Mars Propellant Liquefaction Modeling in Thermal Desktop

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Space Cryogenics Workshop

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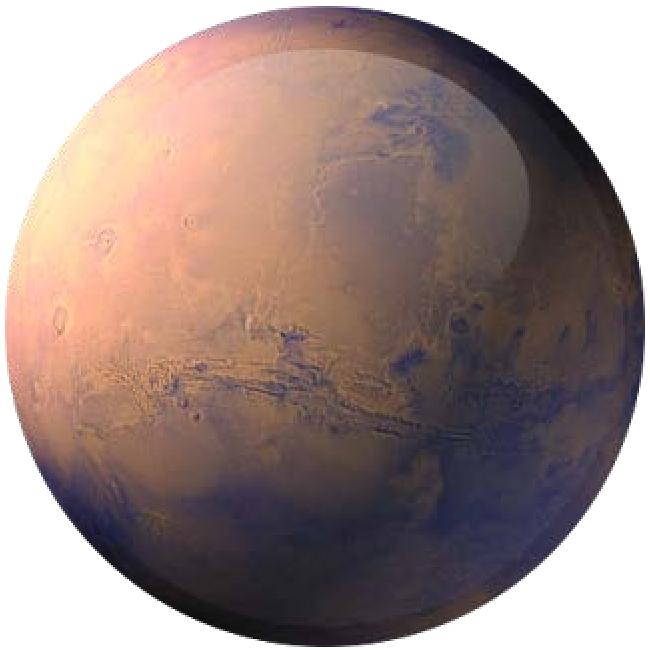
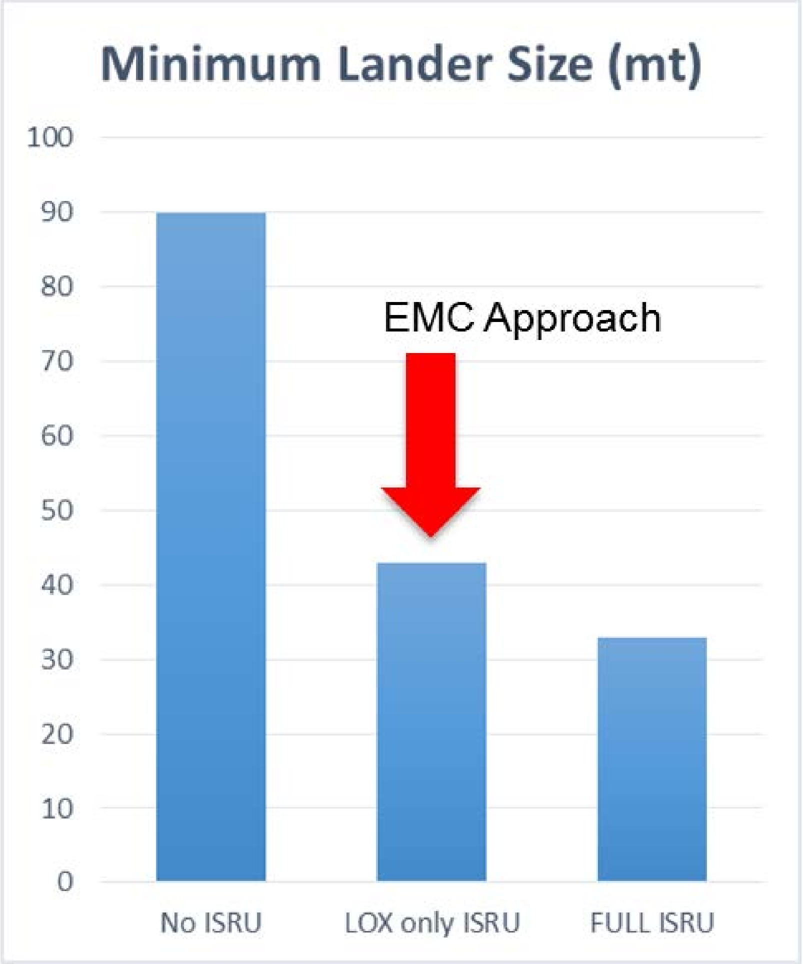
Agenda

- Background/Purpose for Liquefaction
- Broad Area Cooling (Method of Liquefaction) Overview
- MAV Model Overview and Results
- Overview of Zero Boil-off testing campaign at Glenn Research Center
- ZBO Model Overview (similar to MAV Model)
- ZBO Model Validation with Test Results
- Future Work



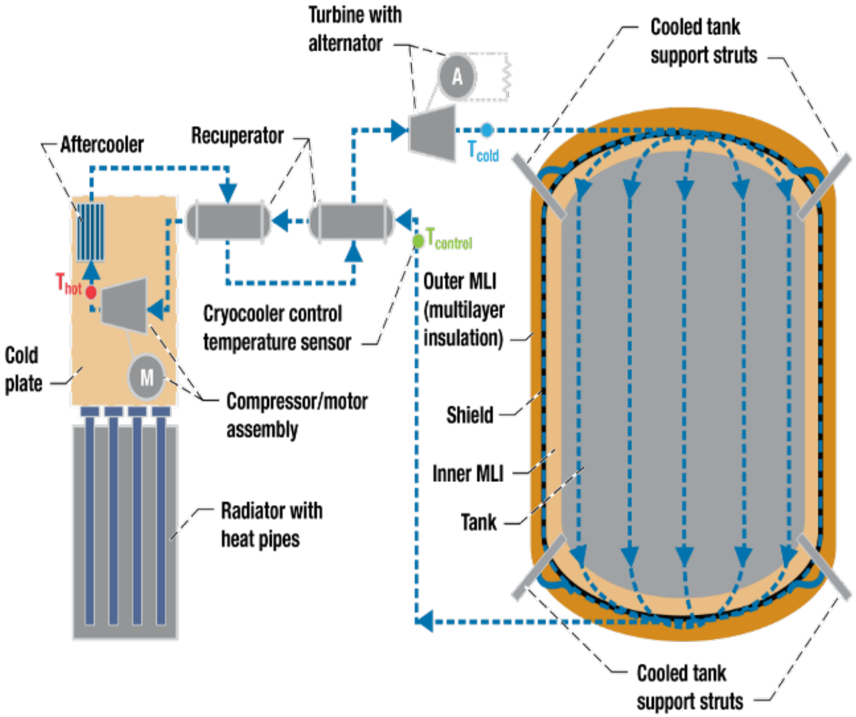
Background

- Current Mars human architectures point to using In-Situ Resource Utilization
- An ISRU plant could potentially reduce the landed mass required by 30000 kilograms
- Gaseous oxygen and methane that ISRU produces must be liquefied and stored as propellants for the Mars Ascent Vehicle (MAV)
- 23 tons (~21000 kg) of liquid oxygen needed in 500+ days
- An energy efficient liquefaction system required



Broad Area Cooling (BAC)

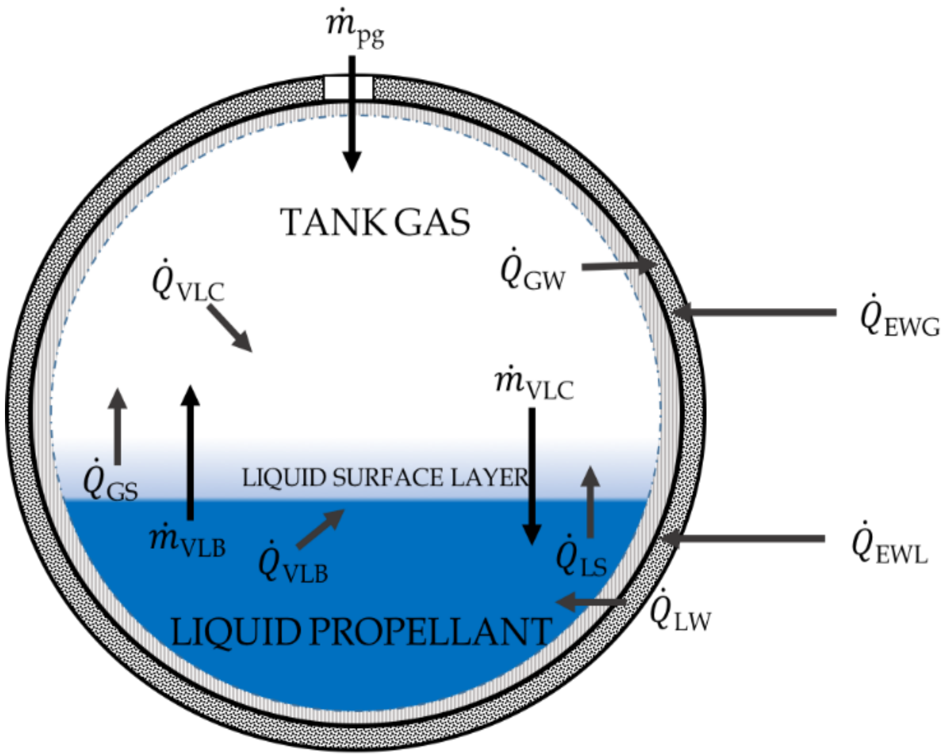
- Working fluid is circulated by a reverse Turbo-Brayton (RTB) cycle cryocooler through a tubing network welded over the whole surface of a cryogenic tank
- Working fluid intercepts the heat that would otherwise go into the propellant
- Interest in using BAC as cooling system for zero boil-off for storage of cryogenic rocket engine propellants
- Now also being considered as a liquefaction method



Model Scope

- Integrated model of MAV sized propellant tank with an integrated reverse Turbo-Brayton cycle cryocooler created in Thermal Desktop
- Predicts liquefaction performance and operation
- Includes Martian daily cycle heat loads and radiator temperatures

- <u>First step</u>: Create a MAV sized spherical propellant tank for liquid oxygen



NOMENCLATURE

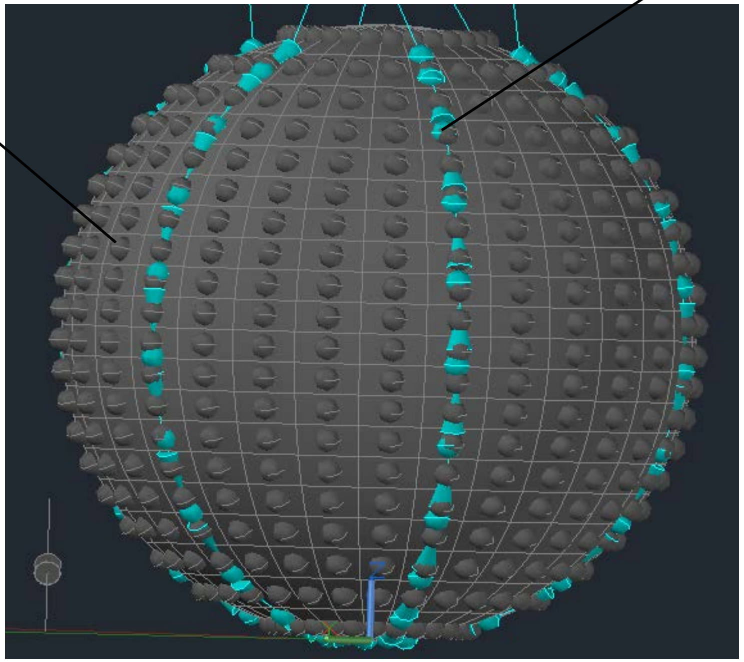
GS: gas surface
GW: gas wall
LS: liquid surface
LW: liquid wall
VLB: boiling
VLC: condensed liquid vapor

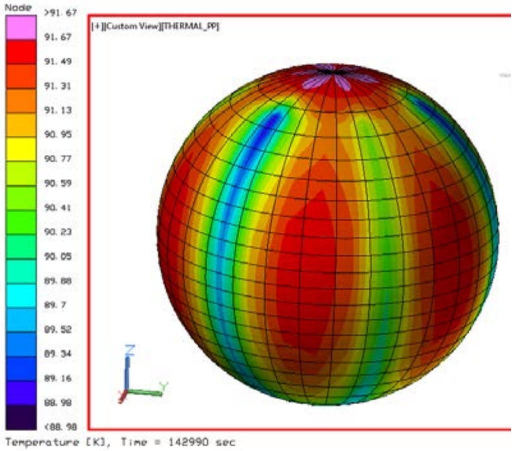
Thermal Desktop Tank Model Details

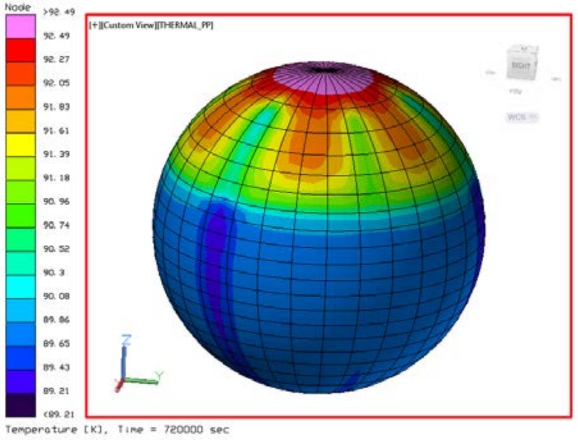
- Tank model is a thin walled spherical aluminum tank with a liquid volume and a gas volume (twinned lump), propellant: liquid oxygen
- Heat transfer between wall and fluid is represented by pool boiling ties ($\dot{Q}_{\mathrm{VLB}}$ and $\dot{Q}_{\mathrm{VLC}}$)
- Heat transfer from environment to tank is represented by a given Martian daily cycle heat load
- <u>No</u> stratification is modeled

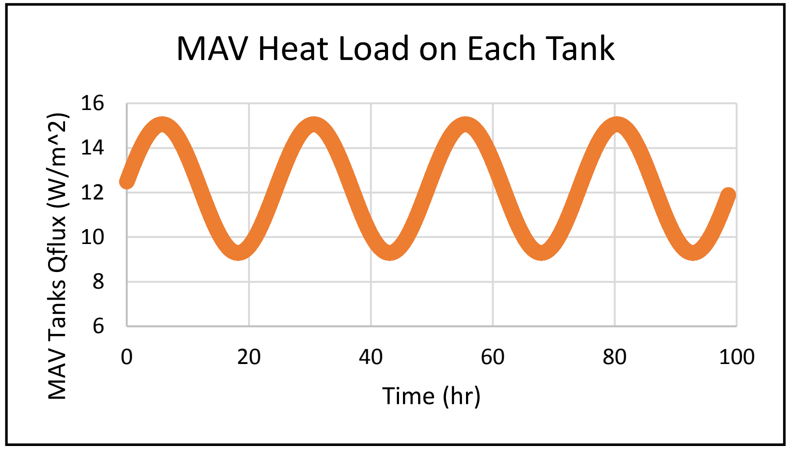
Wall node

Coolant path



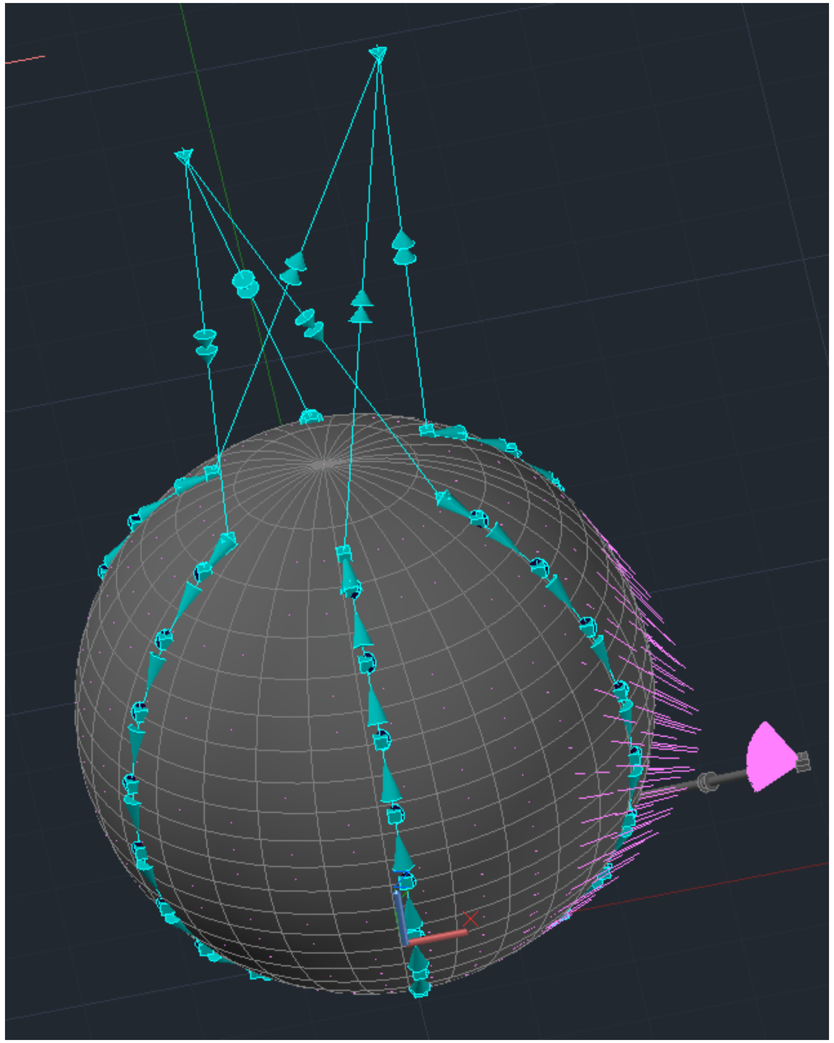






Thermal Desktop Tank Model Details

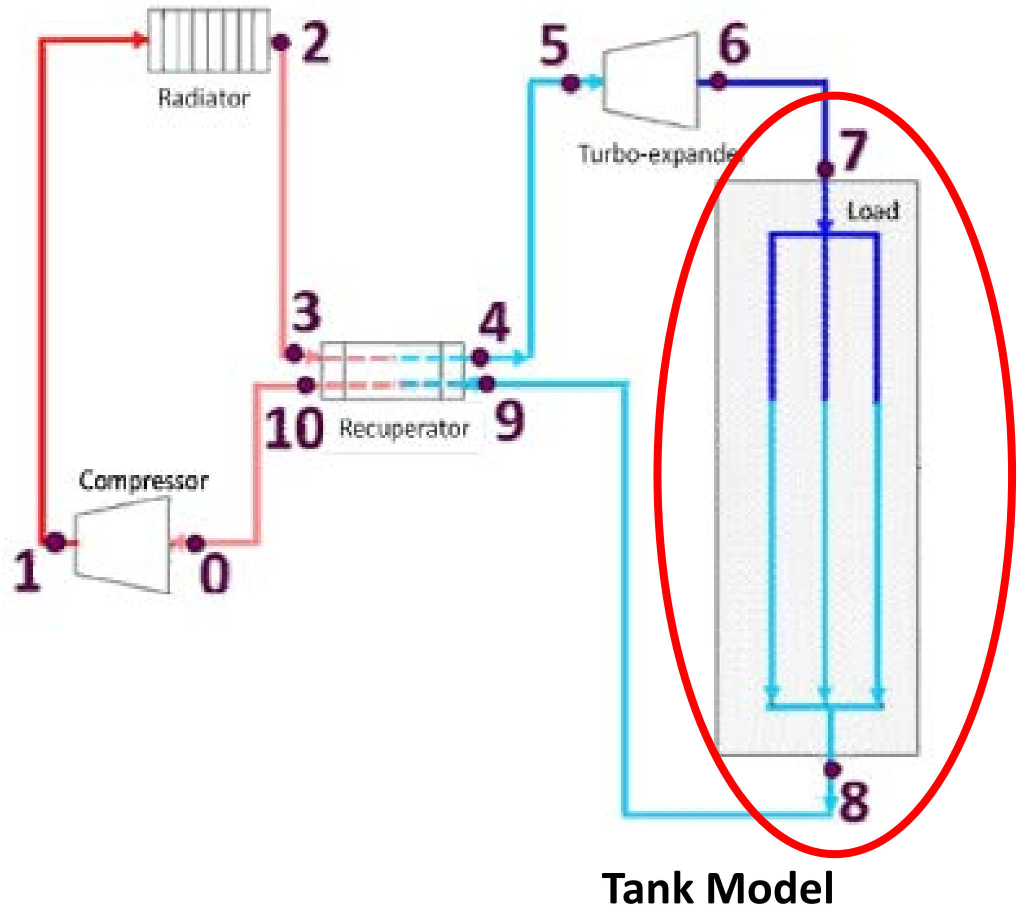
Tank Material	Aluminum 6061-T6				
Tank Outer Diameter	2.65	m	104.33	in	based on MAV tank estimates
Tank Thickness	0.00635	m	0.25	in	
Starting Conditions in Tank					
Liquid oxygen temperature	90	K			
Vapor Temperature	273.15	K			
Pressure	101325	Pa	1	atm	
Void Fraction	0.99				
Initial Tank and Pipe Wall Temperature	90	K			
Flow into Tank					
Mass Flow	2.2	kg/hr			from ISRU estimates
Temperature	273.15	K			
Pressure	101325	Pa	1	atm	
Heat Load	**9 to 15**	W/m^2			modeled as a sine curve
3 pipe loops					
Material	Aluminum 6061-T6				
Outer Diameter	0.009525	m	0.375	in	
Thickness	0.000889	m	0.035	in	
Coolant	Neon				



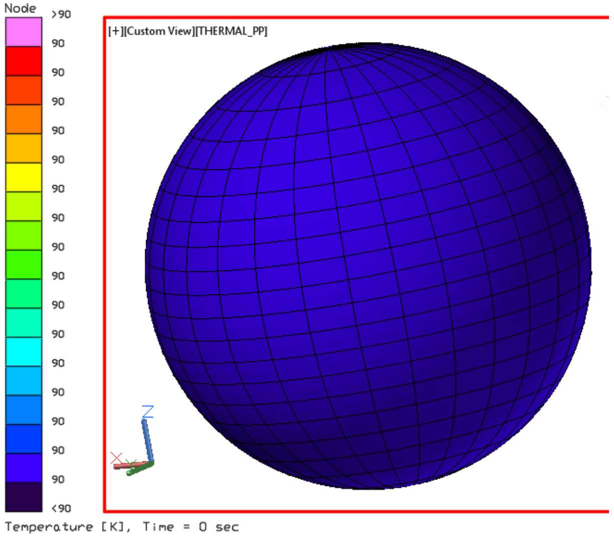
Tank Model integration with Creare Cryocooler Model

- Between 7-8 is the tank model
- Rest of the system is represented by equations for the Creare 90 K and 500 W cryocooler (given by Creare)
- Integrated system modeled in Thermal Desktop

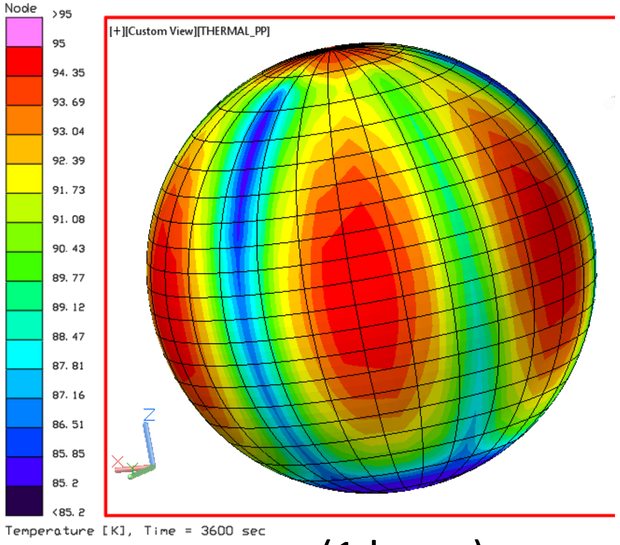
Tank Model	Creare Cryocooler Model
Inputs from Cryocooler	*Inputs from TD Model*
BAC inlet temperature (T7)	BAC outlet temperatre (T8)
Coolant Mass flow Rate (mdot)	Pressure drop from 7 to 8
Outputs	*Outputs*
Tank Wall Temperatures	Net refrigeration
Coolant Temperatures	Coolant Mass Flow
Coolant Pressures	
Liquid Temperature	
Tank Pressure	
Ullage Volume Fraction	
Liquid Mass	



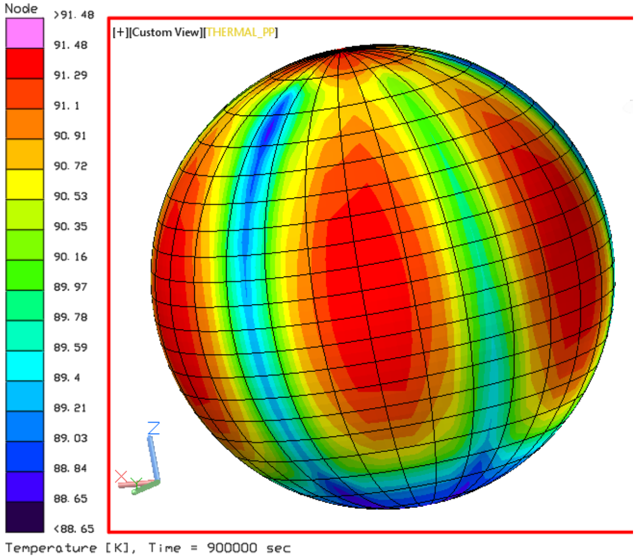
Results - Tank Wall Temperatures (K)



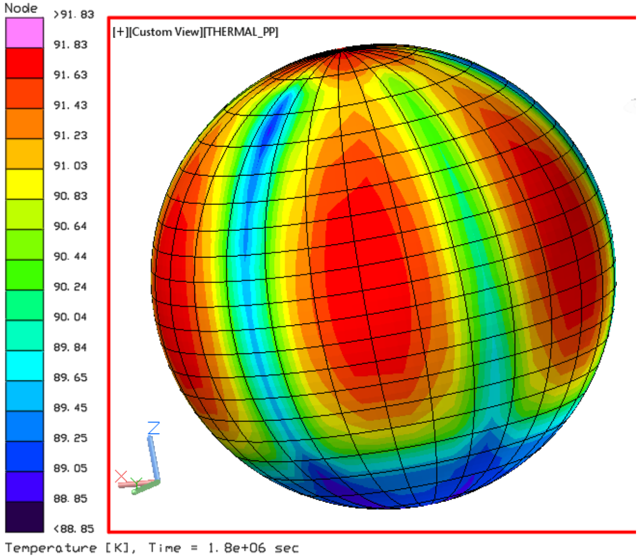
(Initial condition)



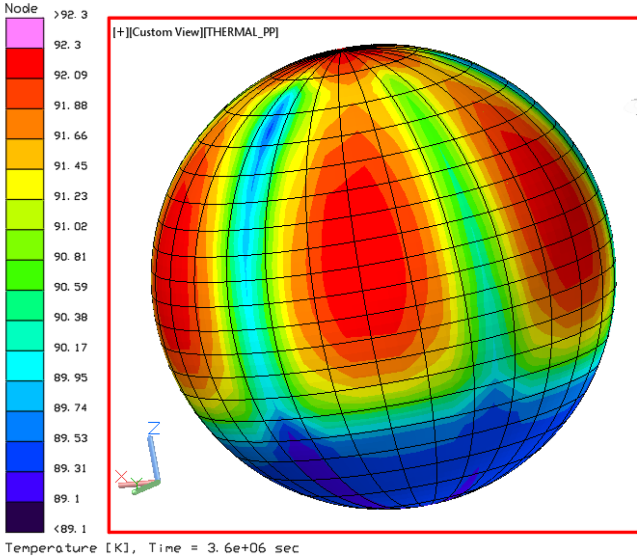
(1 hour)



(250 hours)

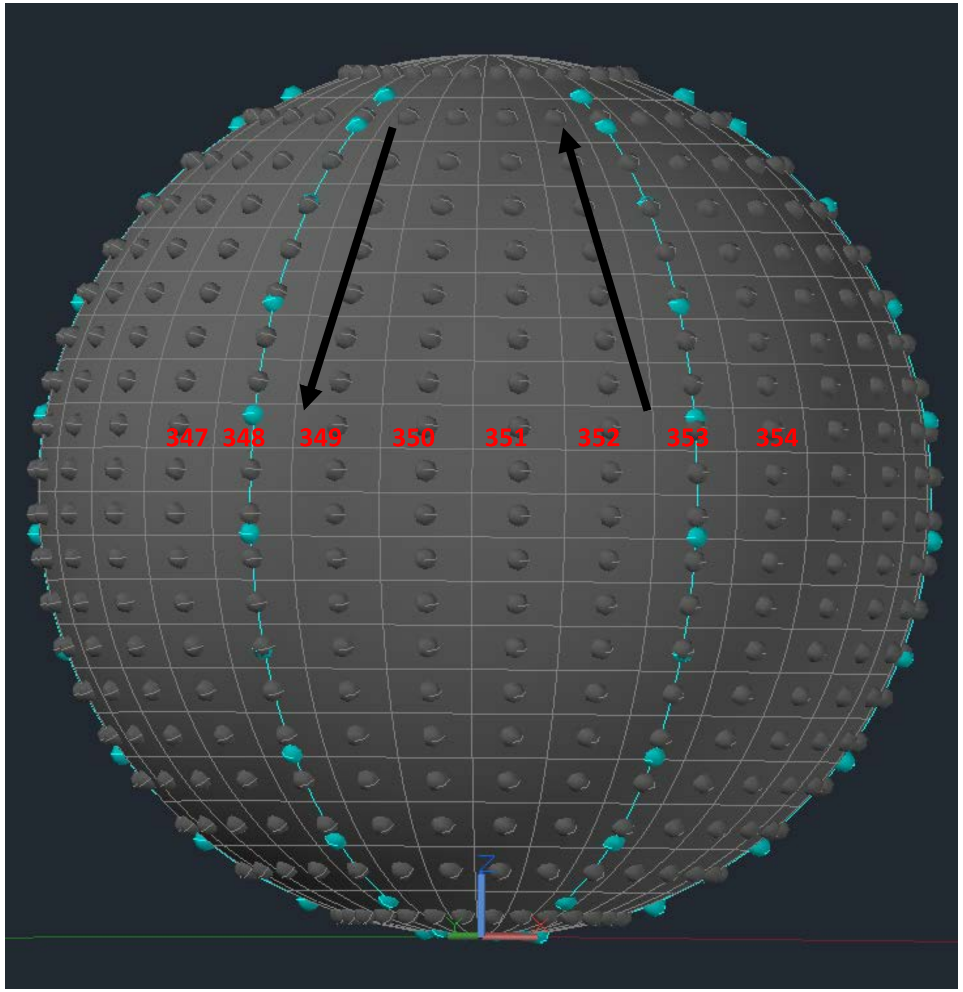


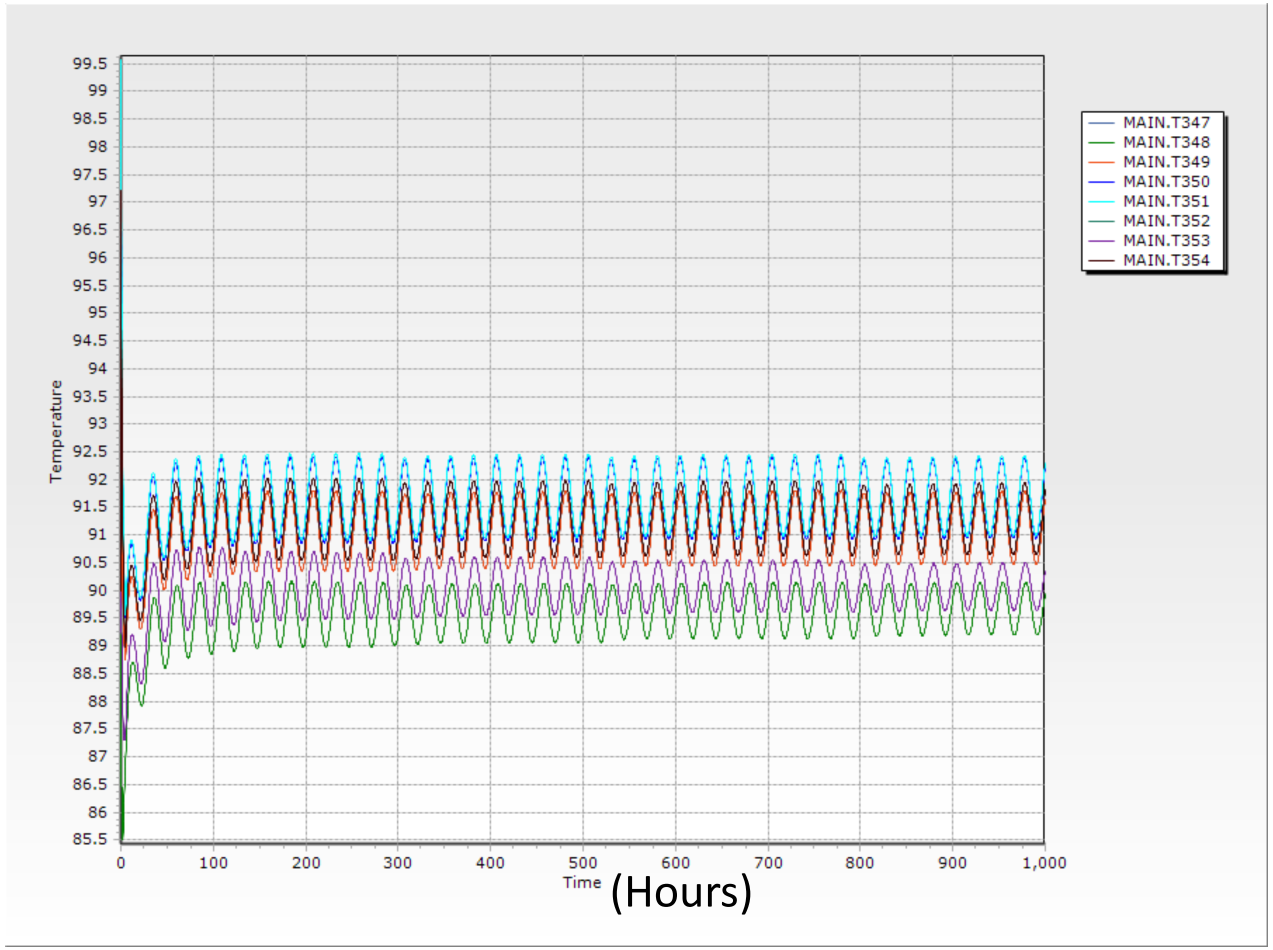
(500 hours)



(1000 hours)

Results - Tank Wall Temperatures (K)





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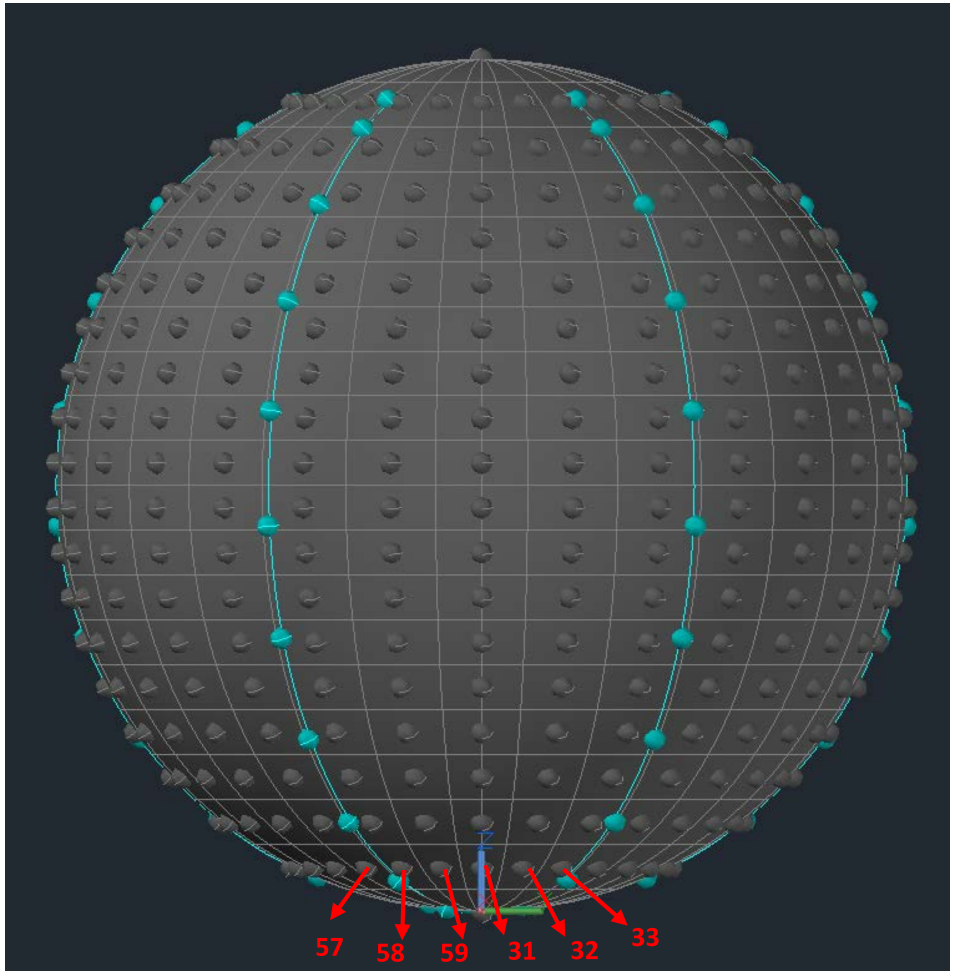

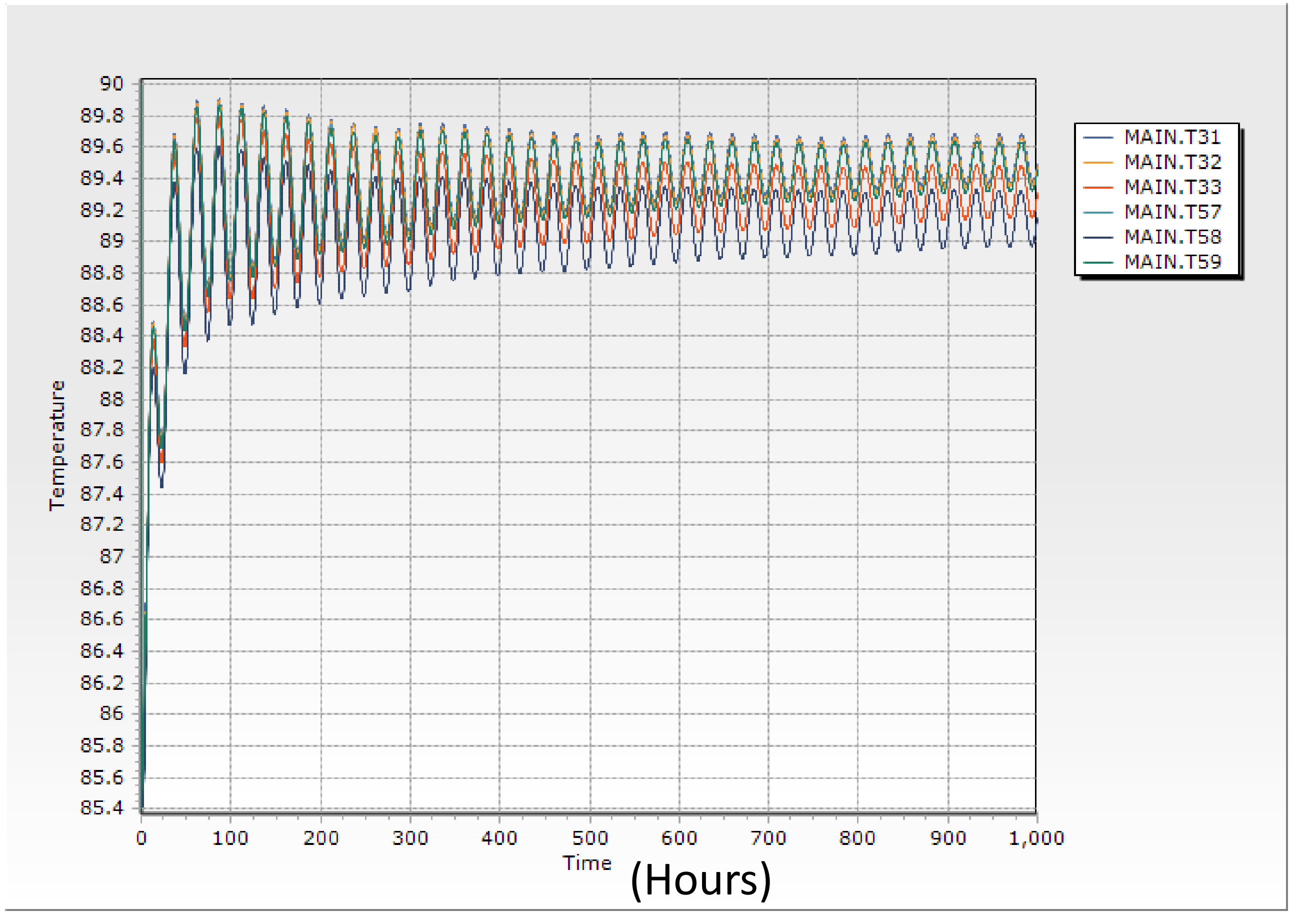

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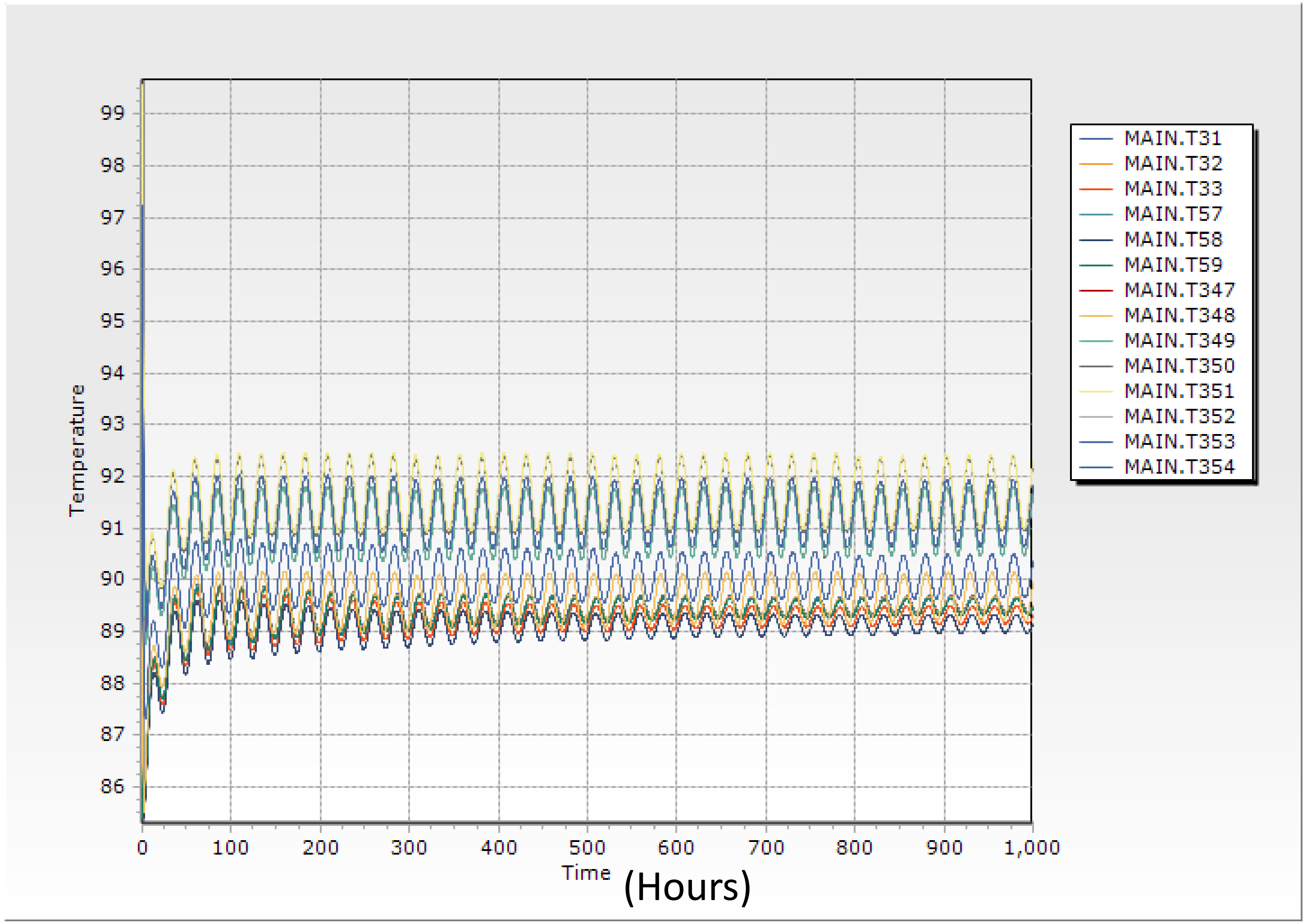
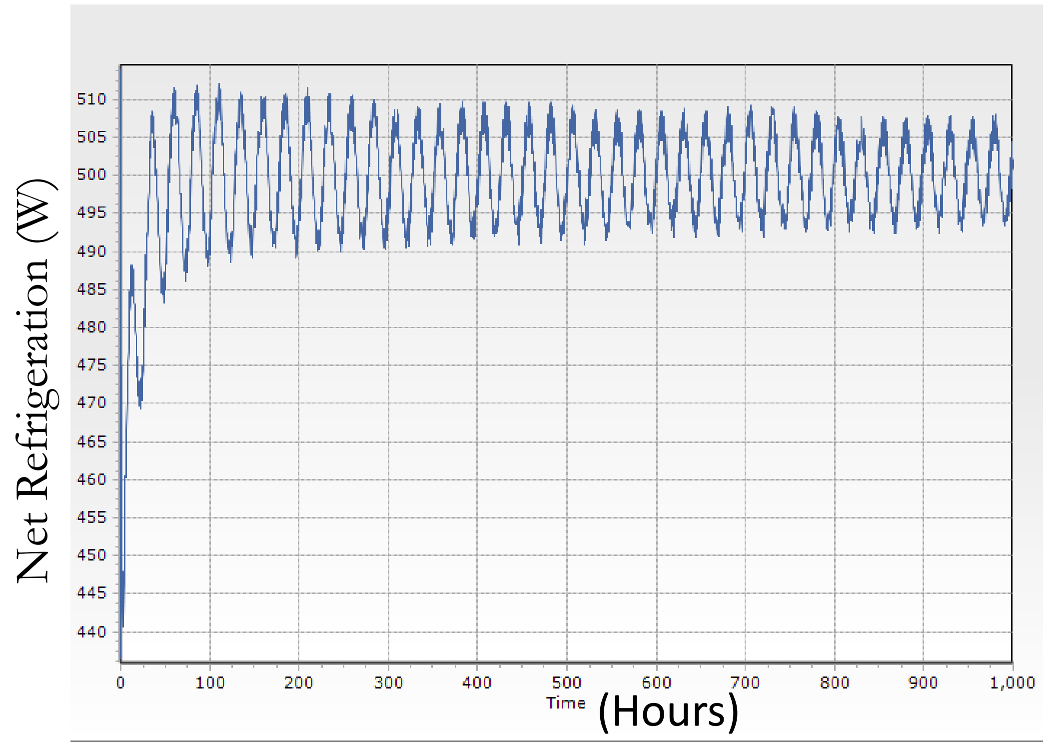
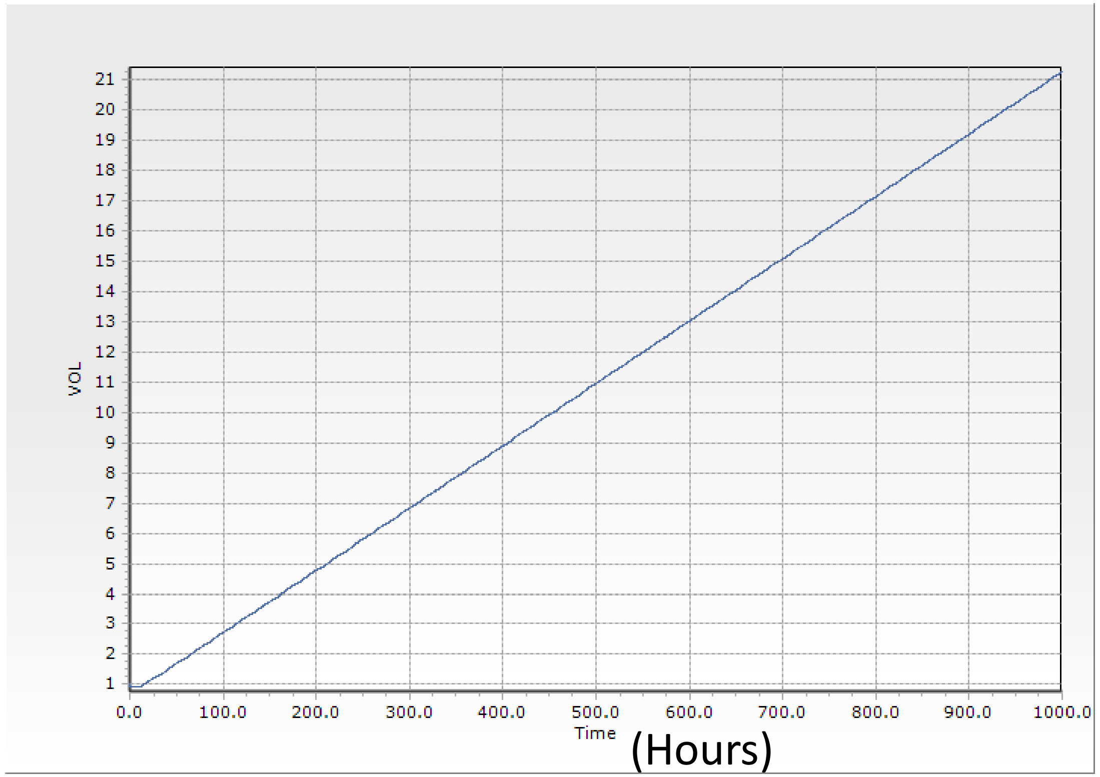


Results – Net Refrigeration (W) and Liquid Volume Fraction (%)

Net Refrigeration (W)

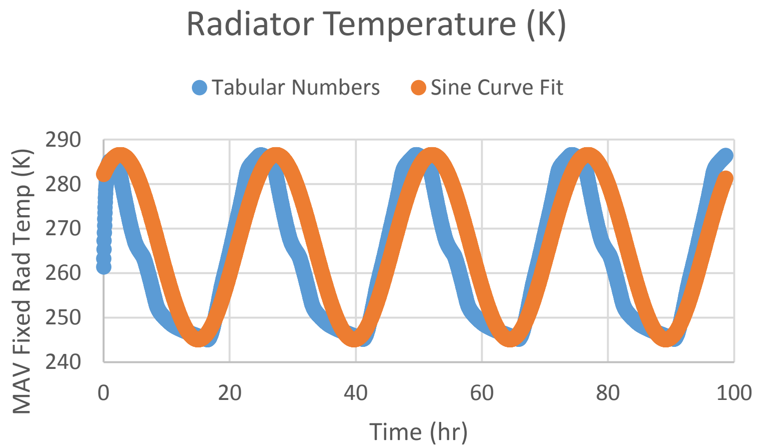


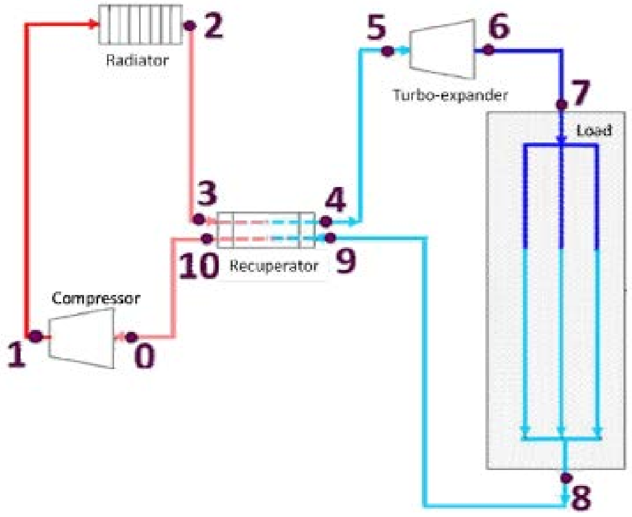
Liquid Volume Fraction (%)



Model Case Runs

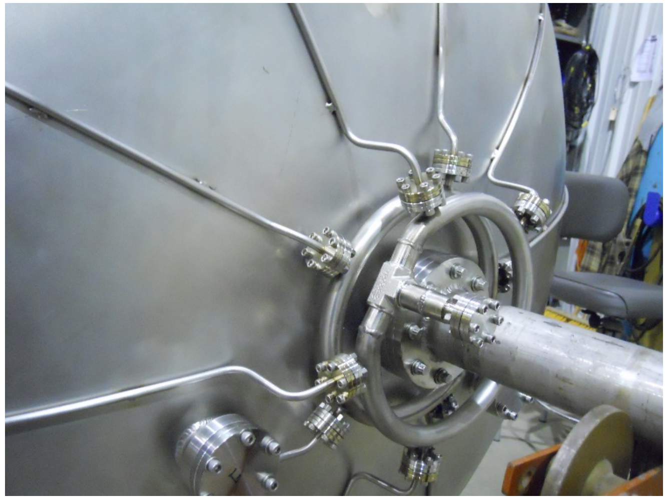
- Radiator temperature is the temperature at point 2 in the diagram (where cryocooler rejects heat)
- Two cases ran: one with a constant radiator temperature of 300 K and one with a sine curve fit from MAV thermal analysis
- Tank starts at an initial ullage volume fraction of 0.99
- Results:
  - Constant Trad – 4750 W
  - Changing Trad – 4000 W
- Mars environmental temperature cycles can potentially reduce cryocooler power and mass by 15-20% with current radiator design



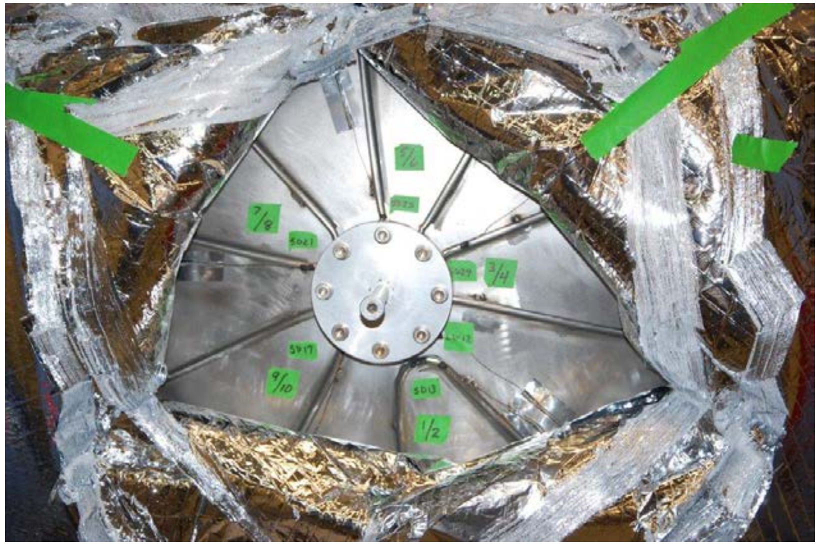


ZBO Model Overview

- Assembly consists of Zero Boiloff (ZBO) test tank, with the tube-on-tank BAC system, covered with insulation
- Propellant: liquid nitrogen
- Coolant: neon
- 10 tests were performed with the ZBO tank
  - Test 1: Passive Boiloff (15 days)
  - Test 2: Passive Pressurization (1 day)
  - Test 3: Active ZBO (6 days)
  - Test 4: Active high power A (1 day)
  - Test 5: Active low power (1 day)
  - Test 6: Active de-stratification (2 days)
  - Test 7: Active high power B (1 day)
  - Test 8: Active low-fill ZBO (7 days)
  - Test 9: Active low fill and high power (1 day)
  - Test 10: Passive boiloff at 300 K (10 days)



Top of ZBO tank



Bottom of ZBO tank

ZBO Test Descriptions

- Test 2: Passive Pressurization
  - Tank fill level at 90%, tank pressure at 82 psi
  - Tank's vent valve was closed, tank self-pressurized
  - Tank pressurization rate – 0.33 psi/hr
  - Tank heat leak - 4.64 W
  - No mixing or cooling occurred
- Test 4: Active Zero Boiloff
  - Cryocooler power increased from 145 W (test 3) to 272 W
  - Initial tank pressure at 82 psi
  - Cryocooler mass flow increased to 2.2 g/s
  - Pressure drop was 0.14 psi/hr (over 16 hours)
- Test 6: Active destratification
  - Cryocooler power on, heaters also powered on to match heat loads in Test 2
  - Compare pressure rise to Test 2
- Test 9: Active Low Fill, High Power
  - Cryocooler power increased to 208 W
  - Tank pressure drop was 0.11 psi/hr (over 23 hours)

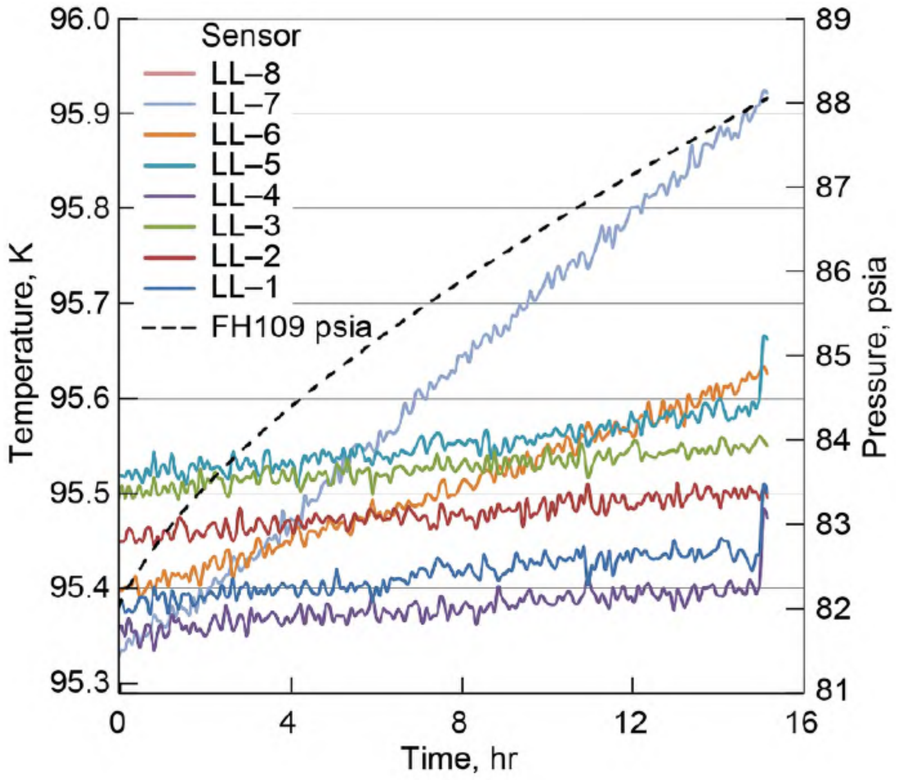
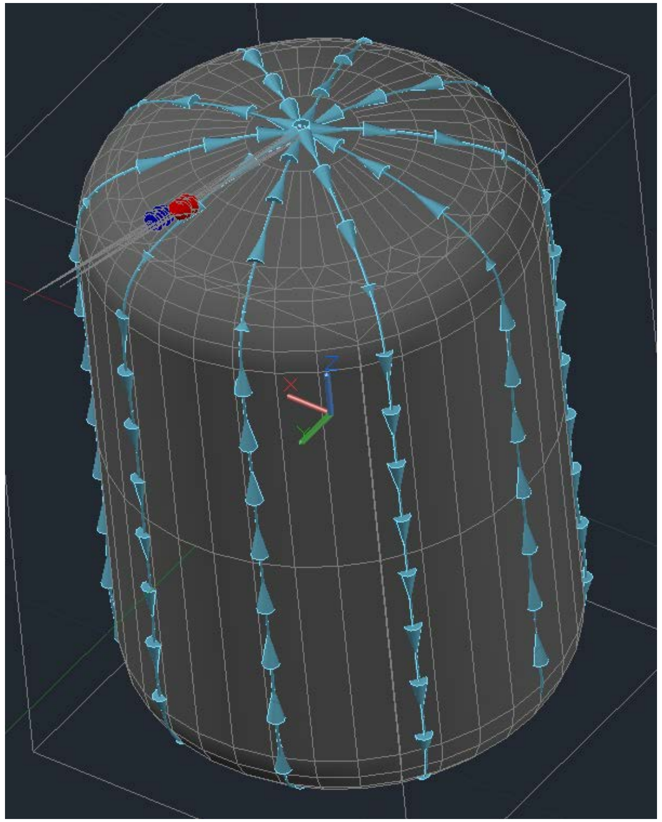
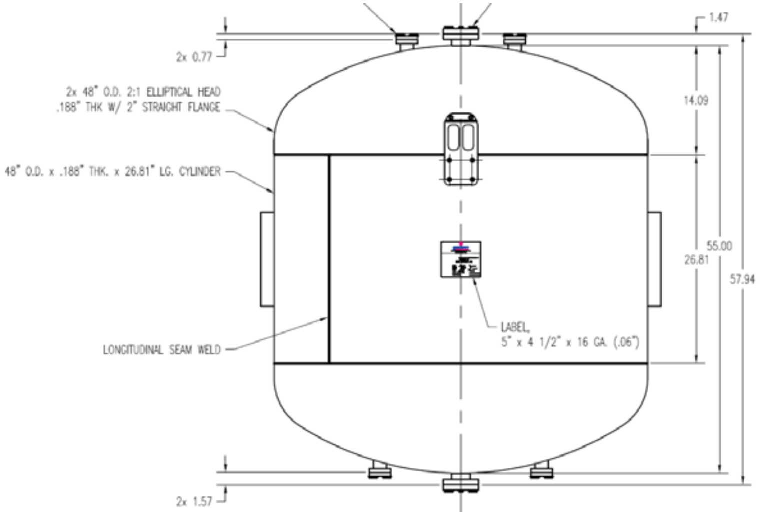


Figure 31.—Test 2 tank pressure and liquid temperatures.

ZBO Modeling Overview

- **Goal:** Compare ZBO thermal desktop model with available data
- Created a model in Thermal Desktop of the liquid nitrogen test tank and BAC cooling loops
  - Tank and pipe walls are modeled with MLI insulation attached
  - No stratification modeled in tank (liquid lump and vapor lump each at one temperature)
  - Strut heat load included as heat loads on 3 tank wall nodes
    - (0.136 W on each wall node)
  - Vent, fill, nipple, strap, and parasitic heat loads applied on tank wall nodes near top of tank





Tank Drawing

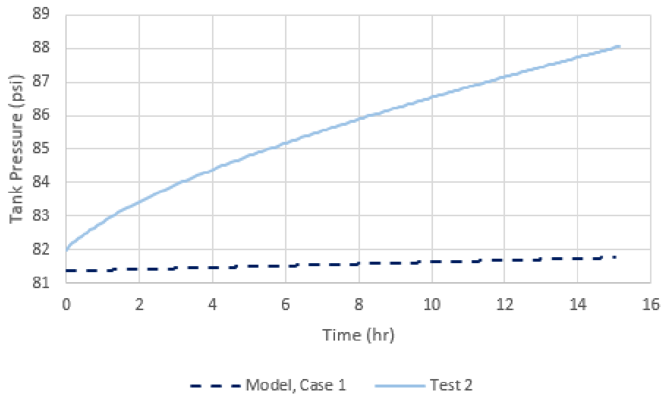
ZBO Model Cases

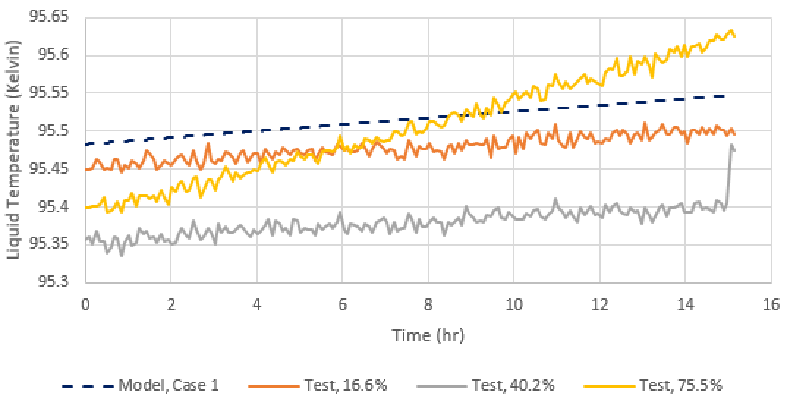
Test Number and Type	**Test Description**	**Test Duration**	**dP/dt (psi/hr)**	**Qfluid (W)**
2 – Passive Pressurization	Tank fill level at 90%, vent valve closed, tank self-pressurized	1 day	0.33	3.80
4 – Active High Power at High Fill	Tank fill level at 90%, cryocooler power on at 272 W	1 day	-0.096	-7.13
6 – Active Destratification	Tank fill level at 90%, cryocooler on to homogenize liquid temperature, heat added to tank to compare with test 2	1 day	0.024	2.75
9 – Active High Power at Low Fill	Tank fill level at 27%, cryocooler power on at 208 W	1 day	-0.11	-2.73

Cases	Test to Compare	Time Duration (hr)	Fill Volume (%)	Initial Tank Vapor Wall Temperature (K)	Initial Tank Liquid Wall Temperature (K)	Initial Tank Liquid Temperature (K)	Initial Tank Vapor Temperature (K)	Initial Tank Pressure (psi)	Coolant Mass Flow (g/s)
1	2	20	95%	105.2	95.3	95.4	98.3	82	0
2	6	20	95%	98.7	95	95.3	96.1	82	0
3	4	20	95%	98.7	95.1	95.4	96.2	82	2.2
4	9	20	27%	98.9	95.3	95.4	96.5	82	1.7

ZBO Model Results – Net Heat Addition Positive

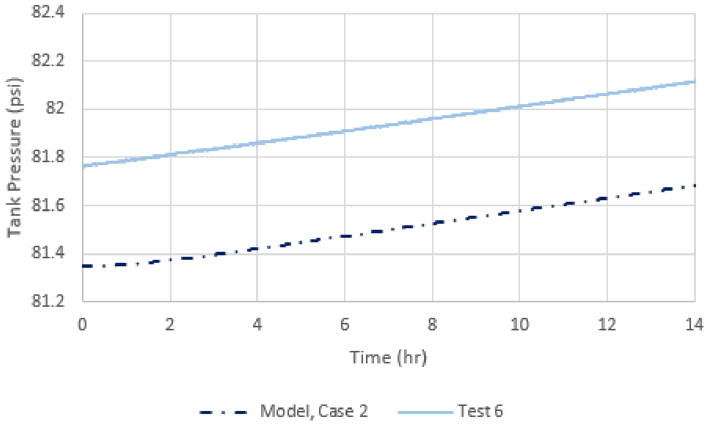
Test 2: Propellant Stratified

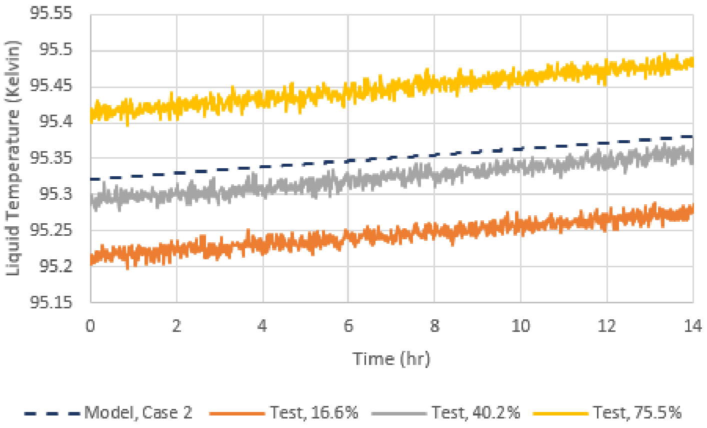




	Model	Data (Test 2)
Pressure rise (psi/hr)	0.026	0.33
Temperature rise (K/hr)	0.0031	0.0043

Test 6: Propellant Behaved De-Stratified

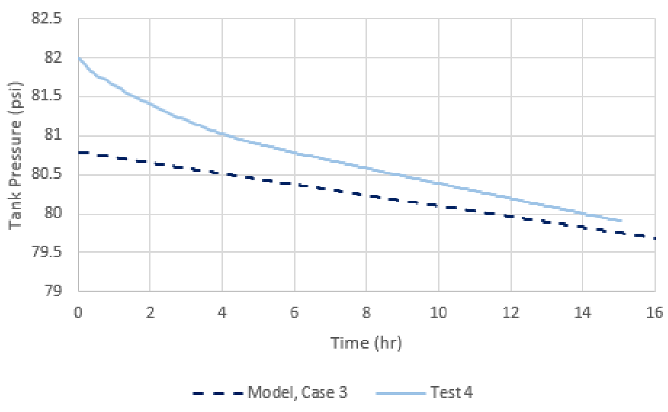


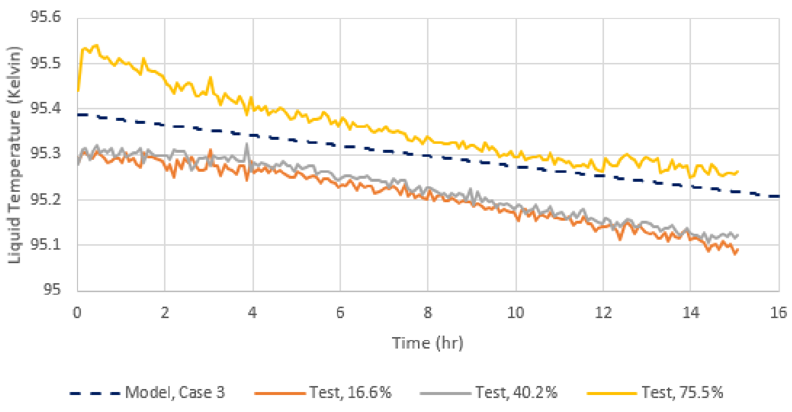


	Model	Data (Test 6)
Pressure rise (psi/hr)	0.0259	0.024
Temperature rise (K/hr)	0.0047	0.0043

ZBO Model Results – Cryocooler on, Net Heat Addition Negative

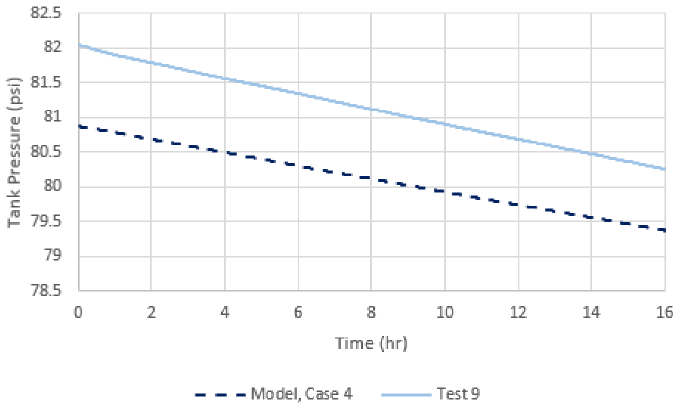
Test 4:
95% Fill Level

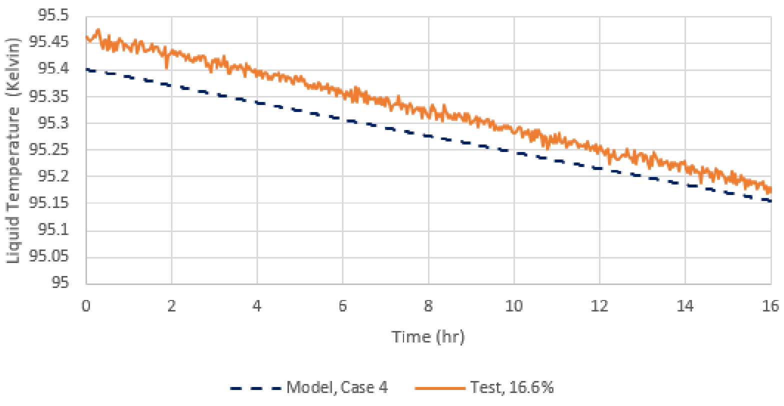




	Model	Data (Test 4)
Pressure rise (psi/hr)	-0.068	-0.096
Temperature rise (K/hr)	-0.014	-0.011

Test 9:
27% Fill Level





	Model	Data (Test 9)
Pressure rise (psi/hr)	-0.093	-0.011
Temperature rise (K/hr)	-0.018	-0.015

Future Work

- Further testing on ZBO test tank
- Validate test matrix by running simulations of planned tests with ZBO model
  - Look at constant versus batch liquefaction
- Look at effects of non-condensable gases on liquefaction performance
- MAV model – also look at constant versus batch liquefaction
  - Cryocooler 12 hours on/12 hours off