

Zero Boil-Off Methods for Large Scale Liquid Hydrogen Tanks using Integrated Refrigeration and Storage

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Abstract. NASA has completed a series of tests at the Kennedy Space Center to demonstrate the capability of using integrated refrigeration and storage (IRAS) to remove energy from a liquid hydrogen (LH₂) tank and control the state of the propellant. A primary test objective was the keeping and storing of the liquid in a zero boil-off state, so that the total heat leak entering the tank is removed by a cryogenic refrigerator with an internal heat exchanger. The LH₂ is therefore stored and kept with zero losses for an indefinite period of time. The LH₂ tank is a horizontal cylindrical geometry with a vacuum-jacketed, multilayer insulation system and a capacity of 125,000 liters. The closed-loop helium refrigeration system was a Linde LR1620 capable of 390W cooling at 20K (without any liquid nitrogen pre-cooling). Three different control methods were used to obtain zero boil-off: temperature control of the helium refrigerant, refrigerator control using the tank pressure sensor, and duty cycling (on/off) of the refrigerator as needed. Summarized are the IRAS design approach, zero boil-off control methods, and results of the series of zero boil-off tests.

1. Introduction

Numerous concepts have been explored to develop zero boil off (ZBO) systems for cryogenic operations, mainly liquid helium and liquid hydrogen systems. Early work focused on reliquefier concepts, using the ullage gas directly as the working fluid [1-3]. As the pressure in the vessel increases, ullage gas is compressed, cooled and then expanded in an open cycle, using recuperative heat exchangers to recover refrigeration. The first re-liquefier proposed for LC-39 was in 1977 by Martin Marietta, but management was concerned that implementation, which required opening the tank and modifying the pressure systems boundary, was a risk to the upcoming Space Shuttle launch [4]. In the early 1990's, Ergenics Inc. proposed a system that would capture boil off losses in a metal hydride compressor bed, used to run a Joule-Thompson refrigerator precooled with liquid nitrogen in batch processes [5]. Hydrogen Consultants Inc. later won a Phase II SBIR grant to prove the concept of a metal hydride compressor design that could run a continuous J-T refrigeration system sized to provide just enough refrigeration to overcome the steady heat leak into the tank [6]. Both these efforts included economic analysis that showed that ZBO at LC-39 was practical and cost effective.

Around the same time, NASA began looking at ZBO concepts using close cycle refrigerators for in-space use. First, these were smaller scale tests using mainly pulse tube and G-M refrigerators. Often, these cryocooler cold heads have been located in the upper region of the tank, condensing the ullage gas

[7]. Similar systems have also been developed to maintain liquid air with the proper oxygen concentrations [8]. For zero gravity operations when the liquid/vapor interface is less well defined, pumps have been used to create a forced convection flow of liquid across the AC cryocooler cold head [9,10]. More recently, ZBO of oxygen and nitrogen have been achieved with a DC refrigerant flow using a tube on tank design, and reduced boil off of LH₂ with a distributed cooling shield has been demonstrated to provide for isothermal tank conditions [11].

After completion of the Shuttle Program, the KSC Propellant Management Group performed a study of LH₂ acquisition, use and loss over the life of the program [12]. It found the Agency's two largest users of liquid hydrogen, KSC and SSC, lose approximately 50% of hydrogen purchased because of a continuous heat leak into storage and transportation vessels, transient chilldown of warm cryogenic equipment, liquid bleeds to maintain interface temperature, ullage losses during venting, and operational methods. These losses were quantified and grouped into three general categories: Replenish Loss, Storage Loss, and Load Loss.

The Replenish Loss can be subdivided into three groups, (1) loss due to heat input into the tanker during transit from source to LC-39, (2) loss required to build pressure during the propellant transfer from tanker to the LC-39 ground storage tank, and (3) loss due to LC-39 replenish system chill-down. Adding the three contributions and normalizing to the total quantity purchased, the overall replenish loss averaged 12.6% of the LH₂ purchased during the program. The storage loss comes from the normal evaporation of the cryogenics due to continuous heat leak. Current LH₂ ground storage tanks are 3,220,000 liters, double walled tank insulated with perlite in a vacuum. Each ground storage tank has its own evaporation profile as a function of the quantity of LH₂ in the tank. The average evaporation rate for the studied period was 1,200 liters/day and 2,700 liters/day for LC-39A and LC-39B, respectively. The loss from normal evaporation accounts for approximately 12.2% of total purchased LH₂. Load losses are due to transient flow processes and boil off in the poorly insulated flight tank. Either high power refrigeration systems or large gas storage volumes are needed to recover load losses and therefore will not be considered further at this time.

For ground systems, the argument for cryogenic refrigeration system for ZBO storage becomes one of pure economics. The economic trade for propellant ZBO depends on the cost of propellant and system performance versus the operational and capital costs of a cryogenic refrigeration system.

Consider the typical cryogenic system. As heat leaks into the system, a predictable mass flow rate exits the gas vent. The mass flow rate is a function of the heat leak, the type of liquid stored, and the temperature as it exits the system. In a pure ZBO system, the refrigerator capacity matches the heat leak. Given the work energy required to produce a quantity of refrigeration depends only on the temperatures of the cycle and the system efficiency, we can find the ratio of electrical work required to hydrogen mass lost. Then multiplying that by electrical rates and delivered hydrogen cost gives the ratio of electrical energy cost per vented hydrogen cost.

$$Cost\ Ratio = \frac{(h_{fg} + c_p \Delta T)}{\frac{T_c}{T_h - T_c} \eta} * \frac{electric\ rate\ (\frac{\$}{kW-hr})}{Hydrogen\ cost\ (\frac{\$}{kg})}$$

The operational cost savings associated with zero boil off is a known function, determined by the price paid for hydrogen, the price paid for electricity, the efficiency of the refrigerator, the heat rejection temperature of the refrigerator, and the temperature that the venting gas leaves the system. Figure 1 shows the relationship for this cost ratio for a variety of efficiencies and electrical and hydrogen costs. The best case scenario is a refrigerator efficiency of 20% and an electric rate of \$0.06 per kW-hr, and the worst case is a refrigerator with an efficiency of 15% and an electric rate of \$0.08 per kW-hr. This demonstrates that ZBO of hydrogen is economical and it is estimated that 12-19 cents in electricity will save one dollar worth of liquid hydrogen. This does not include labor hours, however it is assumed that the additional effort required for refrigerator monitoring and maintenance would be offset by saving (and operational impacts) from requiring less tanker deliveries.

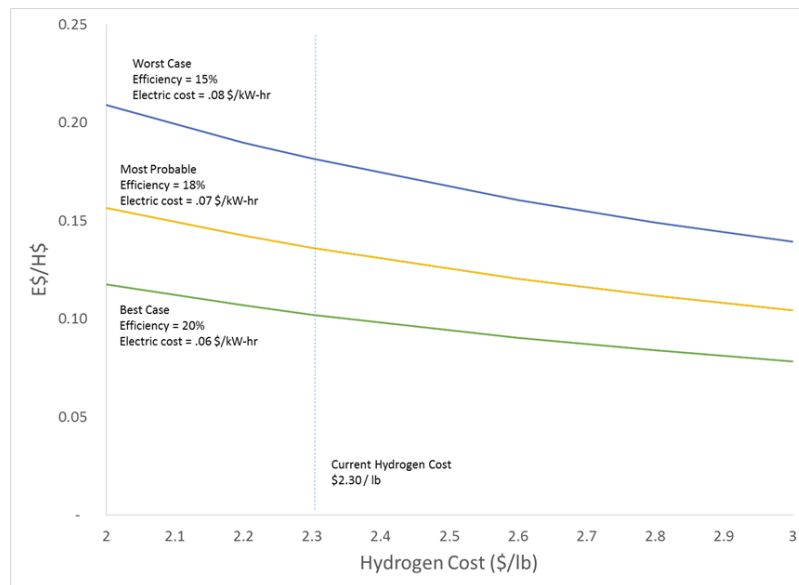


Figure 1. Cost ratio of various IRAS ZBO scenarios

2. Ground Operations Demonstration Unit for Liquid Hydrogen (GODU-LH2)

The IRAS concept is novel in that it cools the liquid directly, minimizing the thermal resistance between the refrigerant and the fluid to be cooled while using only free convection. This offers some advantages over past systems. Cooling the liquid directly allows for control of the bulk temperature of the fluid as opposed to pressure control of the ullage. This also enables conditioning or densification of the propellant, and can be used to store refrigeration energy in the liquid to allow greater response during transient operations. Using free convection requires less active components than the forced convection methods and doesn't add heat from a pumping system.

The research and development of integrated refrigeration systems for small-scale liquid hydrogen tanks have been successfully advanced in recent years. From 2002 to 2006, KSC and The Florida Solar Energy Center (FSEC) collaborated on a small scale IRAS test bed [13]. A commercial Gifford-McMahon cryocooler (Cryomech AL325) was integrated into a 150 liter LH₂ dewar using a heat pipe to transfer refrigeration to copper cooling straps located in the liquid region. Testing was conducted demonstrating the ability to produce zero boil off, densification, liquefaction, tests. With the cryocooler operating at full power, the test bed had the ability to store LH₂ at temperatures close to 15 K.

Recently, NASA's Advanced Engineering Systems program funded development of a large scale prototype cryogenic ground system at KSC deemed the Ground Operations Demonstration Unit for Liquid Hydrogen (GODU-LH2) that utilized IRAS technology. This system was tested throughout 2016, and represented a 700 fold increase in volumetric scale compared to the previously mentioned FSEC effort. Such a significant increase in scale was crucial to demonstrating the capability of IRAS to maintain hydrogen in a system relevant to actual launch facilities.

The IRAS heat exchanger is supplied with approximately 22 g/s of cold gaseous helium from a Linde LR1620 refrigerator—a Brayton cycle unit with piston expansion and provisions for liquid nitrogen (LN₂) pre-cooling. The refrigerator has rated capacities of 880 W and 390 W at 20 K, with and without LN₂ precooling respectively, and employs independent instrumentation and command and control. The cycle is driven by an RSX helium compressor that includes systems for oil separation and gas management. The refrigeration system, along with ancillary equipment, is housed in a standard 12 m ISO shipping container to allow for transportation to other test facilities in the future. A simplified functional diagram of the GODU-LH2 system is given in Figure 2, and depicts how the primary subsystems are integrated. Central to the design is the aforementioned 125,000 liter IRAS tank. This vessel was originally constructed in 1991 and used by the Titian-Centaur program as NBP LH₂ storage at launch complex 40 at the Cape Canaveral Air Force Station, but was repurposed for GODU-LH2 in

2011. It is a horizontal-cylindrical configuration, vacuum-jacketed with 80 layers of multi-layer insulation, and has a steady-state heat leak of approximately 300 W (verified by LH₂ boil-off testing). Modifications were required to transform this standard NBP vessel into a next generation IRAS tank: construction of the internal IRAS heat exchanger, internal stiffening rings to accommodate the sub-atmospheric pressure associated with densification testing, an updated man-way feed-through plug to incorporate instrumentation and refrigerant penetrations, and temperature rakes to map the vertical, axial and radial tank temperature profile (20 silicon diodes in total). Details regarding the design and construction of the IRAS tank have been extensively covered in previous publications [14 &15].

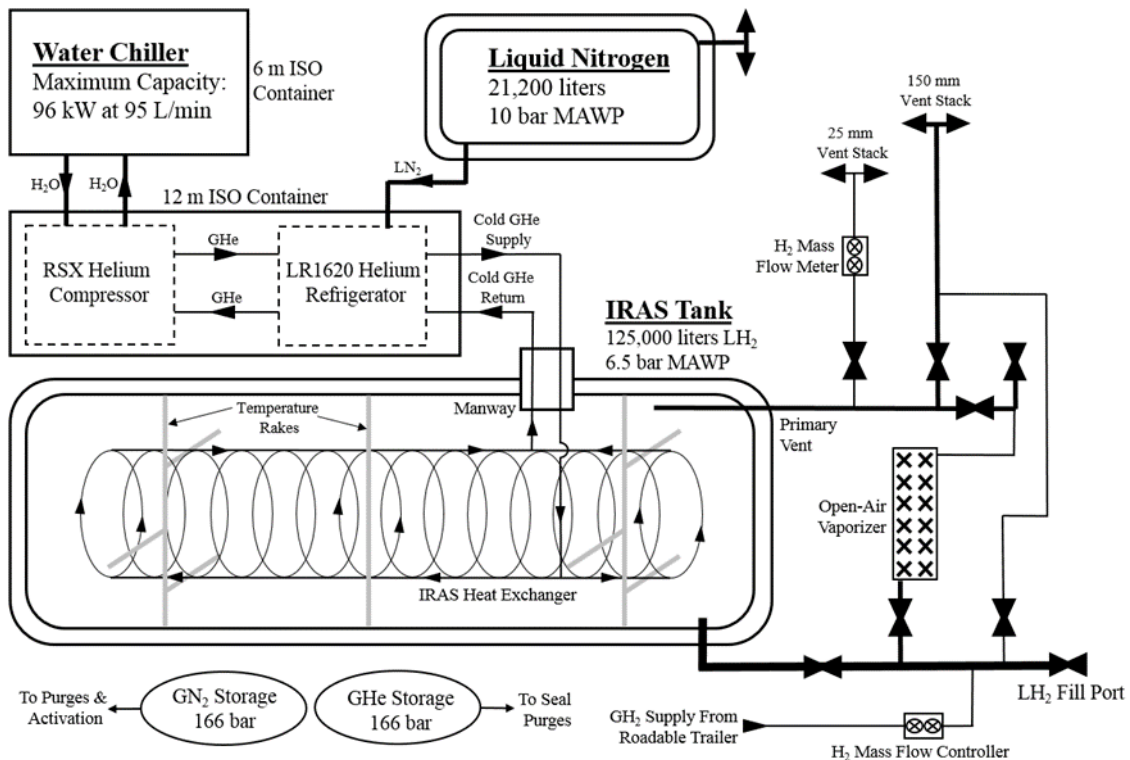


Figure 2. GODU-LH₂ Simplified Functional Diagram

3. IRAS Zero Boil Off Methodology

The GODU-LH₂ project has the following three primary test objectives:

- Zero Loss Storage and Transfer – Use IRAS systems to remove system heat loads from steady heat leak (ZBO) and transient chill down operations
- Propellant Densification – Use IRAS systems to control the storage state of LH₂ below the normal boiling point (NBP)
- In-Situ Liquefaction – Use IRAS systems to demonstrate liquefaction of gaseous hydrogen (GH₂) inside the storage tank.

This paper is focused on just the ZBO portion of the test plan, details on other test results will be published elsewhere. Zero boil off is defined here as the ability to store a cryogenic liquid without venting and product loss for indefinite periods of time. This can be done in continuous processes where the state of the hydrogen is essentially constant, or in batch processes where the hydrogen can undergo periods of pressurization followed by depressurization. But over time the LH₂ must be returned to its original state. In the GODU-LH₂ testing, ZBO was achieved three ways.

- Temperature control – A continuous ZBO process using the refrigerator command and control software to control the helium supply temperature by the refrigerator output heater.

With fixed helium flow rates and temperatures from the refrigerator, the cooling capacity is constant and the LH₂ will eventually reach an equilibrium state in the tank.

- Pressure control – Another continuous ZBO process similar to temperature control except the refrigerator output heater is controlled by NASA software using the IRAS tank pressure as the control point. If the tank pressure increases above the set point, the heater power is reduced and more refrigeration capacity is delivered to the tank.
- Refrigerator duty cycling – The minimum energy ZBO path should depend on no added heat. This can be accomplished by turning on and off the refrigerator and running at full power when it is on. This approach will create pressure and temperature cycles in the LH₂ but over time the LH₂ returns to its initial state and there is no hydrogen vented.

Details of the test results of each of these methods is presented below.

4. Pressure Control Test Results

The GODU-LH₂ system was built with an ability to control the refrigeration power delivered using the tank pressure transducer as the feedback mechanism. The control software was written to use PT1 as the control point and all results in this section are referenced to PT1. 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. Whereas, from below, the software needs to introduce excessive heat into the tank in order to drive the pressure up to the set-point. The standard ZBO-PC test sequence was to set the control pressure to 18.0 psia, wait at least 24 hours after stabilization, then decrease the control pressure to 17.5 psia, wait for at least 24 hours after stabilization, then increase the control pressure to 18.5 psia, stabilize, and finally decrease the control pressure to 16.5 psia. No LN₂ pre-cooling was necessary for the ZBO testing.

The ZBO pressure control test at the 33% fill level was conducted between April 26, 2016 and May 3, 2016. This was immediately after the 33% densification test had been performed. The liquid had warmed back up to above the NBP when the test was started. The start time for the test was when the tank pressure first reached the set point of 17.5 psia. **Error! Reference source not found.** shows the tank pressure and center rake temperatures for the duration of the test. It is apparent that the system is able to control the tank pressure somewhat precisely. For this test the tank pressure is biased slightly lower than the set point, varying from -0.5% to -0.2% from the set point. The average standard deviation over the duration of time for set points 1, 2 and 3 was only 0.04 psi. Based on the undershoot of the first control point and the consistent lower readings, the PID Gain was adjusted multiple times during the testing to allow better control. This adjustment was successful as later ZBO tests provided more precise control of tank pressure. The system responds faster when approaching the set-point pressure from below rather than above. From above, the average slope is roughly 0.07 psi/hr, while from below it is 0.2 psi/hr. As expected, the tank temperatures trended with the pressure although the response time was slower. Data shows a small 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 to the bottom manifold of the heat exchanger.

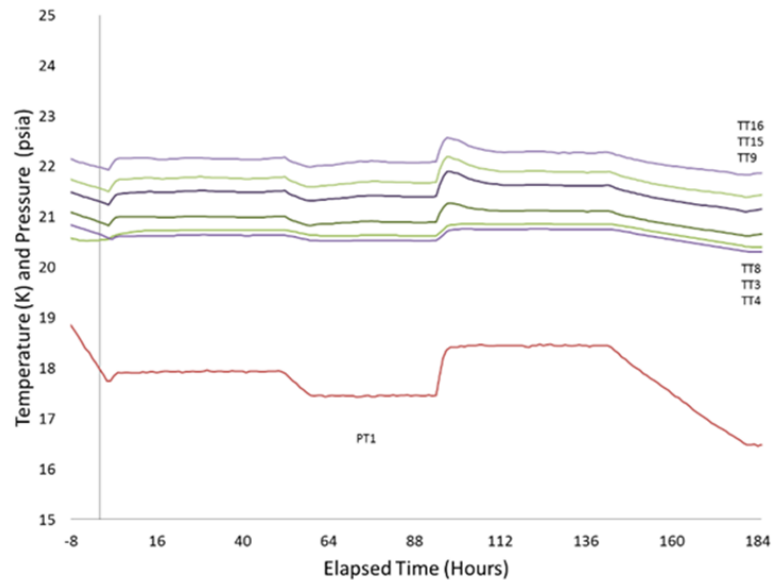


Figure 3. Pressure and Temperature Profile during 33% Fill ZBO Pressure Control Testing

The ZBO pressure control test at the 67% fill level was conducted between June 12, 2016 and June 23, 2016. The previous week the duty cycle ZBO test was conducted so the refrigerator was operating at full capacity and the tank pressure was decreasing. The pressure control test started around midnight when the tank pressure reached the 18 psi set point. There was no overshoot of the control point for this test. The tank pressures were again slightly lower than the set point, averaging 0.03 psi low, but within -0.2% of the set point. The depressurization rate between set points was consistent at -0.04 psi/hr, while the pressurization rate was 0.14 psi/hr. The tank temperatures also tracked the pressure, with the bulk liquid following the saturation temperature curve. The two ullage temperatures on the center rake were within 1K of the bulk liquid. Temperature data was lost late in the test but was working in time to record the final set point equilibrium.

The ZBO pressure control test at the 100% fill level was conducted between August 26, 2016, and September 5, 2016. The test was started two days after the completion of the 100% boil off test and the tank had been locked up and self-pressurized since that time. Again the tank pressure hits the control point within +0.0 / - 0.03 psia. The pressurization rate between tests was 0.13 psi/hr, driven by the refrigerator heater. The depressurization curves were not as linear as the past tests, but averaged -0.07 psi/hr and -0.04 psi/hr. Temperature data during the test was intermittent due to power surges causing the LabVIEW I/O boxes to shut down but shows much more stratification than the previous test, and all the center rake diodes are in the liquid at this time.

The ZBO testing using tank pressure as the control variable was completely successful. Not only did the system show the ability to maintain the liquid hydrogen as a liquid with no losses for an indefinite time period, it demonstrated the ability to control the propellant to any storage condition desired. Testing at the three different liquid levels all showed excellent controllability and the only difference between tests was the amount of time required to reach steady state after changing from one set point to the next. The pressure response is faster than the temperature response, but eventually the liquid temperatures reach a steady state as well.

4. Temperature Control Test Results

The second method of zero boil off control was referred to as temperature control. The Linde refrigerator was supplied with a built in capability to control the supply temperature of the helium. There was more temperature control testing conducted at the 33% fill level than the other fill levels. Temperature control testing with set points of 20K, 19K, 18K, 17K and 16 K were all successfully completed during this time

period as there was no hydrogen venting. The response time of the set point variable was very fast, reaching the prescribed helium temperature via the internal heater in a matter of minutes. But it was found that complete pressure and temperature stabilization of the liquid hydrogen took a much longer time depending on how close the eventual equilibrium point was to the initial conditions. All these tests took a long time period to stabilize and so for later fill levels of 67% and 100% testing was only conducted at 18 K for comparison purposes. The data in the rest of this section therefore only discusses results with a helium supply set temperature of 18 K.

The 33% ZBO Temperature Control test occurred between July 1 and July 11, 2015. The test started when the temperature set point was changed from 19K down to 18K. There was several brief interruptions in the test around the 140 hour and 170 hour times due to planned refrigerator shut down due to software updates. The testing concluded when the temperature set point was decreased to 17K. **Error! Reference source not found.** shows the tank center rake temperatures and tank pressure during the test. It is evident that the conditions in the tank are not in equilibrium and the tank pressure and temperatures never stabilize. The tank is depressurizing at a rate of roughly -0.03 psi/hour. The temperatures show small level of stratification on the center rake with the ullage temperature only 1.5K above the liquid temperature. These temperatures also fail to completely stabilize.

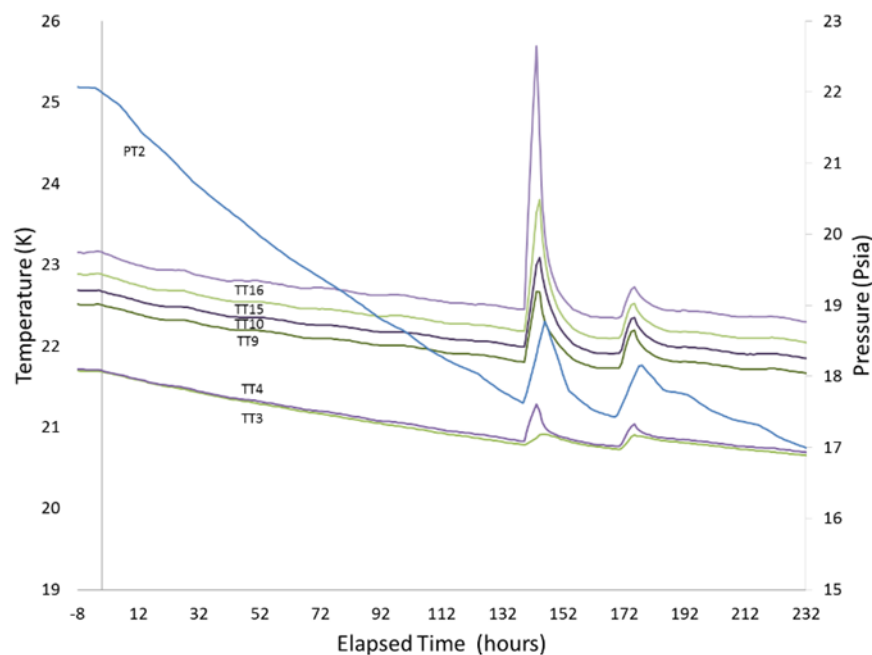


Figure 4. Pressure and Temperature Profile during 33% Fill ZBO Temperature Control Testing

The 67% ZBO Temperature Control Test was conducted between June 21 and June 29, 2016. The test was started at the completion of the 67% ZBO Pressure Control Test, with the tank pressure PT2 stable at 16.0K and liquid temperatures stable between 20.3K- 20.4K. As with the previous test at 33% fill level, the tank pressure and temperature never achieves steady state with a week of testing. The pressure increased from 16 psia to 17.2 psia, a pressurization rate of 0.006 psi/hr. The liquid temperatures show a different stratification pattern, with TT3 reading higher than TT4, TT9, and equal to TT10. The ullage temperatures are slightly stratified, approximately 1.2K above the liquid temperatures. All the temperatures continue to rise during the duration of the test.

The 100% ZBO Temperature Control test was conducted between September 6 and September 12, 2016. Like the 67% fill level test, this was only tested at the 18 K set point. The test duration was slightly less than 1 week due to the end of the fiscal year approaching. The test was started immediately after the ZBO pressure control test and the tank pressure was stable at 16 psia initially. At the conclusion of the test the pressure had climbed to 18.8 psia, for an average pressurization rate of 0.018 psi/hr. The

liquid temperatures were more stratified than in previous tests as described in the ZBO pressure control at 100% test section. Again the tank temperatures never stabilized.

The ZBO testing using temperature control of the helium supply met the test objectives. The system demonstrated the ability to maintain the LH_2 in a liquid state indefinitely without venting. However, achieving a steady state condition was elusive as the fast helium temperature response time did not create an equally fast hydrogen storage response time.

5. Duty Cycle Results

Numerous zero boil off tests were conducted, both intentionally and unintentionally, in a manner where the refrigerator cycled off and then on. This was referred to a duty cycling. Of these numerous tests, one representative test was chosen at each liquid level to be presented in detail in this paper. These tests were used to measure pressurization and depressurization rates, duty cycle ratios, and compare fluid behavior between the different liquid levels.

The ZBO Duty Cycle test data for the 33% fill level was completed between August 4, 2015 and August 10, 2015. The test period officially started at 825 am when the helium compressor shut down due to high helium temperature. The tank was in the process of a ZBO Temperature Control test at the time of the shutdown. The tank pressure was stable at 16.1 psia and the tank center rake temperatures were stable between 20.4 K in the liquid and 22.1 in the gas at the top of the rake. The hydrogen temperatures immediately begin to warm up and stratify. Cooling to the tank was re-established around 4 pm on August 7 with the total pressurization time being 79 hours and 35 minutes. The maximum pressure was recorded as 32.3 psia, resulting in an average pressurization rate of 0.20 psi/hour. The refrigerator was turned on without LN2 pre-cooling and was left on until the tank pressure reached the initial starting pressure of 16.1 psia. The tank pressure decreased rapidly as the temperatures de-stratified. Once this de-stratification was complete, the pressure then slowly decreased over the next two days while heat was being pumped out of the liquid until the original starting point was reached. The depressurization rates for the ullage collapse and liquid cooling phases of the test were -0.56 psi/hour and -0.10 psi/hour, respectively. Data for the tank pressure and center tank temperatures is shown in **Error! Reference source not found.** It took 92 hours for the refrigerator to remove 80 hours of heat leak, giving the refrigerator a duty cycle of 1.15 hours of on time for every hour of off time.

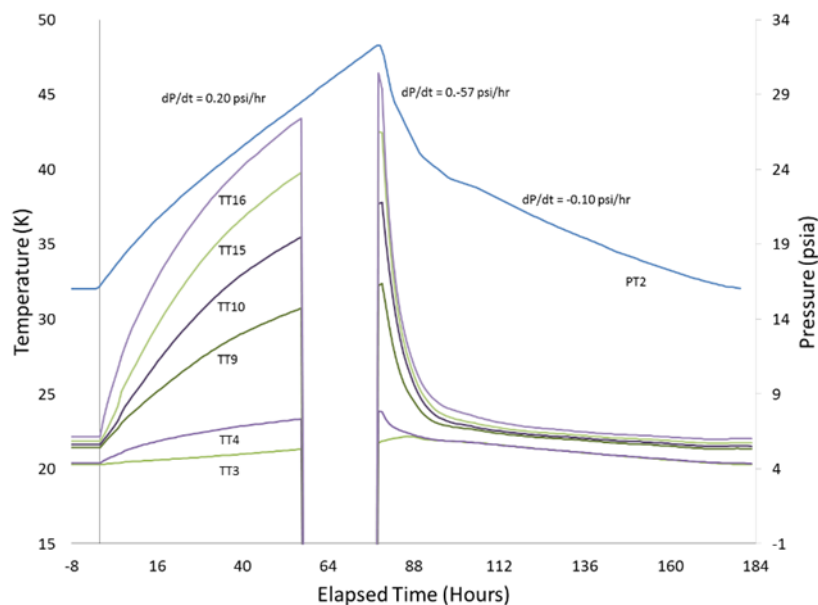


Figure 4. Pressure and Temperature Profile during 33% Fill ZBO Duty Cycle Testing

The ZBO duty cycle testing at the 67% fill level was conducted between June 5 and June 13, 2016. The start time for the test was at 11:21 pm when the refrigerator shut down due to low helium pressure. The system was in a ZBO temperature control test at the time. The tank pressure was stable at 17.5 psia at the time. The center rake temperatures were fairly stable also with liquid temperatures at 20.6 K and ullage temperatures around 22 K. Cooling was re-established around 10 am on June 9, after being off for a total of 82 hours 40 minutes. The maximum pressure was 31.6 psia, corresponding to an average pressurization rate of 0.17 psi/hr. The refrigerator was turned on without LN2 pre-cooling and was left on until the tank pressure approached the initial starting pressure. Again the tank pressure decreased rapidly as the temperatures de-stratified. The depressurization rates for the ullage collapse and liquid cooling phases of the test were 0.43 psi/hour and 0.08 psi/hour, respectively. The duty cycle ratio is calculated to be 1.05.

The duty cycle test for the 100% full liquid level was conducted between August 23 and August 26, 2016. This was near the end of the test period for the project and subsequently the timeline was compressed. The test period officially started at noon when the AROV10 vent valve was closed to stop the 100% boil off heat leak characterization. The tank pressure was stable at 15.9 psia and the tank center rake temperatures all reading liquid temperatures between 20.2 K and 20.3 K. Cooling to the tank was re-established around 2 pm on August 24 with the total pressurization time being 26 hours. The maximum pressure was recorded as 22.5 psia, resulting in an average pressurization rate of 0.25 psi/hour. The next day the refrigerator was turned on without LN2 pre-cooling and opened to the tank. To save time, testing was terminated at the start of the ZBO pressure control test, when the pressure reached 18 psia. This did not allow for a full cycle back to 15.9 psia, but stable depressurization rates were measured and final timelines can be estimated. The depressurization rates for the ullage collapse and liquid cooling phases of the test were 0.27 psi/hour and 0.05 psi/hour, respectively.

Overall, ZBO Duty Cycle operations were accomplished with great success, showing the ability to remove the heat leak during the off cycle with an on cycle of roughly the same time period. There was zero vent loss at every test. Temperatures and pressures were not steady during the test period by definition of being on a cycle, but ending temperatures and pressures matched the start conditions for the 33% and 67% fill level.

6. Conclusion

Using a method called Integrated Refrigeration and Storage, NASA cryogenic engineers have demonstrated the capability to maintain liquid hydrogen in zero boil off state for indefinite time periods. Using a Brayton cycle cryogenic refrigerator coupled to a submerged internal heat exchanger, zero boil off operations were conducted on large quantities of liquid hydrogen for a total period of over 13 months. Three different ZBO methods were tested. Using the tank pressure as the control point demonstrated the most precise control over the state of the fluid, while temperature control of the refrigerant required longer time periods to stabilize and there was less control of the final conditions. Both of these methods added heat using the refrigerator heater. The final method of duty cycling was the minimum energy solution but did not provide continuous control over the fluid state. Results of these tests will be used to help design an IRAS type system into future KSC launch pad architectures.

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