Cryogenic Propellant Storage and Transfer (CPST) Technology Maturation: Establishing a Foundation for a Technology Demonstration Mission (TDM)

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Abstract

As part of U.S. National Space Policy, NASA is seeking an innovative path for human space exploration, which strengthens the capability to extend human and robotic presence throughout the solar system. NASA is laying the groundwork to enable humans to safely reach multiple potential destinations, including asteroids, Lagrange points, the Moon and Mars. In support of this, NASA is embarking on the Technology Demonstration Mission Cryogenic Propellant Storage and Transfer (TDM CPST) Project to test and validate key cryogenic capabilities and technologies required for future exploration elements, opening up the architecture for large cryogenic propulsion stages (CPS) and propellant depots. The TDM CPST project will provide an on-orbit demonstration of the capability to store, transfer, and measure cryogenic propellants for a duration which is relevant to enable long term human space exploration missions beyond low Earth orbit (LEO). Recognizing that key cryogenic fluid management technologies anticipated for on-orbit (flight) demonstration needed to be matured to a readiness level appropriate for infusion into the design of the flight demonstration, the NASA Headquarters Space Technology Mission Directorate authorized funding for a one-year (FY12) ground-based technology maturation program. The strategy, proposed by the CPST Project Manager, focused on maturation through modeling, studies, and ground tests of the storage and fluid transfer Cryogenic Fluid Management (CFM) technology sub-elements and components that were not already at a Technology Readiness Level (TRL) of 5. A technology maturation plan (TMP) was subsequently approved which described: the CFM technologies selected for maturation, the ground testing approach to be used, quantified success criteria of the technologies, hardware and data deliverables, and a deliverable to provide an assessment of the technology readiness after completion of the test, study or modeling activity. This paper will present the testing, studies, and modeling that occurred in FY12 to mature cryogenic fluid management technologies for propellant storage, transfer, and supply, to examine extensibility to full scale, long duration missions, and to develop and validate analytical models. Finally, the paper will briefly describe an upcoming test to demonstrate Liquid Oxygen (LO$_2$) Zero Boil-Off (ZBO).

Nomenclature

AREP	Atlas Reliability Enhancement Program
BAC	Broad Area Cooling
CAT	Cryogenic Analysis Tool
CFD	Computational Fluid Dynamics
CFM	Cryogenic Fluid Management
CPPPO	Computational Propellant and Pressurization Program
CPS	Cryogenic Propulsion Stage
CPST	Cryogenic Propellant Storage and Transfer
CryoSim	Cryogen Storage Integrated Model

CTL   Cryogenic Test Laboratory
DAM   Double Aluminized Mylar
EDS   Earth Departure Stage
ESTF   Exploration Systems Test Facility
GFFSP   Generalized Fluid System Simulation Program
GRC   Glenn Research Center, NASA
GUI   Graphical user interface
KPP   Key Performance Parameters
KSC   Kennedy Space Center, NASA
LAD   Liquid Acquisition Device
LEO   low Earth orbit
LH_2 Liquid Hydrogen
LO_2 Liquid Oxygen
MLI   Multi-Layer Insulation
MSFC   Marshall Space Flight Center, NASA
NASA   National Aeronautics and Space Administration
NVF   No-vent-fill
PCB   Project Control Board
PMD   Propellant Management Device
RBO   Reduced boil-off
SLS   Space Launch System
SMiRF   Small Multi-Purpose Research Facility
SOFI   Spray-On Foam Insulation
TankSim   Tank System Integrated Model Tank System Integrated Model
TCS   Thermal Control System
TDM   Technology Demonstration Mission
TMP   Technology Maturation Plan
TRL   Technology Readiness Level
TVS   Thermodynamic Vent System
VATA   Vibro-Acoustic Test Article
VOF   volume of fluid
ZBO   Zero boil-off

1.0   Introduction

In support of the National Aeronautics and Space Administration's (NASA) Strategic Goal 3.1, "Sponsor early stage innovation in space technologies in order to improve the future capabilities of NASA, other government agencies, and the aerospace industry," studies have pointed to the value of extended use of cryogenic fluids in space. It was announced during September 2011 that NASA had been authorized to proceed with the development of a heavy lift launch vehicle, the Space Launch System (SLS). The Cryogenic Propulsion Stage (CPS) of the SLS is conceived to use liquid oxygen (LO_2) and liquid hydrogen (LH_2) as the propellant combination. In addition, Agency mission architecture studies include consideration of options for propellant resupply, either via tankers or in-space propellant depots.

These mission capability elements have dictated the need for an advanced development program within NASA to mature several Cryogenic Fluid Management (CFM) technologies for in-space mission operations including the long duration storage of cryogenic fluids using both active and passive thermal control and micro-g tank pressure control, tank-to-tank transfer of cryogens, and unsettled propellant mass gauging. An in-space flight demonstration of these technologies is critical to the development of all cryogenic in-space propulsion system, for example, the CPS (Ref. 1).

The current CPST baseline mission architecture is to develop, launch and operate a free flying satellite in low Earth orbit (LEO) to demonstrate and mature CFM technologies. The design concept involves the CPST payload integrated with a spacecraft bus, which will provide attitude control, communication, and propulsion functions for the integrated unit, launched aboard a medium class launch vehicle that delivers the CPST payload to a circular orbit of sufficient altitude to reduce atmospheric drag to acceptable levels. The spacecraft would fly in a solar-inertial attitude with the aft end of the spacecraft pointed toward the sun to reduce solar heating of cryogenic tanks and cold structures.

The CFM technologies included in the planned flight demonstration mission are passive cryogenic propellant storage, tank thermal and pressure control, liquid acquisition, transfer, and several methods of mass gauging. The mission duration is currently estimated to be two months, which is based upon the time needed to complete CFM and spacecraft checkout, passive storage demonstration, and two transfer cycles at unsettled conditions. The mission would conclude with a controlled re-entry. After the mission is complete, data will be analyzed, and a final mission report will be completed for project closeout.

In addition to delivering flight data, the project was tasked: to validate performance models suitable for analyzing full-scale space vehicle tank systems capable of storing LH_2 for an extended duration in microgravity with reduced boil-off (RBO) (including active thermal control technology) and to advance a suite of technologies that would enable spaceflight systems capable of storing large quantities of LO_2 for an extended duration in microgravity with zero boil-off (ZBO).

On June 24, 2011, the CPST Project Control Board (PCB) approved a ground test CFM technology maturation strategy for FY12. This strategy focused on maturation through modeling, studies and ground tests of the storage and fluid transfer CFM technology sub-elements and components that were not at a technology readiness level (TRL) of 5. The CPST Project Manager then directed that a Technology Maturation Plan (TMP) be created describing the CFM technologies selected for maturation, the approach to be used, quantified success criteria of the technologies Key Performance Parameters (KPP) and planned deliverables. The CPST TMP was formally approved by the CPST Project Manager in February 2012.

In the TMP, the CFM technologies to be matured were identified and described in Section 2.0, Core Technologies under the heading of Technology Assessment. Section 3.0 of the TMP and Table 1

Table 1.—FY12 Ground Tests, Studies, and Modeling of Storage and Fluid Transfer
CFM Technology Sub-elements and Components

Test/Task Name	Objective
LH_2 Active Thermal Control Thermal Performance (LH_2 RBO)	Demonstration of a flight representative active thermal control system for RBO storage of LH_2 for extended duration in a simulated space thermal vacuum environment
LH_2 Active Thermal Control Structural Performance (MLI/BAC Vibro-Acoustic Test Article (VATA))	Assess the structural performance of an MLI/BAC shield assembly subjected to launch vibration loads
Active Thermal Control Scaling Study	Conduct study to show relevancy of CPST-TDM active thermal control flight data to full scale CPS or Depot application
Passive Thermal Control—Penetration Heat Leak	Measurement of heat leak due to struts penetration integrated with MLI.
Passive Thermal Control—Composite Strut Thermal Performance in LH_2	Measurement of heat leak due to composite struts integrated with MLI with 20 K boundary temperature.
Passive Thermal Control—Thick MLI Extensibility Study	Assess optimum approach for attachment of thick (40 to 80 layers) MLI to very large tanks
Liquid Acquisition Device (LAD) Outflow and Line Chill	Quantify the LAD stability (no LAD breakdown) due to transfer line chill down transient dynamic pressure perturbations during outflow
Analytical Tool Development	Continue development of tools specific for CPST

presented the full set of FY12 technology maturation activities, including tests, studies and analytical tool development to ensure that the list of selected flight demonstration technologies was at TRL-5, or as mature as possible without flight testing, by the end of FY12.

LO$_2$ ZBO was not considered a technology maturation element but rather a ground demonstration of the capability of storing large quantities of LO$_2$ for an extended duration in microgravity with ZBO and complimentary to the flight mission.

2.0 Technology Maturation: Tests, Studies, Model Development

The following sections describe the background and approach, results, and significance of the tests, studies, and modeling of the storage and fluid transfer CFM technology sub-elements and components that were selected for maturation during FY12.

2.1 LH$_2$ Active Thermal Control

Long duration, space-based storage of LH$_2$ appears feasible only through the use of active cooling. Active cooling can be accomplished using a cryocooler and a closed loop gas as the cryocooler working fluid for distributed cooling (Ref. 2). Despite the improving prospects for high capacity 20 K cryocoolers, this test focused on available cryocooler technology, applying the much more available 90 K cryocooler technology to cool a shield surrounding the LH$_2$ tank for Reduced Boil-Off (RBO) storage of LH$_2$.

Two test bed tank systems were developed to meet the goal of evaluating thermal and structural characteristics of integrated multi-layer insulation (MLI) and broad area cooling (BAC) shield system: the RBO was built to thermally evaluate the system at GRC, and the Vibro-Acoustic Test Article (VATA) was built to structurally evaluate the system at MSFC. RBO and VATA employed very similar tank, thermal control system, and structural penetration configurations. This approach was intended to produce thermal and structural data on the same configuration providing a complete characterization of the system for the CPST project to consider in the context of a flight test.

The RBO and VATA Thermal Control System (TCS) included Spray-On Foam Insulation (SOFI) directly bonded to the tank to satisfy the CPST ground hold requirement. The integrated MLI and BAC shield system were positioned over the SOFI and provided both passive and active cooling components required for long-duration in-space storage of LH$_2$. The MLI blanket included two primary components: a low-density (8-layer/cm) 30-layer blanket between the SOFI and the BAC shield and a standard density (20-layer/cm) 30-layer blanket outside the BAC shield. While the majority of the MLI surface area maintained specified density, the blankets were compressed at the seams where Velcro was sewn to allow for the removal and reinstallation of the blankets. This seam treatment decreased the thermal performance of the blanket. Low conductance polymer standoffs spaced the BAC shield at a proper distance off the surface of the tank and also constrained movement of the shield to prevent damage during estimated dynamic launch loads. The VATA test article employed the appropriate number of standoffs required for a flight-like configuration while RBO used a reduced number of standoffs to improve the thermal performance of the system.

2.1.1 Thermal Performance (LH$_2$ RBO Test)

In the RBO test, the shield is installed within the layers of radiation reflector insulation, effectively cooling them and reducing the exposure temperature of the insulation under the shield, offering a hot side temperature for the LH$_2$ tank of 90 K, instead of the LEO imposed temperature of roughly 200 K. Coupled to this shield are straps and collars to cool the plumbing and tank supports. The selected cryocooler was a 20 W 90 K reverse turbo-Brayton cycle cryocooler, with heat rejection accomplished via a heat pipe radiator mounted integral to the test hardware within the vacuum chamber (Ref. 3). A predictive system thermal model that was developed prior to testing was utilized for detailed design of the experiment as well as to provide insight into the test results.

Figure 1.—Liquid Hydrogen (LH$_2$) RBO Experiment
Test Article Being Lowered into SMiRF Vacuum
Chamber. The white ring above the test tank is
the heat pipe radiator, behind which is mounted
the reverse turbo-Brayton cycle cryocooler.

The purpose of the testing was twofold. First it would demonstrate the integration of a BAC shield embedded in tank-applied thick MLI to a flight representative cryocooler. Second, it would quantify the system thermal performance of a flight representative active thermal control system for RBO storage of LH$_2$ in a simulated space environment. The testing was conducted at Glenn Research Center's (GRC) Small Multi-Purpose Research Facility (SMiRF), which provided the thermal and vacuum environment to simulate space-based conditions. The test article at SMiRF is shown in Figure 1.

Two essential tests were conducted, a "Cooler Off" passive thermal control test, and a "Cooler On" active thermal control test. The Cooler Off test determined the baseline boil-off rate of the system, with the active cooling components in place. The Cooler On test determined the boil-off reduction with the cryocooler system running. The total heat leak to the LH$_2$ tank was measured by boil-off (a flow meter in the vent line) while the tank was kept at constant backpressure. The heat measured is composed of radiation (principally through the MLI) and conduction sources. Conduction heat transfer is readily determined from the temperature data on the respective conduction paths (e.g., support struts, fill and vent lines) into the tank, along with the physical characteristics of those paths. The MLI heat transfer was through the 60 radiation shields, 30 below and 30 over the BAC, and the 15 layers on the penetrations. MLI heat could not be directly measured, but was calculated from the tank overall heat less the conduction heat.

By comparing the Cooler On test to the Cooler Off test, the reduction in heat transfer rates were most significant in the struts, where the heat was reduced by 62 percent, while the fill line heat was cut by 50 percent. The net heat (calculated) to the inner MLI was reduced by 61 percent. Overall, the boil off reduction was 48 percent, less than predicted. Yet, the ratio of active storage system mass per watt of heat removal (kg/W) and ratio of watts of active storage system input power per watt of heat removal (W/W) both exceeded success targets.

The significance of this test effort is that an integrated LH_2 distributed reduced boil off system (test tank, MLI/BAC shield, cryocooler, and radiator) has been demonstrated on the ground, offering potential for the storage of LH_2 for extended durations in space.

2.1.2   Structural Performance (MLI/BAC Shield Acoustic Test)

The combination of MLI and a BAC Shield is a promising thermal solution to heat leak through the tank wall, but the structural properties of the concept must be addressed, as this thermal control system must also withstand launch environmental loads (Ref. 4). As indicated above, the VATA was constructed to be similar to the RBO test article.

The purpose of this testing was to verify the structural integrity of an MLI/BAC shield assembly when subjected to representative launch vehicle vibration and acoustic loads, and to obtain design experience for the BAC shield integration to plumbing, tank supports and foam substrates. The testing was conducted at Marshall Space Flight Center's (MSFC) Exploration Systems Test Facility (ESTF) and Acoustic Test Facility, which provided the thermal, vacuum, and acoustic load environment to simulate launch conditions and perform verifications to determine structural integrity.

The VATA assembly sequence is illustrated in Figure 2.

A worst-case launch load was chosen to best evaluate the structural integrity of the MLI/BAC shield system design. Both random vibration and acoustic tests were considered as possible options to meet this requirement. Random vibration tests are best suited for small and heavy components whose local environment is governed by the surface to which they are mounted. Acoustic tests are best for low mass, large surface area structures whose response is driven by sound pressure. An acoustic test was selected for the integrated MLI and BAC shield system. Acoustic test data analysis showed an acoustic load consistent with the worst-case envelope of all the launch vehicles currently under consideration by the CPST project for the flight payload. The test was successful as:

- Accelerometer data from the acoustic test yielded no unexpected results.
- Thermal tests were conducted before and after the acoustic test and no change was found in the thermal performance of the system.
- Leak checks were performed on the BAC tubes after each test in the series and no leaks were found.
- A visual inspection of the outside of VATA was conducted after the conclusion of the acoustic test with no observation of damage. A small amount of denting was observed on the BAC shield, but this did not result in diminished thermal or structural performance of the system.

It is to be noted that the original relationship between the RBO and VATA tests was altered when the RBO configuration reduced the number of BAC shield standoffs in order to improve thermal performance. Based on this deviation in configuration, the Technology Maturation effort did not yield both a structurally and thermally viable configuration for an integrated MLI and BAC shield TCS.

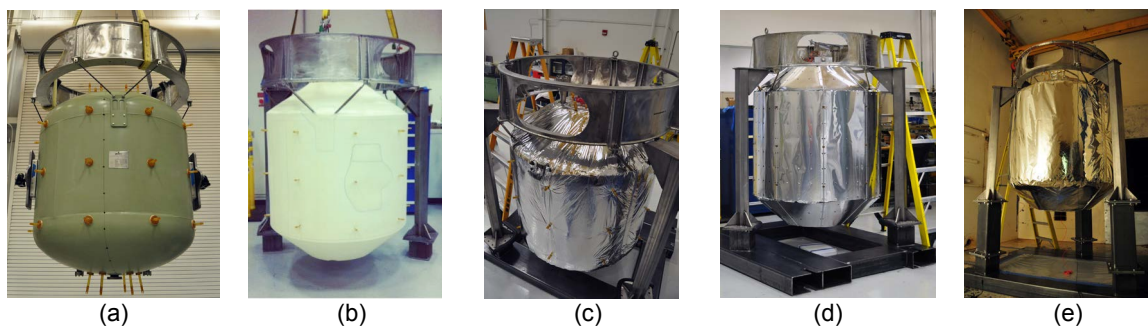| (a) | (b) | (c) | (d) | (e) |

Figure 2.—VATA build sequence: (a) Primed tank with standoffs, (b) Tank-applied SOFI, trimmed to shape, (c) Inner MLI blanket, (d) BAC shield, and (e) Fully assembled VATA, with outer MLI.

The significance of this test effort is that a structurally viable integrated LH_2 distributed reduced boil-off system (test tank and MLI/BAC shield) survived acoustic testing, supporting the potential for the storage of LH_2 for extended durations in space.

2.1.3 RBO II and VATA II

Recently, the RBO and VATA tests were each repeated, but with the inner MLI and BAC Shield standoffs removed and replaced with a self-supporting MLI that is also capable of supporting the BAC shield. Both tests were completed successfully and the results appear promising; however, data reduction and analysis were not complete in time to be included in this paper.

2.1.4 Active Thermal Control Scaling Study

Long term, in-space storage of a full scale CPS or cryogenic propellant depot will require both a robust insulation system and an active thermal control system to minimize the propellant loss due to radiant heat. Active thermal control is being demonstrated for LH_2 (RBO with a 90 K cryocooler, using a BAC shield) and LO_2 (ZBO with a 90 K cryocooler, using distributed cooling applied directly to the test tank) utilizing a 1.2 m diameter test tank in ground based testing. Nevertheless, application of such technologies to large-scale tanks requires some study.

The purpose of the study was to validate the relevancy of a scaled LH_2 RBO active thermal control system ground and flight test approach to a full scale CPS or depot application. While investigating RBO, scalability for subsystem (BAC tube on shield concept, MLI/BAC shield integration, and support system cooling concepts) and component (Turbo-Brayton cryocooler) technologies were considered as well as the development of an active thermal control scheme for a "full scale" application in LEO.

A combination of contracted studies for large cryocoolers, large cryogenic tank structures, and large tank MLI concepts, and in-house studies on BAC and MLI integration techniques (including sizing studies and thermal trades on heat interception straps, BAC shield locations, and radiators) has led to augmentation of a comprehensive spreadsheet sizing tool, from which parametric analyses were performed in order to evaluate the applicability of active cooling as compared to passive-only thermal control for tanks ranging from 2 to 10 m in diameter (Refs. 5 and 6). For each mission architecture, the loiter period at which passive, RBO, and ZBO designs result in the lowest cryogenic system mass is determined through these parametric analyses. Mass, power, and size relationships were traded parametrically to establish the appropriate loiter period where active thermal control reduces mass. The projected benefit is compared for passive, boil-off reduction with a 90 K shield, ZBO (20 K cooling system only), and ZBO with 20 K cooling and a 90 K shield. The analysis shows: (1) a benefit for active thermal control when loiter durations are as little as a few weeks when compared to passive storage, and (2) that two stage cooling reduces power and mass when compared to single stage cooling. Furthermore, active cooling reduces the significance of varied MLI performance, which historically has large performance variability.

The significance of this study effort is that the active thermal control system(s) matured under the FY12 TMP can be scaled to full size future space mission architectures, and that components for full scale applications such as cryocoolers, gas circulators, recuperators, BAC tubing and cooling attachment straps are considered a design issue rather than a technology issue and therefore do not present a scaling risk.

2.2 Passive Thermal Control

The passive thermal controls utilized for advanced cryogenic propellant storage incorporate insulations to prevent heat entering the tank over broad areas and careful design and material selection to deal with point conduction sources (structural supports, plumbing, cabling). The CPST TMP addressed three aspects of passive thermal control: (1) minimizing the insulation performance degradation due to point conduction elements penetrating the envelope; (2) composite materials for structural elements; and (3) application challenges of thick MLI to very large scale propellant tanks.

2.2.1 Penetration Heat Leak Test

Conductive heat transfer in an in-space operational environment is due to structural, fluid, and instrumentation penetrations into the propulsion stage tank, and can be a significant contribution to the total system cryogenic tank heat loads. The impact is not limited to conduction through the penetrating element itself. The manner in which the penetration is integrated with surrounding insulation can also greatly affect heat loads. The state of the art predictive approach combines this effect with multilayer insulation *scaling factors*, which are used to adjust ideal predicted heat load values. These scale factors are typically based on the performance of analogous systems and have significant uncertainty.

The purpose of this testing was to characterize the conductive heat leak of a variety of flight representative fluid lines, electrical connections, and other penetrations through tank insulation (i.e., thermal shorts) and insulation methods on representative thick (>20 layers) cryogenic MLI systems. The parameters included: the attachment mechanism, the buffer material (for buffer attachment mechanisms only), the thickness of the buffer, and the penetration material. The methods of integration investigated were: the use of a buffer to thermally isolate the strut from the MLI and temperature matching the MLI on the strut. These were then compared to the case where no integration was performed. Several buffer materials were investigated, including: aerogel blankets, aerogel bead packages, Cryo-Lite (Johns Manville, Denver, CO) and even an evacuated vacuum space (in essence a no buffer condition). The testing was conducted at Kennedy Space Center's (KSC) Cryogenic Test Laboratory (CTL), in specialized test chambers that provided the thermal and vacuum environment to simulate space-based conditions (Ref. 7).

Over 23 tests were run to help characterize the thermal performance impacts of penetrating MLI. Testing included the development and fabrication of a new calorimeter and test method for two-dimensional thermal performance testing. The testing included null testing of every blanket, no integration testing, buffer testing, and temperature matching testing with different size and material penetrations. The preferred method of isolating penetrations was shown to be the buffer method with Cryo-Lite as the best material to use as a buffer. (This methodology was subsequently employed to integrate strut penetrations with the surrounding insulation for the RBO test article, as shown in Fig. 3.) The thermal degradation or parasitic heat load was shown to be a function of strut diameter, buffer thickness, buffer material, warm boundary temperature, and penetration material. The buffer method was shown to be easier to develop, more robust, and less variable over multiple conditions and environments.

The significance of this test effort is that the effects of penetrations on the thermal performance of cryogenic storage tanks has been investigated, showing the advantages of one or more penetration/MLI closeout methods.
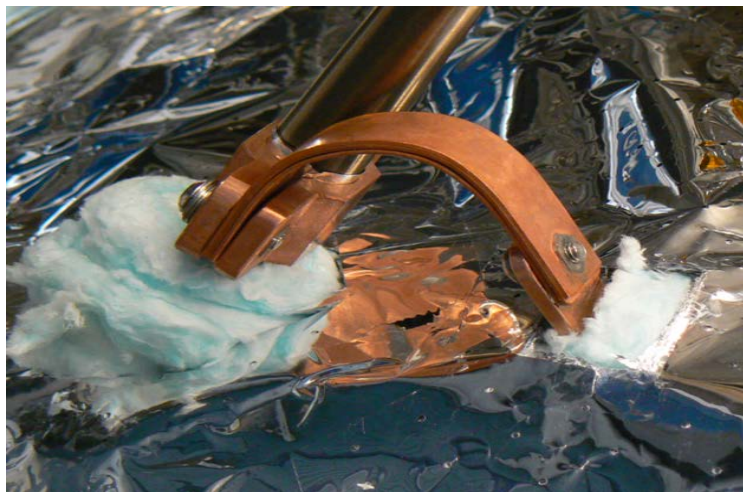

Figure 3.—Cryo-Lite buffer integrated around a penetration (within RBO Experiment Test Article).

2.2.2 Composite Strut Thermal Performance With LH$_2$ Test

One way to reduce the heat leak from a cryogenic support structure is to fabricate the supports out of a low conductivity material. However, even if low conductivity supports are employed, the overall performance of a tank's insulation system is dependent on how that structural member integrates with the tank MLI. The work discussed above was limited to a cold boundary temperature of 77 K. This work was planned for a cold boundary of 20 K.

The purpose of the testing discussed in this section was to measure the heat leak through a flight representative carbon fiber composite strut with one end of the strut at a simulated in-space thermal environment and the other end attached to a LH$_2$ calorimeter. The resulting data would quantify performance degradation of MLI when the composite strut is integrated with various techniques (collars, socks or butt joints) to an MLI blanket. The test was to be performed at GRC's SMiRF facility and employ a flat plate calorimeter from a previous research project. Two differently sized carbon fiber struts were planned for testing. Both struts consisted of IM7/8552 tape. The larger strut with a mid-span diameter of 15 cm. was originally designed for the Altair lunar lander program and had already undergone structural testing at room temperature. The smaller CPST-representative strut had a mid-span diameter of 5 cm.

Testing was terminated due to an unexpected vapor leak from the hydrogen calorimeter. The leak degraded the vacuum level inside the test chamber to the point where any strut heat leak measurements would have been overwhelmed by the increased heat load due to gas conduction in the test rig insulation. Thus, a technology gap remains for low conductivity carbon fiber struts especially at LH$_2$ temperatures. Limited room temperature and LN$_2$ temperature tests have been performed and the results have been promising, but further testing is desirable to support infusion into a cryogenic mission.

2.2.3 Thick MLI Extensibility Study

Long term (>2 weeks) in-space storage of large quantities of LH$_2$ (>4 metric t) required for future exploration missions, without a significant loss of propellant due to boil off from radiation heat sources, will require the application of thick MLI (>7.5 cm) to the outer propellant storage tank walls. Traditional MLI systems (alternating layers of aluminized polymer films separated by polyester or silk netting) have been used for space missions for over 60 years, but limited thermal and structural knowledge exists for the fabrication, installation and venting performance of thick MLI systems applied to very large in-space LH$_2$ storage tanks requiring minimal propellant boil off losses. A candidate insulation system is being demonstrated for LH$_2$ (a BAC shield sandwiched between 30 layers of low density MLI (inner) and 30 layers of higher density MLI (outer)) and LO$_2$ (60 layers of MLI) utilizing a 1.2 m diameter test tank in ground based testing. Nevertheless, application of such technologies to large-scale tanks requires some study. The purpose of the study was to validate the relevancy of a thick MLI (>40 layers) tank attachment and MLI blanket fabrication approach from scaled ground and flight test tanks to a full scale CPS or depot application. The study also assesses options for attaching thick MLI to very large tanks and addresses associated heat loads for each option.

Lockheed Martin's Advanced Technology Center in Palo Alto, California was contracted to perform a study limited to traditional MLI concepts. Traditional MLI is defined herein as Double Aluminized Mylar (DAM) radiation shields separated by one or more layers of netting spacer material such as silk or Dacron. Advanced MLI concepts utilizing alternative spacer concepts are at lower TRL and were not included in the study. The study was focused on the LH$_2$ tank for an Earth Departure Stage (EDS) as a representative large scale CPS. Most results should be extensible to other similar sized cryogenic propellant tanks.

There is relatively little data for thick MLI. For this study, Lockheed Martin defined thick MLI to be thicker than 2.5 cm. Their optimized layer density was 14.5 layers/cm (37 layers/in.), which is similar in layer count to the CPST team definition above. The existing data suggests that there is an increase in the degradation fraction with MLI thickness. The contractor concluded that additional test data is needed

before thick MLI can be used with confidence for flight applications. Their concerns included the following:

- Traditional MLI blankets are typically fabricated into blankets of widths on the order of 1.2 m. Due to the large tank size, the relatively small blanket width results in a substantial number of seams and total seam length.
- Available data for MLI performance on relatively large tanks (all 2 to 3 m in diameter) is sparse and cannot be clearly explained. There are too many unknowns to reach a clear conclusion. It is recommended that a large tank test be conducted with tight controls on layer density variations, minimization of seams and numerous measurements of DAM emissivity.
- There is little data on the performance repeatability of multiple builds of MLI systems. Large uncertainty may be a reality when using traditional MLI.
- A review of environmental test data found examples where MLI was able to withstand testing for acceleration, acoustic and vibration loads, but a full literature survey was not completed. There appears to be a lack of understanding or knowledge on how to structurally model MLI in a meaningful manner.

Lockheed Martin recommends continued use of the well-known "Lockheed Equations" (Ref. 8) for predicting thermal performance of MLI. These equations are based on correlation of calorimeter test results representing ideal conditions of MLI layup with minimal perturbations. Losses due to seams, penetrations, compression and other factors should then be added to predictions. The basis for alternative equations is not clear and these equations have a lesser amount of validation. This recommendation may not be widely accepted within NASA.

Finally, the contractor recommended that a large scale (>4 m test tank) ground storage test be conducted to demonstrate thick MLI technology specifically developed for large storage tanks in a simulated LEO thermal and vacuum environment to reduce the risk of applying unproven thick MLI technology to future space missions.

The significance of this study effort is that a set of factors related to large scale, long duration space-based storage of LH_2 has been identified.

2.3   Liquid Acquisition Device (LAD) Outflow and Line Chill Test

When transferring propellant in space, it is necessary to transfer single-phase liquid from a propellant tank to either an engine or another storage vessel. In Earth's gravity field or under acceleration during "significant" thrusting, propellant transfer is fairly simple: single-phase fluid is transferred by opening a valve at the bottom of the propellant tank and installing an anti-vortex baffle over the tank outlet to prevent vapor and gas ingestion into the outlet. In low gravity where fluid does not sufficiently cover the tank outlet, withdrawing single-phase fluid becomes a challenge. A propellant management device (PMD) is required to ensure single-phase flow, depending on the gravitational environment. One type of PMD, a LAD uses capillary flow and surface tension with a screen/channel device to acquire liquid. Capillary flow LADs have been well characterized for storable propellants (propellants that are liquids at room temperature) for in-space propulsion needs, and capillary flow LADs have also been characterized over a wide range of operating conditions for cryogenic fluids such as LN_2, LO_2 and LCH_4. Some characterization has been performed with LH_2, but additional work is required to characterize LAD performance in LH_2 over a range of conditions that will validate their performance for the CPST flight.

Once bubble free liquid is acquired from the tank, it needs to be transferred through a feedline without creating significant vapor. This requires that the feed-line be pre-chilled. Line chill down is commonly accomplished by absorbing heat into some sacrificial propellant.

The purpose of the testing was to: (1) measure the static and the dynamic screen bubble point pressures using LH_2 as the test fluid for different LAD screen sizes, while conducting a parametric study of LAD screen, LAD channel, frictional and fluid head pressure drops for various LH_2 LAD outflow rates using new, smaller pore size LAD screens, and (2) investigate efficient options for chill down of transfer

line and quantify the LAD stability (no LAD breakdown) due to transfer line chill down transient dynamic pressure perturbations during outflow. Both sets of objectives were accomplished in the same test program conducted at GRCs SMiRF, which provided the thermal and vacuum environment to simulate space-based conditions.

2.3.1 LAD Outflow Test

Inverted vertical outflow testing of two 325 x 2300 full-scale LAD channels in LH_2 was completed. One was a standard LAD screen channel, while the other was thermally flight representative due to the presence of a perforated plate and internal cooling from a Thermodynamic Vent System (TVS). The LADs were mounted in a tank to simulate 1-g outflow over a wide range of LH_2 temperatures (20.3 to 24.2 K), pressures (100 to 350 kPa), and flow rates 0.010 to 0.055 kg/s). Results indicate that the effects on predicted breakdown height (inversely related to bubble point pressure) are dominated by liquid temperature, with a second order dependence on outflow rate through the LAD (Ref. 9). The lowest liquid level breakdown heights (i.e., bubble breakthrough occurs after more of the screen is exposed, thus is indicative of a higher bubble point) are always achieved in the coldest liquid states for both channels, consistent with bubble point theory. Higher flow rates cause the standard channel to break down earlier than the flight channel, where the presence of the perforated plate is believed to enhance wicking and thus screen retention during outflow. Both the heat exchanger and subcooling the liquid are shown to improve LAD performance.

Due to fabrication difficulties a 450 x 2750 screen channel was not available for use in the inverted outflow test. Testing with 325 x 2300 was judged to be adequate to demonstrate that screen channel devices that will be designed for the requirements of the CPST project were capable of handling the required flow rates without breaking down and admitting bubbles. Lack of a 450 x 2750 screen channel for the CPST payload will likely result in the use of He pressurant (which improves bubble point pressure), and probably a LAD TVS system as well.

The significance of this test effort is that a LAD for LH_2 flow rates representative for CPST has been demonstrated on the ground, offering potential to demonstrate the transfer of LH_2 from tank to tank in space.

2.3.2 Line Chill Test

Operation of a cryogenic transfer system is complicated by the requirement to chill it down to allow single phase liquid transfer. The full flush method has been used to cool engine feed lines for upper stages since the 1960s, but is very wasteful in propellant. Pulse and trickle flow also bear a great similarity to the engine feed line cooling techniques investigated in the Atlas Reliability Enhancement Program (AREP) (Ref. 10). This transient must be well understood so as to accurately determine the amount of cryogen required, and the time required to complete the chill down process. Transfer line chill down must also be performed in a manner that will not result in unacceptable pressure fluctuations or stresses in the system that could damage components. The goal of transfer line chill down is to enable the transfer of single-phase liquid at the required condition from a storage vessel to its destination: either another storage vessel or an engine system. Understanding the nature of the transient chill down process, requires an understanding of the fluid physics and the important parameters that affect chill down, including: mass flux, acceleration, the type of two-phase flow induced, heat transfer mechanisms during chill down, and the transfer system physical configuration.

Line chill down testing was conducted to study the chill down of two representative transfer lines utilizing two approaches: trickle flow and pulsed. The testing suggests pulsed chill down, with a duty cycle chosen to minimize either time or mass, as having the most promise. Chill down of a representative line was achievable in less than 90 s while ensuring that vapor free liquid would be available up to the inlet of the receiver tank.

The significance of this test effort is that an effective technique for line chill for LH_2 has been demonstrated on the ground, offering potential to support the transfer of LH_2 from tank to tank in space.

2.4   Analytical Tool Development

Analytical tools are critical for the prediction of space flight system performance (Ref. 11). Analytical tools matured in FY12 under the CPST project include tools to support overall mission performance prediction of CFM system/ subsystems, cryogenic storage thermodynamic and fluid dynamic modeling tools to predict fluid behavior, and component tools to guide the design of component hardware.

The intent of this focus area is to develop and validate analytical tools to be used for the design of the CPST-TDM flight hardware and to predict the fluid dynamics and thermodynamics (heat and mass transfer) of the CPST systems/subsystems in a relevant environment. The development and validation of analytical tools is planned to continue for the life of the project, culminating in the validation and final model refinements against CPST-TDM post-mission flight data. Ideally, the tools developed should be extensible to larger geometric scales (on the order of 5 to 10 m tank diameter) and longer storage durations (on the order of years) compared to the CPST-TDM flight experiment.

A brief description of available codes and their current capabilities are listed in Tables 2 and 3. The list below includes the commercial codes for completeness. The description is focused on those capabilities relevant to modeling the mission phases of: self-pressurization, pressurization, mixing (with or without subcooling), transfer line chill down, tank chill down, and tank filling.

Table 2.—NASA Developed Tools/Codes for Sizing, Optimization, and Analysis

Name	Platform	CFM Technology Addressed	Nodes	Features
Cryogenic Analysis Tool (CAT)	Excel/VBA	Passive and active thermal control	Single	Includes single node (homogenous thermodynamic) model for self-pressurization
CryoSim (Cryogen Storage Integrated Model)	Fortran	Passive and active thermal control		Can be coupled with TankSim to predict self-pressurization and pressure control
TankSim	Fortran	Self-pressurization, spray bar/axial jet pressure control and preliminary model for pressurization	Multi-node	Single node represents a zero-thickness interface between liquid and ullage and the wetted and dry portion of the tank wall. Flat interface or spherical bubble supported for self-pressurization. Creates REFPROP (Ref. 12)-generated property tables and interpolates from these tables.
MLI Ascent Venting	Fortran	MLI performance during launch ascent	Single	Combines continuum and kinetics theory to predict MLI layer transient temperature and pressure
CPPPO (Computational Propellant and Pressurization Program—One dimensional)	Excel/VBA	Self-pressurization and pressurization	Multi-node	Single node represents a zero-thickness interface between liquid and ullage and the wetted and dry portion of the tank wall. Flat interface or spherical bubble supported for self-pressurization.
GFSSP (Generalized Fluid System Simulation Program)	Fortran	Fluid and heat transfer networks	Multi-node	Provides graphical user interface (GUI) for problem setup. Includes a large number of fluid network element options. Implementation of heat and mass transfer across liquid/ullage interface using a zero-thickness node is in progress
NVFILL	Fortran	Tank chill down and no-vent-fill (NVF)	Multi-node	Includes finite-element shell conduction model of heat transfer in thin tank walls and a Lagrangian spray model. Also supports self-pressurization analysis (locked up tank with no inflow).

Table 3.—Commercial Codes Used to Model CFM Fluid and Thermodynamic Processes

Code (Vendor)	Type	CFM Technology Addressed	Standard/Available Options
Thermal Desktop with RadCAD and SINDA/FLUINT (C & R Technologies)	Fortran	Fluid and heat transfer networks	• GUI for problem setup (Thermal Desktop and SINAPS) • Heat and mass transfer across liquid/ullage interface using a zero-thickness node (requires user coding) • Includes a large number of fluid network elements
FLOW-3D (Flow Sciences)	CFD (computational fluid dynamics)	Two phase flow simulations SOA for tank sloshing and settling	• General non-inertial frame of reference • Mass transfer between liquid and ullage using a Schrage type kinetic equation • Lagrangian spray coupled with volume of fluid (VOF) (no atomization, secondary breakup, turbulence/spray interactions, or coalescence models) • Grid generation by the use of Cartesian cut cells
Fluent (ANSYS)	CFD	Two phase flow simulations	• Specialized boundary conditions and physical models • Fixed interface shape, sharp interface model (not using VOF) • General non-inertial frame of reference • Mass transfer between liquid and ullage using a Schrage type kinetic equation • Lagrangian spray coupled with VOF (in progress) • Atomization, secondary breakup, turbulence/spray interactions, or coalescence • Turbulence models • General unstructured (and polyhedral) grids • Shell conduction model (tank chill down)

The significance of this analytical tool development effort is that a foundation has been established for the development and validation of analytical tools necessary to predict the fluid dynamics and thermodynamics (heat and mass transfer) of the CFM systems/subsystems in a relevant environment, for the design of hardware for flight demonstrations (CPST) and ideally extensible to future full scale space missions (CPS and/or depots) with extended in-space storage durations (> 6 months).

3.0   LO$_2$ ZBO Test

LO$_2$ ZBO capability is believed achievable using a 90 K cryocooler with the tubing network located on the tank wall, using the wall to distribute the cooling.

The purpose of this test is to control tank pressure and ultimately LO$_2$ temperature with the active cooling system in a manner that demonstrates robust ZBO. The aspects to understand and validate this are the effect of heat removal rate and its controllability on cryogenic tank pressure. In addition, the distributed cooling system's ability to reduce and control the test tank surface temperature with its inherent variations, particularly the anticipated hotter temperatures around the vent tube at the top of the tank, will be tested. As such, the ZBO system's ability to finely control tank pressure will be tested. The cryocooler will be tested at 25 percent excess capacity, to determine the tank pressure response, and likewise test the system at 25 percent under capacity. In addition, the cooling network's ability to remove heat at two temperatures will be validated: one to demonstrate LO$_2$ ZBO storage at representative propulsion system pressures of 172 kPa (25 psi)—corresponding to a LO$_2$ temperature 96 K—and the other at 82 K, which is comparable to the BAC shield case in the LH$_2$ RBO testing.

This LO$_2$ ZBO test is an important technology step to demonstrate the ability to control tank pressure via a distributed active cooling network, which has not been previously done. Thus, the level of active cooling will be coupled with tank pressure and the fluid's response will be studied. The balancing of the tank heat removal with the nominal passive tank heating rate to achieve ZBO and then disturbing that balance to understand the tank pressure response to varying heat removal rates is critical knowledge. A

robust investigation into the fluid's response to different cooling levels will create curves that show the heat removal effect on tank pressure.

The test article is nearly complete with testing to occur by the end of the calendar year.

4.0   Conclusion

The focus of the FY12 CPST technology maturation effort was to mature selected CFM technologies (nominally to a TRL of 5) through ground based testing, and to show through studies the relevance of the CFM technologies on the CPST flight demonstration to full-scale applications. This effort successfully mitigated budget and schedule risk anticipated in the development of the cryogenic fluid system payload for the CPST flight demonstration. The CPST project is ready to proceed to flight system development with many of these technologies.

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
As part of U.S. National Space Policy, NASA is seeking an innovative path for human space exploration, which strengthens the capability to extend human and robotic presence throughout the solar system. NASA is laying the groundwork to enable humans to safely reach multiple potential destinations, including asteroids, Lagrange points, the Moon and Mars. In support of this, NASA is embarking on the Technology Demonstration Mission Cryogenic Propellant Storage and Transfer (TDM CPST) Project to test and validate key cryogenic capabilities and technologies required for future exploration elements, opening up the architecture for large cryogenic propulsion stages (CPS) and propellant depots. The TDM CPST project will provide an on-orbit demonstration of the capability to store, transfer, and measure cryogenic propellants for a duration which is relevant to enable long term human space exploration missions beyond low Earth orbit (LEO). Recognizing that key cryogenic fluid management technologies anticipated for on-orbit (flight) demonstration needed to be matured to a readiness level appropriate for infusion into the design of the flight demonstration, the NASA Headquarters Space Technology Mission Directorate authorized funding for a one-year (FY12) ground based technology maturation program. The strategy, proposed by the CPST Project Manager, focused on maturation through modeling, studies, and ground tests of the storage and fluid transfer Cryogenic Fluid Management (CFM) technology sub-elements and components that were not already at a Technology Readiness Level (TRL) of 5. A technology maturation plan (TMP) was subsequently approved which described: the CFM technologies selected for maturation, the ground testing approach to be used, quantified success criteria of the technologies, hardware and data deliverables, and a deliverable to provide an assessment of the technology readiness after completion of the test, study or modeling activity. This paper will present the testing, studies, and modeling that occurred in FY12 to mature cryogenic fluid management technologies for propellant storage, transfer, and supply, to examine extensibility to full scale, long duration missions, and to develop and validate analytical models. Finally, the paper will briefly describe an upcoming test to demonstrate Liquid Oxygen (LO2) Zero Boil-Off (ZBO).

15. SUBJECT TERMS
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