Return to service of a liquid hydrogen storage sphere

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Abstract. One, of two, 850,000 gallon liquid hydrogen storage spheres, at NASA's Kennedy Space Center, was decommissioned in 2010. This tank had an abnormally high heat leak that was investigated and determined to be the result of a large void in the perlite insulation. The insulation void was subsequently filled, and the tank was refurbished for its planned use in the Space Launch Systems (SLS) program. Return to service of this tank began in December of 2017 with a partial liquid hydrogen fill. Since that time, routine measurement of the liquid level have been recorded in order to establish a new boiloff rate and associated heat leak. This data shows the perlite top off activities have resulted in a much reduced, and within design specification, heat leak.

1. Introduction

Two 3,218 cubic meter (850,000 gallon) liquid hydrogen storage spheres have supported space flight programs at the Kennedy Space Center since the mid-1960s. These storage spheres, one of which is shown in figure 1, consist of an 18.7 meter (61.5 foot) diameter stainless steel inner sphere concentrically set inside a 21.6 meter (70 foot) diameter carbon steel outer sphere [1]. The annular region is filled with perlite and evacuated to a pressure of approximately 2.67 – 8.0 Pa (20-60 millitorr). The design specification document for the spheres states boiloff losses shall not exceed 0.075% of capacity (2.4 cubic meters/day or 637.5 gallons/day) [2]. Prior to the completion of the Space Shuttle Program, the boiloff losses on the storage sphere at Pad A were estimated to be approximately 1.14 cubic meters (300 gallons) per day, regardless of tank liquid level. However, the Pad B storage sphere boiloff rate had increased to 3.79 cubic meters (1,000 gallons) per day, with variability associated with liquid level [3]. The Pad B sphere was drained, inerted, and decommissioned in 2009. The annular vacuum was released in early 2010 and boroscope inspections revealed a large perlite void existed. Samples of the existing perlite were examined and found to be pristine, so the decision was made to simply top off the annulus with new perlite prior to recommissioning the sphere. The perlite was cracked off-site, and trucked in for installation. Dry air was used to blow approximately 226.5 m^3 (8,000 ft^3) of perlite (density of 168.2 – 200.2 kg/m^3, 105. – 12.5 lb/ft^3) from the trucks into the annular space. The annular space was then sealed with a GN_2 purge while other pad refurbishment activities continued. The vacuum was re-established over the course of four months in 2014. In December of 2017, liquid hydrogen fill of the tank began. With one and a half years of boiloff data collected, the effectiveness of the perlite top-off may now be determined.

Figure 1. Liquid hydrogen storage sphere at NASA's Kennedy Space Center

2. Annular space evacuation

The annular region of the 850,000 liquid hydrogen storage sphere is 1,642.4 cubic meters (58,000 cubic feet). In order to evacuate that space, which had been topped off with perlite, multiple vacuum pumps were used. In March of 2014, a Varian SH100 Dry Scroll Vacuum Pump (peak pump speed of 6.0 m^3/hr, 3.5 cfm) and a Varian SH110 Dry Scroll Vacuum Pump (peak pump speed of 6.6 m^3/hr, 4.0 cfm) were connected to the storage sphere's 20.32 cm (8 inch) vacuum isolation valve. After 72 hours of pumping, over the course of 16 days, the tank pressure was still above the readable range of the vacuum meter (2,666 Pa, 20,000 millitorr). At that point, the Varian SH100 was swapped out for an Anest Iwata ISP-500c (peak pump speed of 30 m^3/h, 17.7 cfm). Twenty-nine days and 147.5 pumping hours later, the storage sphere's vacuum level dropped into the readable range (<2,666 Pa, <20,000 millitorr). Seventy-five pumping hours after that, the vacuum level indicated 266.6 Pa (2,000 millitorr). The Varian SH110 was then removed so that the Anest Iwata ISP-500c was the only pump connected to the system. The vacuum level reached 36.7 Pa (275 millitorr) 20 days and 147 pumping hours later. A Danielson Tribodyn DanVac TD-20 Turbo Drag Dry High Vacuum Pump (peak pump speed of 17 m^3/h, 10 cfm in the high vacuum range) was then connected to the system, with the Anest Iwata still in place. Together they pumped for another 132 hours over 41 days to bring the vacuum level to 9.3 Pa (70 millitorr). The Anest Iwata ISP-500c was then removed and replaced with a Danielson Tribodyn DanVac TD-30 Turbo Drag High Vacuum Pump (peak pump speed of 27.2 m^3/hr, 16 cfm in the high vacuum range). Together, the TD-20 and TD-30 pumps brought the storage sphere's vacuum level to a steady vacuum level of 6 Pa (45 millitorr) in 24 hours of pumping over 3 days' time. The system was then locked up and monitored for 2 weeks with a noted pressure rise of only 0.4 – 0.66 Pa (3-5 millitorr).

3. Liquid hydrogen fill

Chilldown and fill of the liquid hydrogen tank began in December of 2017. Forty tankers were offloaded between December 5th and December 14th resulting in nearly 1,514.2 cubic meters (400,000 gallons) of liquid hydrogen storage. No additional tankers were offloaded until February of the following year and the average boiloff rate during that quiescent time was approximately 1.44 cubic meters (380 gallons) per day. Ten more liquid hydrogen tankers were offloaded into the storage sphere in February, bringing the liquid volume in the sphere to almost 2,082 cubic meters (550,000 gallons). After that time, the sphere sat quiescent for approximately 2 months, and boiled off an average of only 0.83 cubic meters (218 gallons) per day. A pressurization test was then performed to check out the system, after which the tank had its longest duration quiescent period, which lasted nearly 200 days. During that time, the average boiloff rate was 0.77 cubic meters (202 gallons) per day. In November of 2018, fifteen additional liquid hydrogen tankers were offloaded, bringing the storage level up to just over 2,460.5 cubic meters (650,000 gallons). The storage sphere then remained quiescent until the middle of May. During that time (178 days), the average boiloff rate was 0.85 cubic meters (224 gallons) per day. It is reasonable to assume that during the first several months after the initial fill, the boiloff rate was higher than subsequent indications because the storage sphere had previously been at ambient temperature, and it was only filled approximately half way to capacity. It would therefore take some time to reach thermal equilibrium. Considering this, and only averaging the remaining data, the perlite top off operation resulted in a reduction from approximately 3.79 cubic meters (1,000 gallons) per day in boiloff to merely 0.81 cubic meters (215 gallons) per day in boiloff!

During the original investigation into the abnormally high boiloff rate of the Pad B liquid hydrogen storage sphere, infrared imagery was used. Analysis of thermal imagery suggested the anomalous area of the storage sphere was significantly colder than the rest of the external shell [4].

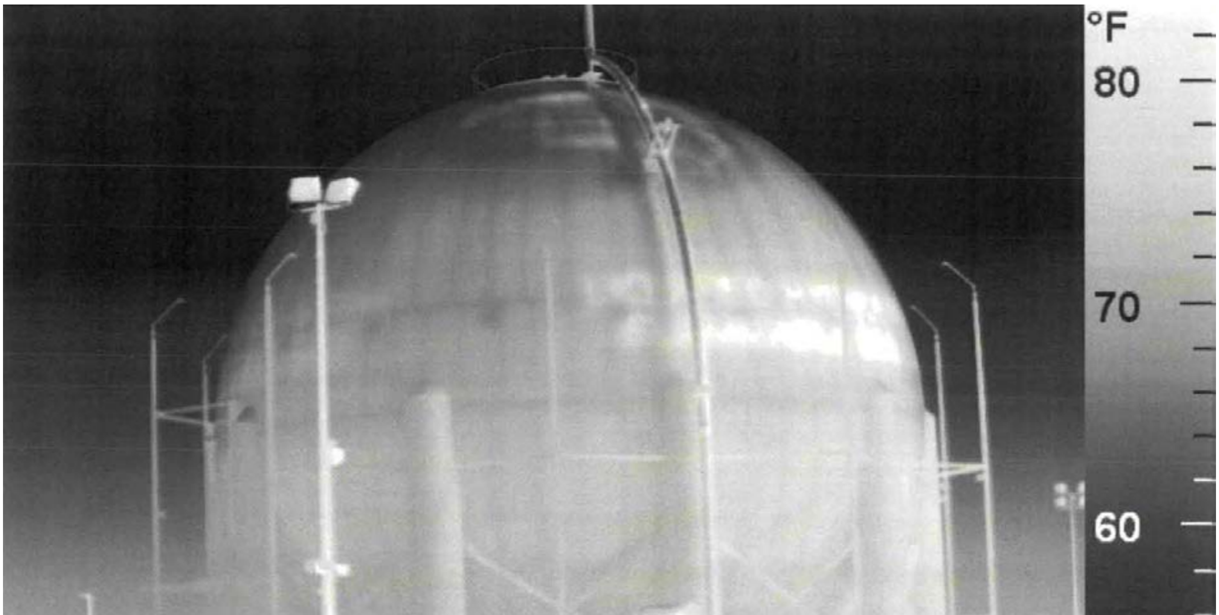

Figure 2. Thermal imagery of the liquid hydrogen storage sphere at KSC's Pad B in August of 2009, showing clear indication of a cold region due to a perlite void in the annular space

After the perlite repair had been completed, and liquid hydrogen had re-filled the storage sphere, additional thermal imagery was taken to help confirm a successful repair. No cold region was noted in any of the thermal images. An example is shown in figure 3, below. Note the stairs were added during the Pad refurbishment activities.

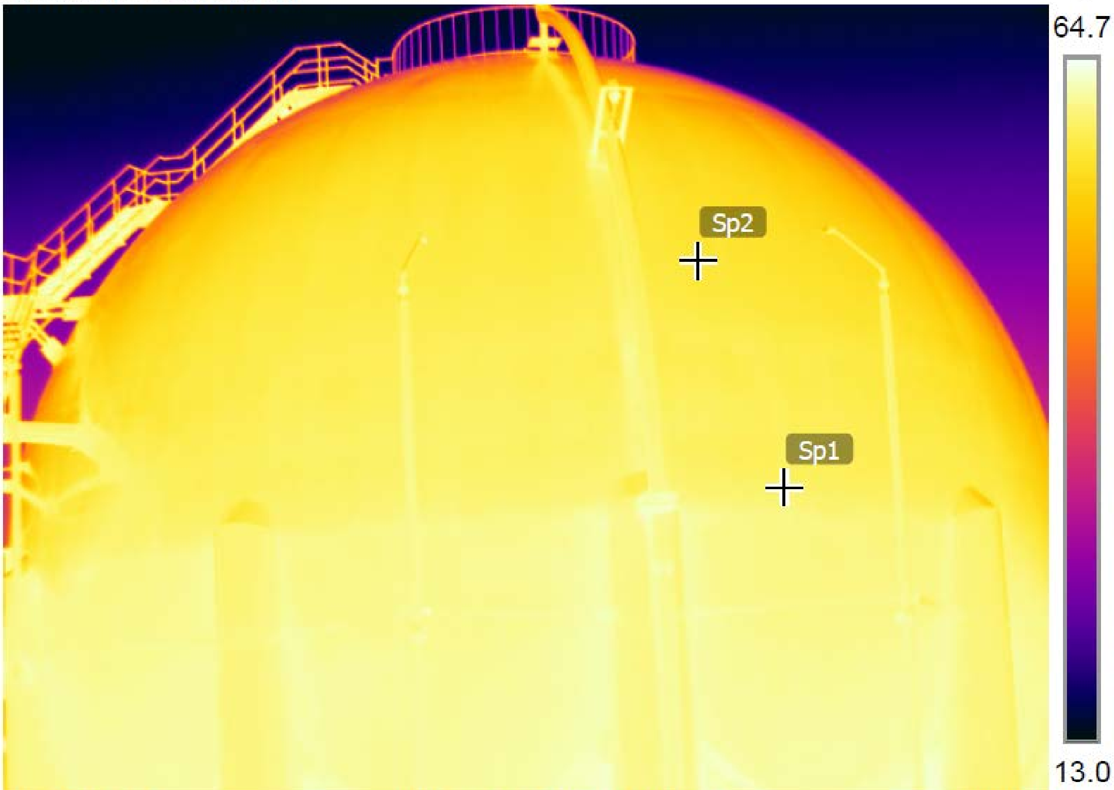

Figure 3. Thermal imagery of the liquid hydrogen storage sphere at KSC's Pad B in April of 20018, showing no indication of a cold region

4. Conclusions

After years of experiencing an abnormally high boiloff rate on the liquid hydrogen tank at KSC's Pad B, current indications are that the perlite refurbishment activities undertaken while the tank was decommissioned were fully successful. The annular vacuum had to be released in order to accomplish the perlite investigation and top off, but was re-established over the course of 4 months, using various vacuum pumps in tandem. Liquid hydrogen fill then commenced, and the liquid level data gathered during the storage sphere's quiescent periods show a huge reduction in boiloff when compared to the previous data. The perlite top off operation resulted in a reduction from approximately 3.79 cubic meters (1,000 gallons) per day in boiloff to merely 0.81 cubic meters (215 gallons) per day in boiloff! Thermal imagery confirms no cold spots persist on the tank. This storage sphere is now poised to support many more years of space flight.

Acknowledgments

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References

[1] Chicago Bridge & Iron Company, "Drawing Number LHCD-40862," *General Plan 850 MG LH2 Sphere Launch Complex 39-B for Catalytic Co.* (1965).

[2] Chicago Bridge & Iron Company, "HT-1 Storage Vessel, 850,000 Gallon Liquid Hydrogen," 75M14524 Requirements Common to Liquid Hydrogen System Components, Sheet 203 (1964).

[3] Krenn AG, Diagnosis of a poorly performing liquid hydrogen bulk storage sphere. *AIP Conference Proceedings.* Vol. 1434. No. 1. AIP, 2012

[4] Arens, E, Cryogenic Storage Tank Non-Destructive Evaluation (2010).

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Introduction

- An 850,000 gallon liquid hydrogen storage sphere, at NASA's Kennedy Space Center, had an abnormally high boil off rate during it's support of the Space Shuttle Program
  - Spec max = 637 gallons/day
  - Average seen = 1,000 gallons/day
- The storage sphere was removed from service in 2009
- Investigations revealed a perlite void in the annular region was the cause of the high boil off rate
- Additional perlite (226.5 m^3, 8,000 ft^3) was blown into the annulus. It was then sealed with a GN2 purge
- The vacuum was re-established over the course of 4 months in 2014
- The storage sphere was re-filled with LH2 beginning in December, 2017

Reference: Krenn AG, Diagnosis of a poorly performing liquid hydrogen bulk storage sphere. *AIP Conference Proceedings*, Vol. 1434. No. 1. AIP (2012)

LH2 Storage Sphere

Annular Space Evacuation

598 hours pump time to pull 58,000 cubic feet of annular space from ambient pressure to 45 millitorr

- Varian SH100 Dry Scroll Vacuum Pump – peak pump speed 3.5 cfm
- Varian SH110 Dry Scroll Vacuum Pump – peak pump speed 4.0 cfm

72 hours pump time, pressure >20,000 millitorr

- Varian SH110 Dry Scroll Vacuum Pump – peak pump speed 4.0 cfm
- Anesta Iwata ISP-500C Scroll Vacuum Pump – peak pump speed 17.7 cfm

223 hours pump time, pressure 2,000 millitorr

- Anesta Iwata ISP-500C Scroll Vacuum Pump – peak pump speed 17.7 cfm

147 hours pump time, pressure 275 millitorr

- Anesta Iwata ISP-500C Scroll Vacuum Pump – peak pump speed 17.7 cfm
- Danielson Tribodyn DanVac TD-20 Turbo Drag High Vacuum Pump – peak pump speed 10 cfm in the high vacuum range

132 hours pump time, pressure 70 millitorr

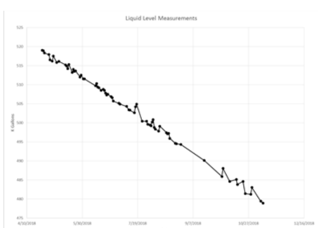
- Danielson Tribodyn DanVac TD-20 Turbo Drag High Vacuum Pump – peak pump speed 10 cfm in the high vacuum range
- Danielson Tribodyn DanVac TD-30 Turbo Drag High Vacuum Pump – peak pump speed 16 cfm in the high vacuum range

24 hours pump time, pressure **45 millitorr**

Liquid Hydrogen Fill

- December 5th – 14th, 2017: 40 tankers offloaded to chilldown and begin fill of the liquid hydrogen storage sphere at KSC's Pad B
- February 5th – 15th, 2018: 10 tankers offloaded to bring liquid level in the tank to 543,000 gallons
- April 19th, 2018: Pressurization Test
- 199 Days of Quiescence

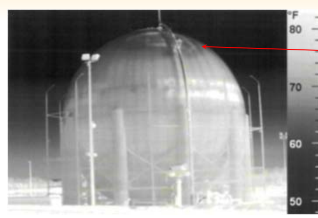
202 gallons/day boiloff during extended quiescent period



- November 13th, 2018: 15 tankers offloaded to bring liquid level to 655,000 gallons

AVERAGE BOILOFF = 215 gallons/day (down from 1,000 gallons/day)

IR Imagery



Cold spot clearly visible

Pad B liquid hydrogen sphere – August 2009

Uniform temperature distribution

Pad B liquid hydrogen sphere – April 2018

Conclusions

- After topping off the annular space of KSC's liquid hydrogen storage sphere at Pad B, a good vacuum was successfully established over the course of 4 months, using several different vacuum pumps
- Approximately a year and a half has passed since liquid hydrogen was re-introduced into the storage sphere
- The average boiloff rate was reduced from 1,000 gallons per day during the Space Shuttle Program to 215 gallons per day currently
- Thermal imagery confirms that no cold spots persist on the tank
- The perlite top-off procedure successfully brought the liquid hydrogen storage sphere back into compliance with its specified maximum allowable boiloff rate (637 gallons per day)

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