Vapor cooling of a structural skirt for a large-scale hydrogen tank

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Abstract. The demonstration of vapor cooling on a structural skirt was one of the main objectives of the Structural Heat Intercept, Insulation, and Vibration Evaluation Rig (SHIIVER) testing. SHIIVER consisted of a 4-meter diameter stainless steel tank with an aluminum forward skirt. The forward skirt was cooled by directing effluent vapor from the tank through two flow channels that each went 360 degrees around the interior of the skirt in a helical pattern. Flow rates, temperatures, and pressures in the system were measured allowing for the calculation of heat load removed via cooling stream and heat load reduction into the tank. Testing occurred at fill levels between 25% and 90% full using both liquid hydrogen and liquid nitrogen. Boil-off rate was varied independent of the skirt performance by adding multilayer insulation over the spray-on-foam insulation on the tank domes, while leaving the barrel insulated only with spray-on-foam. The results from the testing, which demonstrate vapor cooling removed heat flow from the tank flange and reduces total propellant heat load by as much as 19%, are analyzed and discussed.

1. Introduction
Vapor cooling of both acreage insulation and structural heat loads have been routinely used for helium systems in flight [1-3]. These have also been studied for structural applications on large scale systems [4], but have not been previously demonstrated. A methodology for reduction of structural heat loads on flight systems is of great benefit for the development of stages targeting days to weeks of duration.

In order to demonstrate the application of technologies on a relative scale for cryogenic upper stages, NASA developed the Structural Heat Intercept, Insulation, and Vibration Evaluation Rig (SHIIVER) [5]. The main testing objectives for the SHIIVER test hardware were the demonstration of cryogenic flight multilayer insulation (MLI), vapor cooling of structure, and the Radio Frequency Mass Gauge on a 4-meter diameter liquid hydrogen tank.

2. Test Setup
SHIIVER is a 4 meter diameter by 3.88 m tall tank designed to be operated with both liquid hydrogen and liquid nitrogen. An aluminium forward skirt was designed such that it could be cooled with the effluent boil-off vapor or not cooled with the vapor. A stainless-steel structural system, which included an aft skirt, supported the tank within the vacuum chamber. The tank domes and barrel were covered with spray-on foam insulation (SOFI) for all testing. After Baseline testing, a 30 layer multilayer insulation (MLI) system was installed on the forward and aft domes (within the boundaries of the skirts).
Prior to the design and integration onto the SHIIVER test article, a series of sub-scale vapor cooling tests was completed [6]. Based on the sub-scale test results, the final cross-section is shown in figure 1. The channel was made of 1-inch schedule 80 aluminium pipe welded to the two L-brackets. One of the ground rules was to minimize any modification to an existing vehicle, so the cooling channels were bolted to the interior of the skirt wall as shown in figure 2 and figure 3. Additionally, the channels were slanted at an angle of approximately 1.6 degrees (0.34 m rise over the 4 m diameter circumference center-line to center-line) to maintain an approximate spacing of 0.18 m vertically between the passes. The top view of the SHIIVER forward dome and forward skirt is shown in figure 4.

![Figure 1. Cross section of final vapor cooling design with temperature sensor relative locations.](image1.jpg)

![Figure 2. SHIIVER vapor cooling lines showing vapor inlet and outlet with loop 2 in between. (note the Loop 2 inlet/outlet was 180 degrees around the skirt)](image2.jpg)

![Figure 3. SHIIVER instrumented and insulated vapor cooling lines with insulation rolled back and some instrumentation shown. Final installation had insulation installed all the way around the inside (as seen in Figure 4).](image3.jpg)

Internal to the tank were 21 silicon diodes to measure the temperature of the liquid and ullage at approximately every 5% fill level. Similarly, silicon diodes were bonded to the external tank wall to measure the temperatures. Approximately 50 silicon diodes were installed on the forward skirt to help calculate heat loads and fluid heat removal at six different angular locations around the tank. Coriolis flow meters were used to measure both the vapor cooling flow rate as well as the boil-off flow rate through the main vent line.
Figure 4. Top of the SHIIVER tank showing plumbing lines including the vapor cooling lines. This picture was taken prior to the installation of MLI on the domes.

Testing was conducted at the In-Space Propulsion Facility (ISPF) at NASA’s Neil A. Armstrong Test Facility at Glenn Research Center [7]. The vacuum in the ISPF vacuum chamber was maintained at approximately $2 \times 10^{-6}$ Torr and while the environmental cold wall was inactive, it was monitored and for the tests in question, the temperature swing was within a 10 K range, between 270 and 280 K.

Table 1. Simplified SHIIVER test matrix as completed

| Test | Description                                      | Fill level(s), percent | Baseline LH$_2$ | Preacoustic LH$_2$ | Preacoustic LN$_2$ | Postacoustic LH$_2$ |
|------|--------------------------------------------------|------------------------|-----------------|--------------------|--------------------|---------------------|
| 1    | Boiloff test                                     | 90 to 70               | X               | X                  | ----               | X                   |
|      |                                                  | 65 to 25               | X               | X                  | ----               | X                   |
| 2    | Vapor-cooling test                               | 90 to 25               | X               | X                  | X$^a$              | ----                |
| 3    | Transient test with vapor cooling                | 70                     | X               | X                  | ----               | ----                |
| 4    | Cyclical vapor cooling/ pressure rise test       | 50                     | ----            | X                  | ----               | ----                |

$^a$Vapor-cooling testing with LN$_2$ had two drains interspersed between the data. Testing was done between approximately 90 to 80, 50 to 45, and 25 to 24 percent fill.

2.1. SHIIVER test matrix

The full SHIIVER test matrix is available in ref 5, the simplified test matrix addressing vapor cooling is shown in table 1. Testing was performed with both liquid hydrogen (LH$_2$) and liquid nitrogen (LN$_2$). Typical operation of the testing included filling the SHIIVER tank up to above 90% full and allowing it to boil-off to below 25% full. The Baseline test only had SOFI insulation on the domes and tank barrel, the Preacoustic and Postacoustic tests had MLI on the domes and SOFI on the barrel. During the Baseline LH$_2$, Preacoustic LH$_2$, and Preacoustic LN$_2$ tests, this was done twice per test campaign: once with the boil-off flowing through the vapor cooling and once with it directly vented to the atmosphere without using the vapor cooling channels. Transient tests were performed after self-pressurization tests, which were typically performed at approximately 70%, 50%, and 25% fill levels to a pressure level of...
276 kPa. Transient tests consisted of the blow down of the tank from the 276 kPa after a self-pressurization test back to a quasi-steady state boil-off operations at approximately 138 kPa.

3. Test Results
This paper focuses on the results associated with the fluid inside the vapor cooling channels and the system level impacts. Heat load calculations for the tank and around the forward skirt among other locations are covered in much more detail in ref 5.

3.1. Heat Load Reduction Results
The heat loads for each test as a function of fill level are shown in table 2. The heat load reduction due to vapor cooling is shown in table 3 and the associated boil-off flow rate reduction is shown in table 4. As shown in the test matrix, liquid nitrogen boil-off testing was not completed below 70%, and liquid nitrogen vapor cooling data was collected at three limited fill levels, this greatly reduces the amount of liquid nitrogen data available for comparison. These heat loads are calculated from the boil-off flow rate as well as the sensible heat absorbed by the vapor and liquid.

| Test | Fill level (±2.5), percent | Test | Fill level (±2.5), percent |
|------|--------------------------|------|--------------------------|
|      | 90 | 80 | 70 | 60 | 50 | 35 | 25 |
| Liquid hydrogen (LH₂) (MLI) | 7,117 | 6,873 | 6,854 | 6,708 | 6,810 | 6,784 | 6,489 |
| LH₂ vapor cooling (no MLI) | 5,738 | 5,925 | 5,847 | 6,055 | 6,151 | 6,317 | 6,176 |
| Preacoustic LH₂ (MLI on domes) | 3,799 | 3,844 | 3,882 | 3,864 | 3,731 | 3,402 | 2,749 |
| Preacoustic LH₂ vapor cooling (MLI on domes) | 2,671 | 2,669 | 2,698 | 2,915 | 3,070 | 3,301 | 2,666 |
| Preacoustic liquid nitrogen (LN₂) (MLI on domes) | 3,640 | 3,355 | 3,212 | NA | NA | NA | NA |
| Preacoustic LN₂ vapor cooling (MLI on domes) | 3,281 | NA | NA | NA | 2,886 | NA | 1,873 |

| Test | Fill level (±2.5), percent | Test | Fill level (±2.5), percent |
|------|--------------------------|------|--------------------------|
|      | 90 | 80 | 70 | 60 | 50 | 35 | 25 |
| Liquid hydrogen (LH₂) vapor cooling from baseline | 19 | 14 | 15 | 10 | 10 | 7 | 5 |
| Preacoustic LH₂ vapor cooling from baseline | 62 | 61 | 61 | 57 | 55 | 51 | 59 |
| Preacoustic LH₂ vapor cooling from preacoustic LH₂ | 30 | 31 | 30 | 25 | 18 | 3 | 3 |
| Preacoustic liquid nitrogen (LN₂) vapor cooling from preacoustic LN₂ | 10 | NA | NA | NA | NA | NA | NA |

3.2. Detailed Performance Results
During the testing, many different types of tests were run, however, fundamentally, for the vapor cooling test, the tank was filled up to approximately 90% full and allowed to drain to approximately 25% full. As such, heat removal rates are shown plotted as a function of fill level and Reynolds number.
Temperature sensors relative location to the cooling tubes are shown in figure 5. Temperature sensors pairs have the same exterior box lines and plot color in figure 6 and internal box temperature match up with the dots indicating relative sensor location. The average fluid temperature at the inlet and exit of the vapor cooling channels is shown in figure 7 to indicate the stratification in the tank for both the Baseline test and the liquid hydrogen Preacoustic (Thermal #1) test. Temperature differences in the system are plotted in figure 6 for the Preacoustic liquid hydrogen testing.

Table 4. SHIIVER fill level averaged equivalent boil-off rate reduction.

| Test                                                      | Fill level (±2.5), percent | Equivalent boiloff flow rate reduction, percent |
|-----------------------------------------------------------|----------------------------|-----------------------------------------------|
| Liquid hydrogen (LH$_2$) vapor cooling from baseline      | 6 14 49 4 3 –3 7           |                                               |
| Preacoustic LH$_2$ vapor cooling from baseline            | 37 43 60 41 44 56 69       |                                               |
| Preacoustic LH$_2$ vapor cooling from preacoustic LH$_2$  | 31 33 15 –5 –4 3 –3        |                                               |
| Preacoustic liquid nitrogen (LN$_2$) vapor cooling from preacoustic LN$_2$ | 11 15 NA NA NA NA NA |                                               |

Table 5. SHIIVER fill level averaged equivalent boil-off rate reduction.

| Temperature Difference | Warm Diode(s) | Cold Diode(s) | Description                                                                 |
|------------------------|---------------|---------------|------------------------------------------------------------------------------|
| Delta T1               | SD-185        | SD-108        | The temperature difference across the skirt                                  |
| Delta T2               | SD-111        | SD-186        | The temperature difference from the back of the tube to the skirt (i.e. temperature drop across the leg conduction and bolts) approximately 180 degrees into the channel flow |
| Delta T3               | SD-187        | SD-136        | The temperature difference across the skirt                                  |
| Delta T4               | SD-188        | SD-145        | The temperature difference from the back of the tube to the skirt approximately 30 degrees into the channel flow on the cold side |
| Delta T5               | SD-131        | SD-93/94      | The temperature difference on channel 1 (or loop 1) between the exit gas temperature and the tube wall temperature at the exit of the loop |
| Delta T6               | SD-113        | SD-96/96      | The temperature difference on channel 2 (or loop 2) between the exit gas temperature and the tube wall temperature at the exit of the loop |

Figure 5. Vapor cooling line cross section with temperature sensor locations identified and color coded to match Figure 6.
General trends were very similar for the Baseline and Preacoustic liquid hydrogen testing. Delta T1 and Delta T3 demonstrate very little temperature difference, less than 3 K, across the skirt wall itself in the radial direction. Delta T2 and Delta T4 show significant temperature difference across the attachment of the channel to the skirt of between 5 – 15 K, that shrink as the flow progresses along the channel. It is interesting to observe the much larger temperature difference earlier in the flow channel length. Delta T5 and Delta T6 show approximately 5-6 K temperature differential between the tube wall temperature and fluid temperature at the exit of the flow channels. Comparison of these temperature differences suggest that the largest thermal resistance is in the conductance from the channel to the skirt wall. Temperature changes across the cooling channels remained fairly constant at fill levels above 50%, however, they slowly drifted down until crossing the aft flange at just under 30% full.

![Figure 6. Temperature differentials within the vapor cooling system as a function of time during Preacoustic testing.](image)

![Figure 7. Vapor cooling line entrance temperature as a function of fill level in the SHIIVER tank.](image)
Heat load calculations of the two cooling channels are shown in figure 8 for the Baseline and figure 9 for the Preacoustic thermal test with liquid hydrogen. Mass flow is assumed to be equally distributed between the two channels. At the low fill levels in the Baseline testing, there was significant noise in the flow meter calculation which exhibits itself in the heat removal calculation. Lower Reynolds numbers are associated with warmer gas temperatures and lower fill levels. All heat removal calculations are a product of the mass flow rate and the differential enthalpy, however for the Qloop calculations use exclusively wetted gas temperature to calculate the heat flows while the Qtube calculations use exclusively external tube wall temperatures. QtubeX-1 (where X is either 1 or 2) indicate the heat removed over the first half of the channel while it is the colder of the two and QtubeX-2 indicates the heat removal over the second half of the channel while it is the warmer of the two. It should be noted that Qtube1 and Qloop1 are consistent (within about 10%) between the calculated gas temperature heat removal and the calculated tube temperature heat removal, however Qtube2 and Qloop2 have a much larger difference. Additionally, the X-1 and the X-2 tube heat loads follow similar trends between the two channels. The increase in heat transfer at Reynolds numbers < 75,000 (low fill levels) is probably due to the increase in thermal conduction between the tubes and the skin as shown in figure 1 as the temperature of the gas flow and of the metal weld brackets increased. Further evidence of this is shown in the decrease in Delta T2 and Delta T4 at low fill levels in figure 6.

**Figure 8.** Heat removal as a function of Reynolds number for Baseline testing (left) and Preacoustic hydrogen testing (right).

**Figure 9.** Nusselt number as a function of Reynolds number for the Baseline test (left) and Preacoustic hydrogen test (right).
Heat transfer coefficients and Nusselt numbers were calculated from the testing and compared to the correlation provided by Barron (eq 1), which is essentially the Dittus-Boelter correlation adjusted to be a Colburn j-factor. [8] For the calculations, the temperature difference between the fluid and the tube wall was averaged between an assumed value of 0 at the entrance (actual instrumentation showed a slightly negative values) and Delta T5 and Delta T6 depending on the flow loop for the exit. Figure 8 shows the Nusselt number as a function of Reynolds number for both the Baseline and Preacoustic hydrogen tests along with the calculated Nusselt numbers. In general, the correlations agree rather well with the data for most of the lower Reynolds numbers, though as shown in figure 10, at Re > 100,000, the error approaches 100% on loop 2.

\[
 j_H = \frac{0.023}{Re^{0.2}} \times 1.174 \left(\frac{\mu_{avg}}{\mu_{wall}}\right)^{0.14}
\]

Equation 1

Where \( j_H \) is the Colburn j-factor and \( \mu_{avg} \) and \( \mu_{wall} \) are the vapor viscosities of the bulk vapor and wall temperature respectively.

Figure 10. Nusselt number error (assuming test is correct) as a function of Reynolds number for the Baseline test (left) and Preacoustic hydrogen test (right)

Figure 11. Heat removal and Reynolds number as a function of time for the cyclical vapor cooling testing.
During the Pre-Acoustic Thermal Liquid Hydrogen testing, a cyclic vapor cooling test was run. During the cyclic vapor cooling test, the tank self-pressurized to 25 psia, then was blown down to approximately 18 psia, venting through the vapor cooling channels, repeating for three times. While much more detail of this testing is shown in ref. [5], the heat rejection and Reynolds number of the hydrogen flow in the cooling channels are shown in figure 11 as a function of time and in figure 12 with heat rejection as a function of Reynolds number. As with the continuous vapor cooling testing, $Q_{tube2-1}$ is slightly higher than the other three and causes the fluid vs. channel heat loads to diverge. The heat removal vs Reynolds number results from the three different cycles are consistent with the shapes being similar between both the first and second passes for both loops.

4. Conclusions
The demonstration of vapor cooling structural supports on a large-scale liquid hydrogen tank was completed with the tank insulated with SOFI and with the addition of MLI on the forward and aft dome while the barrel remained insulated with SOFI only. Results showed that the heat load was reduced for all cases at all fill levels, however, the boil-off rate was only reduced at fill levels above 50% due to the cooling only being applied on the forward skirt, cooling both skirts would reduce the boil-off rate at all fill levels. Both heat load reduction and boil-off reduction were a function of fill level. Heat load reductions for liquid hydrogen tests ranged from 30% at high fill levels with MLI added to less than 5% at low fill levels in both cases. Boil-off reductions for liquid hydrogen tests ranged from 30% at high fill levels with MLI to essentially 0% at low fill levels in both cases. Heat load and boil-off reduction for liquid nitrogen tests were approximately 10% and only measured at 80-90% full. While nitrogen benefits were lower than hydrogen, they were not zero and further investigation into the benefits of nitrogen should be performed.

Additional data is provided that includes vapor cooling entrance temperature and temperature gradients throughout the system. Additionally, heat removal as a function of fill level and Reynolds number is shown for both insulation configurations. Heat removal was similar at high fill levels for both SOFI only and SOFI plus MLI testing. However, at lower fill levels, SOFI only insulation had slightly higher heat removal rates mainly due to higher flow rates. Finally, the sum of the channel surface calculated heat removal rates is nominally the same as the flow temperature calculated heat removal rates for channel 1, but not for channel 2.
5. References

[1] Cunnington G R, Thermodynamic Optimization of Cryogenic Storage System for Minimum Boiloff. Presented at the AIAA 20th Aerospace Sciences Meeting, Orlando, FL, 1982.

[2] Li Q, Eyssa Y M, and McIntosh G E, Discrete Cooling of Supports and Multi-Layer Insulation in Helium Dewars. Adv. Cryog. Eng., vol. 29, 1984, pp. 785–793.

[3] Hopkins R A and Payne D A, Optimized Support Systems for Spaceborne Dewars. Cryogenics, vol. 27, no. 4, 1987, pp. 209–216.

[4] Canavan E R and Miller F K, Optimized Heat Interception for Cryogen Tank Support. AIP Conf. Proc., vol. 985, 2008.

[5] Johnson W L, Balasubramaniam R, Hibbs 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-2020-5008233, 2021.

[6] Ameen L M, et al.: Testing of Hydrogen Vapor Cooling for Large Scale Structural Applications. Presented at the 28th Space Cryogenics Workshop, Southbury, CT, 2019.

[7] Kudlac M T, Weaver H F, and Cmar M D, NASA Plum Brook’s B–2 Test Facility: Thermal Vacuum and Propellant Test Facility. NASA/TM—2012-217234, 2012

[8] Barron R F, Cryogenic Heat Transfer, Taylor and Francis, Ann Arbor, MI, 1999.

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