations are solved at the branches.
- Gravity, heat and mass transfer at the liquid vapor interface, and heat transfer between solid and fluid are accounted for in the governing equations.
- The model results have been verified by comparing with test data.
- The advantage of using multiple nodes in a system level code is that it allows prediction of recirculation and stratification with a fraction of the computational cost of a high fidelity Navier-Stokes code.

# Acknowledgement

- This work is supported by NASA Space Technology Mission Directorate's Evolvable Cryogenics (eCryo) project
- The authors want to acknowledge Arthur Werkheiser of NASA/MSFC for their contribution

- More information about GFSSP is available at

https://www.nasa.gov/gfssp

- GFSSP is available free of cost for US Government work from MSFC Tech Transfer Office

https://software.nasa.gov/software/MFS-33019-1