

Mars Propellant Liquefaction and Storage Performance Modeling using Thermal Desktop with an Integrated Cryocooler Model

Pooja Desai¹, Dan Hauser², Steven Sutherlin³

¹Johnson Space Center, Houston, TX, 77058, USA

²Glenn Research Center, Cleveland, OH, 44135, USA

³Marshall Spaceflight Center, Huntsville, AL 35812, USA

1.0 Executive Summary

Current NASA Mars human mission architectures point to using In-Situ Resource Utilization (ISRU) on the surface of Mars to decrease required mass to land, reduce launch requirements, and simplify the Entry Descent Landing design. An ISRU plant can significantly reduce the landed mass by 60 metric tons or 60% of the lander mass [1]. The gaseous oxygen (and possibly methane) that the ISRU plant produces must be liquefied and stored as propellants for the Mars Ascent Vehicle (MAV). Based on current architectural assumptions, the production and storage of 23 tons of liquid oxygen needs to occur over a duration of 500+ days [1]. To accomplish this, an energy efficient refrigeration and storage system will be required.

There are several liquefaction methods in practice: conduction, broad area cooling, in-tank heat exchanger, Linde Cycle, and in-line liquefaction. A trade study conducted by NASA looked at these various liquefaction methods and compared them by different parameters, primarily mass and power input along with operational flexibility and reliability. The broad area cooling method, also known as tube on tank, performed well in this trade study and was the method chosen for this modeling effort [2].

In broad area cooling, typically a working fluid such as helium or neon is circulated by a reverse Turbo-Brayton cycle cryocooler through a tubing network welded over the surface of a cryogenic tank. The working fluid, in theory, would intercept the heat that would have otherwise gone into the propellant. The reverse Turbo-Brayton cycle cryocooler is unique because it has the ability to cool and circulate the working fluid efficiently in the same loop as the broad area cooling tubing network, allowing for one cooling gas loop, with the primary heat rejection occurring with a radiator and aftercooler. This eliminates the need for a second fluid and a second heat exchanger. It may be cheaper to develop a Stirling cycle cryocooler with an integrated pumped loop heat exchanger, however, this current effort focuses on the operation of the reverse Turbo-Brayton cycle.

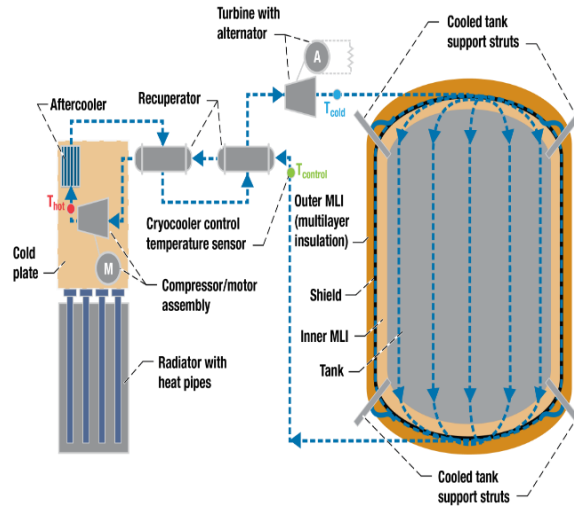


Figure 1. -Broad Area Cooling Architecture [3]

A Thermal Desktop model was created of a MAV sized propellant tank with an integrated reverse Turbo-Brayton cycle cryocooler to predict liquefaction performance and operation. Creare supplied the integrated reverse Turbo Brayton cryocooler model and this model was incorporated into the Thermal Desktop model with user defined functions. The model also included Martian daily cycle heat loads and radiator temperatures from a 2016 MAV study. With the model, it was found that Mars environmental temperature cycles can potentially reduce cryocooler power and mass by 15-20% with the current cryocooler and radiator designs.

2.0 Background

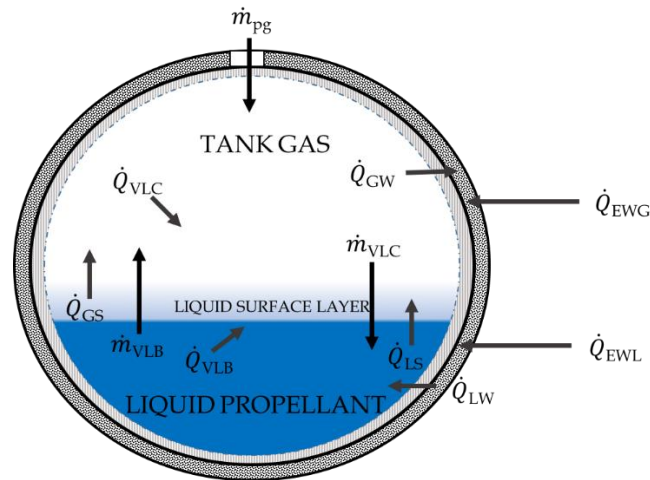
For the past several years, there has been significant interest in using broad area cooling as an active cooling system to achieve zero-boiloff for storage of cryogenic rocket engine propellants for long duration space missions. Parasitic heat loads increase the propellant temperature, causing it to vaporize, also known as boil-off. Because the liquid propellant is continually vaporizing, tank pressure can increase past an unacceptable level. The tank must be vented to keep pressure within design limits and this leads to loss of propellant. This is why boil-off is a key issue in long duration missions because the loss of usable propellant requires additional propellant to be carried on board and increases overall mission mass and cost requirements.

Now, broad area cooling is also being considered as a liquefaction method to liquefy gaseous oxygen and methane into cryogenic propellants. The broad area cooling acts as a heat exchanger to cool and condense the warm propellant entering the tank from the production plant. An analytical approach has been taken to verify that the tank itself provides sufficient heat transfer area for liquefaction at the required rates as well as the convection heat transfer within the tank.

3.0 Modeling Approach

The integrated model of the MAV sized propellant tank and a reverse Turbo-Brayton cycle cryocooler was created in Thermal Desktop, an industry software used to build CAD-based thermal models. FloCAD, a Thermal Desktop software module, adds the ability to build fluid flow models, such as piping systems and tanks, and model convective heat transfer.

First, a MAV sized spherical propellant tank for liquid oxygen was modeled in Thermal Desktop. The model is a thin walled spherical aluminum tank with an initial liquid oxygen volume, an initial gaseous oxygen volume, and gaseous oxygen flowing into the tank at approximately 2.2 kilograms per hour. Modeling the dynamics inside a cryogenic tank is a complex problem because of the different heat and mass transfers taking place, as shown in Figure 2 [4].



NOMENCLATURE

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

Figure 2. -Cryogenic Tank Heat/Mass Transfer Schematic

There is heat transfer between:

- the environment and the tank wall touching gas (\dot{Q}_{EWG})
- the environment and the tank wall touching liquid (\dot{Q}_{EWL})
- the gas and the tank wall touching the gas (\dot{Q}_{GW})
- the liquid and the tank wall touching the liquid (\dot{Q}_{LW})
- the gas and the liquid surface layer (\dot{Q}_{GS})
- the liquid and the liquid surface layer (\dot{Q}_{LS})

With the broad area cooling network, there is also heat transfer between:

- the tank wall and the tubing carrying the coolant
- the coolant and the tubing wall

There is mass transfer:

- between the gas and the liquid
- gaseous oxygen entering the tank (from ISRU plant)

The spherical tank in Thermal Desktop has multiple wall nodes along the length and the circumference of the tank. For simplicity, no stratification is modeled inside the tank; one temperature defines the entire liquid volume and another temperature defines the entire vapor volume.

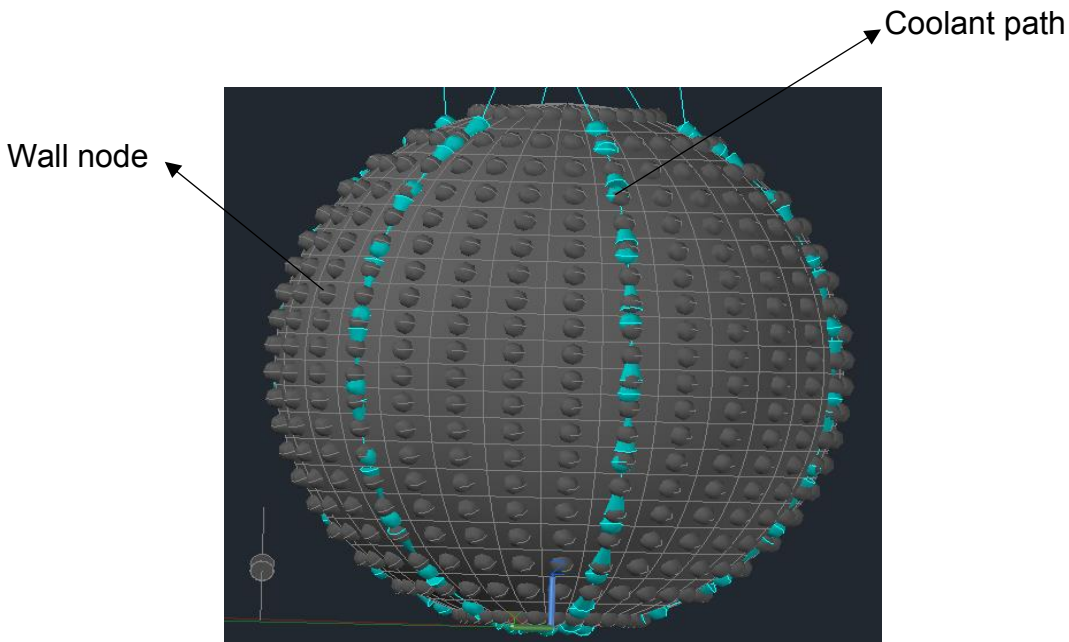


Figure 3. -Tank Nodes in Thermal Desktop

Heat transfer between the Martian environment and the tank wall is modeled by a fluctuating heat load applied to the tank wall nodes. Predicted heat flux values for the MAV cryogenic propellant tanks and temperatures for the MAV radiators were obtained from the 2016 Baseline HAT EMC system-level thermal model for the MAV and MDM in the Mars surface environment using Thermal Desktop. These data are shown in Figure 4 and Figure 6, respectively. Heating rates into the tanks included 25% margin. Radiator panel temperatures represent the average performance of ten separate panels with constant loads and constant working fluid flowrate. Panel were oriented to face the horizon. Use of these predicted temperatures as boundary conditions provides only a rough approximation of panel rejection temperatures, since panel temperature and cryocooler heat rejection rate will be inter-dependent. Turndown of cryocooler power with the colder Mars nightside environment implies a dedicated radiator system for cryocooler heat rejection, separate from that for other types of loads, such as avionics, crew systems, etc.

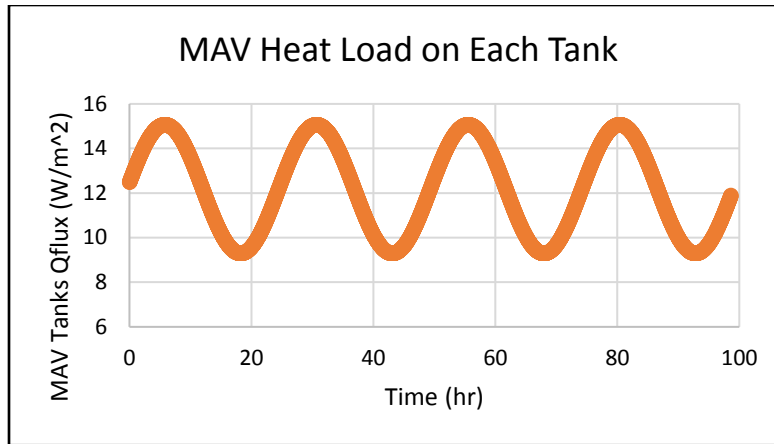


Figure 4. -Heat Load on Tank

Heat transfer between the wall and the fluid inside is modeled with pool boiling ties; these ties do pool boiling calculations and cover condensation and single-phase regimes. The broad area cooling tubing network was added onto the tank with pipe flow components. The coolant gas used in the model was neon. Figure 3 shows a coolant path.

Once the tank model was built, the next step was to integrate Creare's EXCEL model of the 90 Kelvin, 500 Watt cryocooler [5]. Figure 5 shows a schematic of the different components in the Creare cryocooler system; the tubing network on the tank is represented as the load between points 7 and 8. The compressor circulates the coolant gas by increasing its pressure and adds a large amount of heat to the system, which is removed by the radiator. The coolant gas then goes through a recuperator and transfers heat to the gas exiting the broad area cooling shield on the tank. It then enters the turbo-expander which cools the gas even further. After it exits the turbo-expander, the coolant gas flows through broad area cooling network on the tank where it absorbs the heat load from the environment.

The Creare cryocooler model was incorporated into the Thermal Desktop model as user defined functions. The cryocooler model outputs the supply temperature at point 7 and the working fluid (neon) mass flow rate to the tank model. The tank model outputs the return temperature at point 8 and the pressure drop from 7 to 8 to the cryocooler model.

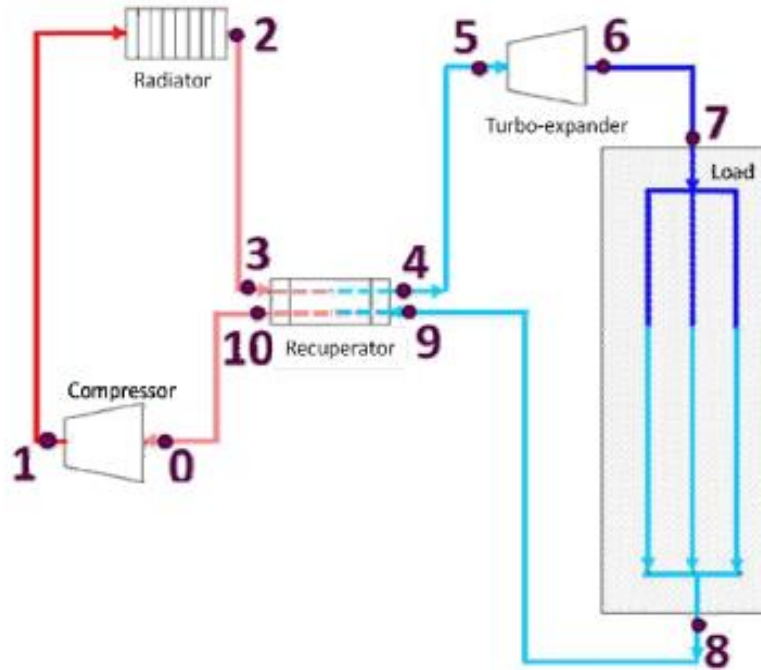


Figure 5. -Single Stage Reverse Turbo-Brayton Cycle Cryocooler System [6]

4.0 Modeling Results

Two different cases were run with the Thermal Desktop model: one with a constant radiator temperature of 300 Kelvin and one with the variable radiator temperature from the MAV thermal analysis approximated with a sine curve, shown in Figure 6. Each case was ran for around 42 days of liquefaction. The tank started at an initial ullage fraction of 0.99 and with oxygen gas coming in at 2.2 kg/hr.

To achieve an average net refrigeration of 500 W, the DC power input to the cryocooler was 4750 W at a constant radiator temperature and 4000 W at a sine-varying radiator temperature. This is a power reduction of approximately 16% due to Mars environmental temperature cycles. Figure 7 shows the net refrigeration achieved in both cases. In the case with the varying radiator temperature, the net refrigeration oscillates at a higher amplitude.

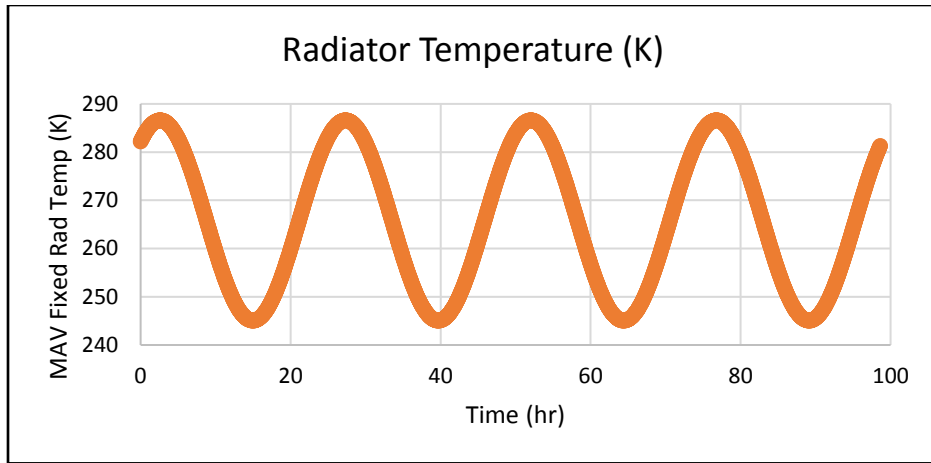
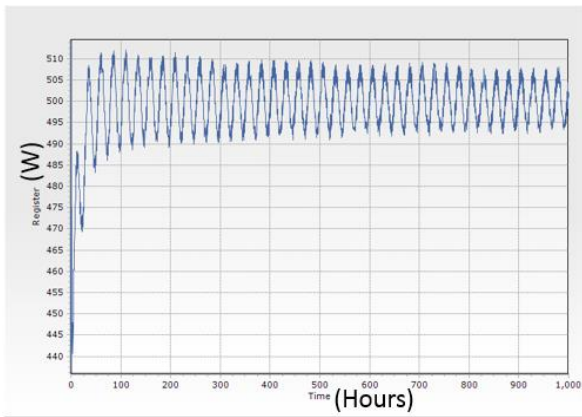
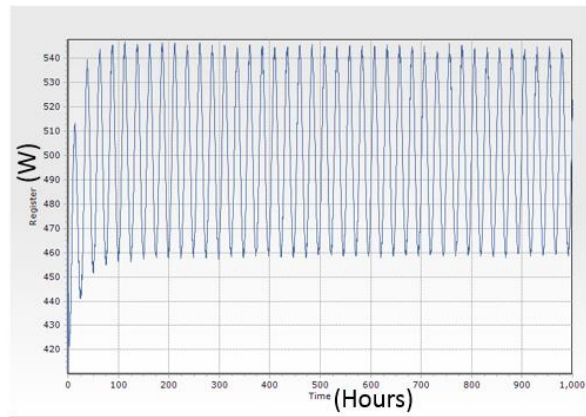


Figure 6. -Varying Radiator Temperature



a) Constant Radiator Temperature



b) Varying Radiator Temperature

Figure 7. -Net Refrigeration (W) for both cases

Figures 8-10 shows how the tank wall temperatures vary across time for the variable radiator temperature case. As the tank fills up with liquid oxygen, the temperature gradient across the tank wall decreases. Figure 9 and 10 show the tank wall temperatures for several nodes not submerged in liquid and several nodes submerged in liquid. As expected, the tank wall nodes not submerged in liquid fluctuate in temperature more than the tank wall nodes submerged in liquid.

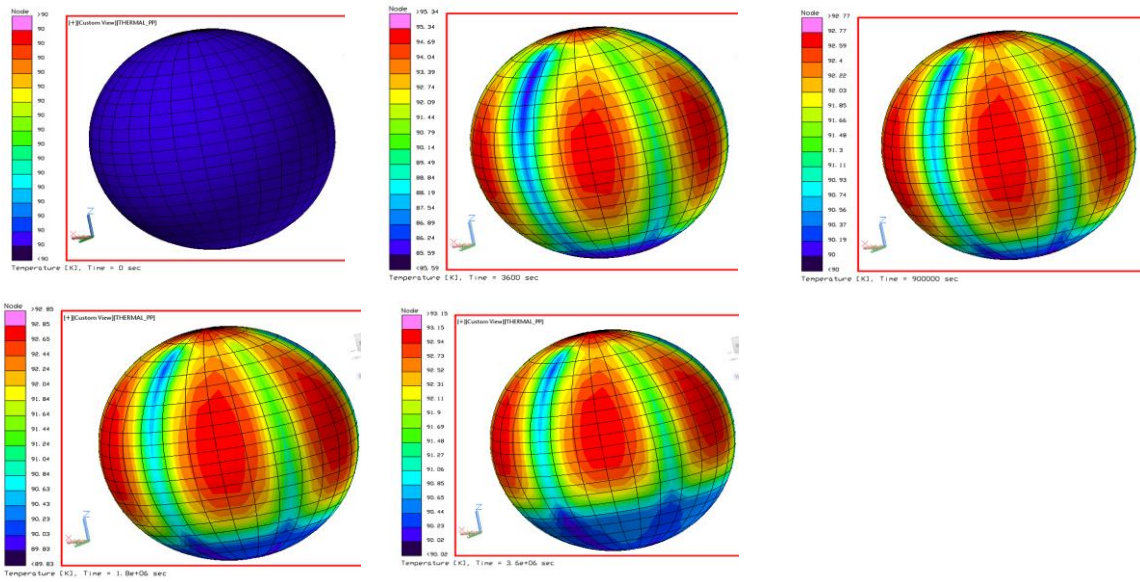


Figure 8. -Tank Wall Temperatures for Varying Radiator Temperature Case

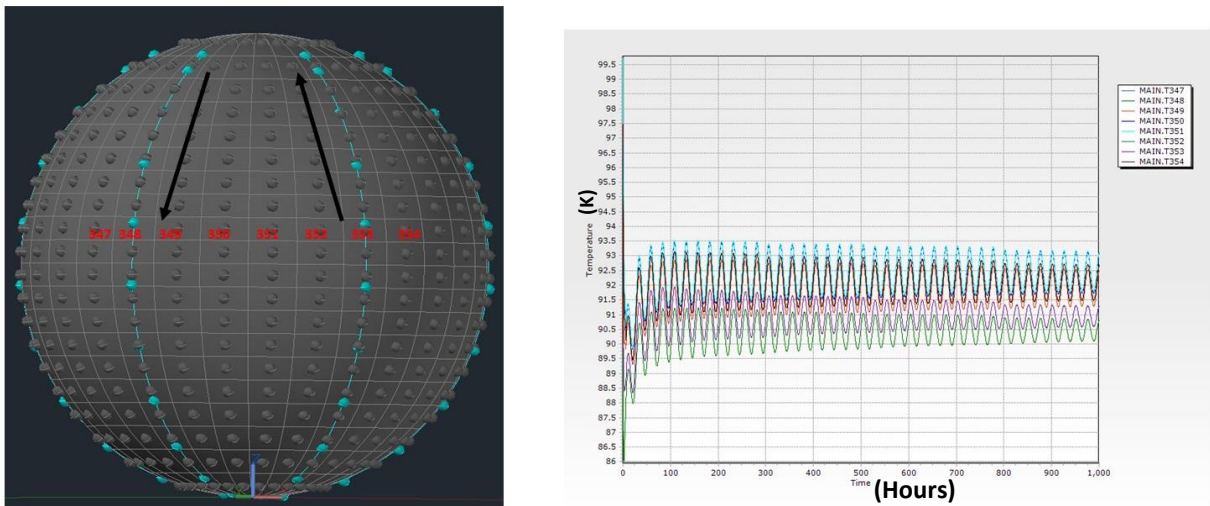


Figure 9. -Tank Wall Temperatures for non-submerged tank nodes

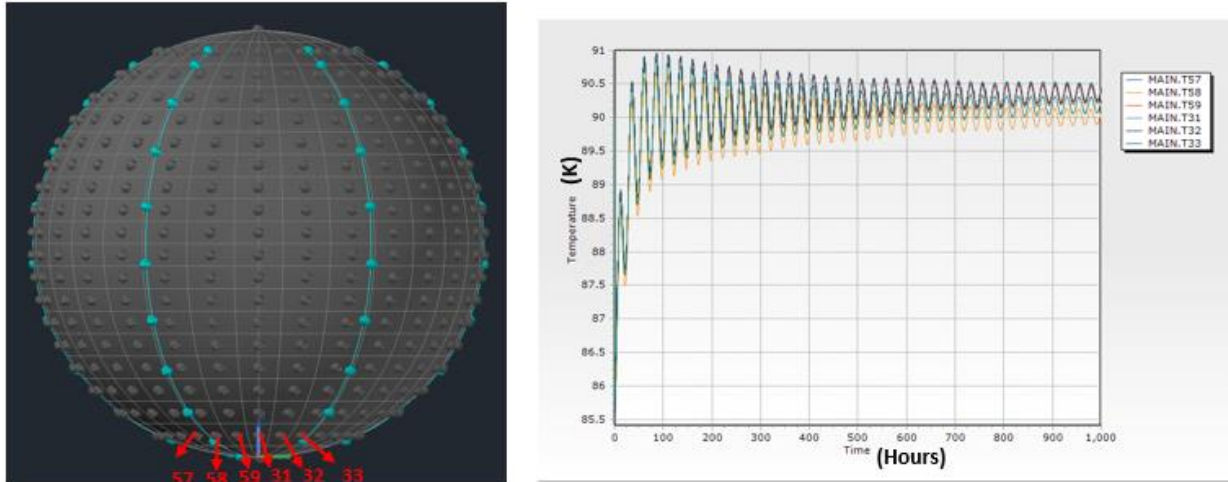


Figure 10. -Tank Wall Temperatures for submerged tank nodes

Figure 11 compares the liquefaction rate and tank pressure between a case that began with a 90% liquid fill level and a case that began with a 1% liquid fill level. Both cases were run with the variable radiator temperature profile. At the lower fill levels, the liquefaction rate oscillates around a steady value of 2.2 kg/hr, the flow rate of oxygen coming into the tank. When the tank starts at 90% fill level, the liquefaction rate also oscillates around a value of 2.2 kg/hr. But the rate decreases sharply when the tank is at 99.2% and the tank pressure spikes up. At the higher fill levels, there is less tank and liquid interface surface area for condensation to occur which causes this sharp drop off. With a change in tank shape to the cylindrical tank with elliptical domes, the fill level at which this drop off occurs will change.

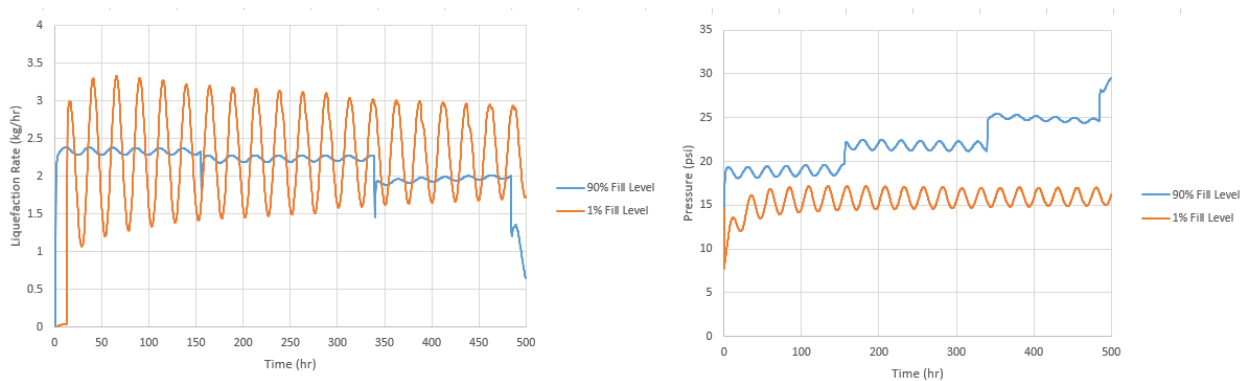


Figure 11. -Liquefaction Rates and Tank Pressures

5.0 ZBO Model Validation

One key aspect in modeling is anchoring the modeling approach to test data. While no test data exists for liquefaction in a MAV-sized tank with broad area cooling, test data does exist for a liquid nitrogen zero-boiloff (ZBO) testing campaign that was run in a thermal vacuum chamber at Glenn Research Center in 2013 [7]. The main objective of the test was to demonstrate a flight

representative ZBO system. The system consisted of a ZBO test tank with a broad area cooling network covered with insulation. A series of 10 tests were run to show the system controlled tank pressure and eliminated tank boiloff. The test article was heavily instrumented to measure various pressures, temperatures, and flow rates including tank pressure and tank liquid and wall temperatures. The tank had an internal silicon diode rake that was used to measure temperature at eight different points between the 1.5 and 96.9 percent liquid level.

A model of the liquid nitrogen test tank and the broad area cooling loops was built in Thermal Desktop using a similar modeling approach as discussed in section 3.0 to compare with pressurization and temperature data. The tank and the tubing loops were modeled with MLI insulation attached. Conductive heat loads from the struts holding the tank and the vent and fill lines (calculated from testing data) were applied to various tank wall nodes. Additional heat loads were added to tank nodes from other sources such as the cryocooler parasitic to match the heat loads seen on the fluid during testing.

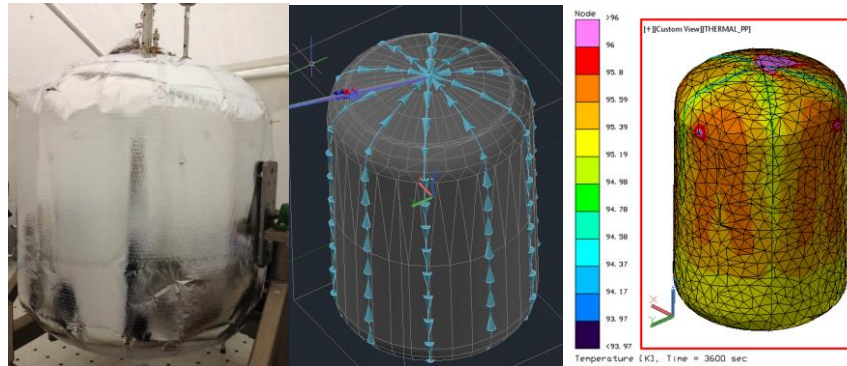


Figure 12. –ZBO test tank, ZBO model, and model result

Four of the 10 tests run were chosen to compare against the model. Table 1 describes these tests and Table 2 shows the four cases that were run with the Thermal Desktop model to compare against these four tests. Test 2 and 6 were chosen to compare how the model performs with the BAC off. Tests 4 and 9 were chosen to compare how the model performs with the BAC loop turned on where the net heat addition is negative.

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

Table 1. –Test Matrix [7]

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

Table 2. – Case Matrix

Tests 2 and 6 were chosen to demonstrate how the model compares against a stratified liquid and a non-stratified liquid. In Test 2, the propellant was stratified and the pressure rate was approximately 0.33 psi/hr. Test 6 was run with the broad area cooling system on to de-stratify the liquid nitrogen and the pressure rate was 0.024 psi/hr.

In Case 1, there is no coolant running through the broad area cooling loop tubing in the model. Figure 13 compares the pressure and liquid temperature rise rates between Test 2 and the model. The liquid temperature shown here from the data is at 16.6, 40.2, and 75.5 percent liquid level.

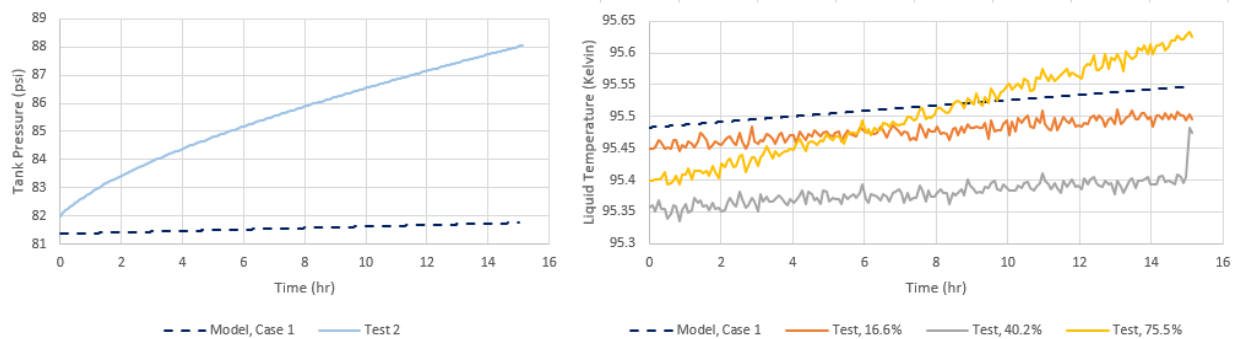


Figure 13. –Test 2 and Model Comparison

As explained in section 3.0, the model currently assumes one temperature for the entire liquid volume in the tank and one temperature for the entire vapor volume in the tank. Because it does not model stratification, the current model does not do a good job in predicting pressurization rate and liquid temperature rise rate at higher liquid levels in a stratified environment. The model predicted a pressurization rate of 0.026 psi/hr while the test pressurization rate was 0.33 psi/hr. This estimate is about an order of magnitude off. However, the model does do well in predicting the pressurization rate in a de-stratified environment.

Case 2 is similar to Case 1 but uses the initial conditions from Test 6. Test 6 was run to match the heat loads seen in Test 2. Figure 14 compares the pressure and liquid temperature rise rates between Test 6 and the model.

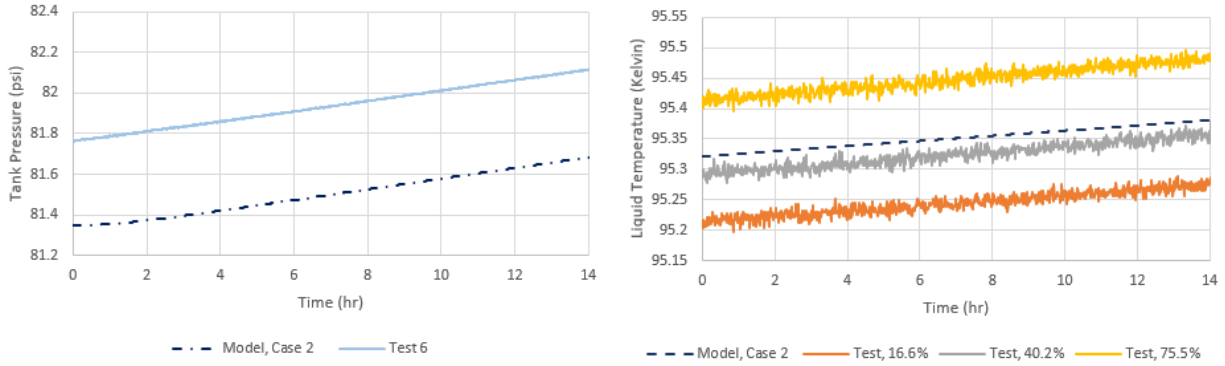


Figure 14. –Test 6 and Model Comparison

While the model does not converge onto the exact initial conditions of the test, it can approximate the pressurization rate and liquid temperature rise rate well. The model predicted a pressurization rate of 0.0259 psi/hr while the test pressurization rate was 0.024 psi/hr.

For cases 3 and 4, neon gas was run through the broad area cooling loops in the model at tank liquid levels of 95% and 27%, respectively. For both these cases the net heat addition in the tank was negative as the cryocooler was turned on and coolant flowed through the BAC loops. As a result of the negative heat addition the pressure in the tank decreases.

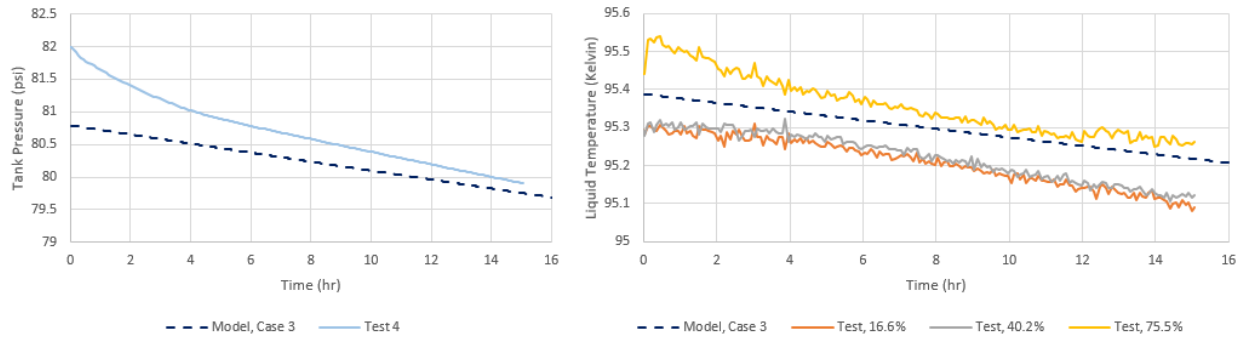


Figure 15. –Test 4 and Model Comparison

In Test 4, the pressurization rate was -0.096 psi/hr while the model predicted a pressurization rate of -0.068 psi/hr. The model also shows the mass in the liquid lump is condensing at 0.002 kg/hr.

The model did a better job at predicting the pressurization rate for Test 9 when the tank liquid level was at a lower level of 27%. The pressurization rate was -0.11 psi/hr while the model predicted -0.093 psi/hr.

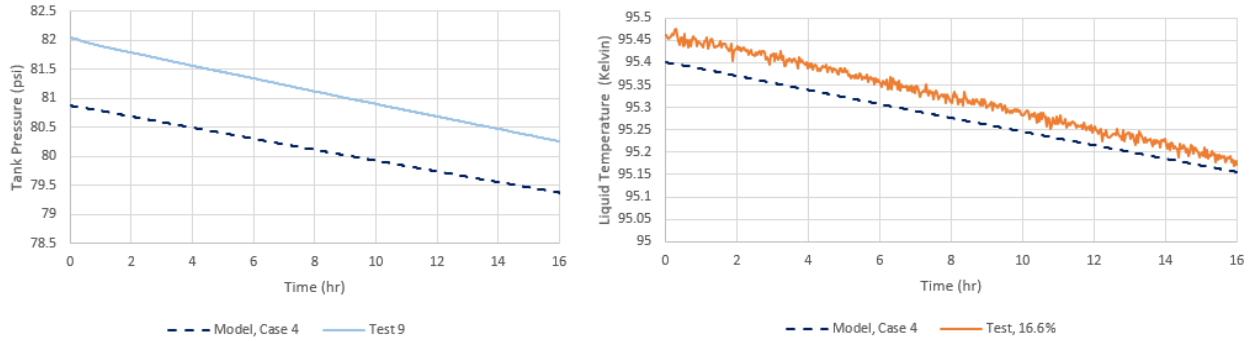


Figure 16. –Test 9 and Model Comparison

Tests	Test Pressure Rate (psi/hr)	Model Pressure Rate (psi/hr)	Pressure Rate % error	Test Liquid Temperature Rate (Kelvin/hr)	Model Liquid Temperature Rate (Kelvin/hr)	Temperature Rate % error
2	0.33	0.026	-92.1	0.0031	0.0043	38.7
4	-0.096	-0.068	-29.2	-0.014	-0.011	-21.4
6	0.024	0.0259	7.9	0.0047	0.0043	-8.5
9	-0.11	-0.093	-15.5	-0.018	-0.015	-16.7

Table 3. –Model Validation Summary

With the cryocooler turned on to intercept the heat entering the tank, the model predicts the depressurization rates for both fill levels reasonably well. Table 3 shows the percent error of the model for all cases for the pressure and temperature rise rates. Additional work needs to be done with the model when the cryocooler is turned off to better model stratification and predict the pressure rise rates in the tank.

6.0 Conclusion

Liquefaction was modeled inside a liquid oxygen tank sized for the Mars Ascent Vehicle with an integrated reverse turbo Brayton cryocooler with Thermal Desktop. Preliminary results show that Mars environmental temperature cycles can potentially reduce cryocooler power and mass by 15-20% with the current radiator design. Further work was done with modeling the zero boiloff tank tested at Glenn Research Center using a similar modeling approach with the MAV model. The model results were compared with test data and gave confidence to the model.

References

- [1] Polsgrove, T.; Thomas, H.D.; Stephens, W.; and Rucker, M.A.: Mars Ascent Vehicle Design for Human Exploration. AIAA-2015-4416, 2015.
- [2] Johnson, Wesley, et al.: Comparison of Oxygen Liquefaction Methods for use on the Martian Surface.
- [3] Plachta, David.; et al.: Mastering Cryogenic Propellants. Journal of Aerospace Engineering, 2013.
- [4] Ring, Elliot: Rocket Propellant and Pressurization Systems. Prentice-Hall, Inc., Englewood Cliffs, NJ, 1964.

[5] Zagarola, Mark: et al: Demonstration of A High-Capacity Cryocooler for Zero Boil-Off Cryogen Storage in Space, International Cryocooler Conference, 2012.

[6] Guzik, Monica.; and Tomsik, Thomas: An Active Broad Area Cooling Model of a Cryogenic Propellant Tank with a Single Stage Reverse Turbo-Brayton Cycle Cryocooler. <http://ntrs.nasa.gov>

[7] Plachta, David.; Feller, Jeffrey.; Johnson, Wesley.; and Robinson, Craig: Liquid Nitrogen Zero Boiloff Testing. NASA/TP-2017-219389, 2017. <http://ntrs.nasa.gov>