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Cryogenic Fluid Storage Technology Development: Recent and Planned Efforts at NASA

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March 2009

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Abstract

Recent technology development work conducted at NASA in the area of Cryogenic Fluid Management (CFM) storage is highlighted, including summary results, key impacts, and ongoing efforts. Thermodynamic vent system (TVS) ground test results are shown for hydrogen, methane, and oxygen. Joule-Thomson (J-T) device tests related to clogging in hydrogen are summarized, along with the absence of clogging in oxygen and methane tests. Confirmation of analytical relations and bonding techniques for broad area cooling (BAC) concepts based on tube-to-tank tests are presented. Results of two-phase lumped-parameter computational fluid dynamic (CFD) models are highlighted, including validation of the model with hydrogen self pressurization test data. These models were used to simulate Altair representative methane and oxygen tanks subjected to 210 days of lunar surface storage. Engineering analysis tools being developed to support system level trades and vehicle propulsion system designs are also cited. Finally, prioritized technology development risks identified for Constellation cryogenic propulsion systems are presented, and future efforts to address those risks are discussed.

Introduction

The Cryogenic Fluid Management (CFM) Project is funded under the National Aeronautics and Space Administration's (NASA) Exploration Technology Development Program (EDTP) to develop, test, and analyze critical cryogenic technologies needed to support lunar mission architectures. The storage area under CFM addresses crosscutting technologies related to tank pressure control, tank thermal control, insulation systems, and associated analysis and modeling tools.

In order to insure the structural integrity of cryogenic tankage, as well as maintain propellants and/or other cryogenic fluids within desired temperature and pressure ranges, appropriate pressure control technologies must be employed. Thermodynamic vent systems (TVS) are an attractive technology for in-space pressure control since they enable tank venting in a micro-gravity environment without requiring propellant settling. In addition, a TVS exploits the latent and some of the sensible cooling capacity of a cryogen by expanding a metered portion of it through a Joule-Thomson (J-T) device rather than directly venting. The CFM Project has tested TVS systems in liquid hydrogen, liquid methane, and liquid oxygen ground tests. J-T performance tests have also been conducted with hydrogen, methane, and oxygen to investigate potential clogging issues.

Broad area cooling methods use a cryocooler coupled to cooling passages that are attached to either the tank wall or a shield within a multilayer insulation (MLI) system. The objective of these systems is to intercept the environmental heat leak before it reaches the cryogen. Initial testing of the tube-to-tank concept has been completed and analyzed. Further testing is planned to investigate a tube-to-shield configuration. These active distributed cooling systems may be needed for extended lunar operations when passive cooling techniques are insufficient to maintain thermal control of a tank within its design range.

Finally, significant effort has been directed toward improving analytical models for predicting fluid, thermal, and system performance for CFM systems. These modeling efforts include engineering tools based on empirical relations, integrated commercial analysis tools (e.g., finite element and finite difference codes), and computational fluid dynamic (CFD) models. The engineering models are essential for performing system trades and early design configuration studies. Likewise, the CFD models are crucial for predicting fluid and thermodynamic behavior of cryogens in a variety of gravity and thermal environments envisioned for the lunar missions. The lack of flight data for extended in-space cryogenic fluid management further highlights the priority of accurate CFD models.

Thermodynamic Vent Systems

The primary function of a TVS is to control the thermodynamic conditions of a cryogenic propellant, namely the pressure and temperature. The fundamental components of the TVS tests highlighted in this report include

(1) A J-T device to expand the fluid to a lower pressure and temperature (e.g., valve or other flow restrictor)
(2) A heat exchanger to transfer heat from the warmer tank bulk liquid to the cooler fluid stream that has been expanded through the J-T device
(3) A pump to withdraw liquid from the tank for the warm side of the heat exchanger, and optionally to provide inlet flow to the J-T device (J-T inlet flow can also be pressure driven)
(4) A method of injecting the cooled bulk liquid back into the tank (e.g., spray bar or fluid jet)
(5) A vent path for the J-T outlet

TVS ground testing has been performed with methane and hydrogen using spray bar liquid injection. Recently, tests have also been completed with oxygen using both axial jet and spray ring liquid injection techniques. The objective of all the tests was to demonstrate the capability of a TVS to control the thermodynamic conditions in cryogenic propellant tanks.

Methane Testing

Methane TVS tests using a spray bar were performed in a 18.09 m^3 tank at NASA’s Marshall Space Flight Center (MSFC) in November of 2006 (Refs. 1 and 2). The tank was cylindrical with 2:1 elliptical heads, having a diameter of 3.05 m and an overall length of 3.05 m. Boundary temperature was controlled to 305 K using a shroud, and testing was performed at heat leak levels of 715 and 420 W at a fill level of approximately 90 percent. A total of 23 TVS cycles were completed.

Figure 1 is a schematic of a spray bar TVS with an ullage shape indicative of low gravity conditions. Figure 2 is a photograph of the upper portion of the test tank showing the TVS spray bar, vent line, and other tank internals. Figure 3 is a photograph of the test tank within the shroud prior to installation in the vacuum chamber.

Several critical results were obtained with this test series, all with helium in the ullage. First, the TVS was able to control ullage pressure within the parameters of the test. Second, controlling TVS operation via ullage pressure alone resulted in a rising saturation liquid temperature. Finally, the TVS was capable of lowering the saturation temperature of the liquid if it was operated for longer cycle periods. All three of these results are evident in Figure 4.

Hydrogen Testing

Prior to the methane tests, hydrogen TVS tests were performed using the same test hardware in August through September of 2005 (Ref. 3). During this test series, a lower environmental heat leak of 70 W was maintained. Fill levels of 90, 50, and 25 percent were tested with pure hydrogen ullage and mixed hydrogen-helium ullage conditions.

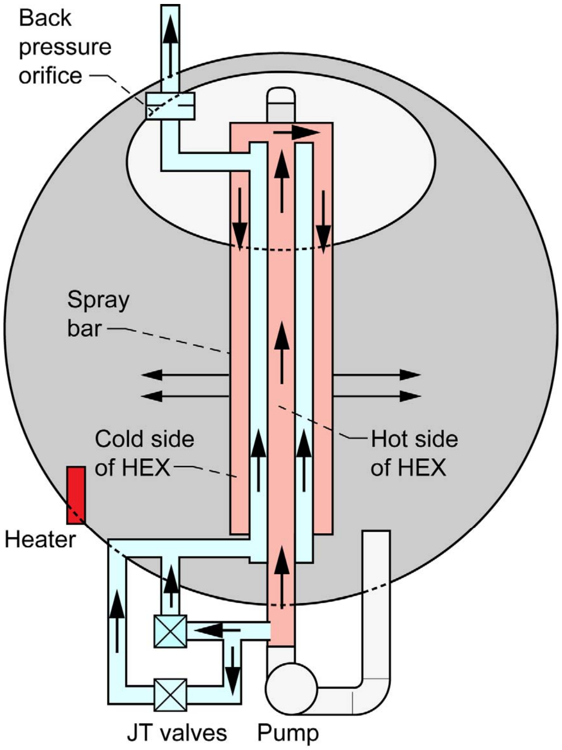

Figure 1.—Spray bar TVS schematic (Ref. 1).

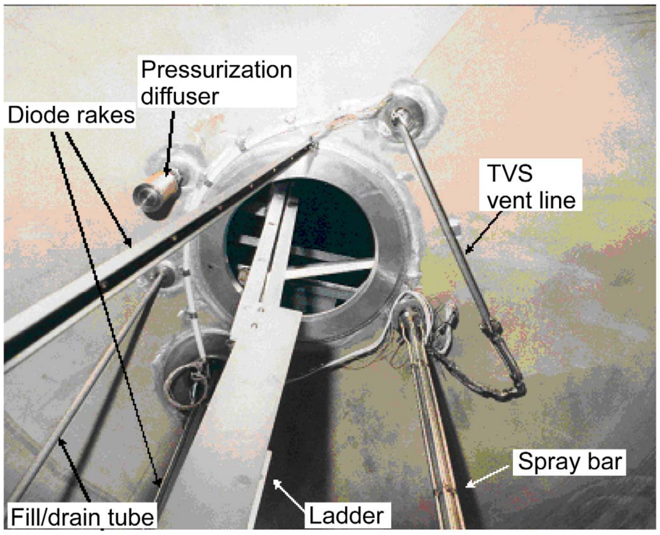

Figure 2.—TVS Hardware and instrumentation (Ref. 2).

Figure 3.—Tank and shroud (Ref. 2).

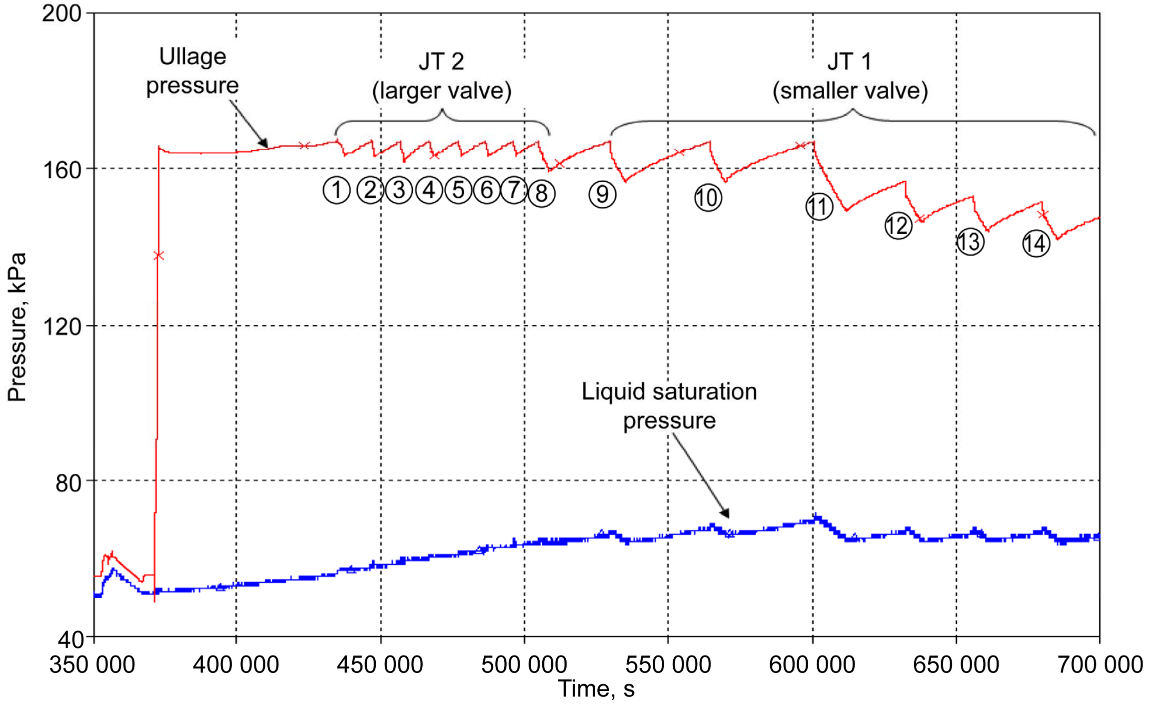

Figure 4.—Ullage and liquid saturation pressures (Ref. 1).

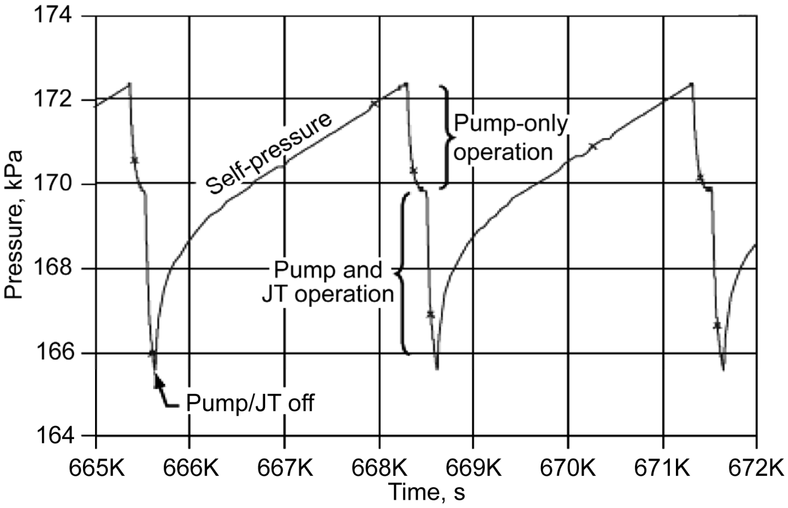

Figure 5.—Typical TVS cycle (90 percent fill, He-H_2 ullage) (Ref. 3).

Figure 5 shows data from a typical TVS cycle and illustrates the control scheme employed for this test series. The cycle starts with self-pressurization of the tank due to environmental heat leak. When the upper pressure control limit is reached, the ullage pressure is reduced by initially operating the TVS in pump-only mode (i.e., J-T valve is bypassed). Additional pressure reduction is then achieved by expanding through the J-T valve. The cycle is complete when the lower pressure control limit is reached, and the TVS is shut down.

Figure 6 provides data on the ullage and liquid saturation pressure for the 90 percent fill level test with a mixed helium-hydrogen ullage. Note that the tank was initially self-pressurizing in pump-only mode until the tank pressure increased above 160 kPa. The TVS was able to control the ullage pressure within ±3.45 kPa. Figure 7 provides the ullage and liquid temperatures for the same test run. Table 1 gives a summary of all the hydrogen TVS tests conducted. Note the extended TVS duty cycle duration required for the mixed helium-hydrogen ullage test at 90 percent fill compared to the pure hydrogen ullage case.

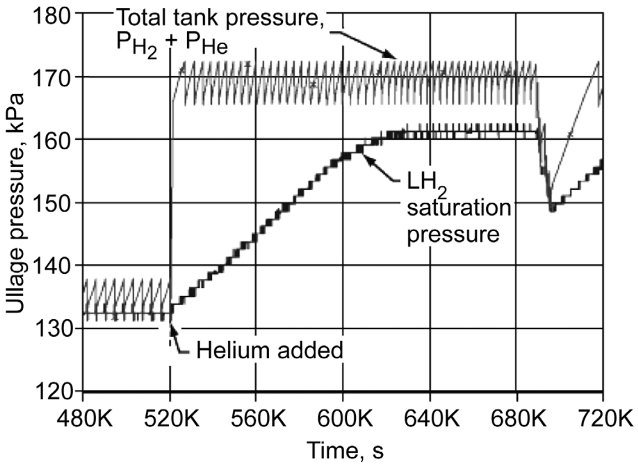

Figure 6.—Ullage and liquid saturation pressures (90 percent fill, He-H$_2$ ullage) (Ref. 3).

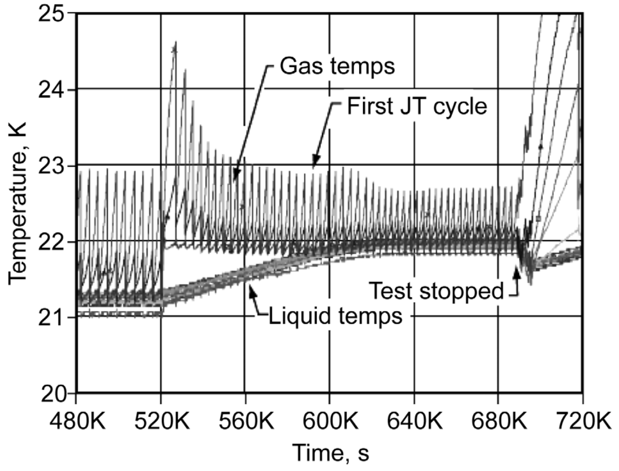

Figure 7.—Ullage and liquid temperatures (90 percent fill, He-H$_2$ ullage) (Ref. 3).

TABLE 1.—HYDROGEN TEST SUMMARY (REF. 3)

Fill level, percent	Approximate mass GHe present, kg	Number of cycles	Typical pressure reduction cycle duration, sec	Typical pump/ JT duty cycle, percent
90	-----	11 Pump only 12 Pump only	189	4.3
90	0.34	18 Pump only 31 Pump and JT	318	10.4
50	0.34	4 Pump only 9 Pump and JT	335	6.7
50	1.95	0 Pump only 15 Pump and JT	512	10.6
25	1.95	0 Pump only 12 Pump and JT	267	5.2
25	3.69	0 Pump only 12 Pump and JT	367	6.6

Oxygen Testing

TVS oxygen testing was recently conducted in a 1.65 m^3 (58.3 ft^3) tank at NASA's Glenn Research Center (GRC) in October of 2008. The objective of the test series was to demonstrate a LOX TVS using an axial jet and spray rings at fill levels of 90 and 50 percent. The axial jet injects the cooled liquid from near the bottom of the tank toward the liquid-ullage interface, resulting in direct cooling and significant mixing of the bulk liquid when the TVS is operated. Conversely, the spray rings inject droplets into the ullage space in the upper portion of the tank, resulting in direct cooling of the ullage.

An additional objective was to investigate control logic schemes that monitor both tank pressure and average liquid temperature. The pump-only mode used in the methane tests was not employed since this mode tends to increase liquid temperature in a mixed helium-oxygen ullage tank due to the heat added by the pump. Baseline tests were run with a pure oxygen ullage using the axial jet. These tests were followed by helium-oxygen ullage tests using: axial jet, combined axial jet and spray rings, and spray rings only.

Controlling the TVS based on a combination of tank pressure and liquid temperature was explored to address the rising liquid temperature observed in previous methane TVS tests. It is believed that this rising temperature is an inherent artifact of operating the TVS over multiple cycles in a tank containing an noncondensable gas in the ullage. To illustrate, as the TVS operates it removes a quantity of liquid, thereby increasing the ullage volume. Since the mass of the noncondensable gas is constant, the increased ullage results in a decrease in helium partial pressure. This in turn allows the partial pressure of the vapor to rise, corresponding to a higher saturation temperature.[1]

Figure 8 shows a schematic representation of the LOX TVS and test tank (Ref. 4). Note that this is a functional schematic, and does not accurately represent the physical locations of the components (e.g., axial jet). Figure 9 is a CAD image showing the spray ring design near the top of the tank. Shown in Figure 10 are photographs of the TVS hardware installed in the bottom of the tank (internally and externally).

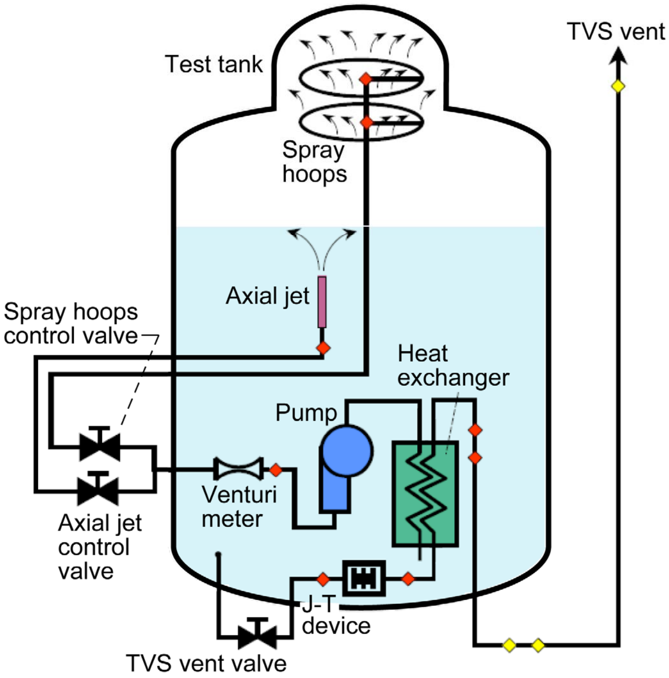

Figure 8.—LOX TVS test schematic (Ref. 4).

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[1] Paraphrased from discussions with Neil Van Dresar.

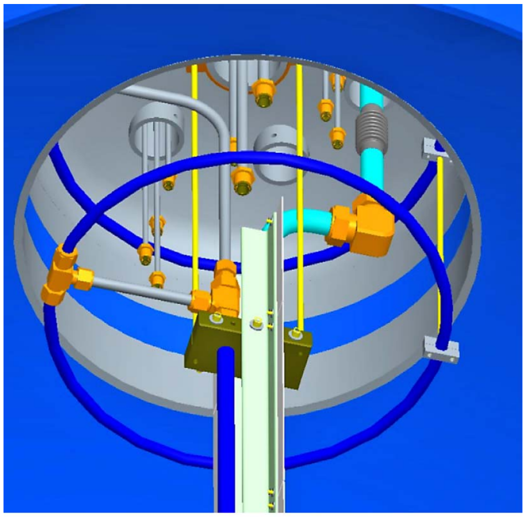

Figure 9.—CAD image of spray rings (Ref. 4).

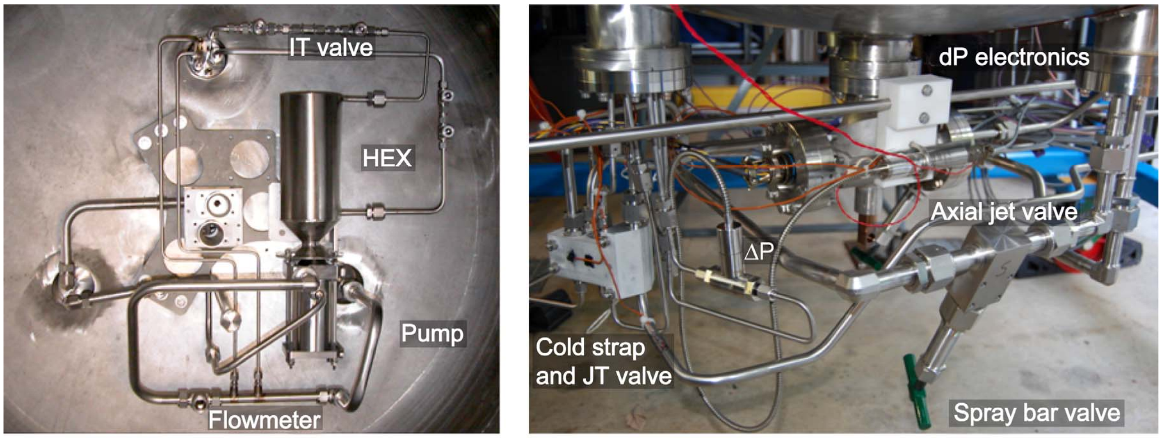

Figure 10.—TVS tank bottom components (internal and external) (Ref. 4).

Data reduction and interpretation are currently being performed on the LOX TVS test data, and will be published when completed. Operationally, the TVS was able to maintain the tank thermodynamic conditions (pressure or temperature) within the prescribed automated control band with all of the liquid injection configurations tested. This was demonstrated for both a pure oxygen and mixed helium-oxygen ullage.

Joule-Thomson Device Performance

A key component of any TVS is the J-T device used to expand the fluid to provide cooling. Previous tests conducted with multiorifice J-T devices in liquid hydrogen have indicated the possibility of clogging under some operating conditions (Ref. 5). It has been postulated that the clogging may be due to the presence of neon impurities in the liquid hydrogen that solidify on the cold surfaces of a J-T device during operation due to the expansion process. Neon impurities as low as parts per billion (ppb) are believed to be sufficient to cause the clogging.

Figure 11 shows a liquid hydrogen J-T test with a 0.254 mm orifice where the flowrate decreases from 37 slpm to nearly zero over an operating time of 20 min (Ref. 6). The clogging has been observed to occur at liquid hydrogen temperatures between 22 and 26 K (37 to 44 °R), with no clogging below or above this range (Ref. 5).

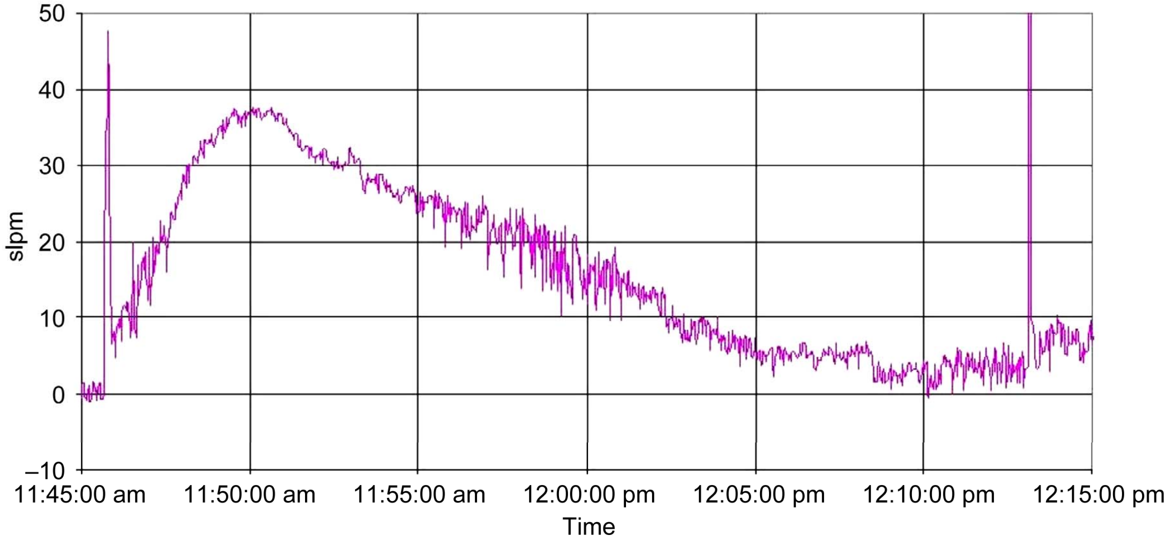

Figure 11.—Flow clogging for liquid hydrogen J-T test (Ref. 6).

Testing was started in October of 2008 at NASA's Glenn Research Center to investigate a variety of clogging mitigation strategies for hydrogen such as (Ref. 7)

(1) Stopping flow, and observing if the device unclogs spontaneously over time
(2) Varying the duty cycle of flow through the device
(3) Using a heater to unclog the device
(4) Switching flow between parallel devices
(5) Running parallel devices simultaneously
(6) Mechanical unclogging techniques (e.g., varying needle valve travel)

No clogging has been observed in testing to date with liquid methane or liquid oxygen[2] (Refs. 6 and 7). Additional testing with methane is planned at higher pressures (i.e., up to 1720 kPa or 250 psia) to insure no clogging occurs under those conditions as well. Table 2 summarizes all the J-T clogging tests completed to date (Ref. 7).

TABLE 2.—J-T CLOGGING TESTS SUMMARY (REF. 7)

Fluid	Temperature range, °R	Pressure range, psia	Test result	Test location
LCH_4	181 to 203	20 to 22	No clogging	GRC CCL-7
LOX	168 to 209	20 to 121	No clogging	GRC SMiRF
LH_2	32 to 47	52 to 60	Clogging	GRC CCL-4
LH_2	39 to 46	29 to 33	Clogging	GRC CCL-7

Active Distributed Cooling

A "tube-to-tank" test series was conducted at NASA's Ames Research Center (ARC) in January of 2008 to validate analytical models that have been formulated for distributed cooling concept designs and trade studies (e.g., broad area cooling) (Refs. 8 to 10). Additionally, the test addressed the thermal and mechanical feasibility of bonding a distributed cooling line to a structure (e.g., a tank wall) that is subject to large temperature variations.

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[2] Liquid oxygen J-T clogging tests were performed at the NASA GRC SMiRF test facility in August, 2007.

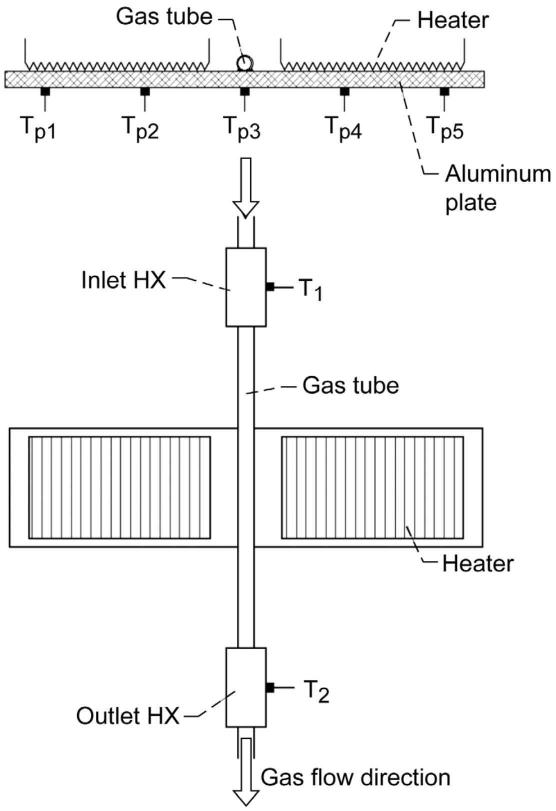


Figure 12.—Tube-to-plate test section (Ref. 8).

Figure 12 illustrates the test article which was comprised of: a 42 long by 19.75 wide by 6.6 mm thick aluminum plate, a 2.6 mm i.d. tube with 0.7 mm wall thickness, heater wire attached with varnish, inlet and outlet heat exchangers consisting of stacked copper screens, and low temperature epoxy bonding the tube to the plate. A Gifford-McMahon cryocooler provided the cooling for the helium stream.

Figure 13 provides the transient temperature profile at various points throughout the test article for one of the tests (Ref. 8). At 23.6 hr, a differential temperature of roughly 200 K exists from the cryocooler cold head to the tube outlet heat exchanger. Less than 6 hr later, the test article temperatures have cooled down to within a few degrees of each other.

Figure 14 shows the thermal resistance between the plate and the helium gas stream (multiplied by the tube effective length) as a function of Reynolds number. The experimentally measured resistance shows good agreement with the calculated resistance for finite tube length. Note that the bond resistance is an order of magnitude smaller than the overall resistance, confirming the bonding technique's feasibility from a thermal performance standpoint. The thermal resistance for an infinite length tube is also plotted.

Figure 15 plots the derived test article heat transfer effectiveness ratio (η) as a function of flow rate (Ref. 8). Again, good agreement between the measured and calculated values is evident. Since the test article used a short tube length, Figure 15 also shows a calculated heat transfer effectiveness ratio trendline for a long tube, as would be typical of a distributed cooling application.

The key result of the test series was confirmation of the overall approach and assumptions of the analytical models for laminar flow conditions. In addition, determination of the thermal resistance between the plate and gas stream, and the heat transfer effectiveness, provides confidence in the tube-to-tank broad area cooling concept.

Tube-to-shield testing is planned next to address the concept of cooling one layer (i.e., shield) of multilayer insulation (MLI). Selection of a layer of MLI to actively cool could make use of the first stage of a two stage cryocooler to intercept environmental heat leak at a higher temperature than at the tank wall.

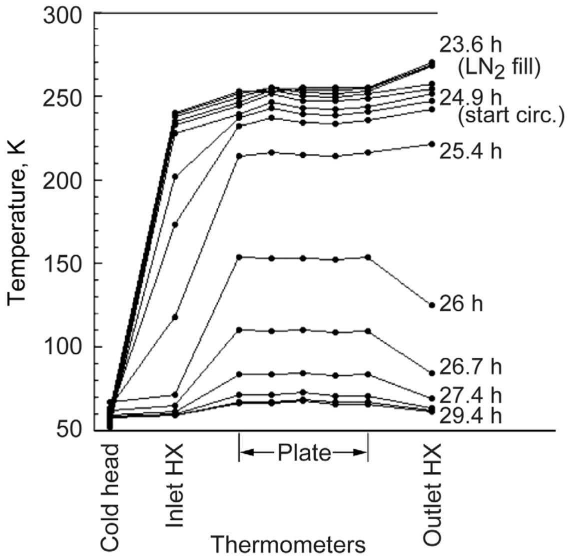


Figure 13.—Temperature profile during initial and cool-down (Ref. 8).

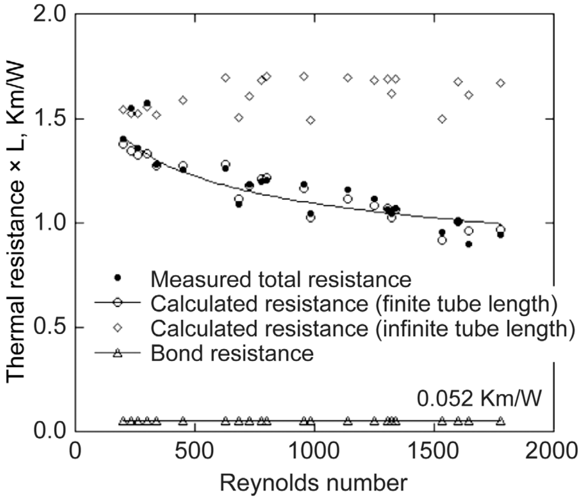


Figure 14.—Thermal line resistance between plate gas stream for two test runs (Ref. 8).

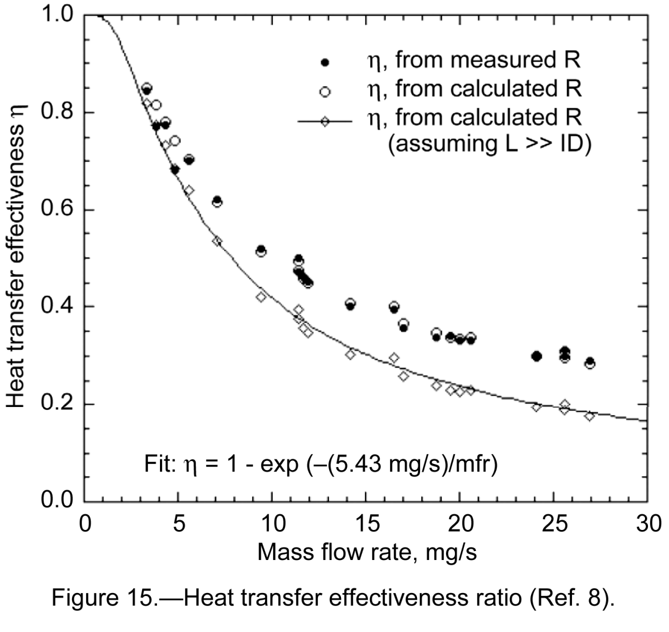


Figure 15.—Heat transfer effectiveness ratio (Ref. 8).

Analytical Modeling

The objectives of the Cryogenic Fluid Management analytical modeling efforts in the storage area are split into two categories based on the intended application

(1) Develop CFD models capable of simulating the thermodynamic and fluid dynamic behavior of cryogenic tankage with high fidelity, particularly for on-orbit and lunar environments where no long duration data is available.

(2) Develop engineering system analysis tools for engineering trades, system performance simulation, and design predictions.

CFD Modeling

A key issue for developing any analytical modeling capability is the need to validate the model with flight and/or test data. NASA's Glenn Research Center conducted liquid hydrogen self-pressurization tests in a 4.955 cm^3 liquid hydrogen flightweight tank under normal gravity conditions in the 1990s (Refs. 11 to 13). This experimental data was used to validate a two-phase lumped-vapor CFD model (Ref. 14).

Figure 16 provides CFD model results for self pressurization of the hydrogen tank at various elapsed times. Temperature isocountours are shown on the left side of the line of symmetry in the liquid, with stream function isocontours on the right side. These plots illustrate the thermal stratification that occurs in a quiescent tank, along with the natural convection flows that are induced, in a normal gravity environment.

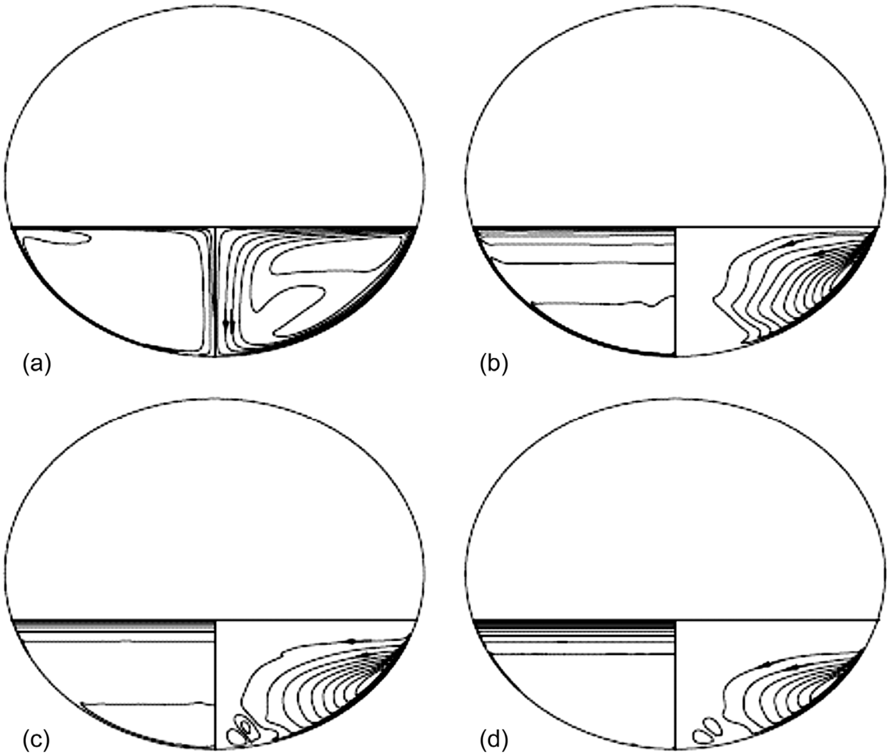


Figure 16.—Temperature and stream function isocontours during self-pressurization (Ref. 14). (a) 0 hr. (b) 1 hr. (c) 6 hr. (d) 12 hr.

Figure 17 provides comparisons of the CFD model results to the experimental data. In general, the model showed good agreement with the test data. The divergence of the results for the higher fill levels is presumed to be due to nonuniform heat flux conditions for the test configuration (Ref. 14).

With some validation of the modeling approach completed, a two-phase lumped-vapor CFD model was developed to account for noncondensable gas (e.g., helium) in the ullage. This modeling approach was applied to a representative Altair ascent stage composed of liquid oxygen and liquid methane propellants, and subjected to a lunar surface thermal environment simulating a 210 day storage period (Ref. 15).

Figure 18 shows the CFD model results of the temperature and flow fields for the liquid methane tank after two days simulated duration on the lunar surface. The reduced gravity at the lunar surface is sufficient to produce thermal stratification and natural convection flows; in this case 98.22 to 98.52 K, and 1.13 mm/s maximum velocity, after two days.

Once a stationary state was achieved within the liquid phase of the model, a reduced multizone model (ullage, liquid, and interface zones) was used to extrapolate the solution for extended periods. Figure 19 shows the methane tank pressure and temperature response over a simulated 210 day lunar surface storage period. Initial tank pressures at launch of 100 and 200 psia are plotted separately. Results for the oxygen tank are similarly presented in Reference 15.

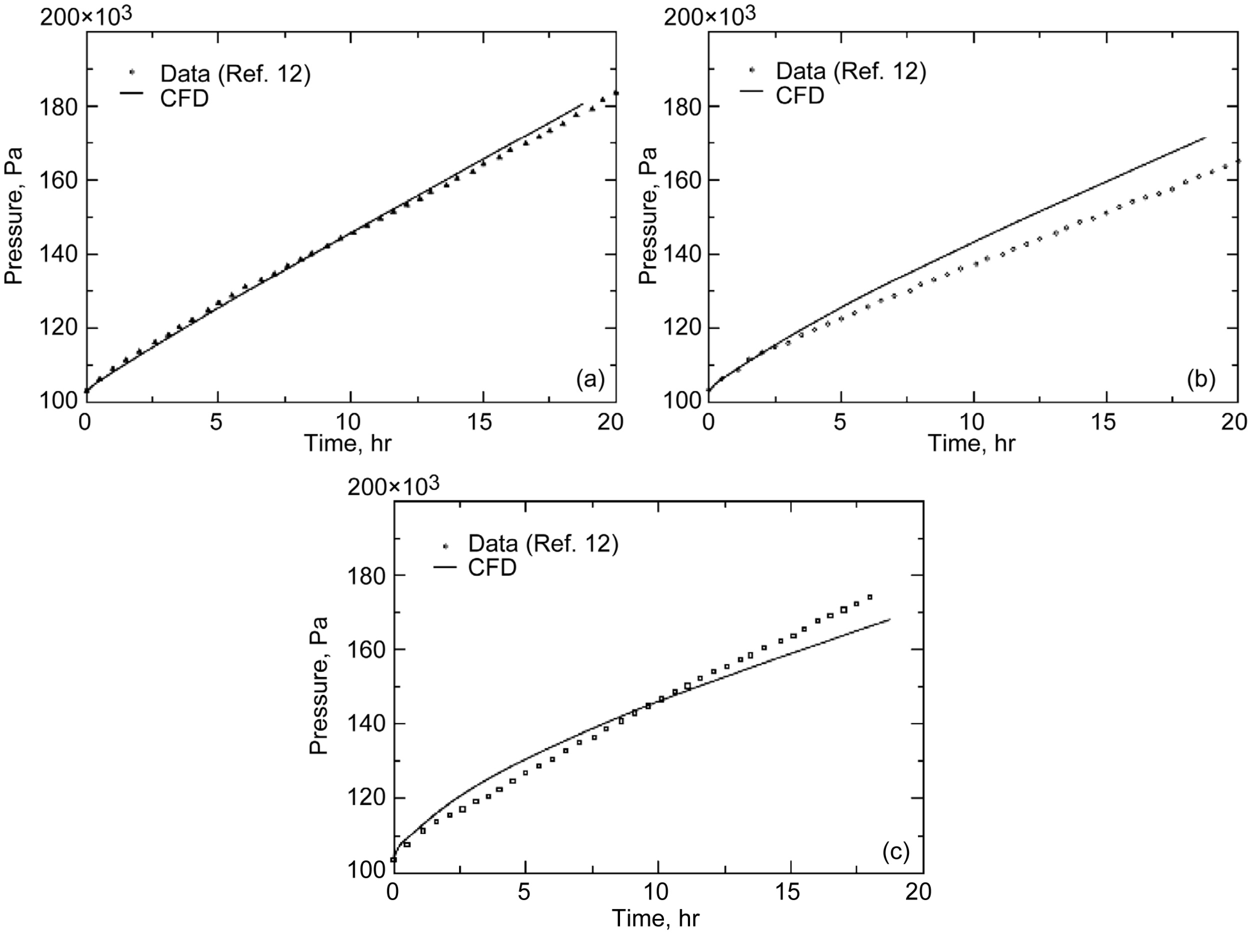


Figure 17.—CFD model versus experimental data (Ref. 14). (a) 29 percent fill. (b) 49 percent fill. (c) 83 percent fill.

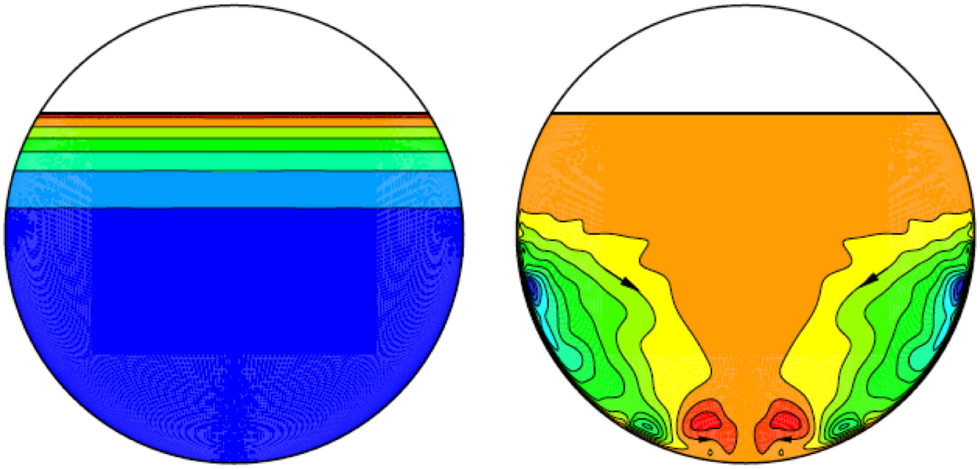


Figure 18.—CFD model temperature (left) and flow (right) fields for methane tank after 2 days on lunar surface (Ref. 15).

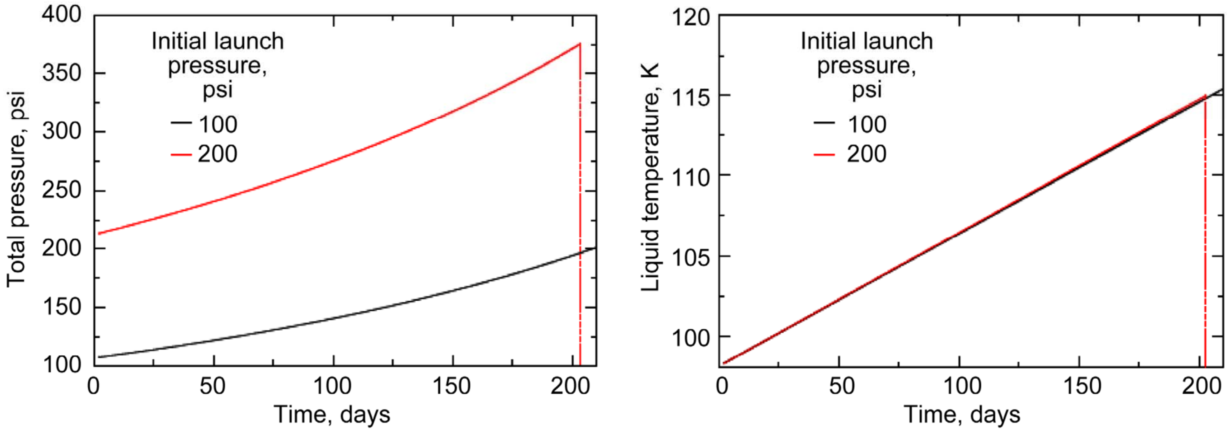


Figure 19.—Methane tank simulated lunar surface temperature and pressure response (Ref. 15).

This CFD modeling approach provides a valuable tool for simulating detailed thermodynamic response of cryogenic tanks on the lunar surface. Ongoing work is addressing other relevant environments and operational conditions to expand the CFD modeling capability for cryogenic tanks.

Engineering System Analysis

In addition to CFD models, system level analytical tools are needed for engineering trades and system design support. There are numerous existing cryogenic system analytical tools of varying complexity, approach, assumptions, and documentation. The verification and validation of these tools also ranges widely. An effort has been undertaken to standardize a portfolio of these analytical tools and make them available as a library of FORTRAN algorithms that can be incorporated into a variety of custom models (e.g., finite difference commercial codes, spreadsheet system models and macros, etc.).

The building blocks of this portfolio of cryogenic system tools includes previously developed legacy codes for passive and active storage calculations (Refs. 16 to 18). In general, these codes employ first principle derivations, engineering correlations, and empirically based relations to predict a range of parameters relevant to cryogenic systems.

Figure 20 shows an example plot from the Passive Cryogenic Storage Analyzer (PCSA) code that provides mass trade study results for a tank wrapped with variable density MLI as a function of the number of layers (Ref. 16). As MLI layers are added, the boiloff mass is reduced due to lower

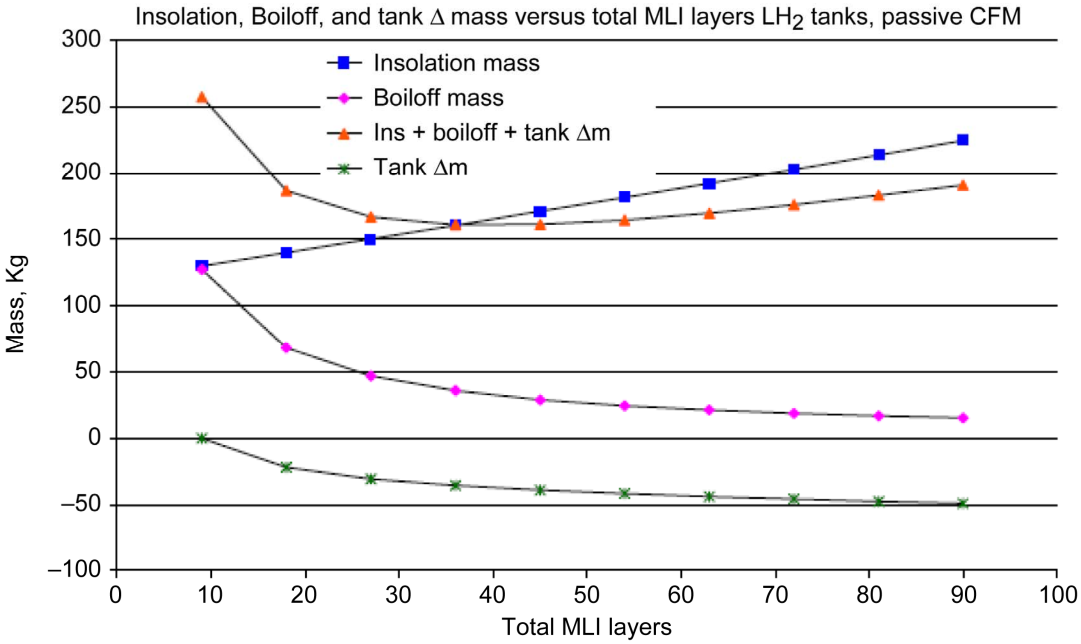
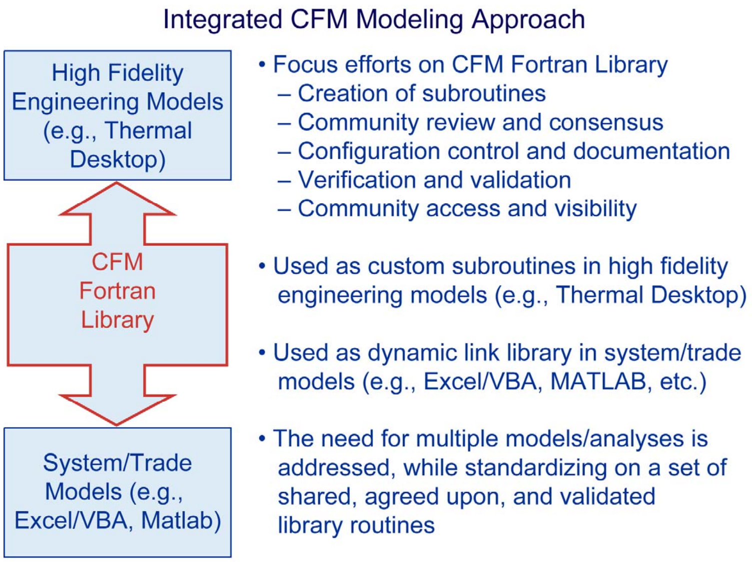


Figure 20.—Example mass trade results for tank with variable density MLI (Ref. 16).



- Focus efforts on CFM Fortran Library
  - Creation of subroutines
  - Community review and consensus
  - Configuration control and documentation
  - Verification and validation
  - Community access and visibility
- Used as custom subroutines in high fidelity engineering models (e.g., Thermal Desktop)
- Used as dynamic link library in system/trade models (e.g., Excel/VBA, MATLAB, etc.)
- The need for multiple models/analyses is addressed, while standardizing on a set of shared, agreed upon, and validated library routines

Figure 21.—CFM FORTRAN library strategy.

environmental heat leak. Likewise, the tank mass is reduced since less tank volume is required to provide the same amount of propellant due to lower boiloff losses. However, the tradeoff occurs due to the increasing MLI mass as more layers are added. It can be seen that the total tankage system weight (denoted as “Ins+Boiloff+Tank Δm” in Figure 20 with the triangle plot symbols) reaches a minimum at approximately 40 to 50 layers of MLI.

Figure 21 summarizes the basic strategy being implemented (Ref. 19). Initially, integration of these analytical tools into vehicle-level SINDA[3] thermal models has been undertaken to support Constellation

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[3] Systems Improved Numerical Differencing Analyzer

Program needs. Expanded capabilities are planned to address launch hold and ascent heating, TVS performance, multilayer insulation optimization, passive vapor cooling, and other key cryogenic system parameters.

Summary and Conclusions

The CFM project has completed several key technology development milestones in the storage area.

1. TVS have been demonstrated in ground tests for hydrogen, methane, and oxygen. In all tests, the total tank pressure was controlled by the TVS for ullages containing both pure vapor, and a mixture of vapor and noncondensable gas. From a control standpoint, the liquid temperatures were found to be a key parameter to monitor in addition to the tank pressure. Automated TVS control by monitoring both tank pressure and liquid temperature was recently demonstrated during the liquid oxygen TVS testing.
2. The Joule-Thomson device clogging observed under some conditions with hydrogen is being addressed in current testing. These tests will indicate which techniques, or set of techniques, are most likely to address the clogging issue in hydrogen. Regarding other cryogenic propellants, testing has ruled out clogging as an issue for oxygen and methane at low pressures. Testing of methane at high pressures is planned to insure no issue exists under these conditions as well.
3. The analytical models formulated for active distributed cooling concepts have been confirmed with the completion of a tube-to-tank test series. The thermal and mechanical feasibility of bonding a cooling tube to an aluminum plate subjected to cryogenic cooldown was also demonstrated. Thermal resistance between the cooling gas stream and aluminum plate were determined, along with the heat transfer effectiveness ratio. The test results showed good overall agreement with analytically calculated values. Testing of a tube-to-shield concept is planned next.
4. Advances have been made in the development of CFD and system analytical modeling tools for cryogenic storage systems. A two-phase lumped-parameter CFD modeling method has been validated against liquid hydrogen self pressurization data taken in ground tests with a flightweight tank. This same modeling approach has been applied to Altair representative methane and oxygen tanks to predict thermodynamic and fluid dynamic behavior during a 210 day lunar surface storage scenario. Likewise, a suite of cryogenic system analytical tools are being developed in the form of a FORTRAN library of algorithms, that have already been implemented in vehicle SINDA analysis models. An expanded set of algorithms is planned to address key cryogenic parameters relevant to the Constellation Program.

Appendix—Future Work

In the Fall of 2007, a CFM Propulsion Workshop was held to identify cryogenic system technology risks associated with the Altair Lunar Lander and the Ares V Earth Departure Stage. Following the identification of these risks, mitigation strategies were developed, and prioritized ranking of the risks was made. Current CFM Storage tasks are addressing many of these risks, and future work is planned to address the remaining risks either directly or in coordination with other efforts. The top eight risk areas identified in the CFM Storage area were

(1) Cryogenic subcooling of propellants (loading and maintenance)
(2) Cryogenic system engineering modeling (appropriate analytical tools)
(3) Heat leak uncertainty (performance prediction and installation of insulation systems)
(4) Cryogenic system advanced materials and structures (COPV, MMOD, etc.)
(5) Uncertainty in initial conditions for analytical model validation
(6) Thermodynamic vent systems
(7) Degraded insulation performance during ground hold and ascent
(8) Large scale insulation systems

In the next year, CFM Storage testing will be focused on a methane lunar storage demonstration to support the Altair decision gate for selecting hypergolics or cryogenic propellants for the Ascent Stage. These tests will demonstrate operation of a TVS in a multilayer insulated tank designed to simulate the thermal and geometric parameters of the flight tanks. A new methane conditioning system will have the capability to supply thermodynamic propellant conditions consistent with any statepoint anticipated throughout a 210 day lunar surface storage duration. A cryoshroud will provide the appropriate thermal boundary to simulate lunar surface conditions.

Figure 22 shows the external and internal features of the methane tank preliminary design (Ref. 20). External protuberances have been minimized to facilitate installation of the multilayer insulation. The top and bottom access hatches are designed to be interchangeable to provide assembly flexibility.

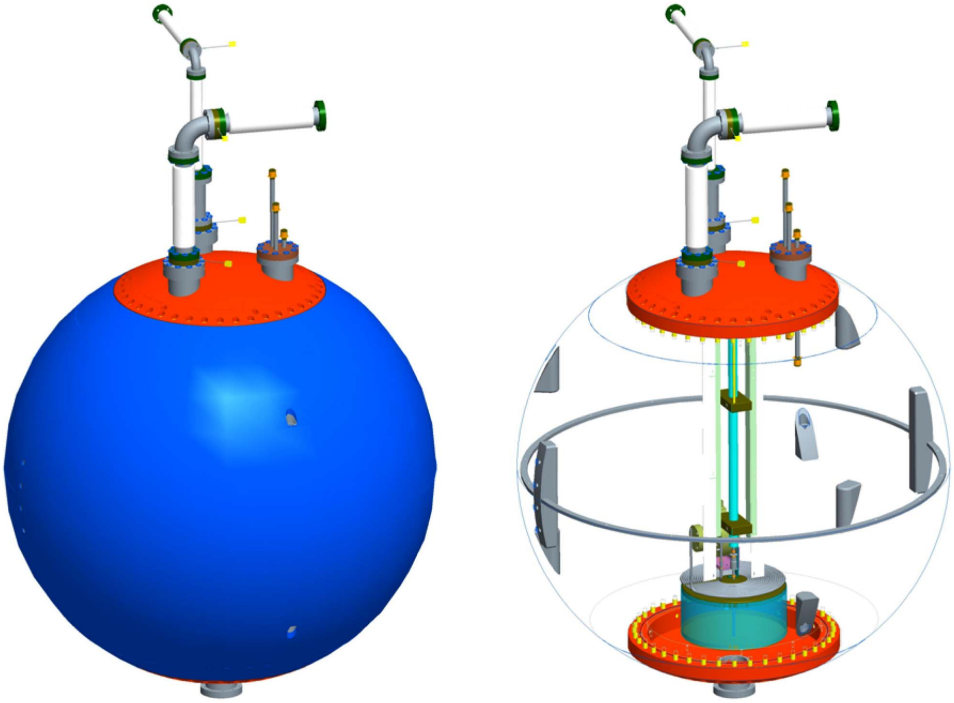

Figure 22.—Methane tank preliminary design (internal and external features) (Ref. 20).

Analytical modeling work will continue to expand the capabilities to support key spacecraft cryogenic system designs and simulate mission operational concepts. Emphasis will remain on verification and validation of the tools against test data. Testing efforts beyond next year will begin to address ascent heating and venting as well as insulation systems (including integrated MMOD shielding) for large tanks.

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

Recent technology development work conducted at NASA in the area of Cryogenic Fluid Management (CFM) storage is highlighted, including summary results, key impacts, and ongoing efforts. Thermodynamic vent system (TVS) ground test results are shown for hydrogen, methane, and oxygen. Joule-Thomson (J-T) device tests related to clogging in hydrogen are summarized, along with the absence of clogging in oxygen and methane tests. Confirmation of analytical relations and bonding techniques for broad area cooling (BAC) concepts based on tube-to-tank tests are presented. Results of two-phase lumped-parameter computational fluid dynamic (CFD) models are highlighted, including validation of the model with hydrogen self pressurization test data. These models were used to simulate Altair representative methane and oxygen tanks subjected to 210 days of lunar surface storage. Engineering analysis tools being developed to support system level trades and vehicle propulsion system designs are also cited. Finally, prioritized technology development risks identified for Constellation cryogenic propulsion systems are presented, and future efforts to address those risks are discussed.

15. SUBJECT TERMS
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