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Solar Thermal Upper Stage Liquid Hydrogen Pressure Control Testing and Analytical Modeling

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An ‘acknowledgment above all others’ is offered to the family of Doug Richards in memory of his technical excellence and dedication to this program, to honor who he was as a person.

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LIST OF ACRONYMS AND SYMBOLS

AITP	aerospace-industry technology project
ATVS	active thermodynamic vent system
CFD	computational fluid dynamics
CFM	cryogenic fluid management
GH_2	gaseous hydrogen
GHe	gaseous helium
GN_2	gaseous nitrogen
H_2	hydrogen
LAD	liquid acquisition device
LH_2	liquid hydrogen
LHSFS	liquid hydrogen space flight systems
LN_2	liquid nitrogen
MLI	multilayer insulation
MSFC	Marshall Space Flight Center
PLC	programmable logic controller
PTVS	passive thermodynamic vent system
RNG	renormalization group
ROV	remote-operated valve
STUSTD	Solar Thermal Upper Stage Technology Demonstrator (program)
TRS	Test Request Sheet
TS	test stand
TVS	thermodynamic vent system
VFD	variable-frequency drive
VJ	vacuum-jacketed

NOMENCLATURE

C_v	valve flow coefficient (dimensionless)
dp	delta pressure (kPa)
dt	delta time (s)
T_c	innermost MLI temperature (coldest layer)
T_h	external MLI temperature (warmest layer)
α	ratio of tank self-pressurization rise rate of interest (measured or calculated) divided by self-pressurization rate for perfectly mixed or homogeneous tank contents (dimensionless)

TECHNICAL PUBLICATION

SOLAR THERMAL UPPER STAGE LIQUID HYDROGEN PRESSURE CONTROL TESTING AND ANALYTICAL MODELING

1. INTRODUCTION

High-energy cryogenic propellant is an essential element in future manned space exploration programs, particularly those leading to manned missions to Mars. Therefore, NASA and its industrial partners are committed to an advanced development/technology program that will broaden the experience base for the entire cryogenic fluid management (CFM) community. The high cost of microgravity experiments has motivated the Marshall Space Flight Center (MSFC)/Boeing team to aggressively explore combinations of ground testing and analytical modeling to the greatest extent possible. An aerospace-industry technology project (AITP), designed to demonstrate technology readiness for a representative solar orbital transfer vehicle (SOTV) concept (fig. 1), was cooperatively performed by a Boeing-led team with representatives from industry, academia, and government.[1] A key element of the Solar Thermal Upper Stage Technology Demonstrator (STUSTD) program was the development of a liquid hydrogen (LH_2) storage and supply system that used all of the vented hydrogen (H_2) for solar engine thrusting, thereby avoiding boiloff losses. The strategy was to balance the LH_2 storage tank pressure control requirements with the engine thrusting timeline during a 30-day solar thermal propulsion mission. The concept for achieving this strategy was to employ an arrangement of thermodynamic venting combined with a capillary screen channel liquid acquisition system, multilayer insulation (MLI), and internal tank heaters to reliably provide H_2, at a controlled rate, to a solar thermal engine in the low-gravity environment of space operation. The STUSTD test data evaluation was initially performed with standard analytical modeling tools and later with advanced computational fluid dynamics (CFD) modeling. The test hardware, test results, and analytical correlations using both the standard and CFD modeling techniques are discussed herein. The analytical modeling correlations are considered a significant element in support of future space exploration efforts. As a matter of convenience, the program and engineering checkout test results are summarized in two previous papers; the documentation presented herein is much more complete and up to date.[2,3]

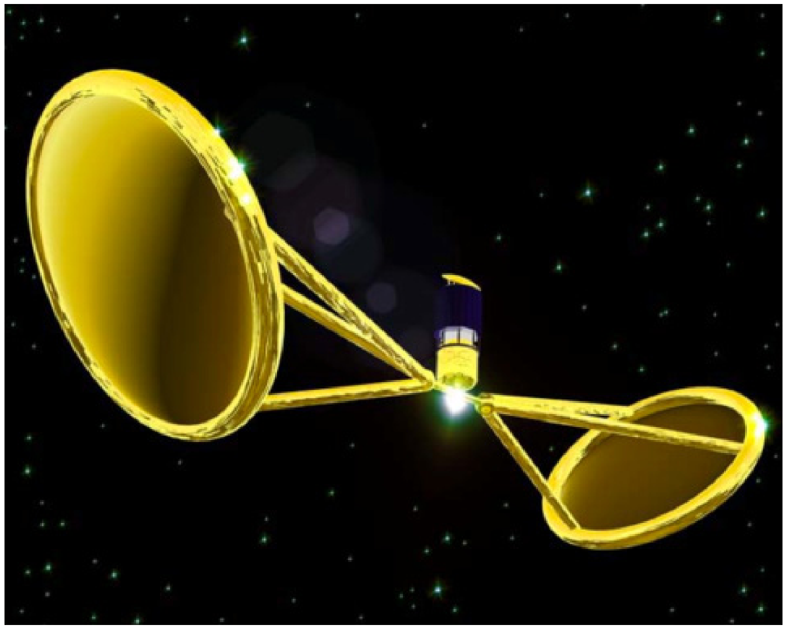


Figure 1. Solar thermal orbital transfer vehicle concept.

2. PROJECT OBJECTIVES AND TEST ARTICLE DESCRIPTION

2.1 Objectives

The test project objectives were to demonstrate the reliable and efficient storage of cryogenic hydrogen both during launch (transport and low Earth orbit) and the low-to-geostationary Earth orbit transfer mission simulation during which the solar engine operates. Specific test objectives were as follows:

(1) Demonstrate MLI purge evacuation and performance.

(2) Deliver near-saturated H_2 vapor at 158–241 kPa (23–35 psia) at 0.91 kg/hr (2 lbm/hr) for 140 cycles over 30 days.

(3) Demonstrate venting/lockup for 140 burns over 30 days (without additional overboard venting required).

(4) Demonstrate use of MLI and heaters to assist control of tank pressure at 310 ± 27.6 Kpa (45 ± 4 psia) while operating.

(5) Demonstrate subcooled liquid acquisition device (LAD)/thermodynamic vent system (TVS) operation in 1 *g* via determination of internal LH_2 tank temperature profile.

(6) Demonstrate LH_2 loading/unloading and LAD filling for ground operations.

The test article and its integration into facilities at the MSFC Test Stand 300 (TS300) vacuum chamber are described in the following sections.

2.2 Test Article and Fluid Systems Integration

An overview of the STUSTD test article configuration and a top view picture of tank internal components are presented in figures 2 and 3, respectively. A picture of the test article installation in the 6.1-m- (20-ft-) diameter vacuum chamber at MSFC TS300 is shown in figure 4.

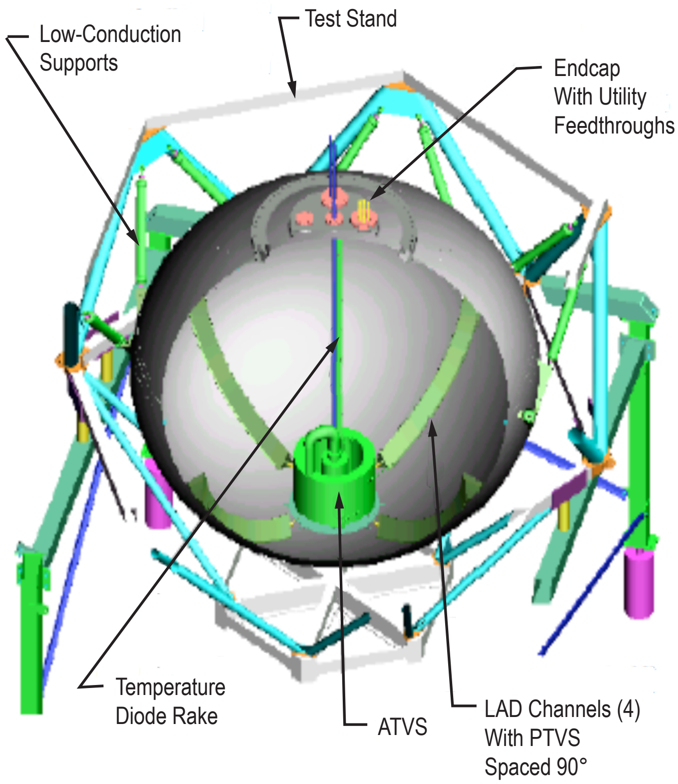


Figure 2. STUSTD test article configuration.

Figure 3. Top view of STUSTD tank internal components on tank bottom.

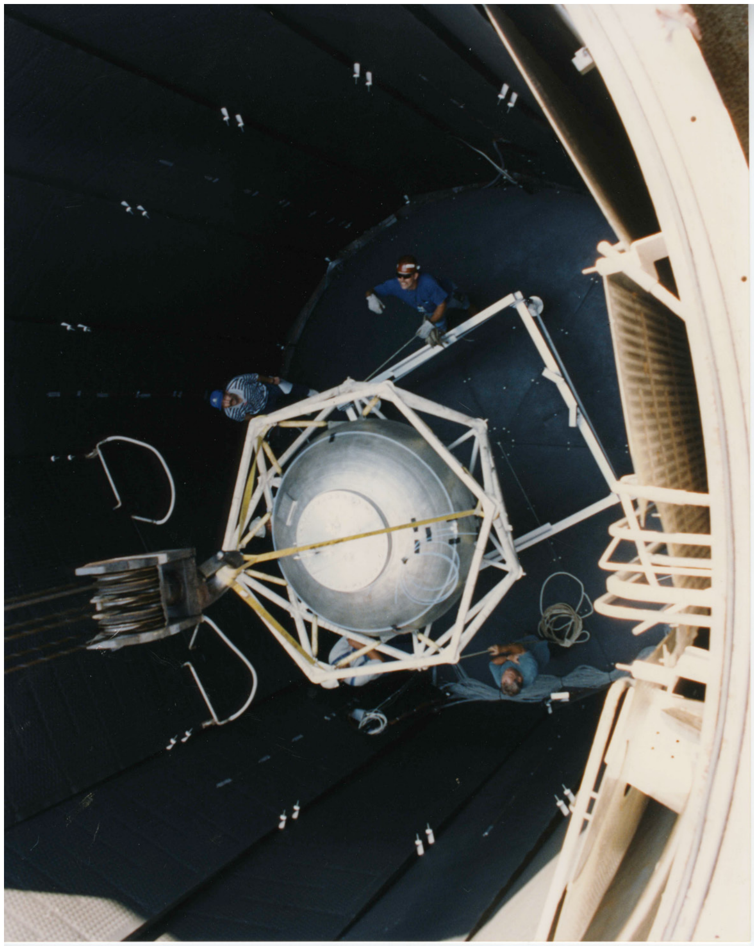


Figure 4. Test article installation in vacuum chamber.

Figure 5 presents a schematic of the instrumented test article interfaces with the corresponding fluid and vacuum chamber facility elements at TS300. The NASA titanium tank has a volume of 2 m^3 (71 ft^3) with 0.707 elliptical heads, a height of 124 cm (49 in), a width of 176 cm (69.3 in), and a LH_2 capacity of 129 kg (284.1 lbm) with a 98% fill level. Twenty silicon diodes were placed in a vertical array to map the bulk fluid and ullage temperatures, with an additional two diodes on one LAD and five diodes placed throughout the MLI. Outflow and ullage pressures were measured along with volumetric flowmeter data. A total of 168 data channels were recorded at selectable data rates of 1, 0.1, and 0.0167 Hz. Further details on both the test article and facility instrumentation are listed in appendix A.

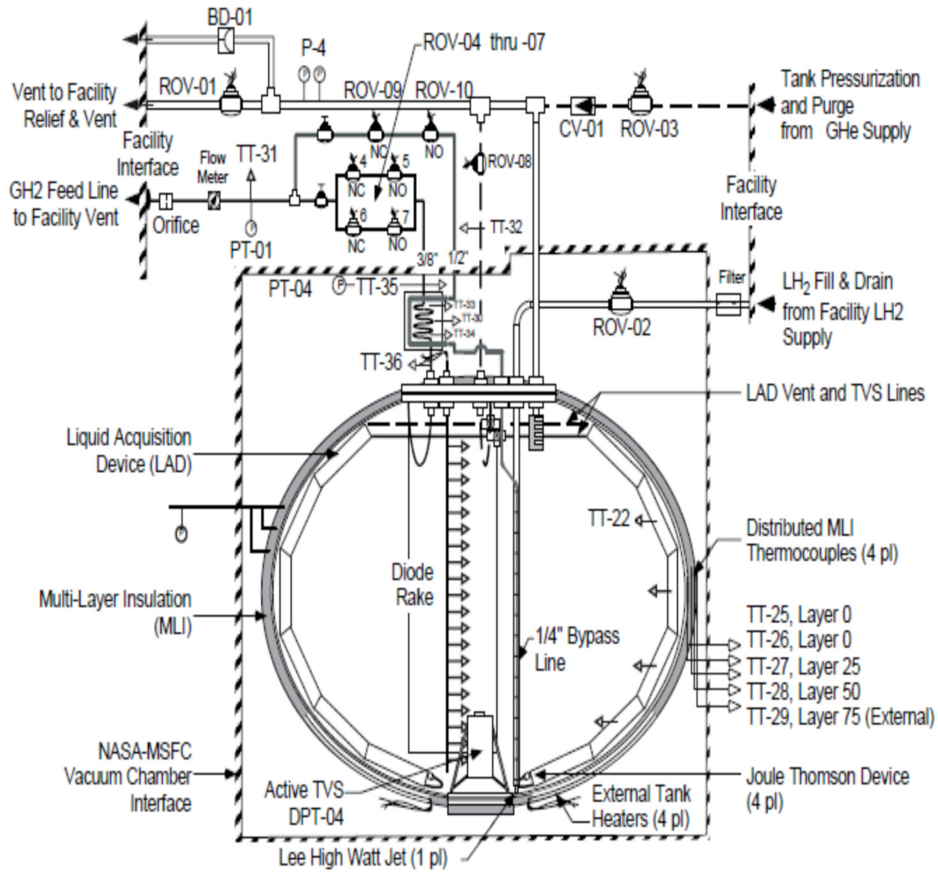


Figure 5. Test article instrumentation and integration with facility fluid systems: TS300 vacuum chamber.

The MLI was double-aluminized Kapton® (DuPont) with alternating layers of Dacron® (DuPont) mesh (B4A). Because of problems during the fabrication of the MLI, the north and south poles had 100-layer pairs and the remaining tank surfaces had 75-layer pairs of MLI. Test article pictures before and during MLI installation are presented in figures 6 and 7, respectively. Further details regarding the MLI design, installation, and analytical modeling are presented in section 4.1.1.

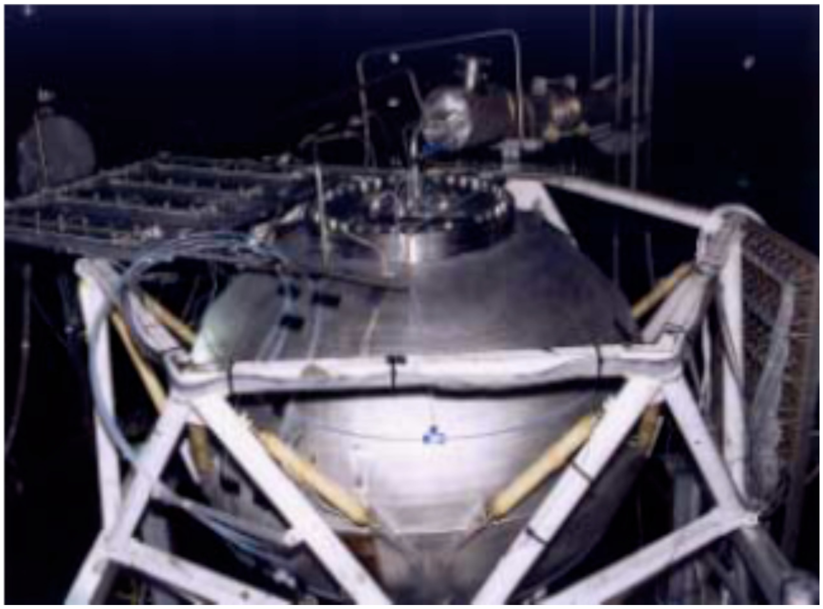


Figure 6. Test article before MLI installation.

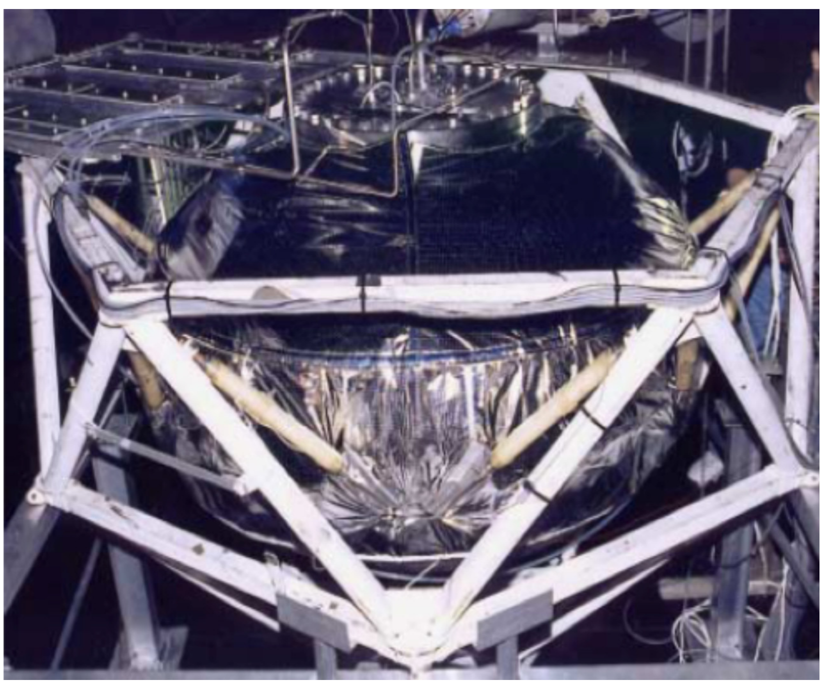


Figure 7. Test article during MLI installation.

2.3 Test Article/Facility Integration and Implementation

The MSFC test crew and their areas of responsibility at TS300 are listed in appendix B. The integrated hardware utilization and operations approach used by the MSFC/Boeing team are listed and defined in this section, beginning with vacuum chamber operations (fig. 8).

Figure 8. TS300 vacuum chamber.

2.3.1 Ascent to Vacuum

The shuttle ascent pressure profile was simulated as follows. The single stage gaseous nitrogen (GN_2) ejector evacuated the chamber per the required profile to a chamber pressure of 40 torr, whereupon the chamber's roughing pumps were engaged and evacuated to <0.1 torr (≈1 hr). Then diffusion pumps reduced the chamber pressure to 10×10^{-5} torr or less within about an hour. The vacuum system was arranged to go into a lockup condition in the event of a power failure. The vacuum facility instrumentation, listed in appendix B, included the following:

(1) Thermal: Thermocouples were attached to the cold walls and used to map the vacuum chamber's thermal environment. The test engineer and test requestor determined the distribution of ≈25 thermocouples based on previous test data. The LN_2 cold wall system enters a vent condition upon power failure.

(2) Dewpoint: A dewpoint meter monitored the chamber gas dewpoint.

(3) Vacuum level: Eight instruments assured coverage from 760 to 10^{-8} torr.

2.3.2 Facility Liquid Hydrogen Fill and Drain

As shown in figure 9, the LH_2 was supplied by trailer and transferred to the test article tank via existing vacuum-jacketed (VJ) facility piping. The supply line to the vacuum chamber wall was 3.8-cm-diameter (1.5-in-diameter) tubing, approximately 18.3 m (60 ft) long. The flow was controlled by a throttle valve, overpressure prevented by a relief valve set at 480.6 kPa (69.7 psia), and supply temperature provided by a thermocouple located in the flow path near the vacuum chamber wall. Test article draining was accommodated through a portion of the fill piping, then out to an existing burn stack.

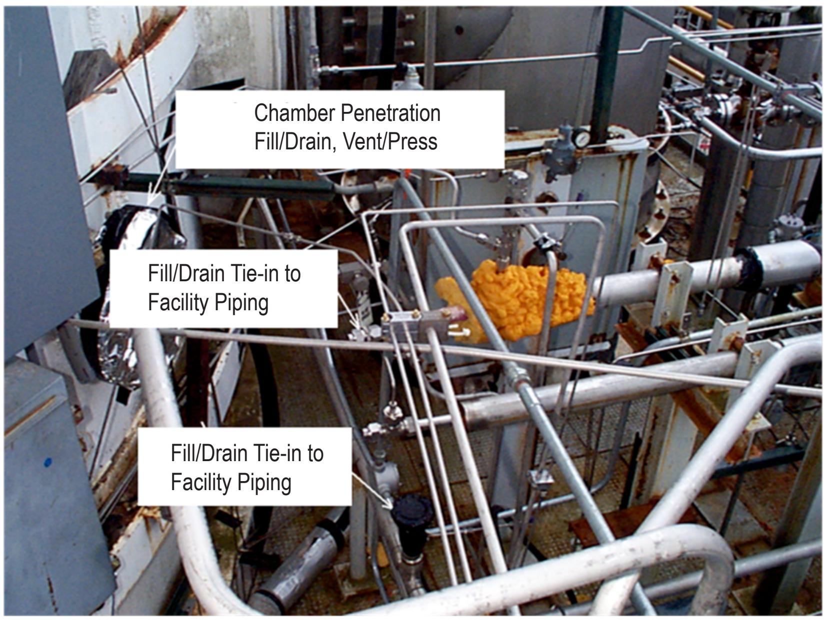


Figure 9. Facility LH_2 fill and drain.

2.3.3 Test Article Piping System

Vacuum-jacketed piping connected the existing facility piping with the test article via facility piping that penetrated the vacuum chamber wall. The inner fill line was wrapped in MLI, and the vacuum jacket was connected to a vacuum pump and evacuated to <1 torr before LH_2 transfer. Foam insulation was applied to the tubing outside the chamber (between the test article and facility VJ piping). The test article VJ piping did not extend completely to the test article tank flange. Therefore, there was approximately 0.61 m (2 ft) of bare tubing that required gaseous helium- (GHe-) purged MLI. The 1.6-cm (5/8-in) electrically actuated fill/drain valve (supplied by Boeing) resided inside the VJ pipe, accessible through a 15.2-cm (6-in) conflat-style port. The outside of the vacuum jacket had a bellows, and the internal lines had either a flex hose or expansion/contraction loops to account for thermal contraction. Outside the vacuum chamber, the vacuum jacket had a vacuum relief valve set at 115.1 kPa (16.7 psig).

2.3.4 Facility Liquid Hydrogen Vent Tie-In to Back-Pressure Control

As shown in figure 10, existing facility piping was used which consisted of 5-cm (2-in) tubing that tied off to a high-flow, chill-down leg and to the back-pressure control, flow measurement leg. The back-pressure control subsystem was used to maintain the tank ullage pressure at the required steady state conditions during the boiloff or heat leak measurement phase of testing. The system was composed of four flow control valves with flow coefficients (C_vs) ranging from 25 to 0.01 that were located in the vent line. Each control valve was regulated through a closed-loop control system. This control loop manipulated the valve positions based on a comparison of the measured tank ullage pressure with the desired set point. An MKS Instruments, Inc., Baratron 0–133 kPa (0–19 psia) absolute pressure transducer (accuracy of ±0.02%) and an MKS delta pressure (*dp*) transducer (1 torr or 133 Pa head with an accuracy of ±0.04%) located outside the vacuum chamber were used to measure ullage pressure. The 1-torr differential transducer had a tank submersed in an ice bath (fig. 11) as a pressure reference source. This tank was charged to 0.5 torr below the desired test article tank ullage pressure before the test start. Downstream of the four control valves, the flow converged to supply five flowmeters, with flow ranges from zero to 4,250 l/m. These were connected in series with a selector valve between each. The arrangement enabled ullage pressure control to within ±0.00689 kPa (±0.001 psi).

Figure 10. Facility LH_2 vent tie-in to back-pressure control.

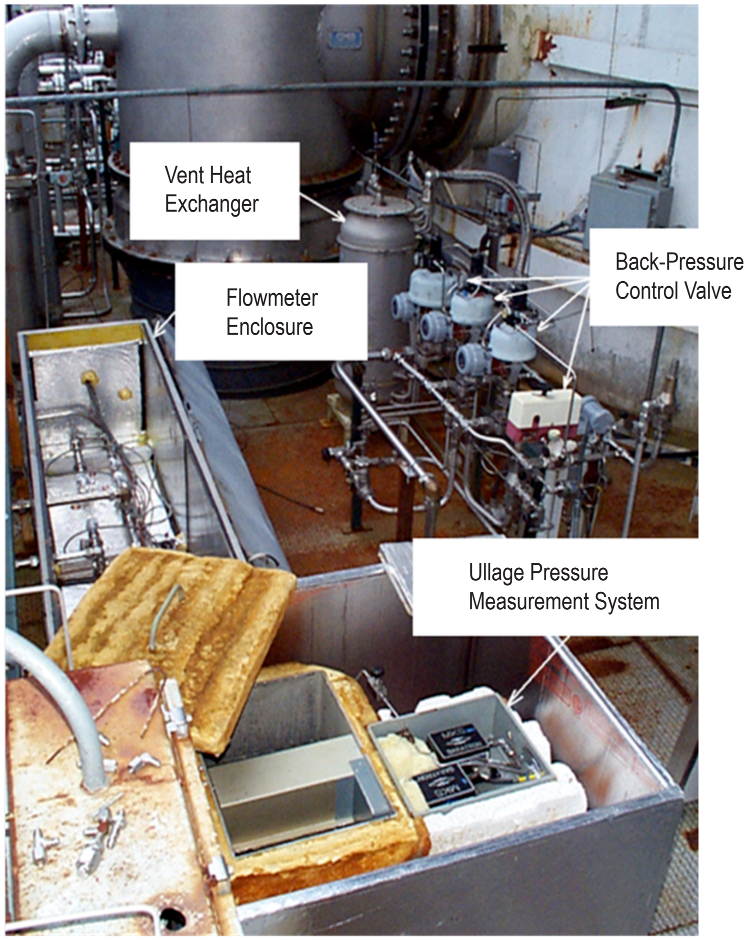


Figure 11. Facility ice bath for back-pressure control.

2.3.5 Test Article Piping

The test article piping resided inside the aforementioned VJ pipe and tied into the facility piping, just outside the vacuum chamber via a 11.4-cm- (4.5-in-) diameter conflat-style flange. It was 1.9 cm (0.75 in) in diameter at the test article tank and expanded to 2.54 cm (1 in) in diameter once inside the VJ pipe.

2.3.6 Overpressure Protection

The Boeing-supplied burst disk was connected to the vent piping, and a relief valve was installed in series with this burst disk for two reasons: (1) In the event the burst disk ruptured, the relief valve allowed self-pressurization for tank draining and (2) it better ensured that all boiloff gaseous hydrogen (GH_2) was measured by the flowmeters. All tank ullage and liquid isolations were double isolated with a leak-check port between the isolations. This allowed verification that no gas was leaking past the first isolation after tanking LH_2.

2.3.7 Test Article Pressurization

An existing pressurization system that used either a trailer or facility-supplied H_2 as its source was used. The pressure was regulated and flow controlled by a control valve. This gas tied into the vent piping, downstream of the back-pressure control valves.

2.3.8 Test Article Conditioning

Test article tank conditioning was accomplished as follows. A dry nitrogen purge (facility nitrogen) was connected to trickle through and maintain a dry test article as soon as it was installed in the chamber. Before tanking liquid nitrogen (LN_2) or LH_2, the vacuum chamber was evacuated to <1 torr. Then the test article tank and its associated piping were evacuated to <0.1 torr and back-filled with GN_2 (if tanking LN_2) or GH_2 or GHe (if tanking LH_2) to 138 kPa (20 ± 1 psia). This was repeated three times. After the last cycle, when the test article tank was again at 138 kPa (20 ± 1 psia), the vacuum chamber could be repressurized if required. Just before tanking, the tank and piping were subjected to five pressure/vent cycles, pressurizing to 204.8 kPa (29.7 psia) and venting to zero pressure using GN_2 (if tanking LN_2) or GH_2 (if tanking LH_2).

2.3.9 Simulated Engine Vent Heat Exchanger

The heat exchanger lines were leak tested with a mass spectrometer and 69 kPa (10 psig) GHe before being installed into the vacuum chamber. The fluid lines were all welded except for the two 0.32-cm (1/8-in) Swagelok® fittings for the thermocouples. The fluid lines were proof tested, mass spectrometer leak tested, and cold shocked per standard procedures.

2.3.10 Simulated Engine Valve Panel

The Boeing-supplied valve panel was located on the top level of the TS. The panel was delivered with an enclosure purged with GN_2. The line that connected this panel with the heat exchanger inside the vacuum chamber was required to be 1.27 cm (0.5 in) in diameter. Downstream of the valve panel was a water-jacketed heat exchanger designed to warm the vent gas to ground water temperature before reaching the simulated engine orifice.

2.3.11 Test Article Liquid Acquisition Device Vent Line

This line was routed inside the test article VJ pipe. Initially, it was a quarter-inch in diameter as it exited the test article tank and expanded to a half-inch in diameter before entering the VJ pipe. A cryogenic-rated bellows seal valve served as the isolation for this tube, instead of the supplied Marotta solenoid valve. This valve was normally closed with limit switches to indicate valve position.

2.3.12 Multilayer Insulation Purge

This system was supplied by the existing facility pressurization system. Up to 446.1 kPa (64.7 psia) GHe was delivered to a metering hand valve, flowmeter, pressure transducer, and vacuum-rated isolation hand valve. The requirement for this system was to supply GHe to create 102 kPa

(14.8 psia) of pressure under the MLI. If, during checkouts, the required flow deviated substantially from this, it was recognized that a modification of the system could be required. Installation of a relief device was not expected. Tubing with a 1.27-cm (0.5-in) diameter was used between the metering valve and test article tie-in. The pressure transducer was positioned on this tubing just outside the vacuum chamber.

2.3.13 Test Article Instrumentation

All test article instrumentation, except for PT4, was provided by Boeing and is listed in appendix A. The MSFC test support personnel mated the test article instrumentation cabling to the facility instrumentation junction boxes and verified operation of test article instrumentation. All test article instrumentation was National Institute of Standards Technology traceable and included the applicable calibration certifications. All test article instrumentation signals were recorded on MSFC's low-speed digital data acquisition system. Test Division supplied all instrumentation signal conditioners. Further details on both the test article and facility instrumentation are listed in appendix A.

2.3.14 Automated Controls

The control room for TS300, located in Building 4650 and shown in figure 12, supported two main operations.

Figure 12. Control room for TS300 vacuum chamber.

2.3.14.1 Valve, Heater, and Camera Power Control. Facility remote-operated valves (ROVs), test article ROVs, facility variable-position valves, test article feed line heat exchanger heaters, test article heaters, and the facility vacuum chamber video camera system were controlled by facility programmable logic controllers (PLCs). The 30-day mission simulation logic was programmed in the facility PLC using ladder logic software.

2.3.14.2 Active Thermodynamic Vent System Pump Variable-Frequency Drive Controller. Depending on the capability of the supplied active thermodynamic vent system (ATVS) pump variable-frequency drive (VFD), pump speed was to be set by sending a remote analog signal from a PLC or individual analog controller to the VFD. The VFD itself was mounted at the test stand. It should be noted, however, that the vendor-supplied controller failed to function with LH_2 and an MSFC-supplied controller was substituted. The pump vendor, lacking LH_2 test facilities, had checked out the pump system in LN_2. However, the controller start-up characteristics were altered considerably by the reduction in electrical resistance that occurred during operation at 20 K, compared with 77 K with nitrogen. The MSFC controller, qualified to operate at LH_2 temperatures, was substituted and the pump start-up was successful.

2.3.15 Special Test Equipment Fabrication and Integration

2.3.15.1 Test Article Vacuum Jacket Piping. The test article VJ piping was designed, fabricated, and installed by MSFC personnel. It was proof tested, mass spectrometer leak tested, and cold shocked per standard MSFC specifications. It consisted of the fill/drain, vent/pressurization, and LAD vent tubes residing inside a 15.2-cm (6-in) schedule-10 pipe jacket.

2.3.15.2 Simulated Engine Vent Water Heat Exchange. The simulated engine vent water heat exchanger consisted of 1-in-diameter stainless steel tube residing inside a 10.2-cm (4-in) PVC jacket. Water flowed through the jacket to warm the gas inside the tube. The length was approximately 2.4–3.05 m (8–10 ft).

For further details regarding the test article receipt and inspection, test article integration into the test facility, systems installation, checkout/verification, and test operations, refer to the Test Implementation Plan.[4]

3. ENGINEERING CHECKOUT TEST

3.1 Approach

The engineering tests consisted of four primary phases: (1) Tank LH_2 fill and stabilization, (2) boiloff measurement to determine the system heat leak, (3) measurement of the tank self-pressurization and heated pressurization rates, and (4) measurements of the passive and active TVS thermal extraction capabilities during several simulated 'burn' periods (outflow from the tank). Details regarding test conditions, control limits, instrumentation versus sampling rates/intervals, etc., are defined in the Test Request Sheet (TRS) shown in appendix C.

During the entire engineering test, the MSFC TS300 LN_2 cold walls were used to simulate the thermal environment of space. After filling the tank with 129 kg (284 lbm) LH_2, the tank pressure was held constant at 116 kPa (16.75 psia) in anticipation of a boiloff test. Once the engineering tests began, however, a leak was indicated by an increasing chamber pressure (fig. 13). A residual gas analyzer verified that H_2 was leaking into the vacuum chamber from the test article.

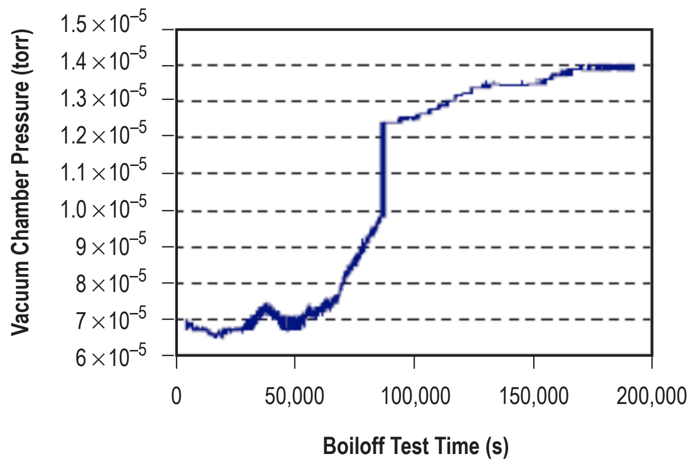


Figure 13. Vacuum chamber pressure during boiloff test.

Subsequently, the LH_2 tank was allowed to self-pressurize to an operating pressure of 311 kPa (45 psia) and the vacuum chamber pressure finally topped out at approximately 5.5×10^{-5} torr, compared with the initial value of 6.5×10^{-6} torr. Because the vacuum pressure appeared to be stabilized, a decision was made by Boeing and MSFC to continue the test with the higher chamber pressure and to account for the increased MLI heat leak in the analytical modeling.

3.2 Engineering Test Results

After the vacuum chamber and boiloff achieved a steady state (fig. 14), 10 hr of stable test data were obtained. The equilibrium boiloff vent rate was 10.8 l/min (660 in^3/min), which corresponded to a system heat leak of 6.7 W.

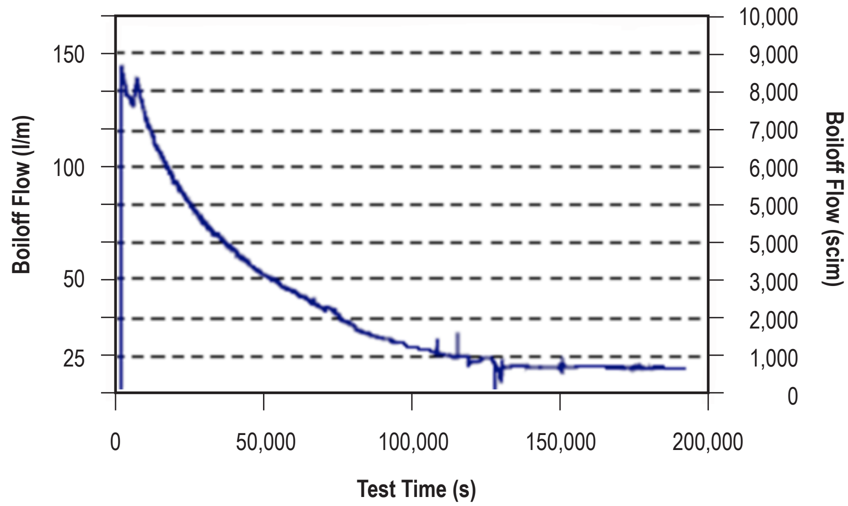


Figure 14. Tank vented flow rate during stabilization period.

The system heat leak increased to ≈18 W during the ATVS testing due to the mixer pump operation combined with the elevated vacuum chamber pressure. The tank was locked up unmixed with 108.9 kg (240 lbm) of LH_2 (LH_2 fill level of about 94 cm (37 in)) for ≈9 hr without tank heaters being used. The pump was turned on from 12.98 to 13.22 hr and, as expected, mixing the tank contents lowered the tank pressure. Destratification in the liquid and ullage is illustrated in figures 15 and 16, respectively.

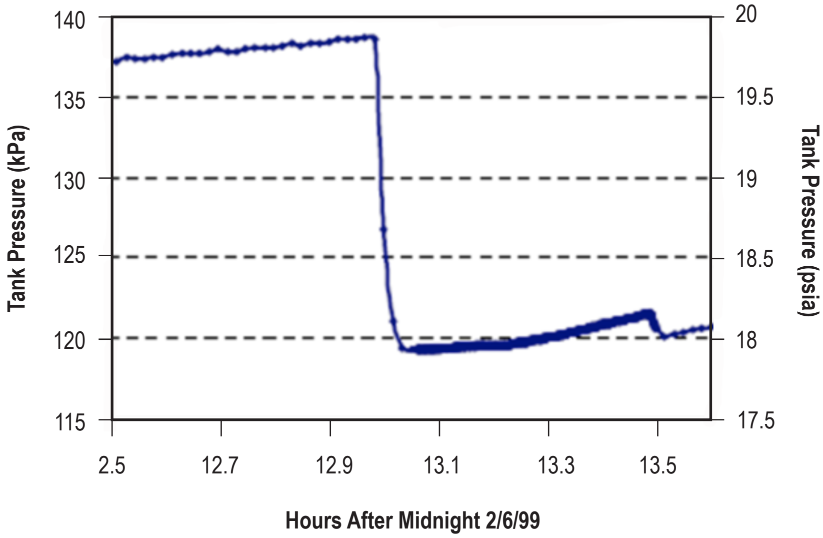


Figure 15. Example of LH_2 destratification effects on tank pressure.

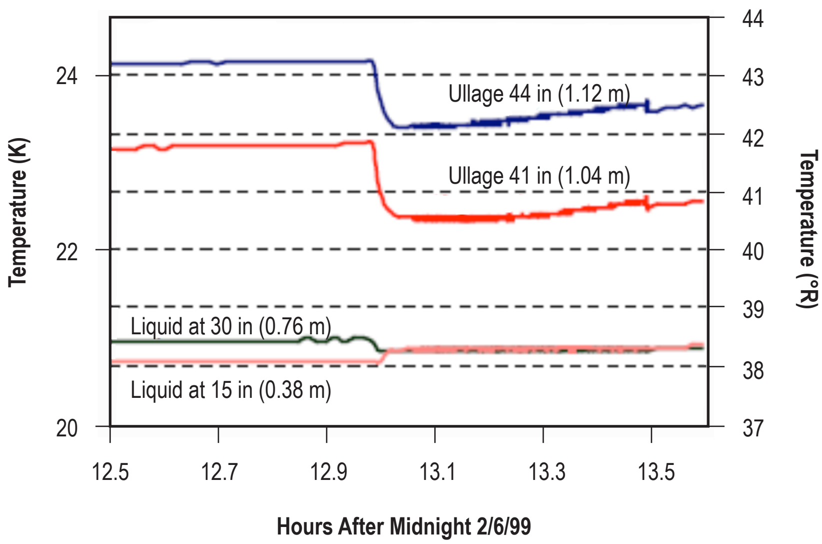


Figure 16. Example of ullage temperature destratification.

Once the full tank reached an operating pressure of 310 kPa (45 psia), the vent system flow tests began. The system was designed to operate at a mass flow rate of 0.9 Kg/hr (2 lbm/hr) with a pressure drop of 75.8 kPa (11 psi) (55.7 kPa (8 psi) from the Joule-Thomson devices, 13.8 kPa (2 psi) from the ATVS cold side line, and 6.9 kPa (1 psi) from the flow lines, heat exchanger plate, instrumentation, etc.). A mass flow rate of 1.18 kg/hr (2.6 lbm/hr) with a pressure drop of 10.35 kPa (1.5 psi) was measured. By reducing restrictions downstream of the valve panel, the system reached a mass flow rate of 2.3 kg/hr (5.1 lbm/hr) at a pressure drop of 69 kPa (10 psi). Because this mass flow rate was approximately twice the expected value for the same system pressure drop, it indicated an internal leak inside the tank into the flow path exiting the tank. A real-time pressure drop analysis indicated that the leak was on the downstream side of the ATVS, shown in figure 17, and was equivalent to an approximate 1-mm-diameter hole. Because the internal components depended on the appropriate pressure and temperature drop to extract energy from the tank contents and thereby control tank pressure, the test was continued with the internal leak and higher mass flow rate, because the expected pressure drop was now being measured. The ATVS and passive thermodynamic vent system (PTVS) required the 55.2 kPa (8 psi) pressure drop through the Joule-Thomson devices to control energy extraction and, therefore, tank pressure.

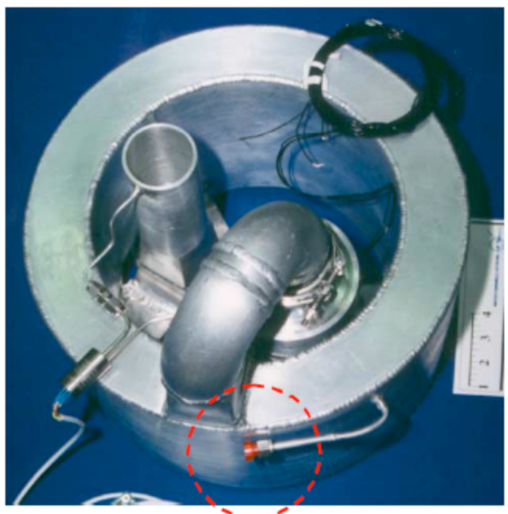


Figure 17. Active TVS.

During tank outflow, the bulk fluid exited the LAD channel, passed through the Joule-Thomson device (which expanded and cooled the flow), and then passed through the PTVS tube brazed into the LAD apex, shown in figure 18. The PTVS removed energy from the tank by condensation and convection. This was an important effect when the LAD surface was exposed. Figure 19 shows the effect of the PTVS on the tank ullage temperature with 12.7 cm (5 in) of LAD exposed. Figure 20 shows that the tank pressure reduction during the burn indicated a larger than expected energy extraction rate of 11.3 W (38.5 Btu/hr). Toward the end of the test, the tank bulk fluid level was reduced to 40.8 kg (90 lbm) or a fill level of 43.2 cm (17 in). Again, the outflow tests indicated a larger than expected PTVS energy extraction rate of 85.6 W (293 Btu/hr). The expected versus analytical energy extraction rates are discussed in section 4.

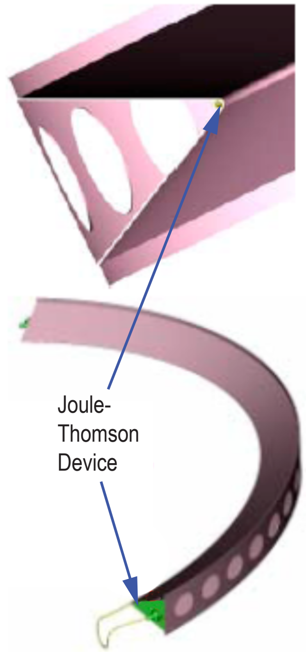


Figure 18. Passive TVS.

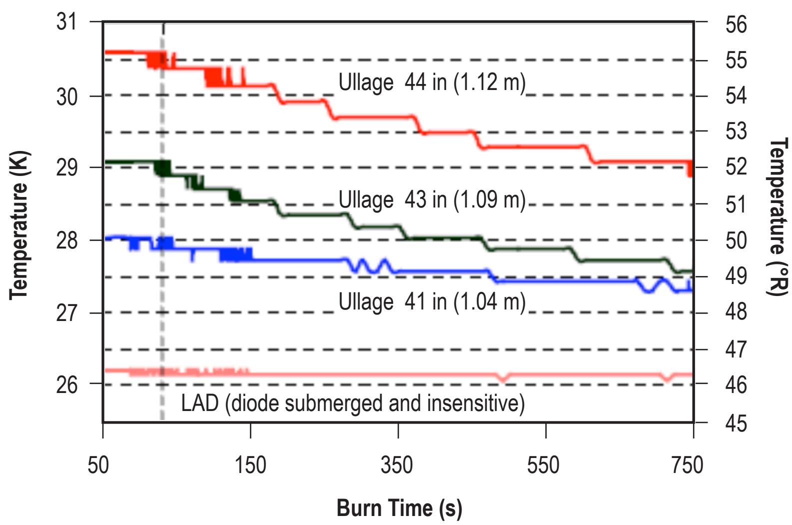


Figure 19. Successful extraction of tank heat by PTVS.

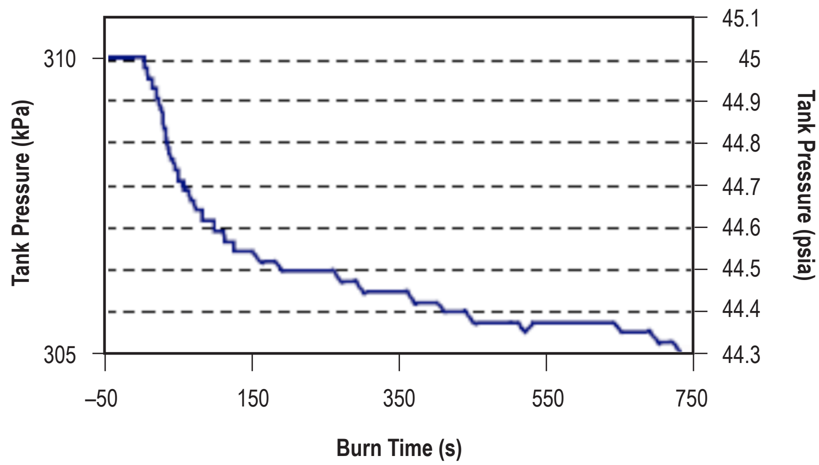


Figure 20. Tank pressure drop due to ullage condensation from PTVS.

4. ANALYTICAL CORRELATION OF ENGINEERING CHECKOUT TEST DATA

The STUSTD test data evaluation was first performed with standard analytical modeling tools and later with advanced CFD modeling. The advantages of standard analytical modeling techniques include: (1) a quick turnaround, (2) use on a wide variety of computers, and (3) have historically been the industry standard for day-to-day design studies and trades. CFD modeling techniques offer simulation of the actual physical phenomena and, therefore, can generally be applied to low-gravity conditions with more confidence than the standard modeling. It is firmly believed that with each CFD code improvement increment, the historic dependence of CFM development on costly on-orbit experimentation is being significantly reduced. Therefore, although CFD modeling is more costly than traditional modeling and requires more experienced personnel, the costs are miniscule compared with on-orbit testing. Hence, the general strategy is to anchor both traditional and CFD modeling techniques with available test data, but use the CFD to model selected conditions in reduced gravity. Then, the CFD modeling can be used to guide or anchor traditional modeling applications to reduced gravity. Application of both standard and CFD techniques to the evaluation of the subject data is presented in the following sections.

4.1 Standard Modeling

4.1.1 Multilayer Insulation Modeling and Test Correlation

The solar propulsion concept involves using the LH_2 tank as an accumulator, with the tank pressure dropping during venting (thrusting) and rising during lockup (coasting). Each pressure excursion depends on the vent rate, the insulation design, and the mission duty cycle. Example engine thrust durations and coast periods for the 30-day mission are presented in table 1. The burn durations ranged from 0.72 hr to 2.29 hr on day 1 and day 30, respectively. Corresponding coast periods between burns ranged from 0.89 hr to 20.26 hr. The long coast periods near the end of the mission require that a high-performance MLI system be used to limit the pressure rise in the tank. The MLI blanket arrangement and its integration with propulsion system mission requirements are summarized here with further details in appendix D.

Table 1. Burn and coast times during the 30-day mission.

Day No.	Burn No.	Burn Duration (hr)	Coast Duration (hr)	*dp*/*dt*, kPa/hr (psi/hr)
1	1	0.23	0.89	6.9 (1)
15	118	0.21	9.20	10 (1.45)
30	140	0.57	20.21	2 (0.29)

The MLI system was GHe purged, and the MLI perforated for evacuation efficiency during ascent. The MLI blankets were conformed around the tank penetrations and supports to restrict the heat leak. The MLI arrangement consisted of four blankets with 25 layers each at the poles, and three blankets with 25 layers each on the equator. Each blanket consisted of ¼-mil aluminized Mylar® with Dacron® (DuPont) net spacers. The final MLI installation, shown in figure 21, resulted in a calculated thermal performance of 6.6 W, as shown in table 2. Boiloff testing indicated an actual heat leak of 6.7 W, which was within 1.5% of the prediction.

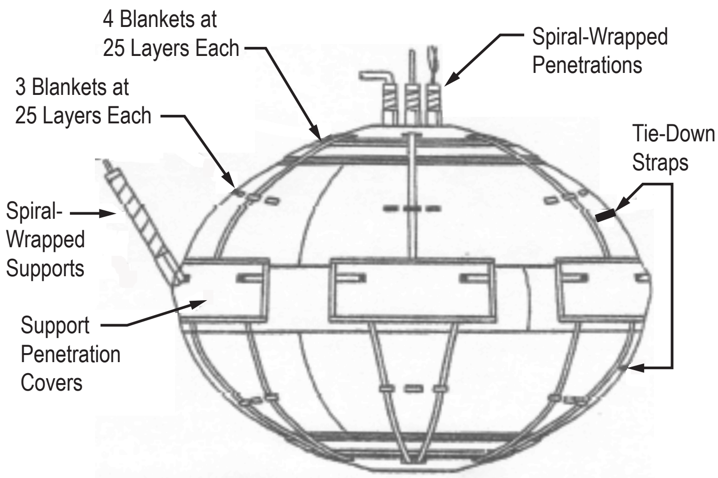


Figure 21. Final MLI installation.

Table 2. STUSTD tank thermal performance.

4 blankets; 25 layer-pairs each DAK/B4A; T_h=200 K, T_c=25 K			
Performance (W)			
	Budget	4 Blankets Calculated	3 + Blankets Calculated
MLI blankets MLI seams MLI supports MLI margin Tank supports	1.6 0.5 0,3 – 2.0	1.68 – – 0.82 2.00*	2.24 – – 0.82 2.00*
Plumbing	1.0	1.31	1.31
Instrumentation wires	0.6	0.06	0.06
Heat leak margin	–	0.23	0.17
Margin	6.0	6.00	6.60

*NASA Glenn Research Center Test Data

4.1.2 Tank Pressure Control

The tank self-pressurization rate modeled using the equation for homogeneous conditions from Lin et al.[5] and a total heat leak of 47.7 W are compared to the measured data "with the mixer on" in figure 22. Assuming that α represents the "subject pressure rise rate divided by the theoretical rate corresponding to homogeneous or fully mixed conditions." The predictions were based on $\alpha = 1$, whereas the actual $\alpha = 1.15$; i.e., the measured rate was 15% more than the rate with fully mixed conditions. This indicates good mixing of the contents with a small ullage. However, with the mixer off, the measured $\alpha = 3.4$ due to stratification within the bulk liquid.

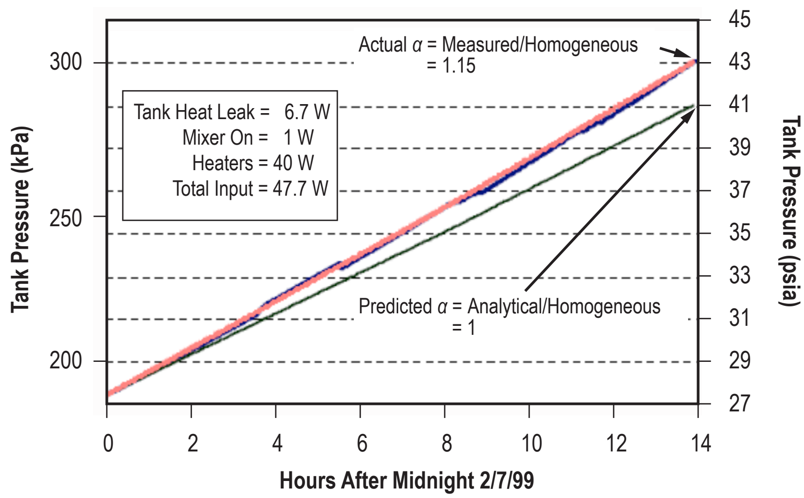


Figure 22. Predicted tank self-pressurization comparison with measured data, mixer on, and 40-W heater input.

The analytical PTVS energy extraction rate during the burn was 3.1 W (10.6 Btu/hr) compared with a measured rate of 11.3 W (38.5 Btu/hr). With the fluid level at 40.8 kg (90 lbm) (a fill level of 17 in), a PTVS energy extraction rate of 7.6 W (26 Btu/hr) was predicted, compared with a measured rate of 85.9 W (293 Btu/hr). The ullage was warmer than expected; a temperature corresponding to saturated conditions had been previously assumed. However, the stratified ullage temperatures ranged from 28 K to 31 K (50 °R to 55 °R), that were well above the saturation temperature of 25 K (45 °R). The warm ullage was attributed to the following: (1) The pump was unable to disturb the liquid-vapor interface sufficiently to achieve ullage cooling, and (2) the heat leak was almost three times greater than expected because the vacuum chamber pressure increased and the MLI performance was affected. However, the major reason for the heat extraction rate difference was the large temperature difference between the warm, stratified ullage and the LAD channel/PTVS, which was much greater than expected. The prediction was based on a perfectly mixed ullage at saturated conditions. Also, underpredictions of condensation heat transfer in the model (using the axial height instead of the true exposed LAD length) were left in the model for conservatism. Figure 23 shows the large PTVS energy extraction versus exposed LAD length when the LAD diode is exposed to the ullage during a burn. Consequently, a rapid drop in LAD temperature occurred whenever the PTVS flow was initiated.

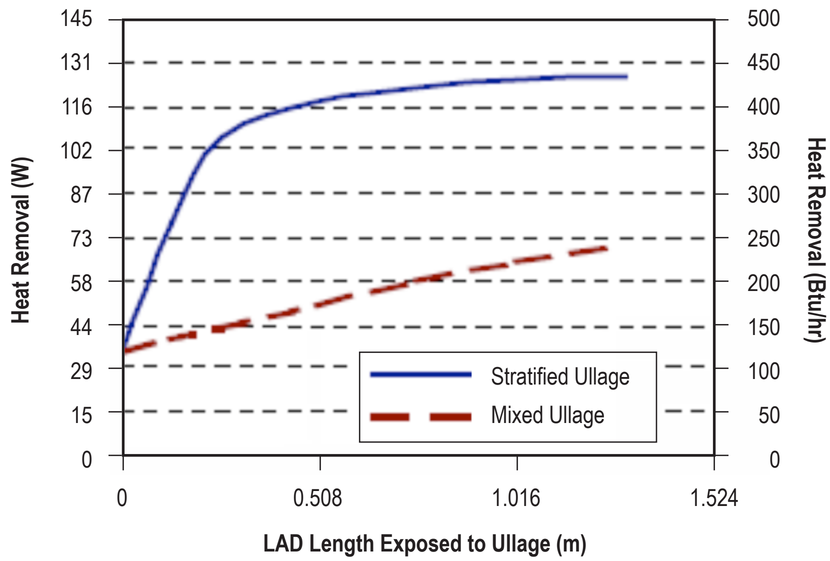


Figure 23. PTVS energy extraction versus exposed LAD length.

4.2 Preliminary Computational Fluid Dynamics Analyses

FLOW-3D is a general Navier-Stokes equation solver with an extensive history of cryogenic tank modeling. FLOW-3D[6] offers several options based on what is important to the problem, including application to reduced gravity environments. Consequently, a preliminary study of the TVS mixer was performed which indicated that the mixer pump was unable to produce a geyser that penetrated or disturbed the liquid-vapor interface sufficiently to achieve adequate mixing of both the ullage and bulk liquid. Referring to figures 24 and 25, the CFD analyses indicated minimal disturbances at the liquid-vapor interface with fill levels of 90% and 40%, respectively. The fluid iso-surface view, shown in figure 26, clearly conveys the very minimal disturbance of the liquid-vapor interface with the 30% fill level. It can be argued that the mixer performance will substantially improve in reduced gravity; however, that is not always the case. Further, the experimentally measured condensation effects can be a significant positive factor in reduced gravity. In conclusion, further testing and analyses would be required to resolve the mixer adequacy question for a particular design and mission.

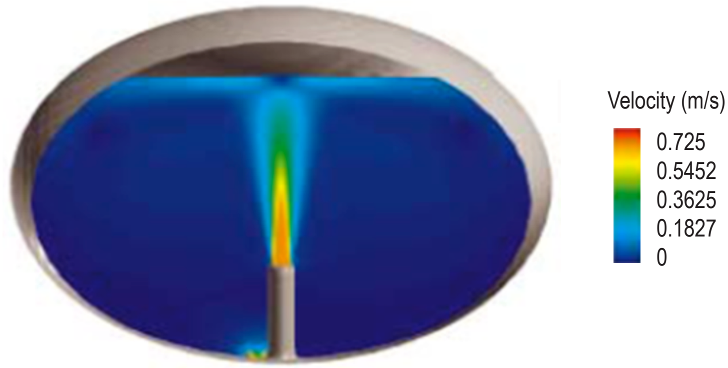


Figure 24. Velocity contours illustrating ATVS mixer pump performance at a 95% fill level.

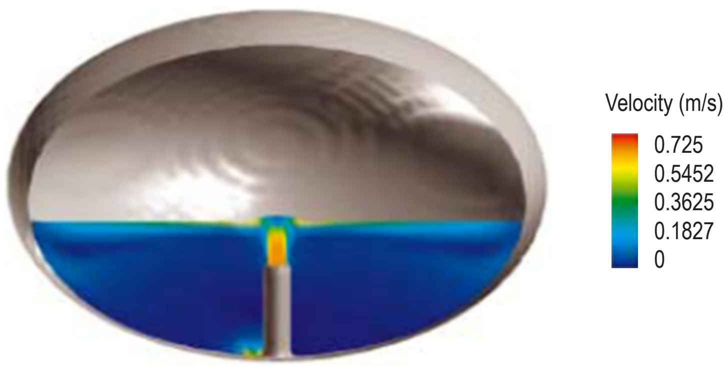


Figure 25. Velocity contours illustrating ATVS mixer pump performance at a 40% fill level.

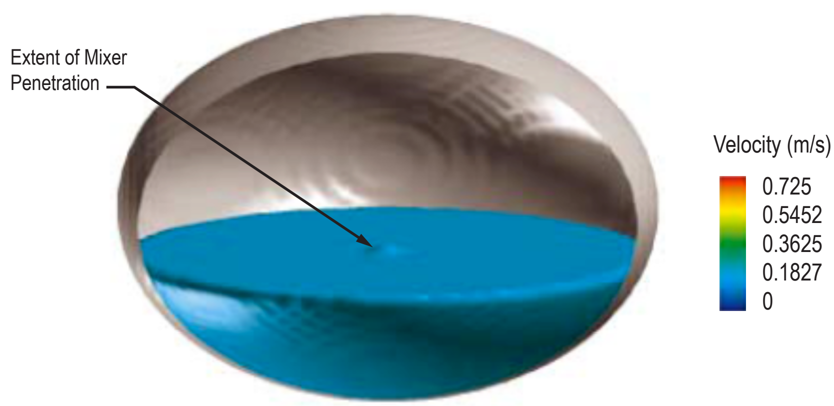


Figure 26. Fluid iso-surface illustrating lack of ullage penetration at a 30% fill level.

The analytical evaluation of pressure rise rates, mixer performance, and energy extraction rates is further pursued in section 4.3.

4.3 Computational Fluid Dynamics Detailed Modeling

As mentioned earlier, the STUSTD data were later evaluated in more detail using a custom version of the commercially available FLOW-3D software to develop the present two-phase cryogenic tank model.[6,7] The customization enabled the model to treat phase-change effects at the liquid-gas interface. First-order approximations for momentum and energy equations, including the two-equation k-ϵ and renormalization group (RNG) turbulence models, were enabled. The ullage region was fully compressible, and liquid density varied with temperature only. Modeling of the heat transfer between the liquid, gas, and tank walls was included to capture thermal stratification within the fluids.

The model setup, analysis results, and conclusions are described in the following sections.

4.3.1 Computational Fluid Dynamics Model Description

The model used a 3,366-cell axisymmetric mesh to simulate the 2.01 m^3 (71 ft^3) ellipsoidal STUSTD tank (fig. 27). The mesh was derived from the S-IVB mesh previously shown to be independent of grid size,[8] therefore, the STUSTD mesh was expected to have little grid-induced effect. The tank had a width of 1.76 m (5.78 ft) and a height of 1.24 m (4.08 ft). LADs were omitted from the model because the engineering checkout tests did not include LAD operation. The ATVS was located in the center of the tank and was 0.29 m (1 ft) in diameter and 0.19 m (0.63 ft) in height. The outlet of the vertical jet was 0.4 cm (0.14 ft or 1.7 in) in diameter.

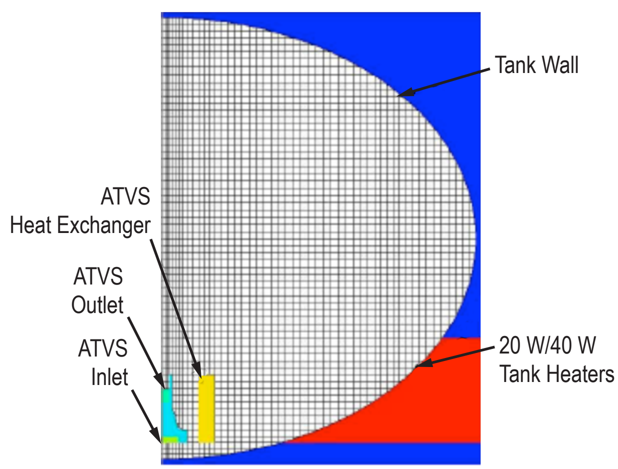


Figure 27. STUSTD model mesh and tank geometry.

A series of tank wall heaters capable of delivering 20–40 W of heating were imbedded in the tank insulation. Because of the axisymmetric mesh, the STUSTD model incorporated these variable-power tank heaters as solid obstacles adjacent to the bulk liquid. The actual tank heaters were approximately 15 cm (6 in) wide by 66 cm (26 in) long. Four of these tank heater strips were evenly distributed on the tank wall.

The ATVS body was considered to be adiabatic, thus contributing a negligible amount of heat to the liquid. The self-pressurization models were initially quiescent. The liquid was assumed to be saturated at a given tank pressure and allowed to heat up. Ullage and liquid stratification profiles were derived from available test data and were used as ‘initial conditions’ on a case-by-case basis.

Table 3 lists the test cases considered in the present analysis. The focus was on normal gravity tank self-pressurization and ATVS performance, and the modeling was anchored by previous correlations with MSFC test data.[9] Test case 3 included ATVS activation, whereas all the other cases strictly treated tank self-pressurization under external heating. The tank heat leak was distributed between the tank wall and the imbedded heater obstacles. When heaters were not used, the incoming tank heat leak was evenly distributed along the tank walls, including the surface of the inactive heaters.

Table 3. STUSTD normal gravity test cases.

Test Case	Test Fluid	Heat Leak (W)	Fill Level (%)	Mixer Type and Flow Rate
1	LH_2	25.7	87	None
2	LH_2	25.7	44	None
3	LH_2	25.7	90	Axial jet/27 gpm

4.3.2 Computational Fluid Dynamic Results and Discussion

Detailed model results for the normal gravity test cases are presented in figures 28–39. Transient ullage pressure histories, ullage and liquid temperatures, histories, liquid temperature histories, temperature contours, and velocity field plots for each case are displayed. Ullage temperatures were measured 1.68 m (44 in) from the bottom of the tank, whereas liquid temperatures were recorded in the bulk liquid. Because of the different fill levels, recorded liquid temperatures for some test cases were measured 0.64 or 0.38 m (25 or 15 in) from the bottom of the tank. The specific temperature sensor location is indicated on each plot.

4.3.2.1 Self-Pressurization. In general, the normal gravity results closely followed the trends evident in the test data. Several results from selected cases without mixing are interpreted and discussed in detail in this section.

In case 1 (25.7 W, 87% fill, no mixer), shown in figures 28–31, the tank heaters operated at half capacity (20 W) and 5.7 W remained evenly distributed along the tank walls. Uniform saturated conditions at 234 kPa, 23.5 K (34 psia, 42.3 °R) and a quiescent velocity field were assumed for the initial conditions. The large natural convection vortices generated in the bulk liquid by the tank heaters were dispersed and slow, on the order of 0.91 cm/s (0.03 ft/s). The results show that the tank heaters impacted the velocity field profiles and magnitudes. Thermal stratification of the ullage was high but relatively constant (≈5 K (9 °R)) throughout the self-pressurization phase, with a peak temperature of 29.8 K (53.7 °R). Model results modeled an average ullage pressurization rate of 6.9 kPa/hr(1 psi/hr), which agreed with the measured 6.34 kPa/hr (0.92 psi/hr) rate. Modeled ullage and liquid temperatures at 1.68 and 0.64 m (44 and 25 in), respectively, also agreed well with the measured test data and were within 0.28 K (0.5 °R) of the actual sensor readings.

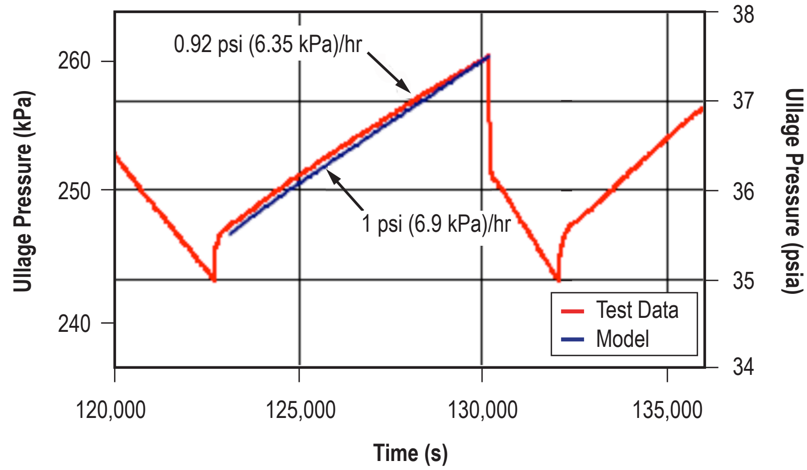


Figure 28. CFD modeled versus measured tank pressure during self-pressurization—87% fill, 25.7-W tank heat leak (case 1, no mixer).

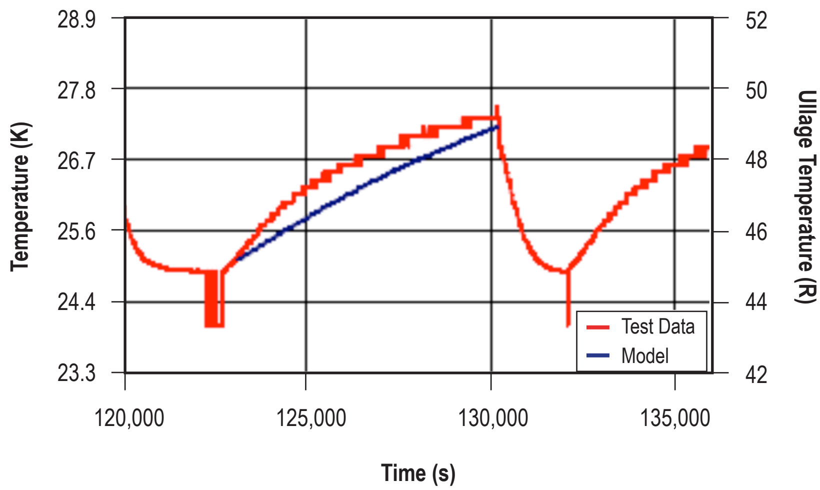


Figure 29. CFD modeled versus measured ullage temperature during self-pressurization—87% fill, 25.7-W tank heat leak (case 1, no mixer).

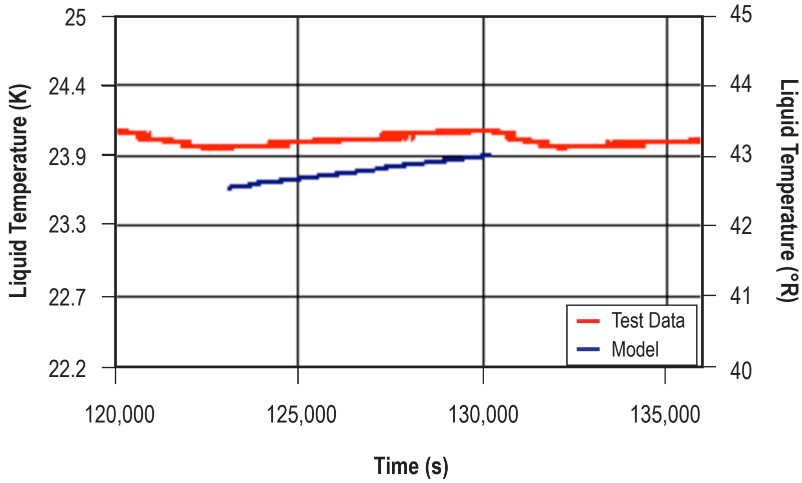


Figure 30. CFD modeled versus measured liquid temperature at 64 cm (25 in) during self-pressurization—87% fill, 25-W tank heat leak (case 1, no mixer).

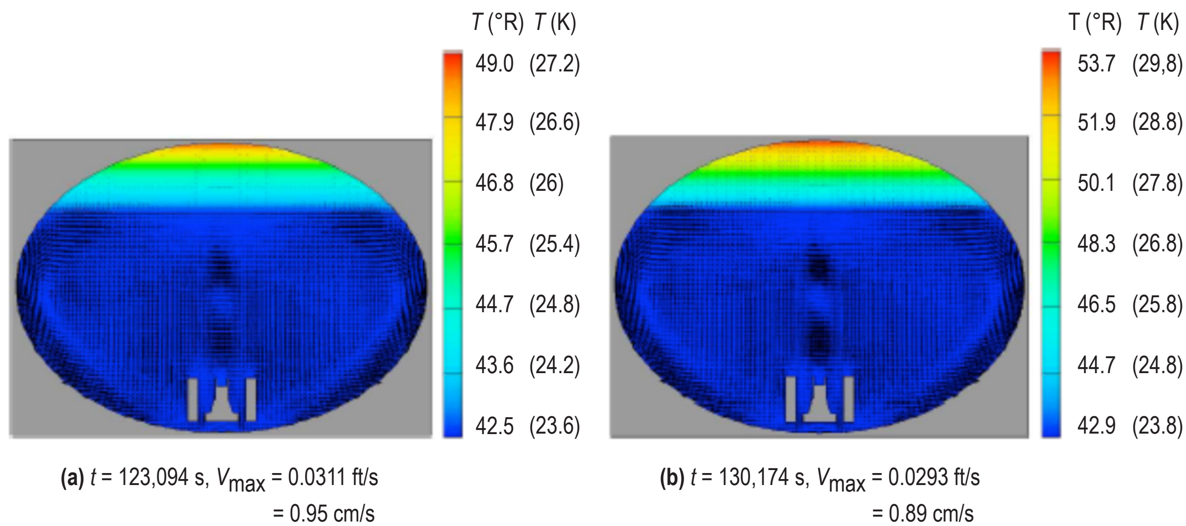


Figure 31. CFD modeled velocity and temperature patterns during self-pressurization—87% fill, 25.7-W tank heat leak (case 1, no mixer).

For case 2 (25.7 W, 44% fill), shown in figures 32–35, the tank heaters were operating at 20 W. The remaining 5.7 W were evenly distributed along the tank walls. The tank was initially quiescent and assumed to be saturated at 241 kPa (23.6 K) or 35 psia (42.5 °R). The ullage was stratified by 4.7 K (8.5 °R) to simulate the temperature distribution in the ullage during the actual test. Both the model and test data illustrated a 10-kPa/hr (1.45-psi/hr) tank pressurization rate. Ullage temperature results illustrated a 1.12 K (2.5 °R) rise over the 13.8 kPa (2 psi) pressure band. Modeled liquid temperature results of 40 cm (15 in) from the bottom of the tank agreed with test data and showed a small rise in temperature. The temperature and velocity field plots illustrated similar bulk liquid fluid dynamics for case 2 as for case 1. Ullage thermal stratification was slightly higher at the lower fill level.

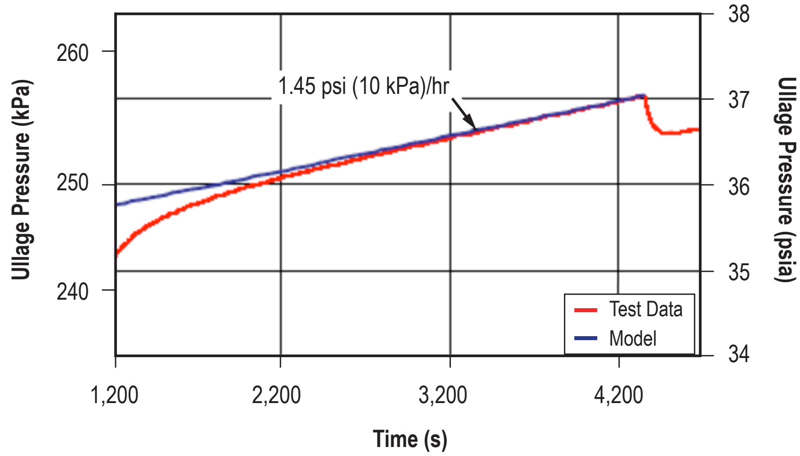


Figure 32. CFD modeled versus measured tank pressure during self-pressurization—44% fill, 25.7-W tank heat leak (case 2, no mixer).

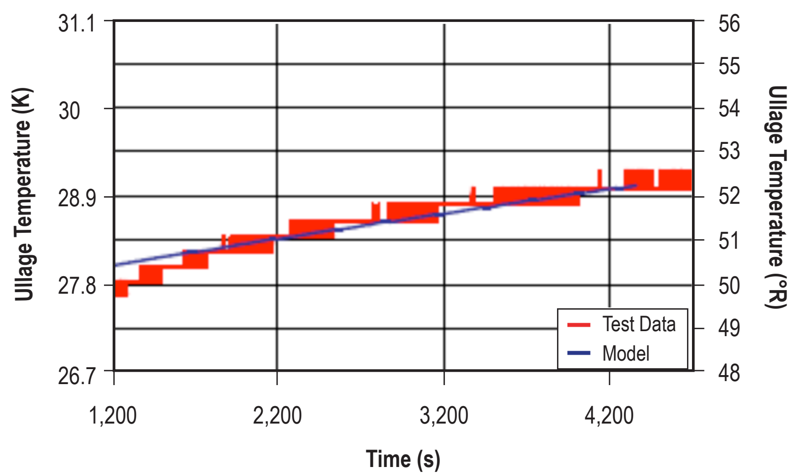


Figure 33. CFD modeled versus measured ullage temperature during self-pressurization—44% fill, 25.7-W tank heat leak (case 2, no mixer).

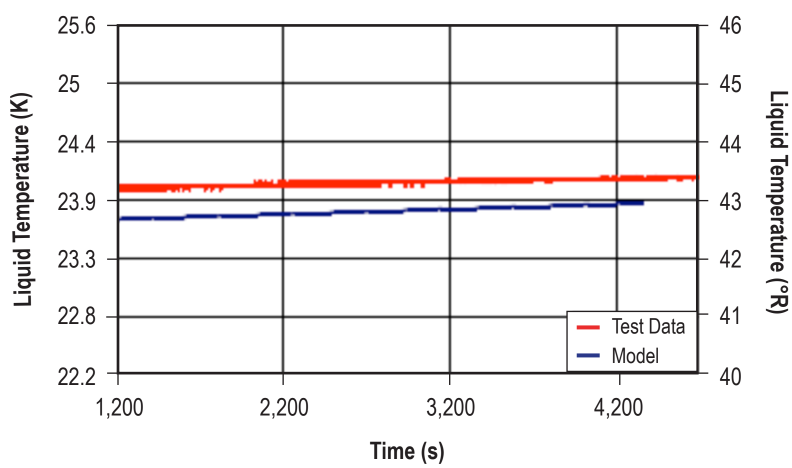
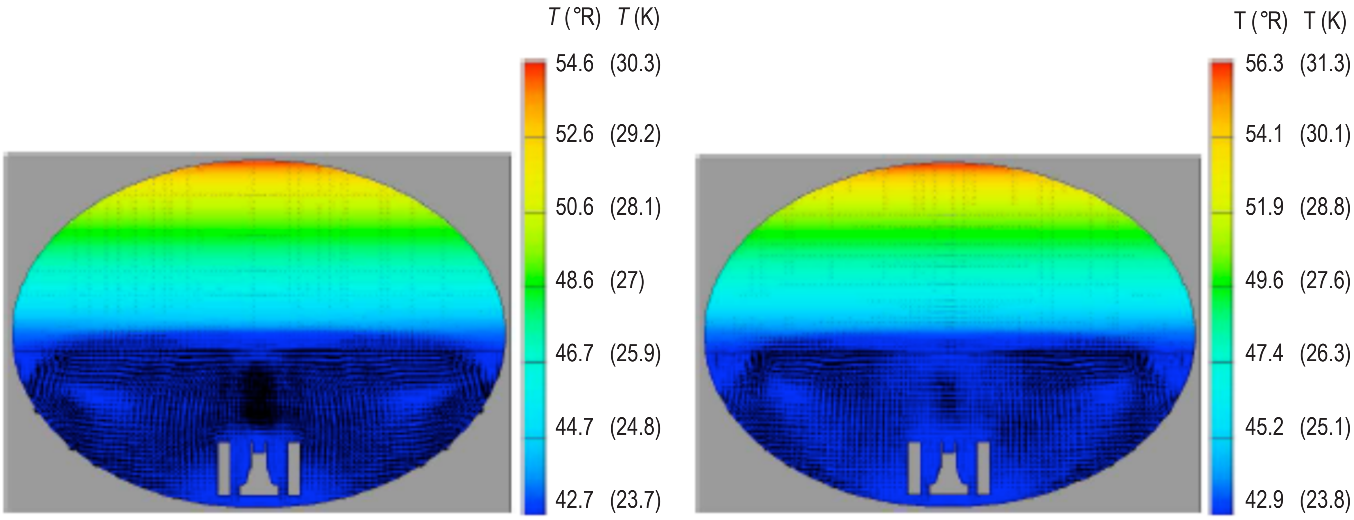


Figure 34. CFD modeled versus measured liquid temperature during self-pressurization—44% fill, 25.7-W tank heat leak (case 2, no mixer (40 cm/15 in).



(a) t = 1,837 s, V_{max} = 0.0934 ft/s = 2.85 cm/s

(b) t = 1,837 s, V_{max} = 0.0840 ft/s = 2.58 cm/s

Figure 35. CFD modeled velocity and temperature patterns during self-pressurization—44% fill, 25.7-W tank heat leak (case 2, no mixer).

4.3.2.2 Active Thermodynamic Vent System Activation. For test case 3 (6.7 W, 90% fill, 102 lpm (27 gpm)), in which the ATVS was used, the temperature and velocity field plots for the self-pressurization, ATVS, and repressurization phases of the pressure control cycle are illustrated (fig. 36). Figure 36(a) illustrates the temperature and velocity distribution once the tank reached its upper pressure limit, hence, the end of the self-pressurization phase. Figure 36(b) displays the temperature and velocity field at the end of the TVS phase, when the ATVS destratified the ullage and dropped the tank pressure to its lower limit. Figure 36(c) illustrates the tank conditions at the end of the repressurization phase, when the tank reached its upper pressure limit once again.

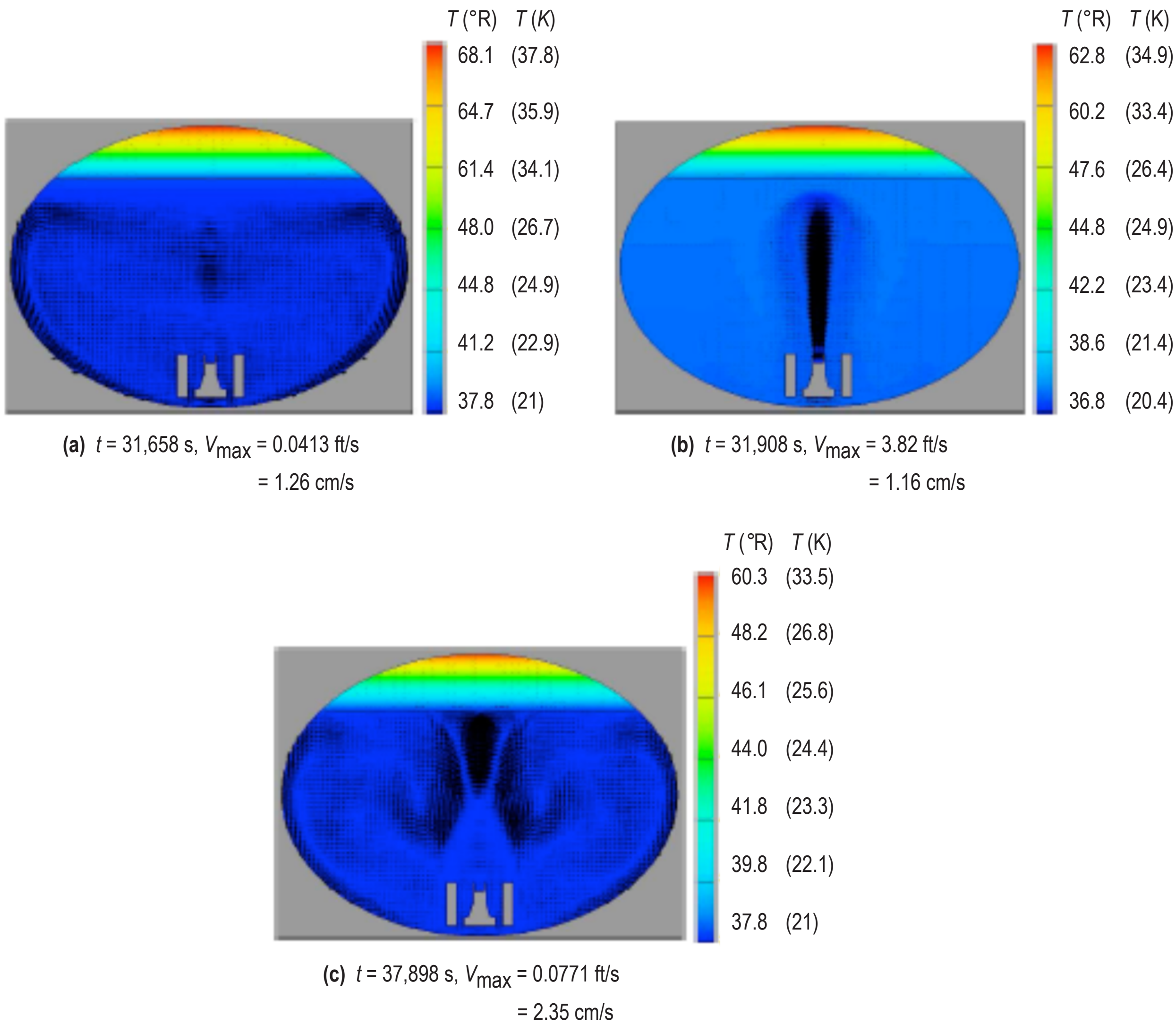


Figure 36. CFD modeled velocity and temperature patterns during mixing—90% fill, 6.7-W tank heat leak (case 3, with mixer).

Other aspects of case 3, which simulated the engineering checkout testing performed following boiloff characterization of the STUSTD tank, are summarized graphically in figures 37–39. The steady boiloff test determined a total system heat leak of 6.7 W. With the heaters off and 6.7 W evenly distributed along the tank walls, the STUSTD tank was locked up and allowed to pressurize to approximately 138 kPa (20 psia), at which point LH_2 at 20.4 K (36.8 °R) was jetted axially at a rate of 102.2 lpm (27 gpm) into the bulk liquid to mix the tank contents and control tank pressure. In case 3, the RNG turbulence model was used instead of the original k-ϵ model used in previous work.[6] RNG is more stable and provides better results for axial jet mixing, and is recommended by the FLOW-3D developers. Once the tank pressure dropped to approximately 124 kPa (18 psia), the ATVS was shut down and the tank repressurized. During tank self-pressurization, the tank heaters were powered up to 40 W. The model assumed uniform saturated LH_2 conditions at 110 kPa, 20 K (16.5 psia, 37.2 °R). The tank was assumed to be initially quiescent. Modeled ullage pressure rise rates agreed very well with available test data. During self-pressurization, the STUSTD tank reached 145 kPa (20 psia) at a rate of 2 kPa/hr (0.29 psi/hr). The tank remained relatively quiescent with maximum velocities on the order of 1.2 cm/s (0.04 ft/s. Natural convection boundary layers were noticed as warm liquid was transported toward the free surface by buoyant forces. As expected, the ullage became thermally stratified. At the end of self-pressurization 145 kPa (20 psia), peak temperatures reached 32.3 K (58.1 °R) and the ullage was thermally stratified by approximately 11.1 K (20 °R).

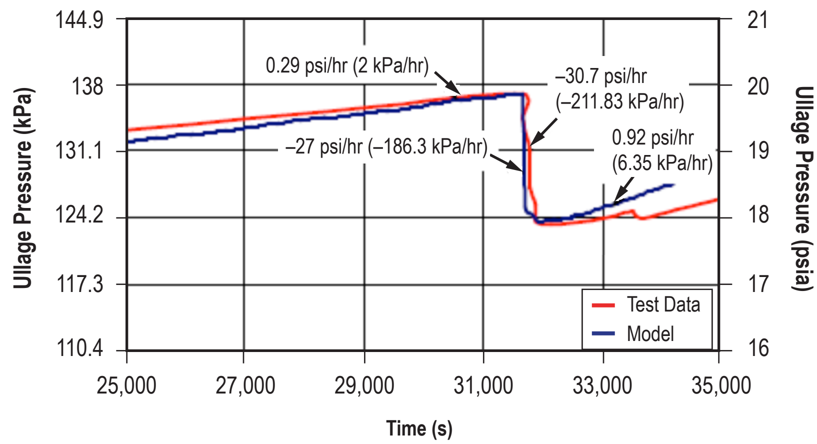


Figure 37. CFD model versus measured tank pressure during self-pressurization cycle—90% fill, 6.7-W tank heat leak (case 3, 102 lpm (27 gpm) mixer).

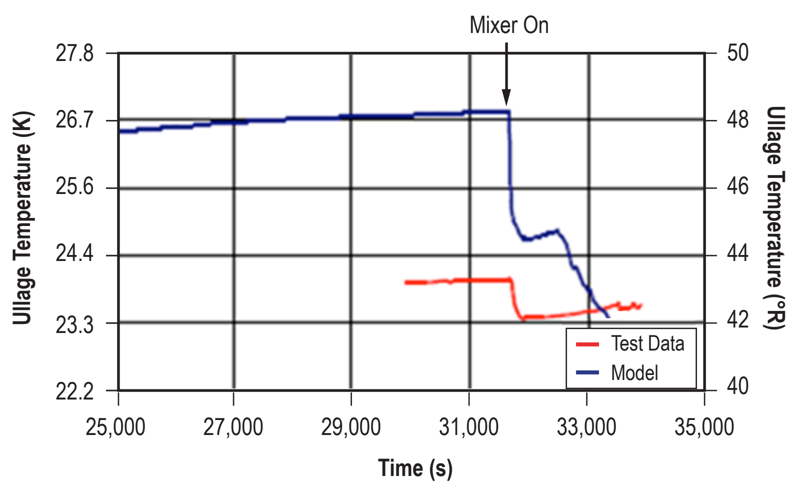


Figure 38. CFD model versus measured tank ullage temperature during self-pressurization and mixing cycle—90% fill, 6.7-W tank heat leak (case 3, 102 lpm (27 gpm) mixer).

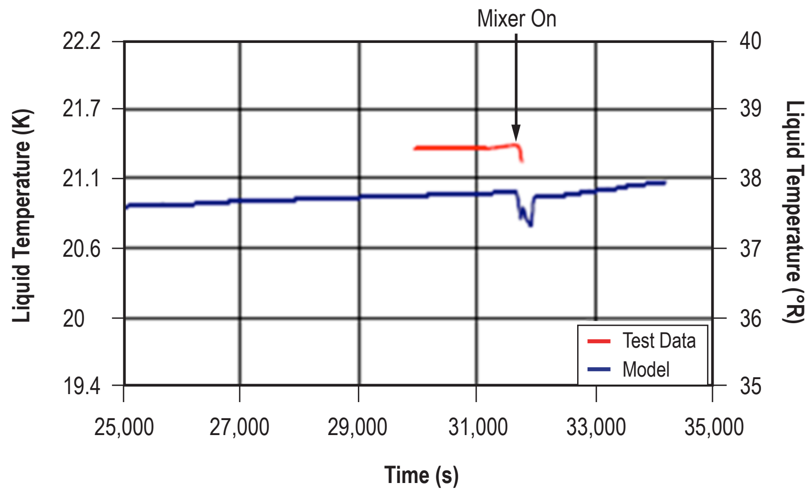


Figure 39. CFD model versus measured liquid temperature at (76.3 cm/30 in) during self-pressurization and mixing cycle—90% fill, 6.7-W tank heat leak (case 3, 102 lpm (27 gpm) mixer.

The test data for case 3 are reported in reference 1. The ullage temperature data 112 and 104 cm (44 and 41 in) and liquid temperature data 76 and 38 cm (30 and 15 in) from the bottom of the tank are available, but for only ≈1,500 s before and after ATVS activation. The model recorded ullage pressure and temperature 112 cm (44 in) and liquid temperatures 76 cm (30 in) from the bottom of the tank. Near the tank top, modeled ullage temperatures were higher than the measured test data. This may be due to constant heat leak boundary conditions that typically overpredict energy exchange between the tank walls and fluids. Both the model and test liquid temperatures showed negligible change during tank self-pressurization.

At 31,658 s (fig. 37), the ATVS in case 3 was turned on and LH_2 at 20.4 K (36.8 °R was injected into the bulk liquid at a rate of 102 lpm (27 gpm). The modeled average ullage pressure drop –186 kPa/hr (–27 psi/hr) during ATVS operation closely followed the test data –212 kPa/hr (–30.7 psi/hr). The jet penetrated the bulk liquid short of the free surface but generated enough mixing with the bulk liquid to drop the ullage thermal stratification to approximately 8.9 K (16 °R) and the peak temperature to 28.9 K (52 °R).

Following TVS activation, the heaters were turned on and operated at 40 W. The tank quickly began to repressurize at a rate of 6.35 kPa/hr (0.92 psi/hr). Approximately 6,000 s after the TVS phase, residual motion from the jet was coupled with heater-generated natural convection boundary layers and large-scale vortices continued to circulate within the liquid at 2.1 cm/s (0.07 ft/s). This residual motion was most likely responsible for the decrease in ullage temperature observed in the model results.

The self-pressurization and destratification model results illustrate steady ullage pressure rise rates and temperatures that agreed with the test data. Important cryogenic tank thermodynamic and fluid dynamic phenomena, such as natural convection boundary layers and ullage thermal stratification, were reflected by the model. A summary of the normal gravity, self-pressurization results is given in table 4, and provides an overall perspective on how the average self-pressurization rate varied with liquid fill level and external heating. With a given heat leak, low fill fraction cases exhibited higher ullage pressure rise rates. For example, at 25.7 W, the 44% fill case (case 2) yielded a self-pressurization rate of approximate 10 kPa/hr (1.45 psi/hr), whereas at an 87% fill case (case 1), the ullage pressure rise rate was 6.9 kPa/hr (1 psi/hr). For the two fill levels studied, the incoming heat was absorbed by the higher thermal capacity liquid and reduced the tank pressurization rate. However, it is cautioned that experience with other tank geometries and/or propellants has demonstrated that the self-pressurization rates do not always vary with fill level in the same way.[10]

Table 4. STUSTD CFD model results summary.

Test Case	Heat Leak (W)	Fill Level %	dp/dt, kPa /hr (psi/hr)
1	25.7	87	6.9 (1)
2	25.7	44	10 (1.45)
3*	6.7	90	2 (0.29)

* Mixer on

5. THIRTY-DAY MISSION SIMULATION

The top-level purpose of the 30-day mission simulation test was to clearly demonstrate feasibility of a concept wherein LH_2 tank pressure is controlled by venting all boiloff through the thruster. Concept success depends on managing tank heat load schedule such that the thruster usage rate simultaneously satisfies the overboard venting necessitated by tank pressure control for the duration of a mission, in this case for 30 days. More specific objectives are as follows:

(1) Demonstrate MLI purge evacuation and performance.

(2) Deliver near-saturated hydrogen vapor at 158.7–241.5 kPa (23–35 psia) at 0.91 kg/hr (2 lbm/hr) for 140 cycles over 30 days.

(3) Demonstrate venting/lockup for 140 burns over 30 days (without additional overboard venting required).

(4) Demonstrate use of MLI and heaters to assist control of tank pressure at 310 ± 27.6 kPa (45 ± 4 psia) while operating.

(5) Demonstrate subcooled LAD/TVS operation in 1 *g* via determination of internal LH_2 tank temperature profile.

(6) Demonstrate LH_2 loading/unloading and LAD filling for ground operations.

The mission simulation approach and test results are described in sections 5.1 and 5.2.

5.1 Mission Simulation Approach

The generalized mission sequence of events was as follows:

(1) Perform MLI purge during tank fill.
(2) Launch preparations.
(3) Ascent flight simulation within the test facility rapid pump-down capabilities.
(4) On-orbit tank self-pressurization with mixing.
(5) Initiate 30-day mission simulation phase.
(6) Monitor system responses to mission transients.

5.2 Mission Simulation Testing and Evaluation Results

The mission simulation testing consisted of the launch and ascent flight phase followed by 140 simulated engine burns during the 30-day, on-orbit simulation phase. Due to the small tank leak, the elevated chamber pressure during the on-orbit simulations necessitated adjustments in the engine burn flow rates and durations to compensate for the elevated tank pressures. Details regarding various mission phase simulations and the scaling adjustments are presented in sections 5.2.1 and 5.2.2.

5.2.1 Launch Preparations and Ascent Flight

The vacuum chamber was filled with GN_2 at 1 atm and the LH_2, tank inerted with GHe in preparation for the simulated ground fill process. As shown in figure 40, the fill process took the first hour; the pressure surge to 172.5 kPa (25 psia) at 0.2 hr occurred when LH_2 first appeared in the tank, then settled out at about 124.1 kPa (18 psia), as expected. The tank lockup and simulated launch began at ≈1 hr. The initial chamber pressure drop and tank pressure surge is shown in figure 40. The chamber pressure follows the shuttle launch profile quite well until 1 hr, at which time it begins to deviate. The initial tank pressure jump to approximately 179.4 kPa (26 psia) was predicted, based on over 5 kW of ambient heat leak into the tank during the initial phases of launch. The vacuum chamber pumps shut down at 1.005 hr, which is why the tank pressure continued to climb. Although the chamber vacuum pumps were restarted after a couple of minutes, <30 torr was not achieved until after the tank pressure had reached 310.5 kPa (45 psia). When the tank reached 310.5 kPa (45 psia), it was vented down to about 241.5 kPa (35 psia), where, due to relatively high vacuum chamber pressure (10–20 torr) the pressure again increased to nearly 345 kPa (50 psia), and necessitated venting. The chamber and tank pressures leveled out at about 1.5 hr, i.e., about 0.5 hr after the simulated launch began.

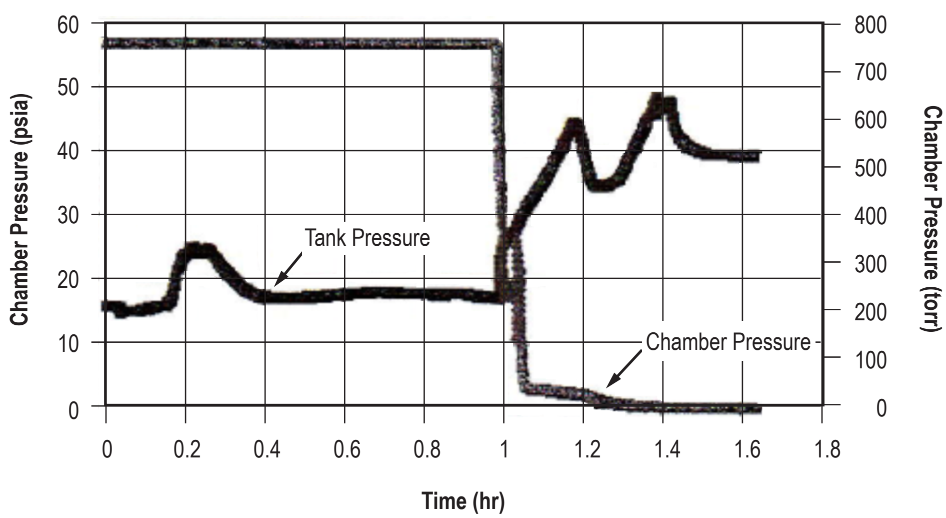


Figure 40. Measured tank and vacuum chamber pressures between ground fill and on-orbit simulation.

As indicated in figure 41, the chamber pressure followed the shuttle launch profile quite well until 1 hr, at which time it began to deviate because of the chamber pump shut-down. Also, the diffusion pumps cannot maintain the shuttle ascent profile after the free molecular flow regime begins in the 10^{-2} to 10^{-3} torr range.

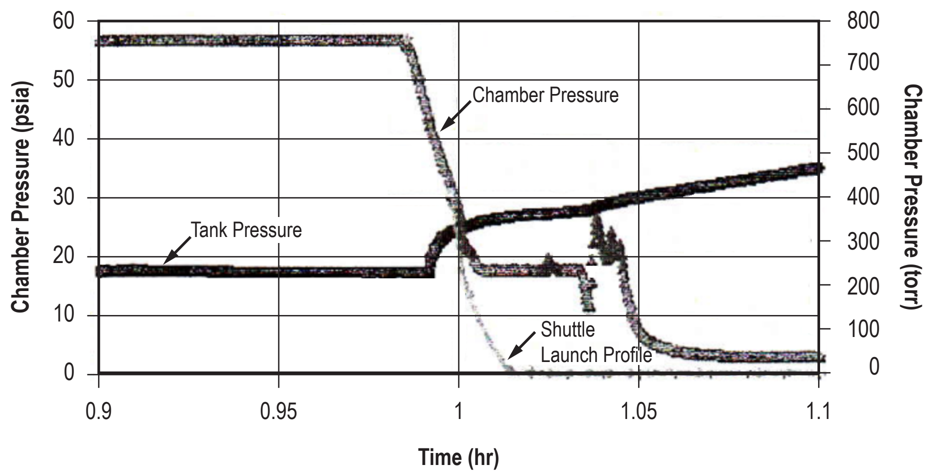


Figure 41. Measured LH_2 tank and vacuum chamber pressure versus shuttle ascent profile.

Because of the inability of the vacuum chamber pumping train to follow the Shuttle Launch profile (reaching hard vacuum in 10–15 min), the capability of the MLI blankets to evacuate GHe rapidly enough to maintain the LH_2 tank pressure below 206.8 kPa (30 psia) could not be verified. However, it was demonstrated that the MLI purge system worked well in allowing LH_2 loading in GN_2 at 1 atm.

Because of the launch simulation problems, the vacuum chamber was pumped down to the lowest pressure the leak would allow (–130 µtorr at 310.5 kPa (45 psia) and the LH_2 tank was vented down to 172.5 kPa (25 psia) and refilled with LH_2 prior to starting the 30-day mission.

5.2.2 On-Orbit 30-Day Mission

The 30-day mission simulation testing and analytical modeling using the standard model described in section 4.1 are presented in this section. The analytically modeled pressure excursions for each of the 140 burns are shown in figure 42; further details are in appendix D. The pressures are arranged as 311 kPa + 0 –Y (45 + 0 –Y psia), rather than as 311 kPa ±Y kPa. The maximum predicted pressure excursion at the penultimate apogee burn (139) was 54.4 or ±27.2 kPa (7.88 or ±3.94 psia). The transitory effects of the ullage conditioning vents are shown. These vents were designed to mix the ullage and reduce the ullage temperature stratification to simulate conditions more representative of low-*g* operation.

A variety of factors are responsible for the measured LH_2 tank pressure before and after each of the 140 engine burn simulations presented in figure 42. The sharp rise in tank pressure for burns l–3, 13, and 14 was because the ATVS was off during these burns. The more moderate rise for burns 4–12 and 15–17 showed that, in spite of the excessive heat leak, the ATVS would have removed sufficient thermal energy to assure pressure control had the coast periods and burn durations been adjusted to compensate for the high chamber pressures, i.e., burns were not long enough for the ATVS and PTVS to remove the extra heat. Note that, for burns 18 and 19, the tank pressure dropped; this was due to burn durations l5 min longer (1,700 s versus 800 s). Even with the ATVS off during these burns, the PTVS was able to remove more than enough heat, thanks to the longer burn times. In figure 43, the tank pressure drop during the burns is the difference between the measured tank pressure before and after each burn.

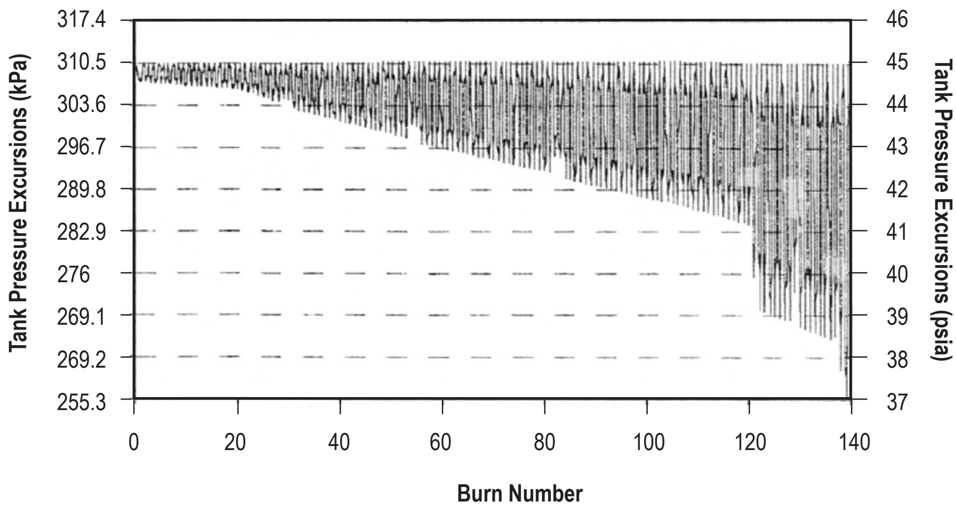


Figure 42. Predicted LH_2 tank pressure as a function of MET.

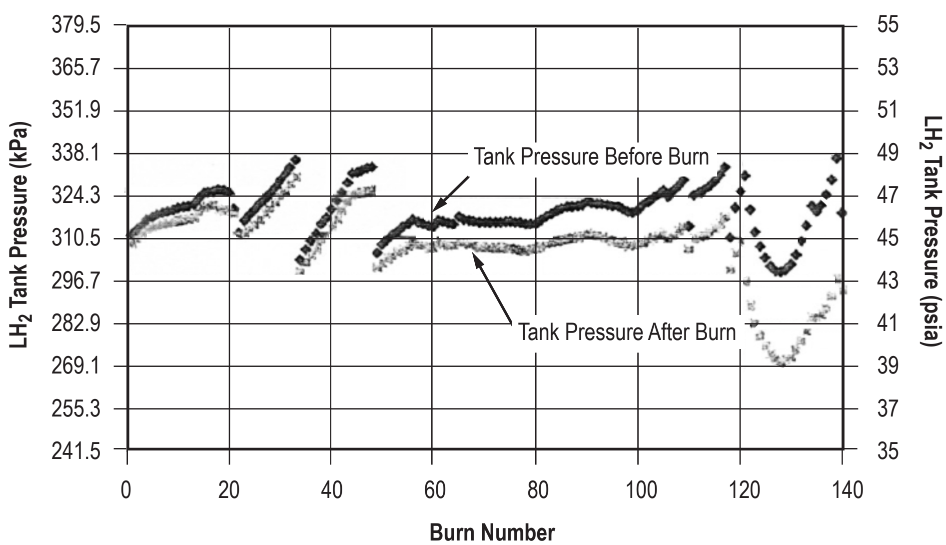


Figure 43. Measured LH_2 tank pressure before and after burn as a function of burn number.

As shown in table 5, the tank pressure drops during the first 20 burns were as expected; however, due to stratification effects on PTVS performance, the actual pressure drops for burn numbers 40–139 were 46%–55% less than the predicted values.

Table 5. Comparison of burn pressure drop data with predictions.

	Tank Pressure Change During Burn	
Burn Number	Modeled, kPa (psid)	Actual, kPa (psid)
20	4.7 (0.69)	4.8 (0.70)
40	9.8 (1.42)	5.3 (0.77)
60	14.3 (2.08)	6.48 (0.94)
80	18.42 (2.67)	8.14 (1.18)
100	22.29 (3.23)	11.32 (1.64)
120	26.4 (3.83)	16.15 (2.34)
122	40.23 (5.83)	31.05 (4.50)
136	44.85 (6.50)	35.54 (5.15)
139	54.37 (7.88)	38.85 (5.63)

After burns 20, 21, 33, 48, 109, and 117, ullage conditioning vents were performed. The conditioning effects on LH_2 tank and chamber pressures are obvious in figure 44 and 45, respectively. Conditioning effects on ullage temperature are shown in figure 45. It can be seen that, as the tank emptied, the average chamber pressure decreased whereas the maximum ullage temperature steadily increased, as expected.

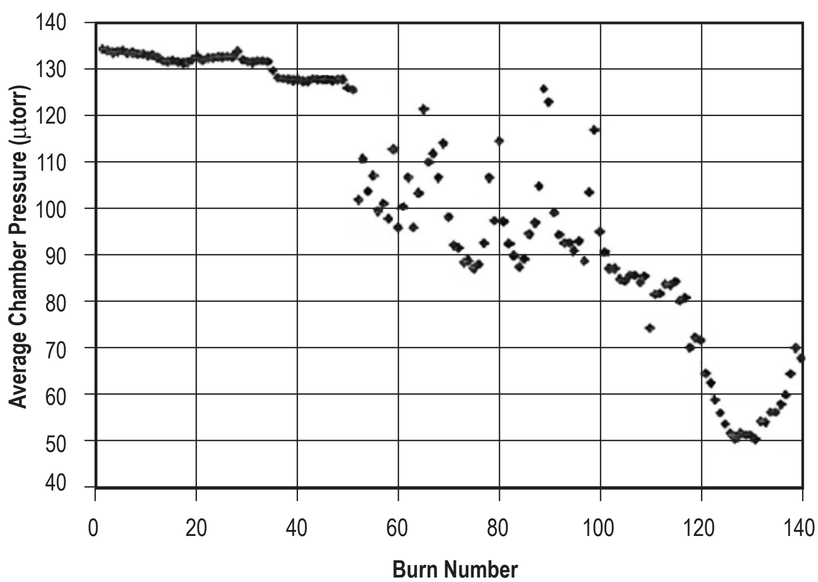


Figure 44. Average chamber pressure as a function of burn number.

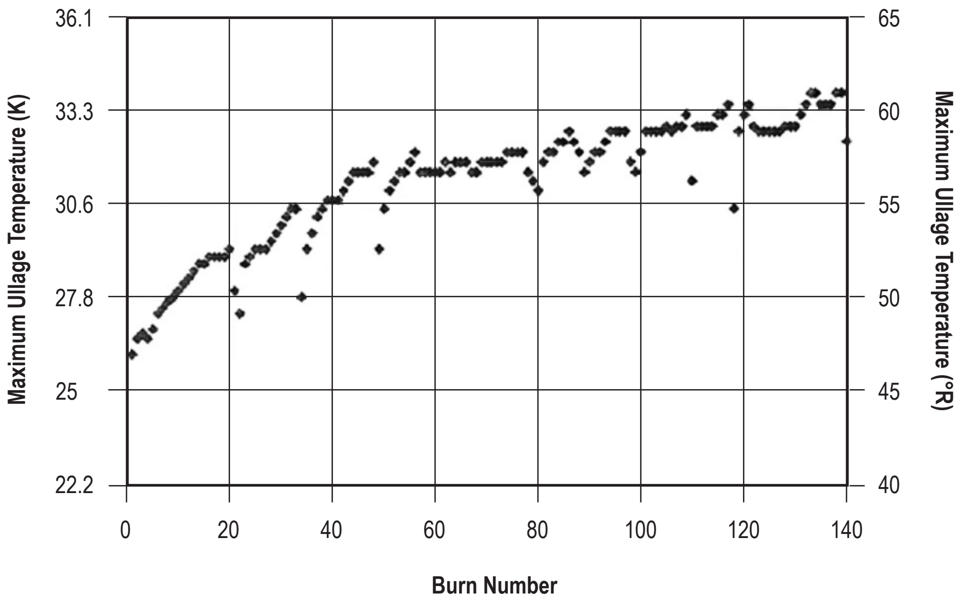


Figure 45. Maximum ullage temperature as a function of burn number.

A detailed plot of the ullage conditioning vent following burn 48 is shown in figure 46. When the valve was actuated for the burn, the ATVS pump was switched from low speed during coast to high speed during burn. The ATVS pump was returned to low speed during the ullage conditioning vent, which was indicated by the high vent flow, and the sharp drop in tank pressure, to 297 kPa (43 psia). Note that the tank pressure rebounded to 300 kPa (43.5 psia) when the ullage vent was closed. This was typical behavior whenever a vent or burn was stopped, and was caused by transient

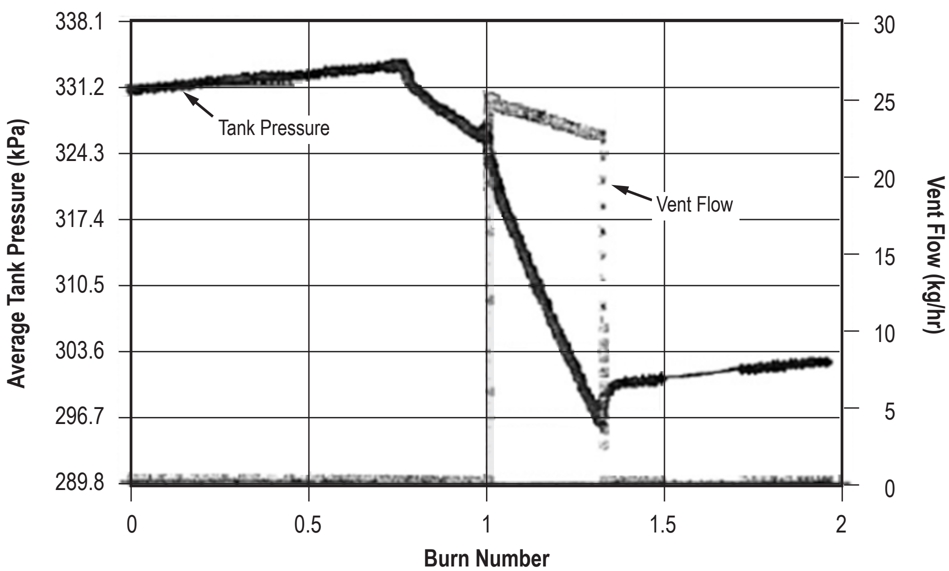


Figure 46. Tank pressure and ullage vent flow rate during ullage vent.

LH_2 boiling as a result of the tank pressure reduction. This characteristic persists until the self-pressurization is sufficient to suppress the boiling.

During a tank conditioning vent or depressurization, the boiling is very effective in destratifying and cooling the ullage, as shown in figure 47. The top four ullage temperatures (T1–T4) converge at about 46 °R (25.6 K), which is essentially the measured LH_2 temperature.

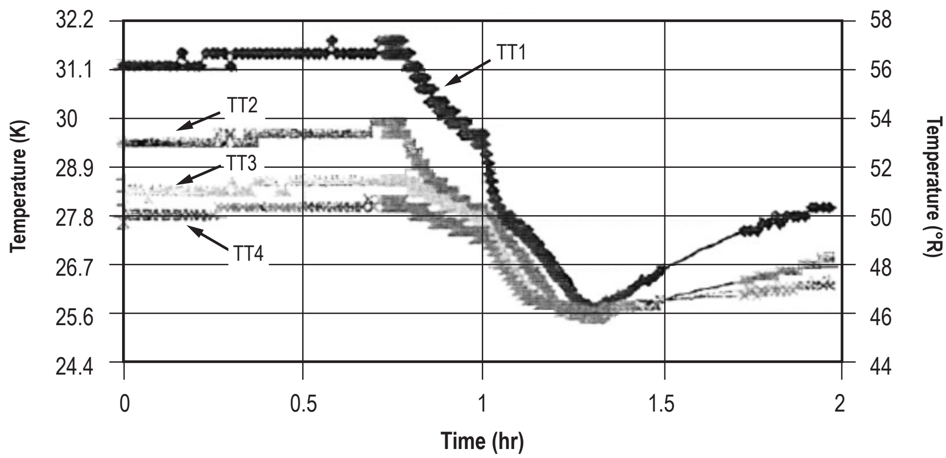


Figure 47. Ullage temperature during ullage vent.

Burns 22–43 were performed with the ATVS off: the steady increase in pressure reflected the inability of the PTVS to extract sufficient heat to keep up with the increased heat flow into the tank and the long coast times. On burns 44–140 (the rest of the mission), the ATVS was on. This was done in recognition of the fact that the extra heat flux from high vacuum chamber pressure made control of the tank pressure intractable without using all of the vent capability available (ATVS plus PTVS).

The variations in tank pressure also affected the overall vent flow rate, as shown in figure 48. The pressure affected both the flow through the VISCO JETs® and the flow through the leak. Note that the flow rate was generally dropping as the tank emptied. This implied that there was some head effect on the leakage flow. (Head should have had essentially no effect on VISCO JET flow.)

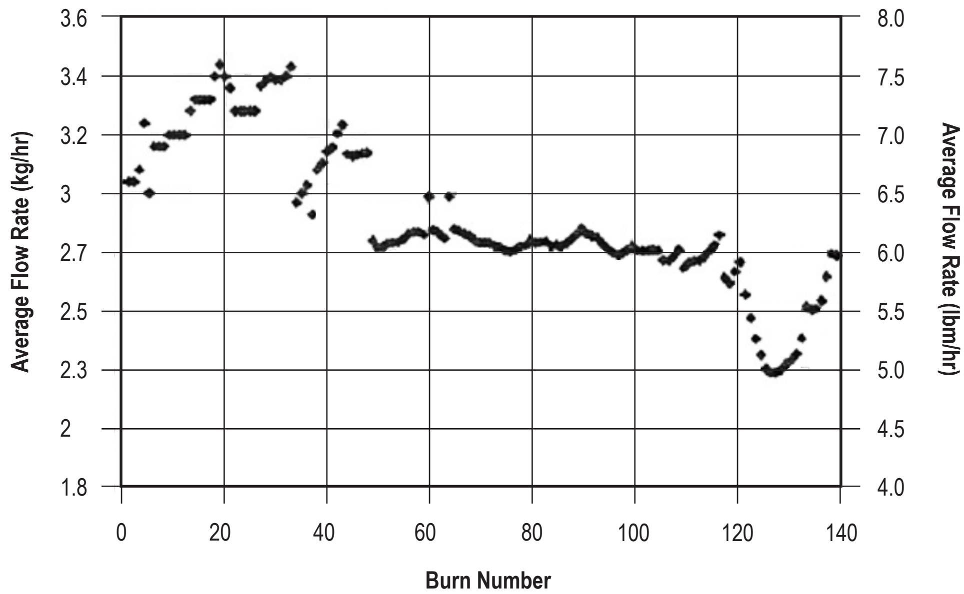


Figure 48. Average feed line flow rate as a function of burn number.

Returning to figure 43 at burn 56, there was a significant change in pressure control capability. This was where the coasts were reduced (from approximately 7,200 s to 4,800 s) to correct for the increased MLI heat flux. The ATVS, together with the PTVS, was able to extract enough heat to more than keep up with heat input from the shortened coast periods. On burns 60 and 64, the ATVS was turned off; note the immediate jump in tank pressure for these burns. This series of burns, from 56 to 80, showed that the ATVS and PTVS could effectively maintain constant tank pressure, as designed.

At burn 80, the tank pressure again trended upward, as the shortened coasts had also reached 7,500 s. This continued until burn 90, when the coast time was again reduced (from approximately 9,100 s to 7,100 s). However, by burn 100, coast times had again reached 9,100 s, and ullage conditioning vents were required at burns 104, 109, and 117 to control the tank pressure below approximately 331 kPa (48 psia) until burn 121. Burn 121 was increased from 749 s to 2,187 s to simulate the STUS apogee burns (121–140). Even though the coast times for burns 121 to 128 increased from approximately 15,000 s to 20,000 s, the longer burn times allowed the ATVS and PTVS to control tank pressure. After run 128, the combination of long coast times (approximately 20,000 to 27,000 s) and excessive MLI heat leak from high vacuum chamber pressure overcame the ability of the ATVS and PTVS to maintain constant tank pressure. Fortunately, run 139, with the final long coast, was reached before the tank pressure reached 349 kPa (49 psia).

6. SUMMARY AND CONCLUSIONS

The programmatic strategy of the AITP was to assemble a technology team (comprised of individuals and small groups representing industry government, academia, and small business) that would enable the sharing of technology skills and facilities in a cost effective and productive manner. The STUSTD program was a major element of the cryogenic solar propulsion AITP cooperatively performed by a Boeing-led team. The technical strategy, hardware performance, test results, and analytical modeling accomplishments are summarized below.

6.1 Technical Strategy and Test Hardware Performance

The STUSTD technical strategy was to balance the LH_2 storage tank venting requirements with the engine thrusting timeline during a 30-day solar thermal propulsion mission, thereby assuring that there were no vent losses. Proof-of-concept testing was performed at MSFC's TS300 vacuum chamber using a 2 m^3 (71 ft^3) LH_2 tank with an arrangement of thermodynamic venting combined with a capillary screen channel LAD, MLI, and internal tank heaters. An engineering test series was first conducted to check out the test equipment and to calibrate or anchor analytical modeling. The checkout testing was followed by a 30-day mission simulation test designed to demonstrate the concept feasibility.

The checkout testing began with an ascent flight simulation that was compromised by vacuum chamber pump-down limitations and a chamber control system malfunction. The on-orbit checkout phase began with a LH_2 boiloff test that indicated a system heat leak of 6.7 W versus a predicted heat leak of 6.6 W, i.e., the actual heat leak was within 1.5% of the prediction. However, upon activation of the ATVS, a small H_2 leak caused the chamber pressure to elevate from 6.75×10^{-6} to 5×10^{-5} torr and increased the tank heat leak to 18 W. The testing was continued, recognizing that analytical modeling would have to reflect the heat leak increase.

Analytical correlations of the engineering checkout test data were initially performed primarily with standard analytical modeling tools and limited CFD modeling. The initial modeling was later bolstered by a comprehensive CFD correlation effort involving the checkout data. However, due to budgetary constraints, only the standard modeling was applied to the 30-day mission.

6.2 Standard Modeling Test Correlations

The original PTVS thermal extraction rate prediction was based on a perfectly mixed ullage at saturated conditions plus a LAD length based on axial height instead of true exposed LAD length. Consequently, in every case, the measured thermal extraction rates exceeded the predictions by a factor of 10 with the PTVS. The 'higher than expected' extraction rates were attributed to the 'warmer than expected' ullage due the previously mentioned elevated MLI heat leak in combination with inadequate TVS pump mixing. (See CFD modeling results in sec. 6.3.) Modifications to the standard analytical algorithms and simulations to account for the relatively warm ullage and actual

LAD length (and, therefore, increased thermal extraction of the PTVS) were made before the 30-day mission simulation. The standard analytical modeling, anchored by the engineering checkout test data and the CFD mixer simulations, enabled pretest predictions that correlated quite well with the 30-day mission simulation test results.

6.3 Engineering Test Results and Computational Fluid Dynamics Modeling

Based on previous experience with reduced gravity pressure control within the S-IVB LH_2 tank, a 3,366-cell axisymmetric mesh was selected to simulate the STUSTD LH_2 tank.[6] Application of this CFD model to the engineering checkout testing yielded the following conclusions:

- The TVS mixer was unable to produce a geyser that penetrated or disturbed the liquid-vapor interface sufficiently to achieve adequate mixing with fill levels of 90% and 40%.

- With a 90% fill level (10% ullage), the analytical and measured self-pressurization rates correlated quite well prior to the mixing cycle; however, the modeled rate was three times the measured rate following the mixing cycle.

- Stabilized self-pressurization conditions prior to the first mixing cycle are more easily simulated than the transient thermodynamic conditions immediately following a mixing cycle.

- Modeling ullage and liquid temperatures were more successful. Compared with measured data, modeled ullage and liquid temperatures were generally within 10% and 2%, respectively.

Therefore, even though additional ullage pressure control modeling improvements are needed, to a significant degree, tank heater-liquid dynamics, natural convection boundary layers, ullage thermal stratification, and ATVS operation were captured by the numerical simulations. Prescribed boundary conditions at the tank walls combined with temporary boiling heat transfer and residual stratification effects represent substantial limitations in self-pressurization CFD modeling between mixing cycles. However, this limitation can be addressed by setting up a computational interface between a thermal code, such as SINDA and the CFD code, thereby enabling the tank calculated structural temperatures to interact with calculated interior thermodynamics and vice versa.

6.4 Standard Plus Computational Fluid Dynamics Modeling Combination

CFD modeling has steadily improved each time it has been challenged with another set of cryogenic test data such as the subject STUSTD data. Therefore, these CFD and standard analytical correlations of an ellipsoidal LH_2 tank with an axial jet mixer have, without a doubt, substantially improved the analytical code validation database for two-phase, on-orbit cryogen storage. In fact, existing CFD codes in combination with traditional models can already be used to at least bracket reduced gravity effects. An overwhelming justification for continued development of CFD modeling lies in its innate capability to simulate reduced gravity effects on basic thermodynamics, fluid dynamics, and heat transfer. It is this reduced gravity capability that can provide the 'bridge' or scaling between normal and reduced gravity CFM. Eventually it will become standard practice to use the CFD codes to anchor traditional codes for reduced gravity applications, thereby enabling rapid turnaround modeling with the less costly and user-friendly traditional codes.

Summation statement: Substantial strides have occurred in recent years as CFD codes continue to be challenged with various sets of cryogenic test data and computer speeds increase. With each CFD code improvement increment, the historic dependence of in-space CFM development on prohibitively expensive on-orbit testing is being significantly reduced.

APPENDIX A—STUSTD INSTRUMENTATION LIST

Channel	Measurement Description	MFG	Serial No.	Range	Units	Cal	Card	Group
101	Chamber dew point	E&H	2009pw-4	-112 to 68	F		se	2
102	Chamber dew point	E&H	2012pw-4	-112 to 68	F		se	2
103	Ullage differential pressure	MKS	536864	1	TORR		se	6
calc	Active TVS in/out delta pressure	PSI	960094-A	0.5	PSID		n/a	
38	Raw millivolts DPT4	PSI	960094-A	-50 TO 50	MV		se	
41	External tank heater 1 voltage	FLEXCORE	8050052	50	VDC	Jul-99	se	
42	External tank heater 2 voltage	FLEXCORE	8050053	50	VDC	Jul-99	se	
43	External tank heater 3 voltage	FLEXCORE	8050054	50	VDC	Jul-99	se	
44	External tank heater 4 voltage	FLEXCORE	8050055	50	VDC	Jul-99	se	
104	LH2 Vent flow rov 20-671	FTI	2402000	165	ACFM	May-00	se	8
105	LH2 Vent flow rov 20-672	FTI	1606628	55	ACFM	May-00	se	8
106	LH2 Vent flow rov 20-673	Hastings	10879	20	SCFM	May-00	se	8
107	LH2 Vent flow rov 20-674	MKS	0558A01738232	2918	SCIM	May-00	se	8
139	Engine feedline flow rate	HASTINGS	18018	10	SCFM		se	
140	MLI He purge rate	FTI	807219	1	ACFM		se	
100	ISUS Vent flow rate	Flow Tech., Inc.	16010078	1760	ACFM	Oct-00		
50	TVS pump frequency			0-400	HZ	n/a		
70	Tank heater On / Off			1000	OFN	n/a		
45	External tank heater 1 current	FLEXCORE	8050107	1	AMP	Jul-99	se	
46	External tank heater 2 current	FLEXCORE	8050108	1	AMP	Jul-99	se	
47	External tank heater 3 current	AAC	3498	5	AMP	Jul-99	se	
48	External tank heater 4 current	AAC	3499	5	AMP	Jul-99	se	
51	TVS current leg A			0-5	AMP	n/a		
52	TVS current leg B			0-5	AMP	n/a		
53	TVS current leg C			0-5	AMP	n/a		
108	Ullage/Vent line pressure	MKS		1000	TORR		se	6
66	Ullage/Vent line pressure	TELEDYNE TABER	781298	50	PSIG	Jul-99	fb	6
110	Reference pressure vessel	MKS		1000	TORR		se	6
111	Ullage pressure	MKS		96	PSIA		se	
112	GN2 supply on roof	STELLAR TECH	940849	5000	PSIG	Jul-99	fb	14
113	GN2 to ejector	STELLAR TECH	951773	1000	PSIG	Jul-99	fb	14
114	GN2 supply to digicell	DYNISCO	24651	3000	PSIG	Jul-99	fb	14
115	Digicell loader operator	TELEDYNE TABER	880264	5000	PSIG	Jul-99	fb	14
116	2nd stage firex	STATHAM	15	1000	PSIG	Jul-99	fb	24
118	LN2 Tank ullage pressure	TELEDYNE TABER	781319	100	PSIG	Jul-99	fb	11
119	LN2 Pump line pressure	TELEDYNE TABER	860548	300	PSIG	Jul-99	fb	11
120	GN2 Supply pressure	MB ELECTRONICS	41029	100	PSIG	Jul-99	fb	11
121	Air manifold	TELEDYNE TABER	888102	5000	PSIG	Jul-99	fb	14
122	Repress stage two	DYNISCO	27686	1500	PSIG	Jul-99	fb	14
123	Repress stage one	TELEDYNE TABER	930869	1000	PSIG	Jul-99	fb	8,10,14

Channel	Measurement Description	MFG	Serial No.	Range	Units	Cal	Card	Group
124	LH2 F/D trailer fill	TELEDYNE TABER	880705	100	PSIG	Jul-99	fb	13
125	LH2 Vent sytem	TELEDYNE TABER	781316	100	PSIG	Jul-99	fb	13
126	LH2 Vent sytem @ pressure control valves	TELEDYNE TABER	931250	100	PSIG	Jul-99	fb	8,13
127	LN2 Supply system rov 20-1700	TELEDYNE TABER	891412	100	PSIG	Jul-99	fb	10
128	GH2 Upstream DLR - 803	TELEDYNE TABER	932076	6000	PSIG	Jul-99	fb	10
129	GH2 Downstream DLR - 803	STELLAR TECH	941210	1000	PSIG	Jul-99	fb	10
130	GH2 Feed line	TELEDYNE TABER	950379	500	PSIG	Jul-99	fb	10
131	GN2 Downstream DLR-2082	TELEDYNE TABER	890938	2000	PSIG	Jul-99	fb	10
132	GHE Upstream DLR-2304	DYNISCO	32121	1000	PSIG	Jul-99	fb	17
133	GHE Downstream DLR-2304	TELEDYNE TABER	751800	200	PSIG	Jul-99	fb	17
134	Tank pressurization	TELEDYNE TABER	890934	2000	PSIG	Jul-99	fb	11
141	Helium purge of MLI	STATHAM	89	2	PSIG	Aug-99	fb	
165	ISUS Vent flow pressure	TELEDYNE TABER	891351	50	PSIA	May-00		
166	Downstream burts disk	TELEDYNE TABER	860736	100	PSIG	Oct-00	fb	
69	LAD pump on / off			100	PER	Jul-99		
136	Feedline pressure downstrm micrometer valve	CEC	2359	50	PSIA	Jul-99	se	
calc	Feedline pressure downstrm heat xchanger	SENSOTRON	1517-3	50	PSIA			
167	Feedline pressure downstrm heat xchanger	TELEDYNE TABER	850786	100	PSIA	Nov-00	fb	
39	Raw millivolts PT4	SENSOTRON	1517-3	139 TO 540	R	n/a	se	
204	LN2 pump line temperature	TYPE E		27 TO 558	R		se	11
205	LN2 Return line temp.	TYPE E		27 TO 558	R		se	11
216	Diff pump #1 water outlet	TYPE K		-100 TO 500	K		se	11
217	Diff pump #2 water outlet	TYPE K		-100 TO 500	K		se	11
218	Diff pump #1oil	TYPE K		-100 TO 500	K		se	11
219	Diff pump #2 oil	TYPE K		-100 TO 500	K		se	11
220	LH2 F/D rov 20-601	TYPE E		27 TO 558	R		se	13
222	LH2 F/D rov 20-676	TYPE E		27 TO 558	R		se	13
224	LH2 Vent line @ chamber penetration	TYPE E		27 TO 558	R		se	13
225	LH2 Vent line flow box	TYPE E		27 TO 558	R		se	8,13
226	LN2 Heat Exchanger #1	TYPE K		-100 TO 500	K		se	14
227	LN2 Heat Exchanger #2	TYPE K		-100 TO 500	K		se	14
228	LN2 Heat Exchanger #3	TYPE K		-100 TO 500	K		se	14
231	LN2 heat exchanger rov 20-1704	TYPE E		27 TO 558	R		se	17
232	LN2 supply rov 20-1700	TYPE E		27 TO 558	R		se	10
233	LH2 vent heat exchanger water discharge temp	TYPE E		27 TO 558	R		se	13
234	Flowbox temperature - feedback	TYPE E		27 TO 558	R		se	8
235	Ice bath reference pressure vessel temp	TYPE E		27 TO 558	R		se	6
236	DP1 hoffman box temperature	TYPE E		27 TO 558	R		se	6
237	Engine feedline temp before ROV's	TYPE E		27 TO 558	R		se	
238	MLI He purge temperature	TYPE E		28 TO 558	R		se	

Channel	Measurement Description	MFG	Serial No.	Range	Units	Cal	Card	Group
239	ISUS Vent flow temperature	TYPE E		27 to 558	R		se	
240	Cabinet 39 air temperature	TYPE E		28 to 558	R		se	
241	Chamber air temperature	TYPE E		28 TO 558	R		se	
142	Ring 1 #1	TYPE E		27 TO 558	R		se	
143	Ring 1 #4	TYPE E		27 TO 558	R		se	
144	Ring 1 #6	TYPE E		27 TO 558	R		se	
145	Ring 1 #8	TYPE E		27 TO 558	R		se	
146	Ring 2 # 11	TYPE E		27 TO 558	R		se	
147	Ring 2 # 15	TYPE E		27 TO 558	R		se	
148	Ring 3 # 21	TYPE E		27 TO 558	R		se	
149	Ring 3 # 25	TYPE E		27 TO 558	R		se	
150	Ring 4 #27	TYPE E		27 TO 558	R		se	
151	Ring 4 #31	TYPE E		27 TO 558	R		se	
152	Ring 5 # 37	TYPE E		27 TO 558	R		se	
153	Ring 5 # 41	TYPE E		27 TO 558	R		se	
154	Ring 6 # 43	TYPE E		27 TO 558	R		se	
155	Ring 6 # 47	TYPE E		27 TO 558	R		se	
156	Ring 7 # 53	TYPE E		27 TO 558	R		se	
157	Ring 7 # 57	TYPE E		27 TO 558	R		se	
158	Ring 8 # 59	TYPE E		27 TO 558	R		se	
159	Ring 8 # 63	TYPE E		27 TO 558	R		se	
160	Ring 9 # 67	TYPE E		27 TO 558	R		se	
161	Ring 9 # 69	TYPE E		27 TO 558	R		se	
162	Ring 9 # 71	TYPE E		27 TO 558	R		se	
163	Ring 9 # 73	TYPE E		27 TO 558	R		se	
164	Ring 9 # 74	TYPE E		27 TO 558	R		se	
37	DPT4 diaphragm temperature (active TVS region)	LAKESHORE		27 to 855	R		ce	
40	PT4 diaphragm temperature	SENSOTRON		140 / 540	R		se	
1	Tank fluid 44 inch	LAKESHORE		27 to 855	R		ce	
2	Tank fluid 43 inch	LAKESHORE		27 to 855	R		ce	
3	Tank fluid 41 inch	LAKESHORE		27 to 855	R		ce	
4	Tank fluid 40 inch	LAKESHORE		27 to 855	R		ce	
5	Tank fluid 37.5 inch	LAKESHORE		27 to 855	R		ce	
6	Tank fluid 35 inch	LAKESHORE		27 to 855	R		ce	
7	Tank fluid 32.5 inch	LAKESHORE		27 to 855	R		ce	
8	Tank fluid 30 inch	LAKESHORE		27 to 855	R		ce	
9	Tank fluid 27.5 inch	LAKESHORE		27 to 855	R		ce	
10	Tank fluid 25 inch	LAKESHORE		27 to 855	R		ce	
11	Tank fluid 22.5 inch	LAKESHORE		27 to 855	R		ce	
12	Tank fluid 20 inch	LAKESHORE		27 to 855	R		ce	
13	Tank fluid 17.5 inch	LAKESHORE		27 to 855	R		ce	
14	Tank fluid 15 inch	LAKESHORE		27 to 855	R		ce	
15	Tank fluid 12.5 inch	LAKESHORE		27 to 855	R		ce	
16	Tank fluid 10 inch	LAKESHORE		27 to 855	R		ce	
17	Tank fluid 7.5 inch	LAKESHORE		27 to 855	R		ce	
18	Tank fluid 6 inch	LAKESHORE		27 to 855	R		ce	

Channel	Measurement Description	MFG	Serial No.	Range	Units	Cal	Card	Group
67	Tank fluid 5 inch	LAKESHORE		27 to 855	R		ce	
20	Tank fluid 4 inch	LAKESHORE		27 to 855	R		ce	
21	TVS 10 inch from LAD bottom	LAKESHORE		27 to 855	R		ce	
22	TVS 10 inch from LAD top	LAKESHORE		27 to 855	R		ce	
23	Inlet line of active TVS	LAKESHORE		27 to 855	R		ce	
24	Outlet line of active TVS	LAKESHORE		27 to 855	R		ce	
25	MLI tank surface, 5/8" below equator at 90 deg	LAKESHORE		27 to 855	R		ce	
26	MLI tank surface, 17.5" below equator at 90 deg	LAKESHORE		27 to 855	R		ce	
27	MLI layer 25, 90 deg at equator	LAKESHORE		27 to 855	R		ce	
28	MLI layer 50, 90 deg at equator	LAKESHORE		27 to 855	R		ce	
29	MLI layer 75, 90 deg at equator	LAKESHORE		27 to 855	R		ce	
49	Feedline heat xchanger surface center	LAKESHORE		27 to 855	R		ce	
68	Feedline fluid temp	LAKESHORE		27 to 855	R		ce	
32	LAD vent line fluid temp	LAKESHORE		27 to 855	R		ce	
33	Feedline heat xchanger surface outlet	LAKESHORE		27 to 855	R		ce	
34	Feedline heat xchanger surface inlet	LAKESHORE		27 to 855	R		ce	
35	Feedline heat xchanger fluid outlet	LAKESHORE		27 to 855	R		ce	
36	Feedline heat xchanger fluid inlet	LAKESHORE		27 to 855	R		ce	
71	ROV 20-1854 position			1000	OFN	n/a	se	
72	ROV 20-1856 position			1000	OFN	n/a	se	
73	VPV 20-661 position			100	PER	n/a	se	
74	VPV 20-662 position			100	PER	n/a	se	
75	VPV 20-663 position			100	PER	n/a	se	
76	ROV 20-1859 open indication			1000	OFN	n/a	se	
77	ROV 20-1859 close indication			1000	OFN	n/a	se	
178	Diffusion pump primer	GRAN.-PHILLIP		10-3 TO 760	TORR		se	23
179	LN2 tank vacuum jacket	GRAN.-PHILLIP		10-3 TO 760	TORR		se	23
180	LH2 F/D vac jacket @ rov 1502	GRAN.-PHILLIP		10-3 TO 760	TORR		se	13
181	LN2 tank vacuum jacket pump (ctrl GE room)	GRAN.-PHILLIP		10-3 TO 760	TORR		se	23
182	Chamber wall box	MKS		1,000.00			se	23
183	Chamber wall box	MKS		1,000.00	TORR		se	23
184	Pump one foreline (outside pump house)	GRAN.-PHILLIP		10-3 TO 760	TORR		se	24
calc	Internal chamber pressure	MKS		0.01 TO 1000	UTORR			6
calc	Chamber wall box	GRANVIL-PHILLIP		0.01 TO 1000	UTORR			6
calc	Internal chamber pressure	GRANVIL-PHILLIP		0.01 TO 1000	UTORR			6
188	RGA Pressure	MKS		1,000.00			se	24
calc	RGA Pressure	GRANVIL-PHILLIP		0.01 TO 1000	UTORR			24
192		GRAN.-PHILLIP		10-3 TO 760	TORR		se	24

Channel	Measurement Description	MFG	Serial No.	Range	Units	Cal	Card	Group
193	test article v.j. piping - top level	GRAN.-PHILLIP		10-3 TO 760	TORR		se	13
194		GRAN.-PHILLIP		10-3 TO 760	TORR		se	24
185	Raw millivolts for VP3010	MKS		5300	MV		se	
186	Raw millivolts for VP3011	GRANVILL-PHILLI		-120	MV		se	
187	Raw millivolts for VP3012	GRANVIL-PHILLIP		4000	MV		se	
189	Raw millivolts for VP3014	GRANVIL-PHILLIP		-120	MV		se	

APPENDIX B—AEROSPACE-INDUSTRY TECHNOLOGY PROJECT SUPPORTING PERSONNEL

EP91		
EP92	Kevin Pedersen	Project Engineer/Mechanical Systems Engineer
EP93	Robert Lake	Instrumentation Engineer
EP93	Jim Crawford	Data Systems Engineer
EP94	Jacob Yarbrough	Control Systems Engineer

LB&B Technicians:

Mech	David Cole	Lead
Mech	Bo Jones	
Mech	Culley Cantrell	
Instr	Ralph Keller	Lead
Instr	Doug McBride	
Instr	Tabitha Neely	
Cont	Joel Wheeler	Lead
Cont	Greg Wirt	
Cont	Cleveland Green	

Support Personnel:

CR20	Rosalyn Patrick	Safety
LB&B	John Webster	Safety
HEI	Alvin Eidson	Safety
HEI	Bill Horn	Quality
LB&B	Dennis Crawford	Quality
LB&B	Donald Lott	Welder/Fitter
LB&B	Van Gassoway	Welder/Fitter
CSC	Fausto Latini	Data Systems Support
CSC	Wade Farris	Data Systems Support
LB&B	Paul Readus	Drafting
LB&B	Tony Hightower	Drafting
LB&B	Paula Nave	Documentation
LB&B	Tammie Rockhill	Configuration Control
LB&B	Jon Keel	Area Coordinator
LB&B	Ron Beasley	Area Coordinator

During Test Only:

EP92	Dennis Strickland	Test Conductor
EP92	Melanie Ramsey	Test Conductor
EP92	Alan Murphy	Test Conductor
EP92	Collie Kellet	Test Conductor
EP93	Keary Smith	Instrumentation Engineer
EP93	John Wiley	Instrumentation Engineer
EP93	Curtis Thompson	Instrumentation Engineer
EP93	Jason Elmore	Data Systems Engineer
EP94	David Jones	Control Systems Engineer
EP94	Ron Smith	Control Systems Engineer
EP94	Judith Gregory	Control Systems Engineer
CSC	Jay Carter	Data Systems Support
CSC	David Jarrell	Data Systems Support
CSC	Frankie Hinkle	Data Systems Support
CSC	Ken Dodd	Data Systems Support
LB&B	Larry Billions	Control Systems Technician

APPENDIX C—STUSTD LIQUID HYDROGEN SPACE FLIGHT SYSTEMS TEST REQUEST SHEET (1/25/99)

STUSTD Boil-off & Engineering Checkout

Test Name: STUSTD LHSFS Boil-off and Engineering Checkout
(Sections 5.1, 5.2, 5.5, 5.6, 5.10, and 5.11 of the STUSTD Test Plan). Sections 5.3 [Simulated Launch] and 5.4 [Boil-off Without Cold Walls] are no longer part of the boil-off or Engineering Checkout plans. The Simulated Launch will be part of the 30-day Mission Simulation.

Test Project ID: **Test Requester:** Ed Cady, Al Olsen, [Boeing-HB], Dan Vonderwell, [Leon Hastings, Robin Flachbart]

Test Date: Feb. 3, 1999 **Test Conductor:** Kevin Pedersen

Test Objectives:

- Develop a data base for the performance of the Solar Thermal Upper Stage Technology Demonstrator (STUSTD) Liquid Hydrogen Storage and Feed System (LHSFS) before the 30-day mission simulation. Data obtained from these tests will characterize and verify the expected performance of the passive and active TVS, the tank heaters, and the valve system.
- Fill the STUSTD tank with LH_2 and monitor thermodynamic characteristics (Sections 5.1 and 5.2 of the Test Plan).
- Measure boil-off with LN_2-cold-walls to determine the heat leak into the tank system (Section 5.5 of the Test Plan)
- The tank will be slowly pressurized from the pressure maintained during the boil-off tests (Section 5.5 of the STUSTD Test Plan, 16.5 to 17 psia) to the operating pressure of 45 psia. The flow metering valve will be calibrated to 2.0 lbm/hr. The Active Thermodynamic Venting System (ATVS) and Passive Thermodynamic Venting System (PTVS) thermal extraction capability will be characterized as a function of burn (vent) time and tank fill level.
- The tank pressure will be controlled to 45 ± 4 psia throughout the entire Engineering Checkout process.
- After the Engineering Checkout process, the tank will be drained and safed per sections 5.10 and 5.11.

Test Fluid: LH_2

Approximate Test Duration: ~312 hrs (13 days) [refer to attached Engineering Test Process description and timeline and to the Test Plan]

DSU Sampling Rate: Per STUSTD LHSFS Test Plan

High: 1 Hz [1 sample per second] (used when test data is changing in a transitory manner, such as during a simulated engine burn or initialization of the ATVS)

Mid: 0.1 Hz [1 sample per 10 seconds] (used when the high data rate is not indicated)

Low: 0.0167 Hz [1 sample per 60 seconds] (*may be used during periods of relative inactivity as determined by the Boeing representative*)

Sampling Start/End Time: Data collection will continue from Section 5.1 (Tank safing), through Section 5.6 (Engineering Checkout), and terminate after the tank is safed again (Section 5.11)

Test data should be dumped to the location accessible by Boeing (i.e. the Jetson server) every **two hours** so that Boeing-HB can track the progress of the tests. **This is a modification to the "every 6 hours" called out in the Test Plan**. The increased frequency of the data dumps is due to the fact that the frequently updated Excel file is no longer available.

Vacuum Chamber/Pump: Evaculate the vacuum chamber to **$1X10^{-6}$ Torr or less and maintain that value for at least 8 hours prior to tanking and during the tank safing and inerting operation. . Hard vacuum conditions are to be maintained throughout the remainder of testing.** The MLI GHe purge will not be used.

AT NO TIME IS THE PRESSURE EXTERNAL TO THE TANK (IN THE VACUUM CHAMBER) TO EXCEED THE PRESSURE INSIDE THE TANK.

Vacuum Chamber Purge: Dry GN_2 (dewpoint 395°R or lower), one atmosphere.

Vacuum Chamber Coldwalls: Cold walls are used at steady state (~140°R) for Section 5.5 of the Test Plan; the cold walls will be maintained throughout the boil-off test and the Engineering Checkout (Sections 5.5 and 5.6). Cold walls will have to reach a steady-state value prior to the cold wall boil-off test.

Back Pressure Control System: Setup ice bath and constant pressure volume/ice bath two days prior to testing to obtain steady state environment. Check ice bath at 1 to 2 hour intervals. Fill or pack as needed to prevent temperature drift. Document all operations in the test log

Flow Meter Box: Setup all flow meter heating purges to 39 ^{o}C a minimum of 24 hours prior to test to obtain steady-state conditions on all hardware. Document all operations in the test log

Other Vacuum Systems: All vacuum jacketed systems are pumped down prior for three days prior to testing (Engineering Checkout)

RGA Operation: Periodic as needed (write DSU times and file # on plots)

Camera Operation: If possible (i.e. if the tapes are external to the vacuum chamber and can be replaced) it would be preferable to periodically operate at least one camera to capture any events internal to the chamber.

Test Article Internal Purge: Tank is purged with 7 ± 1 psig (~22 psia) GHe in Section 5.1 of the Test Plan. **AT NO TIME IS THE PRESSURE EXTERNAL TO THE TANK (IN THE VACUUM CHAMBER) TO EXCEED THE PRESSURE INSIDE THE TANK.**

Test Article Fill Level: 284 lbm LH_2 prior to initiation of Section 5.6 of Test Plan. Filled until TT-04 reads liquid H_2.
284 – 279 lbm LH_2 during metering valve calibration
279 – 270 lbm LH_2 during high-fill-level ATVS / PTVS characterization
270 – 165 lbm LH_2 during "high power" vent
165 – 159 lbm LH_2 during medium-fill-level ATVS / PTVS characterization
159 – 85 lbm LH_2 during "high power" vent
85 – 79 lbm LH_2 during low-fill-level ATVS / PTVS characterization

Test Article Heat Guards: N/A

Test Article Shroud Purge: N/A

Test Article Shroud: N/A

Ground Hold Duration: Not Tested

Test Article Ullage Pressure Control: Applicable only during boil-off tests (Sections 5.4 and 5.5 of Test Plan)

Tank Replenishment: N/A. Tank is drained, safed, and inerted after the Engineering Checkout.

Chamber Pressurization: Hard vacuum (1X10-6 Torr) is maintained throughout the boil-off testing and the Engineering Checkout (Section 5.6).

Specific Test Hardware Parameters:

Real time adjustments of some of the parameters listed below may be required based on actual measured STUSTD heat leak. Document all operations in the test log.

ATVS Pump: Absolute minimum setting: 22Hz (~400 RPM pump rate)
"Low" setting: 30.5 Hz (550 RPM)
"High" setting: 39 Hz (700 RPM)
Absolute maximum setting: 50 Hz (900 RPM)

Tank Heaters: (4) heaters, set at 20, 30, or 40 Watts total as indicated

Flow Rate: (ROV 20-1854 opened) 2.0 lbm/hr

Tank Pressures: Use the backpressure control subsystem to maintain the selected ullage pressure (16.5 – 17 psia) within a tolerance of ± 0.001 psia.

The engineering checkout testing will begin with a pressure of 16.5 – 17 psia. The tank will be allowed to pressurize to the nominal operating pressure of 45± 4 psia.

The 45 ± 4 psia nominal operating pressure will be maintained during Engineering tests.

Additional General Instructions and Comments:

- External HEX plate heaters and / or the valve panel hot-water heat exchanger should be on at all times before flowing to the valve panel. The H_2 flowing through the valve panel should **never** drop below 360°R.
- Generally, whenever the tank heaters are on the ATVS pump should be on at the "low" setting. *Note that this does not constitute "activation" of the ATVS, since the flow control valve has not been opened and there is no thermal extraction.* The pump is turned on when the heaters are on to avoid non-homogenous stratification issues and to avoid "hot-spots" in the tank. **The ATVS pump will NOT be turned on during the two Engineering Test Process high power vents (see attached timeline) even through the tank heaters are activated.** Since ROV 20-1854 is opened and LH_2 is being removed from the tank, this would cause the ATVS to extract heat from the tank and would lower the tank pressure to unacceptable levels.
- There is no simulated launch during the Engineering Tests. The simulated launch from Section 5.3 of the Test Plan is now part of the 30-day mission simulation.
- There is no "without cold walls" boil-off test during the Engineering Tests. Data with hot walls and LN_2 in the chamber will be taken as part of the 30-day mission simulation.
- Tank is to be drained, safed, and inerted after the Engineering Tests (prior to the 30-day mission simulation).
- Tank safing and inerting, boil-off stability requirements, etc. from Sections 5.1 – 5.11 can be found in the STUSTD LHSFS Test Plan.
- Specific comments on the Engineering Test Process, Section 5.6 of the Test Plan, can be found on the pages following.
-

Engineering Checkout (Section 5.6) Comments and Instructions:

A printout of the revised Engineering Test Process, Section 5.6 of the Test Plan, is found at the end of this document.

As a general rule, the following things are important, and the associated actions in the Engineering Test Process should be followed as closely as possible:

- Vent ("burn", ROV 20-1854 open) times
- Heater power
- End of test-section tank pressure (45 psia). In other words, we always want to be at 45 psia before going on to the next test section
- Data rate switches

On the other hand, other things are not important and represent analytic approximations. They should not be followed, since they are essentially educated guesses at this time (in fact, the purpose of the Engineering Test is to refine these analytic models). Any controlling code generally should ***not*** key on the following parameters:

- Self-pressurization hold times
- Tank pressures after each item
- Tank fluid levels

STUSTD Engineering Test Process Description and Goals

The Engineering Test occurs the baseline cold wall boil-off test (Section 5.5 of the Test Plan).

Before the Engineering Tests, the tank has stabilized with LH_2 at ~17 psia to the level of TT-04, which corresponds to a liquid level of about 40 inches.

For each of the following sections, **the important parameter is to get the tank pressure back to 45 psia before going on to the next section**. This will take a certain amount of time, depending upon, for example, whether or not the tank heaters are on. Generally, the amount of time it takes to get back to 45 psia and the fluid level in the tank are not important -- it **is** important to get back to 45 psia before going on to the next section. **The times and tank levels are estimates only**. The point of the entire Engineering Test Process is to refine the computational models to reflect the experimental results, not to try to make the experimental results match the models.

One exception is the burn (vent by opening ROV 20-1854) times called out in the Engineering Test Process. If the Process calls for a 30 minute burn (vent) at a certain data acquisition rate, Boeing would like to keep these times as written. However, "hold" times can (and will) be flexible to allow the tank pressure enough time to reach 45 psia before the next section or segment of the current section.

<u>SECTION A (Items 0 – 19 of the Engineering Test Process)</u>

Brief Description

Essentially, we are trying to pressurize the tank to 45 psia (and learn a few things along the way). The tank heaters begin at 40 Watts, and then are reduced to 20 Watts in an attempt to slowly raise the tank pressure. The goal of this section is to have a final pressure of 45 psia in the tank after a certain amount of time has elapsed. The important parameter is getting to the tank pressure of 45 psia, *not* the amount of time that it takes to get there (although, of course, we are interested in knowing how long it takes). The heaters will be operated in 6-hour blocks, <u>until 45 psia is reached</u>. Generally, the ATVS pump is activated to de-stratify the tank contents. When the tank reaches 45 psia, stop Section A and go on to Section B.

The important thing is to get the tank to 45 psia. Period. The pressures in the P(psi) column of the Engineering Test Process spreadsheet are analytical *estimates*, and are by no means meant to be used for a controlling logic. We want to heat the tank until the pressure reaches 45 psia under saturated, mixed conditions, and the pressures after each heater cycle will be whatever it is.

Item #17 says that we should run the tank heaters for 106 minutes – then the tank will be at 45 psia. Again, this is an estimate. It may reach 45 psia before or after this time. If we reach item #18 before the tank is at 45 psia, continue to heat the tank / run the pump until 45 psia is reached. When the tank reaches 45 psia, stop Section A and go on to Section B.

The operation of the pump, tank heaters, pressure transducers, temperature transducers, data acquisition system, controller code, etc. will be verified in this section. We will also get some additional information about the tank heat leak and fluid stratification from the self-pressurization portion of the test.

Goals

We want to slowly bring the tank from a pressure of ~18 psia to 45 psia. The end pressure is important, not the time it takes to get there. We will make sure that the tank heaters, pump, temperature and pressure transducers, data acquisition system, etc. are all operating properly. Some tank heat-leak and stratification data will be taken by monitoring the self-pressurization rate.

Tank Initial State

284.1 lbm (less boiloff) LH2 at 16.5 – 17 psia. The fluid level is near TT-04.

What is Important?

Getting the tank pressure to 45 psia. Making sure that this is the mixed fluid pressure. The time it takes to get the tank to 45 psia is not important, but we'd like to run the heaters in 6-hour blocks.

Tank Final State

The 284.1 lbm (less boiloff) LH2 will be well mixed at 45 psia at a fluid level slightly above TT-01.

<u>SECTIONS B & C (Items 20 – 69 of the Engineering Test Process)</u>

Brief Description

This purpose of these sections is to verify the remote operation of ROV 20-1854, to adjust the metering valve in the GH_2 vent line (upstream of TT-31 and PT-01), and to provide some preliminary results for the LHSFS PTVS thermal extraction rate and thermodynamic performance. The metering valve needs to be adjusted to ensure that we're flowing 2.0 lbm/hr GH_2 when ROV 20-1854 is opened. That way, we can determine key STUSTD parameters later on at the appropriate flow rate. Also, the 2.0 lbm/hr flow rate is used for the 30-day mission simulation.

TRANSIENT BEHAVIOR:
The initial flow rate may be < 2 lbm/hr. As such, we should wait several (5) minutes before adjusting the metering valve to a value of 2 lbm/hr. Boeing-HB would like to measure and record the transient mass flow rate as a function of time.

Burn (vent by opening ROV 20-1854) times are given in the Test Process. It's important that we try to stick with these times. What *is* flexible, on the other hand, are the hold times dictated by items 29, 39, 49, 59, and 69. **Again, the important thing is to get the ullage pressure back up to 45 psia after items 29, 39, 49, 59, and 69, not the hold time it takes to get there. Run the pump on low for 5 minutes during the unvented hold times** (probably towards the end, when the pressure is approaching 45 psia) to mix the fluid.

Goals

Primarily, to adjust the metering valve so that we are flowing 2.0 lbm/hr GH_2 when ROV 20-1854 is opened. We'll also collect some very good data on the PTVS system performance.

Tank Initial State

284.1 lbm (less boiloff) LH2 at 45 psia. Fluid level is slightly above TT-01.

What is Important?

It is important that the metering valve is adjusted to deliver 2.0 lbm/hr of GH_2 when ROV 20-1854 is opened and transients have died down. It is also important that we try to stick to the burn times of these sections, although these can be flexible if the need arises (i.e., lack of test time, etc.). The given hold times are not important (in fact, probably are not entirely correct), but the tank pressure at the end of the hold time is important. Any "burn" controlling logic should use the burn times indicated in these sections. Any "hold" controlling logic should not be hold time-oriented, but should be pressure-oriented.

Tank Final State

~279 lbm (less boiloff) LH2 at 45 psia. Fluid level is between TT-01 and TT-02.

SECTIONS D & E (Items 70 – 137 of the Engineering Test Process)

Brief Description

These sections are used to determine the heat extraction capabilities of the PTVS and ATVS for different burn times and different pump speeds with a near-full tank. Recall that the ATVS is "activated" by opening ROV 20-1854 with the pump on. After each burn that the PTVS or ATVS has been used (30 minutes in Section D, and one hour in Section E) the tank will be allowed to self-pressurize (no tank heaters) back to 45 psia. The self-pressurization hold time indicated in items 81, 93, 103, 115, 127, and 137 is an estimate. **The important thing is to get the pressure back up to 45 psia after the actions preceding the hold**. Run the pump on low for at least 5 minutes during the unvented hold times (probably towards the end, when the pressure is approaching 45 psia) to mix the fluid.

Goals

We are trying to determine the heat extraction capabilities of the passive and active thermal venting systems for different burn times with a near-full tank.

Tank Initial State

~279 lbm (less boiloff) LH2 at 45 psia. Fluid level is between TT-01 and TT-02.

What is Important?

It is important that we try to stick to the burn times of these sections, although these can be flexible if the need arises (i.e., lack of test time, etc.). The given hold times are not important (in fact, probably are not entirely correct), but the tank pressure at the end of the hold time is important -- that is, we want to be back at 45 psia after each hold, before the next burn. Any "burn" controlling logic should use the burn times indicated in these sections. Any "hold" controlling logic should not be hold time-oriented, but should be pressure-oriented.

Tank Final State

~270 lbm (less boiloff) LH2 at 45 psia. Fluid level is between TT-03 and TT-04.

SECTION F (Items 138 – 150 of the Engineering Test Process)

Brief Description

This is a "high power vent". DO NOT RUN THE ATVS PUMP WHEN THE TANK HEATERS ARE TURNED ON. Essentially, it is intended to vent ("burn") a great deal of fluid out of the tank at a near-constant pressure. Note that the tank heaters are on at 30 Watts.

High Power Vent:

A reasonable amount of operator (i.e. *human*) observation and perhaps intervention will be required for this section. ***If the tank ullage pressure gets below 41 psia, this means that we are extracting too much energy, and the power to the tank heaters will have to be increased to 40 Watts. On the other hand, if the tank pressure gets above 49 psia, we are putting too much energy into the tank and the tank heater power will have to be decreased to 20 Watts.*** If the heater power has to be changed, this is fine -- as long as the time and the heater power is recorded.

We would like to vent/burn H2 for around 50 hours. It is somewhat important that we stick to this time (we are trying to have ~ 170 lbm LH2 left in the tank after the burn/vent), but we can be flexible if necessary.

After High Power Vent:

According to items 144 – 150, we are turning off the heater, continuing venting for approximately 2.5 hours, closing ROV 20-1854, and then allowing the tank to self-pressurize. This is all in an attempt to get the tank pressure back to 45 psia after the high power vent. The operator will need to exert some control at this point. That is: **if we are above 45 psia after the 50 hour vent, turn off the heaters, vent until the tank is at ~44.5 psia, close ROV 20-1854, and then allow the tank to self-pressurize to 45 psia. If we are below 45 psia after the 50 hour vent, turn off the heaters, close ROV 20-1854, and allow the tank to self-pressurize to 45 psia.** If we are well below 45 psia (say, 42 psia) after the 50 hour vent, the tank heaters can be turned on for a little bit to raise the pressure to 45 psia more quickly. Run the pump on low for at least 5 minutes during the unvented hold times (probably towards the end, when the pressure is approaching 45 psia) to mix the fluid.

The end result of this section is that there is much less fluid in the tank after the high power vent. This will allow us to test the performance of the passive and active thermal venting systems with the LADs only partially submerged. Since the LADs are no longer completely submerged, heat will begin to be extracted from the tank fluid by condensation effects in addition to convection effects. We are very interested in this data.

Goals

Reduce the amount of fluid in the tank so that we can test the P/ATVS performance with the LADs only partially submerged.

Tank Initial State

~270 lbm (less boiloff) LH2 at 45 psia. Fluid level is between TT-03 and TT-04.

What is Important?

The vent/burn time is important, since we are trying to end up with ~170 lbm of fluid in the tank at the end of this section. After the 50 hour vent/burn, the operator should return the tank pressure to 45 psia using the methods described in the "Brief Description". *A return to 45 psia is important.*

Tank Final State

~170 lbm (less boiloff) LH2 at 45 psia. Fluid level is between TT-09 and TT-10.

SECTION G (Items 151 – 192 of the Engineering Test Process)

Brief Description

This section is used to determine the heat extraction capabilities of the PTVS and ATVS for different pump speeds with a partially-filled tank (LAD surface is exposed).

After each hour-long burn that the PTVS or ATVS has been used, the tank will be allowed to self-pressurize (no tank heaters) back to 45 psia. The hour-long burn times are important. The self-pressurization hold times indicated in items 170, 182, and 192 are estimates. The important thing is to get the pressure back up to 45 psia after the actions preceding the hold. Run the pump on low for at least 5 minutes during the self-pressurization hold times (probably towards the end, when the pressure is approaching 45 psia) to mix the fluid.

Goals

We are trying to determine the heat extraction capabilities of the passive and active thermal venting systems for different burn times with a partially-full tank.

Tank Initial State

~170 lbm (less boiloff) LH2 at 45 psia. Fluid level is between TT-09 and TT-10.

What is Important?

It is important that we try to stick to the burn times of these sections, although these can be flexible if the need arises (i.e., lack of test time, etc.). The hold times of items 162, 164, 166, and 168 are important. We want this data for these hold times. However, the self-pressurization hold times are not important (in fact, probably are not entirely correct), but the tank pressure at the end of the hold time is important -- that is, we want to be back at 45 psia after each hold, before the next burn.

Tank Final State

~159 lbm (less boiloff) LH2 at 45 psia. Fluid level is around TT-10.

SECTION H (Items 193 - 205 of the Engineering Test Process)

Brief Description

This is another "high power vent". DO NOT RUN THE ATVS PUMP WHEN THE TANK HEATERS ARE TURNED ON. Essentially, it is intended to vent ("burn") a great deal of fluid out of the tank at a near-constant pressure. Note that the tank heaters are on at 30 Watts.

The goal of this Section is to end up with ~90 lbm of LH2 left in the tank.

High Power Vent:

Much like Section F, a reasonable amount of operator (i.e. *human*) observation and perhaps intervention will be required for this section. If the tank ullage pressure gets below 41psia, this means that we are extracting too much energy, and the power to the tank heaters will have to be increased to 40 Watts. On the other hand, if the tank pressure gets above 49 psia, we are putting too much energy into the tank and the tank heater power will have to be decreased to 20 Watts (or even turned off). If the heater power has to be changed, this is fine -- as long as the time and the heater power is recorded.

We would like to vent/burn H2 for around 35 hours. It is of minor importance that we stick to this time (we are trying to have ~90 lbm LH2 left in the tank after the burn/vent).

After High Power Vent:

According to items 199 – 205, we are turning off the heater, continuing venting, closing ROV 20-1854, and then allowing the tank to self-pressurize. This is all in an attempt to get the tank pressure back to 45 psia after the high power vent. The operator will need to exert some control at this point. That is: **if we are above 45 psia after the 35 hour vent, turn off the heaters, vent until the tank is at ~44.5 psia, close ROV 20-1854, and then allow the tank to self-pressurize to 45 psia. If we are below 45 psia after the 35 hour vent, turn off the heaters, close ROV 20-1854, and allow the tank to self-pressurize to 45 psia.** If we are well below 45 psia (say, 42 psia) after the 35 hour vent, the tank heaters can be turned on for a little bit to raise the pressure to 45 psia more quickly. Run the pump on low for at least 5 minutes during the unvented hold times (probably towards the end, when the pressure is approaching 45 psia) to mix the fluid.

The end result of this section is that there is much less fluid in the tank after the high power vent. This will allow us to test the performance of the passive and active thermal venting
systems with the LADs mostly uncovered. Condensation effects will dominate the heat extraction capabilities of the TVS. We are very interested in this data.

Goals

Reduce the amount of fluid in the tank so that we can test the P/ATVS performance with the LADs mostly uncovered.

Tank Initial State

~159 lbm (less boiloff) LH2 at 45 psia. Fluid level is around TT-10.

What is Important?

The vent/burn time is relatively important, since we are trying to end up with ~90 lbm of fluid in the tank at the end of this section. After the 35 hour vent/burn, the operator should return the tank pressure to 45 psia using the methods described in the "Brief Description". A return to 45 psia is important.

Tank Final State

~90 lbm (less boiloff) LH2 at 45 psia. Fluid level is between TT-13 and TT-14.

SECTION I (Items 206 – 246 of the Engineering Test Process)

Brief Description

This section is used to determine the heat extraction capabilities of the PTVS and ATVS for different pump speeds with a partially-filled tank (LAD surface is mostly exposed).

After each hour-long burn that the PTVS or ATVS has been used, the tank will be allowed to self-pressurize (no tank heaters) back to 45 psia. The hour-long burn times are important. The self-pressurization hold time indicated in items 225 and 237 is an estimate. The important thing is to get the pressure back up to 45 psia after the actions preceding the hold. Run the pump on low for at least 5 minutes during the self-pressurization hold times (probably towards the end, when the pressure is approaching 45 psia) to mix the fluid.

Goals

We are trying to determine the heat extraction capabilities of the passive and active thermal venting systems for different burn times with a partially-full tank (LADs mostly exposed).

Tank Initial State

~90 lbm (less boiloff) LH2 at 45 psia. Fluid level is between TT-13 and TT-14.

What is Important?

It is important that we try to stick to the burn times of these sections, although these can be flexible if the need arises (i.e., lack of test time, etc. However, the self-pressurization hold times are not important (in fact, probably are not entirely correct), but the tank pressure at the end of the hold time is important -- that is, we want to be back at 45 psia after each hold, before the next burn.

Tank Final State

~79 lbm (less boiloff) LH2 at 45 psia. Fluid level is between TT-13 and TT-14.

No.	ETT	Description	t (min)	Heater	Pump	Flow	Load	P(psi)	Comments	
	Initial Data rate is LOW									
0	00:00:00:00	Tank filled to TT-04 @ 18 psia					284.10	18.00		
1	00:00:00:00	Vent and fill valves closed					284.10	18.00		
2	00:00:00:00	Hold 6.00 hours	360				284.10	18.66		
3	00:06:00:00	**Activate pump**			Low		284.10	18.66		
4	00:06:00:00	Hold 15 minutes	15		Low		284.10	18.68	Monitor PT-02, PT-03, and DP-Pump	
5	00:06:15:00	**Activate heater to 40 W**		40.00	Low		284.10	18.68		
6	00:06:15:00	Hold 6.00 hours	360	40.00	Low		284.10	23.39		
7	00:12:15:00	**Deactivate pump**		40.00			284.10	23.39	Monitor PT-0 [illegible] Pump	
8	00:12:15:00	Hold 2.00 hours	120	40.00			284.10	25.09		
9	00:14:15:00	**Activate pump**		40.00	Low		284.10	25.09	Monitor PT-0 [illegible] Pump	A
10	00:14:15:00	Hold 6.00 hours	360	40.00	Low		284.10	30.32		
11	00:20:15:00	**Deactivate pump**		40.00			284.10	30.32		
12	00:20:15:00	Hold 2.00 hours	120	40.00			284.10	32.19	Monitor PT-0 [illegible] Pump	
13	00:22:15:00	**Activate pump**		40.00	Low		284.10	32.19		
14	00:22:15:00	Hold 6.00 hours	360	40.00	Low		284.10	37.90		
15	01:04:15:00	Hold 6.00 hours	360	40.00	Low		284.10	43.93		
16	01:10:15:00	**Reduce Heaters to 20W**		20.00			284.10	43.93		
17	01:10:15:00	Hold 106 minutes	106	20.00			284.10	45.00	Monitor PT-02, PT-03, and DP-Pump	
18	01:12:00:60	**Deactivate pump**					284.10	45.00		
19	01:12:00:60	**Deactivate heater**					284.10	45.00		
20	01:12:00:60	Switch to high data rate					284.10	45.00		
21	01:12:00:60	Open ROV-04				2.00	284.10	45.00		
22	01:12:00:60	Hold 2 minutes	2			2.00	284.03	44.98		
23	01:12:02:60	Switch to medium data rate				2.00	284.03	44.98		
24	01:12:02:60	Hold 28 minutes	28			2.00	283.10	44.67		
25	01:12:30:60	Switch to high data rate				2.00	283.10	44.67		
26	01:12:30:60	Close ROV-04					283.10	44.67		
27	01:12:30:60	Hold 2 minutes	2				283.10	44.67		
28	01:12:32:60	Switch to medium data rate					283.10	44.67		
29	01:12:32:60	Hold 2.14 hours	129				283.10	45.00	Analyze data/adjust metering valve	
30	01:14:41:37	Switch to high data rate					283.10	45.00		
31	01:14:41:37	Open ROV-04				2.00	283.10	45.00		
32	01:14:41:37	Hold 2 minutes	2			2.00	283.03	44.97		
33	01:14:43:37	Switch to medium data rate				2.00	283.03	44.97		
34	01:14:43:37	Hold 28 minutes	28			2.00	282.10	44.67		B
35	01:15:11:37	Switch to high data rate				2.00	282.10	44.67		
36	01:15:11:37	Close ROV-04					282.10	44.67		
37	01:15:11:37	Hold 2 minutes	2				282.10	44.67		
38	01:15:13:37	Switch to medium data rate					282.10	44.67		
39	01:15:13:37	Hold 2.16 hours	129				282.10	45.00	Analyze data/ [illegible] tering valve	
40	01:17:22:55	Switch to high data rate					282.10	45.00		
41	01:17:22:55	Open ROV-04				2.00	282.10	45.00		
42	01:17:22:55	Hold 2 minutes	2			2.00	282.03	44.97		
43	01:17:24:55	Switch to medium data rate				2.00	282.03	44.97		
44	01:17:24:55	Hold 28 minutes	28			2.00	281.10	44.67		
45	01:17:52:55	Switch to high data rate				2.00	281.10	44.67		
46	01:17:52:55	Close ROV-04					281.10	44.67		
47	01:17:52:55	Hold 2 minutes	2				281.10	44.67		
48	01:17:54:55	Switch to medium data rate					281.10	44.67		
49	01:17:54:55	Hold 2.16 hours	129				281.10	45.00	Analyze data/adjust metering valve	

Pressurization tests include operation of ATVS pump when heater are on (except where noted). Heaters (40 W), initially a[t] 100%, are reduced to 50%

This series of tests are used to calibrate the metering valve and provide some initial thermal performance. No heaters used.

50	01:20:04:14	Switch to high data rate					281.10	45.00		
51	01:20:04:14	Open ROV-04				2.00	281.10	45.00		
52	01:20:04:14	Hold 2 minutes	2			2.00	281.03	44.97		
53	01:20:06:14	Switch to medium data rate				2.00	281.03	44.97		
54	01:20:06:14	Hold 28 minutes	28			2.00	280.10	44.66	This series of tests is used to verify metering valve setting and obtain baseline data for thermal performance with no ATVS. No heaters used.	
55	01:20:34:14	Switch to high data rate				2.00	280.10	44.66		
56	01:20:34:14	Close ROV-04					280.10	44.66		
57	01:20:34:14	Hold 2 minutes	2				280.10	44.67		
58	01:20:36:14	Switch to medium data rate					280.10	44.67		
59	01:20:36:14	Hold 2.16 hours	129				280.10	45.00		C
60	01:22:45:34	Switch to high data rate					280.10	45.00		
61	01:22:45:34	Open ROV-04				2.00	280.10	45.00		
62	01:22:45:34	Hold 2 minutes	2			2.00	280.03	44.97		
63	01:22:47:34	Switch to medium data rate				2.00	280.03	44.97		
64	01:22:47:34	Hold 28 minutes	28			2.00	279.10	44.66		
65	01:23:15:34	Switch to high data rate				2.00	279.10	44.66		
66	01:23:15:34	Close ROV-04					279.10	44.66		
67	01:23:15:34	Hold 2 minutes	2				279.10	44.67		
68	01:23:17:34	Switch to medium data rate					279.10	44.67		
69	01:23:17:34	Hold 2.16 hours	129				279.10	45.00		
70	02:01:26:52	Switch to high data rate					279.10	45.00		
71	02:01:26:52	Open ROV-04					279.10	45.00		
72	02:01:26:52	Activate pump			High	2.00	279.10	45.00		
73	02:01:26:52	Hold 2 minutes	2		High	2.00	279.03	44.97		
74	02:01:28:52	Switch to medium data rate			High	2.00	279.03	44.97		
75	02:01:28:52	Hold 28 minutes	28		High	2.00	278.10	44.66		
76	02:01:56:52	Switch to high data rate			High	2.00	278.10	44.66		
77	02:01:56:52	Close ROV-04			High		278.10	44.66		
78	02:01:56:52	Hold 2 minutes	2		High		278.10	44.67		
79	02:01:58:52	Deactivate pump					278.10	44.67		
80	02:01:58:52	Switch to medium data rate					278.10	44.67		
81	02:01:58:52	Hold 2.16 hours	129				278.10	45.00	This series of tests is used to establish ATVS performance for 2 pump speeds for "short" burn times. No heaters used.	
82	02:04:08:12	Switch to high data rate					278.10	45.00		
83	02:04:08:12	Open ROV-04					278.10	45.00		
84	02:04:08:12	Activate pump			Low	2.00	278.10	45.00		
85	02:04:08:12	Hold 2 minutes	2		Low	2.00	278.03	44.97		D
86	02:04:10:12	Switch to medium data rate			Low	2.00	278.03	44.97		
87	02:04:10:12	Hold 28 minutes	28		Low	2.00	277.10	44.66		
88	02:04:38:12	Switch to high data rate			Low	2.00	277.10	44.66		
89	02:04:38:12	Close ROV-04			Low		277.10	44.66		
90	02:04:38:12	Hold 2 minutes	2		Low		277.10	44.67		
91	02:04:40:12	Deactivate pump					277.10	44.67		
92	02:04:40:12	Switch to medium data rate					277.10	44.67		
93	02:04:40:12	Hold 2.16 hours	129				277.10	45.00		
94	02:06:49:32	Switch to high data rate					277.10	45.00		
95	02:06:49:32	Open ROV-04					277.10	45.00		
96	02:06:49:32	Hold 2 minutes	2			2.00	277.03	44.97		
97	02:06:51:32	Switch to medium data rate				2.00	277.03	44.97		
98	02:06:51:32	Hold 28 minutes	28			2.00	276.10	44.66		
99	02:07:19:32	Switch to high data rate				2.00	276.10	44.66		
100	02:07:19:32	Close ROV-04					276.10	44.66		
101	02:07:19:32	Hold 2 minutes	2				276.10	44.67		
102	02:07:21:32	Switch to medium data rate					276.10	44.67		
103	02:07:21:32	Hold 2.16 hours	129				276.10	45.00		

104	02:09:30:51	Switch to high data rate					276.10	45.00		
105	02:09:30:51	Open ROV-04				2.00	276.10	45.00		
106	02:09:30:51	Activate pump			High	2.00	276.10	45.00		
107	02:09:30:51	Hold 2 minutes	2		High	2.00	276.03	44.97		
108	02:09:32:51	Switch to medium data rate			High	2.00	276.03	44.97		
109	02:09:32:51	Hold 58 minutes	58		High	2.00	274.10	44.32		
110	02:10:30:51	Switch to high data rate			High	2.00	274.10	44.32		
111	02:10:30:51	Close ROV-04			High		274.10	44.32		
112	02:10:30:51	Hold 2 minutes	2		High		274.10	44.33		
113	02:10:32:51	Deactivate pump					274.10	44.33		
114	02:10:32:51	Switch to medium data rate					274.10	44.33	This series of tests is used to establish P/ATVS performance for 2 pump speeds for "long" burn times. No heaters used.	
115	02:10:32:51	Hold 4.35 hours	261				274.10	45.00		
116	02:14:54:09	Switch to high data rate					274.10	45.00		
117	02:14:54:09	Open ROV-04				2.00	274.10	45.00		
118	02:14:54:09	Activate pump			Low	2.00	274.10	45.00		
119	02:14:54:09	Hold 2 minutes	2		Low	2.00	274.03	44.97		**E**
120	02:14:56:09	Switch to medium data rate			Low	2.00	274.03	44.97		
121	02:14:56:09	Hold 58 minutes	58		Low	2.00	272.10	44.32		
122	02:15:54:09	Switch to high data rate			Low	2.00	272.10	44.32		
123	02:15:54:09	Close ROV-04			Low		272.10	44.32		
124	02:15:54:09	Hold 2 minutes	2		Low		272.10	44.32		
125	02:15:56:09	Deactivate pump					272.10	44.32		
126	02:15:56:09	Switch to medium data rate					272.10	44.32		
127	02:15:56:09	Hold 4.35 hours	261				272.10	45.00		
128	02:20:17:26	Switch to high data rate					272.10	45.00		
129	02:20:17:26	Open ROV-04				2.00	272.10	45.00		
130	02:20:17:26	Hold 2 minutes	2			2.00	272.03	44.97		
131	02:20:19:26	Switch to medium data rate				2.00	272.03	44.97		
132	02:20:19:26	Hold 58 minutes	58			2.00	270.10	44.32		
133	02:21:17:26	Switch to high data rate				2.00	270.10	44.32		
134	02:21:17:26	Close ROV-04					270.10	44.32		
135	02:21:17:26	Hold 2 minutes	2				270.10	44.32		
136	02:21:19:26	Switch to medium data rate					270.10	44.32		
137	02:21:19:26	Hold 4.35 hours	261				270.10	45.00		
138	03:01:40:44	Switch to high data rate					270.10	45.00		
139	03:01:40:44	Open ROV-04				2.00	270.10	45.00		
140	03:01:40:44	Hold 2 minutes	2			2.00	270.03	44.97	"High power vent" intended to vent large quantities of H2 at near constant tank pressure	
141	03:01:42:44	Switch to **low** data rate				2.00	270.03	44.97		
142	03:01:42:44	Activate heater to 30 W		30.00		2.00	270.03	44.97	75% Duty cycle	
143	03:01:42:44	Hold 50.00 hours	3,000	30.00		2.00	170.03	46.85	Procedure - "High power ven	**F**
144	05:03:42:44	Deactivate heater				2.00	170.03	46.85		
145	05:03:42:44	Hold 2.53 hours	152			2.00	164.96	44.49	Procedure - "High power ven	
146	05:06:14:49	Switch to high data rate				2.00	164.96	44.49		
147	05:06:14:49	Close ROV-04					164.96	44.49		
148	05:06:14:49	Hold 2 minutes	2				164.96	44.50		
149	05:06:16:49	Switch to medium data rate					164.96	44.50		
150	05:06:16:49	Hold 2.37 hours	142				164.96	45.00		

151	05:08:38:49	Switch to high data rate					164.96	45.00		
152	05:08:38:49	Open ROV-04				2.00	164.96	45.00		
153	05:08:38:49	Activate pump			High	2.00	164.96	45.00		
154	05:08:38:49	Hold 2 minutes	2		High	2.00	164.90	44.97		
155	05:08:40:49	Switch to medium data rate			High	2.00	164.90	44.97		
156	05:08:40:49	Hold 58 minutes	58		High	2.00	162.96	44.07		
157	05:09:38:49	Switch to high data rate			High	2.00	162.96	44.07		
158	05:09:38:49	Close ROV-04			High		162.96	44.07		
159	05:09:38:49	Hold 2 minutes	2		High		162.96	44.08		
160	05:09:40:49	Deactivate pump					162.96	44.08		
161	05:09:40:49	Switch to medium data rate					162.96	44.08		
162	05:09:40:49	Hold 60 minutes	60				162.96	44.29		
163	05:10:40:49	Activate pump			High		162.96	44.29		
164	05:10:40:49	Hold 15 minutes	15		High		162.96	44.34	Monitor PT-02, PT-03, and DP-Pump	
165	05:10:55:49	Deactivate pump					162.96	44.34		
166	05:10:55:49	Hold 60 minutes	60				162.96	44.55		
167	05:11:55:49	Activate pump			High		162.96	44.55		
168	05:11:55:49	Hold 15 minutes	15		High		162.96	44.61	Monitor PT-02, PT-03, and DP-Pump	**G**
169	05:12:10:49	Deactivate pump					162.96	44.61		
170	05:12:10:49	Hold 111 minutes	111				162.96	45.00		
171	05:14:01:49	Switch to high data rate					162.96	45.00		
172	05:14:01:49	Open ROV-04				2.00	162.96	45.00		
173	05:14:01:49	Activate pump			High	2.00	162.96	45.00		
174	05:14:01:49	Hold 2 minutes	2		High	2.00	162.90	44.97		
175	05:14:03:49	Switch to medium data rate			High	2.00	162.90	44.97		
176	05:14:03:49	Hold 58 minutes	58		High	2.00	160.96	44.07		
177	05:15:01:49	Switch to high data rate			High	2.00	160.96	44.07		
178	05:15:01:49	Close ROV-04			High		160.96	44.07		
179	05:15:01:49	Hold 2 minutes	2		High		160.96	44.07		
180	05:15:03:49	Deactivate pump					160.96	44.07		
181	05:15:03:49	Switch to medium data rate					160.96	44.07		
182	05:15:03:49	Hold 4.36 hours	262				160.96	45.00		
183	05:19:25:21	Switch to high data rate					160.96	45.00		
184	05:19:25:21	Open ROV-04				2.00	160.96	45.00		
185	05:19:25:21	Hold 2 minutes	2			2.00	160.90	44.97		
186	05:19:27:21	Switch to medium data rate				2.00	160.90	44.97		
187	05:19:27:21	Hold 58 minutes	58			2.00	158.96	44.06		
188	05:20:25:21	Switch to high data rate				2.00	158.96	44.06		
189	05:20:25:21	Close ROV-04					158.96	44.06		
190	05:20:25:21	Hold 2 minutes	2				158.96	44.07		
191	05:20:27:21	Switch to medium data rate					158.96	44.07		
192	05:20:27:21	Hold 4.36 hours	262				158.96	45.00		
193	06:00:48:53	Switch to high data rate					158.96	45.00		
194	06:00:48:53	Open ROV-04				2.00	158.96	45.00		
195	06:00:48:53	Hold 2 minutes	2			2.00	158.90	44.97		
196	06:00:50:53	Switch to **low** data rate				2.00	158.90	44.97		
197	06:00:50:53	Activate heater to 30 W		30.00		2.00	158.90	44.97	75% Duty cycle	
198	06:00:50:53	Hold 35.20 hours	2,112	30.00		2.00	88.50	46.76	Procedure - "High power ven	**H**
199	07:12:02:53	Deactivate heater				2.00	88.50	46.76		
200	07:12:02:53	Hold 116 minutes	116			2.00	84.63	44.32	Procedure - "High power ven	
201	07:13:58:53	Switch to high data rate				2.00	84.63	44.32		
202	07:13:58:53	Close ROV-04					84.63	44.32		
203	07:13:58:53	Hold 2 minutes	2				84.63	44.33		
204	07:14:00:53	Switch to medium data rate					84.63	44.33		
205	07:14:00:53	Hold 2.35 hours	141				84.63	45.00		

This series of tests is used to establish P/ATVS performance for "long" burn times. No heaters used.

"High power vent" intended to vent large quantities of H2 at near constant tank pressure

206	07:16:21:53	Switch to high data rate					84.63	45.00		
207	07:16:21:53	Open ROV-04				2.00	84.63	45.00		
208	07:16:21:53	Activate pump			High	2.00	84.63	45.00		
209	07:16:21:53	Hold 2 minutes	2		High	2.00	84.56	44.96		
210	07:16:23:53	Switch to medium data rate			High	2.00	84.56	44.96		
211	07:16:23:53	Hold 58 minutes	58		High	2.00	82.63	43.74		
212	07:17:21:53	Switch to high data rate			High	2.00	82.63	43.74		
213	07:17:21:53	Close ROV-04			High		82.63	43.74		
214	07:17:21:53	Hold 2 minutes	2		High		82.63	43.75		
215	07:17:23:53	Deactivate pump					82.63	43.75		
216	07:17:23:53	Switch to medium data rate					82.63	43.75		
217	07:17:23:53	Hold 60 minutes	60				82.63	44.04		
218	07:18:23:53	Activate pump			High		82.63	44.04		
219	07:18:23:53	Hold 15 minutes	15		High		82.63	44.11	Monitor PT-02, PT-03, and DP-Pump	
220	07:18:38:53	Deactivate pump					82.63	44.11		
221	07:18:38:53	Hold 60 minutes	60				82.63	44.40		
222	07:19:38:53	Activate pump			High		82.63	44.40		
223	07:19:38:53	Hold 15 minutes	15		High		82.63	44.47	Monitor PT-02, PT-03, and DP-Pump	[redacted]
224	07:19:53:53	Deactivate pump					82.63	44.47		
225	07:19:53:53	Hold 111.076670522187 minut	111				82.63	45.00	Monitor PT-02, PT-03, and DP-Pump	
226	07:21:44:58	Switch to high data rate					82.63	45.00		
227	07:21:44:58	Open ROV-04				2.00	82.63	45.00		
228	07:21:44:58	Activate pump			High	2.00	82.63	45.00		
229	07:21:44:58	Hold 2 minutes	2		High	2.00	82.56	44.96		
230	07:21:46:58	Switch to medium data rate			High	2.00	82.56	44.96		
231	07:21:46:58	Hold 58 minutes	58		High	2.00	80.63	43.73		
232	07:22:44:58	Switch to high data rate			High	2.00	80.63	43.73		
233	07:22:44:58	Close ROV-04			High		80.63	43.73		
234	07:22:44:58	Hold 2 minutes	2		High		80.63	43.74		
235	07:22:46:58	Deactivate pump					80.63	43.74		
236	07:22:46:58	Switch to medium data rate					80.63	43.74		
237	07:22:46:58	Hold 4.36 hours	262				80.63	45.00		
238	08:03:08:39	Switch to high data rate					80.63	45.00		
239	08:03:08:39	Open ROV-04				2.00	80.63	45.00		
240	08:03:08:39	Hold 2 minutes	2			2.00	80.56	44.96		
241	08:03:10:39	Switch to medium data rate				2.00	80.56	44.96		
242	08:03:10:39	Hold 58 minutes	58			2.00	78.63	43.72		
243	08:04:08:39	Switch to high data rate				2.00	78.63	43.72		
244	08:04:08:39	Close ROV-04					78.63	43.72		
245	08:04:08:39	Hold 2 minutes	2				78.63	43.73		
246	08:04:10:39	END OF TESTS					78.63	43.73		

This series of tests is used to establish P/ATVS performance for "long" burn times. No heaters used.

APPENDIX D—STUSTD 30-DAY MISSION SIMULATION (3/13/99)

Ullage conditioning vents on burns 29, 30, 54, 55, 82, 83, 121, 129, and 137.

STUSTD 30 Day Mission Simulation (New) 3/13/99

Ullage conditioning vents on Burns 29, 30, 54, 55, 82, 83, 121, 129, 137

Burn	MET	Burn Time (hr)			Coast Time (hr)			40W Heater Time (hr)				Active TVS Time (hr)			
	(hrs)	Start	Duration	End	Start	Duration	End	DC	Start	Duration	End	DC	Start	Duration	End
1	-	-	0.23	0.23	0.23	0.89	1.12	0.29	0.77	0.26	1.03	-	#N/A	-	#N/A
2	1.12	1.12	0.23	1.35	1.35	0.90	2.25	0.29	1.89	0.27	2.16	-	#N/A	-	#N/A
3	2.25	2.25	0.23	2.48	2.48	0.92	3.40	0.30	3.03	0.27	3.30	-	#N/A	-	#N/A
4	3.40	3.40	0.23	3.62	3.62	0.93	4.55	0.30	4.18	0.28	4.46	-	#N/A	-	#N/A
5	4.55	4.55	0.23	4.78	4.78	0.94	5.73	0.31	5.34	0.29	5.63	-	#N/A	-	#N/A
6	5.73	5.73	0.23	5.95	5.95	0.96	6.91	0.31	6.52	0.30	6.82	-	#N/A	-	#N/A
7	6.91	6.91	0.23	7.14	7.14	0.97	8.11	0.31	7.71	0.30	8.01	-	#N/A	-	#N/A
8	8.11	8.11	0.23	8.34	8.34	0.99	9.32	0.31	8.92	0.31	9.23	-	#N/A	-	#N/A
9	9.32	9.32	0.23	9.55	9.55	1.00	10.55	0.31	10.14	0.31	10.45	-	#N/A	-	#N/A
10	10.55	10.55	0.23	10.78	10.78	1.02	11.79	0.32	11.37	0.32	11.69	-	#N/A	-	#N/A
11	11.79	11.79	0.23	12.02	12.02	1.03	13.05	0.32	12.62	0.32	12.95	-	#N/A	-	#N/A
12	13.05	13.05	0.22	13.27	13.27	1.05	14.32	0.32	13.89	0.33	14.22	-	#N/A	-	#N/A
13	14.32	14.32	0.22	14.55	14.55	1.06	15.61	0.32	15.17	0.33	15.50	-	#N/A	-	#N/A
14	15.61	15.61	0.22	15.83	15.83	1.08	16.91	0.32	16.46	0.34	16.80	-	#N/A	-	#N/A
15	16.91	16.91	0.22	17.13	17.13	1.09	18.23	0.32	17.77	0.34	18.12	-	#N/A	-	#N/A
16	18.23	18.23	0.22	18.45	18.45	1.11	19.56	0.32	19.10	0.35	19.45	-	#N/A	-	#N/A
17	19.56	19.56	0.22	19.78	19.78	1.13	20.91	0.32	20.44	0.35	20.79	-	#N/A	-	#N/A
18	20.91	20.91	0.22	21.13	21.13	1.14	22.27	0.32	21.80	0.36	22.16	-	#N/A	-	#N/A
19	22.27	22.27	0.22	22.49	22.49	1.16	23.65	0.32	23.17	0.36	23.53	-	#N/A	-	#N/A
20	23.65	23.65	0.22	23.87	23.87	1.18	25.05	0.32	24.55	0.38	24.93	-	#N/A	-	#N/A
21	25.05	25.05	0.22	25.27	25.27	1.19	26.46	0.34	25.94	0.40	26.34	-	#N/A	-	#N/A
22	26.46	26.46	0.22	26.68	26.68	1.21	27.89	0.36	27.34	0.43	27.77	-	#N/A	-	#N/A
23	27.89	27.89	0.22	28.11	28.11	1.23	29.34	0.37	28.77	0.45	29.22	-	#N/A	-	#N/A
24	29.34	29.34	0.22	29.56	29.56	1.25	30.81	0.39	30.20	0.49	30.68	-	#N/A	-	#N/A
25	30.81	30.81	0.22	31.03	31.03	1.26	32.29	0.41	31.65	0.51	32.17	-	#N/A	-	#N/A
26	32.29	32.29	0.22	32.51	32.51	1.28	33.80	0.43	33.12	0.55	33.67	-	#N/A	-	#N/A
27	33.80	33.80	0.22	34.02	34.02	1.30	35.32	0.44	34.61	0.57	35.19	-	#N/A	-	#N/A
28	35.32	35.32	0.22	35.54	35.54	1.32	36.86	0.46	36.12	0.60	36.73	-	#N/A	-	#N/A
29	36.86	36.86	0.22	37.08	37.08	1.34	38.42	0.39	37.76	0.52	38.28	-	#N/A	-	#N/A
30	38.42	38.42	0.22	38.64	38.64	1.36	40.00	0.40	39.32	0.54	39.86	-	#N/A	-	#N/A
31	40.00	40.00	0.22	40.21	40.21	1.38	41.59	0.52	40.75	0.71	41.46	-	#N/A	-	#N/A
32	41.59	41.59	0.22	41.81	41.81	1.40	43.21	0.53	42.33	0.74	43.07	-	#N/A	-	#N/A
33	43.21	43.21	0.22	43.43	43.43	1.42	44.85	0.54	43.95	0.76	44.71	-	#N/A	-	#N/A
34	44.85	44.85	0.22	45.07	45.07	1.44	46.51	0.55	45.58	0.79	46.37	-	#N/A	-	#N/A
35	46.51	46.51	0.22	46.73	46.73	1.47	48.20	0.55	47.24	0.81	48.05	-	#N/A	-	#N/A

STUSTD 30 Day Mission Simulation (New) 3/13/99

Ullage conditioning vents on Burns 29, 30, 54, 55, 82, 83, 121, 129, 137

	Burn	MET	Burn Time (hr)			Coast Time (hr)			40W Heater Time (hr)				Active TVS Time (hr)			
		(hrs)	Start	Duration	End	Start	Duration	End	DC	Start	Duration	End	DC	Start	Duration	End
2	36	48.20	48.20	0.22	48.41	48.41	1.49	49.90	0.55	48.93	0.83	49.75	-	#N/A	-	#N/A
	37	49.90	49.90	0.22	50.12	50.12	1.51	51.63	0.56	50.62	0.85	51.48	-	#N/A	-	#N/A
	38	51.63	51.63	0.22	51.84	51.84	1.53	53.38	0.57	52.35	0.87	53.22	-	#N/A	-	#N/A
	39	53.38	53.38	0.22	53.59	53.59	1.56	55.15	0.57	54.10	0.89	54.99	-	#N/A	-	#N/A
	40	55.15	55.15	0.22	55.36	55.36	1.58	56.94	0.58	55.88	0.91	56.78	-	#N/A	-	#N/A
	41	56.94	56.94	0.22	57.16	57.16	1.60	58.76	0.58	57.68	0.93	58.60	-	#N/A	-	#N/A
	42	58.76	58.76	0.22	58.98	58.98	1.63	60.61	0.58	59.50	0.94	60.44	-	#N/A	-	#N/A
	43	60.61	60.61	0.21	60.82	60.82	1.65	62.47	0.58	61.34	0.96	62.31	-	#N/A	-	#N/A
	44	62.47	62.47	0.21	62.69	62.69	1.68	64.37	0.59	63.22	0.98	64.20	-	#N/A	-	#N/A
	45	64.37	64.37	0.21	64.58	64.58	1.71	66.29	0.59	65.12	1.00	66.12	-	#N/A	-	#N/A
	46	66.29	66.29	0.21	66.50	66.50	1.73	68.24	0.59	67.05	1.02	68.06	-	#N/A	-	#N/A
	47	68.24	68.24	0.21	68.45	68.45	1.76	70.21	0.59	69.00	1.03	70.03	-	#N/A	-	#N/A
	48	70.21	70.21	0.21	70.42	70.42	1.79	72.21	0.59	70.98	1.05	72.03	-	#N/A	-	#N/A
3	49	72.21	72.21	0.21	72.42	72.42	1.82	74.24	0.59	72.99	1.07	74.06	-	#N/A	-	#N/A
	50	74.24	74.24	0.21	74.45	74.45	1.85	76.30	0.59	75.03	1.08	76.11	-	#N/A	-	#N/A
	51	76.30	76.30	0.21	76.51	76.51	1.88	78.39	0.59	77.10	1.10	78.20	-	#N/A	-	#N/A
	52	78.39	78.39	0.21	78.60	78.60	1.91	80.51	0.58	79.20	1.11	80.32	-	#N/A	-	#N/A
	53	80.51	80.51	0.21	80.72	80.72	1.94	82.66	0.58	81.33	1.13	82.46	-	#N/A	-	#N/A
	54	82.66	82.66	0.21	82.87	82.87	1.97	84.84	0.45	83.76	0.88	84.64	-	#N/A	-	#N/A
	55	84.84	84.84	0.21	85.05	85.05	2.00	87.05	0.44	85.96	0.89	86.85	-	#N/A	-	#N/A
	56	87.05	87.05	0.21	87.26	87.26	2.03	89.30	0.58	87.91	1.18	89.09	-	#N/A	-	#N/A
	57	89.30	89.30	0.21	89.51	89.51	2.07	91.58	0.58	90.18	1.19	91.37	-	#N/A	-	#N/A
	58	91.58	91.58	0.21	91.79	91.79	2.10	93.89	0.57	92.48	1.21	93.68	-	#N/A	-	#N/A
	59	93.89	93.89	0.21	94.10	94.10	2.14	96.24	0.57	94.81	1.21	96.03	-	#N/A	-	#N/A
4	60	96.24	96.24	0.21	96.45	96.45	2.18	98.63	0.56	97.19	1.22	98.41	-	#N/A	-	#N/A
	61	98.63	98.63	0.21	98.84	98.84	2.21	101.05	0.56	99.60	1.23	100.83	-	#N/A	-	#N/A
	62	101.05	101.05	0.21	101.26	101.26	2.25	103.51	0.55	102.04	1.25	103.29	-	#N/A	-	#N/A
	63	103.51	103.51	0.21	103.73	103.73	2.29	106.02	0.54	104.54	1.25	105.79	-	#N/A	-	#N/A
	64	106.02	106.02	0.21	106.23	106.23	2.33	108.56	0.54	107.07	1.26	108.33	-	#N/A	-	#N/A
	65	108.56	108.56	0.21	108.77	108.77	2.37	111.14	0.53	109.64	1.27	110.90	-	#N/A	-	#N/A
	66	111.14	111.14	0.21	111.35	111.35	2.42	113.77	0.53	112.25	1.27	113.53	-	#N/A	-	#N/A
	67	113.77	113.77	0.21	113.98	113.98	2.46	116.44	0.52	114.91	1.29	116.19	-	#N/A	-	#N/A
	68	116.44	116.44	0.21	116.65	116.65	2.50	119.15	0.52	117.61	1.29	118.90	-	#N/A	-	#N/A
	69	119.15	119.15	0.21	119.36	119.36	2.55	121.91	0.51	120.36	1.29	121.66	-	#N/A	-	#N/A
5	70	121.91	121.91	0.21	122.12	122.12	2.60	124.72	0.50	123.16	1.30	124.46	-	#N/A	-	#N/A

STUSTD 30 Day Mission Simulation (New) 3/13/99

Ullage conditioning vents on Burns 29, 30, 54, 55, 82, 83, 121, 129, 137

Burn	MET (hrs)	Burn Time (hr) Start	Duration	End	Coast Time (hr) Start	Duration	End	40W Heater Time (hr) DC	Start	Duration	End	Active TVS Time (hr) DC	Start	Duration	End
71	124.72	124.72	0.21	124.93	124.93	2.65	127.58	0.49	126.01	1.30	127.31	-	#N/A	-	#N/A
72	127.58	127.58	0.21	127.79	127.79	2.70	130.48	0.49	128.90	1.31	130.21	-	#N/A	-	#N/A
73	130.48	130.48	0.21	130.69	130.69	2.75	133.44	0.48	131.85	1.32	133.17	-	#N/A	-	#N/A
74	133.44	133.44	0.21	133.65	133.65	2.80	136.45	0.47	134.85	1.33	136.17	-	#N/A	-	#N/A
75	136.45	136.45	0.21	136.66	136.66	2.86	139.52	0.46	137.91	1.32	139.23	-	#N/A	-	#N/A
76	139.52	139.52	0.21	139.73	139.73	2.91	142.64	0.46	141.02	1.33	142.35	-	#N/A	-	#N/A
77	142.64	142.64	0.21	142.85	142.85	2.97	145.82	0.45	144.19	1.34	145.53	-	#N/A	-	#N/A
78	145.82	145.82	0.21	146.03	146.03	3.03	149.06	0.44	147.42	1.34	148.76	-	#N/A	-	#N/A
79	149.06	149.06	0.21	149.27	149.27	3.09	152.37	0.44	150.71	1.35	152.06	-	#N/A	-	#N/A
80	152.37	152.37	0.21	152.57	152.57	3.16	155.73	0.43	154.07	1.34	155.42	-	#N/A	-	#N/A
81	155.73	155.73	0.21	155.94	155.94	3.22	159.16	0.42	157.49	1.35	158.84	-	#N/A	-	#N/A
82	159.16	159.16	0.21	159.37	159.37	3.29	162.67	0.32	161.28	1.06	162.34	-	#N/A	-	#N/A
83	162.67	162.67	0.21	162.87	162.87	3.36	166.24	0.31	164.86	1.04	165.90	-	#N/A	-	#N/A
84	166.24	166.24	0.21	166.45	166.45	3.44	169.88	0.38	168.23	1.31	169.54	-	#N/A	-	#N/A
85	169.88	169.88	0.21	170.09	170.09	3.51	173.60	0.37	171.95	1.30	173.25	-	#N/A	-	#N/A
86	173.60	173.60	0.21	173.81	173.81	3.59	177.40	0.36	175.74	1.30	177.04	-	#N/A	-	#N/A
87	177.40	177.40	0.21	177.61	177.61	3.67	181.28	0.36	179.61	1.30	180.91	-	#N/A	-	#N/A
88	181.28	181.28	0.21	181.49	181.49	3.75	185.24	0.35	183.57	1.30	184.86	-	#N/A	-	#N/A
89	185.24	185.24	0.21	185.45	185.45	3.84	189.29	0.34	187.61	1.30	188.91	-	#N/A	-	#N/A
90	189.29	189.29	0.21	189.50	189.50	3.93	193.43	0.33	191.74	1.30	193.04	-	#N/A	-	#N/A
91	193.43	193.43	0.21	193.64	193.64	4.03	197.66	0.32	195.96	1.30	197.26	-	#N/A	-	#N/A
92	197.66	197.66	0.21	197.87	197.87	4.12	202.00	0.31	200.29	1.29	201.58	-	#N/A	-	#N/A
93	202.00	202.00	0.21	202.20	202.20	4.22	206.43	0.30	204.73	1.28	206.01	-	#N/A	-	#N/A
94	206.43	206.43	0.21	206.64	206.64	4.33	210.97	0.29	209.26	1.27	210.53	-	#N/A	-	#N/A
95	210.97	210.97	0.21	211.17	211.17	4.44	215.61	0.29	213.90	1.27	215.17	-	#N/A	-	#N/A
96	215.61	215.61	0.21	215.82	215.82	4.55	220.38	0.28	218.66	1.26	219.92	-	#N/A	-	#N/A
97	220.38	220.38	0.21	220.59	220.59	4.67	225.26	0.27	223.54	1.25	224.79	-	#N/A	-	#N/A
98	225.26	225.26	0.21	225.47	225.47	4.80	230.27	0.26	228.54	1.24	229.79	-	#N/A	-	#N/A
99	230.27	230.27	0.21	230.47	230.47	4.93	235.40	0.25	233.68	1.23	234.91	-	#N/A	-	#N/A
100	235.40	235.40	0.21	235.61	235.61	5.06	240.68	0.24	238.95	1.22	240.17	-	#N/A	-	#N/A
101	240.68	240.68	0.21	240.88	240.88	5.21	246.09	0.23	244.36	1.21	245.57	-	#N/A	-	#N/A
102	246.09	246.09	0.21	246.30	246.30	5.36	251.65	0.22	249.92	1.19	251.12	-	#N/A	-	#N/A
103	251.65	251.65	0.21	251.86	251.86	5.51	257.37	0.21	255.64	1.18	256.82	-	#N/A	-	#N/A
104	257.37	257.37	0.21	257.58	257.58	5.68	263.26	0.20	261.53	1.16	262.69	-	#N/A	-	#N/A
105	263.26	263.26	0.21	263.46	263.46	5.85	269.31	0.20	267.59	1.14	268.73	-	#N/A	-	#N/A

STUSTD 30 Day Mission Simulation (New) 3/13/99

Ullage conditioning vents on Burns 29, 30, 54, 55, 82, 83, 121, 129, 137

	Burn	MET (hrs)	Burn Time (hr)			Coast Time (hr)			40W Heater Time (hr)				Active TVS Time (hr)			
			Start	Duration	End	Start	Duration	End	DC	Start	Duration	End	DC	Start	Duration	End
	106	269.31	269.31	0.21	269.52	269.52	6.03	275.55	0.19	273.83	1.12	274.94	-	#N/A	-	#N/A
	107	275.55	275.55	0.21	275.76	275.76	6.22	281.97	0.18	280.26	1.09	281.35	-	#N/A	-	#N/A
	108	281.97	281.97	0.21	282.18	282.18	6.42	288.60	0.17	286.89	1.07	287.96	-	#N/A	-	#N/A
12	109	288.60	288.60	0.21	288.81	288.81	6.63	295.44	0.16	293.73	1.05	294.77	-	#N/A	-	#N/A
	110	295.44	295.44	0.21	295.65	295.65	6.85	302.50	0.15	300.79	1.02	301.81	-	#N/A	-	#N/A
	111	302.50	302.50	0.21	302.71	302.71	7.09	309.79	0.14	308.10	0.99	309.09	-	#N/A	-	#N/A
	112	309.79	309.79	0.21	310.00	310.00	7.34	317.34	0.13	315.65	0.96	316.61	-	#N/A	-	#N/A
13	113	317.34	317.34	0.21	317.55	317.55	7.60	325.15	0.12	323.47	0.92	324.39	-	#N/A	-	#N/A
	114	325.15	325.15	0.21	325.36	325.36	7.88	333.24	0.11	331.57	0.88	332.45	-	#N/A	-	#N/A
	115	333.24	333.24	0.21	333.45	333.45	8.18	341.63	0.10	339.97	0.84	340.81	-	#N/A	-	#N/A
14	116	341.63	341.63	0.21	341.84	341.84	8.50	350.34	0.09	348.69	0.80	349.49	-	#N/A	-	#N/A
	117	350.34	350.34	0.21	350.55	350.55	8.84	359.39	0.09	357.75	0.75	358.50	-	#N/A	-	#N/A
15	118	359.39	359.39	0.21	359.60	359.60	9.20	368.80	0.08	367.18	0.70	367.88	-	#N/A	-	#N/A
	119	368.80	368.80	0.21	369.01	369.01	9.59	378.60	0.07	377.00	0.64	377.64	-	#N/A	-	#N/A
	120	378.60	378.60	0.21	378.80	378.80	10.00	388.80	0.06	387.22	0.59	387.80	-	#N/A	-	#N/A
16	121	388.80	388.80	0.61	389.41	389.41	8.49	397.90	0.18	395.50	1.55	397.05	0.50	389.05	0.30	389.35
	122	397.90	397.90	0.60	398.51	398.51	8.80	407.30	0.21	404.57	1.86	406.42	-	#N/A	-	#N/A
17	123	407.30	407.30	0.60	407.90	407.90	9.12	417.03	0.20	414.32	1.79	416.11	-	#N/A	-	#N/A
	124	417.03	417.03	0.59	417.62	417.62	9.47	427.09	0.18	424.43	1.71	426.14	-	#N/A	-	#N/A
	125	427.09	427.09	0.59	427.68	427.68	9.84	437.52	0.17	434.91	1.63	436.54	-	#N/A	-	#N/A
18	126	437.52	437.52	0.59	438.11	438.11	10.24	448.35	0.15	445.78	1.55	447.33	-	#N/A	-	#N/A
	127	448.35	448.35	0.58	448.94	448.94	10.67	459.61	0.14	457.09	1.46	458.54	-	#N/A	-	#N/A
19	128	459.61	459.61	0.58	460.19	460.19	11.14	471.33	0.12	468.86	1.35	470.21	-	#N/A	-	#N/A
	129	471.33	471.33	0.58	471.90	471.90	11.64	483.54	0.08	481.50	0.88	482.38	0.50	471.56	0.29	471.85
20	130	483.54	483.54	0.58	484.12	484.12	12.18	496.29	0.09	493.98	1.10	495.07	-	#N/A	-	#N/A
	131	496.29	496.29	0.57	496.87	496.87	12.76	509.63	0.08	507.38	0.97	508.35	-	#N/A	-	#N/A
21	132	509.63	509.63	0.57	510.20	510.20	13.40	523.61	0.06	521.42	0.85	522.27	-	#N/A	-	#N/A
22	133	523.61	523.61	0.57	524.18	524.18	14.11	538.28	0.05	536.16	0.71	536.87	-	#N/A	-	#N/A
	134	538.28	538.28	0.57	538.86	538.86	14.88	553.73	0.04	551.68	0.56	552.24	-	#N/A	-	#N/A
23	135	553.73	553.73	0.57	554.30	554.30	15.72	570.03	0.03	568.05	0.40	568.45	-	#N/A	-	#N/A
24	136	570.03	570.03	0.57	570.60	570.60	16.67	587.26	0.01	585.37	0.23	585.60	-	#N/A	-	#N/A
	137	587.26	587.26	0.57	587.83	587.83	17.71	605.55	-	#N/A	-	#N/A	0.83	587.31	0.47	587.78
25	138	605.55	605.55	0.57	606.12	606.12	18.89	625.01	-	#N/A	-	#N/A	0.23	605.93	0.13	606.06
26	139	625.01	625.01	0.57	625.58	625.58	20.21	645.79	-	#N/A	-	#N/A	0.49	625.24	0.28	625.52
27	140	645.79	645.79	0.57	646.36	646.36	-	646.36	-	#N/A	-	#N/A	-	#N/A	-	#N/A

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14. ABSTRACT
The demonstration of a unique liquid hydrogen (LH_2) storage and feed system concept for solar thermal upper stage was cooperatively accomplished by a Boeing/NASA Marshall Space Flight Center team. The strategy was to balance thermodynamic venting with the engine thrusting timeline during a representative 30-day mission, thereby, assuring no vent losses. Using a 2 m^3 (71 ft^3) LH_2 tank, proof-of-concept testing consisted of an engineering checkout followed by a 30-day mission simulation. The data were used to anchor a combination of standard analyses and computational fluid dynamics (CFD) modeling. Dependence on orbital testing has been incrementally reduced as CFD codes, combined with standard modeling, continue to be challenged with test data such as this.

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low-gravity cryogenic fluid management, liquid hydrogen thermodynamic vent system/liquid acquisition device thermal integration, on-orbit liquid hydrogen pressure control, use of liquid hydrogen boiloff for solar propulsion

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