TITLE: Investigation of a Liquefaction Methodology to Enable the Utilization of In-Situ Produced Propellant on the Lunar and Martian Surfaces

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To enable NASA's plans to return astronauts to the lunar surface and eventually to Mars, the agency is putting emphasis on reusable cryogenic systems. Such systems will require replenishing of cryogens on-orbit via a cryogenic tanker or refueling depot, and potentially on the lunar or Martian surfaces with the utilization of in-situ resources. Surface replenishing requires the in-situ production of gaseous oxygen (and hydrogen if on the lunar surface), followed by liquefaction and storage. The liquefaction system can be integrated into the propulsion system propellant tanks, or in a separate storage facility and transferred to the propulsion system when needed.

In interest of developing a liquefaction and storage system that is efficient, reliable and scalable, a multicenter team of NASA engineers was formed. The team conducted trade studies on various system level concepts including multiple heat exchanger configurations to be integrated with active cooling (cryocoolers) [1]. When the trade studies concluded, the team settled on a system level configuration which included a propellant tank outfitted with a tube-on-tank heat exchanger integrated with a cryocooler. The team executed a development plan to include: 1) a "brassboard" level test series to demonstrate proof of concept, 2) model development to predict system performance, 3) model validation utilizing "brassboard" test results, 4) the design, development and demonstration of a Mars surface liquefaction and storage system prototype, and 5) eventually conduct an end-to-end demonstration to include in-situ production, liquefaction, and long duration storage of cryogens with zero boil-off. The effort is currently in the "brassboard" level testing phase which will be discussed here.

Hardware and Experimental Setup

The test article assembled for the "brassboard" test series includes Glenn Research Center's (GRC) Zero Boil-Off (ZBO) propellant tank [2]. Constructed of stainless steel, the mass and volume are approximately 630 lbm and 48.5 ft^3, respectively. ZBO hangs from six low conductivity struts connected to an upper support ring which rests on a steel support frame. The tank penetrations include both pressurization and vent ports, and a fill/drain port connected to a dip tube internal to the tank. Unique to ZBO is the tube-on-tank Broad Area Cooling (BAC) exterior heat exchanger configuration to be integrated with a refrigeration loop. The tank exterior is covered with a Multi-Layer Insulation (MLI) blanket and at vacuum conditions, the heat load is estimated to be approximately 18.9 W.

The cryocooler utilized in this experiment is a commercially available Gifford-McMahon industrial cryocooler having approximately 120 W of refrigeration capability at 90 K. Mounted to the refrigerator is a custom made heat exchanger specifically designed to be integrated with a neon refrigeration loop. A CryoZone Noordenwind Cryofan forces neon gas across this heat exchanger where heat is removed. The neon is then filtered and the flowrate measured prior to being introduced into the tube-on-tank BAC inlet port. Cold neon flows through the refrigeration tubes removing heat from the exterior tank walls enabling both zero boil-off conditions and liquefaction.

The test article was placed inside the 9 ft X 20 ft vacuum chamber at Marshall Space Flight Center's (MSFC) Exploration Systems Test Facility (ESTF) and was exposed to pressures as low as $4.0E10^{-6}$ Torr. The ZBO Test Article Setup is shown below in Figure 1.

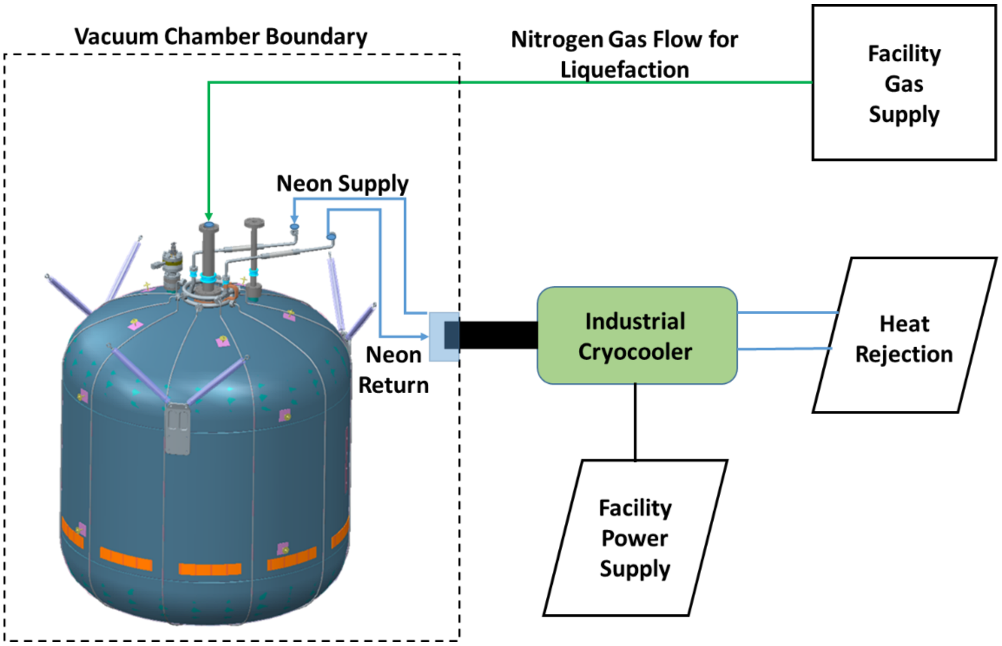

Figure 1 Test Article Setup

Steady-State Heat Load

The first step in starting the test series was to determine the total heat load associated with ZBO. Filled with liquid nitrogen and at steady-state conditions, the boil-off rate was measured to be approximately 0.54 lbm/hr and the total heat load (sensible and latent) was estimated to be 18.9W.

Zero Boil-Off Demonstration

Once the heat load was determined, the next step was to demonstrate zero boil-off. With ZBO filled with liquid nitrogen and controlled to 18 PSIA maximum, the neon loop was activated and the tank pressure decreased at a rate of 0.13 PSI/hour to 6 PSIA prior to the test being terminated. If the tank internal pressure remained constant, this would be an indicated of zero boil-off conditions. However, in this demonstration, the continued pressure decay indicated that not only were zero boil-off conditions achieved, but the tank ullage collapsed and some liquefaction likely occurred.

Constant Liquefaction

The objective of the constant liquefaction tests is to determine the liquefaction rates associated with various fill levels. The belief here is that the liquefaction rate should be highest when starting with an empty tank due to the entire inner wall surface area being available for liquefaction. A total of five liquid levels were tested: 0%, 25%, 50%, 75% and 100%. The 0% case was identified as the "baseline" to determine the relative reduction in liquefaction rates as the tank began to fill. Starting with the tank internal pressure at approximately 14.7 PSIA, gaseous nitrogen was introduced through the pressurization port at a rate of 1.0 lbm/hr. Each test was allowed to run for approximately seven days before discontinuing the flow. However, to determine liquefaction rates, no test was terminated until the tank pressure reduced back to the original level at the start of the test, approximately 14.7 PSIA. The higher liquid levels led to an increased pressure rise due to the lower liquefaction rates associated with the decreased surface areas and the small ullage volume. Relative to the baseline case, the liquefaction rates (% of baseline) are shown in Figure 2.

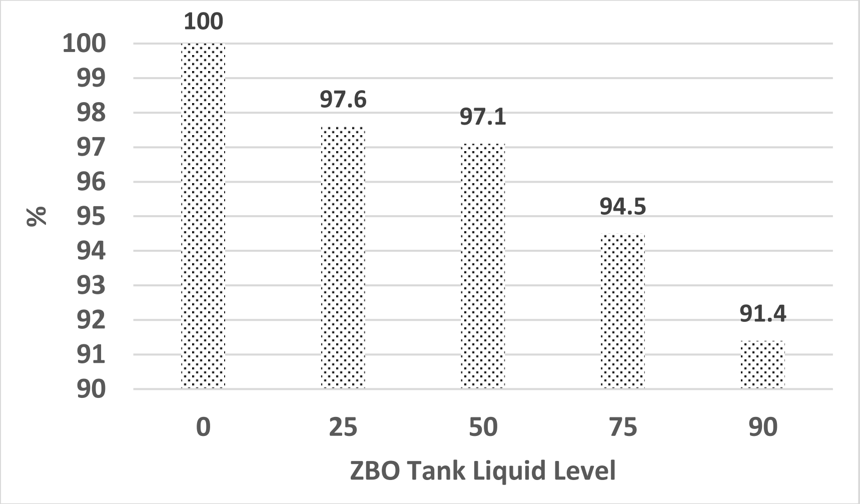

Figure 2. Liquefaction Rate Relative to Baseline Case

Non-Constant Liquefaction

In an attempt to capture the effects of the diurnal cycles associated with a Martian day and assuming the power budget allowed for continuous operation of the cryocooler only, the disruption of in-situ produced propellant is simulated by intermittently stopping gaseous nitrogen flow into the propellant tank for twelve hours at a time. This process was completed for 0%, 50% and 90% liquid levels. Similarly to the results from the constant liquefaction tests, the increases in tank pressure were more significant at the higher liquid levels due to the smaller ullage volume and the decrease liquefaction rate associated with the smaller inner tank wall surface area available for liquefaction. During the twelve hour period the flow of gaseous nitrogen was discontinued, the decreased liquefaction rates were evident as it took considerably longer for the tank pressure to decrease.

Sub-Surface Injection

To evaluate the potential benefits associated with sub-surface injection, three of the constant liquefaction cases were repeated introducing the nitrogen gas stream through the ZBO internal dip tube. The potential benefit here is a significant increase in the liquefaction rate which results in lower tank pressures. As the nitrogen gas passes through the submerged dip tube, it is pre-chilled before injected beneath the liquid surface. When using this approach, the nitrogen introduced into the tank rapidly condenses. Preliminary results indicate a 35% reduction in tank pressure when using this approach. As expected, the benefits become more evident as the tank fills due to the increased submersion of the dip tube, and the cold gas being injected further beneath the surface of the liquid.

Conclusions

Higher liquid levels result in increased pressure rise and decreased liquefaction rates. These results were noted for both the constant and non-constant liquefaction cases when the gaseous nitrogen was introduce through the ZBO pressurization port. Sub-surface injection of gas through the ZBO dip tube provided an opposite effect. The higher liquid level resulting in further precooling prior to being injected beneath the surface of the liquid resulting in higher liquefaction rates and lower pressures. These preliminary results indicate that subsurface injection through a dip tube may likely be the preferred method to be implemented in the prototype testing.

One lesson learned to be taken from the “brassboard” test series is that the cryocooler needs to be close-coupled to the BAC tube interfaces to minimize the plumbing exposed to the atmosphere. Excessive line lengths and insufficient insulation leads to additional heat being absorbed into the neon loop system and a significant degradation in zero boil-off and liquefaction capability.

The twelve hour period when the flow of gaseous nitrogen was interrupted did provide some benefit as it allowed time for the cryocooler to cool and liquefy ullage gas resulting in reduced pressure.

Future Work

Modeling efforts of this system are currently in-work and the “brassboard” test data will be used to validate those models. Once validated, these models will then be used to assist in the design of the prototype system and to conduct test predictions.

One final objective to be completed in the “brassboard” test series is to evaluate the liquefaction rates in the presence of a non-condensable gas (helium). ZBO will be pressurized with helium to some predetermined partial pressure, then at least two of the constant liquefaction tests will be repeated. Modeling of the liquefaction process in the presence of a non-condensable gas will also be modeled and validated.

References

[1] W.L. Johnson, D.M. Hauser, B.F. Banker, J.R. Stephens, D.W. Plachta, P.S. Desai, A.M. Swanger and X-Y.J. Wang, "Comparison of Oxygen Liquefaction Methods for Use on the Martian Surface", presented at the 27th Space Cryogenics Workshop, July 2017

[2] D.W. Plachta, W.L. Johnson, and J.R. Feller, "Zero Boil-Off System Testing", presented at the 26th Space Cryogenics Workshop, June 2015

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