Pressure-Based Venting Model for the *Dream Chaser*® Spacecraft Cargo System

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Outline

- Background
- Venting and Repressurization (VRP) Methodology
- Thermal Desktop Model Setup
- Comparison of Matlab, Thermal Desktop and VRP Stand-Alone Models
- Conclusions

Background

- Sierra Nevada Corporation (SNC) is developing the Dream Chaser Cargo System
  - Lifting body spacecraft with disposable cargo module
  - Provide cargo resupply services to the International Space Station (ISS)
  - Dispose of unneeded cargo
  - Return cargo from the ISS to NASA

Background

- SNC had a need to simulate the venting and repressurization of the Dream Chaser Cargo System unpressurized bays within its Thermal Desktop (TD) Dream Chaser Cargo System Integrated Thermal Model (ITM) during ascent and reentry
- Three modeling options considered:
  - Use existing Matlab module
    - Too slow for running multiple mission phases
  - Develop FloCAD module
    - Implementation limited by number of FloCAD licenses available
  - Develop Venting and Repressurization (VRP) software package
    - Stand-alone (FORTRAN-based) or coupled with TD
    - Does not require any extra licenses
- SNC chose to work with ATA to develop the new VRP software package

VRP Methodology

- Geometry consists of compartments, or "tanks," that are attached to other tanks through small orifices
- Conservation of mass and energy equations as applied to a system of tanks and orifices are solved
- Pressure, density and temperature is calculated at each tank
- Assumptions
  - Velocity of air moving in a tank is low, therefore does not need to be included in energy or mass flow equations
  - Air acts as an ideal gas
  - Heat transfer to the tank walls occurs through natural convection only

VRP Methodology

- Model Inputs
  - Tank Definitions
    - Number of tanks
    - Tank volume
    - Tank wall area
    - Tank wall initial Temperature
    - Wall Capacitance
  - Orifice Definitions
    - Number of orifices
    - Orifice area
- Boundary Condition Inputs
  - Inlet temperature vs. time
  - Inlet pressure vs. time
  - Acceleration vs. time

VRP Methodology

- Model Outputs as a function of time
  - Tank air mass
  - Tank air temperature
  - Tank air pressure
  - Tank air enthalpy
  - Mass flow through each orifice
  - Tank wall heat transfer coefficient
  - Tank wall temperature

VRP Methodology

- By rearranging the equations for conservation of mass and energy, a relation for the change in tank temperature vs. time can be obtained

$$\text{Conservation of Mass:}\qquad \frac{dM_{tank}}{dt} = \dot{m}_{in} - \dot{m}_{out}$$

$$\text{Conservation of Energy:}\qquad \frac{dH_{tank}}{dt} = \dot{Q}_{in} - \dot{Q}_{out} + V\frac{dP}{dt}$$

$$\boxed{M_{tank}\frac{dT_{tank}}{dt} = \dot{m}_{in}(\gamma T_{in} - T_{tank}) - \dot{m}_{out}(\gamma - 1)T_{tank} + \frac{hA}{C_v}(T_{wall} - T_{tank})}$$

$$\begin{matrix} \dot{m}_{in}, T_{in} \\ \dot{Q}_{in} = \dot{m}_{in}C_pT_{in} \end{matrix} \longrightarrow \boxed{\begin{matrix} M_{tank}, T_{tank} \\ H_{tank} = M_{tank}C_pT_{tank} \end{matrix}} \longrightarrow \begin{matrix} \dot{m}_{out}, T_{tank} \\ \dot{Q}_{out} = \dot{m}_{out}C_pT_{tank} \end{matrix}$$

- Because heat transfer in the fluid is driven by pressure, temperature-based equations can lead to instabilities in the numerical solution

VRP Methodology

- By using the ideal gas equation of state substituted into the energy equation, a relation for the change in tank pressure vs. time can be obtained

$$Ideal\ Gas\ Equation\ of\ State: \qquad P = \rho RT$$

$$V_{tank}\frac{dP_{tank}}{dt} = \gamma \dot{m}_{in}\frac{P_{in}}{\rho_{in}} - \gamma \dot{m}_{out}\frac{P_{tank}}{\rho_{tank}} + (\gamma - 1)hA(T_{wall} - T_{tank})$$

- For a system of tanks and orifices, the energy equations can be written in matrix form

$$\boxed{[V]\frac{d\vec{P}_{tank}}{dt} + [\dot{V}]\vec{P}_{tank} = \vec{Q}}$$

VRP Methodology

- Mass flow rates are based on orifice equations for either choked or non-choked flow

$$\dot{m}(P_1, \rho_1 P_2) = C_d A \sqrt{\gamma P_1 \rho_1 \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma+1}{\gamma-1}}}$$

$$\dot{m}(P_1, \rho_1 P_2) = C_d A \sqrt{2 P_1 \rho_1 \left(\frac{\gamma}{\gamma - 1}\right)\left[\left(\frac{P_2}{P_1}\right)^{\frac{2}{\gamma}} - \left(\frac{P_2}{P_1}\right)^{\frac{\gamma+1}{\gamma}}\right]}$$

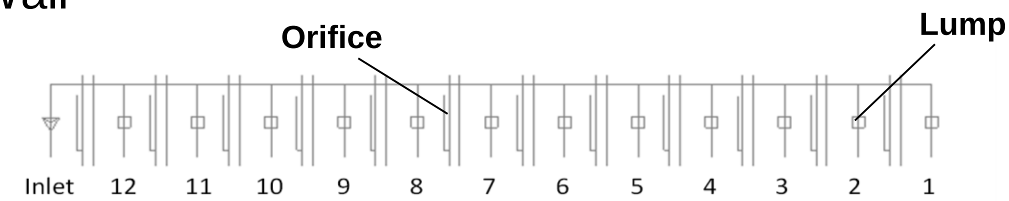
- The heat transfer coefficient between the air and the tank walls is based on natural convection of a closed sphere

$$Nu_D = 0.59(Ra_D)^{1/4} \qquad Nu_D = 0.13(Ra_D)^{1/3}$$

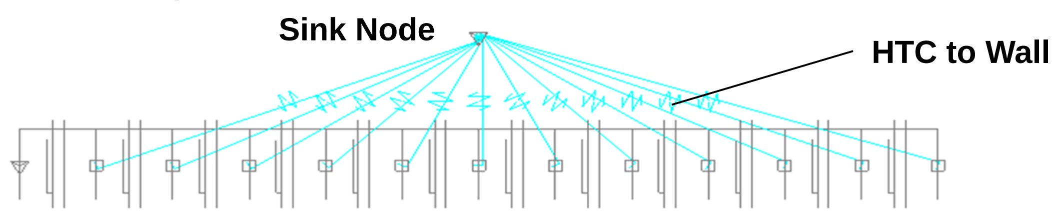
$$Nu_{D,trans} = \left(\frac{0.59}{0.13}\right)^{12}$$

Thermal Desktop Model Setup

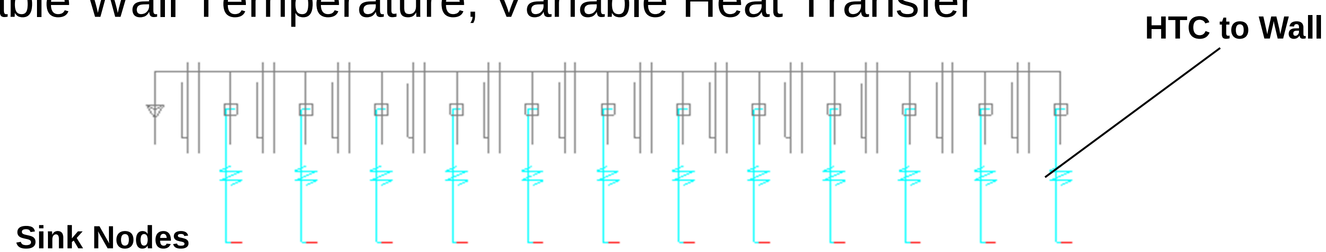
- A FloCAD model was created to validate the VRP code
  - Four simulations were run, investigating different heat transfer characteristics from the tank air to the tank wall
    - Adiabatic Wall



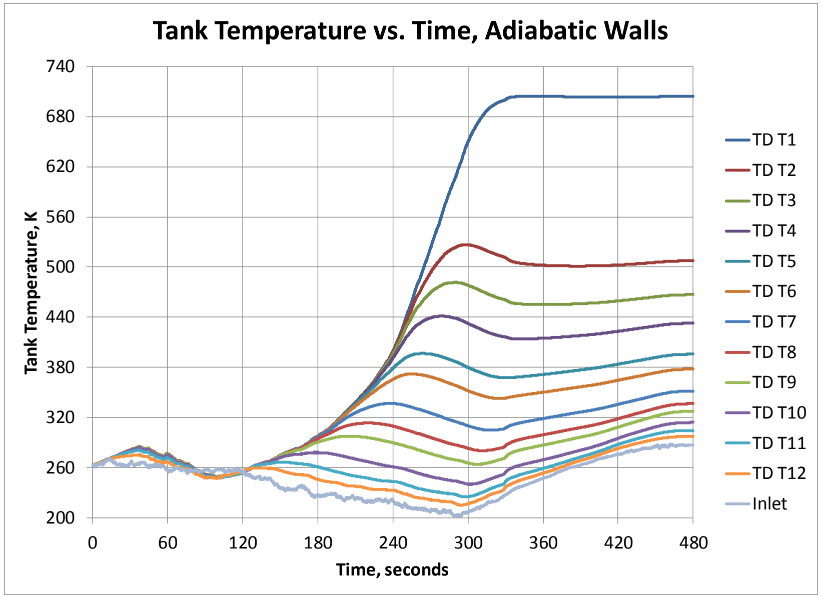
    - Constant Wall Temperature, Constant Heat Transfer



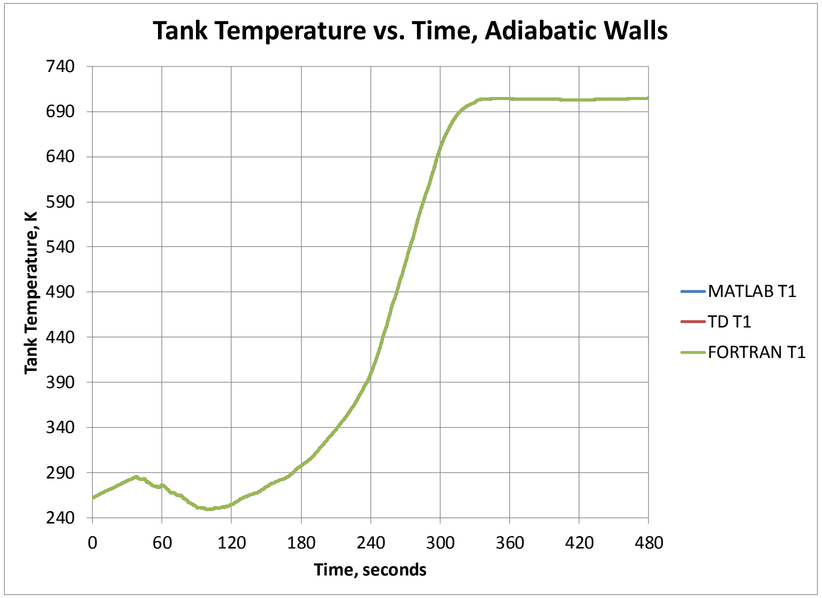
    - Constant Wall Temperature, Variable Heat Transfer
    - Variable Wall Temperature, Variable Heat Transfer



- Case 1: Adiabatic Wall
  – Enthalpy from incoming air is used to heat up only the air in each of the tanks
  – Tank temperatures increase from inlet to last tank (Tank 1) due to gas compression and build up of mass
  – All three models produce similar results

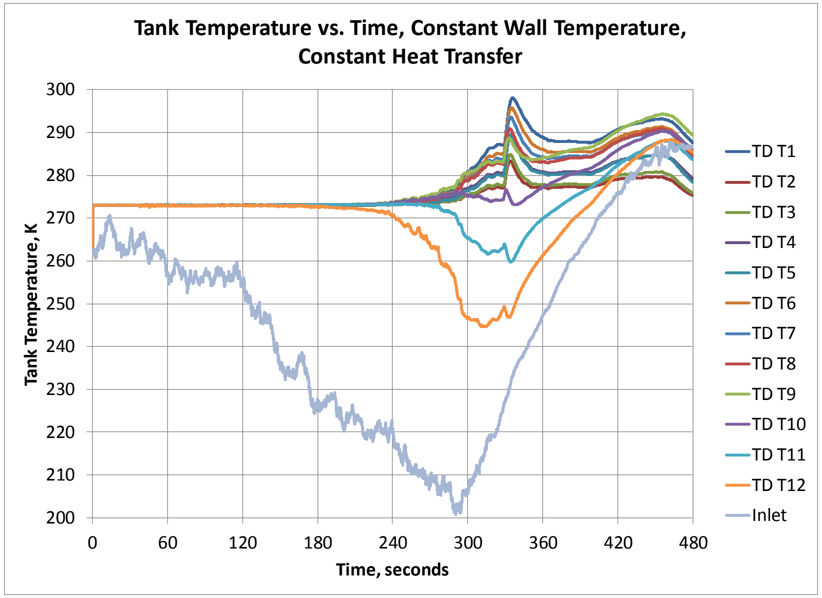


Tank temperature vs time using VRP code, all tanks

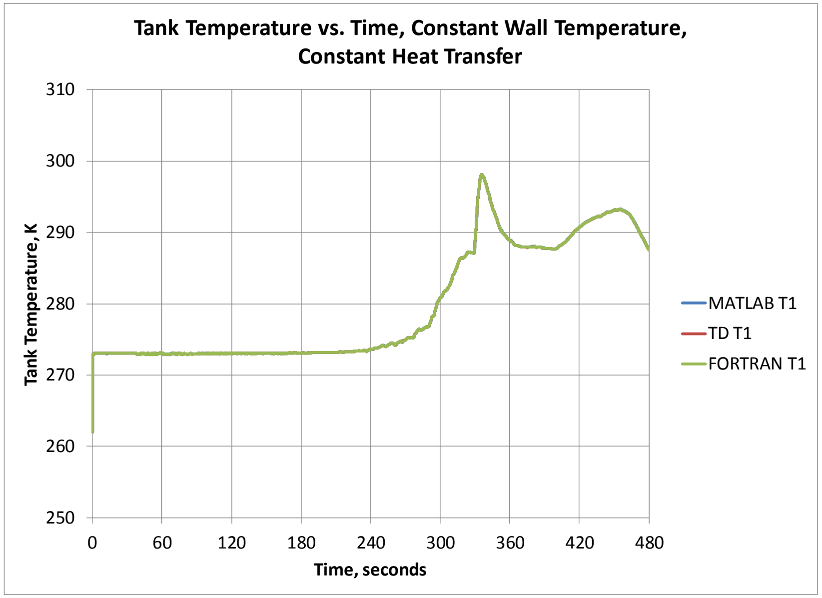


Temperature of Tank 1, three different models

- Case 2: Constant Wall Temperature, Constant Heat Transfer
  - Tank air stays near the wall temperature of 273 K for ~200 seconds, as incoming enthalpy of air is transferred to wall sink temperature
  - After 200 seconds, the mass flow rate is sufficient to cause a rise in air temperatures, which reach below 300 K due to heat transfer to the wall
  - All three models produce similar results



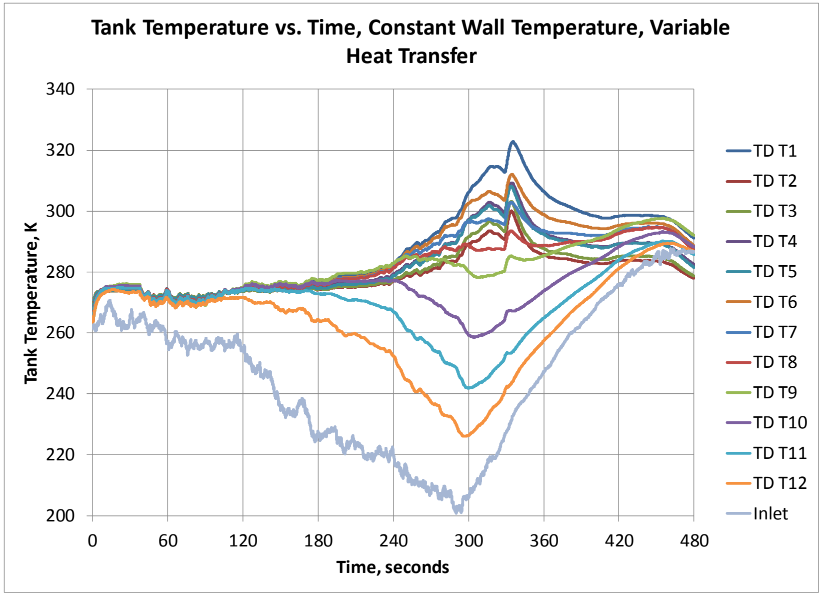
Tank temperature vs time using VRP code, all tanks



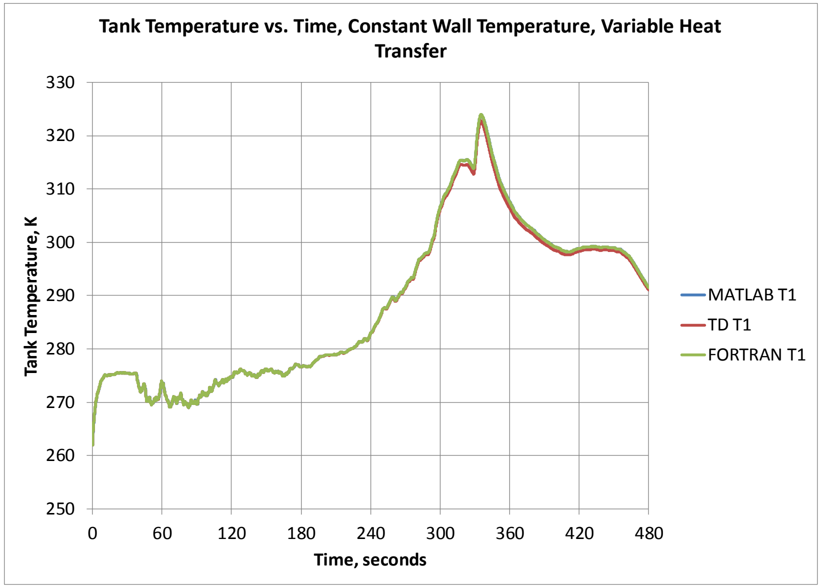
Temperature of Tank 1, three different models

Results

- Case 3: Constant Wall Temperature, Variable Heat Transfer
  - Variable natural convection HTC is dependent on tank pressure, density, temperature and acceleration
  - Tank air temperatures are higher than the 273 K wall temperature in the first 200 seconds due to low heat transfer to the wall
  - Tank temperatures away from inlet increase due to gas compression
  - All three models produce similar results, within 2 K



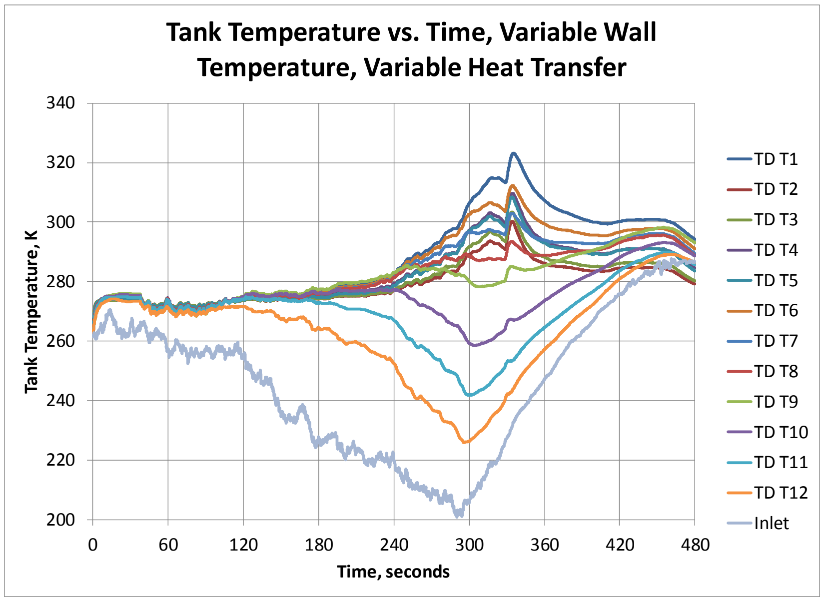
Tank temperature vs time using VRP code, all tanks



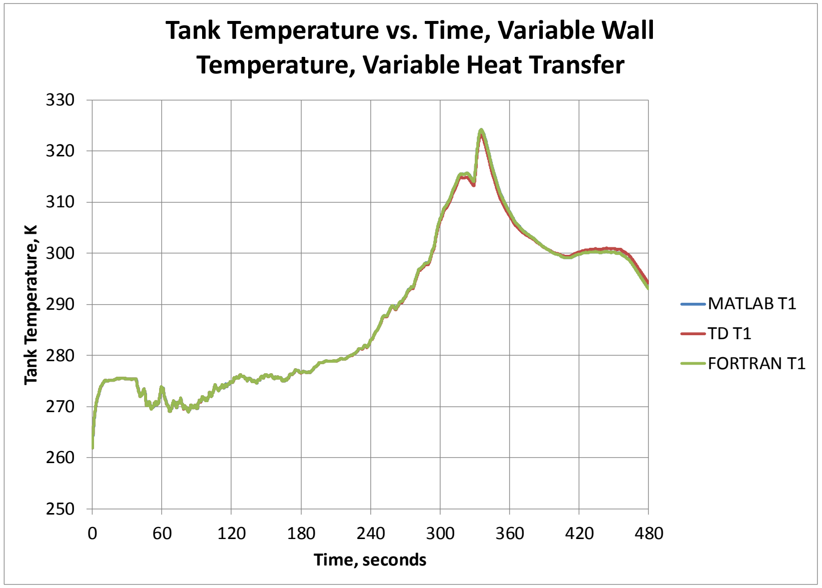
Temperature of Tank 1, three different models

Results

- Case 4: Variable Wall Temperature, Variable Heat Transfer
  - Each air compartment is connected to a wall node with an initial temperature of 273 K and a thermal mass
  - Wall temperatures change due to heat loss/gain from tank air
  - Results are similar to Constant Wall Temperature, Variable Heat Transfer case
  - All three models produce similar results, within 2 K



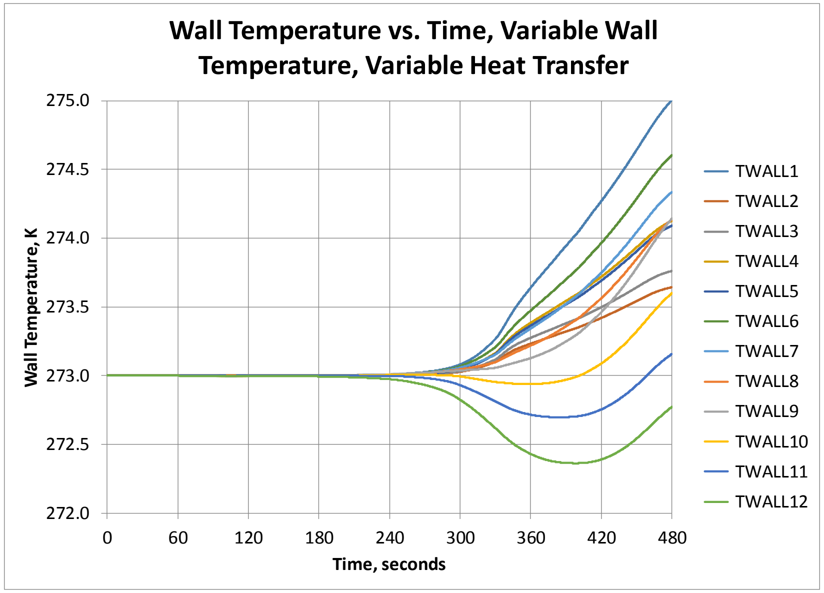
Tank temperature vs time using VRP code, all tanks



Temperature of Tank 1, three different models

Results

- Case 4: Variable Wall Temperature, Variable Heat Transfer
  - Large thermal mass of tank wall results in small wall temperature change during repressurization (maximum of 2 K)
  - Modeling the tank walls at a fixed temperature is a reasonable approximation



Wall temperature vs time using VRP code, all tanks

Conclusions

- VRP successfully matches predictions from two independently developed methods (MATLAB, FloCAD)
- Reduction in simulation time achieved
  - Matlab code runs in 10 minutes
  - VRP runs in < 1 minute
- VRP has been integrated into the Dream Chaser Cargo System Integrated Thermal Model (ITM) using FORTRAN subroutine codes
  - Incorporates the effects of venting or repressurization on internal structure and components
- Results indicate it is important to model each bay explicitly, as opposed to combining multiple bays into a single compartment

Questions