Technology Maturation in Preparation for the Cryogenic Propellant Storage and Transfer (CPST) Technology Demonstration Mission (TDM)

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ABSTRACT

In support of its goal to find an innovative path for human space exploration, NASA embarked on the Cryogenic Propellant Storage and Transfer (CPST) Project, a Technology Demonstration Mission (TDM) to test and validate key cryogenic capabilities and technologies required for future exploration elements, opening up the architecture for large in-space cryogenic propulsion stages and propellant depots. Recognizing that key Cryogenic Fluid Management (CFM) technologies anticipated for on-orbit (flight) demonstration would benefit from additional maturation to a readiness level appropriate for infusion into the design of the flight demonstration, the NASA Headquarters Space Technology Mission Directorate (STMD) authorized funding for a 1-year technology maturation phase of the CPST project. The strategy, proposed by the CPST Project Manager, focused on maturation through modeling, concept studies, and ground tests of the storage and fluid transfer of CFM technology sub-elements and components that were lower than 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. The specific technologies selected were grouped into five major categories: thick multilayer insulation, tank applied active thermal control, cryogenic fluid transfer, propellant gauging, and analytical tool development. Based on the success of the technology maturation efforts, the CPST project was approved to proceed to flight system development.

INTRODUCTION

As part of U.S. National Space Policy [1], NASA is seeking an innovative path for 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 the Moon, asteroids, Lagrange points, and Mars and its environs. Mission architecture studies have consistently identified the need for in space propulsion stages using high performance liquid oxygen (LO_2) and liquid hydrogen (LH_2) as the propellant combination to enable more efficient crewed exploration [2]. In addition, some mission architecture studies include consideration of options for propellant resupply, either via tankers or in-space propellant depots [3]. These various mission capability elements have dictated the need for a technology development project within NASA to mature CFM technologies for in-space mission operations including the long-duration storage of cryogenic fluids (passive and active thermal control (PTC and ATC) and micro-g tank pressure control), tank-to-tank transfer of cryogens, and unsettled propellant mass gauging.

To mature these technologies and mitigate the risk of infusing them into future systems, NASA embarked on a project to conduct an in-space CPST Demonstration [4]. This flight demonstration mission would test and validate key cryogenic capabilities and technologies, generating critical microgravity data to assess performance. NASA Headquarters assigned responsibility to the NASA Glenn Research Center (GRC) to manage the design and acquisition of this in-space CFM flight demonstration. 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 1) storing LH_2 for an extended duration in microgravity with reduced boil off (RBO) (including active thermal control technology), 2) storing large quantities of LO_2 for an extended duration in microgravity with zero boil off (ZBO), and 3) transfer cryogenic hydrogen and oxygen from one tank system to another, in-space, without requiring propellant settling maneuvers.

STMD had additional requirements that the Project was asked to address: 1) the maturity of each CFM technology needed to be ready for infusion into the design of the flight demonstration prior to approval of the Authority to Proceed (ATP) into flight system design, and 2) the flight system would be designed, manufactured, assembled, integrated, and tested by NASA, in-house. Given those requirements, a strategy was developed that focused on maturation through modeling, analytical studies, and ground tests of the storage and fluid transfer CFM technology sub-elements and components that were not at a TRL of 5. A Technology Maturation Plan (TMP) was created to document the CFM technologies selected for maturation, identify the approach to be used, quantify success criteria for each technology's Key Performance Parameters (KPPs), and denote deliverables.

In February 2014, the flight system development portion of the CPST project was terminated, due to constraints in the Agency's budget. With this decision, the goal of collecting critical microgravity data will not be realized. However, with the completed technology maturation phase, the CPST Project provided a substantial contribution to the community. The technology maturation effort stands on its own as significant progress was achieved toward the ultimate goal of readying advanced CFM technologies for infusion on future NASA missions. This report will summarize the CPST technology maturation activities and results. In addition, results of a test program to demonstrate liquid oxygen zero boil-off capability (LO_2 ZBO) will be summarized.

TECHNOLOGY MATURATION: TESTS, STUDIES, MODEL DEVELOPMENT

The focus of the CPST technology maturation effort was: (1) to mature selected CFM technologies (nominally to a TRL of 5) through ground-based testing, and (2) to show, through analytical studies, the relevance of the CPST CFM technologies to full-scale applications. This effort was successful in mitigating budget and schedule risks for developing the cryogenic fluid system payload for the CPST flight demonstration mission which was approved by the Agency.

The CPST technology maturation team selected the following activities as they addressed flight mission concerns or were associated with the LO_2 ZBO demonstration. The efforts were grouped into five major categories:

1. Thick multilayer insulation (MLI) technology maturation efforts, including Penetration Heat Leak and a Thick MLI Extensibility Study
2. Tank-applied active thermal control (ATC) technology maturation, including: LH_2 RBO thermal performance and MLI/Broad Area Cooling (BAC) shield structural integrity, a second concept for LH_2 RBO using an advanced, self-supporting, MLI technology, a LO_2 ZBO ground demonstration, and an ATC Scaling Study
3. Cryogenic Fluid Transfer including: Screen channel liquid acquisition device (LAD) outflow and transfer line chill-down
4. Propellant Gauging
5. Analytical Tool 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 the maturation phase of the CPST Project.

Thick MLI Tank-Applied Technology

The passive thermal controls utilized for advanced cryogenic propellant storage incorporate insulation to prevent heat entering the tank over broad areas, 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.

A significant component of conductive heat transfer into the liquid cryogen during in-space storage is from the tank structural supports, piping, and electrical interfaces. Particular care must be addressed where these elements penetrate the MLI to avoid significant degradation to the insulation performance. Calorimeter test data taken for small diameter penetrations (0.5 in.) at a cold boundary temperature of 77 K (calorimeter hardware capability) from the CPST Penetration Heat Leak test series showed that a doughnut-shaped buffer around the interface fabricated from Cryo-Lite™ material provided the optimal MLI performance. It satisfied requirements for both simple, low-cost installation, and for robust and repeatable thermal performance. The test data was used to validate an analytical model developed by the NASA Kennedy Space Center (KSC)/GRC personnel (see Figure 1) [5]. The model was extrapolated to predict the MLI degradation due to penetrations and struts connected to a tank with fluid stored at LH_2 temperatures (20 K) and to select the MLI/strut/penetration integration techniques for the CPST-sized LH_2 tank. The uncertainty of the predicted MLI degradation at the boundary temperature of 77 K based on the analytical model was estimated at 10%.

Future exploration missions will require long-term (>2 weeks) in-space storage of large quantities of LH_2 (>4 metric tons) without a significant loss of propellant due to boil off from radiation heat sources. To meet that requirement, the application of thick MLI (>7.5 cm) to the outer propellant storage tank wall is needed. Traditional MLI systems (alternating layers of aluminized polymer films separated by polyester or silk netting, or fiberglass paper) have been used for space missions for over 60 years. Based on the results of the CPST Thick MLI Extensibility Study, limited thermal and structural knowledge exists for the fabrication, installation, and venting performance of thick MLI systems applied to large in-space LH_2 storage tanks requiring minimal propellant boil off losses.

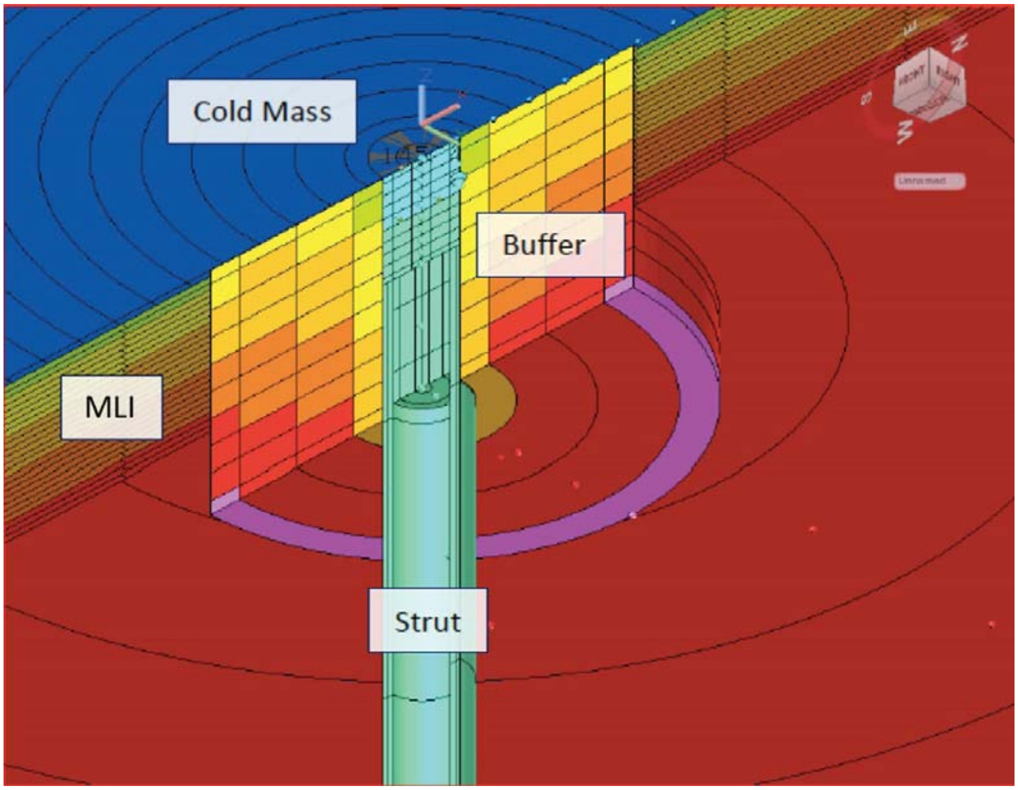

Figure 1: Thermal model of MLI penetrated by a strut with a buffer interface.

Active Thermal Control Technology

Studies of LH_2 stored for long durations (>2 months) have shown that RBO of LH_2 from in-space radiation can be achieved by a combination of a low thermal conductivity composite support structure, thick MLI, and an ATC system (refrigeration) technique of integrating a cryocooler to intercept and collect heat from the tank support structure and a BAC shield embedded in the propellant tank insulation [6]. Active cooling can be accomplished using a cryocooler and a closed loop of gas as the cryocooler working fluid for distributed cooling. Despite the improving prospects for high capacity 20 K cryocoolers, CPST testing focused on available cryocooler technology, applying the much more available 90 K cryocooler technology to cool a shield surrounding the LH_2 tank for RBO storage of LH_2. A critical challenge for the BAC was the development of a method to support the shield and its cooling loop tubing within the MLI blanket.

Two test-bed tank systems were developed to meet the goal of evaluating thermal and structural characteristics of integrated MLI and BAC shield system: the RBO (test article) 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. The RBO and VATA tests 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 test article at GRC's Small Multi-Purpose Research Facility (SMiRF) is shown in Figure 2, and the VATA test article at MSFC is shown in Figure 3.

Figure 2: 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.

Figure 3: Vibro-Acoustic Test Article (VATA) being prepared in the MSFC acoustic test chamber for structural assessment of the thick MLI construction.

The RBO and VATA Thermal Control System (TCS) included Spray-On Foam Insulation (SOFI) directly bonded to the tank. 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: an inner blanket between the SOFI and the BAC shield and an outer blanket outside the BAC shield. 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.

Following this first test setup, the NASA's STMD's Game Changing Development program provided funding to demonstrate an advanced MLI concept with these test articles. 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 was also capable of supporting the BAC shield (tests are referred to as RBO-II and VATA-II). The Self Supporting MLI (SSMLI) utilizes rigid spacers bonded to the radiation shield layers to limit conductive heat transfer between radiation shields while providing self-support between the layers thereby eliminating the need for the polymer standoffs used in the original RBO and VATA tests to support a BAC shield [7]. Both tests were completed successfully, with results for RBO-II showing reduction in heat leak with the active thermal control system operating of up to 58%, while the VATA-II test likewise showed that the SSMLI/BAC system can survive acoustic loading with no physical damage to structure [7,8].

The CPST Project also had a program level requirement to demonstrate the capability to store LO_2 without propellant loss (ZBO) using a system that is relevant to large-scale flight applications. To meet this requirement, a ground-based demonstration of ZBO using LN_2 at 82 psi (surrogate for LO_2 stored at 25 psi) was conducted. The purpose of this demonstration was to control tank pressure and ultimately LO_2 temperature with an active cooling system in a manner that demonstrates robust ZBO, employing a cryocooler with a heat lift capacity of 15 W at 90 K. A tubing network circulating cooled neon gas was attached directly onto the tank wall, effectively using the wall to distribute the cooling. Testing was also conducted both above and below nominal power levels of the cryocooler, to evaluate tank internal pressure response, at two tank fill levels, 25 and 90%. The testing was successful, with zero boil off achieved at input electrical power levels well within the capacity of the cryocooler. When the cryocooler was operated at a higher power level, the system showed the ability to significantly drop tank pressure, while tank pressure rise data was gathered for the lower cryocooler power level. The cryocooler system also demonstrated the ability to achieve ZBO at low fill level (that is, a tank with a large ullage which normally has a high level of thermal stratification in the fluid leading to increased pressurization rates). When run at higher input power, the system again demonstrated the ability to drop tank pressure and liquid temperatures at low fill levels. Overall, the test demonstrated: the technique to attach cooling tubes on the tank, the design of supply and return manifold designs for uniformity of flow distribution, the BAC ability to intercept both heat flux through MLI and local heat loads from tank supports and penetrations, the robust application of traditional MLI blankets with low heat leak and low degradation (scale) factors, and the successful integration of a reverse turbo-Brayton cycle cryocooler for zero boil off storage of LO_2. 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 had not been previously accomplished.

Long-term in-space storage of a full-scale cryogenic propellant stage or depot will require both a robust insulation system and an ATC system to minimize the propellant loss due to radiant heat. The Active Thermal Control Scaling Study determined that the ATC system matured under the CPST technology maturation testing can be efficiently scaled to full-scale future space mission architectures [9]. Components for full-scale applications such as turbo-Brayton cryocoolers, gas circulators, recuperators, BAC tubing, and cooling attachment straps are not considered a technology issue and are not a scaling risk.

Fluid Transfer Technologies

To date, no in-space resupply of cryogenic fluid has occurred for any NASA space missions. Traditionally, cryogenic upper stages have used auxiliary thrusters to settle the propellants prior to transferring fluid from the storage tanks to the engines. After settling of the fluids in the propellant tanks, the engine feedline and turbopumps must be chilled down to cryogenic temperatures prior to the turbopump startup to prevent cavitation in the turbopump. For efficient in-space tank-to-tank propellant transfer, settling by thrusters is undesirable. The unsettled fluid transfer technologies of screen channel liquid acquisition devices (LADs) and mass efficient transfer line chill-down techniques were the focus of the CPST Technology Maturation LAD Outflow and Line Chill investigation. A test article was constructed that incorporated several sample LAD channels which could be tested for performance under dynamic outflow conditions. In addition to traditional temperature and pressure measurements, visualization sections downstream of the LAD channels allowed video observation of bubbles in the flow, indicating breakdown of the screen's capillary retention capability. The complexity of this test rig, which enabled investigation of multiple parameters and configurations, is illustrated in Figure 4.

LAD pressure drop measurements (across the screen, along channel, and channel outlet) of a 325×2300 (wires per inch) mesh screen channel during tank outflow over thermal conditions representative of a low pressure LH_2 propellant tank were in agreement with predicted values. The use of a 325×2300 mesh screen channel LAD has been recommended for the CPST flight demonstration. However the testing has suggested that several techniques—operating at a colder liquid temperature (<20 K), pressurizing the tank with a noncondensable pressurant (gaseous helium (GHe)), or the use of a finer screen (450×3250 mesh size) can extend the point at which the screen breaks down and admits vapor into the channel. All three of the methods significantly enhance the expulsion efficiency of the LAD, or the amount of propellant removed versus the total starting volume. Assuming the successful performance of the CPST LAD design, full-scale LH_2 flight application LADS are not considered a scaling risk. Both component and scalable LAD testing in LH_2 provided new and rare performance data to update and extend analytical models that have been used historically for storable propellants to make predictions for cryogenic propellants [10].

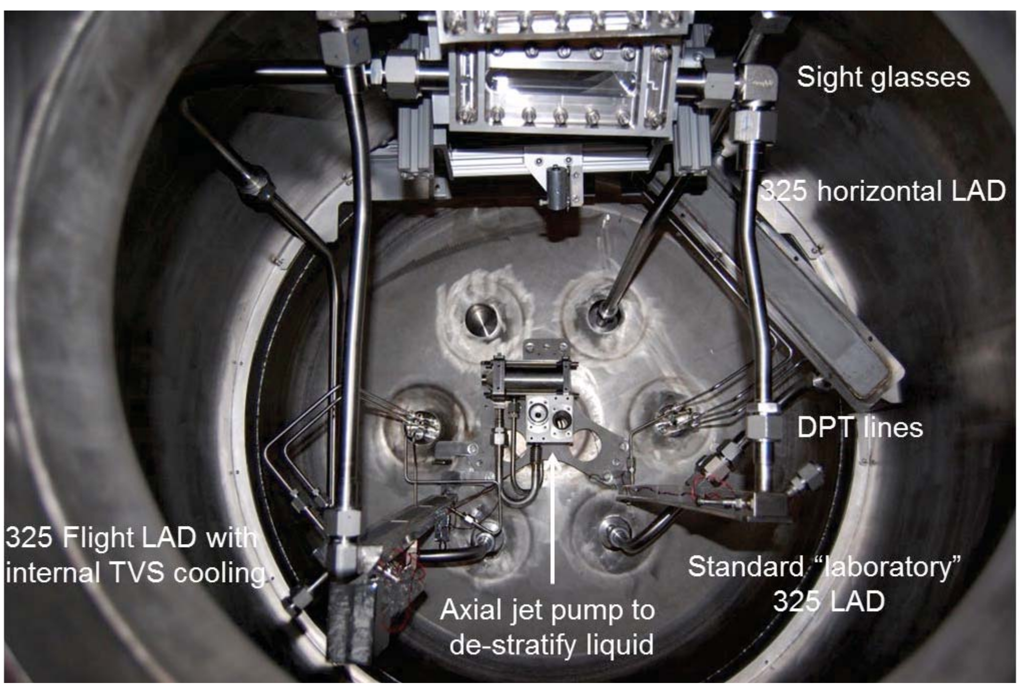

Figure 4: Layout of the LAD hardware inside the test tank for the LAD Outflow and Line Chill-down test series. The sight glass is used to identify bubble in the outflow when the LAD screen is breaking down and allowing vapor to pass through. Note: DPT = differential pressure transducer.

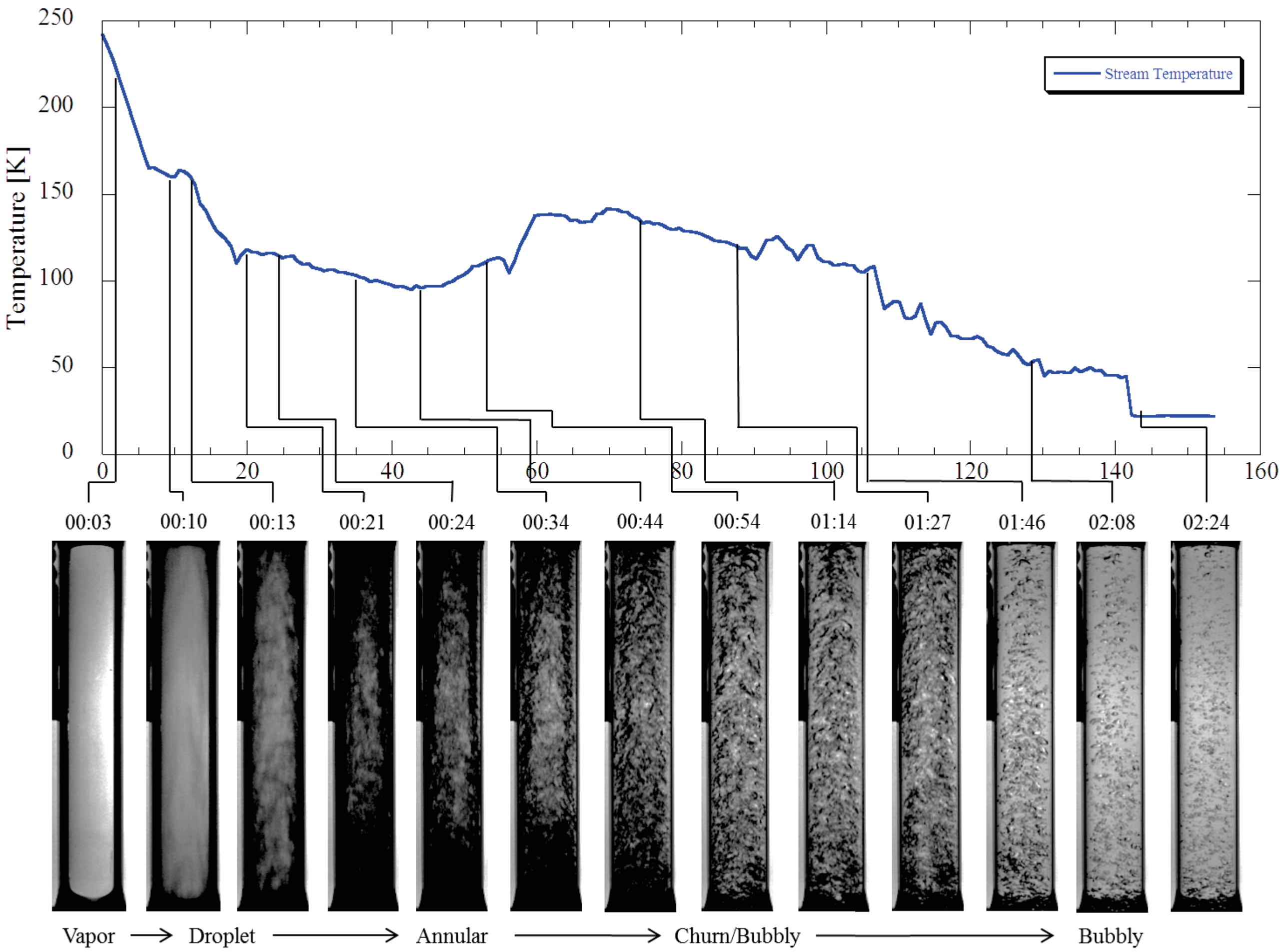

Figure 5: Internal Stream Temperature as a Function of Time. Superimposed are time-correlated video stills which show the evolution of the liquid hydrogen transfer line chill down.

Since the 1960s, a full flush transfer line chilldown technique has been used to cool engine feedlines for upper stages. During the CPST Technology Maturation phase testing, trickle flow and pulsed flow chill-down methods were parametrically tested across a range of LH_2 temperatures, pressures, and transfer flow rates to investigate optimal transfer line chill-down for a tank-to-tank transfer. Figure 5 shows a progression of trickle flow during line chill down, from all vapor, to droplets forming in the vapor, to annular flow, to bubbly flow, to liquid flow. The line chill portion of the CPST technology maturation LAD Outflow and Line Chill tests affirmed the mass savings benefit of the pulsed flow applied to transfer lines and was recommended as the transfer line chill-down technique for the CPST flight demonstration [11].

Propellant Gauging

Mass gauging in an unsettled propellant condition is required to obtain the mass of the cryogenic liquid in the propellant tank without having to accelerate the vehicle (and position the liquid propellant) using an ancillary propulsion system. Unsettled mass gauging can quantify the liquid mass before, during, and after a propellant transfer in microgravity as well as to understand propellant losses during storage without requiring a propulsive system to settle the fluid within the tank, thus it is an enabling technology. However, no state-of-the-art gauge exists for unsettled mass gauging of cryogenic propellant tanks in microgravity, so NASA has been developing an omni-gravity gauging technology known as the Radio Frequency Mass Gauge (RFMG). The basic principle of this technique requires incorporation of a simple antenna into the propellant tank. A broad frequency spectrum of RF energy is introduced into the tank and the response is analyzed. Due to the difference in dielectric constant between the vapor and liquid phase of the propellant, the response is dependent on tank fill fraction. Smaller effects of fluid position are addressed through detailed simulations [12].

During the CPST technology maturation effort, several tasks were completed that further advanced the RFMG technology in preparation for a flight demonstration.

Structural analysis and vibration testing of RFMG antennas, used to transmit and receive the RF signal inside the tank, were successfully completed. A series of electromagnetic interference and compatibility tests were also completed using a prototype RFMG electronics unit. Several commercial RF analyzers were successfully evaluated for use in a spaceflight electronics application.

In addition to the RFMG hardware development, the Surface Evolver–Fluid Interface Tool (SE-FIT) software package, developed externally with NASA funding and originally released in January 2011, was revised and released with significant upgrades [13]. The SE-FIT software is used to generate low-gravity fluid configurations in tanks. These fluid configurations are used to calculate RF tank modes at different fluid fill levels and liquid configurations as part of the RFMG database used for gauging.

Analytical Tool Development

The development and validation of analytical tools to predict the fluid dynamics and thermodynamics (heat and mass transfer) of the CFM systems/subsystems under settled and unsettled conditions will reduce the development cost and risk for future NASA exploration missions employing in-space cryogenic storage and transfer systems. Such tools need to model the following processes: self-pressurization, pressurization (autogenous or non-condensable gas), pressure control, line or tank chilldown, and transfer operations (to the engine or filling another tank). The tools should be applicable to future cryogenic systems for a range of length scales and storage durations. 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. Thus, the analytical tool development effort has focused on the development of both CFD tools and faster running multi-node tools to eventually enable end-to-end mission simulations during settled and unsettled mission phases.

An example of CFD development and validation is the simulation [14] of storage tank pressure control for a 1g LH_2 axial jet mixing experiment. The experiment [15] used a flight-weight ellipsoidal 2.2 m diameter LH_2 tank with liquid fill levels of 49 and 86% and axial jet flow rates corresponding the jet Reynolds numbers (based on a jet nozzle inner diameter of 2.21 cm) from 80,000 to 495,000. CFD simulations were performed with the commercial code ANSYS® Fluent, version 13.0; the Volume of Fluid (VOF) method was used for modeling the two-phase flow. Custom user-defined functions were developed for mass transfer across the liquid/ullage interface, and liquid flow into the pump and out of the axial jet nozzle. Figure 6 shows the comparison of CFD simulations and experimental data for ullage pressure at two jet flow rates (160,000 and 304,000 jet Reynolds numbers) for a liquid fill level of 86%.

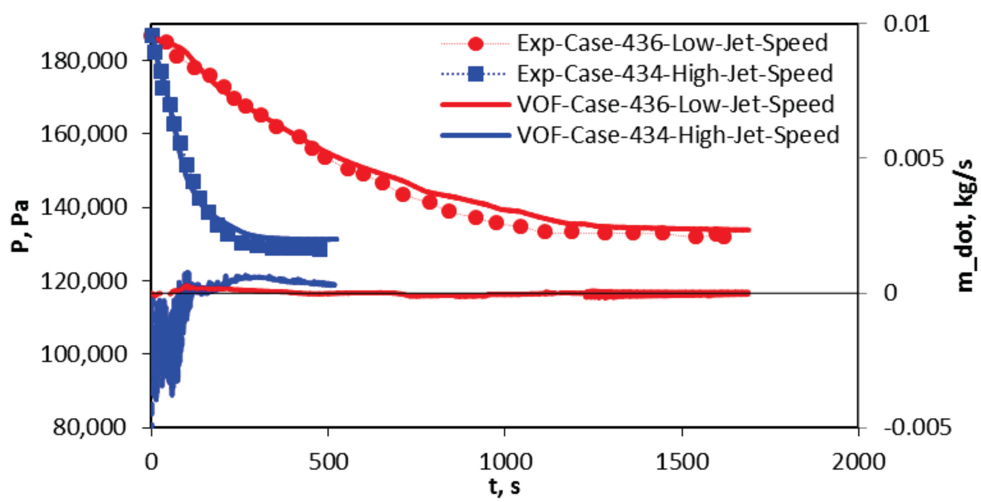

Figure 6: Comparison of Fluent VOF simulations (lines) and experimental measurement (symbols) for ullage pressure at two axial jet flow rates (K-site Test Runs 436 and 434). Also shown (lower part of plot) are predictions of the net mass transfer rate (kg/s) across the liquid/ullage interface.

CONCLUSION

The focus of the CPST Project's technology maturation phase 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 CPST CFM technologies to full-scale applications. This effort successfully mitigated budget and schedule risks anticipated in the development of the cryogenic fluid system payload for the CPST flight demonstration. Based on the success of the technology maturation efforts, the CPST Project was approved to proceed to flight system development with many of these technologies. The specific technologies addressed were grouped into five major categories: thick multilayer insulation, tank applied active thermal control, cryogenic fluid transfer, propellant gauging and analytical tool development.

In February 2014, NASA terminated the flight demonstration mission of these technologies due to budget constraints, Nonetheless, the Technology Maturation effort made significant contributions to the evolution of CFM technologies readying them for infusion into future NASA missions.

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