National Aeronautics and Space Administration

eCryo SHIIVER Customer/Stakeholder Checkpoint Briefing

June 30, 2015

NASA Glenn Research Center

Introduction

- This checkpoint meeting is to inform project stakeholders as to the current status of the SHIIVER product development status.
- A short review of the how/why SHIIVER was formulated will be presented.
- SHIIVER is currently in the initial planning stages. Technical studies and analyses performed to guide the development effort have been conducted and a summary of the work as of today will be discussed.
- An overview of the draft Concept of Operations will then be presented.
- Opportunity for feedback and discussion will conclude the briefing.

Background

- Given the wide diversity of cryogenic fluid management technology that had been developed at the research level, there was a need for eCryo to prioritize and focus on a limited subset of the possibilities in order to set a practical scope.
- As part of the effort to determine that focus, a survey was conducted in May of 2014 to solicit opinions of members of the aerospace industry as to what they considered the most important and beneficial cryogenic technologies to be developed in the near term.
- The project was also directed to consider the SLS exploration upper stage (EUS) as a potential infusion target, and to focus on technology that would provide the most immediate benefit to a cryogenic system of that type.

Industry Survey

- **The industry survey polled contacts at several companies involved with launch vehicle and/or propellant system development, including Boeing, Lockheed Martin, ULA, SpaceX, Northrop Grumman, and Ball Aerospace. The discussions were deliberately informal and candid.**

- **The opinions varied with regard to the timeline of need, the relative importance of specific technologies, and the level of technological maturity required for a given technology to be considered for implementation.**

- **Most indicated that the answer depended to large extent on their customer base. Launch vehicle attributes needed for commercial launch applications are well established.**

Industry Survey

- **It was generally recognized that advanced cryogenic technologies would be needed for large cryo systems and longer duration missions, but most of those surveyed indicated that the timeline of need was generally long term (beyond at least 10 years), and this was driven primarily by the government (i.e., NASA) rather than the commercial sector.**

- **The complexity and reliability issues involved with active cooling system machinery would require considerable effort to resolve and has to be weighed against the cost, demand, and necessity.**

- ***The implication is that if NASA believes it is going to need it, NASA needs to take the lead in developing it.***

SHIIVER Origins

- **As part of the formulation of eCryo, a large scale cryogenic tank test was envisioned to demonstrate the application of cryogenic insulation and other thermal management technologies to test configurations representative of upper stage vehicle installations.**
- **This would include features such as skirt structures and fluid line configurations typical of upper stages and would be at a scale on the order of upper stage tanks.**
- **With the direction to consider the SLS exploration upper stage (EUS) as an infusion target, discussions were held with EUS to inquire where they might gain the most benefit, with the understanding that this may not necessarily lead to implementation.**
- **The discussions pointed to two areas: tank insulation, and mitigation of heat loads coming from the forward skirt.**

Objectives and Approach

Objectives:

- **The Structural Heat Intercept, Insulation, and Vibration Evaluation Rig (SHIIVER) will consist of a large cryogenic tank assembly with geometry, support structure, skirt and fluid penetrations comparable to an actual space flight vehicle configuration and will be used to investigate three main areas:**

  - **structural cooling using tank boil off vapor to intercept conductive heat leak**
  - **design, construction, and performance of MLI on a large flight tank configuration**
  - **MLI blanket durability under launch acoustic vibration conditions**

Approach:

- **The tank, structures, and insulation requirements and specifications will be developed by the NASA engineering team. Detailed design and fabrication of the tank and insulation blanket will be external contract items. Structures and the vapor cooling system will be designed by the NASA team.**

- **The tank, structure, and insulation assembly will be integrated at Plum Brook and installed in B2 for thermal testing. It will then be relocated to RATF for vibro-acoustic testing, then returned to B2 for repetition of the thermal testing to evaluate the insulation integrity**

SHIIVER Preliminary Concept Studies

- To develop the concept and testing plans for SHIIVER, preliminary studies have been conducted to answer various questions about the potential performance of MLI and vapor cooling applications, and how the performance can be evaluated effectively.
- Effort has been made to assess the potential benefits of insulation and vapor cooling as applied to an EUS type of configuration, with a focus on shorter duration missions (a few hours to several days).
- Where applicable, analyses have been initially based upon the EUS tank size, with the intent to adjust the SHIIVER test configuration to be similar to the full size model, rather than arbitrarily developing SHIIVER and then trying to scale the results up to the EUS size.

SHIIVER Analyses and Assessments

- **The analyses and assessments conducted to date include:**
  - Multi-Layer Insulation performance vs. weight
  - Venting of MLI and thermal transient behavior
  - MLI Outer Layer Sensitivity to emissivity variation
  - Evaluation of Vibro-Acoustic Testing Needs and Benefits
  - One dimensional skirt cooling analysis
  - Three dimensional skirt cooling analysis
- **In addition, analytical methodologies have been developed to estimate:**
  - Effective/equivalent conductivity of iso/orthogrid structures
  - Dynamic response of a thin membrane subject to acoustically driven differential pressure

SHIIVER Stakeholders' Briefing

Multi-Layer Insulation Analyses

Wesley Johnson, Monica Guzik, and Neil Van Dresar

NASA GRC

LTF / Fluid and Cryogenic Systems Branch

Multi Layer Insulation

- **The ability to predict the performance of Multi-Layer Insulation (MLI) when applied to a large launch or space vehicle propellant tank is currently limited by lack of information about several factors:**
  - Fabrication, assembly, and installation techniques of large blankets
  - The effects of seams and construction resulting from tailoring
  - The effects of fit to an actual flight tank installation with fluid lines and structural attachments

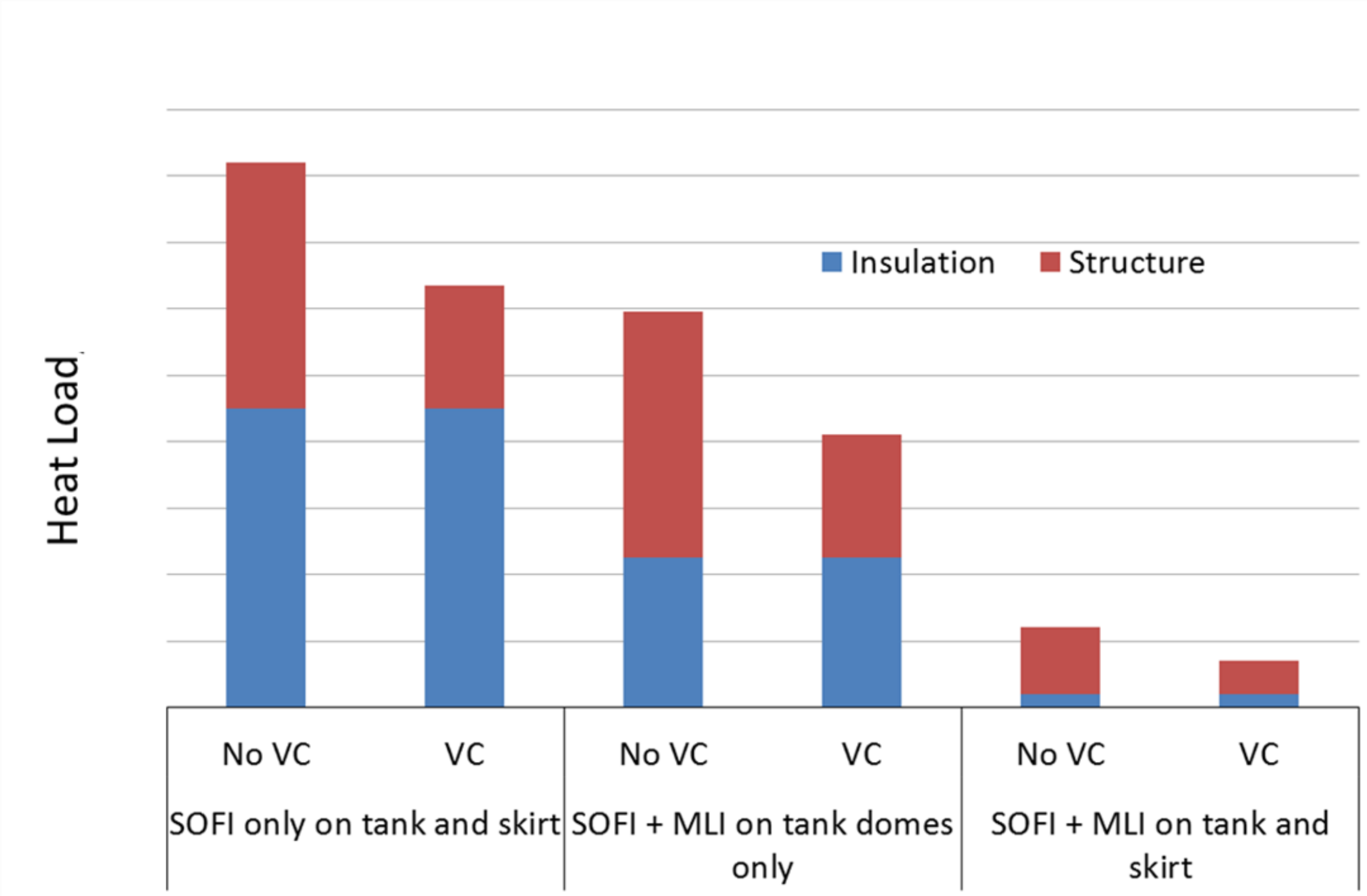
- **Near term applications for shorter mission may not require maximum thermal performance**
  - Higher performance requires more layers = more weight

What is Multilayer Insulation?

Multilayer Insulation (MLI) is a composite system that alternates highly reflective shields with highly porous, low conductivity spacers.

- There are many different “types” of MLI and there are many different ways to make a functional MLI blanket
  - They are all based on thermal radiation shielding principles
  - Manufacturing and assembly details vary from one manufacturer to another
  - The analysis presented here considers only basic principles; individual manufacturers’ methods are not described
- MLI for cryogenic applications can be very different than standard spacecraft blankets
  - No blanket sewing (direct thermal shorts!) is allowed
  - More care taken in lay-ups as cryogenic applications are less forgiving (i.e. less margin allowed)
  - Number of attachment mechanism minimized

Relative Benefit of MLI on a Tank



SHIIVER Insulation System

- **The SHIIVER insulation system is currently planned to consist of SOFI and MLI**
- **The SOFI is mainly on the tank for two reasons:**
  1. To provide benchmark testing prior to installation of the MLI
  2. To make the insulation system more representative
- **The MLI will be designed in a manner representative for installation on a 8 – 10 m diameter tank**
  - There will be seams, lots of them
  - The system will have to hang off of existing hardware such as the skirts or the tank itself
  - The system will need to be installed in a manner that is representative of how it would be installed on a flight system
  - The system will adapt around various lines, penetrations, and skirts

Why SOFI?

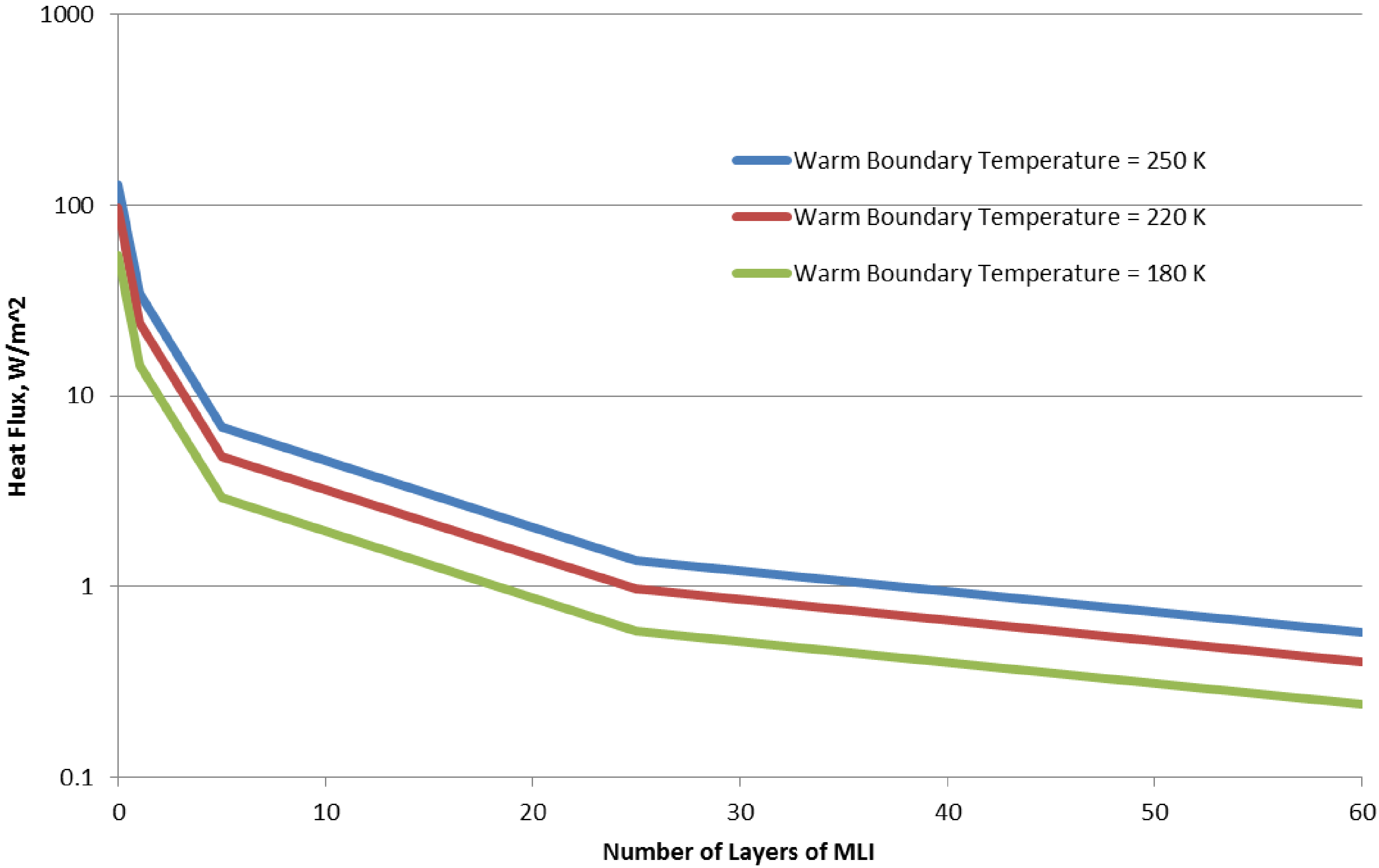
- **EUS currently plans to use SOFI on their tanks**
- **When MLI is filled with nitrogen or air, it has a lower thermal conductivity than SOFI by ~25%**
- **If MLI is filled with nitrogen without SOFI, the nitrogen will condense and solidify on the tank wall.**
  - If there is any oxygen present, this becomes an additional hazard
  - The solid nitrogen would short out the layers and take a very long time to outgas on orbit, hurting the MLI performance for a long time
  - The alternative to nitrogen is helium
- **SOFI prevents MLI from being required to be filled/purged with helium gas**
  - Helium gas is expensive
  - Helium gas has a conductivity on the order of 5 x higher than nitrogen
  - SOFI is a better insulation than helium gas filled MLI

Assessments Performed

- **Insulation system mass vs. heat load reduction**
- **Venting of the MLI and transient performance**
- **Outer layer emissivity sensitivity for possible photogrammetric strain measurements**

Insulation system mass vs. heat load reduction

MLI Heat Flux vs. Number of Layers

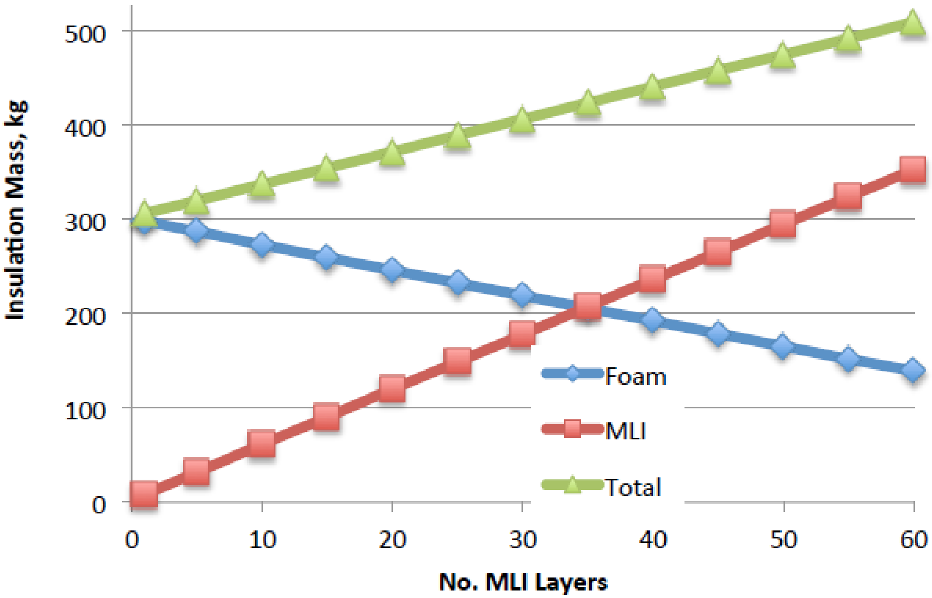


A vacuum pressure < 10^{-5} torr is assumed

Insulation System Mass

- MLI systems are generally lightweight
  - ~100 kg would fully insulate a 8.4 m tank with ~15 layers of MLI

- SOFI Insulation mass changes with numbers of MLI layers. Thickness driven by:
  - Ground heat loads
  - Liquefaction (amount of MLI)
  - Application limits



Venting of the MLI and transient performance

Background:

- **For short missions there is a thermal transient time from launch to LEO steady state that is some what undetermined**
- **Evacuation of the blanket has been assumed to be the main cause of that transient**
- **Analysis was performed to try to get a handle on how this might play into the overall mission analysis**
- **Due to facility limitations at B2, SHIIVER cannot perform rapid evacuation testing**

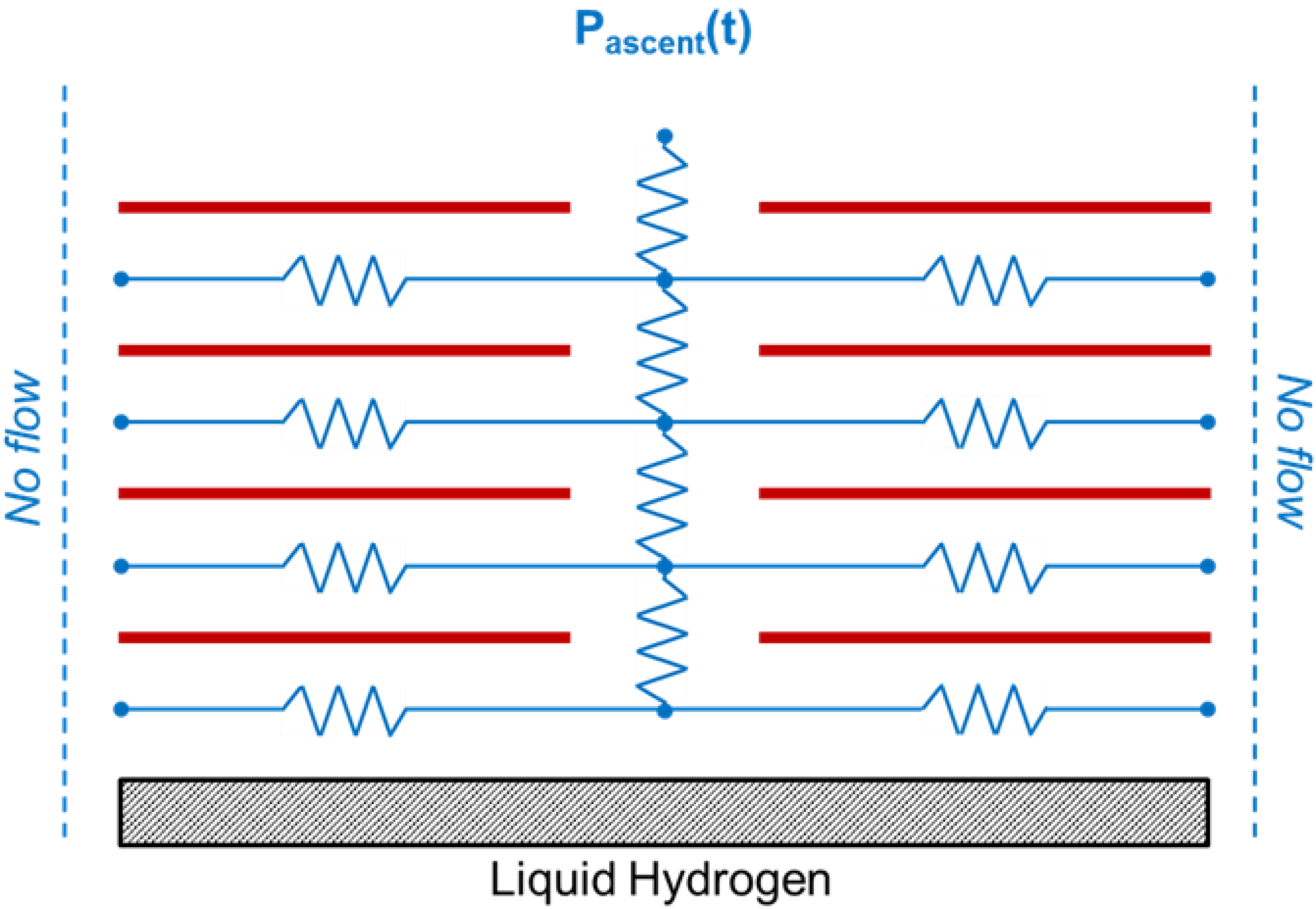
Insulation Inputs

- **Traditional MLI blanket**
  - 20 layers/cm
  - Unperforated (for simplicity of runs)
  - Single butt seam (for simplicity of runs) shared by all layers
    - 24 inch width (can by blankets in 48” max width)
  - Vary total number of layers: 30 layers, 15 layers, 5 layers

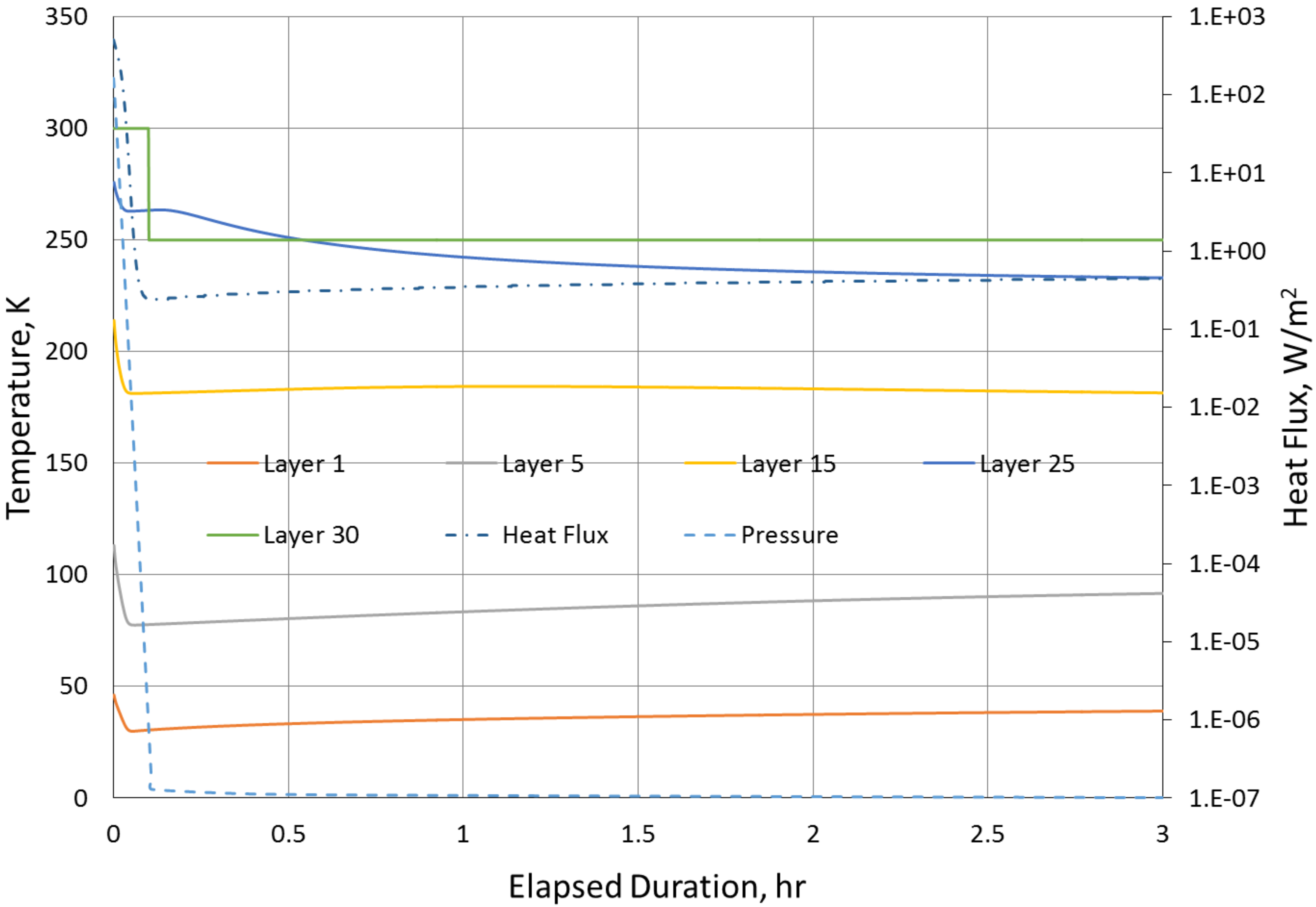
- **Analyze first 5 hours of mission duration only**

- **Use Launch Ascent Tool (LAsT) to analyze the MLI evacuation as a function of time.**

Model Physical Layout



Temperature and Heat Flux Profiles



Evacuation/Transient Conclusions

- With 48 inch wide MLI material, depressurization of the MLI using butt seams is very fast
- The predicted thermal response corresponding to the vent rate is much faster than observed in test data
- The transient heat load that is often ascribed to MLI is not fully the result of MLI performance during depressurization
- Review of rapid depressurization test data on tanks of different materials suggests that the tank wall thermal capacity appears to have just as much if not more responsibility for this heat load as the MLI does

MLI Outer Layer Emissivity Sensitivity

- **The use of photogrammetry to capture the dynamic response of the outer MLI layer both during evacuation and acoustic-vibe testing is being considered. The technique requires optical treatment of the outer layer which would increase its emissivity**

- **An analysis was completed to determine the sensitivity of general MLI blanket thermal performance to changes in outer cover emissivity**

- **The results indicated that a relatively high emissivity outer layer would have minimal effect on MLI performance, and therefore the use of photogrammetry in this application is feasible**

National Aeronautics and Space Administration

SHIIVER Stakeholders' Briefing

Vibration Testing Assessment

Jeffrey Oliver

Jacobs ESSSA Group / DCI

NASA MSFC

Propulsion Structural & Dynamics Analysis Branch / ER41

MLI Acoustic Vibration Sensitivity

- **Large MLI blankets are low mass/large area structures and would tend to be sensitive to acoustic pressure fluctuations during launch.**

- **There is limited information on the durability of cryogenic MLI blankets with regard to acoustic loading.**

- **The basic material (Mylar) is a plastic film which has good damping properties, but in this application it is also very thin (0.25 mil)**

- **Because of the large size, the blankets are expected to be sensitive to lower acoustic frequencies (below 50 Hz). This precludes sub-scale or coupon testing.**

Acoustic Vibration Test Assessment

- **An assessment was conducted to evaluate whether full-scale vibro-acoustic testing of MLI blankets on the SHIIVER tank would be likely to produce useful results. This considered (4) questions:**
  - Is full-scale vibro-acoustic testing of the MLI blanket on the SHIIVER tank the appropriate test or can the same results be achieved with sub-scale testing?
  - Can various MLI and Broad Area Cooling (BAC) tank attachment methods be structurally tested at the subscale level or is full-scale testing required?
  - For an acoustic test, is there a risk of damaging the MLI blanket in low tension regions (tank bottom where insulation will likely sag)? Will measuring MLI blanket deformation during a full-scale acoustic test yield useful, meaningful results?
  - Are there cases for the stiffer Self Supporting Multi-Layer Insulation (SS-MLI) and BAC assemblies that can be evaluated analytically?

Acoustic Vibe Assessment Question 1

Is full-scale vibro-acoustic testing of the MLI blanket on the SHIIVER tank the appropriate test or can the same results be achieved with sub-scale testing?

- **The assessment noted that MLI has flown numerous times but limited test evaluations have been made of integrated MLI/BAC system. Acoustically driven launch environments are expected to be the most critical vibration environment for the blankets, due to the large surface areas, large area to weight ratios, and relatively delicate materials.**

- **Subscale testing might be used for trade studies or down-select, but to fully characterize system level damping and modal performance of MLI at low acoustic vibration frequencies (below 50 Hz), full-scale acoustic testing is needed.**

Acoustic Vibe Assessment Question 2

Can various MLI and Broad Area Cooling (BAC) tank attachment methods be structurally tested at the subscale level or is full-scale testing required?

- **For relatively stiff support elements, acoustic testing is not expected to impart significant structural loading. Random vibration testing would be appropriate, however this can be done by sub-scale testing individual supports with lumped masses representing the supported insulation material. Subscale testing would also be cost-effective for evaluating low temperature adhesives and attachment methods to SOFI.**

Acoustic Vibe Assessment Question 3

For an acoustic test, is there a risk of damaging the MLI blanket in low tension regions (tank bottom where insulation will likely sag)? Will measuring MLI blanket deformation during a full-scale acoustic test yield useful, meaningful results?

- **Risk of direct physical damage (tearing or separation) in low tension regions of the MLI is likely to be very low . However, the tension or lack thereof throughout the blanket may affect the thermal performance and the acoustic driven motion may produce shifting , compression, or shorting within the layers which may result in a change in performance. Visual inspection is unlikely to be able to detect these effects, therefore a repeat thermal performance test would be appropriate.**

Acoustic Vibe Assessment Question 4

Are there cases for the stiffer Self Supporting Multi-Layer Insulation (SS-MLI) and BAC assemblies that can be evaluated analytically?

- **The structural stiffness of SS-MLI and BAC type assemblies is expected to be greater than conventional blankets. This would result in lower energy absorption and less damping, and generally would be more structurally robust. The stiffer components could probably be more reliably evaluated analytically, and therefore results from analysis and sub-scale testing would be expected to be applicable to the full size assemblies, precluding a need for full scale testing. However, there may be a thermal penalty for the stiffer supports.**

SHIIVER Stakeholders' Briefing

Vapor Cooling Analyses

Xiao-Yen Wang and Lauren Best-Ameen

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LTF / Fluids and Cryogenic Systems Branch

Vapor Heat Interception Rationale

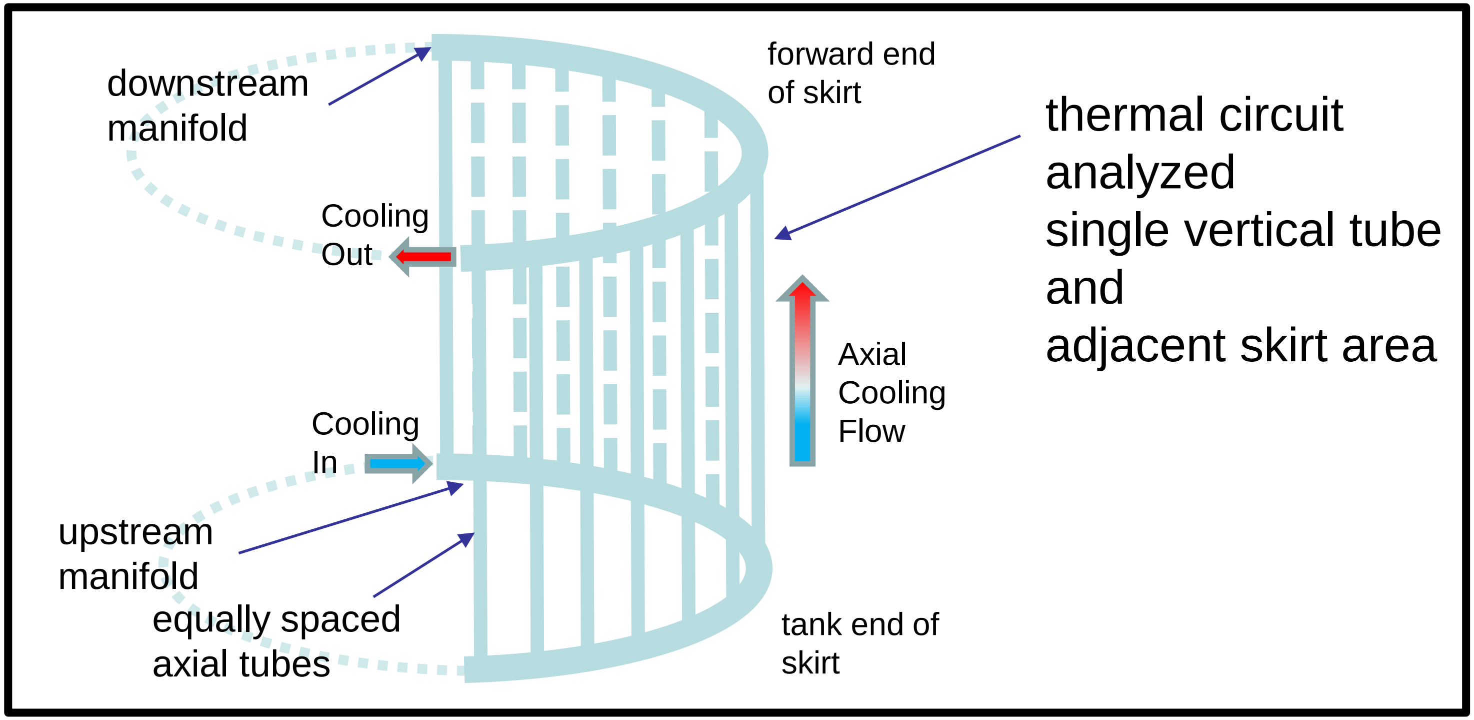
- **Thermal modeling of the EUS has indicated large heat loads to the LH2 tank through the forward and aft skirts**

- **Heat leaks cause the liquid hydrogen to vaporize, resulting in boil-off which must be vented overboard and wasted**

- **If the cold boil-off vapor could be utilized for cooling the structures attached to the tank, modify the thermal gradient and therefore the conductive heat leak into the tank can be reduced, resulting in a reduction in boil-off**

1D Analysis

- **1D thermal model considered:**
  - Diameter of cooling tubes
  - How much of the skirt length to be cooled
  - Number of the cooling tubes



Model

1D Results

- **Vapor cooling heat intercept applied to a skirt can reduce the conductive heat leak by approximately 50%**
- **For a given flow and tube length, using smaller diameter tubing provides:**
  - Less heat to the tank, since convective heat transfer is greater
  - Higher pressure drop, but even 1/8 inch tubing was well below tank operating pressure
- **Reducing the thermal gradient in the skirt near the tank is key; applying cooling to 1/4 of the skirt is nearly as effective as cooling the entire skirt**
- **More tubes improves heat reduction but with diminishing returns**

3D Analysis

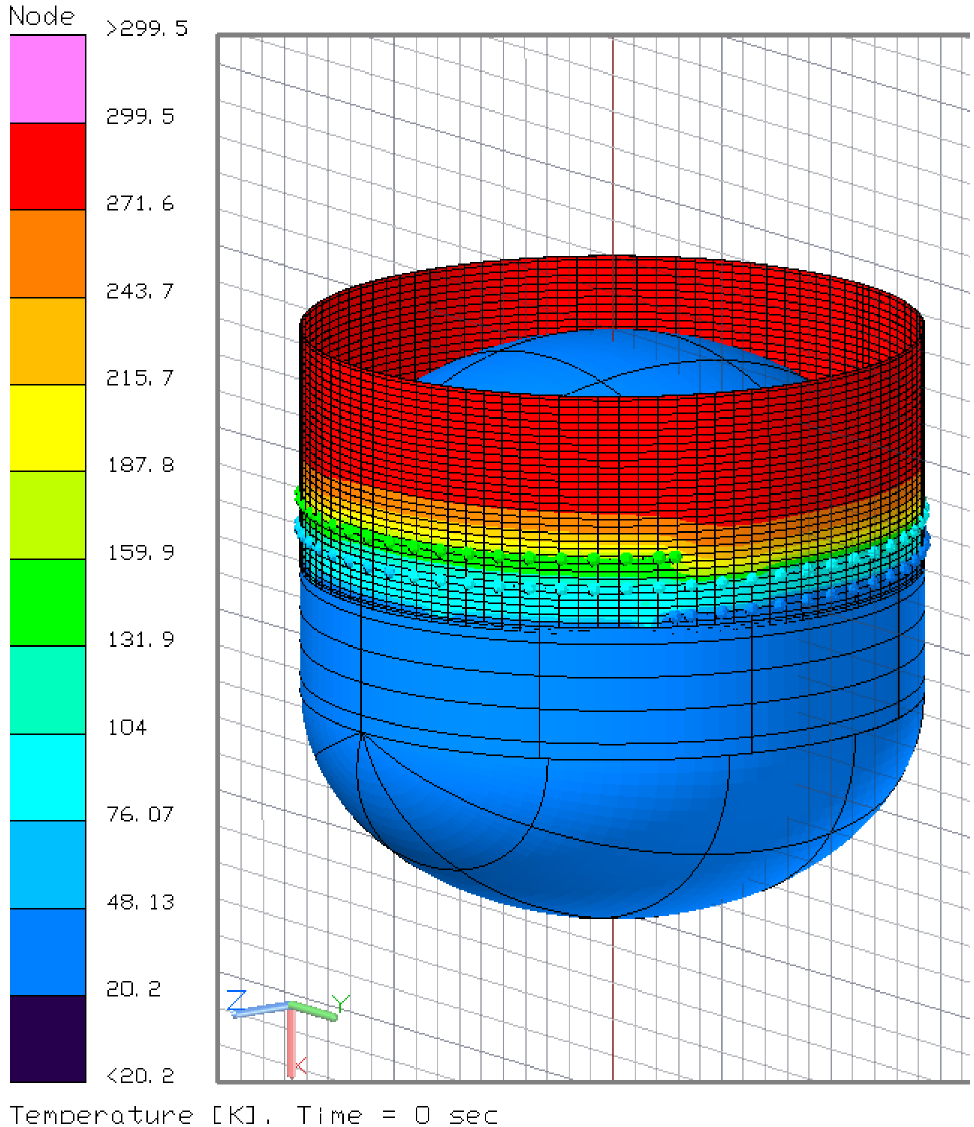
- **A Thermal Desktop (TD) model was developed with an 8.4 meter diameter tank and forward skirt**

- **Cooling was applied to the skirt using several different configurations:**
  - Spiral tubes vs. axial tubes
  - Number of turns for spiral tubes
  - Number of spiral tubes
  - Pitch of spiral tubes along the skirt

- **Radiation heating was applied to the skirt surface, and the steady state conductive heat leak into the tank was determined for each case, along with a baseline no-cooling case**

- **Additional transient cases were run to investigate a 5 day trans-lunar insertion mission with a 3 hour loiter in low earth orbit**

3D Analysis Steady State Example



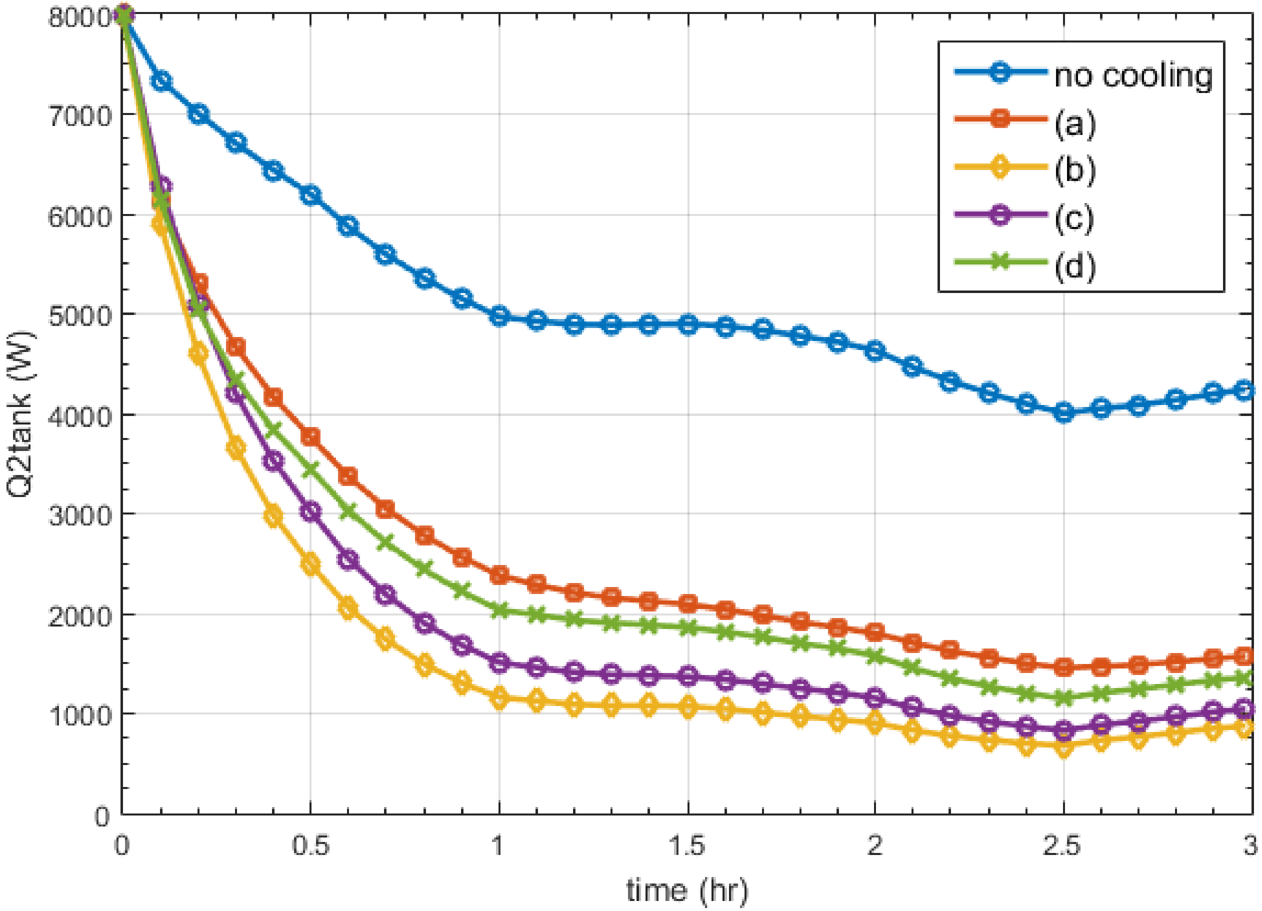
"Configuration B":

- Single spiral tube
- 2 turns over ¼ of skirt
- T_s = 300 K

Vapor mass flow rate (kg/s)	Q2tank (W)	Q2fluid (W)
uncooled	8013	n/a
0.006	2666	11884

Other configurations gave similar reduction in heat to tank transmission

3D Analysis LEO Transient Analysis



3D Results:

- **Similar benefit to that indicated by 1-D model results (approximately 50% reduction in conductive heat leak)**
- **Concentrating the cooling closer to skirt/tank connection appears to be more effective than cooling the entire skirt**
- **Multi-tube axial configuration was not as effective as spiral tubes, and is less mass efficient**
- **Transient results indicate that if cooling is initiated upon reaching orbit it is fully effective in less than 1 hour**
- **Preliminary mass estimate for applying cooling to 8.4 m skirt is ~ 300 lbm**

SHIIVER Stakeholders' Briefing

Concept of Operations

Joseph Zoeckler

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Concept of Operations Introduction

- **The SHIIVER Concept of Operations (CONOPS) formulates the next steps required to address the scope of SHIIVER.**

- **It develops a more specific description of the system to be developed, produced, and operated to meet the needs, goals, and objectives within the project scope.**

- **It considers the development objectives for MLI and vapor cooling and identifies the test capability required to perform this development as well as the gap in current capabilities.**

- **It identifies the operational support infrastructure, processes, and personnel needs required to operate the system.**

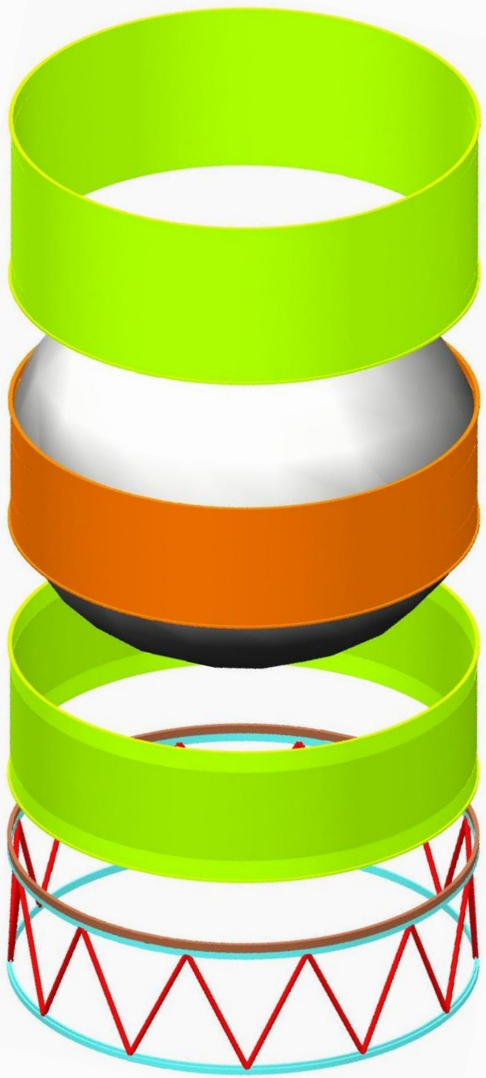
- **It describes test scenarios that will be pursued under the eCryo project, along with others representative of future development work.**

SHIIVER Goals

- SHIIVER will be capable of testing the performance of different types of stage-like heat intercept approaches.
- It will allow the performance of each heat intercept approach within a heat intercept system to be determined.
- It will allow the performance impact on a stage-like heat intercept system to be determined as a consequence of an induced environment.
- It will allow the performance impact on a stage-like heat intercept system to be determined as a consequence of physical configuration.
- It can be modified to study non-heat intercept cryogenic fluid system technologies that might be employed on a stage.

SHIIVER Description

- **A 4 meter diameter tank with forward and aft structural skirt flange connections**
- **Skirts to simulate the thermal loading due to vehicle structure**
- **Fluid lines configured as they would be in a launch vehicle main propulsion system**
- **Features to accommodate future modifications for additional heat intercept and cryogenic fluid management technology development testing**
- **Designed for installation into B-2 for thermal vacuum testing, and RATF for acoustic vibration testing**



Capability Gaps

- **Although large facilities exist for this type of testing, most of the thermal management research has been done at smaller scale**
- **Most research is focused on specific technology with considerable effort to isolate the phenomenon under study**
- **The application of basic performance data to a complex system encounters many factors which complicate the environment and make it difficult to predict performance. The whole is not equal to the sum of the parts.**
- **SHIIVER will develop a bridge to take the parts, put them together in ways that would be applicable to vehicle installations, and learn how they work together.**

Test Elements

- **Using SLS EUS as a reference point, the project will pursue a configuration that could provide a benefit to a stage of that type for shorter duration missions ranging from several hours in LEO to a trans-lunar mission of several days.**

- **The largest heat leak sources are the tank wall and the structural skirts. SHIIVER will initially be used to evaluate two heat intercept elements: MLI and vapor based heat intercept.**

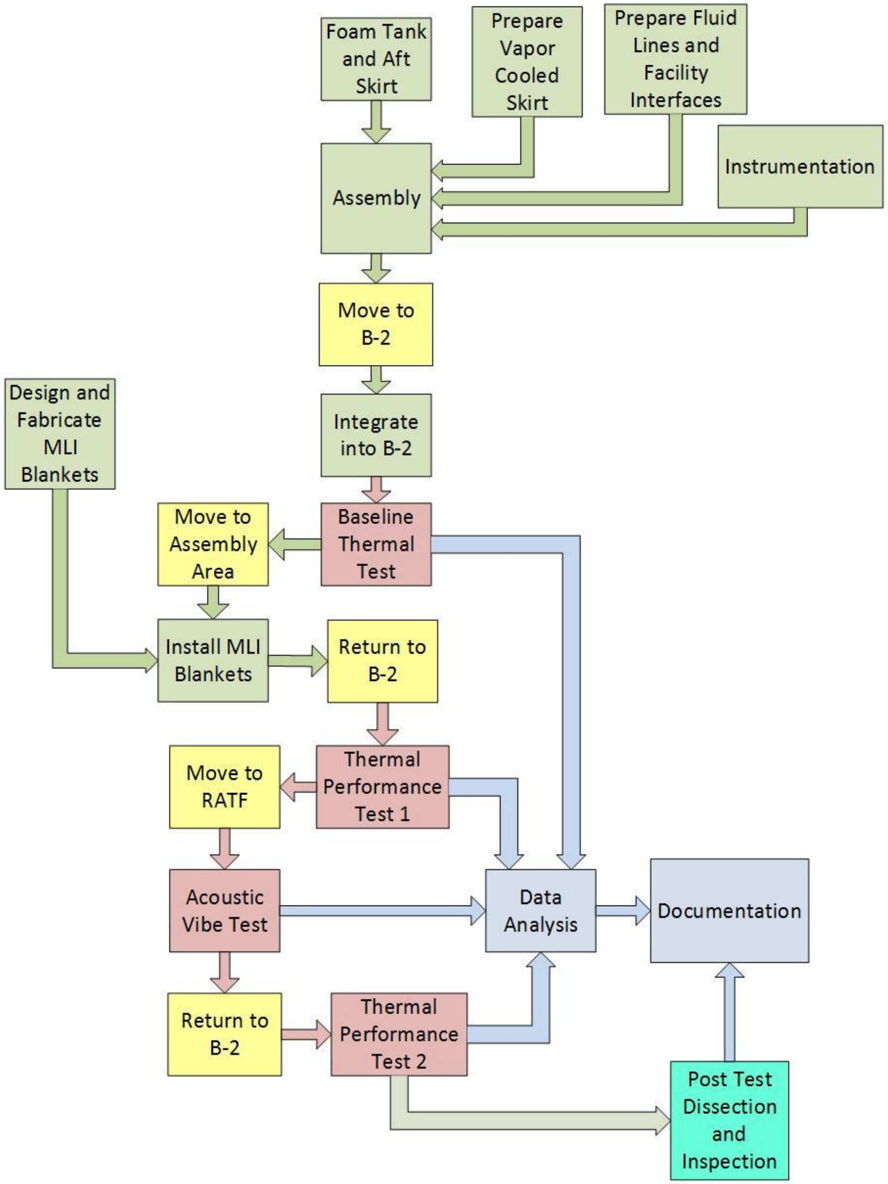
- **The MLI blankets will be designed for an EUS size tank, but then scaled down for the SHIIVER tank. This is intended to capture seam and panel features of the larger tank driven by material constraints.**

- **The vapor cooled heat intercept system will be developed for the forward skirt.**

Operational Concept

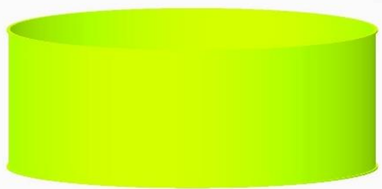
- **The operational concept consists of three basic parts:**
  - **Assembly and integration**
  - **Testing**
  - **Data collection and analysis**
- **These processes are summarized in the following chart**

Operational Flowchart

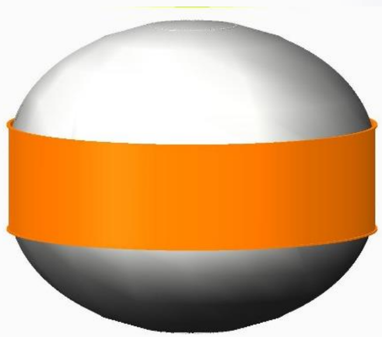


Operational Flow Pictorial

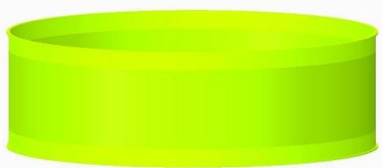
Metallic forward skirt with heaters and Vapor Cooling



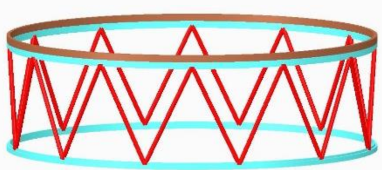
4m diameter liquid hydrogen tank, insulated with SOFI and MLI



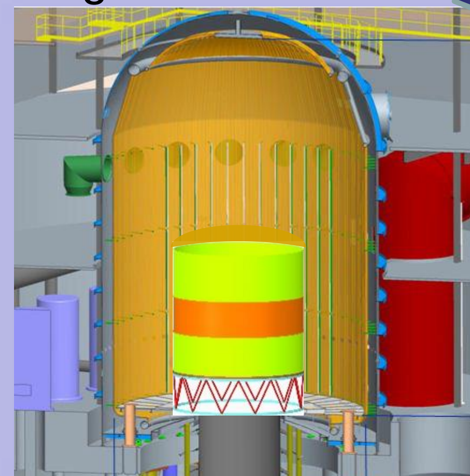
Aft skirt



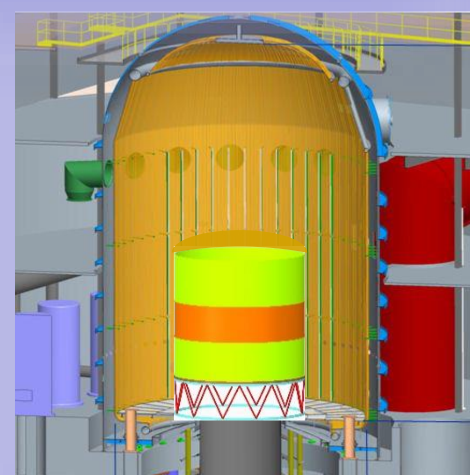
Support structure



Thermal performance testing in B-2:



Acoustic vibration test at RATF:



Repeat thermal performance testing in B-2

Test Scenarios

- **The test scenarios describe potential assembly configurations which could be considered for utilization of the asset.**

- **They are intended to describe the test configurations and operation in order to help identify the features that will be needed in the design of SHIIVER and the detailed technical requirements that will provide those features.**

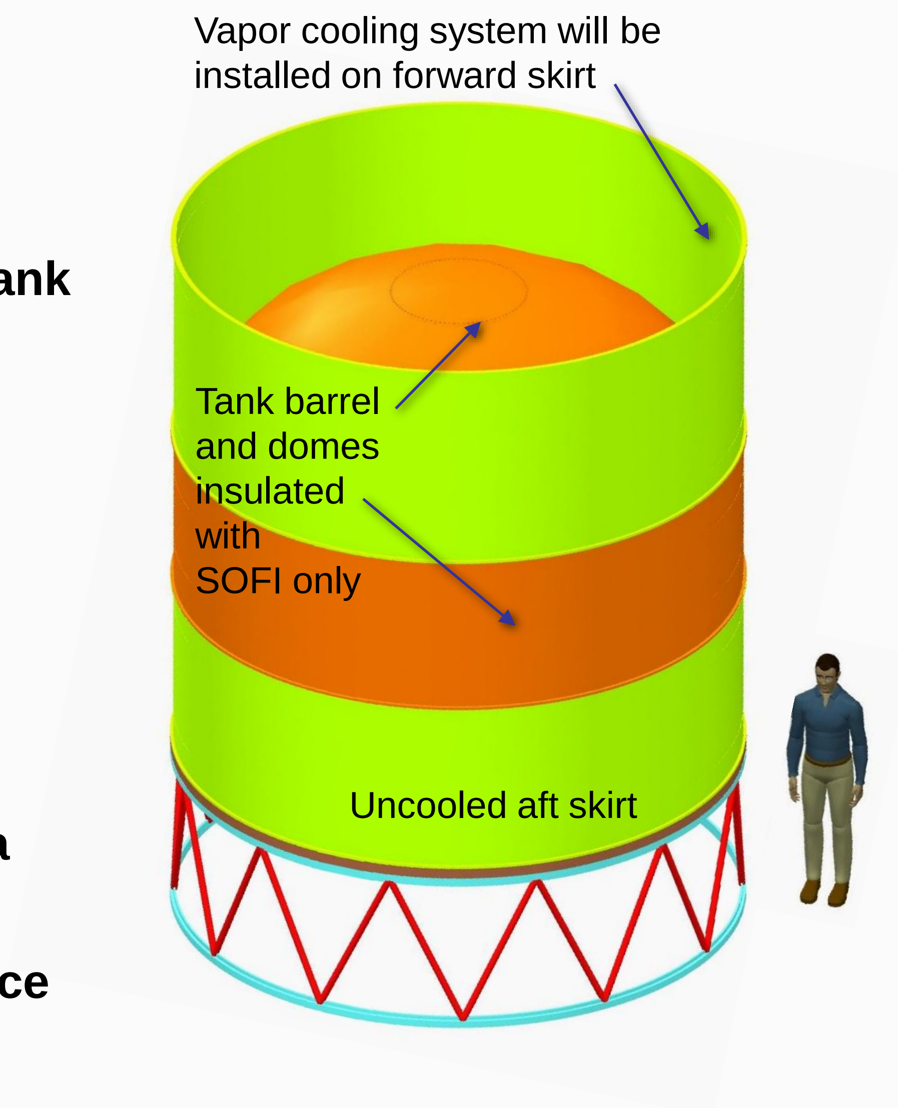
- **They are not necessarily going to all be tested within the current project scope.**

- **They are not intended to be a comprehensive collection of all possible uses of the asset, but should extend somewhat beyond the immediate project test scope to provide future flexibility and adaptability.**

Currently test scenarios 1, 2 and 3 are within the eCryo scope.

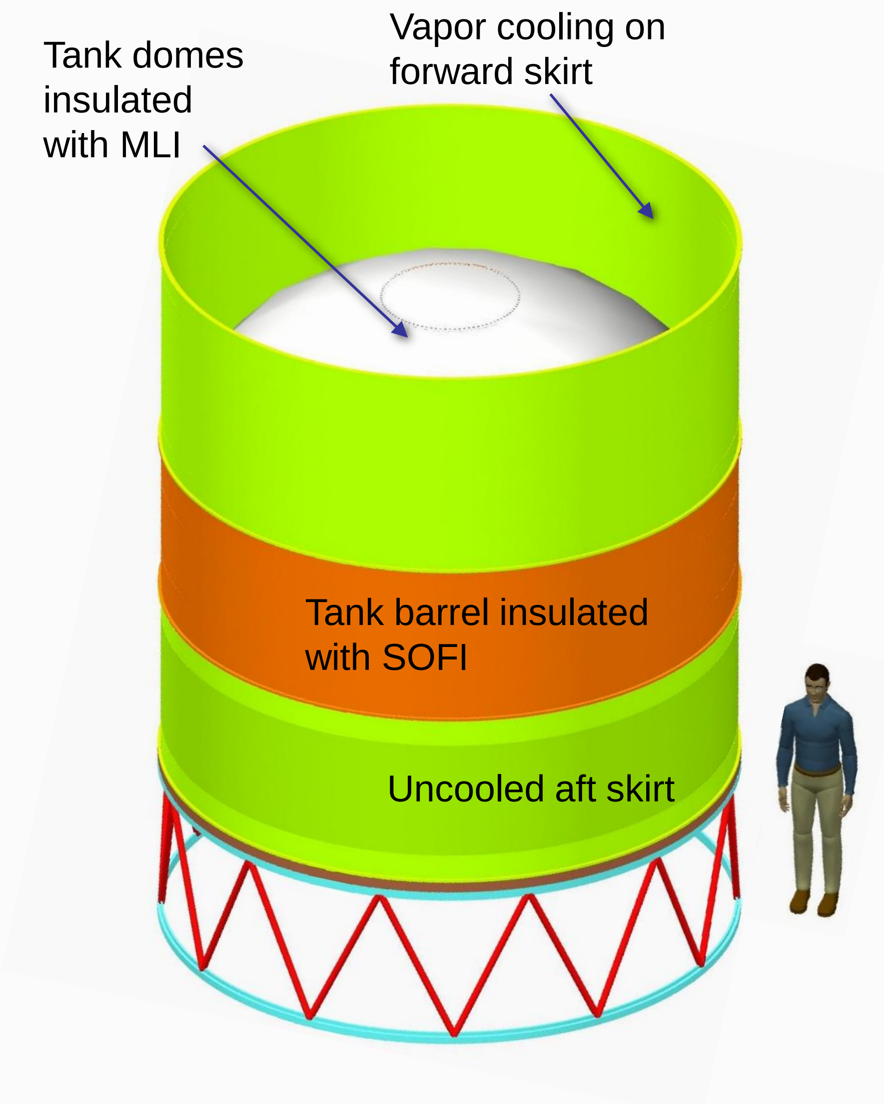
Test Scenario 1 : Thermal Baseline

- **This test will establish the basic thermal performance of the SHIIVER assembly without application of any thermal management systems**
- **It will be a thermal vacuum test of the tank with basic SOFI applied, but no MLI**
- **It will provide a baseline reference for subsequent tests of thermal control applications on SHIIVER**
- **It will also provide a valuable scaling reference that can be compared to EUS modeling results and development data**
- **The vapor cooling system will be in place on the forward skirt and could also be tested**



Test Scenario 2: Short Duration Mission Simulation

- **This scenario would test the assembly with the addition of MLI blankets installed on the domes of the tank**
- **The vapor cooling system on the forward skirt would also be tested**
- **This configuration is intended to be applicable to a short duration mission similar to an EUS-type 2-orbit/3-hour loiter**
- **After thermal vacuum testing, the assembly will be taken to RATF for acoustic vibration exposure, then returned to B-2 for a repeat of the thermal vacuum testing to check for degradation in thermal performance**



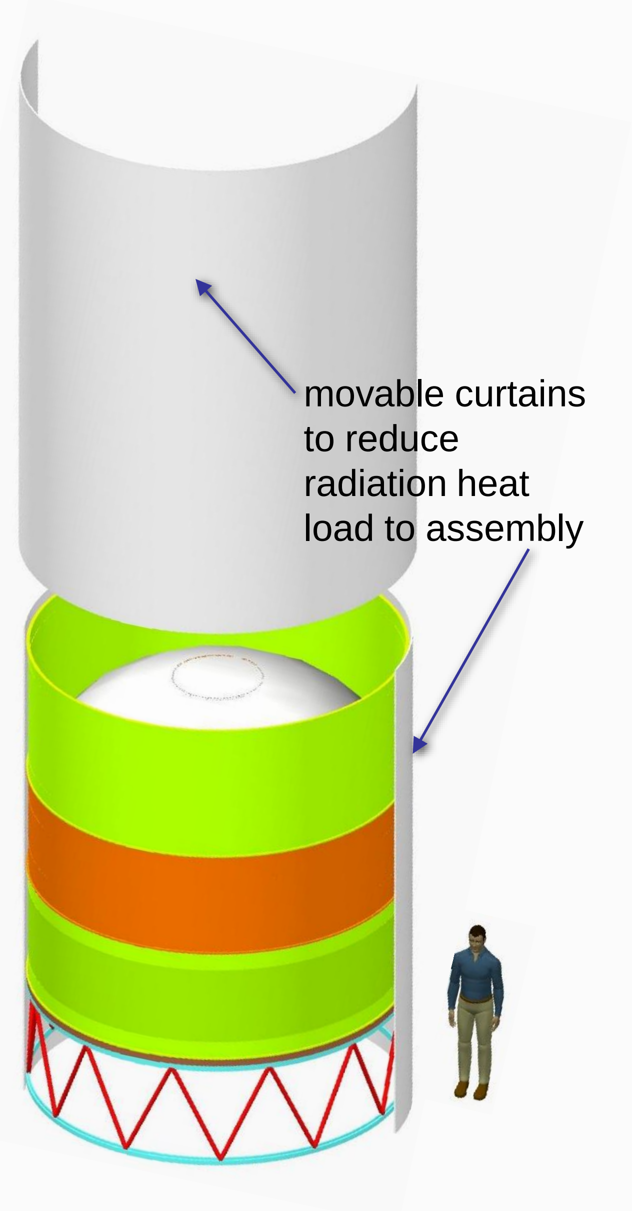
Test Scenario 3: Addition of MLI Curtains

- This scenario would be similar to scenario 2, but would add separately mounted MLI curtains to the installation in B-2 which could be raised and lowered to shield the skirt and barrel sections of the tank

- Only the MLI actually applied to the assembly (domes) would be exposed to vibro-acoustic testing

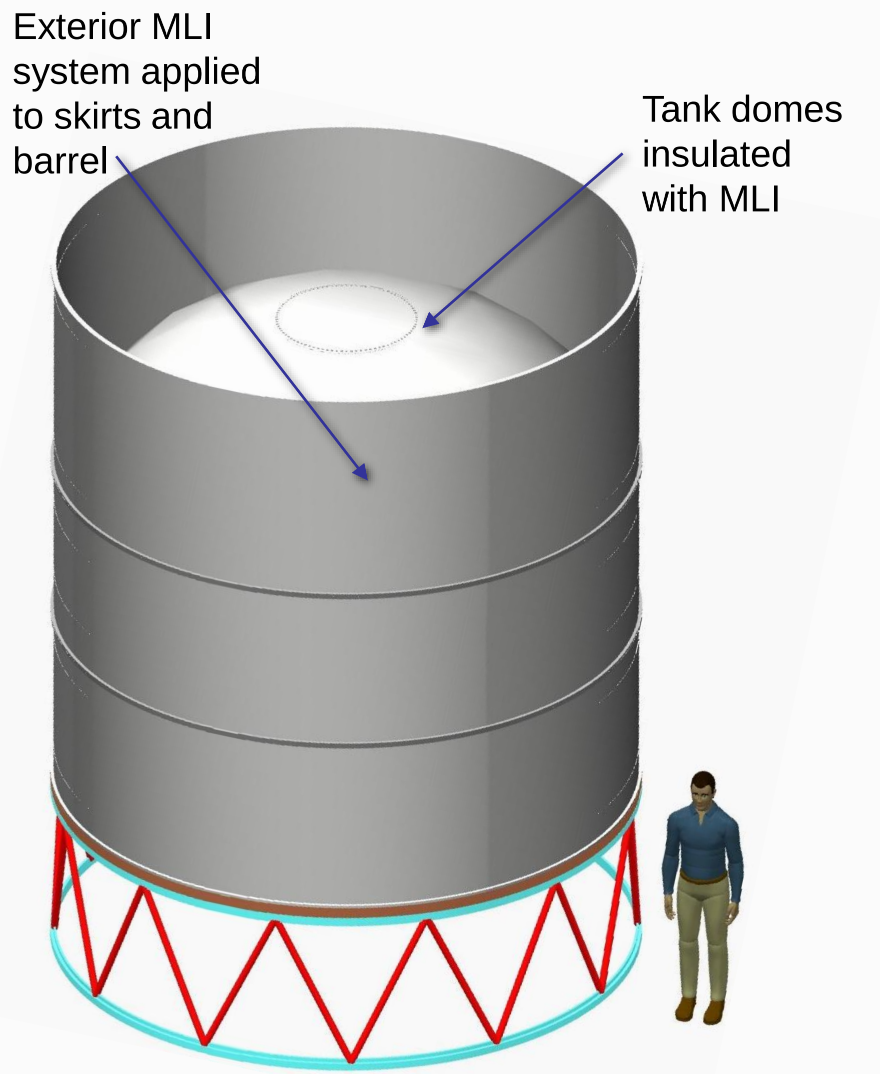
- This would reduce the total heat input to the tank, allowing for a more precise measure of the on-tank MLI performance, including its sensitivity to acoustic vibration

- It would provide the ability to vary the exposure of the skirt to simulate the effectiveness of vapor cooling in a “broadside to sun” orientation



Test Scenario 4: Addition of Exterior MLI

- **Test scenario 4 would include exterior MLI if/when it becomes available or if exterior MLI with a lightweight shroud/cover design were developed.**
- **In this case the barrel section and possibly the skirts would have some type of either exterior MLI or MLI with shroud cover attached**
- **The entire assembly would undergo thermal testing and vibro-acoustic testing for durability evaluation**



This scenario is currently outside of the eCryo scope.

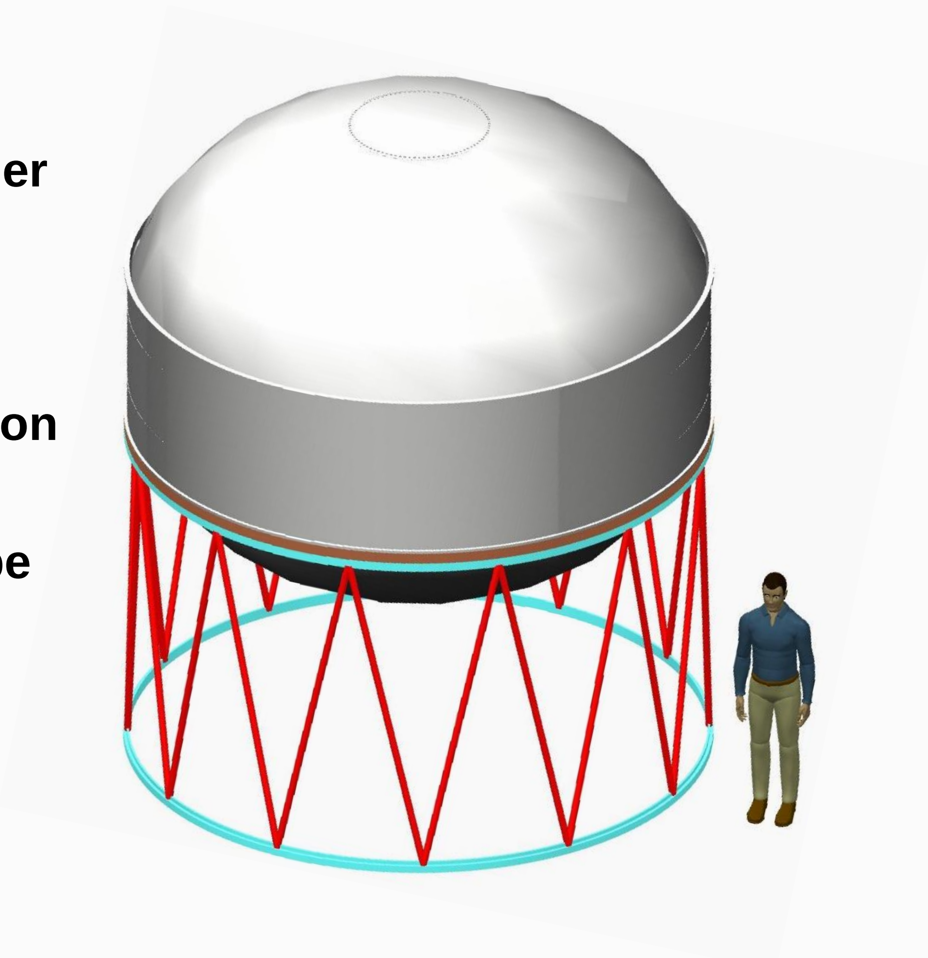
Test Scenario 5: Long Duration Mission MLI

- Test scenario 5 would apply thicker, higher performance MLI to the entire tank, possibly with the skirts replaced with low conductivity strut structure more representative of a depot or longer duration mission configuration

- The fluid line configuration would be arranged for a storage/depot application

- The emphasis in this scenario would be evaluation of thermal management systems for long duration missions

- It would also be exposed to acoustic vibration testing



This scenario is currently outside of the eCryo scope.

Next Steps

- Concept Review
- Finalize Tank Configuration/Specification
- Tank RFQ
- MLI discussions
- MLI contract SOW development
- MLI contract
- Vapor cooling development
- Structural Support
- Facility interface definitions

Feedback and Discussion