Integrated Refrigeration and Storage for Advanced Liquid Hydrogen Operations

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ABSTRACT

NASA has used liquefied hydrogen (LH_2) on a large scale since the beginning of the space program as fuel for the Centaur and Apollo upper stages, and more recently to feed the three space shuttle main engines. The LH_2 systems currently in place at the Kennedy Space Center (KSC) launch pads are aging and inefficient compared to the state-of-the-art. Therefore, the need exists to explore advanced technologies and operations that can drive commodity costs down, and provide increased capabilities. The Ground Operations Demonstration Unit for Liquid Hydrogen (GODU-LH2) was developed at KSC to pursue these goals by demonstrating active thermal control of the propellant state by direct removal of heat using a cryocooler. The project has multiple objectives including zero loss storage and transfer, liquefaction of gaseous hydrogen, and densification of liquid hydrogen. The key technology challenge was efficiently integrating the cryogenic refrigerator into the LH_2 storage tank. A Linde LR1620 Brayton cycle refrigerator is used to produce up to 900W cooling at 20K, circulating approximately 22 g/s gaseous helium through the hydrogen via approximately 300 m of heat exchanger tubing.

The GODU-LH2 system is fully operational, and is currently under test. This paper will discuss the design features of the refrigerator and storage system, as well as the current test results.

INTRODUCTION

In the 1960s NASA drove a great deal of large scale liquid hydrogen technology development in preparation for the Apollo moon missions, and continued to be one of the largest consumers of LH_2 through the end of the Space Shuttle program in 2011. In the 50 years since this early period of innovation however, the state-of-the-art in cryogenic systems has transitioned to industry, and NASA has found itself utilizing inefficient equipment. Over the duration of the Space Shuttle program NASA lost approximately 50% of the hydrogen purchased due to continuous heat leak into ground and flight vessels, transient cool-down of warm cryogenic equipment, boil-off during transport, liquid bleeds, and vent losses [1]. Since production of liquid hydrogen is an energy intensive process, these losses constituted a large, unrecoverable cost on the order of several million dollars a year. This cost caused NASA to invest in next-generation cryogenic storage and transfer systems, and drove the development of the Ground Operations Demonstration Unit for Liquid Hydrogen (GODU-LH2) at KSC. Figure 1 shows a ground level view of GODU-LH2 test site.

At the heart of the GODU-LH2 system is the concept of Integrated Refrigeration and Storage (IRAS)—controlling the state of the fluid inside the storage tank via direct removal of energy from the liquid using an integrated heat exchanger coupled with a cryogenic refrigerator. The IRAS concept pursues four capabilities: (1) Zero loss LH_2 tanker offloads: tankers can be offloaded into the cold IRAS tank with only minimal purging required, and then the refrigerator is used to decrease the pressure that builds up during liquid transfer as opposed to venting; (2) Zero Boil-Off (ZBO): if the refrigerator lift and intrinsic tank heat-leak are balanced ($Q_{lift}/Q_{tank} = 1$) and no mass is being added or removed then the pressure and liquid level will remain constant indefinitely; (3) Liquefaction: gaseous hydrogen can be introduced into the IRAS tank and liquefied in-situ to fill the vessel as opposed to using liquid tankers; and (4) Densification: if the refrigeration lift is greater than the tank heat-leak ($Q_{lift}/Q_{tank} > 1$) and no mass transfer exists then the LH_2 can be cooled below its normal boiling point (NBP) becoming denser as a result.

Capabilities 1 through 3 have economic benefits for launch pad architectures, the advantages of densification however, are a little more abstract. Cooling LH_2 from its NBP of 20.4 K to just above the triple-point of 13.9 K yields a density increase of roughly 9%, yet requires a hefty 3.8 kJ of energy removal per liter of liquid. And this required cooling becomes increasingly difficult as the temperature decreases, resulting in an additional Carnot penalty of 33% that must be paid in order to reach the triple-point. There are however, substantial benefits of propellant densification as it pertains to space launch vehicles. It has been reported that the positive impact on payload mass fraction can be quite significant, ranging from 4.9% to 17.5% to low-Earth orbit depending on launch platform and densification temperatures, and up to 26% if slush hydrogen is employed [2]. Other advantages can be derived from the lower vapor pressures and increased sensible heat associated with densifying propellants [3]. Lower operating pressure can have a profound effect on storage and flight tank designs, potentially decreasing weight and/or increasing life cycle; and gaining any amount of sensible heat can ease pumping and chill-down of equipment, decrease overall loading time, and may have a positive effect on unfavorable phenomena such as geysering.

To-date each one of the advanced capabilities described above has been successfully demonstrated with the GODU-LH2 system at the 30% LH_2 fill level. Testing at the 60% level is underway, and 90% is scheduled for late 2016.

Figure 1: GODU-LH2 Test Site

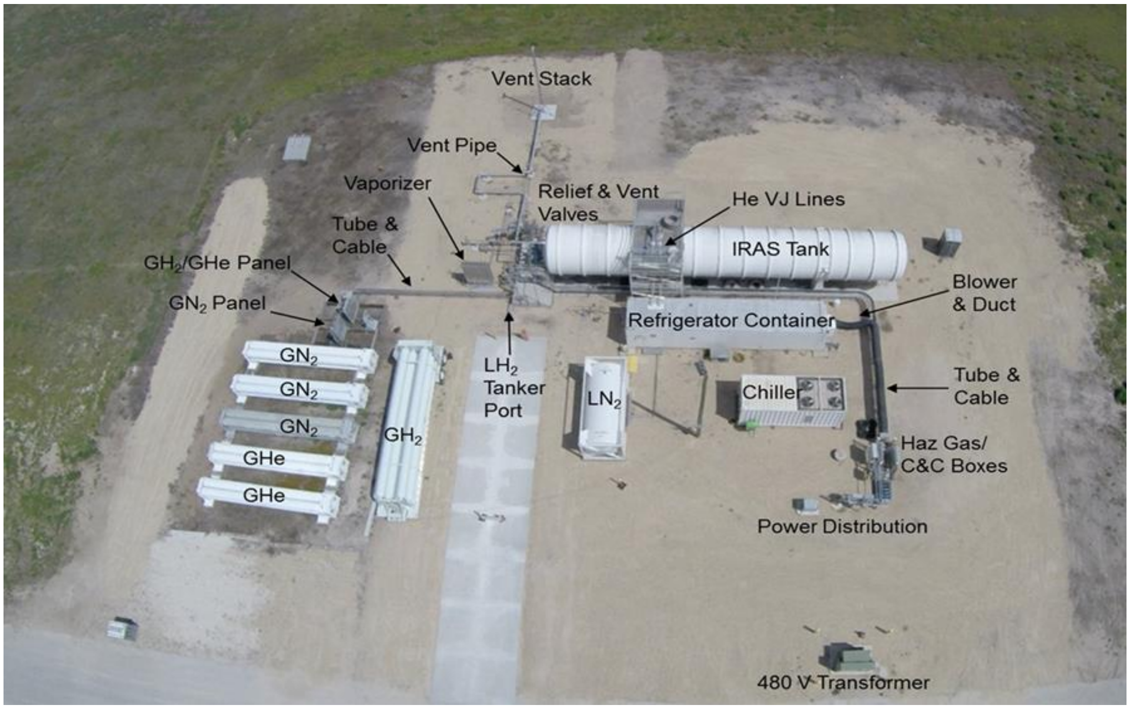

Figure 2: Aerial View of the GODU-LH2 Test Site

GODU-LH2 SYSTEM OVERVIEW

The IRAS concept was first demonstrated on a small scale (180 L) with hydrogen in 2006 by Notardonato et.al. [4]. This system employed a Gifford-McMahon cryocooler, heat-pipe, and braided copper heat exchanger integrated to a dewar. During testing the vessel was successfully filled via liquefaction of GH_2, and the liquid was densified to approximately 15.7 K. Demonstration on a more significant scale was necessary however, in order to validate the use of IRAS on a system as large as the LH_2 facility at the KSC launch pads (3,200 m^3 or more).

The GODU-LH2 site is located in an open field within a controlled area at KSC, and is comprised of four primary subsystems (1) IRAS tank, (2) Refrigeration unit, (3) IRAS tank vent system, and (4) Pneumatics (gaseous nitrogen, helium and hydrogen). Ancillary systems include a water chillier unit, electrical power distribution (480 V and 120 V), hazgas detection for hydrogen leaks, command and control (C&C), and liquid nitrogen (LN_2) for refrigeration precooling. Figure 2 shows and aerial view of the entire site.

IRAS Tank

GODU-LH2 repurposed a 125 m^3 cylindrical LH_2 storage tank originally built by Minnesota Valley Engineering in 1991 to support the Titan-Centaur rocket program at Cape Canaveral Air Force Station. It is a high performance vessel—vacuum-jacketed with 80 layers of multi-layer insulation (MLI)—has original pressure and temperature ranges of 0 to 655 kPa (gauge) and 20 K to 311 K respectively, an inner diameter of 2.9 m and length of 21.8 m.

Five primary tank modifications were required to facilitate GODU-LH2 testing: (1) construction of the internal heat exchanger, (2) incorporating internal stiffening rings to accommodate the sub-atmospheric pressure associated with densification testing, (3) An updated man-way feed-through plug to incorporate instrumentation and refrigerant penetrations, (4) Recertification of the tank per the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (BPVC) to the new operating conditions, and (5) Temperature rakes to map the vertical, axial and radial tank temperature profile (24 silicon diodes in total).

Introduction of all internal components can best be described as a “ship in a bottle” approach, since all hardware, tools, personnel, etc. had to fit through the 53 cm diameter man-way port at the top of the tank. This required that the stiffening rings, heat exchanger and rakes be modular—fabricated in pieces capable of being transported into the tank, and then assembled by hand. All modifications were performed by KSC personnel in 2013, and were covered extensively by Swanger et.al. [5,6].

Design of the internal heat exchanger is highly 3-dimensinal in order to effectively distribute the cold helium refrigerant throughout the tank volume, and provide some structural rigidity. It consists of supply and return manifolds (total of 37 m of 25 mm OD tubing, and located at the 25% and 75% fill levels respectively), 40 cooling coils (total of 244 m of 6.4 mm OD tubing), and has a total heat transfer area of approximately 11 m^2. Refrigerant flows were balanced end-to-end using precision orifice fittings as previously reported by Fesmire et.al. [7]. Two 25 mm diameter by 3 m long flexible lines connect to the man-way feedthrough to each manifold. Each of these tubing sections had to be interfaced using fittings with ultra-low leak rates, and high reliability. Swagelok VCR type units with silver-plated nickel gaskets and retainer rings were chosen for this task. Figure 3 shows the as-built internal IRAS configuration with heat exchanger, stiffening rings, and temperature rakes.

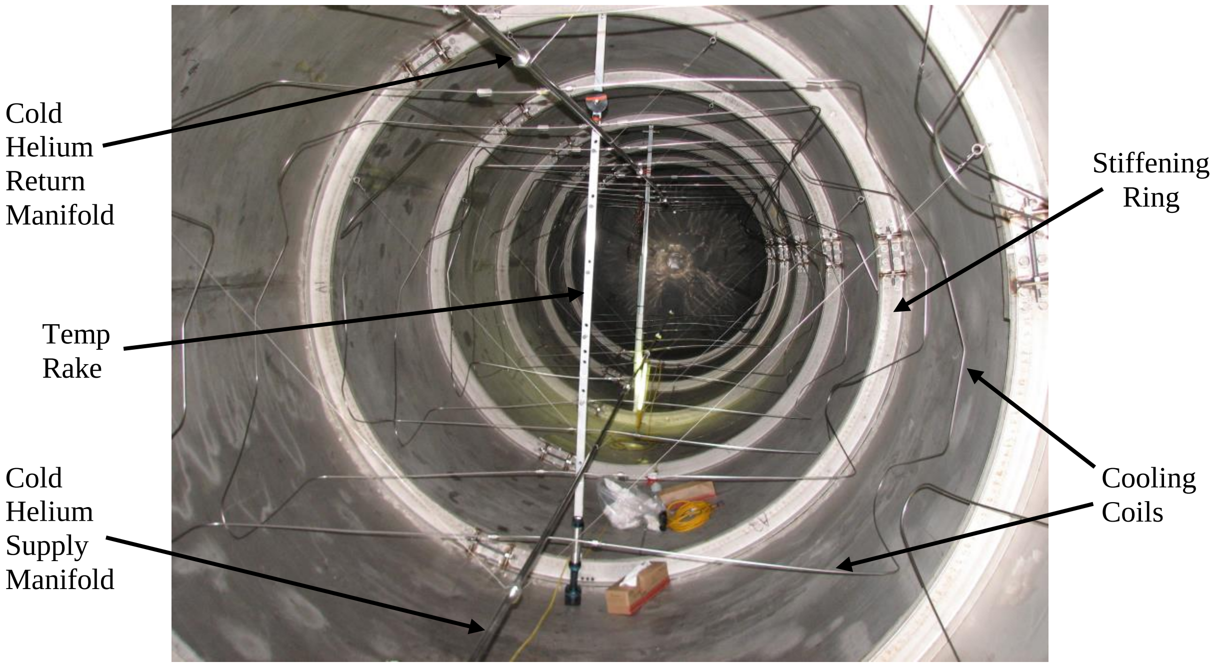

Figure 3: Internal IRAS Tank Modifications

Figure 4: Refrigeration Container Showing the Refrigerator Module (foreground) and RSX Compressor (background) (left); GHe VJ Piping Interfaced to IRAS Tank (right)

Refrigeration System

The cryocooler selected for the GODU-LH2 system is a Linde LR1620 model with an RSX helium compressor. This reverse-Brayton cycle refrigerator employs two parallel piston expanders with 4-stages of recuperation, and can officially provide 400 W lift at 20 K, or 850 W with LN_2 precooling at 22 g/s mass flow rate. However, initial performance testing yielded elevated capacities of roughly 500 W and 900 W with and without precooling respectively. Cold, ultra-high purity (UHP) helium from the refrigerator is routed to and from the IRAS tank through 8.5 m (each way) of 25.4 mm x 63.5 mm vacuum-jacketed (VJ) hard piping.

During system conception it was estimated that the intrinsic heat leak of the retrofitted LH_2 dewar was around 350 W. This yielded a refrigeration ratio (Q_{lift}/Q_{tank}) of 1.1 and 2.4 at the rated lift capacities, with and without precooling respectively; and 1.4 and 2.6 using the actual system performance numbers. As previously noted, a ratio greater than 1.0 was necessary to achieve all the test objectives. Furthermore, a large positive margin afforded even greater test flexibility and control by increasing system response.

Housing the refrigerator and compressor modules—equipment that does not comply with the National Fire Protection Association (NFPA) requirements for operation in explosive gas environments—in close proximity to the IRAS tank was achieved using a standard 12 m ISO shipping container constantly purged with fresh air (outside the NFPA Class I, Division II area) via a blower unit. Pressure inside the semi-sealed container is kept at roughly 0.5 inH_2O above atmospheric at all times when hydrogen was present in the tank to ensure that, in the case of a leak, no GH_2 could infiltrate the purged environment. Integrating the entire refrigeration system into the shipping container also allowed for the possibility of transporting it to a future location in an assembled, serviced state. Only the refrigerant supply and return lines, cooling water lines, and power to the system must be de-mated prior to transporting.

Rejecting the heat of compression and cooling the compressor oil is accomplished via a custom built chilled water unit that complies with NFPA regulations to operate within a Class I, Division II zone. Similar to the refrigerator and compressor modules, this unit was built into an ISO shipping container (6 m instead of 12 m), and can be easily transported. 25 mm diameter PVC lines interface the chiller to the RSX compressor, and provides a constant supply of 16°C water to the system. Figure 4 shows the refrigerator and compressor modules inside the shipping container, and the VJ interface piping.

Liquid nitrogen for helium precooling is supplied from a 20,000 L US Department of Transportation (DOT) approved transportable dewar placed adjacent to the refrigeration container. It interfaces to the refrigerator module through 11 m of 13 mm x 51 mm VJ hard piping. Pressure is allowed to build in the LN_2 tank from natural boil-off, and is maintained around 103 kPa by periodically venting the ullage space. While running in precooling mode the internal Linde control software maintains a boiling LN_2 pool inside the refrigerator using a bang-bang control scheme. Incoming GHe from the compressor is partially routed through the LN_2, heat exchanger, dropping its temperature close to the LN_2 boiling point before being fed back into the recouperators. Boil-off vapor is vented to atmosphere out the side of the refrigeration container. Use of LN_2 in this manner accounts for the 400 W increase in refrigeration capacity over the standard closed-loop cycle.

Control of the lift capacity is accomplished by adding heat to the cold GHe exiting the piston expanders via an in-line resistive heater. An exit or return temperature set point can be entered into the standard Linde software, which in turn adds heat as required. Custom software was also developed for GODU-LH2 that interfaces with the Linde package, and controls the heater to achieve a desired IRAS tank pressure.

IRAS Vent System & Pneumatics

The IRAS tank vent system was designed to meet the unique test requirements of the GODU-LH2 project, as well as those established in the ASME BPVC. Two vent paths can be utilized depending on the mode of operation: A 150 mm line and 7 m tall vent stack accommodates large vent rates, and routes flow from the relief devices in case of an over pressurization event; and a 25 mm path directs normal boil-off flow to a 3 m tall stack during IRAS tank heat leak testing, and when the refrigeration system is down for repair or maintenance. Each of these legs ties into the 100 mm primary IRAS tank vent, and are activated remotely from the command and control trailer. A vertical, open-air vaporizer is also employed in the system to provide tank pressurization for possible future LH_2 transfer testing. Since an overarching theme of GODU-LH2 is to minimize, or completely eliminate, any hydrogen losses, under normal operation the IRAS tank is isolated from the vent system, and the refrigerator is used to control the pressure. During densification testing, when the tank is allowed to go sub-atmospheric, any interface to the ullage space (flanges, valves, fittings, etc.) is “bagged” and purged with gaseous helium. This is done as a precaution, in case a leak occurs helium instead of air will be drawn into the tank.

To reduce project cost, several pneumatic panels and gas storage bottles were reused from the Space Shuttle program to provide gaseous helium, hydrogen and nitrogen to the system. Two 16.5 MPa movable storage units (MSU) provide a 2,265 m^3 helium storage capability, and three additional 16.5 MPa MSUs store up to 3,400 m^3 of gaseous nitrogen.. The facility nitrogen panel reduces the 16.5 MPa down to several 5 MPa sources as well as up to twenty 700 kPa sources used for valve actuation, panel inerting, and purging of lines. Gaseous hydrogen is supplied to the site by compressed gas trailers, is regulated from 25.5 MPa down to 1,030 kPa and used for liquefaction supply as well as purge and pressurization of lines and the IRAS tank [8].

GODU-LH2 TESTING RESULTS

The GODU-LH2 test matrix consists of three primary objectives (zero-loss offloading and storage, liquefaction, and densification) conducted at three different IRAS tank fill levels (30%, 60%, and 90%). Measurable differences in system efficiency and response are expected at the different fill levels as the internal heat exchanger becomes increasingly submerged in LH_2.

Initial system start-up and testing began in March 2015 with an LN_2 cold-shock of the IRAS tank, followed by evacuation and GH_2 purge cycles until the proper purity was achieved. The refrigerator was then used to bring the inner tank wall temperature down to roughly 55 K in order to facilitate a zero-loss tanker offload of approximately 45,000 L of LH_2 (i.e. no hydrogen was lost during the offload process), and afterward to re-condense the ullage vapor that accumulated during the transfer [9].

This first tanker offload effectively brought the fill level to around 30%, and once the pressure stabilized close to the NBP, testing to determine the intrinsic tank heat leak commenced. Over a three week period the steady-state boil-off was measured using a Brooks Instruments mass flow meter, and was determined to be 257 SLPM on average, at a tank pressure of 104.8 kPa (absolute). This equates to a heat leak of 292 W, and refrigeration ratios of 1.7 and 3.1 with and without LN_2 precooling within the refrigeration system. Once the heat leak was known the refrigerator was started, IRAS tank brought online, and ZBO, liquefaction and densification testing began.

Zero Boil-Off/Pressure Control

In order to demonstrate full control of the tank pressure with the GODU-LH2 software it was desirable to test the response of the system when a set-point is chosen at both higher and lower values than the tank pressure at that time—to converge to the desired pressure from “above” and “below.” From above, the control logic has to allow the refrigerator to run at maximum capacity in order to drop the pressure as fast as possible, and then introduce heat until the refrigerator lift balances the tank heat leak (i.e. a refrigeration ratio of 1). Whereas, from below, the software needs to create and refrigeration ratio less than 1 by introducing excessive heat into the tank in order to drive the pressure up to the set-point. This test sequence was performed over a 9 day period, using four different set-points, and without LN_2 precooling for the refrigerator. Figure 5 shows the results of the ZBO testing.

Figure 5 shows that the system is able to control the tank pressure very precisely, and has a relatively fast response time for a large ullage volume. It is apparent from the transient periods that the system responds faster when approaching the set-point pressure from below rather than above. From above, the average slope is roughly 0.5 kPa/hr, and from below it is 1.4 kPa/hr. On average the tank pressure was 0.35 kPa below the set-point, attributed to PID loop tuning, and the average standard deviation over the duration of time for set points 1, 2 and 3 was only 0.07 kPa. As expected, the tank temperatures trended with the pressure and show a small, but obvious amount of ullage stratification, save the inversion of the bottom two readings seen at roughly 40 hours. This anomaly is most likely due to the proximity of the liquid-vapor interface at the 30% fill level to the bottom manifold of the heat exchanger. The top most ullage temperature line in Figure 5 is located 2 m from the inner tank floor, just below the top manifold, while the lowest line (labeled as the “liquid temperature”) is 0.6 m from the floor, just below the bottom manifold, and is completely submerged at the reported fill level. The location of the other four temperature readings are spaced evenly between these two.

Hydrogen Liquefaction

Liquefaction testing at the 30% fill level was conducted over a day and a half period and consisted of feeding gaseous hydrogen from a mobile compressed gas trailer to a Brooks Instruments mass flow controller, which fed directly into the IRAS tank via the vent line. The refrigerator was operated at full capacity (i.e. with LN_2 precooling), and the control logic managed the mass flow in order to achieve a constant tank pressure.

It must be stated that due to budget constraints the GODU-LH2 system in its current configuration is not optimized to conduct hydrogen liquefaction. Feeding ambient temperature GH_2 directly into the tank is not the preferred method due the non-trivial ortho-to-para energy penalty that must be paid. As a result, the GODU-LH2 liquefaction testing is aimed more at validating the ability of IRAS to liquefy on a large scale, and testing the software control schemes, rather than maximizing the liquid yield. To these ends 30% testing was successful. The control logic maintained a constant tank pressure using the mass flow controller, and the increase in liquid volume was captured by the liquid level sensor via a ΔP reading.

Figure 6 shows the results of the liquefaction testing. The average tank pressure during liquefaction was 127.6 kPa, with a standard deviation between hour 26 and 58 of 0.2 kPa. Average GH_2 mass flow rate was 113.6 SLPM, and the head pressure increase (ΔP reading) was 0.02 inH_2O. In all, roughly 295 L of liquid was produced during the 30% testing.

Hydrogen Densification

Densification testing officially began when the tank pressure went sub-atmospheric and the liquid hydrogen dropped below its normal boiling point of 20.4 K. The refrigerator was run at full power, and successfully densified the LH_2 for roughly 14 days prior to a component failure and subsequent shutdown. Figure 7 shows the temperature and pressure data from the 30% densification testing.

Many notable features can be seen in figure 7, most obvious is the minimum temperature reported by many of the diodes. Values well below the triple point were seen not only in the bulk liquid, but also in the vapor space a significant distance from the liquid-vapor interface, the farthest being approximately 0.6 m away. This result is not completely understood at this time. It implies that not only was a significant amount of solid hydrogen being formed inside the IRAS tank, but that it was somehow also being cooled below its freezing point. Preliminary calculations estimate that roughly 1,134 kg of hydrogen ice was produced during the test, and it is believed that it existed as a homogenous bulk slush mixture as opposed to solid formations clinging to the cold heat exchanger surfaces. The minimum temperature witnessed during the test was 12.6 K; a full degree below the triple point value.

Another interesting feature is the sharp dip in ullage temperatures seen around hour 260, at the same time the tank pressure appears to reach the triple point. This is not believed to be a coincidence. Instead, when solid hydrogen began to form—which would take place mostly at the bottom heat exchanger manifold submerged in the liquid, and coincide with the tank pressure reaching the triple point—the bulk of the cooling power transitioned from the bottom manifold to the cooling coils running up the tank wall. This resulted in a swift decline in ullage temperatures until the LN_2 precooling was turned off briefly. Densification testing at the 60% and 90% fill levels will hopefully shed more light on the unique behavior seen here since there will be greater resolution into the bulk liquid (or slush) temperatures.

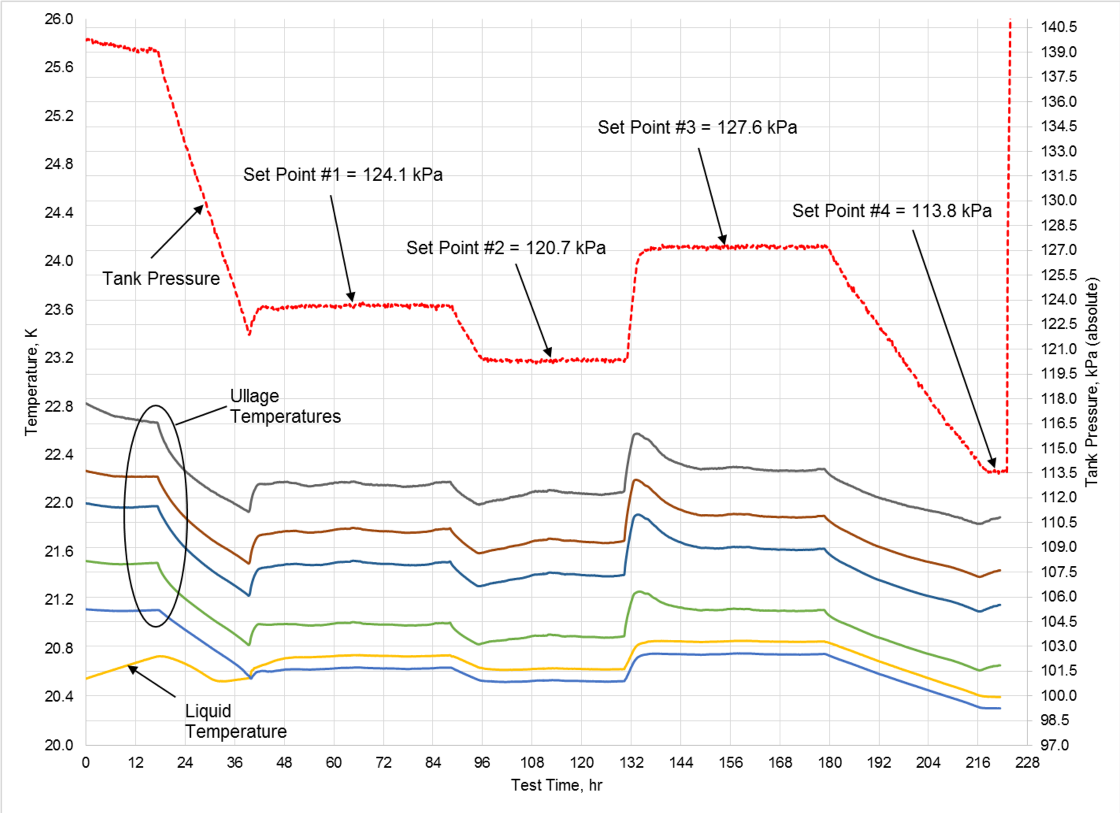

Figure 5: ZBO Test Results at the 30% Fill Level

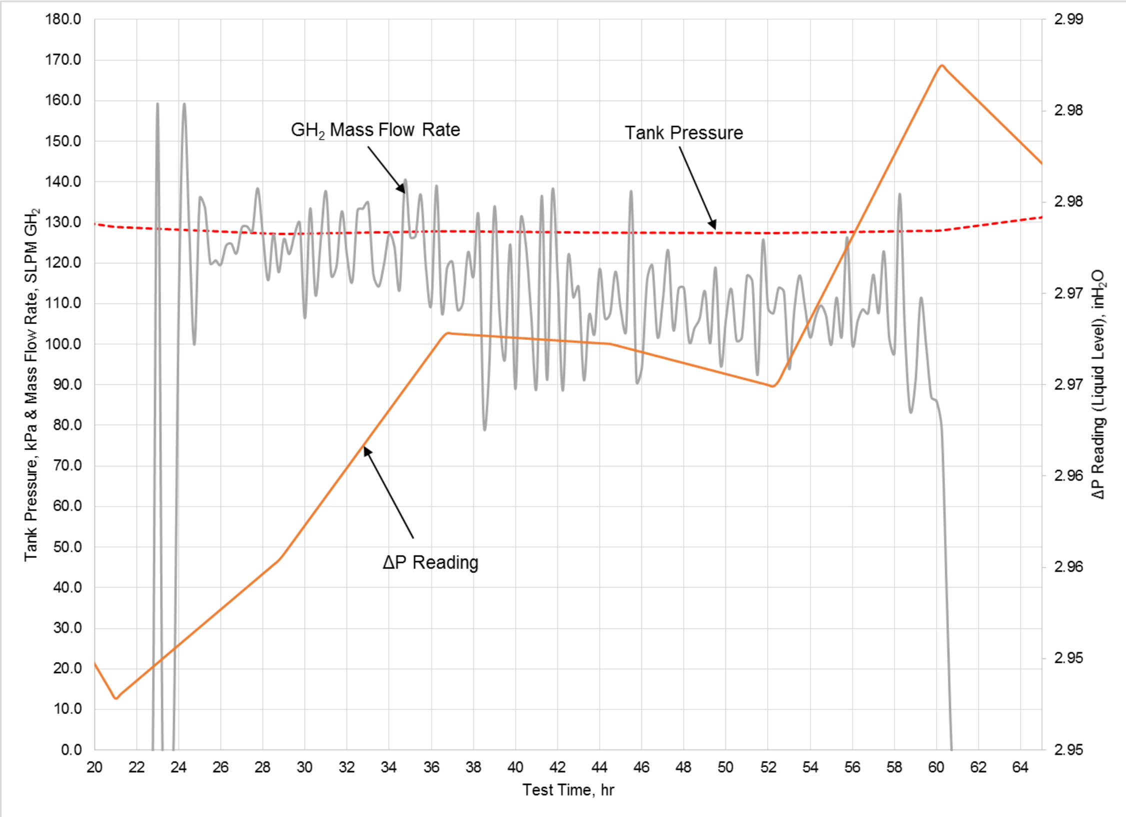

Figure 6: Liquefaction Test Results at the 30% Fill Level

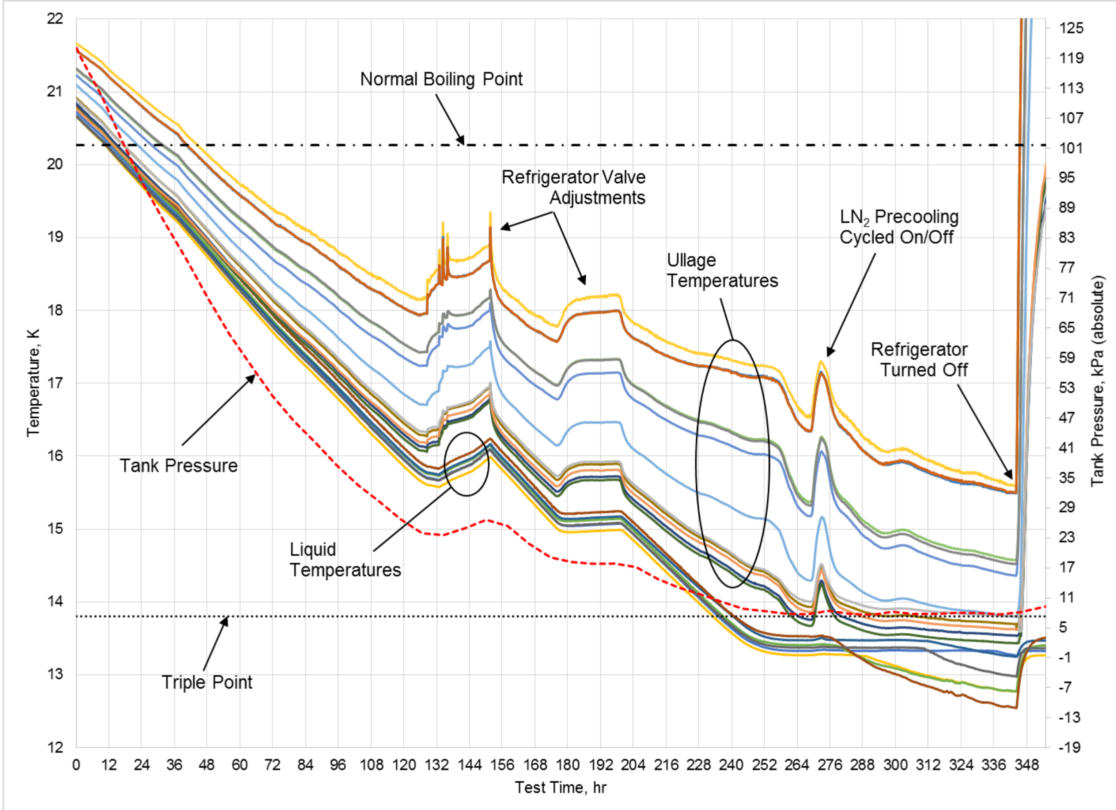

Figure 7: Densification Test Results at the 30% Fill Level

CONCLUSION

The GODU-LH2 system has successfully demonstrated zero-boil-off, liquefaction, and densification of hydrogen in a 125 m^3 tank at approximately 30% full using Integrated Refrigeration and Storage (IRAS). Two un-vented tanker off-loads were also performed with no liquid in the tank (the worst case scenario). Further demonstrations will repeat these at LH_2 fill levels of approximately 60% and 90%.

Initial results indicate that this type of IRAS system could be readily scaled to support space launch vehicle and pad operations by lowering the cost of cryogenic propellant maintenance, affording greater flexibility for propellant handling, and providing increased mission capability.

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