Cryogenics 88 (2017) 147–155

Contents lists available at ScienceDirect

Cryogenics

journal homepage: www.elsevier.com/locate/cryogenics

Research paper

# Final test results for the ground operations demonstration unit for liquid hydrogen

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ABSTRACT

Described herein is a comprehensive project—a large-scale test of an integrated refrigeration and storage system called the Ground Operations and Demonstration Unit for Liquid Hydrogen (GODU LH2), sponsored by the Advanced Exploration Systems Program and constructed at Kennedy Space Center. A commercial cryogenic refrigerator interfaced with a 125,000 l liquid hydrogen tank and auxiliary systems in a manner that enabled control of the propellant state by extracting heat via a closed loop Brayton cycle refrigerator coupled to a novel internal heat exchanger. Three primary objectives were demonstrating zero-loss storage and transfer, gaseous liquefaction, and propellant densification. Testing was performed at three different liquid hydrogen fill-levels. Data were collected on tank pressure, internal tank temperature profiles, mass flow in and out of the system, and refrigeration system performance. All test objectives were successfully achieved during approximately two years of testing. A summary of the final results is presented in this paper.

## 1. Introduction

Recognizing the need for more capable and efficient cryogenic systems, NASA's Advanced Exploration Systems (AES) Program funded the development of the Ground Operations Demonstration Unit for Liquid Hydrogen (GODU $LH_2$) in 2012. The GODU $LH_2$ project is a relevant-scale prototype of an advanced $LH_2$ system using Integrated Refrigeration and Storage (IRAS) technology to enable new types of operations not previously possible at the launch pads. IRAS couples state-of-the-art reverse-Brayton-cycle cryogenic refrigerators with liquid storage dewars using a submerged cold heat exchanger to remove energy directly from the fluid. If the refrigeration capacity matches the heat leak, a range of zero boiloff (ZBO) operations is possible. If the refrigerator capacity exceeds the heat leak, the liquid can be conditioned or densified, or gaseous hydrogen can be introduced to be liquefied. Small scale demonstrations of the IRAS technology were successfully completed with liquid hydrogen in 2005 [1] at the Florida Solar Energy Center and later with liquid oxygen at the Kennedy Space Center in 2009 [2]. The GODU $LH_2$ project had three primary demonstration objectives for using IRAS on a relevant scale: (1) zero-loss storage and transfer of $LH_2$, (2) densification of $LH_2$, and (3) liquefaction of gaseous hydrogen ($GH_2$). Design and construction took three years between 2012 and 2014, and 19 months of testing was completed between March 2015 and September 2016. A high level summary of all the test results are presented here. Additional details of zero boil off tests and densification tests done during the GODU LH2 testing are available in other published papers [3,4].

## 2. Ground operations demonstration unit for liquid hydrogen

The functional diagram of the GODU $LH_2$ system is given in Fig. 1. The GODU $LH_2$ system uses a 125 $m^3$ vacuum-jacketed (VJ) IRAS tank with multilayer insulation as the primary storage vessel. This tank was previously used on Launch Complex 41 for the Titan-Centaur Program. Pretest estimates of the tank heat leak from analysis and past operational data were approximately 300 W. The IRAS tank is instrumented to record tank pressure and liquid and vapor temperatures. Three temperature rakes with Si-410 silicon diodes accurate to ± 0.1 K are installed and located to provide vertical, longitudinal, and radial temperature gradients. The forward and aft rakes include arms to measure temperatures near the wall away from the centerline, whereas the center rake has only centerline diodes for better vertical resolution. The inner tank was modified with stiffening rings to allow for sub-atmospheric operation. The tank has redundant transducers for monitoring tank pressure. There are two vent systems, a 15 cm stack sized for high flow venting and emergency relief and a smaller 2.5 cm stack sized for the normal evaporation rate with a mass flow meter to monitor the flow rate during venting. Inside the IRAS tank is a cold heat exchanger

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http://dx.doi.org/10.1016/j.cryogenics.2017.10.008
Received 9 July 2017; Received in revised form 27 September 2017; Accepted 4 October 2017
0011-2275/ 

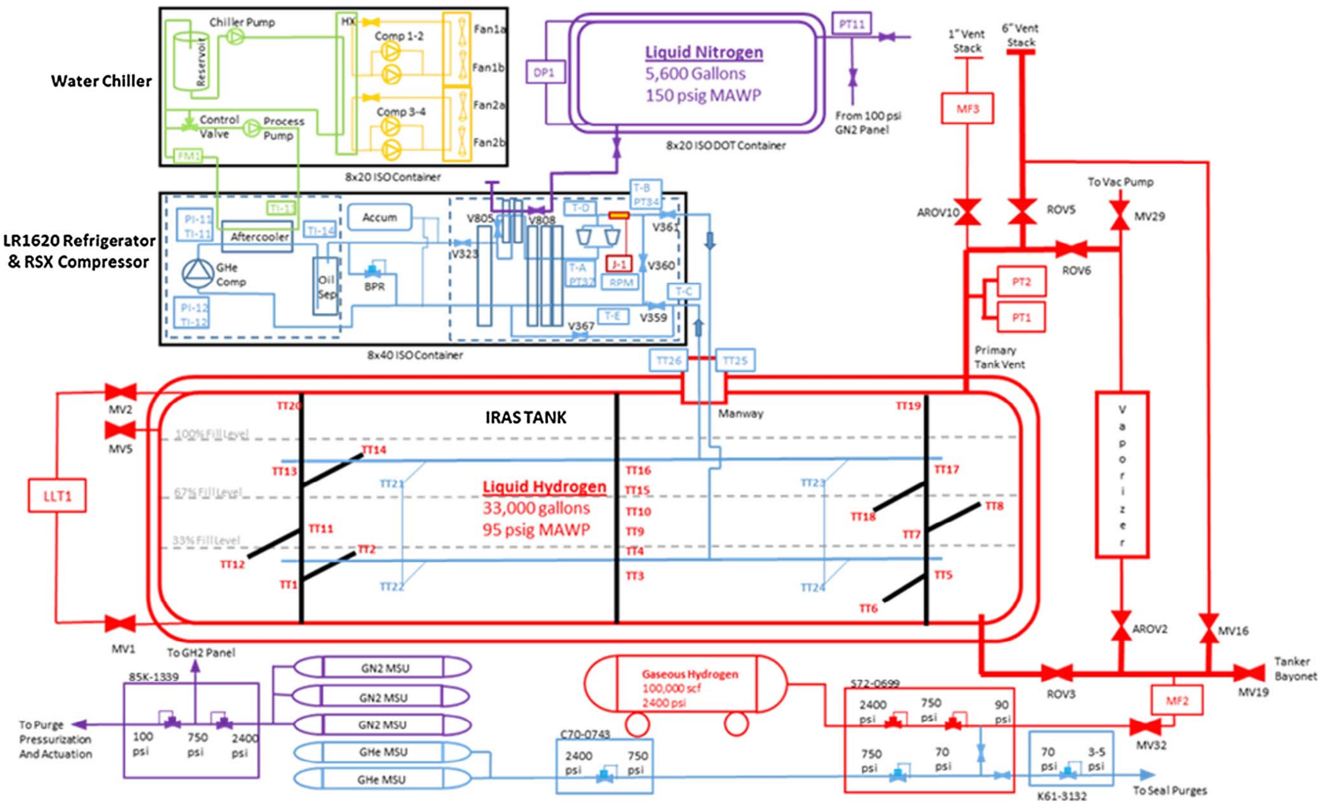


**Fig. 1.** GODU LH2 functional diagram.

(CHX), using gaseous helium which is connected to a cryogenic refrigerator. The CHX consists of 2.5 cm (1 in.) tubular stainless-steel supply and return headers located at the 25% and 75% fill levels and connected by 40 parallel 0.6 cm (1/4 in.) tubes that make up the bulk of the CHX surface area of approximately 83.6 $m^2$ (900 $ft^2$). Two of these tubes are instrumented with diodes to record helium inlet and outlet temperatures. The CHX is supplied with cold gaseous helium (GHe) from a Linde LR1620 refrigerator and RSX compressor at approximately 22 g/s. This system uses a reverse Brayton cycle with piston expansion engine and includes provisions for liquid nitrogen ($LN_2$) precooling. The refrigerator has a rated capacity of 390 W at 20 K *without* $LN_2$ precooling and up to 880 W at 20 K *with* $LN_2$ precooling. The refrigerator has independent command and control and instrumentation, notably for expander speed and cold helium supply and return temperature. A separate command and control system developed by NASA is also used for controlling refrigerator capacity based on IRAS tank pressure during some phases of testing. The RSX compressor is cooled by a separate 96 kW circulating water chiller at 292 K and includes systems for oil separation and gas management. The entire refrigeration system is containerized to allow for transportation to other test facilities, and this container has an integrated purge blower to keep the container at a slightly positive pressure to allow for operation in Class 1 Division 2 locations. Details of the refrigeration system, the IRAS tank, and the test plan have been published previously [5,6].

## 3. Test plan

The GODU $LH_2$ test matrix includes testing of each of the primary objectives at three different fill levels—33%, 67%, and 100%—with one delivered tanker of $LH_2$ filling roughly ⅓ of the tank. Additional boil off testing occurred at each fill level to characterize the tank heat leak as a function of liquid level.

The zero-loss storage and transfer objective consisted of multiple tests split between ZBO tests storage tests and zero-loss chilldown and tanker offload transfer tests. The ZBO storage tests were performed at each liquid level using three different control methods: helium supply temperature control, IRAS tank pressure control, and on/off duty cycling. Temperature control tests used Linde software to control the helium refrigerant supply temperature to the tank. Pressure control tests used KSC developed software to control the refrigeration power based on tank pressure response. Both these tests used internal heaters in the refrigerator to vary the helium temperature as needed, thereby introducing heat into the system to allow for continuous control. The duty cycling tests did not provide for continuous control, instead refrigeration was supplied in batch processes at full power. None of the ZBO storage tests required LN2 precooling. For the zero-loss-transfer objective, all tanker supply operations were performed with no venting losses, saving roughly 13% more of the delivered $LH_2$ quantity than typical KSC practices. After each no loss tanker offload was complete, a short boil off test was completed to characterize the tank heat leak at that fill level. The initial cooldown of the tank was also done using the refrigerator to cool the $GH_2$ in the tank to the normal boiling point (NBP). These zero-loss transfer tests typically used LN2 precooling to maximize refrigerator capacity and minimize required test time.

Densification tests were also conducted at each of the three liquid levels. During each densification test, all the tank liquid and vent valves are closed. The refrigerator is run at full power mode with $LN_2$ precooling active. During densification operations, the IRAS tank pressure and liquid temperature decrease as long as the refrigerator capacity is greater than the tank heat leak. No helium gas pressure is applied to the ullage, and the tank pressure goes below atmospheric pressure. When the IRAS tank reaches the NBP, a low-pressure helium gas purge is applied to the stem seals and backside of all isolation valves and around the perimeter of all the flanges to prevent the intrusion of atmospheric air in the event of a leak. Eventually the system reaches an equilibrium temperature where the cryocooler refrigeration power equals the ambient heat load on the tank and refrigeration system. The pretest estimated minimum temperature for the system was 15 K. Data are