Modification of a LH$_2$ Tank for Integrated Refrigeration and Storage

Adam Swanger$^1$, Kevin Jumper$^2$, James Fesmire$^3$ and Bill Notardonato$^3$

$^1$NASA Kennedy Space Center, Cryogenics Test Laboratory, NE-M5-B, KSC, FL 32899 USA
$^2$Sierra Lobo ESC, Kennedy Space Center, Cryogenics Test lab, ESC-47, KSC, FL 32899 USA
$^3$NASA Kennedy Space Center, Cryogenics Test Laboratory, UB-R1, KSC, FL 32899 USA

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• **Integrated Refrigeration and Storage (IRAS) Concept**
  – Interface a refrigerator to a storage tank via an internal heat exchanger

• **Benefits**
  – Reduced commodity losses (i.e. no venting).
    • During the Space Shuttle program NASA lost 50% of the hydrogen purchased.
  – Control the state of the fluid via system heat removal to achieve:
    • Zero Boil-Off (ZBO)
    • Liquefaction
    • Densification (sub-cooling)
    • Zero-Loss Tanker Off-loads

• **Requires Unique Hardware & Equipment**
  – No large COTS IRAS tanks exist for LH₂.
  – Must operate over a wide range of pressure and temperature conditions.
GODU-LH2 Project

• Ground Operations Demonstration Unit for Liquid Hydrogen (GODU-LH2) Project
  – Transform an existing 125,000 Liter horizontal dewar into an IRAS tank to test next generation storage and transfer methods for liquid hydrogen.

  Tank Info
  • LH$_2$ storage vessel built in 1991 by MVE.
  • Used by Titan program until 2005.
  • Vacuum-jacketed (26 cm annular space).
  • Inner tank diameter = 2.9 m, length = 21.8 m
  • Inner tank material is SA240 304L stainless steel.
  • Original ASME ratings: 0 to 655 kPa (gauge) (95 psig), and 20 K to 311 K
• Three major internal IRAS modifications were made to the tank
  1. Structural stiffening rings & stringers
  2. Balanced flow, broad-area heat exchanger
  3. Temperature instrumentation rakes

All components, tools, personnel, etc. had to fit through the 58 cm diameter man-way.
Design & Installation of Structural Modifications

- Internal stiffening rings were required by the ASME Boiler & Pressure Vessel Code (BPVC) in case annulus vacuum was lost while at sub-atmospheric tank pressures.
  - LH₂ densified to 15 K → tank pressure ≈ \textbf{13.8 kPa (2 psia)}.  
  - Calculated minimum tank pressure at 15 K, w/o stiffening rings ≈ \textbf{87 kPa (12.6 psia)}.

- BPVC was used to determine stiffener section and quantity
  - 9 total rings, made from C5x6.7 C-channel, 304L stainless steel

- Custom designed rings were divided up into 3 segments to fit through the man-way port, then bolted together to form a continuous ring.
Longitudinal stringers were required to prevent out-of-plane movement of the rings if they became loose.

- Only sets of rings were tied together, not all nine.
- Custom-built stringers are telescoping to allow for thermal contraction.
Heat Exchanger Design & Installation

- **Detailed HX design presented at 2013 CEC in Anchorage, AK**

- **“Whale Skeleton” construction to provide maximum heat transfer area, flexibility, and modularity.**
  - 25 mm OD supply and return manifolds + forty 6.4 mm OD cooling lobes (≈300 m total).
  - Tubing connected using **Swagelok VCR-type fittings** with silver plated gaskets.
  - **Flow balanced system** using precision orifice plates.
  - Suspended from stiffening rings via stainless steel wire (≈123 kg total weight).
  - Employs 4 **custom in-line GHe flow temperature sensors**, silicon diode type.
Temperature Rake Design & Installation

- Three rakes installed to measure temperature distribution inside the tank.
  - Total of 20 silicon diode sensors.
  - Two rake designs: 1x vertical-only data, 2x vertical + radial data.
  - Aluminum box-beam center support with G10 arms and stand-off’s for sensor isolation.
  - Modular: foldable system lowered through man-way and deployed inside.
  - Attached to the stiffening rings via J-hooks.
  - Wire bundles suspended by carabineer clamps used to support the HX (farthest rake is 9 m from the connector interface).
• New man-way plug assembly was designed and fabricated at Stennis Space Center in Mississippi.

• Features include:
  – Four, 24-wire Conax brand instrumentation feedthroughs.
  – Three bayonet-style fluid feedthroughs.
  – Volume filled with 3M brand type K1 glass bubbles and evacuated.
  – Five polished aluminum radiation shields to further reduce heat-leak.
Unique Challenges & Lessons Learned

• Structural mods are extremely **labor intensive** to perform on an existing vessel.

• Unfavorable **working conditions** inside the tank → unbearably hot in the Summer, noise was amplified, trip hazards.

• Maintaining **tank cleanliness** is an issue → water condensation on the inner tank wall, difficult to clean.

• **More instrumentation** would be preferable → camera, tank wall temperatures, etc.

• **Recertification** is a significant challenge → 2 year effort; extensive analysis, inspection and testing, could not recertify to the lower temperature due to impact test requirements.
Conclusion

• **Modification of an existing VJ LH$_2$ tank for IRAS operations was fully successful.**
  – Tank was subjected to a positive and negative pressure test, and LN2 cold-shock for ASME recertification (officially granted in October 2014).
  – Heat exchanger underwent overpressure and decay tests, and has been performing as designed since March 2015.
  – Data from all silicon diode temperature sensors inside the tank are intact, and working properly down to 20 K.
  – Data from the custom in-line GHe temperature sensors also working properly.

• **Future Plans**
  – Testing different modes of operations at various fill levels.
  – Research investigations of bulk fluid dynamics and heat leak.
  – Various testing of densified LH$_2$ dynamics.