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Structural Heat Intercept, Insulation, and Vibration Evaluation Rig (SHIIVER)

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ABSTRACT: The Structural Heat Intercept, Insulation, and Vibration Evaluation Rig (SHIIVER) is a large scale cryogenic fluid management (CFM) test bed designed to scale CFM technologies for inclusion on large, in-space stages. A part of the evolvable Cryogenics (eCryo) project, SHIIVER is a technology development task that is supportive of future exploration propulsion needs. Technologies developed under the eCryo Project will play a critical role in enabling increasingly longer duration in-space missions beyond Low Earth Orbit (LEO).

As NASA moves towards exploration beyond LEO, long duration storage and management of cryogenic fluids will become crucial. SHIIVER is designed to be a long term test bed for scaling technologies, however in its initial test phase, it is focusing on testing three technologies. Multilayer insulation (MLI) will be applied to the tank domes to quantify the thermal performance of thick (≥10 layers) MLI blankets at conditions and configurations representative of SLS upper stage mission implementations. Vapor cooling will be applied to the forward structural skirt to demonstrate benefit of using the boil-off gas from the tank to reduce the structural heat load. A Radio Frequency Mass Gauge (RFMG) will be installed inside the tank, to test scaling of the RFMG technology in a large scale cryogenic tank.

SHIIVER is a 4 meter diameter test tank and is currently being designed to include skirt structural systems representative of what might be found on a launch vehicle. In order to provide test data showing the benefit of scaling technologies and comparison with analytical models on a tank with representative heat loads, the technologies will be designed for an 8.4 meter application and scaled down to a 4 meter tank. Thermal vacuum testing will be performed using liquid hydrogen in a manner that demonstrates not only the performance of the system, but the direct benefits to a large stage. Multiple fills and drains of the tank will be performed to evaluate the performance of the technologies as a function of fill level within the tank. In order to prove that the MLI and vapor cooling attachment methods are structurally sound, reverberant acoustic testing will also be performed on the system. The test tank with insulation and vapor cooled shield installed will be tested thermally at the In-Space Propulsion Facility at NASA's Plum Brook Station and after being acoustically tested at Plum Brook's Space Environments Complex.

1. INTRODUCTION

NASA has a long history of developing technologies for the storage and transfer of cryogenic fluids [1]. While developing these technologies, many tests have been performed on many different scales. Nearly all of the tests have been focused on specific technologies as opposed to integrated systems testing.

In order for technologies to be used in actual large scale flight systems, it is desirable to first demonstrate them on large scale test systems that are very similar to flight configurations. This helps to identify factors affecting design, implementation, and performance that arise from the physical constraints imposed by size and configuration. Ecryo will design, build, and test a 4 m diameter, 3.5 m tall tank known as the Structural Heat Intercept, Insulation, and Vibration Evaluation Rig (SHIIVER). SHIIVER will be configured with structural skirts and fluid lines similar to a launch vehicle upper stage arrangement.

Testing (as shown in Figure 1) will include a series of initial baseline thermal tests, a second series of thermal vacuum testing for initial technology demonstration testing, a reverberant acoustic test, and a third series of thermal tests to evaluate the change in thermal performance caused by the acoustic exposure. Similar testing was performed on a smaller scale test tank in 2013 with no measurable change in performance [2].

There will be three main technologies demonstrated in the initial test hardware: multilayer insulation, vapor cooling on the structural forward skirt using the boil-off gas, and radio frequency mass gauging (RFMG). The tank will be insulated on the top and bottom domes with multilayer insulation (MLI) over a layer of Spray on Foam Insulation (SOFI). The barrel section of the tank is intended to mimic the outer mold line of a vehicle, and will therefore only have SOFI applied. The insulation system will be designed for an 8.4 m diameter tank and scaled down to the 4 m test article. The vapor cooling lines will route the boil-off vapor from the tank around the forward skirt (see Figure 2). Two RFMG antennas will be placed inside the tank to monitor liquid fill level during testing. While this will not prove out the microgravity aspects of the RFMG system, it will help to assess the scaling nature of the technology.

The performance goals of the SHIIVER testing involve demonstrating the improved performance (through reduced boil-off) provided to a large scale liquid hydrogen tank by applying MLI and vapor cooling of skirts. The first goal is to show a 40% reduction in total boil-off to the tank by adding the MLI on the domes. The second goal is for that boil-off reduction to remain the same after the reverberant acoustic testing. The third goal is to show that the vapor cooling reduces the boil-off to the tank by 15% while the liquid is at approximately 50% full.

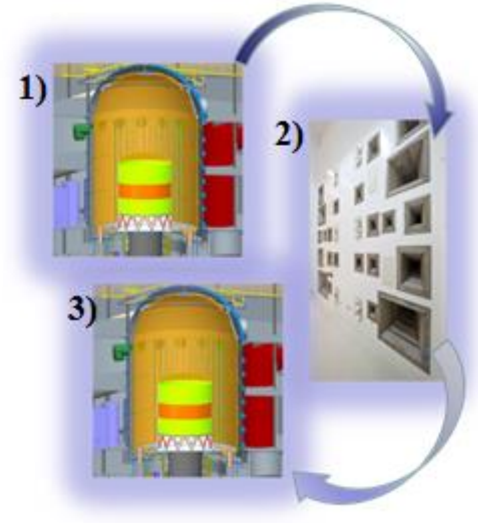

Figure 1: SHIIVER test sequence: 1) Thermal Vacuum, 2) Reverberant Acoustic, 3) Thermal vacuum

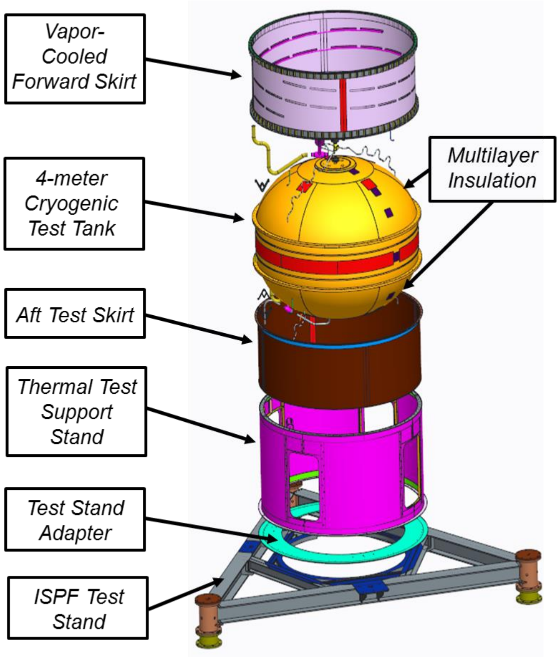

Figure 2: SHIIVER thermal vacuum test stack showing location of externally applied demonstration technologies.

In addition to the performance goals, SHIIVER also has mass goals. The goal for the MLI mass is to be no more than 41 kg as installed. The goal for the vapor cooling system is to be no more than 102 kg.

2. MULTILAYER INSULATION

It is acknowledged that the manufacturing and installation of MLI blankets will always involve a certain level of technician skill and experience. However, design details such as blanket seams, attachment of the blanket to a tank, and repeatability of blanket manufacture and installation have not been investigated in a methodical, scientific manner. Ecryo has been investigating these issues, especially as pertains to SHIIVER, but also looking at developing a more methodical approach to integrating seams into a complete insulation design approach. Using this data, the design, fabrication, and installation of MLI blankets for SHIIVER can be extended to large tanks such as the 8.4 meter diameter upper stage hydrogen tank of the SLS. This will involve the scaling of the detailed design and applicable thermal performance information obtained from small scale systems up to a SHIIVER sized tanks or even larger.

2.1 Small Scale Testing

In order to assess the design features as designed into the SHIIVER blanket, it was desired to perform subscale testing of these features. A calorimeter was developed to accurately perform small scale testing of MLI down to 20 K [3]. This calorimeter (see Figure 3) uses cryocoolers to maintain the cold boundary at temperatures close to 20 K and can control the warm boundary between 70 K and 300 K. SHIIVER used this calorimeter to establish baseline data and principles for SHIIVER specific MLI design details.

Details that were investigated include the number of layers of MLI, the thermal effect of the pre-determined seams on the blanket performance, and the thermal effects of the preferred structural attachment mechanism that holds the blanket onto the tank and skirt.

Calorimeter data showed that the heat load through the 30 layer system (3 sub-blankets of 10 reflectors each) was similar to the 50 layer system (5 sub-blankets of 10 reflectors each), and as such, the lower mass of the 30 layer system was preferred. It also showed that the seam on the 30 layer system had a heat load of approximately 0.15 W/m_{seam}. A test with four structural mounts had an extra heat load of 52 mW, suggesting a thermal penalty of 13 mW/attachment. The attachment heat load was validated by analytical calculations similar to reference [4].

Figure 3: Technicians installing a SHIIVER test coupon blanket onto the calorimeter.

Additional testing was completed to assess issues associated with electrical charging on MLI blankets. Based on the testing results, there was no need for special accommodations within the blankets to mitigate environmental charging.

2.2 Large Scale Implementation and Testing

Ensuring the results from the multilayer insulation blankets scale to be relevant to NASA's current 8.4 m diameter upper stage is important for SHIIVER. Since the current NASA upper stage is an inline tank (the barrel of the hydrogen tank is the outer mold line of the vehicle), MLI cannot be placed there with existing technology as the airflow during launch would rip it off. Thus, the MLI will only be placed on the domes for initial testing. However, SHIIVER will also have curtains that can drop over the outer diameter of the tank to help predict the improved performance if an advanced MLI system could be developed to survive that type of environment or if the stage could be placed in a shroud.

The final design is thirty layers of double aluminized reflectors, with each reflective layer separated by two layers of netting. The thirty layers are split into three sub-blankets made of ten layers each with outer, more durable, cover sheets on each side. The mass for each dome is expected to be 19 kg for a total mass of 38 kg. There is a single seam that overlaps at the sub-blanket level on each dome. Scaling by surface area, this will allow for twice the seam length in the actual application. Additionally, there will be a polar cap that will close out around the plumbing lines at the top and bottom of the tank. Evacuation of the blanket will be through the single seam, along the bottom and top edges, and around the polar cap. The only stitching goes through the sub-blankets is on the warm sub-blanket, which holds the structural restraints in place.

Historical data [5] suggests that the area weighted maximum differential pressure in the blanket will be less than 670 Pa (5 torr). There are 44 circumferential restraints that attach to the skirts to hold the blankets in place. For the dome area of 17.4 m^2, the maximum loading on the blanket is approximately 11.6 kN. At a maximum acceleration of 5 g's (49 m/s^2), the total force due to the mass of the blanket is only 910 N, which is much less than the depressurization load. Each restraint will need to withstand approximately 284 N to support the total load. Testing of five individual restraints at -80 ° C showed that each held in excess of 495 N with two of the five holding until 650 N. The demonstrated structural strength of the restraints give a factor of safety of 1.75.

The total heat load expected through the system is approximately 19.2 W per dome, for a heat flux of 1.1 W/m^2. When the system was adjusted for the domes of an 8.4 m diameter tank, the heat load is projected to be 82.8 W, for a heat flux of approximately 1.1 W/m^2.

Most testing will occur with a full tank. However, lower fill level data will be taken (most notably around the 50% and 25% levels) to understand how the heat load and boil-off rates change as the fill level drops below the various interfaces between the tank and skirts. Temperatures at the entrance to the vent line will be used to determine the enthalpy of the vapor exiting the tank and the total heat load.

3. VAPOR COOLING OF SKIRTS

While MLI will drastically reduce heating loads through the tank surface area, it does not address the large heat loads coming through the support structure to the propellant tank. Helium and other cryogenic fluid based dewars for various orbital telescopes and observatories have long used the boil-off vapor routed around structural elements to reduce the heat coming through the structure [6-7]. Most of these dewars used strut based mechanical supports to minimize heat load into their relatively small tanks [7-8]. Most launch vehicles use skirt type mechanical supports due to the location of the tanks in the structural design. Similarly to vapor cooling on dewars, it has been proposed to route propellant boil-off vapor around skirts to reduce heating into the propellant tanks. Ecryo developed initial models that show a great benefit (nearly 50% reduction in heating from the skirt) by using the boil-off vapor to intercept the heat being conducted down the skirts. Small scale testing has shown that to be a conservative estimate.

3.1 Small Scale Testing

In order to predict the amount of heat that is intercepted by the cooling channel, it is necessary to predict is the thermal conductance between the cooling tube and the skirt wall (see Figure 4). The convection heat transfer coefficient, contact resistance, and contact area play a key roles in removing the heat from the skirt wall and transferring it to the boil-off vapor. In order to understand how these issues might affect the performance of a system, a sub-scale test (the Small-scale Laboratory Investigation of Cooling Enhancement, or SLICE) was run on different attachment options (see Figure 5).

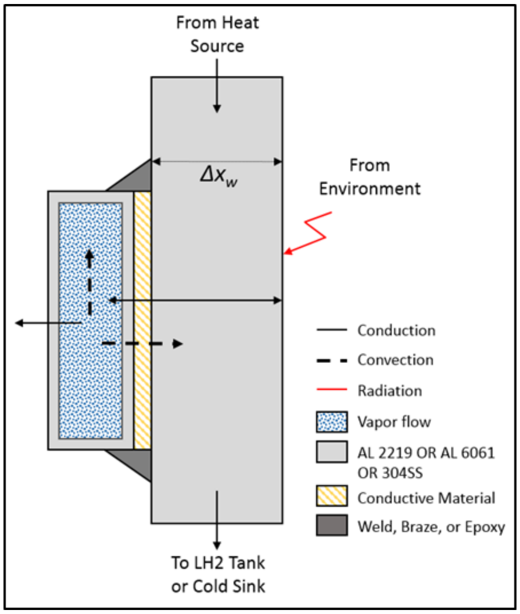

Figure 4: Thermal path from boil-off vapor to skirt wall.

Three different attachment mechanisms and sections were tested in order to understand the effects of the variables that affect the thermal performance of the heat intercept. The attachment mechanisms tested included a channel welded to the skirt body with no interface materials in the heat intercept path (see Figure 6), a channel with a bolted flange (instead of the weld, see Figure 7), and finally a tube that was attached via a bolted bracket (see Figure 8). Within each test, the simulated hydrogen boil-off conditions were adjusted for different runs to understand the effects mass flow rate being vented through the tubing, and temperature of the gas being vented (affected by tank fill level).

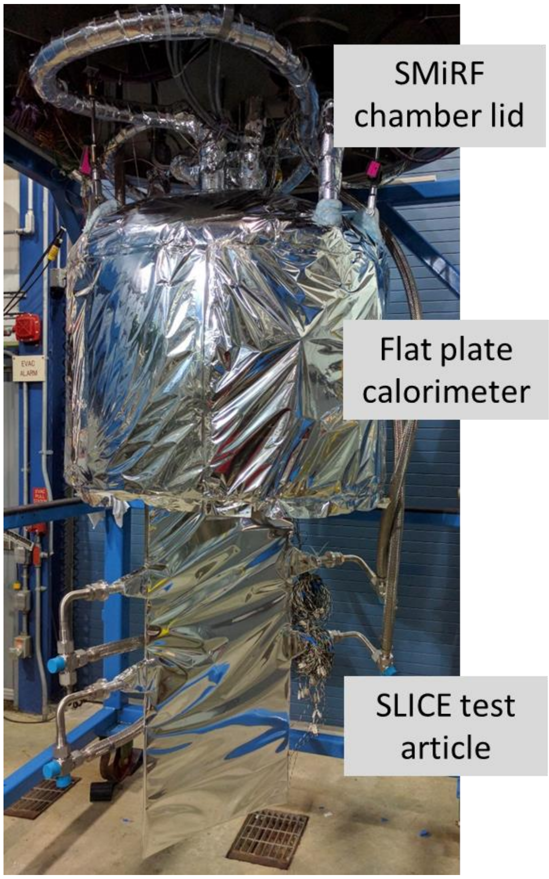

Figure 5: SLICE test article hanging from a liquid hydrogen calorimeter.

Results from the welded and bolted channel tests showed little sensitivity to the attachment mechanism, even as the number of bolts was reduced from 20 bolts to 4 bolts over the 630 m length of skirt. Based on these results, a bolted tube concept was developed and tested that showed skirt heat load decreases between 50% and 75% depending on channel inlet temperature and flow rate.

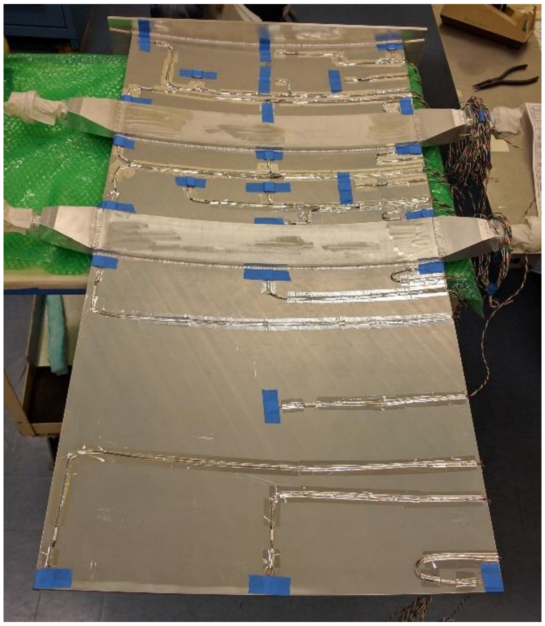

Figure 6: SLICE welded tube test article.

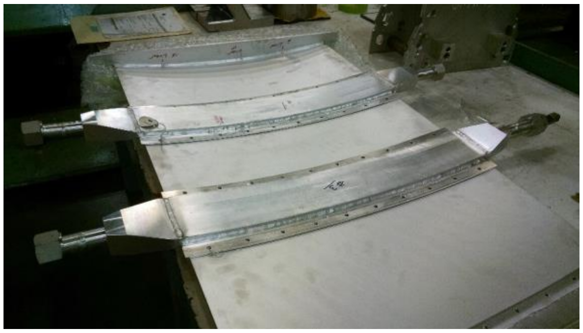

Figure 7: SLICE bolted channel test article.

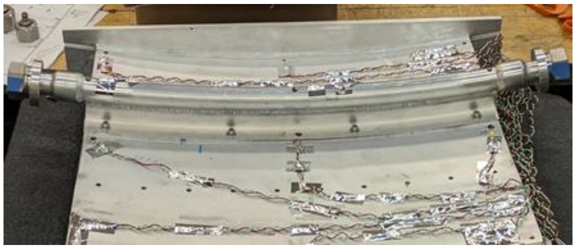

Figure 8: SLICE bolted tube test article.

3.2 Large Scale Implementation and Testing

SHIIVER will also apply vapor cooling of skirts at the 4 m diameter scale. The forward (top) skirt will have cooling channels similar to those tested in the small scale testing. The final cooling system will look very similar to the bolted tube design (see Figure 8).

Testing of the vapor cooling on SHIIVER will occur at several fill levels. While a 90% full tank is the simplest to extract boil-off comparison data from, most upper stages tend to have the coast portions of their missions at fill levels between 40% and 70%. As such, special attention will be paid to these fill levels as the flow rate drops and inlet temperature rises due to the decrease of heat load into the liquid and increase of heat load into the vapor portions of the tank. Additionally, SHIIVER will be able to bypass some of the boil-off vapor flow and cool the skirt with only a portion (nominally half) of the boil-off to assess the benefits of cooling both skirts as opposed to a single skirt.

It is not expected that the acoustic testing will have an effect on the performance of the vapor cooling system along the skirt or cause damage to the skirt itself, however this will also be demonstrated during the second thermal vacuum test of SHIIVER.

4. RADIO FREQUENCY MASS GAUGE

The RFMG is a propellant quantity gauge being developed for low-gravity applications with possible use in long-duration space missions utilizing cryogenic propellants. The RFMG operates by measuring the natural electromagnetic eigenmode frequencies of a tank. Because the liquid slows the speed of light in a known way, the changes to the electromagnetic modes of the tank can be computed and those simulations are used to compare with the measured tank spectrum. A database of RF simulations of the tank containing various fluid fill levels and liquid configurations is generated for comparison to the measured data. The best match between the measured tank mode frequencies and the computed tank mode frequencies occurs at some fill level, which is then reported as the gauged liquid level in the tank [9].

Previous testing of the RFMG has focused on tanks that were in the 1 – 2 m diameter range [9-10]. The main goal of putting an RFMG into the SHIIVER tank is to demonstrate scaling to a tank that is twice the size of previous tests. The RFMG will be active during many of the fills and drains that are planned in the test matrix. The output will be compared to a capacitance probe for verification of accuracy.

5. TEST PLANS

As shown in Figure 1, SHIIVER will go through three thermal vacuum test sequences plus reverberant acoustic testing. Thermal vacuum testing will be performed at the In-Space Propulsion Facility (ISPF) at Plum Brook Station. Reverberant acoustic testing will take place at the Reverberant Acoustic Test Facility (RATF), also at Plum Brook Station. For all thermal vacuum testing, the environmental temperature will be approximately 290 K and the vacuum pressure will be less than 1 x 10^{-5} torr.

Initial thermal vacuum testing will develop a baseline system performance for a tank insulated with only spray-on-foam insulation. Both the thermal performance and the benefit of vapor cooling the forward skirt will be evaluated without the MLI on the domes.

Following installation of the MLI on the domes of the SHIIVER tank, a second thermal vacuum test will occur to investigate the thermal benefit of the MLI on the domes. The vapor cooling tests will also be run to assess the impacts of the dome MLI on the vapor cooling system benefits. An MLI curtain will be lowered around the SHIIVER tank to provide technical rationale for the performance benefit to insulating the entire tank in MLI if the tank can be contained within a shroud or if an MLI system could be developed to survive on the outside of a launch vehicle.

The reverberant acoustic testing will apply acoustic levels that will be experienced on the Space Launch System during both lift-off and the aeroacoustics at maximum dynamic pressure. The lift off acoustic test will be approximately 150 dB over a specified frequency spectrum for the duration of 40 seconds. The aeroacoustic environments are at a level of 159 dB for a duration of 20 seconds. A more detailed configuration of the frequency spectrums have been defined by the test team, but are not presented here. As the testing of SHIIVER occurs in more than one facility, it will also have to be transported over the road between the facilities. In between each of the transportation and reverberant acoustic activities, inspections will be made looking for changes and possible damage to the blankets.

The SHIIVER test article will then encounter a third thermal vacuum test to determine the thermal effects of any damage the reverberant acoustic testing caused in the MLI.

6. SUMMARY

SHIIVER is maturing cryogenic fluid management technologies needed for both near and far term applications on cryogenic propulsion systems. Both MLI and vapor cooling will reduce boil-off and enable a stage to carry more usable propellant for longer duration missions for a given stage design. SHIIVER is targeting the understanding of the performance of the MLI and vapor cooling independently and together as a thermal system. The demonstration of the scaling of the RFMG will help ready that technology for infusion into large tanks. The data developed using SHIIVER will be directly applicable to large upper stages.

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