Performance Testing of Liquid Hydrogen Tanks

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Testing the performance of liquid hydrogen in tanks brings many unique challenges. Often methods used even for liquid nitrogen need to be modified to be able to address the details required to fully understand the performance of the tank. During the development and characterization of many novel insulation systems both for in-space and ground applications, NASA has tested many liquid hydrogen tanks where performance was a key outcome. Over the course of analyzing the performance of multiple different hydrogen tests, including several with both hydrogen and nitrogen, differences in the details of test data interpretation become clear. One of these key details is the thermal stratification of the tank and what it can tell you about the heat load dispersion. Let's explore this more fully using several tests recently performed by NASA.

First, we examine the Structural Heat Intercept, Insulation, and Vibration Evaluation Rig (SHIIVER) test [1]. During SHIIVER, a 4 m diameter tank was tested with both liquid nitrogen and liquid hydrogen in several different insulation configurations. Testing was performed by allowing the tank to boil-off from 90% full to 25% full, only stopping for self-pressurization tests at key fill levels. From Figure 1 and Figure 2, we can see differences in the heat load and the boil-off rate as a function of fill level for liquid hydrogen. In general, for all tests, the heat load stays fairly constant as a function of fill level (for a given test configuration), at least until the liquid-vapor interface starts to interact with the flange between the forward skirt and barrel of the tank (a few inches above the start of the barrel – see Figure 3 for the SHIIVER test configuration). However, the boil-off flow rate decreases significantly with fill level. This is caused by the increasing temperature of the ullage. Figure 4 shows us that for the Pre-Acoustic LH2 test, the ullage started out with temperatures as high as 80 K at 50% full that got up to 160 K at 25% full.

The second adjustment that should be made is for the density ratio between the liquid and vapor phases. Any liquid that boils-off or evaporates in a fixed volume system must be replaced by vapor. To account for the fraction of boil-off vapor that replaces the liquid, a term must be added to the energy balance [3]. Thus, the heat load from the boil-off rate becomes:

$$\dot{Q} = \dot{m}_{boil-off}\left(h_{Texit} - h_{liq}\right)\left(\frac{\rho_{liq}}{\rho_{liq} - \rho_{vap}}\right)$$

Where h_{Texit} is the temperature of the gas at the exit of the tank and ρ_{vap} is the saturated vapor density. This factor is plotted for parahydrogen, helium, and nitrogen in Figure 5 as a function of saturated liquid pressure. The correction for nitrogen is very small, especially around 100 kPa (1 bar), less than 0.2%. However, parahydrogen and helium have much larger density correction factors.

While SHIIVER was a more complicated and quasi-transient test, the Cost-Efficient Storage and Transfer (CESAT) test was an intentionally quasi-steady state test [2]. During the test, the annulus of the vacuum jacketed tank was filled separately with perlite and glass bubbles for testing with both liquid hydrogen and liquid nitrogen. Test data was reported at approximately 80% full. The published heat loads and system thermal conductivities are simply based on the boil-off flow rate times the heat of vaporization. However, using the data provided at the top of the tank (see Figure 6), we can adjust the data. If we make the assumptions that the differential temperature between the saturated liquid and the top of the tank is approximately the same for liquid nitrogen testing as liquid hydrogen testing (which is probably incorrect, but we will do so for comparison), we can do similar calculations. Table 1 shows the published heat load and boil-off rate data along with the heat of vaporization for nitrogen and parahydrogen at 101 kPa. Based on the plotted gas exit temperature, a new enthalpy change is calculated. The heat load and total system thermal conductivities can then be multiplied by the ratio of the new enthalpy change to the heat of vaporization and the density correction factor (1.02). This adjustment causes a 58% change in the heat load calculated for the liquid hydrogen tests, but only a 13% change for the liquid nitrogen tests. While 58% seems like a large adjustment for this value, at 80% full, nearly 30% of the surface area of a sphere is still in the vapor. The much lower 13% change for nitrogen indicates that either the temperature at the top of the tank was much higher than we assumed in the calculation, or more thermal energy was able to conduct down the tank wall from the vapor space to the liquid.

A third test can also be examined that reinforces this point. During Cryogenic Boil-off Reduction system test series 2 [4], a test was run at 25% full to compare to the 90% full baseline. Both tests were run in a quasi-steady state configuration. On this test, a cryocooled shield was inserted into the MLI and attached to the tank structural and plumbing lines. For both tests, the cryocooler was run at the same return temperature. At 25% full, the vented hydrogen exit temperature was 36.9 K compared to 23.4 K at 90% full, accounting for a 33% increase in enthalpy absorbed by the boil-off gas). Even though the mass flow rate decreased from 2.43 to 1.84 slpm at 153 kPa constant pressure (a decrease of 32%), the net heat load didn’t change (1.71 W at 90% full and 1.70 W at 25% full).

The results of these tests imply that determining a tanks performance with liquid hydrogen is much more sensitive to several key parameters than testing with liquid nitrogen. Accurate measurement of the temperature of the effluent gas as it vents from the tank should be required to fully account for all of the heat coming into the tank. Additionally, properly accounting for the boiled-off liquid in the tank when testing with hydrogen and helium can also eliminate a possible source of error. Understanding the difference between boil-off and heat load going into the tank and the different environments that may cause within a tank, especially as a function of fill level is a key aspect of operating the tank efficiently.

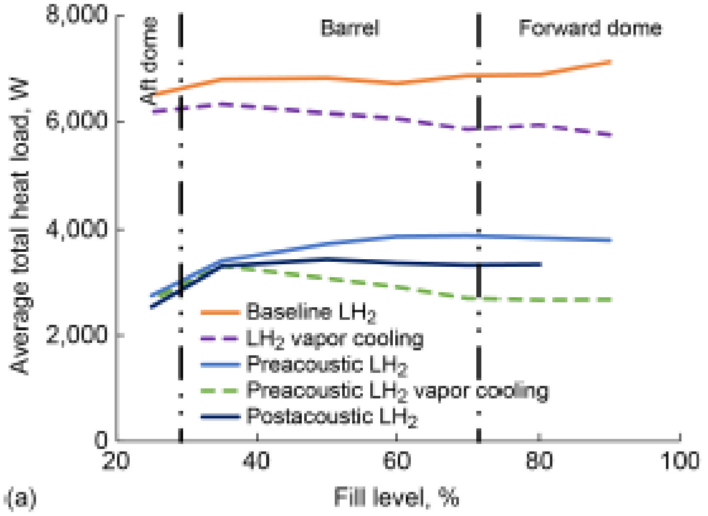

Figure 1: SHIIVER calculated heat loads as a function of Fill Level. Note that MLI was applied to the tank for Pre-acoustic and Post-acoustic testing, but after Baseline testing.

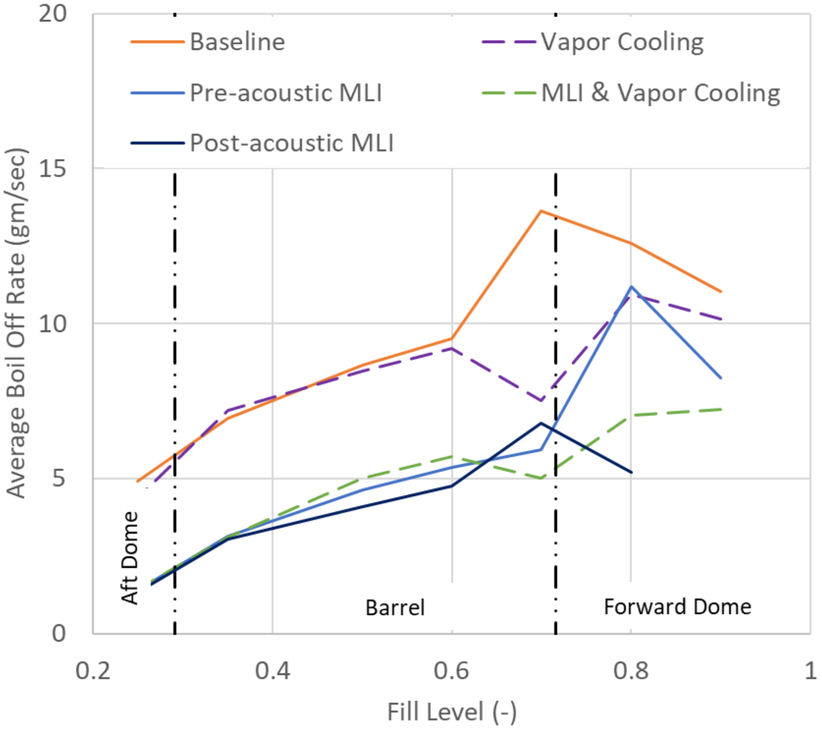

Figure 2: SHIIVER measured boil-off rates as a function of fill level with Liquid Hydrogen.

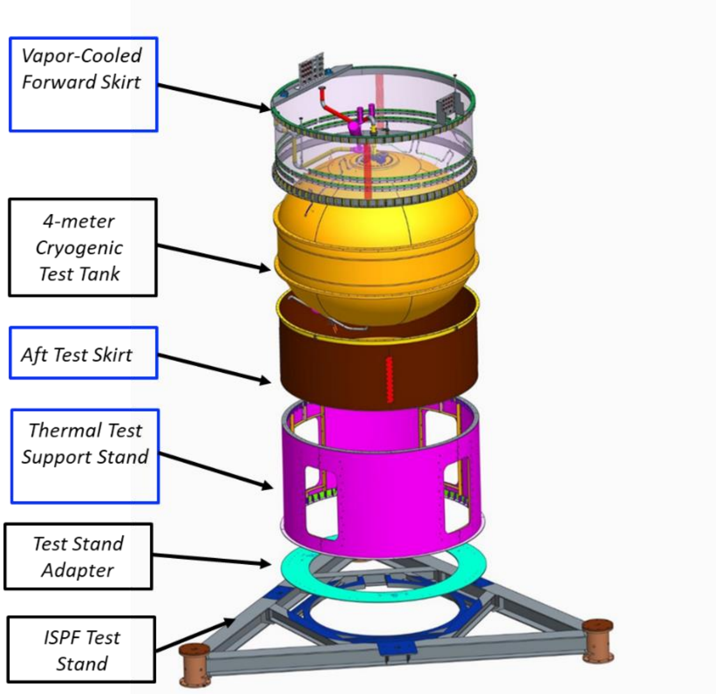

Figure 3: SHIIVER Test Article

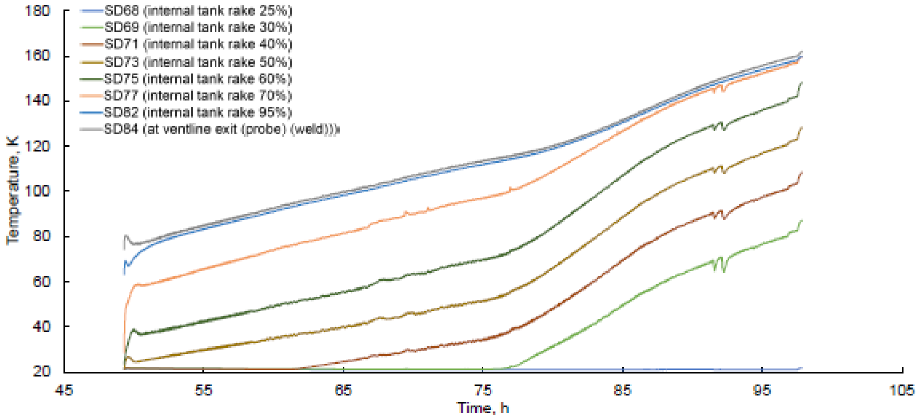

Figure 4: SHIIVER hydrogen ullage temperatures during Pre-Acoustic Testing between 50 and 25 percent full.

Table 1: CESAT data

Variable	Perlite LN2	Perlite LH2	Glass Bubbles LN2	Glass Bubbles LH2
Published boil-off flow rate (sccm) [2]	4142	20125	3001	13212
Published heat load (W) [2]	15.9	12.6	11.5	8.3
Heat of Vaporization (J/g)	199.2	446.1	199.2	446.1
ks Published (mW/m/K) [2]	1.63	1.03	1.19	0.68
Temperature at Tank top (K) [2]	100	43	100	43
Change in Enthalpy (J/g)	224	693	224	293
Adjusted Heat Load (W)	17.8	19.5	12.9	12.8
Adjusted k-value (mW/m/K)	1.84	1.63	1.35	1.08
% Change	13%	58%	13%	58%

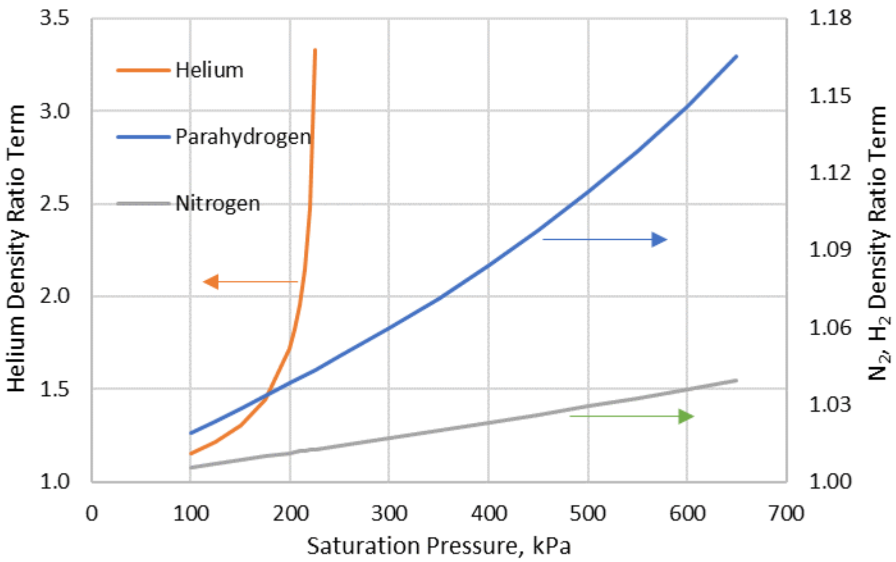

Figure 5: Density Term Adjustment Factor for Nitrogen, Parahydrogen, and Helium

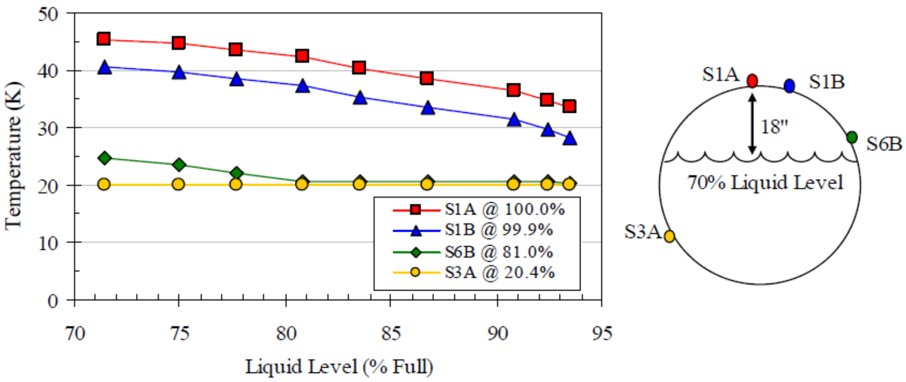

Figure 6: CESAT tank wall temperature profiles for liquid hydrogen boil-off tests with glass bubbles insulation (Figure 7 in Ref 2).

References:

[1] Johnson W L, Balasubramaniam R, et. al. “Demonstration of Multilayer Insulation, Vapor Cooling of Structure, and Mass Gauging for Large-Scale Upper Stages: Structural Heat Intercept, Insulation, and Vibration Evaluation Rig (SHIIVER) Final Report”, NASA TP-20205008233, 2021.

[2] Sass J P, Fesmire J E, Nagy Z F, Sojourner S J, Morris D L, and Augustynowicz S D, “Thermal Performance Comparison of Glass Microspheres and Perlite Insulation Systems for Liquid Hydrogen Storage Tanks”, Advances in Cryogenics Engineering, Vol 53, 2008, pg1377.

[3] ASTM C-1774

[4] Plachta D W, Johnson W L, and Feller J F, “Cryogenic Boil-off Reduction System Testing”, AIAA-2014-3579, 2014.