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Technology Demonstration Mission (TDM) Evolvable Cryogenics (eCryo) Project

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

Test Plan

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Change History

Revision *("Basic" or "Letter")*	**Effective Date** *(date document is published for release)*	**Description** *(e.g., describe state, change description, CR#, approval/board date, etc.)*
Basic	1/25/17	Initial approval
A	6/12/18	Updated contents throughout
B	11/20/18	Update transient test plans and remove references to curtains
C	4/29/19	Added section 2.3.16. to describe microphones. Update master measurement list (Table 2, section 2.3) and critical instrumentation list (Table 3, section 2.3.1.) Update Acoustic testing test matrix in section 2.6.2. and data requirements in section 2.7.2.
D	6/24/19	Updated Acoustic profile (Figure 6 and Table 7) to accommodate test facility and extensibility goals. Add Appendix B: Test Procedure
E	8/6/19	Updated section 2.5.4 with reference to transient testing. Clarified Table 6 bands for tolerance. Remove Appendix A: Modeling of Transient Thermal Test Update Appendix B: Test Procedure, removing all heater based testing. Add Appendix C: SHIIVER Deviation Policy
F	8/22/19	Update Appendix B: Test Procedure based on pre-Baseline test review.
G	9/19/19	Update Appendix B: Test Procedure based on actuals for Baseline and Thermal Testing #1 (both hydrogen and nitrogen).
H	10/8/19	Update Tables 2, 3, and 7 and Figure 6 with updated instrumentation and test profile information for the acoustic testing. Update section 2.6.2.1 to more appropriately reflect how the acoustic test profile was generated.
I	1/9/20	Update Appendix B: Test procedure updated with actuals from Thermal Test #1 nitrogen testing. Thermal Test #2 updated. Thermal Test #3 removed.

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1 INTRODUCTION

The initial test of the SHIIVER system includes multilayer insulation and vapor cooled structure. Testing will occur in the In-Space Propulsion Facility (thermal/vacuum) and RATF (acoustic) facilities at Plum Brook Station in Sandusky Ohio. The testing will demonstrate the performance benefits of multilayer insulation and vapor based heat intercept on a “large scale” test article in a manner befitting large upper stages.

1.1 Background

The current design methodology of upper stages prioritizes structural design over thermal design. Because of the duration of the missions that such stages undergo, it is assumed to be wisest to oversize the tank and take the propellant losses that accompany the poor thermal performance. Recent analysis has shown that even on 3 orbit (~5 hours) Low Earth Orbit (LEO) missions, significant savings can be gained. Similar efforts with MLI were undertaken by Lockheed on the Titan IV based Centaur G-Prime. Using just three layers of MLI on the sidewalls, the Centaur liquid oxygen and liquid hydrogen heat fluxes were cut to nearly half of the baseline heat load using Spray on Foam Insulation (SOFI) on the tank surface [1].

In order to demonstrate both the full performance after vibration, as well as the impacts and improvements of the system, the SHIIVER test article will go through a sequential order of thermal/vacuum testing, acoustic testing, and thermal/vacuum testing. An initial thermal/vacuum “baseline” test with SOFI as the only insulation on the tank will be performed to set a baseline that is similar in configuration to current upper stage designs for comparison of all future testing. In order for the SHIIVER demonstration to give insight into the fabrication costs, installed masses, and associated thermal performance benefits for insulation and vapor cooling structure, the actual fabrication and demonstration must be performed on a fairly large and representative system.

1.2 Test Objectives

An objective from the SHIIVER Work Authorization (eCryo-WA-0027) is to "Perform an initial test of the large rig under mission-representative environmental conditions using one configuration of a possible stage-like heat intercept system."

There are two test objectives for the current SHIIVER testing that can be derived from the aforementioned work authorization objective, the first with regard to vapor cooling and the second with regard to insulation, each with a subset of objectives:

1.2.1 Vapor Cooling Test Objectives

The vapor cooling objective is to demonstrate vapor cooling of a representative structural system on a representative scale liquid hydrogen test hardware.

This can be broken down into a subset of objectives:

1.2.1.1 Intercept heat from a skirt structural support using the boil-off vapor from a liquid hydrogen tank.

1.2.1.2 Accurately predict the thermal performance change of a system when vapor cooling is used on a representative system.

1.2.1.3 Measure the increase in thermal performance of a system when vapor cooling is used on a representative system.

1.2.2 Insulation Test Objectives

The main insulation objective is to demonstrate the benefit of insulation on a representative scale liquid hydrogen, test hardware. More specifically, the implementation of this insulation should be using a combination of spray on foam insulation (SOFI) and multilayer insulation (MLI).

This can be broken down into a subset of objectives:

1.2.2.1 Insulate a representative scale, liquid hydrogen, test apparatus with SOFI and MLI.

1.2.2.2 Measure the thermal performance of the insulation system on the representative scale, liquid hydrogen, test apparatus and compare the results to the baseline test.

1.2.2.3 Measure the thermal performance degradation of the insulation system when exposed to representative reverberant acoustic loading.

1.2.2.4 Accurately predict the thermal performance of the insulation system on the representative scale, liquid hydrogen, test apparatus.

1.2.3 Combined Effect of MLI and Vapor Cooling Test Objective

Additionally, to the individual test objectives, there is one additional point of interest, which is to understand the combined effects of MLI and vapor cooling in reducing the heat load to the system. The MLI should reduce the heat load to the vapor cooled skirt as shown in Figure 1 and should also decrease the temperature of the gas at the skirt inlet. These should both increase the effectiveness of the cooling.

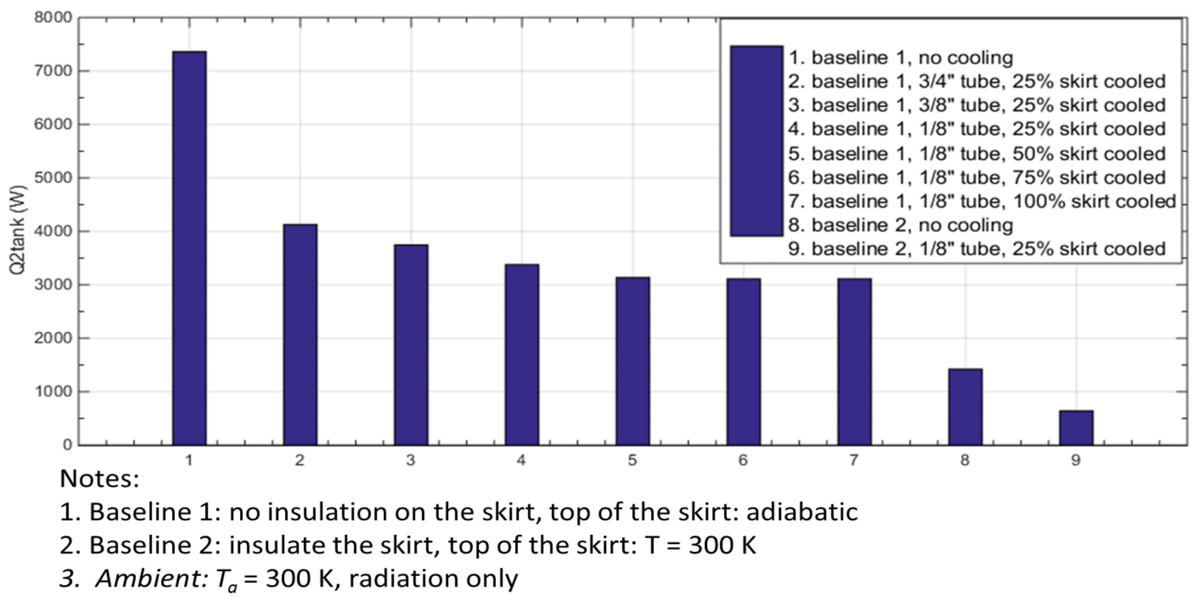

Figure 1: Performance of an 8.4 m Skirt with and without Vapor Cooling.

1.3 Justification

The Key Performance Parameters (KPPs) for SHIIVER are shown in Table 1. These cover the expected performance of the SHIIVER test article and test plan. The minimal testing must meet these KPPs. It should be noted that in the project requirement for MLI characteristics (eCryo-RQMT-0014, eCryo-REQ-IFU-1.1) the concept of "thick MLI" is defined as greater than 10 layer. Also, defining some acronyms: Cryogenic Propellant Storage and Transfer (CPST), Reduced Boil-off (RBO), Vibro-Acoustic Test Article (VATA), and vapor cooling (VC).

Table 1: SHIIVER KPPs

Program Requirement	Key Performance Parameter (KPP)	Current State of the Art	Threshold	Project Goal
eCryo-REQ-1.003 Heat Intercept	MLI Thermal Performance on a 4 m tank	SOFI baseline testing done by eCryo	40% boil-off reduction	40% boil-off reduction after exposure to acoustic vibration loads
eCryo-REQ-1.003 Heat Intercept	MLI Mass on a 4 m tank	Thick MLI has not been demonstrated in a manner representative of an upper stage flight application.	MLI added mass of not more than 3% of tank fluid mass	MLI added mass of not more than 2% of tank fluid mass
eCryo-REQ-1.003 Heat Intercept	Vapor Based Heat Intercept Thermal Performance on a 4 m tank	Small flight helium dewars (<2 m). CRYOTE testing (0.75 m)	15% boil-off reduction on small-scale testing	15% boil-off reduction on 4 m tank at 50% full
eCryo-REQ-1.003 Heat Intercept	Vapor Based Heat Intercept Mass on a 4 m tank	CRYOTE testing (.75 m tank) 9% of tank fluid mass (using LH2 density)	Not more than 7% of tank fluid mass	Not more than 5% of tank fluid mass

1.4 Theory and Analysis to be Performed

The data from SHIIVER will be used multiple ways, from basic analysis to verification of complex computational models.

The simplest analysis done will be to determine the heat load of the SHIIVER tank. The heat load is determined via boil-off calorimetery as:

$$\dot{Q}_{System} = \dot{m}\left(h_{v,exit} - h_{liq}\right)\left(\frac{\rho_{liq}}{\rho_{liq} - \rho_{vap}}\right)$$

Where $\dot{m}$ is the mass flow rate, h is the enthalpy of the vapor vent temperature (v,exit) and liquid (liq) respectively, and ρ is the averaged density of the phases. The densities are a function of local temperature and tank pressure. The density term on the end correct for the volume that the liquid left behind that must be filled with vapor (it is approximately 1.03 for liquid hydrogen).

The vapor cooling flow cooling can be calculated as:

$$\dot{Q}_{cooling} = \dot{m}_{vent}\left(h_{loop,out} - h_{loop,in}\right)$$

Where $\dot{m}_{vent}$ is the mass flow rate through the cooling tubes, and $h_{loop,in}$ and $h_{loop,out}$ are the inlet and outlet temperatures of the cooling loop.

Next the heat load of various conduction paths will be calculated using the Fourier equations.

$$\dot{Q}_{Cond} = kA\frac{\Delta T}{\Delta x}$$

Where k is the temperature dependent thermal conductivity, A is the cross sectional area of heat flow, ΔT is the temperature difference between two temperature sensors spaced Δx apart. All conduction paths into the tank (including but not limited to the vent line, fill line, structure, skirts, and instrumentation wires) will need to be measured.

Then the insulation heat load and heat flux is then calculated from the residual heat load:

$$\dot{Q}_{INS} = \dot{Q}_{System} - \sum \dot{Q}_{Cond}$$

Since the conduction heat loads are much larger than the MLI heat loads (but not necessarily the SOFI heat loads), $\dot{Q}_{System}$ will be compared across tests, the KPPs were written to take this into account. However, for component performance, which is a highly desired output of the testing, further analysis as shown will be done. The uncertainty of the two derived portions are directly related to $\dot{Q}_{System}$ and other calculations such as $\dot{Q}_{Cond}$. This means that the uncertainties also propagate through the system to the component calculations. To further reduce this uncertainty, heat flux sensors have been placed on both domes and the barrel section (see Figure 2 and Figure 3) to measure the relative heat fluxes. Current requirements are based on readily available sensors and relative uncertainties.

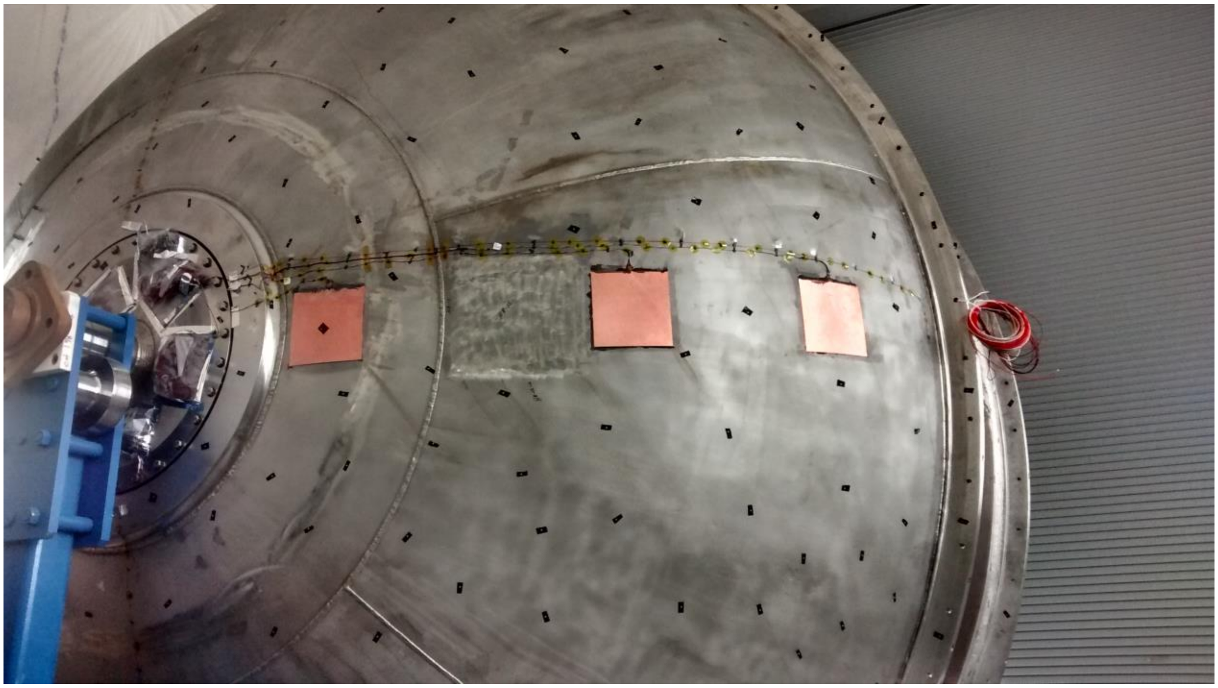

Figure 2: Heat Flux Sensors Mounted on Forward Dome prior to SOFI Spray

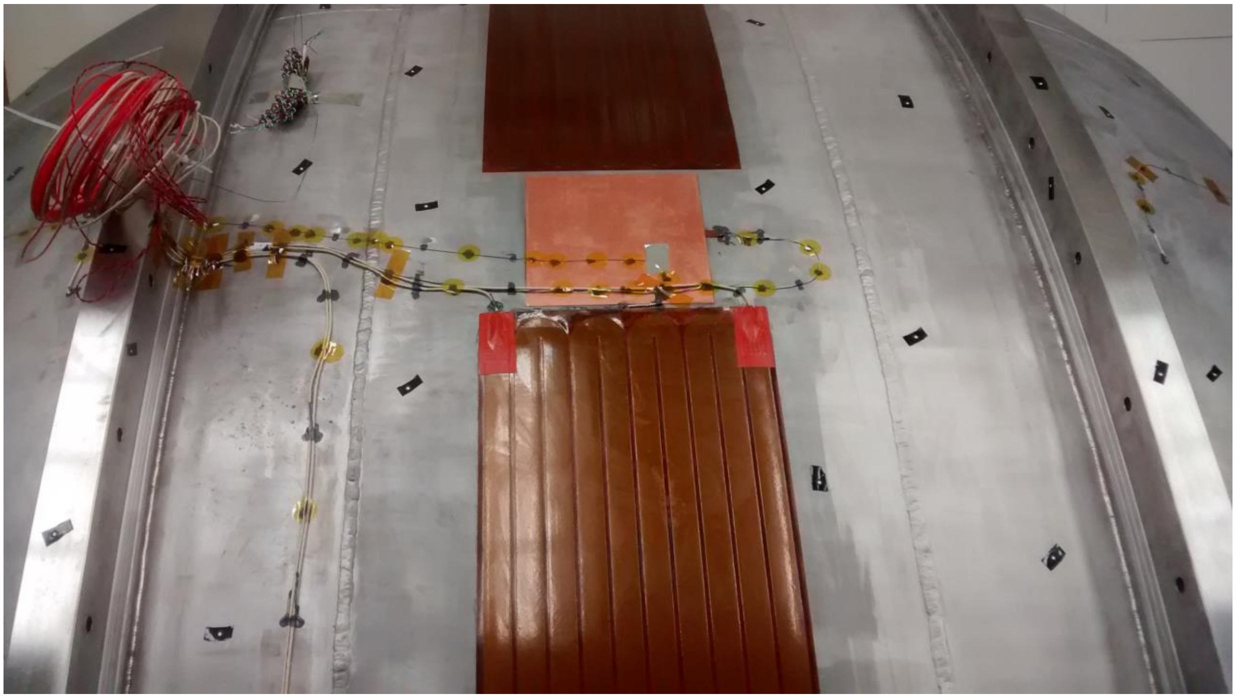

Figure 3: Heat Flux Sensor and Heaters Mounted on Barrel prior to SOFI Spray

2 TEST DESCRIPTION

The SHIIVER experiment is designed for thermal vacuum and reverberant acoustic testing at Plum Brook Station. Thermal vacuum testing will occur in In-Space Propulsion Facility (ISP) and acoustic-vibe testing will occur in the Space Power Facility's Reverberant Acoustic Test Facility (RATF). MSFC will install instrumentation and heaters on the tank, then apply SOFI. The tank will be delivered to PBS for test article assembly. A baseline thermal/vacuum test will be performed without any MLI. The test article will then be insulated with the MLI for additional thermal vacuum testing. After initial thermal vacuum testing with MLI at ISP, the test article will be transported to RATF for acoustic/vibe testing. The test article will then be transported back to ISP for thermal vacuum testing to determine if any damage was done to the insulation system during acoustic/vibe testing.

Thermal vacuum testing is planned to include boil-off testing to determine the total system heat load (from which the MLI heat load will be calculated) at a minimum of two fill levels (~95% full and ~50% full) with two more fill levels highly desired (70% and 25%). Similarly, pressure rise testing will occur at the same fill levels and different heat loads for ullage modeling of locked up scenarios. The vapor cooled heat exchanger on the skirt will be activated at various times throughout the test matrix to evaluate multiple variations of vapor cooling. If time allows, further fill levels or scenarios of vapor cooling may be evaluated.

The SHIIVER test article configuration consists of 3 main components: the liquid hydrogen tank, a vapor cooled forward test skirt, and the aft test skirt. The test article will have a two different support structures, one for the thermal/vacuum testing and one for the acoustic testing. The assembly for testing in the ISP test chamber is shown in Figure 4.

A 4 m diameter tank was chosen as the biggest tank that could be fabricated without a huge impact to the transportation costs of the tank. The tank will be supported as shown in Figure 4 with the pink thermal test support stand and maroon upper and lower skirts. The relationship between SLS, EUS, and SHIIVER is shown in Figure 5.

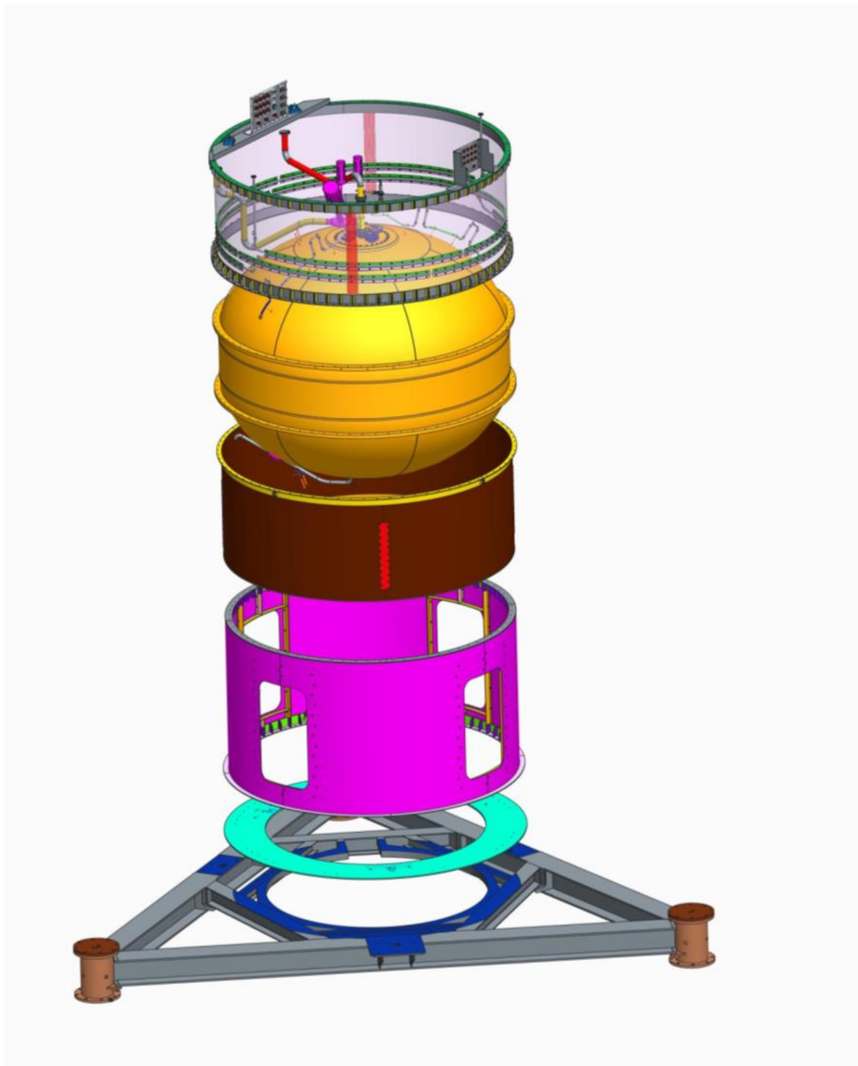

Figure 4: SHIIVER Test Article Installed in B2

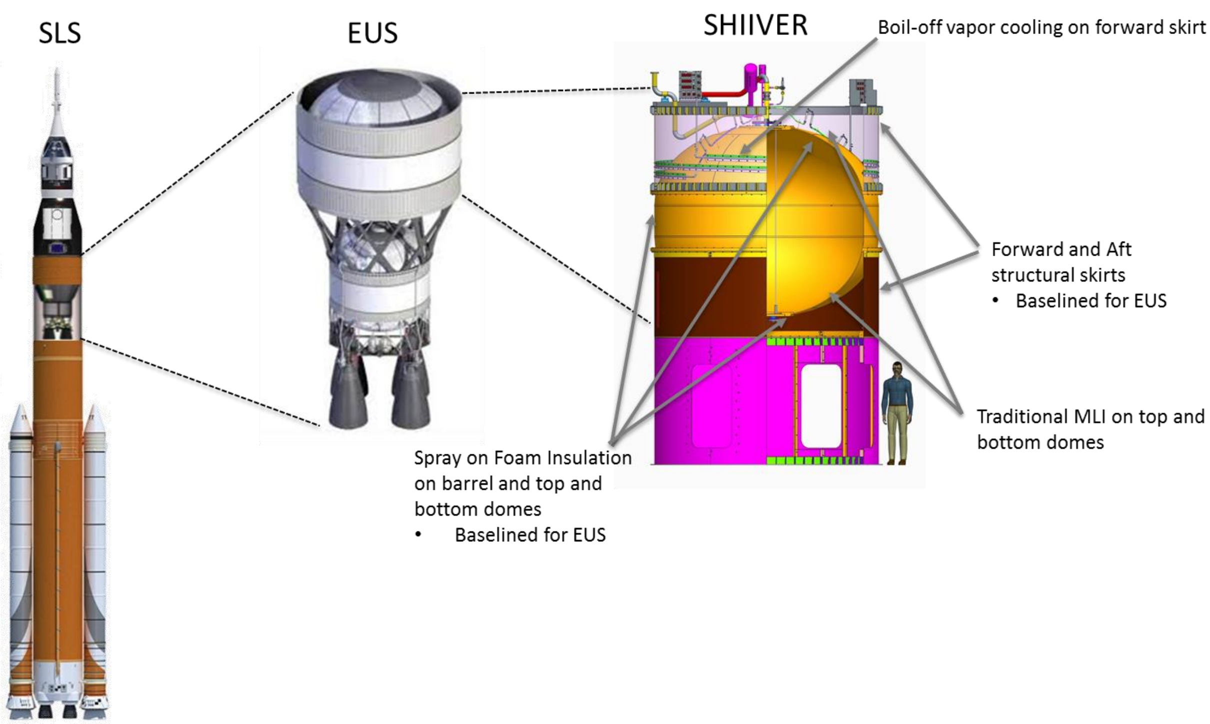

Figure 5: Relationship between SLS, EUS, and SHIIVER.

2.1 Description of Experiment

The experimental portion of SHIIVER includes two elements: insulation and vapor cooling.

Initially, the tank will be covered in spray on foam insulation (SOFI). After baseline testing, the tank domes will be insulated with a MLI blanket on top of the SOFI (but not mechanically attached to the SOFI). The blanket will be made of traditional MLI materials and will incorporate features such as seams and attachment mechanisms that closely approximate how a system would be installed on a real flight tank. This insulation will also be designed go around various features like the skirt/tank flange and the fill and vent lines. The performance of the insulation will be demonstrated in the initial thermal vacuum test. The acoustic test will demonstrate the capability of the insulation system to survive the acoustic loads of the launch environment. The follow on thermal vacuum test will quantify any damage done to the insulation system during the acoustic test. Temperature sensors will be in place throughout the test article to assess structural and plumbing heat loads and separate them from the insulation heat load.

The upper skirt will include a vapor cooling fluid network. The fluid network will consist of some combination of tubing and manifolds that routes the boil-off vapor along the skirt from which heat will be intercepted. The tubing will run from the vent along the top of the tank and then to the skirt. The tubing will then wrap around the skirt and be recollected in a manifold for venting out of the vacuum chamber. Attachment of the tubing to the skirt will be fairly significant in determining the heat exchanger effectiveness and as such will be closely monitored during fabrication and post-test. The thermal performance of the tank with vapor cooling will be assessed by comparing the performance with and without the cooling loops activated. Temperature sensors will be located along the length of the skirt and tubing to better understand the heat transfer and effectiveness of the heat interception system. The vapor based heat intercept system will be insulated on the interior by MLI.

The structural support of the tank will be accomplished in a manner that represents stage heating into the tank. This will allow for the effectiveness of the main test objectives to be more clearly understood.

A radio frequency mass gauge with two antennas will be installed into the tank as a secondary objective for testing. The mass gauge will operate throughout the life of the testing with the tank going from empty to full over the course of multiple days.

2.2 Identification of Key Test Parameters (a.k.a. Critical Measurements/Controls)

There will be key test parameters and measurements that need to be monitored or controlled for each major objective. If one of these parameters fails, then the test should be stopped and the parameter repaired before continuing. Those parameters are identified below:

2.2.1 General Parameters

2.2.1.1 Tank Pressure: The tank pressure will need to be controlled to within +/- 0.01 psia of the desired set pressure at all times during steady state boil-off testing in order to allow a steady state condition to be achieved.

2.2.1.2 Tank/Fluid Temperatures: The tank and fluid temperatures will need to be monitored at all times to determine the fluid state.

2.2.1.3 Vacuum Chamber Pressure: The vacuum chamber pressure will need to be maintained at less than 1×10^{-5} Torr for the duration of testing to ensure the insulation is thoroughly evacuated.

2.2.2 Parameters for Vapor Cooling Testing

2.2.2.1 Fluid Network Outlet Temperature: The outlet temperature of the vapor in the fluid network will need to be monitored during all vapor cooling testing to know the amount of heat absorbed from the fluid network.

2.2.2.2 Fluid Network Inlet Temperature: The inlet temperature of the vapor in the fluid network will need to be monitored during all vapor cooling testing to know the amount of heat absorbed from the fluid network.

2.2.2.3 Vapor Flow Rate: The flow rate of vapor through the fluid network will need to be monitored to know the amount of heat absorbed from the fluid network.

2.2.2.4 Axial Temperatures: Temperature measurements will need to be monitored during all vaporing cooling testing to understand the amount of heat absorbed from the fluid stream and how this effects the temperature gradient along the skirt wall.

2.2.3 Parameters for Insulation Testing

2.2.3.1 Vent Line Entrance Temperature: The vent line entrance temperature will need to be monitored during insulation system testing to ensure that the sensible heat of the vapor is included in the total heat load calculation.

2.2.3.2 Boil-off Flow Rate: The boil-off flow rate will need to be monitored at all times during insulation testing to know the total heat load to the system.

2.2.4 Parameters for Acoustic Testing

2.2.4.1 The acoustic testing will need to follow the profile defined in Section 2.6.2.1

2.3 Measurements

The measurements required for the SHIIVER test include temperature, pressure, flow rates, vacuum pressure, heat flux, acceleration, and fill level. Local humidity sensors at the test facility will help to understand any differences that occur between tests.

The temperature measurements will be required on every element to map the system heat flow as well as within the tank to determine the hydrogen state and thermophysical properties of the fluid. Pressures will be used to determine the hydrogen state within the tank as well as the flow losses experienced by the vapor cooled heat exchanger. The vacuum chamber pressure will need to be monitored to determine the background pressure and ensure steady state criteria are met.

Table 2: Master Measurement List

Type/Location	Range	Number	Accuracy	Basis for Estimate
Temperature		~170		
Inside Tank (Vert. Rake)	20 K – 50 K	20	+/- 0.1 K	Wet/Dry rake inside tank + tank stratification
Tank Piping (vent line entrance)	20 K – 50 K	2	+/- 0.1 K	Redundant sensors at vent line entrance for total heat load
Tank Wall (outer)	20 K – 100 K	30	+/- 0.25 K	5% levels in one direction, 25% levels in other three
SOFI Surface	20 K – 300 K	8	+/- 0.5 K	Four MLI temperature profiles
MLI	20 K – 300 K	30	+/- 0.5 K	Four MLI temperature profiles, 6 sensors each, MLI outer surface temperatures with thermocouples.
Forward Skirt	20 K – 300 K	52	+/- 0.25 K	For characterizing fluid cooling network effect
Fluid Temperatures on vapor Cooling	20 K – 300 K	8	+/- 0.1 K	For characterizing fluid cooling network
Other Structure	20 K – 300 K	12	+/- 0.25 K	For Heat Map, 3 on each conduction point, especially if radiation important
Cold Wall Temperature	150 K – 300 K	12	+/- 0.5 K	Know sink temperature profile
Pressure		4		
Tank Pressure	0 – 30 psia	2	+/- 0.01 psia	Need tank pressure, ability to control back pressure
Exit of flow/Vent Pressure	0 – 30 psia	2	+/- 0.01 psia	Characterize pressure drop across fluid network.
Vacuum Pressure		2		
Ion Gauge	10^{-7} to 10^{-5} Torr	2	+/- 0.1 decade	Facility Measurement, one each on top and bottom of vacuum chamber
Flow Rate		5		
Vent Flow Rate	0 – 85,000 slpm H2	1	+/- 0.25%	Heat loads up to 52 kW
Vent Flow Rate	0 – 19,000 slpm H2	1	+/- 0.25%	Heat loads up to 12 kW

Vent Flow Rate	0 – 7400 slpm H2	1	+/- 0.25%	Up to 5000 W
Cooling Flow Rate	2-30 g/s	1	+/- 1%	Expected flow rates through VCS
Capacitance Probe	5 – 100%	1	+/- 1%	For liquid level of the test tank
Acoustic				
Microphones	4 Hz to 70 kHz, 30 – 172 dB	8	+/- 1.6 mV/Pa	To Verify acoustic test loads
Accelerometers (3-axis)	0 – 500 g	12	10 mV/g	To measure structural response and prevent damage to test hardware.
Heat Flux				
Heat Flux Meters	0 – 100 W/m^2	4	+/- 1 %	Used on a skirt and under SOFI
Heat Flux Meters	0 – 2 W/m^2	8	+/- 1 %	Used under the MLI

2.3.1 Critical sensor list

A critical sensor list will be created to ground rule sensors that are required for successful test operations. If a critical sensor is not reading properly, it must be fixed prior to continuing the test. These are closely related to the Key Parameters:

Table 3: Critical Instrumentation List

Sensors	# In System	# Required	Rationale	Test Required for
Vent Line Entrance Temperature	2	1	Vent Line Temperatures set the tank exit temperature for thermal balance	Boil-off
Boil-off Flow Meter	3	1 (in range)	Boil-off flow rate directly proportional to the heat load	Boil-off
Cooling Flow meter	1	1	Measuring cooling flow rate to quantify cooling rejection temperature	Vapor Cooling
Tank Pressure	2	1	Tank Pressure sets fluid state	All Thermal Vac
Liquid Level	3	1	Liquid level required to split phases in pressure rise test	Thermal Vac
Vapor Cooling Inlet Temperatures	2	1	Needed to set state and determine heat gained by coil	Vapor Cooling
Vapor Cooling Outlet Temperatures	2	1	Needed to set state and determine heat gained by coil	Vapor Cooling
Vapor Cooling Outlet Pressure	2	1	Needed to set the state for heat gained by the coil	Vapor Cooling
Vacuum Chamber Pressure	2	1	Needed to verify orbital environment	All Thermal Vac
Cold Wall Temperature	12	3	Needed to verify orbital environment	All Thermal Vac
Microphones	8	7	Needed to verify acoustic environment	Acoustic
Accelerometers on manways	1	2	Needed to verify structural survival of test	Acoustic

2.3.2 Sensor Purposes & Descriptions

Each group of sensors on the SHIIVER test article are in place for a purpose. Those purposes and general locations are described here:

2.3.2.1 Internal Tank Temperatures: The tank internal temperature rakes are located within the tank and are generally in a straight line either vertically or horizontally. The vertical temperature rakes are historically as close to the center of the tank as possible (note: they may be off center if a mixing pump is placed in the center). The vertical rakes determine the temperature profile through the bulk liquid and vapor and the associated stratification and destratification of the fluid. Generally, the sensors in a vertical rake are evenly spaced along the length of the tank, however, they may also be closely grouped around a target fill level to provide more discrete data near the liquid/vapor interface. The temperature rake is used for anchoring computational models to the test data. Additionally, there are two sensors to be placed in the vent line entrance, these sensors will be used to determine the temperature and thus enthalpy of the vapor leaving the tank. This will be directly used to solve for the total tank heat load. Fluid enthalpy are very temperature dependent, so the sensor uncertainty needs to be less than +/- 0.1 K.

2.3.2.2 Outer Tank Wall Temperatures: The temperature along the wall of the tank serve a similar purpose as the vertical temperature rake. However, instead of measuring fluid temperature, they measure wall temperature. This is especially important in the ullage to be able to determine the energy flow through the tank wall in various directions. Generally the sensors are evenly spread across the length of the tank. Multiple sensor paths can be used to measure the effect of increased heat flux associated with structural attachments to the tank. Tank wall temperatures need less certainty than fluid temperatures, but still require reasonable accuracy.

2.3.2.3 SOFI Surface and MLI Temperatures: The temperature sensors within the MLI blankets and on the SOFI surface will help to extend the results of the single performance test to multiple environments. Since the general heat flux through the blanket should be known, the number of layers required to achieve that heat flux at different environmental temperature can be determined from the temperature profile. The profile will be measured at 4 different locations, which allows for comparison of profiles to understand differences in the installation or if any compression or sagging in the blankets may be present. Uncertainty in temperature measurement on SOFI and MLI doesn’t need to be better than half a Kelvin due to the relatively wide range of temperatures being measured.

2.3.2.4 Forward Skirt Temperatures: The temperatures measured along the upper skirt will aid in understanding the reduction in boil-off due to the activation of the vapor cooled skirt.

Since conductive heat loads are driven by spatial temperature gradients, measuring these temperature gradients (by measuring multiple temperature locations) will give a more detailed description of heat flow paths than just measuring the change in boil-off. Sensor uncertainty on the upper skirt is TBD.

2.3.2.5 Other Structural Temperatures: Temperature sensors will be places along the length of other structural and fluid members to help to map the heat flow into the tank. Understanding the heat load brought in via the structural supports, plumbing line, and even instrumentation wires can help to decrease the uncertainty of the reduction in performance directly due to particular changes. A minimum of two working sensors in different locations on each line will be required, a third sensor location would allow for picking up radiation effects. Due to the relative sensitivity and need for sensors to be fairly close together to minimize the impact of radiation in measuring structural heat loads, sensors need an uncertainty within a quarter of a Kelvin.

2.3.2.6 Cold wall temperature: In order to fully understand the heat flow to the tank, the temperature of the environment (i.e. the cold wall) needs to be understood. The data from these sensors will be used to establish the environment for models that are being anchored by the test data. Cold wall temperature uncertainty is not as important due to averaging and can be up to half of a Kelvin.

2.3.2.7 Tank Pressure: The tank pressure is required to set the thermodynamic state of the fluid. Additionally, it will be needed as a parameter to be controlled to dampen out the fluctuation in local ambient pressure. These fluctuations can cause the fluid in the tank to be used as a battery to store and release energy. These pressure sensors will also be used as the inlet pressures of the vapor cooled skirt for setting the state of the vapor. Due to the sensitivity of fluid state to tank pressure, as well as the requirements for controlling the pressure, the uncertainty of the sensor needs to be less than +/- 0.02 psia.

2.3.2.8 Vapor cooled skirt exit pressure: The exit pressure of the vapor cooled shield is needed to both set the state of the fluid at the exit for determining shield efficiencies and also for determining pressure drop in the line. Due to similar sensitivity as tank pressure, uncertainty of the pressure sensor needs to be less than 0.01 psia.

2.3.2.9 Vacuum Pressure: The vacuum pressure of the chamber is needed to know when the system is in an operable condition and also to determine steady state. It may also be used in an attempt to determine various system level effects that can be achieved in transient applications. Uncertainty of the vacuum pressure needs to be less than the second digit of the gauge.

2.3.2.10 Boil-off Flow rates: The boil-off flow rate is needed to determine the base heat load into the tank. Along with the vent line vapor temperatures, this is the most important measurement to be made. The heat load into the tank in a steady state scenario is directly proportional to the boil-off flow rate. A wide range of flow meters with minimal uncertainty will be needed due to the wide range of test conditions. Additionally, this will be needed to measure the flow rate of vapor through the vapor cooled skirt. Uncertainty of the flow meters are extremely important and need to be less than 1% of the measurement.

2.3.2.11 Cooling loop flow rates: The cooling loop flow rate is needed to quantify the amount of heat intercepted by the cooling loop. Uncertainty of the flow loop should be on the order of 1%.

2.3.2.12 Capacitance Probe: The capacitance probe will help to better understand the fill level in a continuous manner as opposed to the internal diode rake which gives discrete location understanding, but in between those discrete locations is not informative.

2.3.2.13 Accelerometers: During the reverberant acoustic testing, the accelerometers will measure the loads put on the tank at various locations. This will ensure that the tank remains structurally stable and also give insight into any driving vibrations that are on the tank body (under the MLI).

2.3.2.14 Heat Flux Meters: Heat Flux meters may be used on the skirts or underneath the SOFI and MLI to help with the flow balances and direct measure of insulation performance.

2.3.2.15 Microphones: During the reverberant acoustic testing, the microphones will measure the output of the horns and also provide feedback control to the horns. This will ensure that the profile is appropriate for the testing.

2.4 Facility Capabilities Needed

- The vapor cooling valves shall be able to be controlled in ON/OFF modes from outside the vacuum chamber.
- Venting and measuring boil-off flow rates between 100 slpm and 40,000 slpm
- Measuring vapor intercept flow rates
- Vacuum maintenance (less than 1 x 10^{-5} Torr) for several months
- Liquid hydrogen fill/drain, top-off
- Liquid nitrogen fill/drain, top-off
- Gaseous helium supply
- Heaters for warming up test article
- Heaters to warm up test article

2.5 Procedures

Experimental procedures and processes (i.e. what is steady state), include initial and final conditions. The research team reserves the right to adjust the criteria during testing as is appropriate, taking into account what is learned. The test procedures will define the procedures for final test determinations. Detailed test procedures will be prepared separately for the actual operation of the test facility.

Prior to starting testing, the tank will be cooled down and allowed to come to a quasi-steady state condition. This will probably require topping off after the tank has been filled and cooled down.

2.5.1 Steady State Criteria (Thermal – Boil-off)

Steady state shall be declared with the following criteria are met:

1. The chamber vacuum pressure is less than 1 x 10^{-5} Torr
2. The shroud temperature has diversions of no more than +/- 5 K per day
3. The tank pressure is being maintained at the desired set pressure and controlled to within a tolerance of +/- 0.25 psia.
4. The vented ullage gas temperature is level or increasing with time (the dome is no longer cooling)

2.5.2 Steady State Criteria (Thermal – Vapor Cooling)

Steady state shall be declared with the following criteria are met:

1. The chamber vacuum pressure is less than 1 x 10^{-5} Torr
2. The shroud temperature has diversions of no more than +/- 5 K per day
3. The tank pressure is being maintained at the desired set pressure and controlled to within a tolerance of +/- 0.25 psia
4. The fluid network temperatures are changing at a rate less than 0.05 K/hr (TBR)
5. The mass flow through the fluid network is changing less than 5%/hour (TBR)

2.5.3 Start of Pressure Rise Test

To initiate a pressure rise test, the follow procedure should be followed:

1. The tank has met the steady state criteria described in section 2.5.1.
2. Close the tank vent valve
3. Allow the pressure to rise to a maximum of 30 psig, a minimum pressure increase of 10x the pressure transducer uncertainty.

2.6 Test Matrix

In order to meet the test objectives, a comprehensive test matrix and test schedule are in development. In their current forms, they should not be construed as final, but rather representative of the various possible types of testing to take place.

The initial testing will set the baseline for comparison and serve as a proxy for the current state of the art. The insulation will consist of approximately one inch of SOFI on nominally all surfaces. Testing will occur both with and without vapor cooling. This allows for understanding the improvement that can be achieved with vapor cooling on existing stages without an insulation system improvement. This testing will occur at a baseline fill level, which will be repeated in all follow on testing.

Once the MLI is installed, a series of thermal vacuum tests will be conducted prior to the acoustic testing. This data will indicate the performance benefit of the MLI on the domes as well as any impact it has on the vapor cooling system performance benefits. In studying the sensitivities of the impacts of vapor cooling, several variables were shown to be important. Heat input to the tank is the most important parameter as that is proportional to the vapor generated to be used for cooling. Fill level is also important. When the fill level is above the intersection of the structural skirts with the tank, the heat load is affected. The lower the fill level, the more sensible heat (temperature rise of the vapor) is absorbed prior to entering the cooling loop and the loop may become less effective or since the skirt will also be warming up, it may not become less effective. Since there are two skirts, it makes sense to test at levels above the first, in between the two, and below both intersections. Heaters may also be used to increase the heat load to the tank in either the vapor or liquid regions. It should be noted that not all configurations and combinations will be tested in the pre-acoustic testing and some will be postponed to the post-acoustic testing.

Acoustic testing will be used to subject the MLI (due to its' direct coupling to the skirt, the vapor cooling is not expected to be affected by the acoustic testing) to the worst case reverberant acoustic environments that may be seen during its operational life. The testing is needed to demonstrate that MLI can survive these environments.

To determine any impacts in thermal performance due to the acoustic testing, a post-acoustic thermal vacuum test will be conducted. Any difference in thermal performance will be noted and minimal difference will indicate survival of the blankets. After repetition of the baseline thermal testing, more variations on the vapor cooling will be tested to further understand some of the important parameters. At this point, helium may be injected into the tank to simulate pressurization with helium vapor (often used to pressurize the propellant tanks for outflow to an engine) and understand the effect that the residual helium would have on vapor cooling (helium has a lower specific heat than hydrogen and different volumetric expansion as well).

2.6.1 Thermal Test Matrix

Table 4: The NOTIONAL thermal test matrix is shown below (not in chronological order):

Test Name	Vapor Cooling (On/Off)	Liquid Level (%)	Baseline Testing (SOFI)	Pre-Acoustic Testing	Post-Acoustic Testing
Fill of warm tank (in Vacuum)	Off	0 – 90	X	X	
Boil-off/Heat Load High Fill	Off	90	X	X	X
Boil-off/Heat Load Med Fill	Off	50	X	X	X
Vapor Cooling max flow	On	50	X	X	
Vapor Cooling – Nominal	On (partial flow)	50		X	
Vapor Cooling/ High fill	On	90	X	X	
Pressure Rise, High Fill	Off	90	X	X	X
Cycling Flow	On	50		X	
Boil-off Low Fill	Off	25	X	X	X
Transient Vapor Cooling	On	75	X	X	
Transient No Vapor Cooling	Off	75	X	X	
Vapor Cooling – Low Fill	On	25	X		

2.6.2 Acoustic Test Matrix

Table 5: Acoustic Test Matrix

No.	Test Name	Profile	Final OASPL relative to 144.2 dB	Duration
1	Full Level -6dB	Combined Envelope	-6 dB	30 s
2	Full Level -3dB	Combined Envelope	-3 dB	30 s
3	Full Level	Combined Envelope	0 dB	130 s
4	Proto-qual	Combined Envelope	+ 3dB	130 s
5	Post-Signature	Combined Envelope	-6 dB	30 s

2.6.2.1 Reverberant Acoustic Test Profile

Figure 6 shows two different acoustic spectra: ‘Developed’ and ‘Achievable.’

The ‘Developed’ spectrum is the acoustic environment that is the envelope (maximum at each 1/3 octave band) of several spectra to which the SOFI & MLI may be exposed.

The RATF chamber has certain limitations in spectrum shaping (e.g., RATF closed-loop control is applied only from the 31.5 OTOB – 1250 Hz OTOB). Based on SHIIVER empty chamber results that were achieved in August 2019, it is expected that with SHIIVER in the chamber the ‘Achievable’ spectrum (as shown in Figure 6) will be within the test tolerances of Table 6.

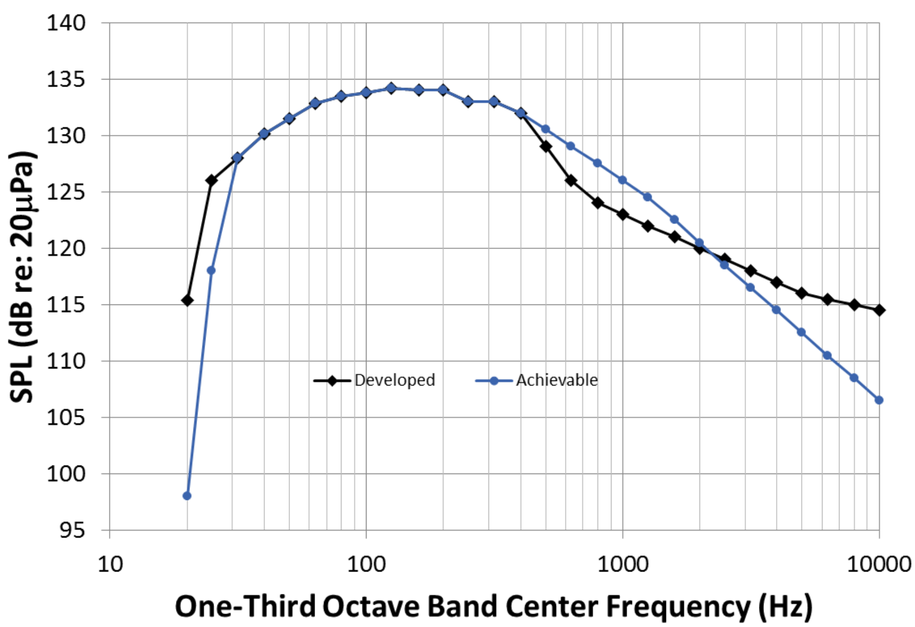

Figure 6: Internal Cavity Acoustics Profile

Table 6: Test Tolerances for SHIIVER Acoustic Testing

Test Tolerances (from Figure 6)	
Individual 1/3-Octave Bands (31.5-1,250 Hz)	±3 dB
Individual 1/3-Octave Bands (1,600-10,000 Hz)	±5 dB
Overall Sound Pressure Level	±3 dB
Test Duration	+10%,-0%

Table 7: External Test Spectrum

One-Third Octave Center Frequency (Hz)	Developed (dB re: 20 μPa)	Achievable (dB re: 20 μPa)
20	115.4	98.0
25	126.0	118.0
31.5	128.0	128.0
40	130.1	130.1
50	131.5	131.5
63	132.8	132.8
80	133.5	133.5
100	133.8	133.8
125	134.2	134.2
160	134.0	134.0
200	134.0	134.0
250	133.0	133.0
315	133.0	133.0
400	132.0	132.0
500	129.0	130.5
630	126.0	129.0
800	124.0	127.5
1000	123.0	126.0
1250	122.0	124.5
1600	121.0	122.5
2000	120.0	120.5
2500	119.0	118.5
3150	118.0	116.5
4000	117.0	114.5
5000	116.0	112.5
6300	115.5	110.5
8000	115.0	108.5
10000	114.5	106.5
Overall Sound Pressure Level	144.1	144.2
Test Duration	130 seconds	130 seconds

2.7 Data Requirements

Requirements for data gathering, real time calculations, form of delivery, etc.

- All data shall be recorded to either comma or tab delimitated format for input into excel and other various data reduction software.
- All data files shall be recorded in engineering units.
- All data files shall include headers that clearly document the engineering units used.
- A location will be determined where completed data files should be dropped.

2.7.1 Thermal Vacuum Data Requirements

- Data collection during thermal vacuum testing at rates no greater than 6 Hz and no less than 0.1 Hz depending on the location within the test matrix.
- Data shall be identified by day and by test within the test matrix.
- Real time calculations may include total heat loads and heat loads of various components.
- Valve positions shall be recorded in science data (as required)
- A standard Silicon diode curve will be provided
- All data collection systems shall be time synced

2.7.2 Acoustic Data Requirements

- Acoustic microphone data shall be collected at a rate greater than 24 kSample/sec to allow for full resolution of the system inputs and responses.
- Accelerometer data shall be collected at a rate greater than 24 kSample/sec or greater to allow for full resolution of the system inputs and responses.
- Data files shall be in the UFF58 format.
- Data files shall be separated by test within the test matrix.
- No real time calculations will be made on system responses.

3 REFERENCES

[1] J. S. DeKruif and B. F. Kutter, "Centaur Upperstage Applicability for Several Day Mission Durations with Minor Insulation Modifications," AIAA-2007-5845, 2007.

Appendix A – Reserved

Appendix B – Test Procedure

Operation 100: Baseline Test

Step Number:	Step:	Date and Time Completed:	By:
100.01	Prepare Vacuum Chamber and Tank Per PBISP-049, Sections 1-5 and PBISP-127A, Sections 1 – 5 [PBISP-127, 4.4.3] Vacuum Pressure Achieved: ________ Torr (IG-0120) ________ Torr (IG-0121)		
100.02	Fill Tank per PBISP-127A, Section 6 [PBISP-127A, 6.18] Stop fill at 95% full Acquire RFMG data during tank Fill and Cold Soak		
100.03	Cold soak system for approximately 2 hours [PBISP-127A, 6.18] Start time: ___________ [PBISP-127A, 6.28] Stop time: ___________		
100.04	Replenish SHIIVER tank per PBISP-127A, Section 6 [PBISP-127A, 6.33] Stop fill at 95% full ROV-2236 (V2) – OPEN ROV-2238 (V4) – CLOSED ROV-2239 (V5) – CLOSED		
100.05	After replenish: [PBISP-127A, 6.37] Back pressure control: 20 psia Flow Meter valve configuration[1] ROV-2204 (V10) - CLOSED ROV-2205 (V11) - OPEN		

	ROV-2206 (V12) – CLOSED ROV-2207 (V13) - CLOSED		
100.06	Inform SHIIVER Test Conductor that research team is ready to begin execution of PBISP-127A, Section 9		
100.07	Conduct Boil-off Test per PBISP-127A, Section 9.2.1 (Operation 120) Control pressure at 20 psia. Stop boil-off testing at 70% full		
100.08	Conduct Pressure Rise Test per PBISP-127A, Section 9.2.2 (Operation 125) ROV-2236 (V2) – CLOSED ROV-2238 (V4) – CLOSED ROV-2239 (V5) – CLOSED Stop pressure rise testing at 40 psia		
100.09	Conduct Boil-off Test per PBISP-127A, Section 9.2.1 (Operation 120) ROV-2236 (V2) – OPEN ROV-2238 (V4) – CLOSED ROV-2239 (V5) – CLOSED Control pressure at 20 psia. Open Flow Valve[1]: ROV-2205 (V11) Stop boil-off testing at < 25% full.		
100.10	Replenish SHIIVER tank per PBISP-127A, Section 10 [PBISP-127A, 10.20] Stop fill at 95% full ROV-2236 (V2) – OPEN ROV-2238 (V4) – OPEN ROV-2239 (V5) – OPEN		
100.11			

	Allow system to cold soak for approximately 2 hours [PBISP-127A, 10.20] Start time: ___________ [PBISP-127A, 10.30] Stop time: ___________		
100.12	Replenish SHIIVER tank per PBISP-127A, Section 10 [PBISP-127A, 10.35] Stop fill at 95% full ROV-2236 (V2) – OPEN ROV-2238 (V4) – OPEN ROV-2239 (V5) – OPEN		
100.13	After replenish: [PBISP-127A, 10.39] Back pressure control: 20 psia Flow Meter valve configuration[1] ROV-2204 (V10) - CLOSED ROV-2205 (V11) - OPEN ROV-2206 (V12) – CLOSED ROV-2207 (V13) - CLOSED		
100.14	Conduct Vapor Cooling Test per PBISP-127A, Section 9.2.3 (Operation 130) Stop Vapor-Cooling Test at 70% full		
100.15	Conduct Pressure Rise Test per PBISP-127A, Section 9.2.2 (Operation 125) ROV-2236 (V2) – CLOSED ROV-2238 (V4) – CLOSED ROV-2239 (V5) – CLOSED Stop pressure rise testing at 40 psia		
100.16	Conduct Vapor Cooling Test per PBISP-127A, Section 9.2.3 (Operation 130) ROV-2236 (V2) – OPEN ROV-2238 (V4) – OPEN ROV-2239 (V5) – OPEN		

	Stop Vapor-Cooling Test at <25% full ROV-2238 (V4) – CLOSED ROV-2239 (V5) – CLOSED		
100.17	Replenish SHIIVER tank per PBISP-127A, Section 10 [PBISP-12A, 10.20] Stop fill at 75% full ROV-2236 (V2) – OPEN ROV-2238 (V4) – OPEN ROV-2239 (V5) – OPEN		
100.18	After replenish: [PBISP-127A, 10.39] Back pressure control: 20 psia Flow Meter valve configuration[1] ROV-2204 (V10) - CLOSED ROV-2205 (V11) - OPEN ROV-2206 (V12) – CLOSED ROV-2207 (V13) - CLOSED		
100.19	Conduct Pressure Rise Test per PBISP-127A, Section 9.2.2 (Operation 125) ROV-2236 (V2) – CLOSED ROV-2238 (V4) – CLOSED ROV-2239 (V5) – CLOSED Stop pressure rise testing at 40 psia ROV-2236 (V2) – OPEN ROV-2238 (V4) – OPEN ROV-2239 (V5) – OPEN Run for 3 hours after pressure returned to 20 psia		
100.20	Conduct Helium Pressurization Test (Operation 199)		

100.21	Drain Tank and Purge SHIIVER Tank per PBISP-127A, Sections 11 and 12 Collect RFMG data during tank drain		

[1] The transition from FM2 (ROV-2205/V11) to FM3 (ROV-2206/V12) may occur when FM2 reaches within 50% of its lower limit, and/or pressure drop from PT-2219 to PT-2213 approaches 0.35 psi. Similarly, the transition from FM3 (ROV-2206/V12) to FM4 (ROV-2207/V13) may occur when FM3 reaches within 25% of its lower limit, and/or pressure drop from PT-2219 to PT-2213 approaches 0.42 psi.

Notes:

Operation 200: Pre-Acoustic Test

Step Number:	Step:	Date and Time Completed:	By:
200.01	Prepare Vacuum Chamber and Tank Per PBISP-049, Sections 1-5 and PBISP-127A, Sections 1 – 5 [PBISP-127, 4.4.3] Vacuum Pressure Achieved: ________ Torr (IG-0120) ________ Torr (IG-0121)		
200.02	Fill Tank per PBISP-127A, Section 6 [PBISP-127A, 6.18] Stop fill at 95% full Acquire RFMG data during tank Fill and Cold Soak		
200.03	Cold soak system for approximately 5 hours [PBISP-127A, 6.18] Start time: ___________ [PBISP-127A, 6.28] Stop time: ___________		
200.04	Replenish SHIIVER tank per PBISP-127A, Section 6 [PBISP-127A, 6.33] Stop fill at 95% full ROV-2236 (V2) – OPEN ROV-2238 (V4) – CLOSED ROV-2239 (V5) – CLOSED		
200.05	After replenish: [PBISP-127A, 6.37] Back pressure control: 20 psia Flow Meter valve configuration[1] ROV-2204 (V10) - CLOSED ROV-2205 (V11) - CLOSED ROV-2206 (V12) – OPEN ROV-2207 (V13) - CLOSED		

200.06	Inform SHIIVER Test Conductor that research team is ready to begin execution of PBISP-127A, Section 9		
200.07	Conduct Boil-off Test per PBISP-127A, Section 9.2.1 (Operation 120) Control pressure at 20 psia. Stop boil-off testing at 70% full		
200.08	Conduct Pressure Rise Test per PBISP-127A, Section 9.2.2 (Operation 125) ROV-2236 (V2) – CLOSED ROV-2238 (V4) – CLOSED ROV-2239 (V5) – CLOSED Stop pressure rise testing at 40 psia ROV-2236 (V2) – OPEN ROV-2238 (V4) – CLOSED ROV-2239 (V5) – CLOSED		
200.09	Conduct Boil-off Test per PBISP-127A, Section 9.2.1 (Operation 120) ROV-2236 (V2) – OPEN ROV-2238 (V4) – CLOSED ROV-2239 (V5) – CLOSED Control pressure at 20 psia. Stop boil-off testing at ~50% full.		
200.10	Conduct Pressure Rise Test per PBISP-127A, Section 9.2.2 (Operation 125) ROV-2236 (V2) – CLOSED ROV-2238 (V4) – CLOSED ROV-2239 (V5) – CLOSED Stop pressure rise testing at 40 psia ROV-2236 (V2) – OPEN ROV-2238 (V4) – CLOSED ROV-2239 (V5) – CLOSED		

200.11	Conduct Boil-off Test per PBISP-127A, Section 9.2.1 (Operation 120) ROV-2236 (V2) – OPEN ROV-2238 (V4) – CLOSED ROV-2239 (V5) – CLOSED Control pressure at 20 psia. Stop boil-off testing at <25% full.		
200.12	Conduct Pressure Rise Test per PBISP-127A, Section 9.2.2 (Operation 125) ROV-2236 (V2) – CLOSED ROV-2238 (V4) – CLOSED ROV-2239 (V5) – CLOSED Stop pressure rise testing at 40 psia ROV-2236 (V2) – OPEN ROV-2238 (V4) – CLOSED ROV-2239 (V5) – CLOSED		
200.13	Replenish SHIIVER tank per PBISP-127A, Section 10 [PBISP-127A, 10.20] Stop fill at 95% full ROV-2236 (V2) – OPEN ROV-2238 (V4) – OPEN ROV-2239 (V5) – OPEN		
200.14	Allow system to cold soak for approximately 2 hours [PBISP-127A, 10.20] Start time: ___________ [PBISP-127A, 10.30] Stop time: ___________		
200.15	Replenish SHIIVER tank per PBISP-127A, Section 10 [PBISP-127A, 10.35], Stop fill at 95% full ROV-2236 (V2) – CLOSED ROV-2238 (V4) – OPEN ROV-2239 (V5) – OPEN		

200.16	After replenish: [PBISP-127A, 10.39] Back pressure control: 20 psia Flow Meter valve configuration[1] ROV-2204 (V10) - CLOSED ROV-2205 (V11) - CLOSED ROV-2206 (V12) – OPEN ROV-2207 (V13) - CLOSED		
200.17	Conduct Vapor Cooling Test per PBISP-127A, Section 9.2.3 (Operation 130) Stop Vapor-Cooling Test at 70% full		
200.18	Conduct Pressure Rise Test per PBISP-127A, Section 9.2.2 (Operation 125) ROV-2236 (V2) – CLOSED ROV-2238 (V4) – CLOSED ROV-2239 (V5) – CLOSED Stop pressure rise testing at 40 psia ROV-2236 (V2) – CLOSED ROV-2238 (V4) – OPEN ROV-2239 (V5) – OPEN		
200.19	Conduct Vapor Cooling Test per PBISP-127A, Section 9.2.3 (Operation 130) Stop Vapor-Cooling Test at 50% full		
200.20	Conduct Cyclic Vapor Cooling Test per PBISP-127A, Section 9.2.6 (Operation 210) Conduct 3 cycles to 25 psia as practical Flow Meter valve configuration[1] ROV-2204 (V10) - CLOSED ROV-2205 (V11) - OPEN ROV-2206 (V12) – CLOSED ROV-2207 (V13) - CLOSED		

200.21	Conduct Vapor Cooling Test per PBISP-127A, Section 9.2.3 (Operation 130) Stop Vapor-Cooling Test at 25% full		
200.22	Drain Tank and Purge SHIIVER Tank per PBISP-127A, Sections 11 and 12 Collect RFMG data during tank drain		

[1] The transition from FM2 (ROV-2205/V11) to FM3 (ROV-2206/V12) may occur when FM2 reaches within 50% of its lower limit, and/or pressure drop from PT-2219 to PT-2213 approaches 0.35 psi. Similarly, the transition from FM3 (ROV-2206/V12) to FM4 (ROV-2207/V13) may occur when FM3 reaches within 25% of its lower limit, and/or pressure drop from PT-2219 to PT-2213 approaches 0.42 psi.

Notes:

Operation 250: Pre-Acoustic Nitrogen Test

Step Number:	Step:	Date and Time Completed:	By:
250.01	Prepare Vacuum Chamber and Tank Per PBISP-049, Sections 1-5 and PBISP-127C, Sections 1 – 5 [PBISP-127B, 4.4.3] Vacuum Pressure Achieved: ________ Torr (IG-0120) ________ Torr (IG-0121)		
250.02	Fill Tank per PBISP-127C, Section 4 [PBISP-127C, 4.10] Stop fill at 95% full Acquire RFMG data during tank Fill and Cold Soak		
250.03	Cold soak system for approximately 5 hours [PBISP-127C, 4.10] Start time: ___________ [PBISP-127C, 4.13] Stop time: ___________		
250.04	Replenish SHIIVER tank per PBISP-127C, Section 4, [PBISP-127C, 4.16] Stop fill at 95% full ROV-2236 (V2) – OPEN ROV-2238 (V4) – CLOSED ROV-2239 (V5) – CLOSED		
250.05	After replenish: [PBISP-127C, 4.19] Back pressure control: 20 psia Flow Meter valve configuration[1] ROV-2204 (V10) - CLOSED ROV-2205 (V11) - OPEN ROV-2206 (V12) – CLOSED ROV-2207 (V13) - CLOSED		

250.06	Inform SHIIVER Test Conductor that research team is ready to begin execution of PBISP-127C, Section 5		
250.07	Conduct Boil-off Test per PBISP-127C, Section 5.2. (Operation 120) Control pressure at 20 psia. Stop boil-off testing at 7 AM, 10/7/2019		
250.08	Replenish SHIIVER tank per PBISP-127C, Section 6, [PBISP-127C, 6.10] Stop fill at 90% full ROV-2236 (V2) – OPEN ROV-2238 (V4) – OPEN ROV-2239 (V5) – OPEN		
250.09	Allow system to cold soak for approximately 2 hours [PBISP-127C, 6.10] Start time: ___________ [PBISP-127C, 6.13] Stop time: ___________		
250.10	Replenish SHIIVER tank per PBISP-127C, Section6 [PBISP-127C, 6.16], Stop fill at 90% full ROV-2236 (V2) – OPEN[2] ROV-2238 (V4) – OPEN ROV-2239 (V5) – OPEN		
250.11	After replenish: [PBISP-127C, 6.19] Back pressure control: 20 psia Flow Meter valve configuration[1] ROV-2204 (V10) - CLOSED ROV-2205 (V11) - OPEN ROV-2206 (V12) – CLOSED		

	ROV-2207 (V13) - CLOSED		
250.12	Conduct Vapor Cooling Test per PBISP-127C, Section 5.4 (Operation 130) Stop Vapor-Cooling Test at 8 AM, 10/9/2019		
250.13	Drain SHIIVER Tank to no less than 50% full per PBISP-127C, Section 7 Collect RFMG data during tank drain		
250.14	Conduct Vapor Cooling Test per PBISP-127C, Section 5.4 (Operation 130) Stop Vapor-Cooling Test at 8 AM, 10/10/2019 (optional) or 10/11/2019		
250.15	Optional Drain SHIIVER Tank to no less than 50% full per PBISP-127C, Section 7 Collect RFMG data during tank drain		
250.16	Conduct Vapor Cooling Test per PBISP-127C, Section 5.4 (Operation 130) Stop Vapor-Cooling Test at 8 AM, 10/11/2019		
250.17	Drain SHIIVER Tank to no less than 25% full per PBISP-127C, Section 7 Collect RFMG data during tank drain		
250.18	Conduct Vapor Cooling Test per PBISP-127C, Section 5.4 (Operation 130) Stop Vapor-Cooling Test at 8 AM, 10/12/2019		
250.19	Drain SHIIVER Tank per PBISP-127C, Section 7 Collect RFMG data during tank drain		

[1] The transition from FM2 (ROV-2205/V11) to FM3 (ROV-2206/V12) may occur when FM2 reaches within 50% of its lower limit, and/or pressure drop from PT-2219 to PT-2213 approaches 0.35 psi. Similarly, the transition from FM3 (ROV-2206/V12) to FM4 (ROV-2207/V13) may occur when FM3 reaches within 25% of its lower limit, and/or pressure drop from PT-2219 to PT-2213 approaches 0.42 psi.

Notes:

Operation 300: Reverberant Acoustic Test

Step Number:	Step:	Date and Time Completed:	By:
300.01	Prepare Acoustic Chamber for Testing per SPF-SOP-201		
300.02	Inspect Test Hardware per SHIIVER-Memo-0030		
300.03	Conduct Full Level -6 dB Test per SPF-SOP-201		
300.04	Inspect Test Hardware per SHIIVER-Memo-0031		
300.05	Conduct Full Level -3 dB Test per RATF SPF-SOP-201		
300.06	Conduct Full Level Test per SPF-SOP-201		
300.07	Inspect Test Hardware per SHIIVER-Memo-0031		
300.08	Conduct Proto-Qual Test per SPF-SOP-201		
300.09	Conduct Post Signature Test per SPF-SOP-201		
300.10	Inspect Test Hardware per SHIIVER-Memo-0031		

Notes:

Operation 400: Post-Acoustic Test

Step Number:	Step:	Date and Time Completed:	By:
400.01	Prepare Vacuum Chamber and Tank Per PBISP-049, Sections 1-5 and PBISP-127A, Sections 1 – 5 [PBISP-127A, 4.4.3] Vacuum Pressure Achieved: ________ Torr (IG-0120) ________ Torr (IG-0121)		
400.02	Fill Tank per PBISP-127A, Section 6 [PBISP-127A, 6.18] Stop fill at 95% full Acquire RFMG data during tank Fill and Cold Soak		
400.03	Cold soak system for approximately 8 hours [PBISP-127A, 6.18] Start time: ___________ [PBISP-127A, 6.28] Stop time: ___________		
400.04	Replenish SHIIVER tank per PBISP-127A, Section 6, [PBISP-127A, 6.33] Stop fill at 95% full ROV-2236 (V2) – OPEN ROV-2238 (V4) – CLOSED ROV-2239 (V5) – CLOSED		
400.05	After replenish: [PBISP-127A, 6.37] Back pressure control: 20 psia Flow Meter valve configuration[1] ROV-2204 (V10) - CLOSED ROV-2205 (V11) - OPEN ROV-2206 (V12) – CLOSED ROV-2207 (V13) - CLOSED		

400.06	Inform SHIIVER Test Conductor that research team is ready to begin execution of PBISP-127A, Section 9		
400.07	Conduct Boil-off Test per PBISP-127A, Section 9.2.1 (Operation 120) Control pressure at 20 psia. Stop boil-off testing at 70% full		
400.08	Conduct Pressure Rise Test per PBISP-127A, Section 9.2.2 (Operation 125) ROV-2236 (V2) – CLOSED ROV-2238 (V4) – CLOSED ROV-2239 (V5) – CLOSED Stop pressure rise testing at 40 psia ROV-2236 (V2) – OPEN ROV-2238 (V4) – CLOSED ROV-2239 (V5) – CLOSED		
400.09	Conduct Boil-off Test per PBISP-127A, Section 9.2.1 (Operation 120) ROV-2236 (V2) – OPEN ROV-2238 (V4) – CLOSED ROV-2239 (V5) – CLOSED Control pressure at 20 psia. Open Flow Valve[1]: ROV-2205 (V11) Stop boil-off testing at < 25% full.		
400.10	Drain Tank and Purge SHIIVER Tank per PBISP-127A, Sections 11 and 12 Collect RFMG data during tank drain		

[1] The transition from FM2 (ROV-2205/V11) to FM3 (ROV-2206/V12) may occur when FM2 reaches within 50% of its lower limit, and/or pressure drop from PT-2219 to PT-2213 approaches 0.35 psi. Similarly, the transition from FM3 (ROV-2206/V12) to FM4 (ROV-

2207/V13) may occur when FM3 reaches within 25% of its lower limit, and/or pressure drop from PT-2219 to PT-2213 approaches 0.42 psi.

Notes:

Appendix C – SHIIVER Deviation Policy

1. No work shall be performed on the SHIIVER test article electrical or fluid systems, or on facility hardware while in direct communication (electrical or fluid) with the test article, without a pre-approved, documented procedure.
2. A deviation is any action which falls outside the parameters predefined in the approved, written procedure.
3. For purposes of this policy, "SHIIVER Liquid Hydrogen Operations" shall include:
    a. PBISP-127A Section III, Operations 5 – 15, and
    b. SHIIVER Test Flow operations 100 – 400 contained in Appendix B of eCryo-PLN-0079.
4. Any deviations to the documented procedures for SHIIVER Liquid Hydrogen Operations at ISPF shall require:
    a. For Deviations to PBISP-127A
        i. Approval by:
            1. Test Conductor (TC),
        ii. and concurrence from the:
            1. Principle Investigator (PI),
            2. Product Lead Engineer (PLE),
            3. Project Manager (PM).
    b. For Deviations to Test Flow operations 100 – 250
        i. Approval by:
            1. Principle Investigator (PI),
        ii. and concurrence from the:
            1. Test Conductor (TC),
            2. Product Lead Engineer (PLE),
            3. Project Manager (PM).
    c. Approval shall be documented in writing.
5. If the PI, PLE, or PM are not "on station" at the time of the deviation, the SHIIVER engineering representative or the SHIIVER research representative may "sign for" the PI, PLE, or PM after obtaining concurrence by phone or other means.
    a. Ex: "*Joe Powell* for David Koci"
6. Operational actions necessary to protect personnel or hardware from imminent harm are not subject to this restriction.