Modification of a liquid hydrogen tank for integrated refrigeration and storage

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Abstract. The modification and outfitting of a 125,000-liter liquid hydrogen tank was performed to provide integrated refrigeration and storage capability. These functions include zero boil-off, liquefaction, and densification and therefore require provisions for sub-atmospheric tank pressures within the vacuum-jacketed, multilayer insulated tank. The primary structural modification was to add stiffening rings inside the inner vessel. The internal stiffening rings were designed, built, and installed per the ASME Boiler and Pressure Vessel Code, Section VIII, to prevent collapse in the case of vacuum jacket failure in combination with sub-atmospheric pressure within the tank. For the integrated refrigeration loop, a modular, skeleton-type heat exchanger, with refrigerant temperature instrumentation, was constructed using the stiffening rings as supports. To support the system thermal performance testing, three custom temperature rakes were designed and installed along the 21-meter length of the tank, once again using rings as supports. The temperature rakes included a total of 20 silicon diode temperature sensors mounted both vertically and radially to map the bulk liquid temperature within the tank. The tank modifications were successful and the system is now operational for the research and development of integrated refrigeration technology.

1. Introduction
Utilization of liquid hydrogen as rocket fuel for launch vehicles has been a reality since the dawn of the space age. During the 1960s two identical 3.4M liter LH 2 spheres were constructed at NASA Kennedy Space Center (KSC) Launch Complex 39 A & B to service the first and second stages of the Saturn V moon rocket, and were later used to load the Space Shuttle’s External Tank (ET) for flight.

Extremely low density and high specific impulse makes LH 2 a superior propellant, however, possessing the second lowest normal boiling point (NBP) of all the common cryogens (20.4 K) also makes utilizing this commodity exceedingly difficult and costly. Over the duration of the Space Shuttle program NASA lost approximately 50% of the hydrogen purchased because of 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 endeavor, these losses constituted a large, unrecoverable cost. This reality made apparent the fact that NASA needed to invest in next-generation cryogenic storage and transfer technologies, and drove the development of the Ground Operations Demonstration Unit for Liquid Hydrogen (GODU-LH 2) at KSC.

Central to GODU-LH 2 is the concept of Integrated Refrigeration and Storage (IRAS), which allows energy to be removed directly from the LH 2 via a broad area heat exchanger inside the tank integrated...
with a cryogenic refrigerator, and affords three unique capabilities: (1) Zero Boil-Off (ZBO): if the tank heat-leak and refrigeration power are balanced ZBO can be achieved, and the liquid level can be maintained indefinitely; (2) Liquefaction: gaseous hydrogen can be introduced into the vessel and liquefied to fill the tank, as opposed to using liquid tanker trucks; and (3) Densification: if the refrigeration power is greater than the tank heat-leak the liquid can be cooled below its NBP and made more dense in the process.

Construction of a large-scale IRAS tank elevates the issue of how to evenly distribute the refrigeration power throughout the entire liquid volume coupled with the sub-atmospheric pressures associated with densified operations. For GODU-LH$_2$, IRAS modifications were made to a 125,000 liter horizontal LH$_2$ storage tank originally fabricated by Minnesota Valley Engineering in 1991 for the Titan program. The vessel has an overall length of 21.3 m (12.2 m length between saddle supports), a 2.90 m diameter inner vessel constructed of SA240 304L stainless steel, 58.4 cm diameter man-way port, and a 655 kPa (gauge) design pressure. Figure 1 shows the GODU-LH$_2$ test site with the completed IRAS tank.

A reverse Brayton cycle cryocooler is used to provide cold helium refrigerant to the IRAS tank heat exchanger. This unit is a Linde Cryogenics model LR1620S, capable of 850 W of cooling at 20 K. The task of distributing this cold power throughout the inner tank is accomplished by a “whale skeleton” type heat exchanger for which the design details have been previously reported [2]. Operating at full power, the system has the capacity to sub-cool (i.e. densify) LH$_2$ to around 15 K, corresponding to a vapor pressure of 12.9 kPa (abs). Since no pressurant will be introduced to maintain the IRAS tank at a positive gauge pressure, the inner tank must be able to withstand an external pressure load in case the annulus vacuum is lost during densification operations. This requirement led to the decision to employ internal stiffing rings to strengthen the vessel, and required recertification of the tank per the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (BPVC).

To characterize the system performance, 24 silicon diode temperature sensors are employed inside the IRAS tank at strategic locations. Three different temperature rakes, housing 20 of the 24 diodes, are installed down the length of the tank to map the vertical and radial temperature profiles, and in-line feedthroughs report temperature readings of the cold helium refrigerant at two locations on the inlet and return manifolds inside the vessel.
2. Approach to the modified design

There were three high-level design drivers for the IRAS tank modifications. First, as the only means of entry and exit into the vessel was via the small man-way port located at the top of the tank, all components, materials, tools, etc. required to execute the modifications necessarily had to utilize this access point. Also, no welding was permitted due to safety and technical concerns, as well as to protect the delicate multi-layer insulation (MLI) wrapped around the outside of the inner vessel. These constraints meant that the stiffening rings, heat exchanger, and temperature rakes all had to be modular and assembled using fittings and bolted joints.

Second, as the tank was originally intended to be used only for normal boiling point (NBP) storage and transfer, the inner vessel wall was essentially smooth; no attach points existed that could be used to accommodate additional internal hardware. Therefore, synergy had to exist for the system of IRAS components being added. Design of the rings, heat exchanger and rakes had to be done in such a way as to exploit their individual and collective attributes.

Third, successful initial integration of all internal IRAS equipment was paramount—essentially, there was only one chance to get it right. Once the man-way was closed-out, the tank purged and cooled down, and the system made operational, it would be practically impossible to re-enter the tank in order to repair faulty instrumentation, leaking fittings, or to modify hardware.

3. Structural modification details and installation

Following the methodology found in the 2013 version of the ASME BPVC Section VIII, paragraphs UG-28 and UG-29, the maximum allowable external working pressure of the inner tank in its original, unmodified configuration was calculated and found to be only 14.5 kPa (gauge). This value was significantly lower than the estimated 87.6 kPa (gauge) that could be possible during a failure scenario assuming loss of annulus vacuum while densified to 15 K. Therefore, stiffening rings were required, and the BPVC was once again utilized to determine the adequate section, quantity and placement of the stiffeners. Various stiffener cross sections and quantities were explored until a satisfactory approach was developed: nine total rings, evenly spaced at 2.1 m intervals, with a C5x6.7 channel cross-section. This cross-section satisfied the required moment of inertia with considerable margin while keeping the total weight per ring to a minimum [3].

An additional requirement for non-welded internal stiffening rings was that an adequate means of support was necessary to prevent out-of-plane movement under radial loading. As a bonus, these supports would protect against potential ring tipping during cool-down of the inner tank, when large temperature differences between the top and bottom of the vessel could create unusual thermal contraction issues, and potential loosening of the rings from the tank wall. A system of 15 longitudinal stringers was devised to tie sets of stiffening rings together, effectively eliminating the chance that any one ring could tip were it to become loose. These stringers must also be allowed to contract length-wise without imparting large loads to their associated rings during cool-down from ambient temperature, so a telescoping feature—accomplished via precision bored, slip-fit pipes—was incorporated that allowed for some axial flexibility.

Because of the first design driver mentioned above, each ring had to be broken into three equal sections in order to fit through the man-way port. These sections would then be placed into their proper positions and bolted together with joint splices to form a continuous ring. Since no welding was allowed inside the tank, a means of loading each ring segment against the inner wall was necessary to maintain proper orientation. This was accomplished by incorporating a “thrust bolt” at each joint to force the three ring segments outward. These threaded rods spanned the three joints on the ring assemblies, and nuts were torqued outwards, acting on welded plates at the ends of each ring segment.

Accommodating other system design requirements—including the need for drain holes at the lowest point in the ring, placement holes for the longitudinal stringers, and attach points for the refrigeration heat exchanger—ultimately resulted in ring assemblies containing three unique segments. Figure 2 shows the design for a typical system of stiffening rings and stringers, and an installed bolted joint assembly.
A four-person team performed the ring and stringer installations. Initial placements were measured out and marked prior to beginning assembly, and then each of the nine rings was constructed as close to its final position as possible, using only pre-loading to hold them in place. Once all the rings were placed the stringers were installed and used as gauges to properly align the assemblies. Following this alignment and final adjustment each ring assembly was loaded to the maximum extent possible with the thrust bolts, and final torqueing of the joint fasteners commenced.

Overall, installation of the additional IRAS structural components was straightforward but extremely labor intensive. No major issues arose during installation, however, due to the weight of each ring segment (≈28 kg), construction of the ring assemblies required excessive physical effort—segments had to be manipulated and held in place for non-trivial periods of time while the bolted joints were constructed by other team members. Initial positioning and alignment of the rings proved crucial also, since once a ring assembly was completely bolted together, but not yet loaded against the tank wall, any adjustments had to be made incrementally using a dead-blow hammer. This action was undesirable for a number of reasons, hence care was taken to place the rings as close as possible to their final positions during initial construction.

4. Heat exchanger details and installation
Design of the “whale skeleton” heat exchanger was highly three-dimensional, with strategically bent cooling lobes to increase the heat transfer area, provide a flexible but stable structure, and intercept the maximum amount of heat at the tank boundaries. The broad area, networked heat exchanger includes supply and return manifolds (total of 37 m of 25 mm OD tubing, and located at the 25% and 75% fill levels respectively) and 40 cooling lobes (total of 244 m of 6.4 mm OD tubing). The flows were balanced end-to-end using precision orifice fittings as previously reported [2]. 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.

For the heat exchanger to be placed in the center of the tank volume, provisions were made to suspend it from the stiffening rings. This design feature was accomplished by four strategically placed eyebolts on each ring assembly, two inner and two outer. As manifold tubes were installed they were suspended from the eyebolts by stainless steel wire, the lower supply from the outer and the upper return from the inner. After leveling the supply and return tubes, each of the 40 cooling lobes was sequentially installed. Figure 3 shows the suspension methodology and a section of the completed heat exchanger assembly.
5. Instrumentation details and installation

To map the temperature profile during operation, three sensor rakes were designed and installed down the length of the tank. These employed a total of twenty silicon diode sensors: fourteen at vertical locations and six at radial locations. The middle rake reported only vertical data and was placed at the center of the tank, while the outer units had three radial arms each, and read both vertical temperatures as well as those close to the tank wall.

Common to each rake was a 38 mm x 38 mm aluminum box-beam center support that fastened vertically to the upper and lower parts of a chosen stiffening ring using J-hooks. Sensor stand-offs and radial arms were fabricated from G10 fiberglass tubes that interfaced to the box-beam via slip-fit holes so they could be removed and folded up during assembly. Stubs of round bar G10 were bored with through-holes to match the tips of the silicon diodes. The stub/sensor assemblies were affixed to their respective stand-offs using Stycast 2850FT (with catalyst 28LV) cryogenic epoxy, and wiring was fed up through the aluminum support beam and out the top. Adequate lengths of wire were left that could reach to the man-way feedthrough, and the ends were fitted with military spec round locking connectors. Each rake assembly was fully assembled in the laboratory, folded up, and delivered to the site for insertion through the man-way and subsequent installation within the tank.

In addition to the rake-mounted sensors, four diodes were also mounted in-line with the helium cooling lobes to determine the effectiveness of the heat exchanger. Two were placed in the supply side, and two in the return, at either end of the heat exchanger. Figure 4 shows the temperature rake configurations and an in-line feedthrough.
6. Man-way feedthrough details and installation
The original man-way plug had no instrumentation or fluid penetrations, only a capacitance probe for liquid level detection; it was therefore necessary to design and fabricate an updated unit for GODU-LH2. This task was completed at NASA Stennis Space Center (SSC) in Mississippi, and the unit shipped to KSC as an ASME BPVC certified vessel.

The updated design includes three bayonet-style fluid connections, two that interface to the refrigerator cold helium supply and return, and one for gaseous hydrogen supply. On the tank side, 25 mm Swagelok VCR fittings connect the helium supply and return ports to the heat exchanger flexible hoses.

For minimum heat leak, the empty volume inside the plug is filled with type K1 glass bubbles by 3M and evacuated. Also, five polished aluminum radiation shields are employed on the tank side, and are held in place by G10 hardware.

Four 24-wire Conax brand instrumentation feedthroughs are used to accommodate the silicon diode sensor wires exiting the tank. As with the temperature rakes, the ends of the feedthrough wiring are connectorized. This decision was debated due primarily to the fact that the military spec connectors available had not been certified to the low temperatures that they could be exposed to during GODU-LH2 testing. Exposure testing with LN$_2$ was performed in the laboratory with good results and the team ultimately agreed that the potential issues regarding hard-wiring all 96, 36-gauge diode wires in the field constituted a greater chance of instrumentation problems than would the mil-spec connectors. Also, the connectors were ultimately positioned above the radiation shields, keeping them significantly warmer than if they were to hang in the ullage space.

Figure 5 shows the man-way feedthrough during installation (note the five radiation shields, flexible hoses running to the heat exchanger, and instrumentation connectors), and after final closeout with the refrigeration supply and return lines connected.

![Figure 5](image_url)

7. Post-modification tests and final certification
Following close-out of the man-way feedthrough, the tank was subjected to a series of three tests required to gain ASME recertification: a positive and negative pressure test of the inner vessel, and a cold-shock using liquid nitrogen.

Per the BPVC, the positive pressure test was carried out at 125% of the design pressure using gaseous nitrogen. The negative pressure check was accomplished by breaking the vacuum in the annulus with
gaseous nitrogen, and then evacuating the inner vessel to a pressure corresponding to 1.1 times the 
maximum pressure difference possible during a failure. Once these tests were completed the annulus 
vacuum was restored, and two 15,000 L liquid nitrogen tankers were emptied into the warm vessel. 
Liquid level was monitored using the temperature rakes inside the tank and reported that roughly 19,000 
L remained after the initial cool-down.

Following the successful completion of all three required tests, the IRAS tank was officially 
recertified per ASME and fitted with an updated nameplate that reflects the new minimum operating 
pressure of 96.5 kPa (abs). The certified minimum operating temperature remains 20 K (even though 
the GODU-LH\textsubscript{2} target is 15 K) due to irreconcilable requirements put forth in the BPVC regarding 
Charpy impact testing. No fabrication or material specification documentation exists from the 
construction of the original tank. Therefore, in order to satisfy the impact test requirements at the lower 
temperature, coupons would have to be cut from various areas of the actual inner tank and tested. This 
approach would have rendered the vessel unusable, thus was never a realistic option. Instead, to operate 
at the lower temperature a waiver to the ASME certification is required, and must be approved by the 
owner/operator (NASA-KSC in this particular case).

In addition to the tests required to validate the tank structural modifications, over-pressure and decay 
checks were also conducted on the IRAS heat exchanger to verify integrity of the fluid system prior to 
interfacing the refrigerator to the man-way plug assembly.

8. Unique challenges and lessons learned

Beyond the original design challenges associated with the IRAS components, many others—both unique 
and underlying—existed that were uncovered during construction planning, and also in real-time during 
installation work inside the tank. The three main issues included (1) determining an efficient means of 
hanging the heat exchanger manifold tubes using stainless steel wire that was both strong enough, and 
provided the adjustability needed for leveling; (2) routing of the fragile instrumentation wire bundles 
from the temperature rakes, down the length of the tank to the man-way plug; and (3) maintaining overall 
cleanliness of the inner tank.

Coincidently, the solution for the first issue also took care of the second: the use of stainless steel 
carabineer style clamps at one end of each hanger wire. During assembly these clamps could be fastened 
to a stiffening ring eyebolt, and the free end of the wire used for adjustment. This task could be carried 
out by one person, freeing up others to aid in leveling.

Not only did the carabineer clamps simplify the process of suspending manifold tubes, they also 
provided a convenient hanger for the silicon diode wire bundles running down the length of the tank. 
At the rake farthest from the man-way the bundle had to cover a distance of roughly 9 m to reach the 
interface connector. Not enough length existed, nor was it desired, to allow the excess slack to rest on 
the tank floor; and the eye-bolts—the only real attach points inside the tank with which to hang hardware 
from—were too small to allow the bundle connector to pass through. The carabineer clamps however, 
had a spring-loaded breaking feature that easily accommodated the wire bundles.

Maintaining cleanliness inside the IRAS tank proved extremely difficult. This was due in part to the 
numerous entries and exits of tools, hardware and personnel; but was exacerbated by the condensation 
of water on the inner tank wall from the humid outside air piped in by a blower unit. During the winter 
months the inner tank wall temperature was cold enough to condense large amounts of water out of the 
purge air. This water collected in puddles on the floor and had to be cleaned up using rags. Once all 
hardware had been installed the inner tank was vacuumed out using a shop-vac and thoroughly cleaned 
by hand with isopropyl alcohol. This procedure was agreed upon by the GODU-LH\textsubscript{2} project to provide 
an acceptable level of cleanliness to achieve the project goals. Figure 6 shows the silicon diode wire 
bundles suspended from a carabineer clamp, and the fully completed inner IRAS tank modifications.
9. Conclusion
Modification of an existing LH₂ tank for detailed integrated refrigeration system experimental studies was successfully completed at the NASA Kennedy Space Center in Florida. The IRAS design required innovative approaches for synergy amongst pressure vessel requirements, heat exchanger system, and instrumentation. Internal stiffening rings were installed to provide additional strength and also the means of attaching the heat exchanger and temperature rakes. The most significant challenge was the need for a modular design and piece-wise assembly off all internal components due to a singular, small man-way port (i.e. “ship in a bottle” style).

The GODU-LH₂ system is now fully operational and initial performance results indicate the instrumented IRAS tank is functioning as designed [4]. Extensive tests of liquefaction, zero boil-off, and densification tests are scheduled for 2015.

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