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NASA's Evolvable Cryogenics (eCryo) Project

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ABSTRACT: The evolvable Cryogenics (eCryo) Project is a technology development project in the Technology Demonstration Mission (TDM) Program of the NASA's Space Technology Mission Directorate (STMD). This project will leverage expertise in cryogenic fluid management (CFM) technologies from multiple NASA Centers with access to an array of enhanced test facilities and new test rigs to further mature CFM technologies that are supportive of future exploration propulsion needs and upgraded versions of the Space Launch System (SLS). Technologies developed under the eCryo Project will play a critical role in enabling increasingly longer duration in-space missions beyond Low Earth Orbit (LEO). This paper will provide a description of the eCryo project highlighting its four primary areas of focus, plans for the enhanced CFM test capabilities currently being developed, and a status of the technology development efforts to date.

1. INTRODUCTION

As NASA moves from "Earth Reliant" to "Proving Ground" and eventually into "Mars Ready" missions, long duration storage and management of cryogenic fluids will become crucial. The high specific impulse of liquid oxygen and liquid hydrogen chemical rockets or even hydrogen based nuclear rockets is needed to provide the large thrusts to deliver sizable payloads into Martian transfer orbit, into Martian orbit, and then into a return orbit. Liquid oxygen and liquid methane chemical rockets become more attractive when in-situ resource utilization is used to produce the propellants on the Lunar or Martian surface.

To ensure the maturation of CFM technologies that can enable the capabilities needed for NASA's missions, eCryo will address four focus areas: 1) Analysis Tools – Development and validation of computer codes (multi-node and computational fluid dynamics (CFD)) capable of predicting boil off, tank mixing, pressurization, and chill down phenomena for both settled and unsettled cryogenic fluid systems. 2) Multi-Layer Insulation (MLI) Characterization – Testing and analysis to quantify the thermal performance of thick MLI (≥10 layers) blankets at conditions and configurations representative of SLS upper stage mission implementations. 3) Vapor based heat intercept – Subscale characterization of the potential benefit of using vapor vented from a propellant tank to intercept heat coming into the tank through structural members. Building on this subscale testing, the eCryo team will demonstrate vapor based cooling at near full scale and in a configuration representative of a potential upper stage. 4) Radio Frequency Mass Gauging (RFMG) – Quantifying the microgravity performance and accuracy of an RFMG implemented in a cryogenic tank flown as a demonstration on the International Space Station.

2. ANALYSIS TOOLS

The Development and Validation of Analysis Tools (DVAT) to predict the fluid dynamics and thermodynamics for cryogenic fluid management systems/subsystems under settled (Bond number greater than 1) and unsettled (Bond number less than 1) conditions has been a continuing effort under eCryo. The objective of this task is to improve the capability to provide predictive simulations of the fluid dynamics and thermodynamics for cryogenic fluid management systems/subsystems for in-space cryogenic systems with propellants in a settled and an unsettled states. The maturation of these capabilities will reduce the development cost and risk for future NASA exploration missions employing in-space cryogenic storage and transfer systems. The mission phases that will be addressed by the DVAT developed simulation capability are:

- Self-pressurization (pressure increase in the tank due to heat entering the closed tank)
- Pressure control (axial jet and spray bar Thermodynamic Vent System)
- Pressurization (helium and autogenous, various degrees of submergence of the pressurant injection into the tank)
- Transfer line chilldown (pulsed or continuous flow) & tank chilldown (charge-hold-vent)
- Tank filling and draining

In order to provide accurate predictions of cryogenic fluid management systems, it is necessary for the simulations to accurately capture the heat transfer into the tank system as well as the fluid dynamics and thermodynamics within the fluid. In the space environment, the heat transfer to the tank system includes both radiative and conductive heat transfer. The DVAT approach to heat transfer determination is to apply existing thermal analysis tools (e.g. Themal Desktop^{TM}) with updated models for multilayer insulation and unique features such as thermal straps. For the fluid dynamic and thermodynamic predictions, the analytical tool effort is focused on the development of both computational fluid dynamics (CFD) tools and faster running multi-node tools to eventually enable end-to-end mission simulations during settled and unsettled mission phases.

Validation of the simulation tools is ongoing utilizing experiment datasets both against cryogenic ground test data (settled conditions) and subscale micro-g flight data (unsettled conditions). An example result from a recent validation effort for models in the commercial CFD code Ansys FLUENT against unsettled data is shown in figure 1. The Tank Pressure Control Experiment (TPCE) flew several times on the Space Shuttle (ref NASA-CR-191012 (1993), NASA-TP-3564 (1996), AIAA-1997-2816). The experiment utilized a 25.4 cm diameter by 35.6 cm long transparent cylindrical tank, partially filled with a simulant fluid (Freon-113). For the test run shown in the figure (STS-43, test run 4), the tank was filled to 83%, and the ullage bubble was initially located near the center of the tank. A pump was used to draw liquid out of tank through a liquid acquisition device and returned it via and axial jet (vertically from the bottom of the tank). The figure shows a comparison of a still image from the video of the experiment on the right, and

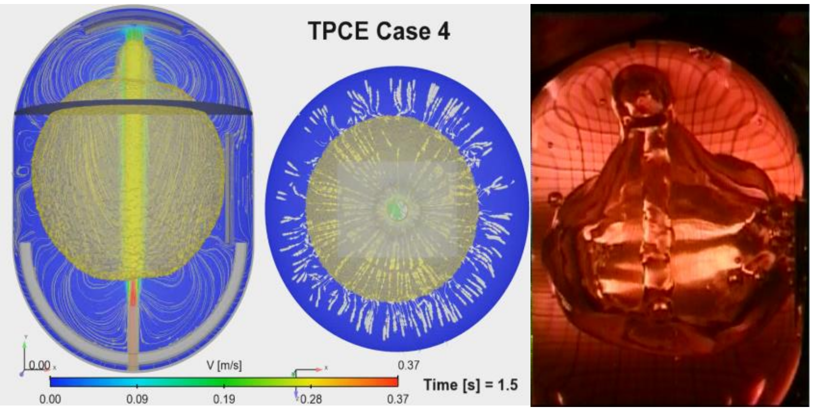


Figure 1. Comparison of CFD simulation (left and center) to a still image captured from the video (right) from the Tank Pressure Control Experiment (TPCE, STS-43 run 4). The axial jet flow Weber number = 4.74, tank fill level 83%.

the result of the simulation (streamlines, velocity magnitude and semi-transparent ullage bubble boundary shown in yellow) on the left at 1.5 seconds after the axial jet flow was initiated. In addition to a view from the simulation comparable to the video image, a cross section looking down from the top of the tank is also provided. The simulation qualitatively captured the key flow features observed in the experiment, including penetration of the ullage bubble by the jet.

Model developments are underway in several areas. The capability to simulate unsettled conditions is a major challenge. Processes in which significant liquid/ullage interface deformation and/or breakup occurs currently require computational fluid dynamics (CFD) simulations. However, for storage durations approaching several days or longer, CFD simulations are not currently a practical design tool. The mass transfer and turbulence interactions at the liquid/vapor interfaces are not well understood for these cryogenic systems and it is possible that different phenomena are important depending on the interface type (large flat or large radius of curvature interface, small bubbles, droplets moving through the ullage gas). Improved two-phase heat transfer correlations for a range of fluids are required for line chill down processes. In addition, more directly relevant datasets (either focused on specific phenomena, more specific measurements, or larger scale, unsettled, cryogenic fluid systems) could improve validations.

3. MULTILAYER INSULATION

eCryo is investigating cryogenic multilayer insulation with two tasks. The first task is to advance the design of multilayer insulation blankets from an art form to more of an engineering process. It is understood that manufacturing of MLI blankets will always involve a certain level of art form. 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. The second task is to extend the design, fabrication, and installation of MLI blankets 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 on small scale systems up to a representative sized tank.

3.1 Small Scale Testing

A calorimeter was developed to accurately perform small scale testing of MLI down to 20 K. This calorimeter 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. eCryo plans to use this calorimeter in addition to other calorimeters across the country to establish baseline data and principles for various MLI design details.

Figure 2: Calorimeter for testing multilayer insulation as low as 20 K.

Multiple sources over the years have investigated the bulk or ideal thermal performance of insulation systems. However, this is not the main goal of the eCryo small scale MLI testing. In 2012, Johnson, Kelly, and Jumper investigated the integration of small penetrations such as fill lines, engine feed lines, and vent lines [1]. eCryo is looking to build upon this research and extend it to understand the effects of integrating large penetrations such as structural skirts which are currently the desired structural solutions for existing and planned upper stages. These structural "skirts" go around the circumference of flight tanks up to 8.4 m in diameter and transfer the structural loads from the rocket through the stage tank. The skirts act as radiative fins on orbit and must be insulated to minimize the heat load into the cryogenic tank.

Every insulation system is held together by a combination of tape, pins, Velcro and other attachment methods. The thermal penalties of these, while often individually small, can add up for large MLI blankets. Taping every layer to itself in a temperature-matching type fashion has been shown to be an effective solution [2], however it would be very labor intensive when installing a system on an 8.4 m diameter stage. It is expected the blankets will likely be prepackaged in panel type sections for installation. Additionally, the attachment mechanisms for the panels must survive any structural and vibration loads they will encounter during launch.

Various specific seam configurations have been studied [3], but beyond a single butt seam [4], [5], [6], no effort has been made to scientifically characterize complicated seams. Most types of seams that are used today on insulation systems are difficult to analyze due to the anisotropic thermal properties of multilayer insulation. Practical experience has shown that staggering seams (whether butt joints or overlapped joints) can reduce the heat load, but have not been methodically analyzed experimentally. A closed form analytical solutions is probably not achievable, however, with a combination of experiments and system analytical models, it is hoped that semi-empirical solutions for staggered seams can be obtained.

Due to the expense of thermal vacuum testing, MLI data to date has typically been obtained with limited or no variation of test configuration. While some vendors have established general ranges of performance of their specific insulation scheme based on experience, these ranges have not been experimentally confirmed. Furthermore, repeatability of identical systems installed multiple times is necessary for a statistical prediction of performance variation of the insulation system. NASA is currently funding ongoing work at Florida State University and Yetispace to establish the repeatability of multiple identical coupons. Boundary conditions for this testing include 20 K to 300 K, 77 K to 300 K, and 20 K to 100 K.

3.2 Large Scale 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. This will help 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. The tank will be insulated on the top and bottom domes with multilayer insulation 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.

Prior to installation of the MLI, the assembly will undergo thermal vacuum testing with only SOFI on the tank surface. This will be the baseline heat load by which to mark future improvements. The MLI will then be applied to the tank. In this tank geometry, approximately 80% of the tank surface area is on the domes. The heat load reduction on the full system is expected to be approximately 40% just by adding the MLI to the domes.

The SHIIVER assembly will undergo thermal vacuum testing loaded with liquid hydrogen in NASA's B2 thermal vacuum chamber located at Plum Brook Station. After the completion of this testing, the assembly will be relocated to the

Reverberant Acoustic Test Facility (RATF) to expose the MLI to reverberant acoustic loading representative of launch conditions. This test will be conducted with the tank empty and at ambient temperature conditions. The assembly will then be transported back to B2 to undergo another round of thermal vacuum testing to determine and quantify MLI performance degradation due to the reverberant acoustic testing (see Figure 3).

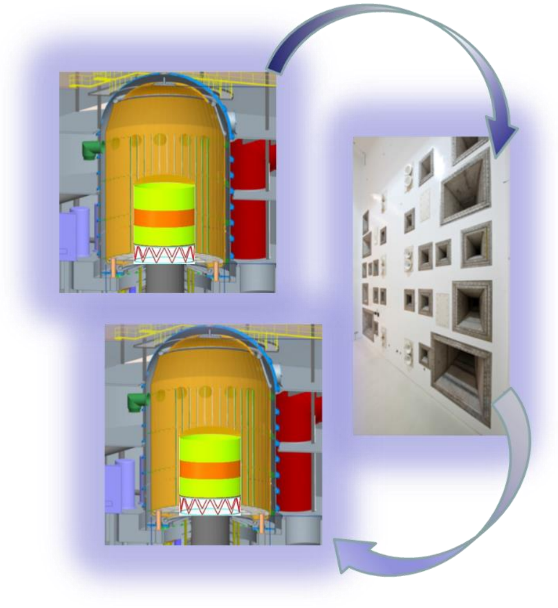


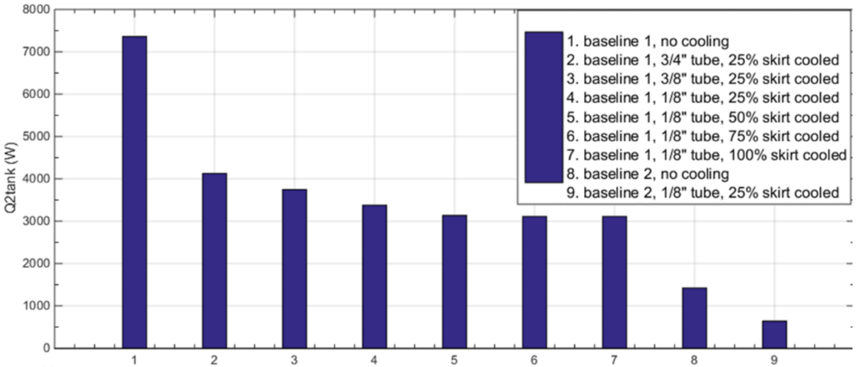
Figure 3: SHIIVER test sequence: 1) Thermal Vacuum, 2) Reverberant Acoustic, 3) Thermal vacuum

Reverberant acoustic testing was chosen rather than mechanical vibration testing due to the low mass, high surface area nature of MLI. As such, acoustic loads are expected to be more likely than vehicle structural vibrations to excite the MLI and cause structural failure. Previous reverberant acoustic testing on 1.2 m diameter tanks indicated no damage [7], and it is hoped that if no damage occurs during this testing, structural risks of insulation damage during launch can be retired.

4. VAPOR BASED HEAT INTERCEPT

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. [8] [9] Most of these dewars used strut based mechanical supports to minimize heat load into their relatively small tanks. [9] [10] Most launch vehicles use skirt type mechanical supports due to the tanks being in the structural load path and the need for mass efficient structural designs. Similarly to vapor based heat intercept on dewars, it has been proposed to route propellant boil-off vapor around skirts to reduce heating into the propellant tanks. [11] eCryo has developed initial models that show a great benefit (nearly 50% reduction in heating) by using the boil-off vapor to intercept the heat being conducted down the skirts. Figure 4 shows some of the results from the initial modeling. The models show that only a quarter of the length of the skirt needs to be cooled and that cooling is independent of tube size.

4.1 Small Scale Testing



Notes:
1. Baseline 1: no insulation on the skirt, top of the skirt: adiabatic
2. Baseline 2: insulate the skirt, top of the skirt: T = 300 K
3. *Ambient:* T_a = 300 K, radiation only

Figure 4: Performance of an aluminum skirt with and without vapor cooling.

Several assumptions had to be made in order to predict the results in Figure 4. The most difficult to predict is the thermal conductance between the cooling tube and the skirt wall (see Figure 5). The contact resistance and area plays a key role in removing the heat from the skirt wall and transferring it to the boil-off vapor. In order to maximize this conductance, several different conductive materials are being tested for thermal conductance as a function of temperature and contact force. These results will then be incorporated into the Small-scale Laboratory Investigation of Cooling Enhancement, where a small section of the full skirt will be tested in a thermal vacuum environment to measure the reduction in heat load reaching the simulated tank (see Figure 6).

Several different attachment mechanisms and sections will be tested in order to understand the effects of the variables that affect the thermal performance of the heat intercept. Some variables may include thermal contact materials and pressure between the tubes and skirt, pitch of the tubing, mass flow rate being vented through the tubing, and temperature of the gas being vented (affected by tank fill level).

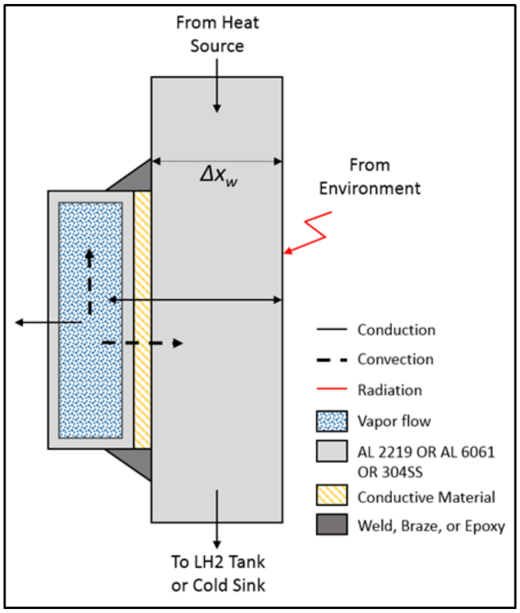


Figure 5: Thermal path from boil-off vapor to skirt wall.

4.2 Large Scale Testing

SHIIVER will also apply vapor based heat intercept at the 4 m diameter scale. The forward (top) skirt will have cooling channels on it similar to those tested in the small scale testing. Results from the small scale testing will drive the design of the SHIIVER skirt. For the single design, the effects of fill level, mass flow rate, and insulation around the skirt will be demonstrated. Instrumentation will be placed around the skirt to attempt to pick up detailed thermal maps and performance, but general boil-off level will be used to gauge initial performance.

It is not expected that the acoustic testing will affect the performance of the vapor based heat intercept along the skirt, however, this will also be demonstrated during the second thermal vacuum test of SHIIVER.

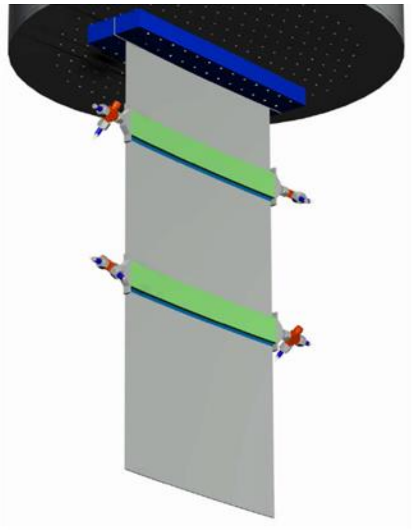


Figure 6: Small-scale Laboratory Investigation of Cooling Enhancements

5. RADIO FREQUENCY MASS GAUGE

The RFMG is a fluid gauge being developed for low-gravity applications for possible use in long-duration space missions utilizing cryogenic propellants. The RFMG operates by measuring the natural electromagnetic eigenmode frequencies of a tank, and comparing these frequencies with a database of RF simulations of the tank containing various fluid fill levels and liquid configurations. Because the liquid slows the speed of light in a known way, the changes to the electromagnetic modes of the tank can be computed a-priori and those simulations are used to compare with the measured tank spectrum. A 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. [12]

Currently the eCryo project is developing an RFMG system to be demonstrated on the Robotic Refueling Mission 3 (RRM3), a mission led out of the NASA Goddard Spaceflight Center (GSFC) through the Satellite Servicing Capabilities Office (SSCO). One of the goals of the RRM3 mission will be to demonstrate storage and transfer of a cryogenic fluid on the International Space Station (ISS). The payload will be mounted to the exterior of the ISS on the Express Logistics Carrier (ELC). The mission will evaluate the feasibility and accuracy of the RFMG technology in a low-gravity environment. This will be an important step in advancing the Technology Readiness Level (TRL) of the RFMG, and open up possibilities of infusing to other in-space missions requiring measurement of fluid levels in a tank.

6. SUMMARY

eCryo is maturing cryogenic fluid management technologies needed for both near and far term applications on cryogenic propulsion systems. Both general and detailed analysis tools are needed to be able to predict the behavior of fluids for long duration storage and transfer of cryogenic fluids in microgravity. High fidelity liquid level measurements will allow more efficient use of propellant, especially at low gravitational levels. These improved predictions and better understanding of tank conditions will allow for better understanding of stage conditions resulting in better stage efficiency and usage.

The development of a “tool-box” of MLI solutions will allow for a better understanding of the thermal and structural performance of MLI as it could be applied to large tanks. Using vapor that is already being vented to reduce the structural heat load into a tank shows great promise in lowering the mass penalties associated with use of cryogenic propellants. Both MLI and vapor based heat intercept will reduce boil-off and enable a stage to carry more usable propellant for longer duration missions for a given stage design.

These technologies all have application on the Space Launch System and other future upper stages. They enable “Proving Ground” and Martian architectures. However, they also will benefit short duration missions. This will give vehicle and mission design engineers familiarity with the technologies prior to use in missions. eCryo is actively looking for the possibility of transferring the technology currently under development to missions, both within NASA and within the launch industry.

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