NASA-KSC & Liquid Hydrogen: Past, Present & Future

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As I sat down at my desk at NASA Kennedy Space Center (KSC) in Florida to begin preparing this article I was interrupted by the distinct sound of supersonic gas exiting a converging-diverging nozzle nearby: the low rumble of thunder in the distance, steadily increasing to a crescendo that shook the third-floor windows and ceiling tiles of the office building before trailing off again. Standing at the window watching the Space X Falcon 9 rocket hurdle into the cloudless, blue April sky, two thoughts came to mind: 1. The frequency of launches must have grown substantially over the past few years since I totally forgot this one was happening, and 2. The raw power produced by mixing large quantities of liquid oxygen and fuel together in an rocket engine never gets old! The fuel in this case was not liquid hydrogen but kerosene; however, the results are the same…..thrust and pageantry!

NASA's history with liquid hydrogen (LH_2) as a rocket fuel goes all the way back to the infancy of spaceflight and standing-up of the Agency in the late 1950's. By the mid-1960's KSC had become the owner and operator of the largest LH_2 storage and transfer systems in the world—a fact that still remains today—in support of the Apollo moon program and massive Saturn V rocket. Twin 3,200 m^3 LH_2 vessels were constructed, one at each launch pad, to supply the second and third stages of Saturn V. Identical in design and construction, these vessels were double-walled spheres that employed bulk-fill perlite insulation under vacuum to achieve boiloff losses of roughly 0.03% per day, or equivalent to about a 370-watt heat load. LH_2 was pressure-fed from the sphere to the launch pad surface roughly 300 m away, and over 100 m vertically up the launch tower though vacuum-jacketed piping to the vehicle propellant tanks. Boiloff losses were piped away from the vehicle and/or tank and safely flared-off; in a burn pond in the early days, and then a stack in more recent times. This general configuration was utilized throughout the Apollo program (1961 - 1972) and was carried over into the Space Shuttle era (1972-2011) where it supported another 135 missions. During the Shuttle program, and indeed to this day, no large hydrogen liquefiers existed in Florida, so waves of tanker trucks transported LH_2 from production facilities in Louisiana or Alabama to replenish the tanks.

In the subsequent years since the Space Shuttle retired NASA has been designing and building a new heavy lift launch vehicle called the Space Launch System (SLS). The on-board quantity of liquid hydrogen for SLS is about 20% higher than for the Space Shuttle; which, when combined with the intrinsic losses associated with cryo loading/draining, analysis revealed that the legacy tank could not support the required number of consecutive launch attempts. Various options were explored to address this issue, ultimately resulting in the design and construction of a new LH_2 sphere to supplement the original. Located adject to the existing tank, this new vessel is roughly 50% larger at 4,700 m^3 usable volume and is of the same general construction. Where it does make a substantial departure from the old design however is in the inclusion of two new technologies pioneered by the Cryogenics Test Laboratory at KSC: Glass Bubble bulk-fill insulation as a replacement for traditional perlite, and an Integrated Refrigeration and Storage (IRAS) heat exchanger[1] for future controlled storage capability.

"Bubbles are Better!"

As their name implies, glass bubbles are just that: hollow spheres made from borosilicate glass. The 3M corporation K1-type product, which has been the primary focus of R&D efforts for LH_2 tank insulation, has a bulk density of 125 kg/m^3, and individual bubbles have average diameter of 65µ and are filled with a partial vacuum of SO_2. R&D for the use of glass bubbles—a.k.a. glass microspheres, glass beads, and microballoons—bulk-fill material as part of a cryogenic tank insulation system began in the early 1970's[2]. Beginning in the 1990's the Cryogenics Test Laboratory embarked on multiple R&D efforts to thoroughly characterize the thermal and mechanical performance of K1 glass bubbles for LH_2 storage tanks, ultimately culminating in a larger scale test where a 190 m^3 perlite-insulated vessel located at NASA Stennis Space Center in Mississippi was retrofitted with glass bubbles in 2008. Various goals were achieved through this test campaign, including insulation loading processes, vacuum pump-down characteristics, thermal cycling effects, and long duration boiloff performance. In 2015, after collecting roughly 6 years' worth of data, the LH_2 boiloff reduction versus the original perlite insulation was found to be 46%[3]. As a direct result of NASA's R&D efforts with glass bubbles the insulation was included in the specification of the new 4,700 m^3 LH_2 sphere currently being constructed. Filling of the annular space with an estimated 1.3 quadrillion individual bubbles is schedule to take place in August 2021, followed by tank commissioning in early 2022.

Gaining Control

Fundamentally, Integrated Refrigeration and Storage is about control. Or, perhaps more appropriately, it provides a means of gaining control over a situation that had previously called the shots—namely, the necessary venting of hazardous and precious hydrogen to balance out the heat absorbed throughout the LH_2 supply chain. Since Sir James Dewar first liquefied hydrogen in 1898, safely dealing with flammable vent gas caused by continuous and unavoidable heat ingress through the storage vessel has been of utmost importance. And as large scale LH_2 systems began to emerge in the 1950's the issue became even more imperative; so much so that it effectively shaped large parts of what we now consider traditional LH_2 storage and transfer system designs and operations. Additionally, there can be significant economic impacts associated with venting boiloff losses. During the Space Shuttle program NASA lost almost 50% of the LH_2 purchased due to combined heat leak[4]. Depending on the cost of LH_2 at a given location and time, which historically can vary significantly, these losses may constitute meaningful financial impacts.

IRAS provides a means of reducing and/or eliminating LH_2 losses—which also indirectly reduces risk and increases operational safety by eliminating the need to purposely vent hydrogen—by removing heat directly from the bulk fluid inside the storage vessel via an internal heat exchanger connected to an external cryogenic refrigeration system. Just as the invention of the "artificial ice machine," or home refrigerator, liberated us from the use of consumable ice blocks by simply plugging into a wall outlet, IRAS can liberate us from the heretofore unavoidable tax paid to the universe in the form of boiloff gas to access all the benefits LH_2 has to offer.

The Cryogenics Test Laboratory began IRAS research efforts in the early 2000's, culminating in the design construction, and testing in 2016 of the Ground Operations Demonstration Unit for Liquid Hydrogen (GODU-LH2)[5]—a custom-built 125 m^3 horizontal-cylindrical LH_2 IRAS storage tank coupled to an 880 W at 20 K Brayton cycle helium refrigerator. GODU-LH2 successfully demonstrated the five primary advanced capabilities afforded by IRAS: 1. Zero-loss tank chill-down from ambient temperature, 2. Zero-loss LH_2 tanker offloads, 3. Long duration zero-boiloff of LH_2, 4. In-situ hydrogen liquefaction, and 5. Densification of LH_2 down to the triple point. Post-test economic analysis of zero boiloff testing revealed that for every dollar spent on electricity to power the GODU-LH2 system roughly 7 dollars' worth of LH_2 was saved (based on $0.06/kWh electricity cost and $5.20/kg LH_2 cost); a fact that played an important role in infusing the technology into the new launch pad sphere.

Setting the Benchmark

With the inclusion of glass bubbles and future controlled storage via IRAS the new LH_2 sphere currently being constructed at KSC has the potential set a new standard for large scale liquid hydrogen storage and operations. And as the technical community tackles a host of new challenges brought on by mega-scale LH_2 initiatives—land a sea–based tanks pushing 200,000 m^3 capacity—driven by a collective global momentum aimed at addressing climate change, advanced designs and methodologies that increase efficiency and make LH_2 a more viable contender in the energy market will prove to be invaluable.

References

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