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Large-Scale Liquid Hydrogen Tank Rapid Chill and Fill Testing for the Advanced Shuttle Upper Stage Concept

R.H. Flachbart (retired), A. Hedayat, K.A. Holt, J. Sims, and E.F. Johnson
Marshall Space Flight Center, Huntsville, Alabama

L.J. Hastings
Alpha Technology Inc., Huntsville, Alabama

T. Lak (retired)
The Boeing Company, Huntington Beach, California

April 2013

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National Aeronautics and
Space Administration

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LIST OF ACRONYMS AND SYMBOLS

ASUS	advanced shuttle upper stage
CAP	capacitance probe
CFM	cryogenic fluid management
GN_2	gaseous nitrogen
GFSSP	Generalized Fluid System Simulation program
LH_2	liquid hydrogen
MHTB	multipurpose hydrogen test bed
MLI	multiple-layer insulation
MSFC	Marshall Space Flight Center
SOFI	spray-on foam insulation
STF	Structural Test Facility
TC	thermocouple
TRS	test request sheet

TECHNICAL PUBLICATION

LARGE-SCALE LIQUID HYDROGEN TANK RAPID CHILL AND FILL TESTING FOR THE ADVANCED SHUTTLE UPPER STAGE CONCEPT

1. INTRODUCTION

1.1 Background

Because of the high energy density of cryogenic propellants, a cryogenic upper stage is a significant asset to the payload community. However, the use of cryogenic upper stages in manned programs has been limited to the Saturn Apollo program, primarily due to safety considerations involving the former Shuttle Transportation System. There was the risk of a ‘return to launch site’ abort with a full or partial load of cryogenic propellants in the cargo bay, which could overpressurize after landing. The advanced shuttle upper stage (ASUS) concept proposed by Boeing Aerospace, Huntington Beach, CA, addressed this concern.[1] The basic concept was that the ASUS (fig. 1) would launch empty and begin filling from the shuttle external tank after the atmosphere could no longer sustain an explosion due to the low oxygen content. However, due to the shuttle’s rapid ascent rate, the fill had to be accomplished in about 5 min. Furthermore, the concept would have used propellants normally thrown away as external tank residuals.

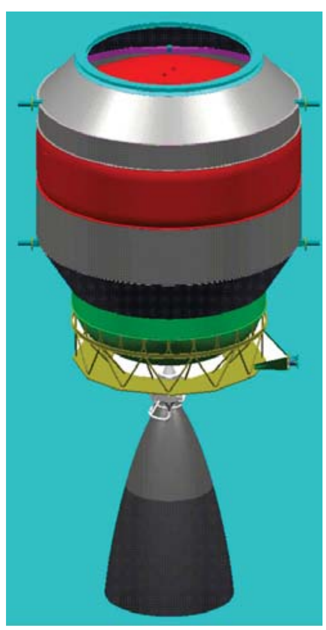

Figure 1. ASUS concept.

The propellant transfer concept was to employ a pressure-fed rapid chill and fill concept, which was quite simple. During a fill operation, a spray bar was to be used to chill down the ASUS tank wall while the vaporized propellant safely exited through a normal vent system. Once the tank walls were chilled to an acceptable level or 'target temperature,' the residual thermal energy was sufficiently low for closing the vent and begin filling. This chill and no-vent fill process is often considered for in-space propellant transfer because the no-vent fill process can proceed independent of propellant position within the tank. Therefore, it was reasoned that the data and 'lessons learned' generated under this program would also significantly assist reduced gravity, cryogen transfer technology.

1.2 Objectives and General Approach

The primary objective of this test program was to develop and demonstrate rapid chill and fill procedures for a liquid hydrogen (LH_2) tank in an ambient environment, an essential step toward establishing the ASUS concept feasibility. The data gathered were to be used to anchor computational models and specifically included the following: tank pressure and chilldown characteristics versus fill rate, and tank pressure rise rate and fill level achieved after vent valve closure without exceeding peak pressure limits. The rapid chill/fill test was to be deemed successful if vented chill and nonvented fill within 5 min was demonstrated and data adequate to anchor analytical models were obtained. A secondary, but important, objective was to consider application of the data to orbital cryogenic propellant resupply.

The rapid chill and fill concept was tested in a gaseous nitrogen (GN_2) environment, slightly above atmospheric pressure, using the multipurpose hydrogen test bed (MHTB) at NASA Marshall Space Flight Center (MSFC) in the summer of 2000. The test facilities, supporting equipment, and procedures are discussed in this Technical Publication.

2. TEST TANK AND SUPPORTING EQUIPMENT

Testing was conducted at the Structural Test Facility (STF) of the MSFC West Test Area, building 4699, using the MHTB, which is illustrated in figures 2 and 3. The MHTB is a test bed designed to evaluate various cryogenic fluid management technologies in a large-volume tank. The MHTB is an 638.5 ft^3 (18 m^3) cylindrical 5083 aluminum tank with 2:1 elliptical domes, is 10 ft (3.3 m) high with a diameter of 10 ft (3.3 m), and has a wall thickness of approximately 0.5 in (1.25 cm). The tank rests on four low-heat-leak composite legs. The tank assembly is mounted within a work platform, which allows easy access to the tank for installation and maintenance procedures. Tank level versus percent fill and other details are presented in appendix A.

Figure 2. Multipurpose hydrogen test article.

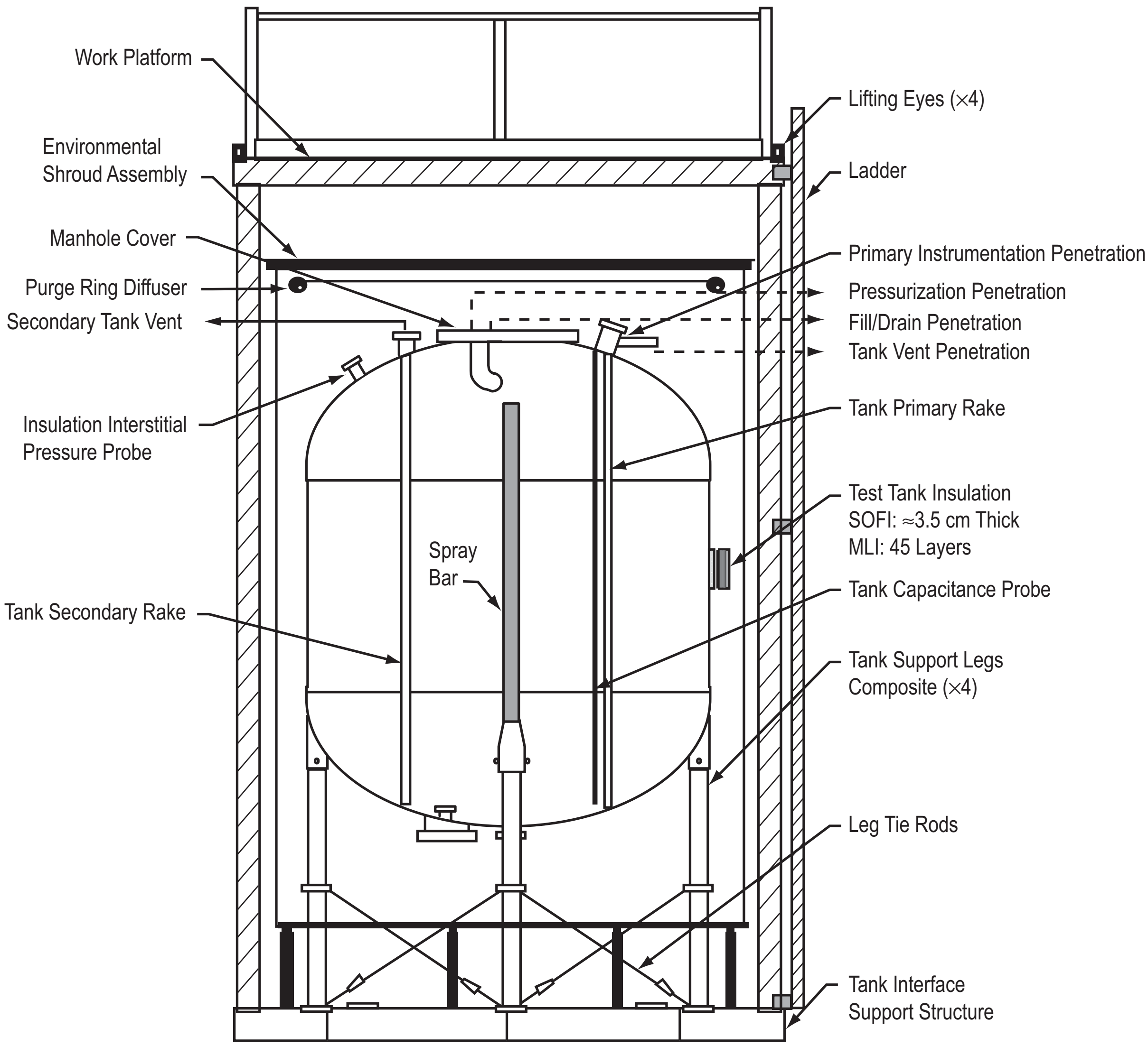

Figure 3. MHTB setup schematic.

The tank thermal protection system consisted of two parts: (1) Spray-on foam insulation (SOFI), which was designed for a ground hold scenario, and (2) a variable density multilayer insulation (MLI) designed to perform in an on-orbit, high vacuum environment of space. Because this test series was conducted in a 1-atm environment, foam served as the primary insulation. The MHTB was also equipped with a thermal shroud, which was designed to control MHTB exterior surface temperatures. The shroud also contained a purge ring, which was used to distribute dry GN_2 over the exterior surface of the MLI, thereby preventing condensation on the insulation surface.

2.1 Spray Bar

A spray bar, specifically designed and fabricated for this application by Boeing Aerospace, Huntington Beach, CA, was mounted longitudinally inside the LH_2 tank (fig. 4). The spray bar, aligned parallel with but slightly offset from the tank longitudinal axis, and had 6,000 orifices along its length and circumference that directed the spray onto the tank walls, thereby promoting structural chill down. The flow rate capacity was designed for up to 1,100 gpm (4.16 m^3 pm).

Figure 4. Spray bar water flow test at Boeing.

2.2 Instrumentation

A complete listing of instrumentation used in the testing is in appendix B. The primary instrumentation used for the chill/fill performance, presented in table 1 and figures 5 and 6, consisted of an ullage pressure measurement, plus thermocouples (TCs) and silicon diodes to measure fluid and tank wall temperatures. The tank was equipped with a capacitance probe for continuous measurement of the liquid level during fill. There were two silicon diode rakes (fig. 5) that provided temperature gradient measurements within both the ullage and liquid, an ullage pressure measurement, and wall temperature measurements distributed longitudinally along one side of the tank (fig. 6). The rake diodes, attached at 9 in (22.9 cm) intervals, also served as backup to the capacitance probe (LL1) during fill. The flow rate into the MHTB tank was monitored using a facility flow meter termed FM3125. Because the spray bar jets impinged on the two temperature rakes during the checkout tests, 12 diodes on rake 1 (TD01–TD12) were electronically converted to heated element liquid level sensors. Additional instrumentation placement information regarding the upper dome region is presented in appendix C.

Table 1. Primary chill/fill test instrumentation.

MID	Measurement Description
PL25	25% point level sensor
TD24	Rake 2 – 4.3% fill level
TD23	Rake 2 – 11.5% fill level
TD22	Rake 2 – 20.3% fill level
TD21	Rake 2 – 29.3% fill level
TD12	Rake 1 – 1.8% fill level
TD11	Rake 1 – 7.6% fill level
TD10	Rake 1 – 15.8% fill level
TD9	Rake 1 – 24.8% fill level
TD8	Rake 1 – 33.9% fill level
TW1	Tank wall temperature 6 in/15.24 cm (1.1%) fill
TW2	Tank wall temperature 1 ft /30.48 cm (16.3%) fill
TW3	Tank wall temperature 2 ft 8 in/81.28 cm (36.4%) fill
TW4	Tank wall temperature 4 ft 4 in/132.08 cm (56.5%) fill
TW5	Tank wall temperature 6 ft/182.88 cm (76.7%) fill
TW6	Tank wall temperature 7 ft 8 in/233.68 cm (95.1%) fill
LLI	Continuous capacitance probe
Dew1	Dewpoint sensor – heater shroud dewpoint
TVL4	Rake 1 – 99.4% fill level positioned just below vent penetration
TVL5	Rake 1 – 99.4% fill level positioned just below vent penetration
TMN1	Manhole flange temperature

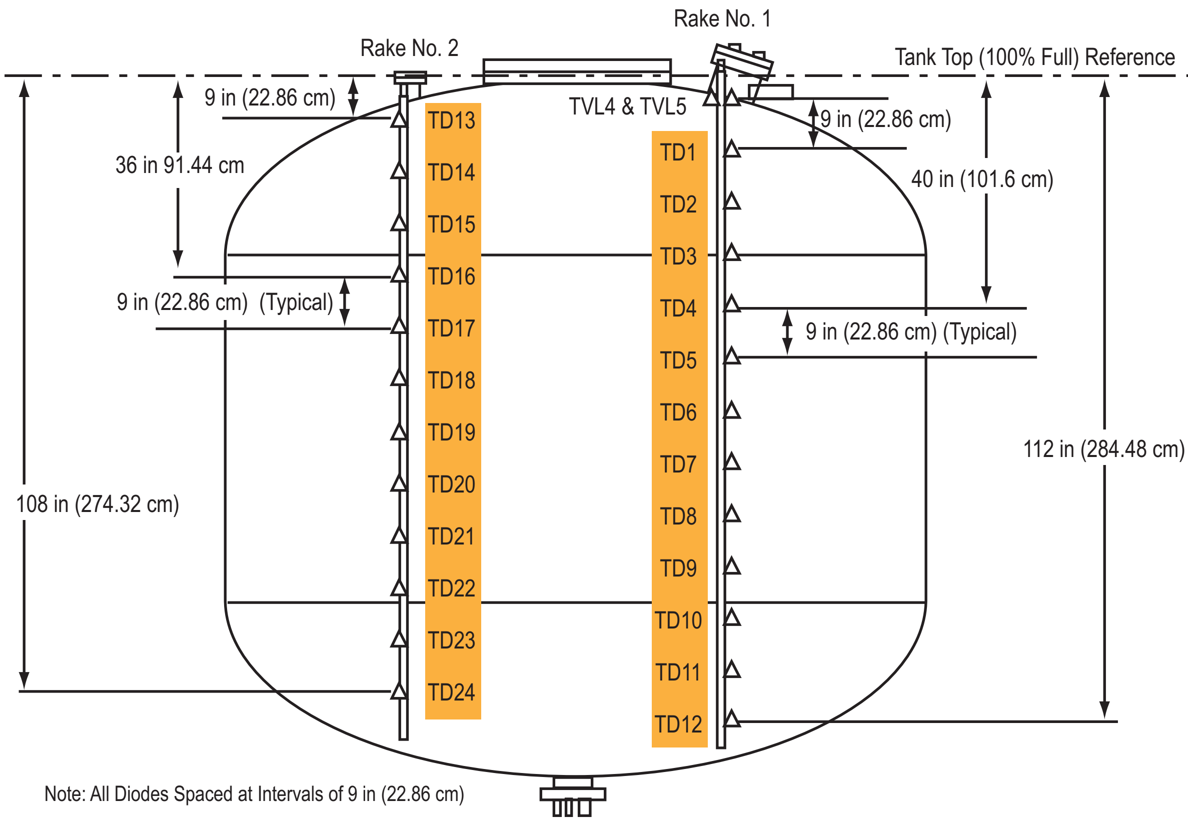

Figure 5. Measurement positions on internal rakes.

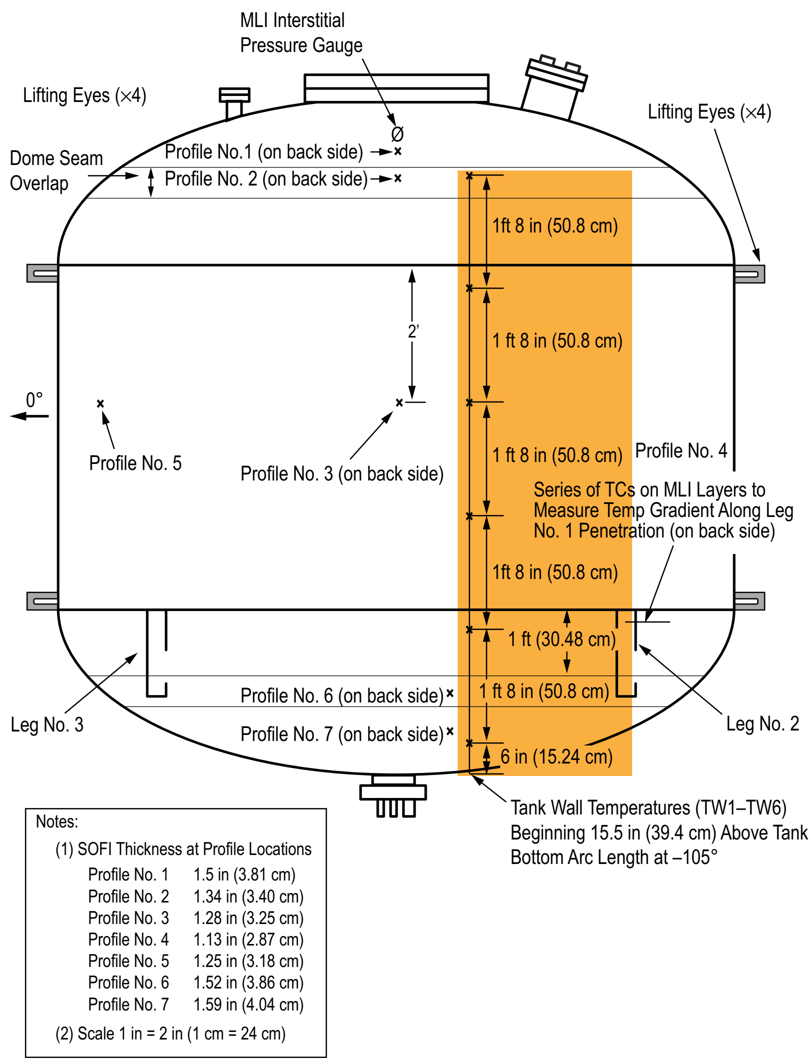

Figure 6. MHTB tank wall temperature measurement positions.

3. TEST FACILITY REQUIREMENTS AND PROCEDURES

Testing was conducted in the MSFC West Test Area STF, building 4699. The test facility requirements are summarized below, with further details provided in appendix D. Basically, the facility purge systems were required to provide dry GN_2 and air conditioning to the internal facility volume, thereby maintaining a safe environment and uniform initial conditions for the test article.

3.1 Pretest Conditions

The MHTB shroud purge ring was used to purge with dry GN_2 until a GN_2 atmosphere was established within the enclosure volume. The internal facility temperature, dew point, and relative humidity were measured and recorded at least once per hour on the day of a test to insure that no condensation occurred once propellant tanking began.

3.2 Test Tank Conditioning

Electrically heated, dry GN_2 was used to condition the MHTB tank and provide the initial temperature. Each GN_2 purge of the MHTB tank was followed by a dry GH_2 purge to remove the condensable GN_2. The initial tank average temperature was required to be 530 ± 10 °R (294 ± 5.6 K), which was to be met prior to GH_2 cycle purging. The facility maintained a positive pressure to prevent air ingestion.

Data were recorded throughout the entire operation to baseline the initial instrument and test article conditions. A dry GH_2 purge followed each test until the tank walls were warm enough to preclude condensing GN_2 on the tank inner walls.

3.3 Chill/Fill Requirements

The facility fill system was equipped with a bypass valve as close to the MHTB interface as possible so that LH_2 could be used to precondition the majority of the facility feed system. The facility was capable of delivering a maximum LH_2 flow rate of 1,100 gpm (4.16 m^3pm). The specified LH_2 flow rate was established through the bypass line prior to opening the MHTB pre-valve. LH_2 temperature, measured at the outlet of the storage tank, was to be no greater than 40 °R (22 K) throughout the chill and fill process. A mechanical relief valve was used to restrict the test article to a maximum pressure of 50 psia or 35 psig (345 kPa). An automatic redline cutoff was programmed to terminate LH_2 flow (and to open the vent valve, if necessary) when the MHTB ullage pressure reached 47 psia or 32 psig (324 kPa).

3.4 Vent Flow Measurement Requirements

The vent system was insulated with SOFI and chilled prior to testing. The measurement system was capable of handling a transient maximum 1,100 gpm (4.16 m^3pm) flow rate of nearly saturated GH_2 without large pressure losses.

3.5 Test Facility Controls

Test facility large control screens provided the test engineer and the entire support team simultaneous 'real-time' visibility of key control elements and instrumentation readouts regarding temperatures, pressure, flow rate, fill level, and redlines. Figures 7 and 8 illustrate the functionality of the control screens for the pressurization and vent system and the fill and drain system, respectively.

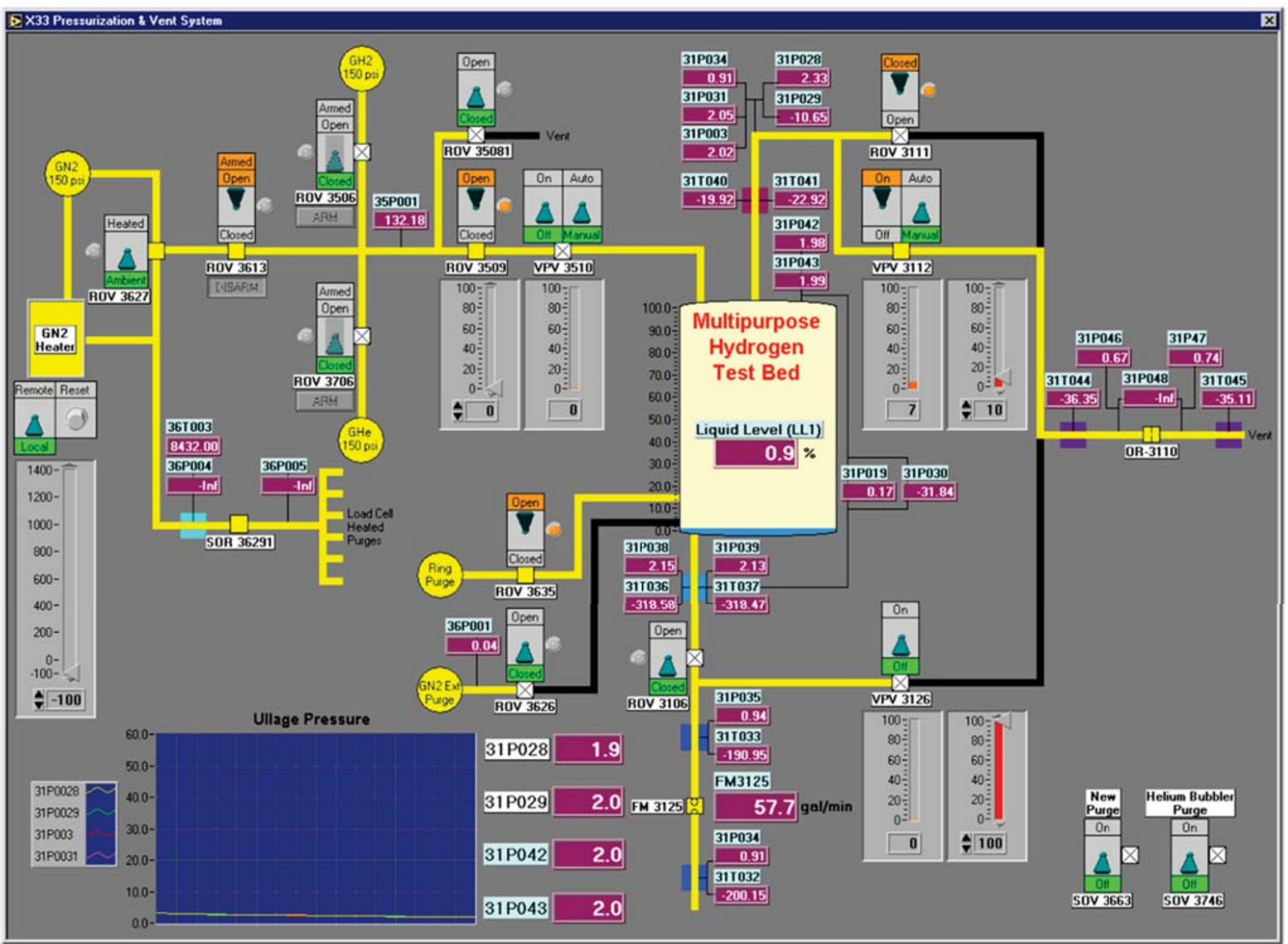

Figure 7. Test control screen for pressurization and venting operations.

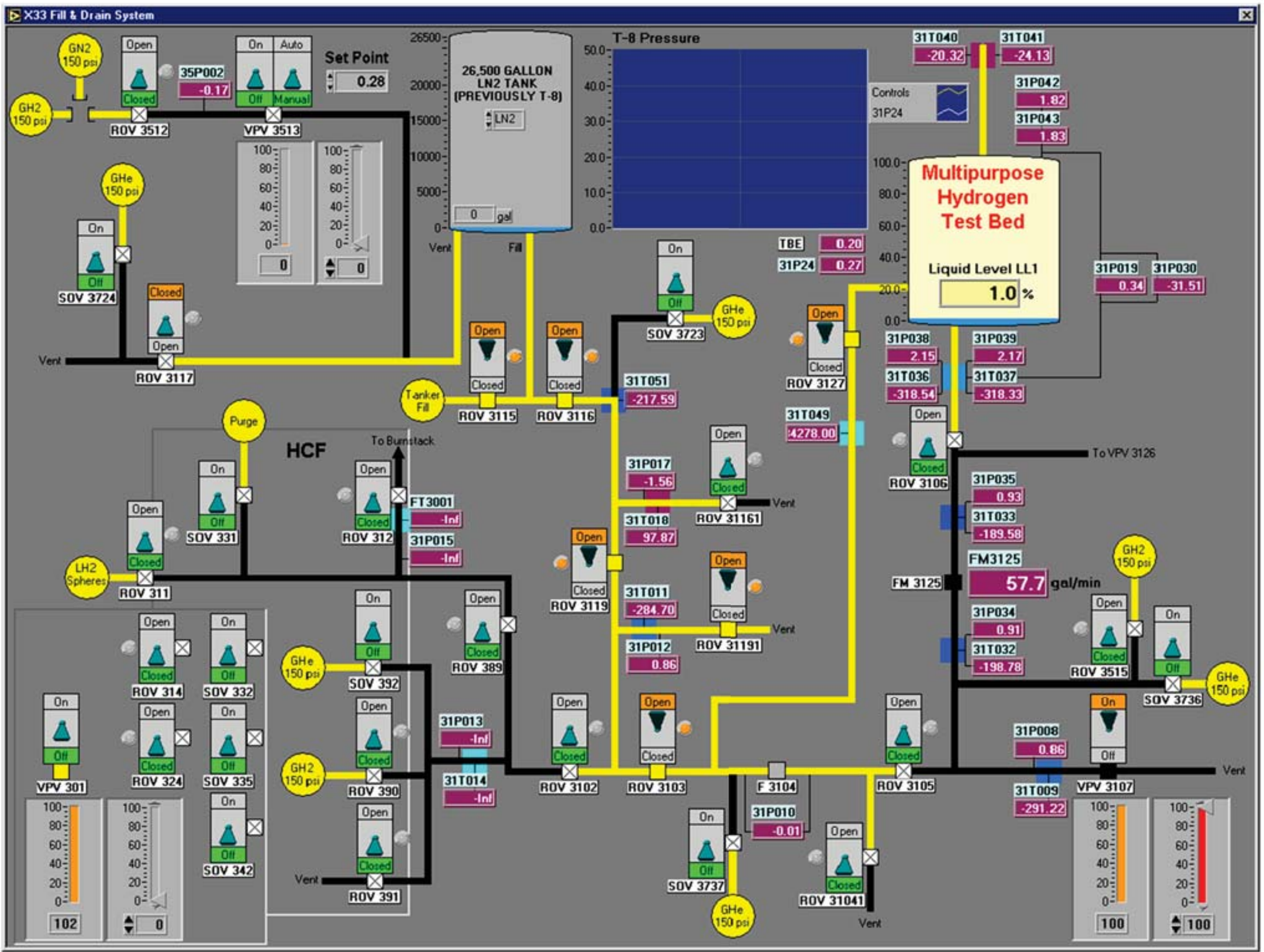

Figure 8. Test control screen for fill and drain operations.

4. INTEGRATED SYSTEM CHARACTERIZATION

The performed test matrix is presented in table 2. First, a series of eight tests was conducted to check out the test hardware and characterize the integrated system operation with LH_2. Then a series of six tests was conducted to establish chilldown performance versus sequencing timelines and other parameters as appropriate. In support of test planning and checkout testing, analytical models for the chilldown, fill, and venting operations were developed. The analytical modeling and system checkout testing are discussed below.

Table 2. Chill/fill conducted test matrix.

	Test Number	Description	Supply Pressure		MHTB Peak Pressure*		Fill Level (%)
			psia	(kPa)	psia	(kPa)	
Checkout Tests	1	LN_2 cold shock	~0.3	99	N/A	N/A	N/A
	2	Vented fill	12	184	9.9	170	6
	3	Vented fill	11.9	183	9.8	169	31
	4	Vented fill	32.8	327	24.3	269	63
	5	Vented fill	32.8	327	24.4	270	99
	6	Vented fill	42.9	397	28.6	299	98
	7	Vented fill/attempted no-vent fill	42.9	397	28.2	296	98
	8	Vented fill	36.8	355	27.7	292	13
Performance Tests	9	Vented fill	44.9	411	26.6	285	91
	10	Vented fill/attempted no-vent fill	44.9	411	27.2	289	90
	11	Vented fill	44.8	410	27.4	290	90
	12**	Vented fill/attempted No-vent fill	44.8	410	26.3	283	(a) 90, (b) – , (c) –
	13**	Vented fill/attempted no-vent fill	44.8	410	26.8	286	(a) 90, (b) 73, (c) 83
	14**	Vented fill/attempted no-vent fill	44.8	410	26.2	282	(a) 90, (b) 79, (c) 90

* Initial pressure surge as empty tank fill began.
** (a) Vented fill level, (b) tank drained back to this level, and (c) refill attempt with vent closed.

4.1 Liquid Hydrogen Fill Rate Analyses

The objective of this analysis was to predict the steady-state LH_2 fill flow rates during rapid chill and fill testing, thereby supporting test planning and real-time testing. The Generalized Fluid

System Simulation Program (GFSSP) was used to model the MHTB fill system.[2] The GFSSP model was run at supply tank pressures of 26.3, 48, and 67 psia (181, 331, and 462 kPa). For each run, the lowest MHTB tank pressure was assumed to be 15 psia (104 kPa). To prevent structural damage to the MHTB, the maximum pressure was not allowed to exceed 50 psia, as required by the test requirements document.[2] Figure 9 depicts the predicted LH_2 fill flow rate versus the ullage pressure for the three supply pressures.

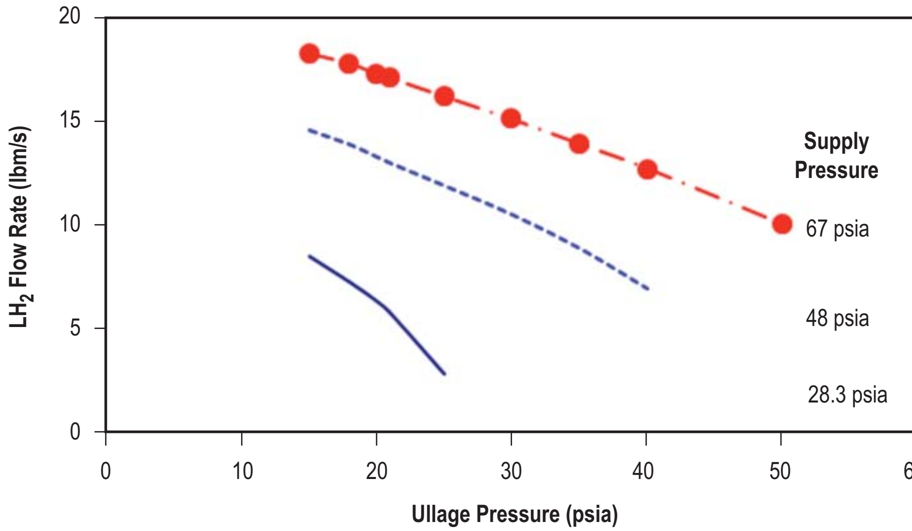

Figure 9. LH_2 flow rate versus ullage pressure for various supply tank pressures.

4.2 Vent System Sizing Analyses

By measuring temperature and pressure immediately upstream and downstream of an orifice placed in the vent line, the vented GH_2 flow rate could be calculated. The objective of this analysis was to size the orifice and to evaluate the performance of the vent system during testing. The ASME MFC-3M-1989 recommended model,[3] in combination with the GFSSP vent model, was utilized with the following assumptions:

- Surrounding environment = 14.7 psia, 0 psig (101 kPa) and 530 °R (294 K).
- MHTB tank ullage pressure = 15–50 psia, 0.3–33.3 psig (104–345 kPa).

The GFSSP models were run for orifice flow coefficients of 0.7, 0.6, and 0.5. The orifice flow coefficient of 0.6 was selected based on predicted GH_2 vent flow rates ranging from about 0.5 to 10 lb/s (0.23 to 4.5 kg/s) with corresponding tank ullage pressures of 15 to 50 psia or 0.3 to 34.6 psig (104 to 345 kPa); see figure 10.

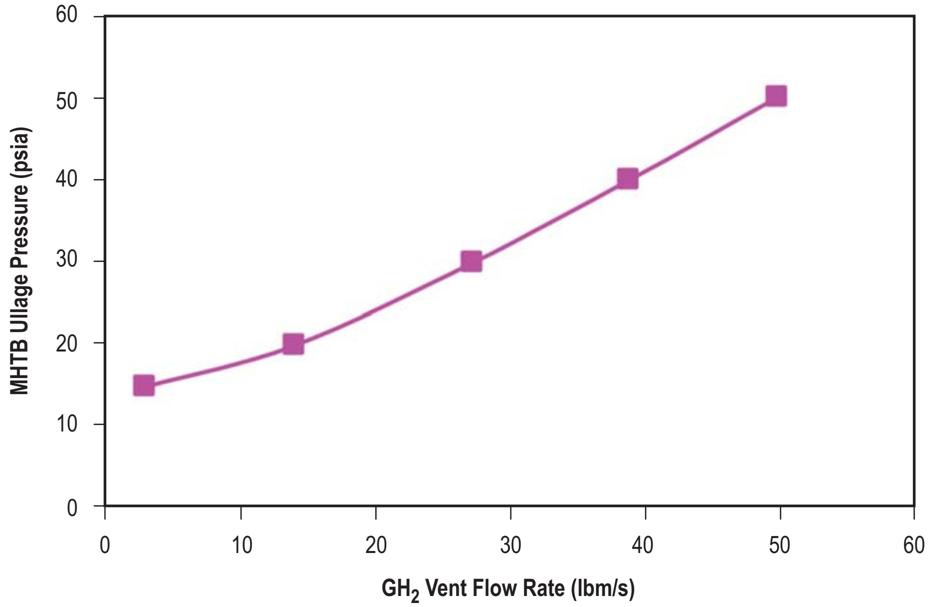

Figure 10. GH_2 vent flow rate versus MHTB ullage pressure.

4.3 System Operational Checkout Testing

Following the LN_2 cold shock test, a series of seven tests (tests 2–8, table 2) was performed to characterize how the assembled system would respond during LH_2 fill. Because the fill system was pressure fed, the supply tank pressure had to be set so as to maximize the fill flow rate while still ensuring that the MHTB pressure remained below the 50 psia or 34.7 psig (345 kPa) redline cutoff. Therefore, the supply tank pressure was incrementally increased to ensure that the maximum pressure in the MHTB did not exceed the redline limit. The fill level goal was also incrementally increased as operational experience was acquired with the system. With the exception of a minor data system problem during the first checkout test, no significant problems were encountered. The characterization tests successfully enabled the team to do the following: (1) Set the supply pressure to safely maximize the fill flow rate, and (2) acquire operational confidence with the system setup.

5. PERFORMANCE TEST RESULTS AND EVALUATION

As stated earlier, the performance test objectives (for tests 9–14) were to assess the spray bar capability and the feasibility of the rapid chill and fill concept. All of the tests were preceded by a chilldown of the facility. The objective of filling the vented tank within 5 min was accomplished during all six performance tests; however, the chill portion of the test occurred more slowly than expected. Therefore, regardless of the fill and vent valve closure sequencing attempted, incomplete nonvented fill levels were achieved. Further details regarding the tank wall chilldown and fill performance are presented in sections 5.1 and 5.2, respectively.

5.1 Tank Wall Chilldown

Prior to testing, it was assumed that the tank walls would rapidly chill, before any liquid began to accumulate in the tank. However, as indicated in figure 11, liquid actually began to accumulate almost immediately and the tank side walls gradually chilled throughout the test. However, in the upper dome region, the manhole temperatures remained above 300 °R (167 K) throughout and after the fill process as shown in figures 11 and 12, respectively. The tank side walls began to chill at a uniform rate only after the liquid level had passed a particular position, indicating that the chilldown rate due to the spray was less than anticipated. Additionally, even after the liquid passed a given position, liquid temperatures did not occur until 60 to 80 s later, after the wall temperature was reduced to the 80 to 100 °R (44 to 56 K) range and rapid chilldown rates associated with nucleate boiling occurred.

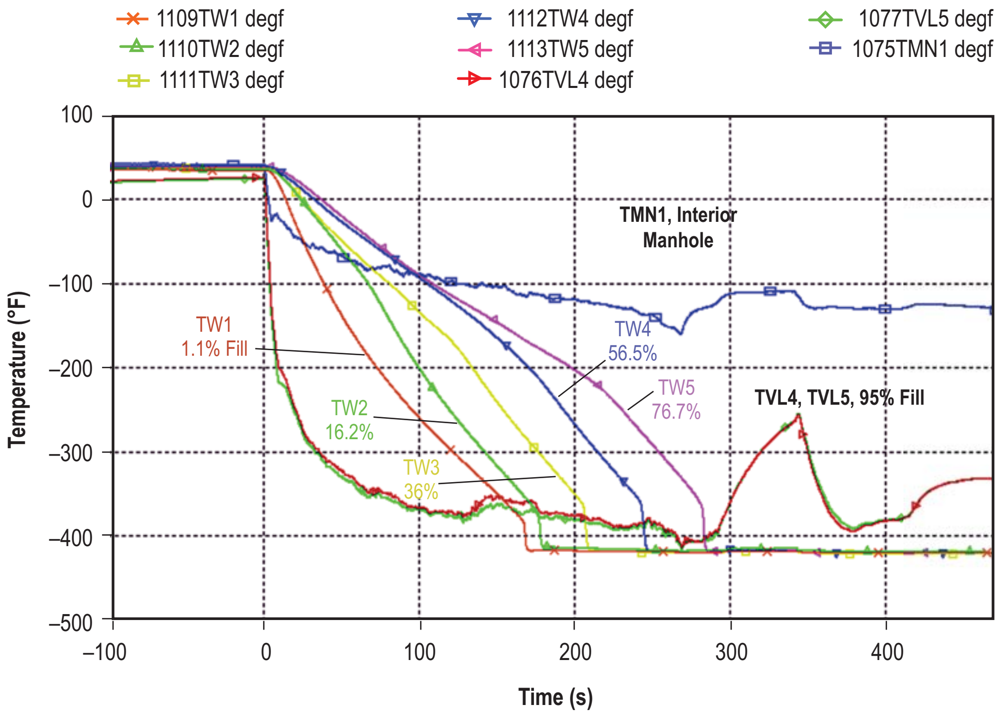

Figure 11. Measured tank sidewall and upper dome area temperatures during vented fill, test 14.

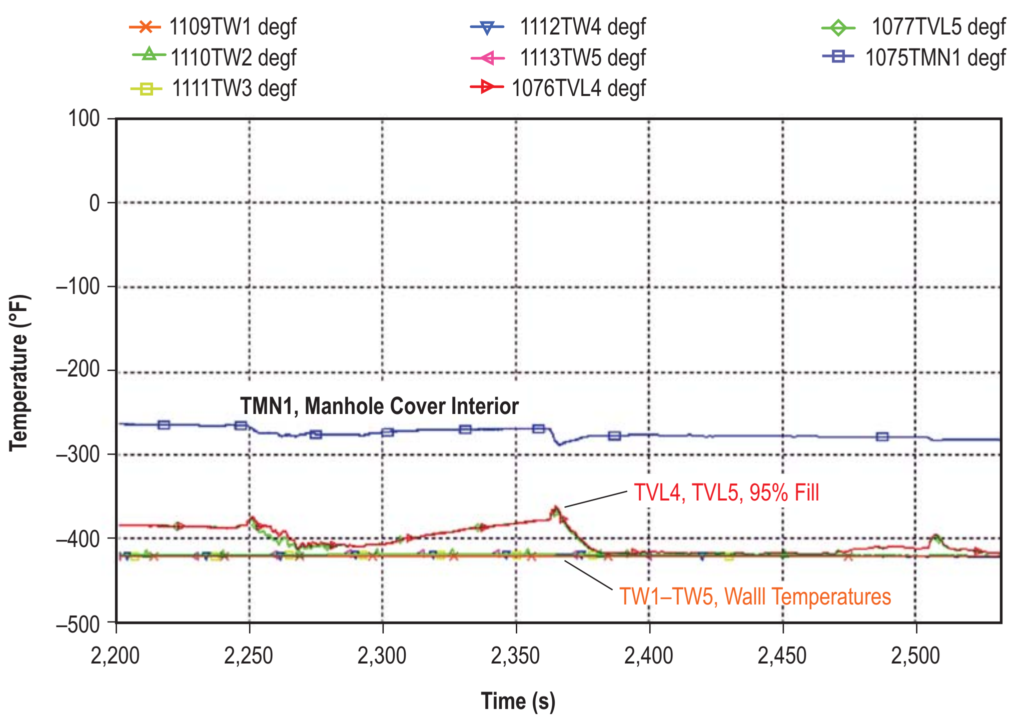

Figure 12. Measured tank sidewall and upper dome area temperatures during unvented fill segment, test 14.

Referring to the boiling heat transfer regimes diagramed in figure 13, it was quickly recognized that the elevated tank wall temperatures below the liquid level were characteristics typical of film boiling. Film boiling is attributed to a vapor film, which can occur at high temperature differences between a surface and saturated liquid and insulates the heated surface. Therefore, nucleate boiling and rapid chilldown are precluded until the vapor generation is sufficiently reduced to allow liquid contact with the heated surface. Therefore, a laboratory bench experiment was devised to experimentally demonstrate the dramatic effects of boiling regime on tank wall chilldown time. The overall strategy of the bench test was to devise a low-cost, rapid turnaround test setup that would physically demonstrate the effects of boiling heat transfer regimes on a thick aluminum wall chilldown, and at the same time, provide quantified data. With this strategy in mind, the test approach described below was implemented.

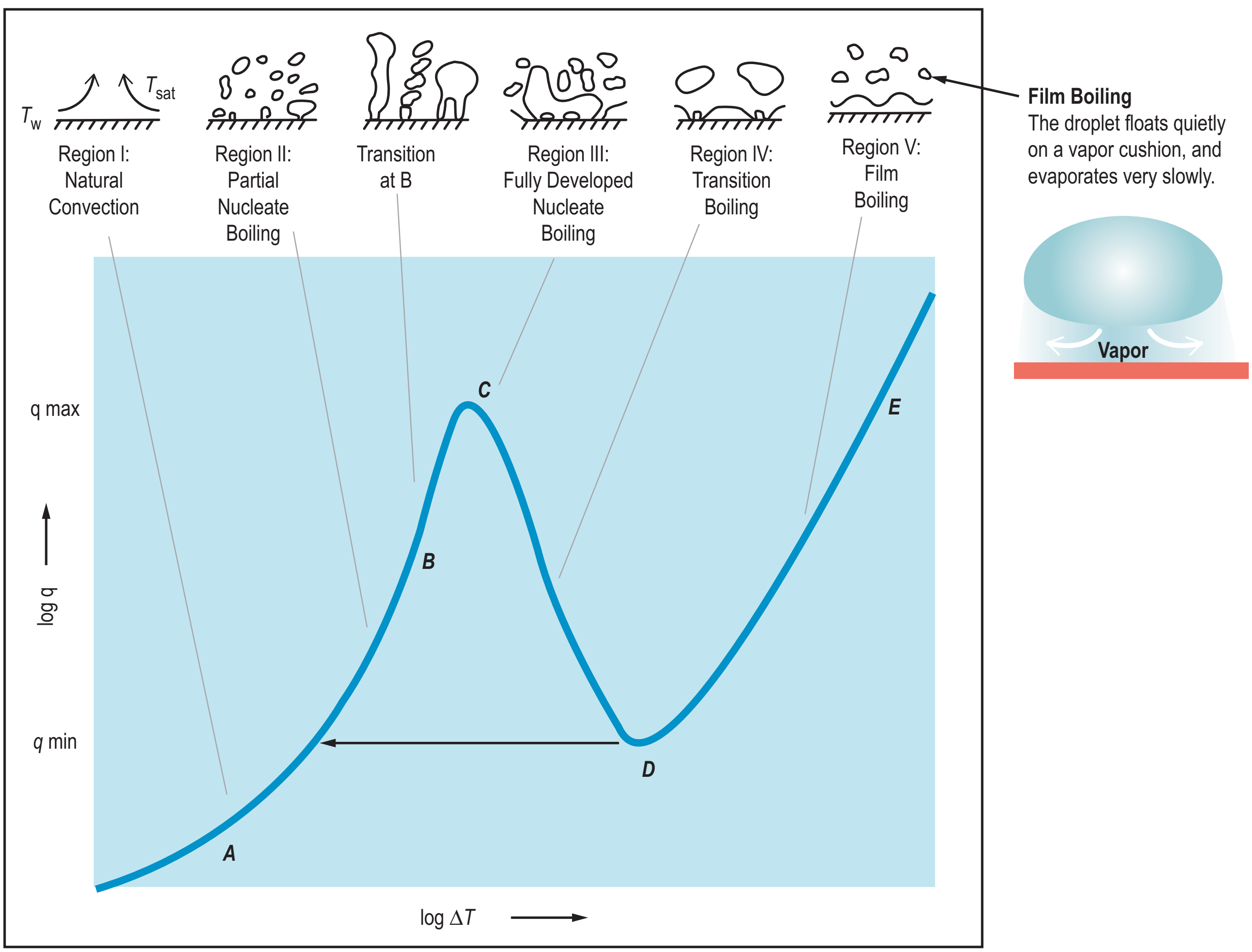

Figure 13. Boiling heat transfer regime versus wall-to-liquid temperature difference.

5.1.1 Laboratory Bench Test Approach

To minimize safety concerns and cost, and to support bench-type testing, LN_2 was selected as the test fluid. The test specimen was an instrumented 1.27-cm-thick (0.5-in-thick) by 25-cm (12-in) square aluminum plate. The test objectives were as follows: (1) To determine the total time to cool the plate from room temperature to saturated LN_2 temperatures, and (2) to measure the temperature delta across the plate as a function of time. The test article, illustrated in figure 14, consisted of an open (6061-T6 aluminum) container formed by using the test specimen as the bottom, with 0.635-cm-thick (0.25-in-thick) and 10-cm-high (4-in-high) walls. The container exterior was coated with Great Stuff™ expanding foam at an approximate thickness of 2.54 cm (1 in) on the sides and 5.1 cm (2 in) on the bottom. Data from type E TCs attached to both the inner and outer surfaces near the center of the plate were recorded by a PC/LabVIEW-based data acquisition system. The TCs were rigidly 'pinged' into the surface (into approximately 0.16 cm (1/16 in) deep holes) to secure the bead, and covered with Stycast® cryogenic epoxy. The data A typical test procedure consisted of the following:

(1) Fill two small portable Dewars from a facility LN_2 storage tank.
(2) Start data acquisition system.
(3) Rapidly pour Dewar contents into test container.
(4) Refill portable Dewars.
(5) Manually add LN_2 as needed to maintain the LN_2 level between 2.5 and 5 cm (1 and 2 in) of LN_2.
(6) Terminate test when saturated LN_2 temperatures are verified on both test specimen TCs.

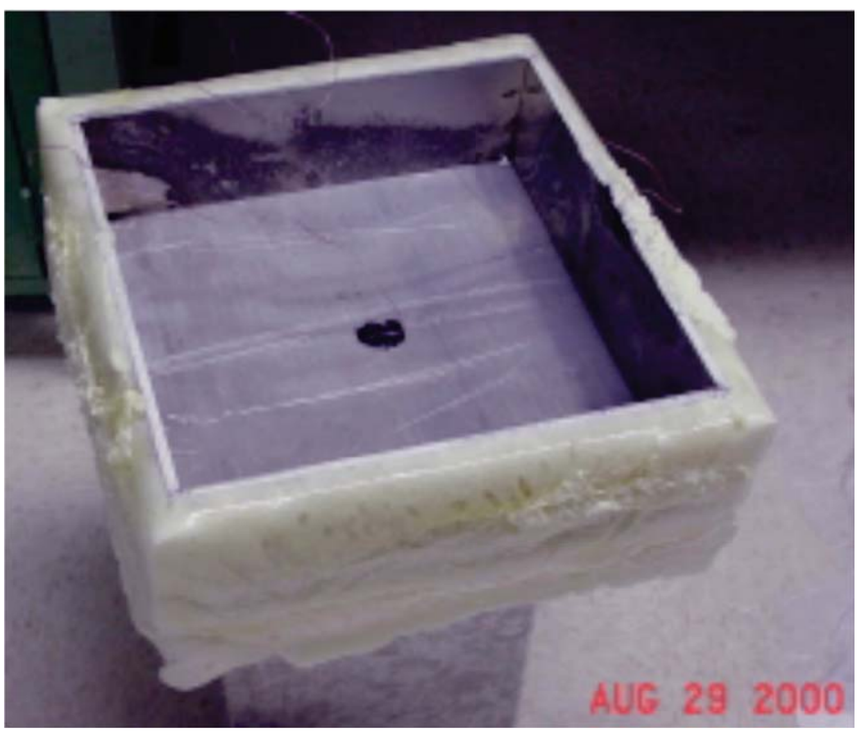

Figure 14. Test container used to demonstrate effects of film boiling on chilldown.

5.1.2 Bench Tests Conducted and Results

A total of three tests were performed: Tests A and B with identical test conditions to verify data repeatability, and test C to demonstrate the effectiveness of a thin insulating coating on chill-down time reduction. The test results in the form of measured wall temperature versus time are presented in figure 15. Although there was an overall data offset (of ≈ 5 K) between test A and B that was attributed to an offset in the LabVIEW TC reference junction, the trends were identical. As expected, very little gradient was measured across the aluminum plate (<2 K) due to the high thermal conduction of aluminum. In both tests A and B, a gradual decline in temperature for about the first 450 s was followed by a rapid drop in the final 8 to 10 s to saturation (77 K (139 °R)) for a total time of 460 s required to chill the plate from ambient to saturation conditions. This overall response is a classic example of how film boiling constrains the heat transfer until the surface temperature is reduced to the point where nucleate boiling can be sustained (in this case, about 113 K (203 °R)). In fact, the boiling patterns could be visually and audibly observed during the testing.

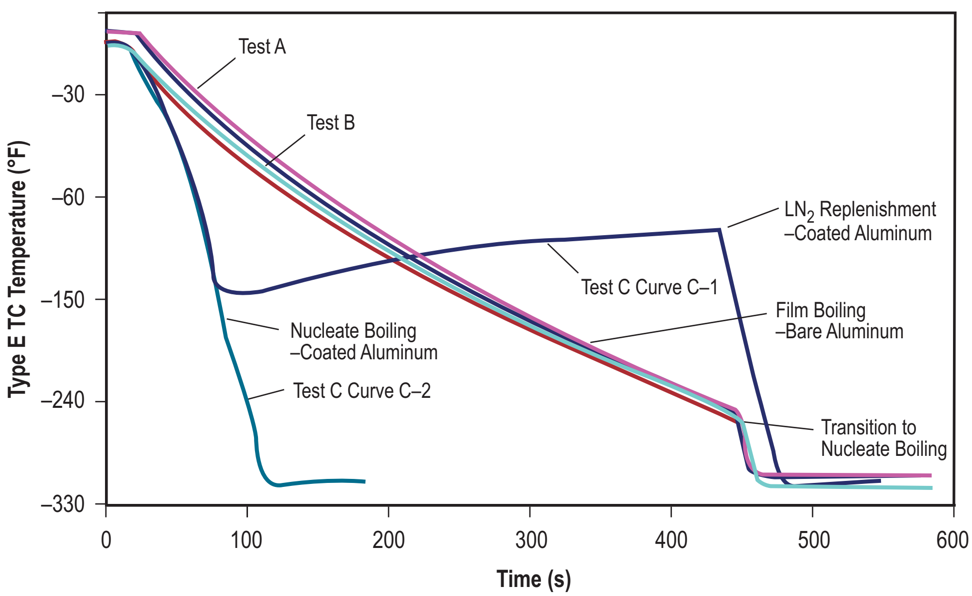

Figure 15. Effects of liquid nitrogen film boiling on chilldown time.

Prior to test C, approximately 3 mils of an insulating material was applied to all internal surfaces of the test container. This material was an electronics varnish used to coat printed circuits, and although not rated for cryogenic temperatures, was adequate for one chilldown demonstration. The basic concept is that the insulator reduces the temperature difference between the liquid and surface (maintains a high delta temperature across its small thickness), thereby preventing vapor film formation and enabling nucleate boiling to proceed. During test C, the two portable Dewars of LN_2 were added to the test container and produced boiling that was much more rapid than tests A and B. As illustrated in figure 15, the temperature drop quickly accelerated, and within 50 s, all LN_2 was boiled out of the container and warming began (depicted in curve C-1). This rate was faster than the portable Dewars could be refilled for top-off. Therefore, a real-time decision was made to continue the test by adding top-off LN_2 while the surface was partially chilled down. This was performed approximately 500 s into the test run, and aluminum temperatures again quickly dropped until saturation conditions were met. By numerically subtracting the warm-up period and continuing with data for the second stage of chilldown, the test curve C-2 was generated. The potential value of thin coatings was clearly demonstrated by the chilldown time reduction by a factor of 4.6 (460 s without coating compared with 100 s). However, it must be noted that considerable effort remains in finding coating materials that can withstand extended cryogenic exposure durations without degradation and contamination issues.

5.2 Fill Performance and Data Evaluation

The objective of filling the vented tank within 5 min was accomplished during all six performance tests. However, with the slow tank wall chilldown results in mind, it was not surprising that the vent valve could not be closed without incurring excessive ullage pressures. Regardless of the fill and valve closure sequence procedure, it was evident that residual energy remaining in the tank walls was too high to allow valve closure within the allotted time. Further details regarding fill performance and system level analyses are discussed in the following sections.

5.2.1 Fill Performance

Referring to table 2, three vent valve closure sequences were attempted during the first five performance tests: (1) Vent closing during fill (tests 9 and 10), (2) vent closing and stopping fill simultaneously (test 11), and (3) (a) filling the tank until liquid exited the vent, (b) draining it back, allowing time for transients to subside, and (c) then continuing a no-vent fill (tests 12–14).

In tests 9–11, the ullage pressures increased rapidly (approximately 0.2–0.5 psi/s (1.38–3.45 kPa/s) upon valve closure and quickly activated the redline ullage pressure setting. Because the tank was filled, drained, and then refilled, three fill levels for tests 12–14 are indicated in table 2 as (a), (b), and (c). The measured in-flow rate, fill level, supply pressure, and ullage pressure versus time for test 14, which is considered representative of the both the vented and nonvented fill sequences, are presented in figures 16 and 17, respectively. The vented fill terminated at a test time of about 275 s and a 90% fill; then the vent was closed at 290 s and reopened about 50 s later when the redline ullage pressure occurred (fig. 16). The nonvented fill sequence was initiated at the 79% fill level and had achieved about 90% fill when the redline pressure occurred 40 s later (fig. 17) Therefore, even with the decreasing refill rate as the ullage pressure approached the supply pressure, the redline ullage pressure rapidly occurred following vent valve closure in each of the three tests (tests 12–14).

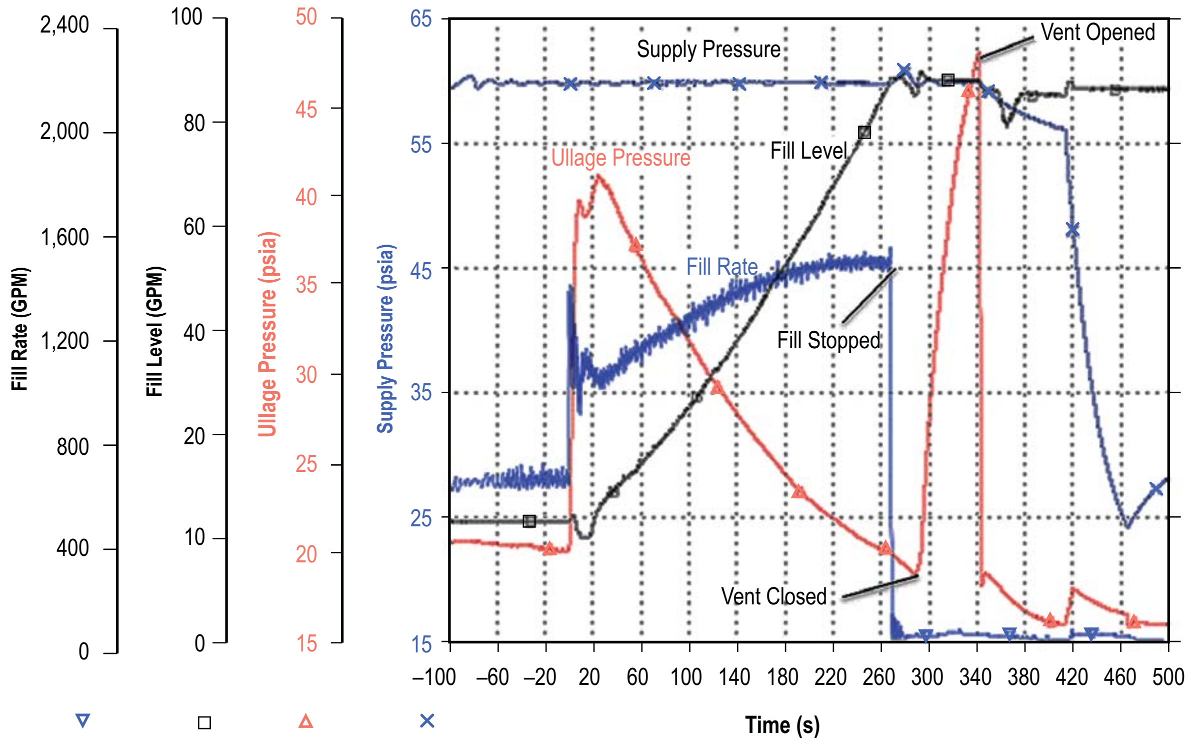

Figure 16. Measured ullage pressure, fill flow rate, and liquid level for vented fill, test 14.

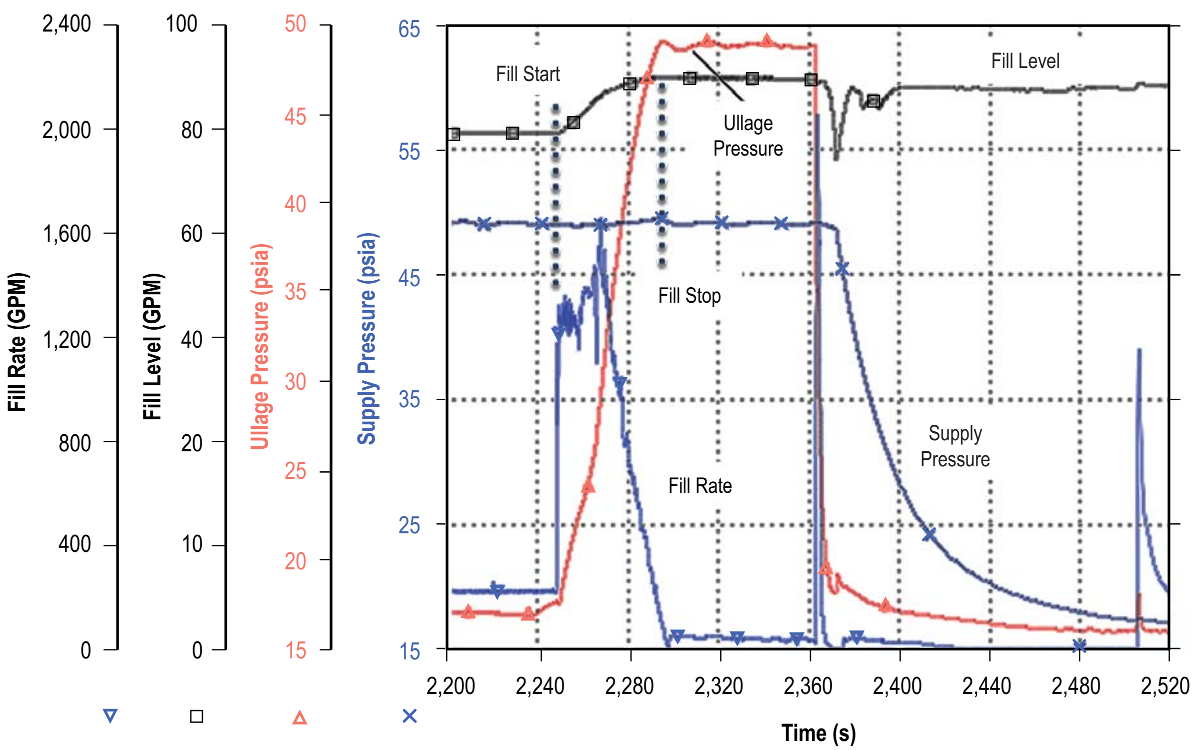

Figure 17. No-vent fill beginning with 79% fill level for test 14.

5.3 System Level Modeling

A FORTRAN model of the tank was built with the objective of modeling the complex thermodynamic and heat transfer phenomena within the MHTB to support the following: (1) For test planning and system characterization testing (discussed in sec. 4), and (2) to assist with the fill performance data evaluation (described in sec. 5.2). The three-node model, which consisted of one node each for the tank wall, ullage, and propellant, was used to simulate the chill/fill process. Although the model was greatly simplified, the vented fill pressure peak was predicted to within 5% to 10% of the measured data for tests 7–14, during which the measured peak pressure ranged from 26.2 to 28.2 psig (282 to 296 kPa). Also, as shown in figure 18, the average wall temperature transients predicted by the one-node model were comparable to the measured temperatures in the lower regions of the tank.

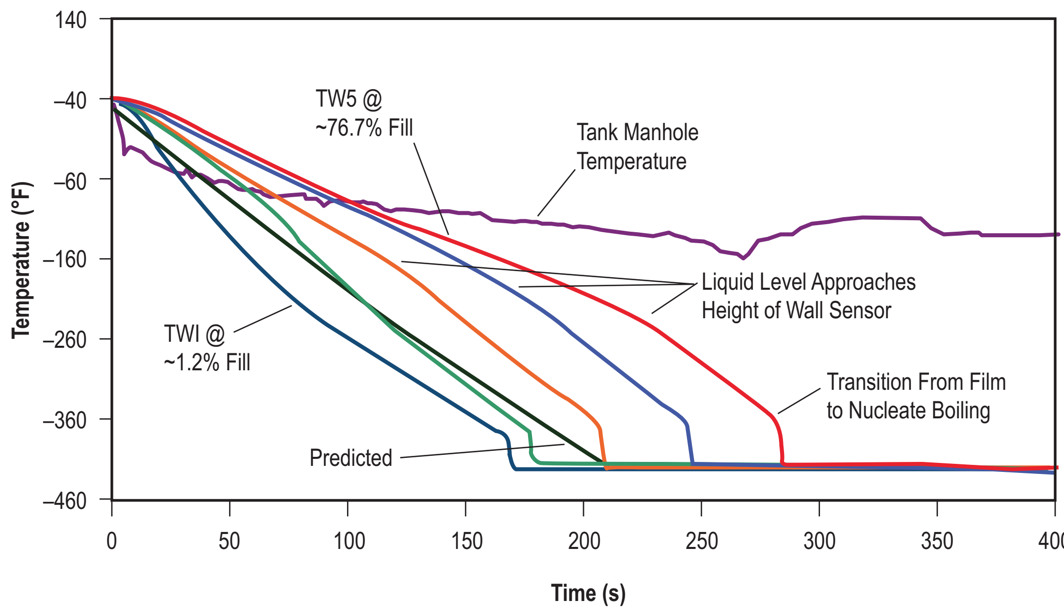

Figure 18. Predicted average wall temperature versus measured data, test 14.

However, the model was set up for a scenario wherein the tank structure chilldown occurred rapidly due to a uniformly distributed spray and the high heat absorption or removal capability that is characteristic of nucleate boiling combined with forced convection due to the spray. In such a case, the sprayed liquid is rapidly vaporized as it removes the thermal energy stored in the tank structure. Then as the tank structural chilldown nears completion, the vaporization process decreases and the accumulation of liquid or tank fill begins. However, as previously noted, the actual scenario was quite different. First, there was the prolonged existence of film boiling, as opposed to nucleate boiling, which inhibited heat transfer out of the tank walls to such an extent that the tank fill began almost immediately and was completed before chilldown completion. Second, only a partial chill down of the massive manhole cover area in the upper dome region of the tank was achieved.

5.4 Implications for Reduced Gravity Tank Chilldown

The use of spray bars has long been considered as a means for accomplishing on-orbit tank chilldown prior to cryogenic propellant transfer (fig. 18). Therefore, testing herein has substantial implications for on-orbit cryogen transfer applications. The film boiling encountered in the subject testing could become even more of an obstacle in reduced gravity because the formation of a vapor film would be much less inhibited due to the reduced buoyancy effects. In fact, the wall temperatures required to initiate normal gravity film boiling could be substantially reduced in the long-term low-gravity environments of space. One method for mitigating the reduced gravity effects on buoyancy is to assure adequate liquid motion, or velocity, for vapor removal and forced convection. In other words, if a prescribed velocity or flow pattern can be assured in reduced gravity, then predictable forced convection conditions follow.

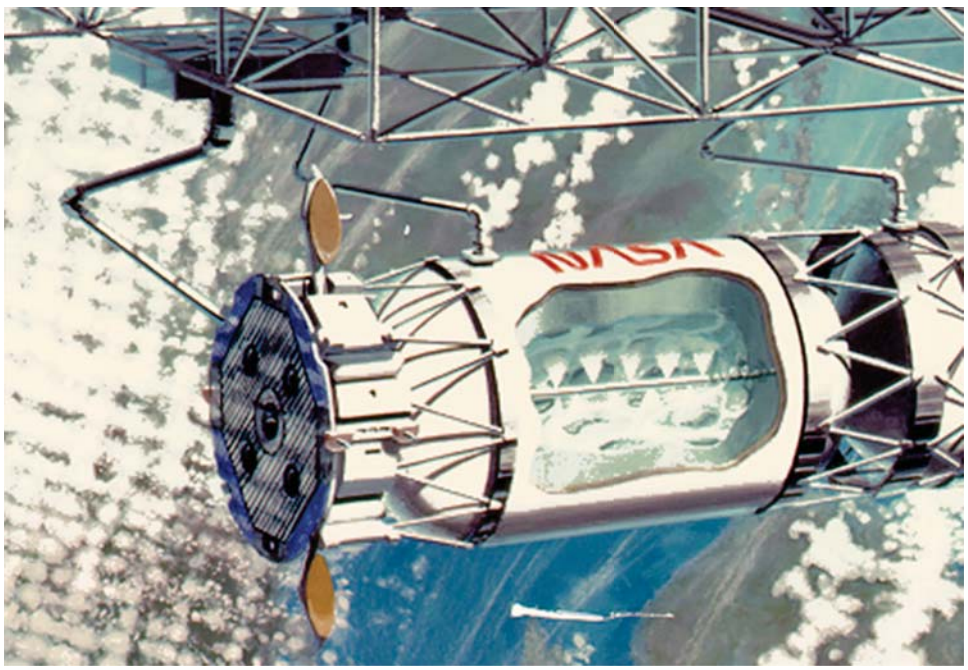

Figure 19. On-orbit cryogenic tank chill/fill using spray bar.

Although the thick aluminum tank walls were a handicap in achieving the objectives in the ASUS program, the heavy walls could become an asset in normal gravity testing for reduced gravity applications. The rationale is as follows: If film boiling can be inhibited by the production of predictable flow velocities or patterns in normal gravity cryogenic testing with thick walls, then analytical modeling successfully anchored with such data could be applied to reduced gravity environments with a reasonable degree of confidence. Additionally, the use of thin film coatings could prove to be very useful in space by helping to assure predictable chilldown scenarios.

6. CONCLUSIONS

The testing was successful in demonstrating the ability to fill a flight volume tank with LH_2 within 5 min; however, the tank fill occurred before chilldown of the 0.5-in-thick (1.27-cm-thick) aluminum walls and heavy manhole cover in the upper dome region could be achieved. In fact, rapid chilldown began only after the wall temperature was reduced to the 80 to 100 °R (44 to 56 K) range; therefore, saturation temperatures did not occur until 60 to 80 s after the liquid level had passed a given tank wall position. It was evident that the elevated tank wall temperatures below the liquid level were characteristic of film boiling. Therefore, a laboratory LN_2 bench experiment was used to physically demonstrate the effects of boiling heat transfer regimes on a 0.5-in-thick (1.27-cm-thick) aluminum wall chilldown. The bench test clearly proved that the prolonged existence of film boiling had substantially inhibited heat transfer out of the tank structure. Additionally, the bench testing demonstrated the potential value of thin coatings by reducing the chilldown time by a factor of 4.6 (460 s without the coating compared to 100 s with). However, considerable effort remains in finding coating materials that can withstand extended cryogenic exposure durations without degradation and contamination issues. In addition to the slow chilldown of the tank side walls, chilldown of the massive manhole cover area in the upper dome was incomplete, i.e., the temperatures remained above 300 °R (167 K) throughout the fill process.

With the slow tank structure chilldown results in mind, it was not surprising that the vent valve could not be closed without incurring excessive ullage pressures. Regardless of the fill and valve closure sequence procedure, it was evident that residual energy remaining in the tank walls was too high to allow valve closure within the allotted time interval of 5 min. The use of a flight-weight tank and possibly a redesigned spray bar with increased spray directed at the tank top would have improved the likelihood of achieving a no-vent fill. Although the simple three-node model of the system yielded useful data for setting critical test operation parameters and initially characterizing the system, its fidelity was inadequate to fully characterize the complex thermodynamic and heat transfer phenomena.

The test results herein have substantial implications for on-orbit cryogen transfer since the formation of a vapor film would be much less inhibited due to the reduced buoyancy. One method for mitigating the reduced buoyancy effects and improving confidence in analytical modeling is to assure liquid motion adequate for vapor removal and forced convection. Therefore, it seems that heavy tank walls could become an asset in normal gravity testing for on-orbit transfer. The rationale is as follows: If film boiling in an MHTB type tank can be inhibited in normal gravity, then the analytical modeling anchored with such data could be applied to reduced gravity environments with increased confidence. Additionally, the use of thin film coatings could prove to be very useful in achieving predictable in-space chilldown.

APPENDIX A—MULTIPURPOSE HYDROGEN TEST BED TANKING STATISTICS

The MHTB tanking statistics are found in table 3.

Table 3. Tanking table.

Height		Volume		Ullage	Liquid	Liquid Mass	Liquid Mass
(in)	(cm)	(ft^3)	(m^3)	(%)	(%)	(lbm)	(kg)
0	0	0	0	100	0	0	0
0.5	1.27	0.05	0.0015	99.99	0.01	0.24	0.1087
1	2.54	0.22	0.0061	99.97	0.03	0.95	0.4324
1.5	3.81	0.48	0.0137	99.92	0.08	2.13	0.9673
2	5.08	0.85	0.0242	99.87	0.13	3.77	1.7098
2.5	6.35	1.33	0.0375	99.79	0.21	5.86	2.656
3	7.62	1.9	0.0537	99.7	0.3	8.38	3.8025
3.5	8.89	2.57	0.0727	99.6	0.4	11.34	5.1453
4	10.16	3.33	0.0944	99.48	0.52	14.73	6.6809
4.5	11.43	4.19	0.1187	99.34	0.66	18.53	8.4055
5	12.7	5.15	0.1457	99.2	0.8	22.74	10.3154
5.5	13.97	6.19	0.1753	99.03	0.97	27.35	12.4068
6	15.24	7.32	0.2073	98.85	1.15	32.36	14.6762
6.5	16.51	8.54	0.2419	98.66	1.34	37.74	17.1198
7	17.78	9.85	0.2788	98.46	1.54	43.51	19.7338
7.5	19.05	11.23	0.3181	98.24	1.76	49.64	22.5146
8	20.32	12.7	0.3597	98.01	1.99	56.13	25.4585
8.5	21.59	14.25	0.4035	97.77	2.23	62.97	28.5618
9	22.86	15.88	0.4495	97.52	2.48	70.15	31.8207
9.5	24.13	17.58	0.4977	97.25	2.75	77.67	35.2316
10	25.4	19.35	0.5480	96.97	3.03	85.52	38.7907
10.5	26.67	21.2	0.6003	96.68	3.32	93.68	42.4943
11	27.94	23.12	0.6546	96.38	3.62	102.16	46.3388
11.5	29.21	25.1	0.7109	96.07	3.93	110.94	50.3204
12	30.48	27.16	0.769	95.75	4.25	120.01	54.4354
12.5	31.75	29.28	0.829	95.42	4.58	129.37	58.6801
13	33.02	31.46	0.8907	95.08	4.92	139	63.0509
13.5	34.29	33.7	0.9542	94.73	5.27	148.91	67.5439
14	35.56	36	1.0193	94.37	5.63	159.08	72.1556
14.5	36.83	38.36	1.0861	94	6	169.5	76.8821
15	38.1	40.77	1.1545	93.62	6.38	180.16	81.7198
15.5	39.37	43.24	1.2243	93.24	6.76	191.06	86.665

Table 3. Tanking table (Continued).

Height		Volume		Ullage	Liquid	Liquid Mass	Liquid Mass
(in)	(cm)	(ft^3)	(m^3)	(%)	(%)	(lbm)	(kg)
16	40.64	45.76	1.2957	92.84	7.16	202.19	91.714
16.5	41.91	48.32	1.3684	92.44	7.56	213.55	96.863
17	43.18	50.94	1.4425	92.03	7.97	225.11	102.1084
17.5	44.45	53.6	1.5179	91.62	8.38	236.88	107.4464
18	45.72	56.31	1.5946	91.19	8.81	248.84	112.8734
18.5	46.99	59.06	1.6724	90.76	9.24	261	118.3856
19	48.26	61.85	1.7515	90.33	9.67	273.33	123.9794
19.5	49.53	64.68	1.8316	89.88	10.12	285.83	129.651
20	50.8	67.55	1.9128	89.43	10.57	298.5	135.3967
20.5	52.07	70.45	1.9949	88.98	11.02	311.32	141.2128
21	53.34	73.39	2.078	88.52	11.48	324.29	147.0957
21.5	54.61	76.35	2.162	88.06	11.94	337.4	153.0415
22	55.88	79.35	2.2469	87.59	12.41	350.64	159.0467
22.5	57.15	82.37	2.3325	87.12	12.88	364	165.1074
23	58.42	85.42	2.4188	86.64	13.36	377.48	171.22
23.5	59.69	88.49	2.5059	86.16	13.84	391.06	177.3808
24	60.96	91.59	2.5935	85.67	14.33	404.74	183.5861
24.5	62.23	94.71	2.6818	85.19	14.81	418.51	189.8321
25	63.5	97.84	2.7705	84.7	15.3	432.36	196.1152
25.5	64.77	100.99	2.8598	84.2	15.8	446.29	202.4317
26	66.04	104.16	2.9494	83.71	16.29	460.28	208.7778
26.5	67.31	107.34	3.0394	83.21	16.79	474.32	215.1498
27	68.58	110.53	3.1298	82.71	17.29	488.42	221.5441
27.5	69.85	113.73	3.2204	82.21	17.79	502.56	227.9569
28	71.12	116.93	3.3112	81.71	18.29	516.73	234.3845
28.5	72.39	120.15	3.4021	81.21	18.79	530.92	240.8233
29	73.66	123.36	3.4932	80.7	19.3	545.14	247.2695
29.5	74.93	126.58	3.5843	80.2	19.8	559.36	253.7193
30	76.2	129.8	3.6755	79.7	20.3	573.58	260.1718
30.5	77.47	133.02	3.7666	79.19	20.81	587.8	266.6225
31	78.74	136.23	3.8577	78.69	21.31	602.02	273.0731
31.5	80.01	139.45	3.9489	78.19	21.81	616.24	279.5237
32	81.28	142.67	4.04	77.68	22.32	630.47	285.9743
32.5	82.55	145.89	4.1311	77.18	22.82	644.69	292.425
33	83.82	149.11	4.2222	76.68	23.32	658.91	298.8756
33.5	85.09	152.33	4.3134	76.17	23.83	673.13	305.3262
34	86.36	155.54	4.4045	75.67	24.33	687.35	311.7768
34.5	87.63	158.76	4.4956	75.17	24.83	701.57	318.2275
35	88.9	161.98	4.5868	74.66	25.34	715.79	324.6781
35.5	90.17	165.2	4.6779	74.16	25.84	730.01	331.1287
36	91.44	168.42	4.769	73.66	26.34	744.24	337.5793

Table 3. Tanking table (Continued).

Height		Volume		Ullage	Liquid	Liquid Mass	Liquid Mass
(in)	(cm)	(ft^3)	(m^3)	(%)	(%)	(lbm)	(kg)
36.5	92.71	171.63	4.8601	73.15	26.85	758.46	344.03
37	93.98	174.85	4.9513	72.65	27.35	772.68	350.4806
37.5	95.25	178.07	5.0424	72.15	27.85	786.9	356.9312
38	96.52	181.29	5.1335	71.64	28.36	801.12	363.3818
38.5	97.79	184.51	5.2247	71.14	28.86	815.34	369.8325
39	99.06	187.73	5.3158	70.64	29.36	829.56	376.2831
39.5	100.33	190.94	5.4069	70.13	29.87	843.78	382.7337
40	101.6	194.16	5.498	69.63	30.37	858	389.1843
40.5	102.87	197.38	5.5892	69.13	30.87	872.23	395.635
41	104.14	200.6	5.6803	68.62	31.38	886.45	402.0856
41.5	105.41	203.82	5.7714	68.12	31.88	900.67	408.5362
42	106.68	207.03	5.8626	67.62	32.38	914.89	414.9868
42.5	107.95	210.25	5.9537	67.11	32.89	929.11	421.4375
43	109.22	213.47	6.0448	66.61	33.39	943.33	427.8881
43.5	110.49	216.69	6.1359	66.11	33.89	957.55	434.3387
44	111.76	219.91	6.2271	65.6	34.4	971.77	440.7893
44.5	113.03	223.13	6.3182	65.1	34.9	986	447.24
45	114.3	226.34	6.4093	64.6	35.4	1000.22	453.6906
45.5	115.57	229.56	6.5005	64.09	35.91	1014.44	460.1412
46	116.84	232.78	6.5916	63.59	36.41	1028.66	466.5918
46.5	118.11	236	6.6827	63.09	36.91	1042.88	473.0425
47	119.38	239.22	6.7738	62.58	37.42	1057.1	479.4931
47.5	120.65	242.43	6.865	62.08	37.92	1071.32	485.9437
48	121.92	245.65	6.9561	61.58	38.42	1085.54	492.3943
48.5	123.19	248.87	7.0472	61.07	38.93	1099.76	498.845
49	124.46	252.09	7.1384	60.57	39.43	1113.99	505.2956
49.5	125.73	255.31	7.2295	60.07	39.93	1128.21	511.7462
50	127	258.53	7.3206	59.56	40.44	1142.43	518.1968
50.5	128.27	261.74	7.4117	59.06	40.94	1156.65	524.6475
51	129.54	264.96	7.5029	58.56	41.44	1170.87	531.0981
51.5	130.81	268.18	7.594	58.05	41.95	1185.09	537.5487
52	132.08	271.4	7.6851	57.55	42.45	1199.31	543.9993
52.5	133.35	274.62	7.7763	57.05	42.95	1213.53	550.45
53	134.62	277.83	7.8674	56.54	43.46	1227.76	556.9006
53.5	135.89	281.05	7.9585	56.04	43.96	1241.98	563.3512
54	137.16	284.27	8.0496	55.54	44.46	1256.2	569.8018
54.5	138.43	287.49	8.1408	55.03	44.97	1270.42	576.2525
55	139.7	290.71	8.2319	54.53	45.47	1284.64	582.7031
55.5	140.97	293.93	8.323	54.03	45.97	1298.86	589.1537
56	142.24	297.14	8.4142	53.52	46.48	1313.08	595.6043
56.5	143.51	300.36	8.5053	53.02	46.98	1327.3	602.055

Table 3. Tanking table (Continued).

Height		Volume		Ullage	Liquid	Liquid Mass	Liquid Mass
(in)	(cm)	(ft^3)	(m^3)	(%)	(%)	(lbm)	(kg)
57	144.78	303.58	8.5964	52.52	47.48	1341.53	608.5056
57.5	146.05	306.8	8.6875	52.01	47.99	1355.75	614.9562
58	147.32	310.02	8.7787	51.51	48.49	1369.97	621.4068
58.5	148.59	313.23	8.8698	51.01	48.99	1384.19	627.8575
59	149.86	316.45	8.9609	50.5	49.5	1398.41	634.3081
59.5	151.13	319.67	9.0521	50	50	1412.63	640.7587
60	152.4	322.89	9.1432	49.5	50.5	1426.85	647.2093
60.5	153.67	326.11	9.2343	48.99	51.01	1441.07	653.66
61	154.94	329.33	9.3254	48.49	51.51	1455.29	660.1106
61.5	156.21	332.54	9.4166	47.99	52.01	1469.52	666.5612
62	157.48	335.76	9.5077	47.48	52.52	1483.74	673.0118
62.5	158.75	338.98	9.5988	46.98	53.02	1497.96	679.4625
63	160.02	342.2	9.69	46.48	53.52	1512.18	685.9131
63.5	161.29	345.42	9.7811	45.97	54.03	1526.4	692.3637
64	162.56	348.63	9.8722	45.47	54.53	1540.62	698.8143
64.5	163.83	351.85	9.9633	44.97	55.03	1554.84	705.265
65	165.1	355.07	10.0545	44.46	55.54	1569.06	711.7156
65.5	166.37	358.29	10.1456	43.96	56.04	1583.29	718.1662
66	167.64	361.51	10.2367	43.46	56.54	1597.51	724.6168
66.5	168.91	364.73	10.3278	42.95	57.05	1611.73	731.0675
67	170.18	367.94	10.419	42.45	57.55	1625.95	737.5181
67.5	171.45	371.16	10.5101	41.95	58.05	1640.17	743.9687
68	172.72	374.38	10.6012	41.44	58.56	1654.39	750.4193
68.5	173.99	377.6	10.6924	40.94	59.06	1668.61	756.87
69	175.26	380.82	10.7835	40.44	59.56	1682.83	763.3206
69.5	176.53	384.03	10.8746	39.93	60.07	1697.06	769.7712
70	177.8	387.25	10.9657	39.43	60.57	1711.28	776.2218
70.5	179.07	390.47	11.0569	38.93	61.07	1725.5	782.6725
71	180.34	393.69	11.148	38.42	61.58	1739.72	789.1231
71.5	181.61	396.91	11.2391	37.92	62.08	1753.94	795.5737
72	182.88	400.13	11.3303	37.42	62.58	1768.16	802.0243
72.5	184.15	403.34	11.4214	36.91	63.09	1782.38	808.475
73	185.42	406.56	11.5125	36.41	63.59	1796.6	814.9256
73.5	186.69	409.78	11.6036	35.91	64.09	1810.82	821.3762
74	187.96	413	11.6948	35.4	64.6	1825.05	827.8268
74.5	189.23	416.22	11.7859	34.9	65.1	1839.27	834.2775
75	190.5	419.43	11.877	34.4	65.6	1853.49	840.7281
75.5	191.77	422.65	11.9682	33.89	66.11	1867.71	847.1787
76	193.04	425.87	12.0593	33.39	66.61	1881.93	853.6293
76.5	194.31	429.09	12.1504	32.89	67.11	1896.15	860.08
77	195.58	432.31	12.2415	32.38	67.62	1910.37	866.5306

Table 3. Tanking table (Continued).

Height		Volume		Ullage	Liquid	Liquid Mass	Liquid Mass
(in)	(cm)	(ft^3)	(m^3)	(%)	(%)	(lbm)	(kg)
77.5	196.85	435.53	12.3327	31.88	68.12	1924.59	872.9812
78	198.12	438.74	12.4238	31.38	68.62	1938.82	879.4318
78.5	199.39	441.96	12.5149	30.87	69.13	1953.04	885.8824
79	200.66	445.18	12.6061	30.37	69.63	1967.26	892.3331
79.5	201.93	448.4	12.6972	29.87	70.13	1981.48	898.7837
80	203.2	451.62	12.7883	29.36	70.64	1995.7	905.2343
80.5	204.47	454.83	12.8794	28.86	71.14	2009.92	911.6849
81	205.74	458.05	12.9706	28.36	71.64	2024.14	918.1356
81.5	207.01	461.27	13.0617	27.85	72.15	2038.36	924.5862
82	208.28	464.49	13.1528	27.35	72.65	2052.58	931.0368
82.5	209.55	467.71	13.244	26.85	73.15	2066.81	937.4874
83	210.82	470.93	13.3351	26.34	73.66	2081.03	943.9381
83.5	212.09	474.14	13.4262	25.84	74.16	2095.25	950.3887
84	213.36	477.36	13.5173	25.34	74.66	2109.47	956.8393
84.5	214.63	480.58	13.6085	24.83	75.17	2123.69	963.2899
85	215.9	483.8	13.6996	24.33	75.67	2137.91	969.7406
85.5	217.17	487.02	13.7907	23.83	76.17	2152.13	976.1912
86	218.44	490.23	13.8819	23.32	76.68	2166.35	982.6418
86.5	219.71	493.45	13.973	22.82	77.18	2180.58	989.0924
87	220.98	496.67	14.0641	22.32	77.68	2194.8	995.5431
87.5	222.25	499.89	14.1552	21.81	78.19	2209.02	1001.9937
88	223.52	503.11	14.2464	21.31	78.69	2223.24	1008.4443
88.5	224.79	506.33	14.3375	20.8	79.2	2237.46	1014.8949
89	226.06	509.54	14.4286	20.3	79.7	2251.68	1021.3456
89.5	227.33	512.76	14.5198	19.8	80.2	2265.9	1027.7962
90	228.6	515.98	14.6108	19.3	80.7	2280.12	1034.2433
90.5	229.87	519.19	14.7019	18.79	81.21	2294.33	1040.6895
91	231.14	522.41	14.7929	18.29	81.71	2308.52	1047.1282
91.5	232.41	525.61	14.8837	17.79	82.21	2322.69	1053.5559
92	233.68	528.81	14.9743	17.29	82.71	2336.83	1059.9687
92.5	234.95	532	15.0646	16.79	83.21	2350.93	1066.363
93	236.22	535.18	15.1546	16.29	83.71	2364.98	1072.735
93.5	237.49	538.35	15.2443	15.8	84.2	2378.97	1079.0811
94	238.76	541.5	15.3335	15.3	84.7	2392.89	1085.3976
94.5	240.03	544.63	15.4223	14.81	85.19	2406.74	1091.6807
95	241.3	547.75	15.5105	14.33	85.67	2420.51	1097.9267
95.5	242.57	550.84	15.5982	13.84	86.16	2434.19	1104.132
96	243.84	553.92	15.6852	13.36	86.64	2447.78	1110.2928
96.5	245.11	556.97	15.7716	12.88	87.12	2461.25	1116.4054
97	246.38	559.99	15.8572	12.41	87.59	2474.61	1122.4661
97.5	247.65	562.99	15.942	11.94	88.06	2487.85	1128.4713

Table 3. Tanking table (Continued).

Height		Volume		Ullage	Liquid	Liquid Mass	Liquid Mass
(in)	(cm)	(ft^3)	(m^3)	(%)	(%)	(lbm)	(kg)
98	248.92	565.95	16.026	11.48	88.52	2500.96	1134.4171
98.5	250.19	568.89	16.1091	11.02	88.98	2513.93	1140.3
99	251.46	571.79	16.1913	10.57	89.43	2526.75	1146.1161
99.5	252.73	574.66	16.2724	10.12	89.88	2539.42	1151.8618
100	254	577.49	16.3526	9.67	90.33	2551.92	1157.5334
100.5	255.27	580.28	16.4316	9.24	90.76	2564.26	1163.1272
101	256.54	583.03	16.5095	8.81	91.19	2576.41	1168.6394
101.5	257.81	585.73	16.5861	8.38	91.62	2588.37	1174.0664
102	259.08	588.4	16.6615	7.97	92.03	2600.14	1179.4044
102.5	260.35	591.01	16.7356	7.56	92.44	2611.71	1184.6498
103	261.62	593.58	16.8084	7.16	92.84	2623.06	1189.7988
103.5	262.89	596.1	16.8797	6.76	93.24	2634.19	1194.8478
104	264.16	598.57	16.9496	6.38	93.62	2645.09	1199.793
104.5	265.43	600.98	17.0179	6	94	2655.76	1204.6307
105	266.7	603.34	17.0847	5.63	94.37	2666.18	1209.3572
105.5	267.97	605.64	17.1498	5.27	94.73	2676.34	1213.9689
106	269.24	607.88	17.2133	4.92	95.08	2686.25	1218.4619
106.5	270.51	610.06	17.2751	4.58	95.42	2695.88	1222.8327
107	271.78	612.18	17.335	4.25	95.75	2705.24	1227.0774
107.5	273.05	614.23	17.3932	3.93	96.07	2714.31	1231.1924
108	274.32	616.22	17.4494	3.62	96.38	2723.09	1235.174
108.5	275.59	618.14	17.5037	3.32	96.68	2731.57	1239.0185
109	276.86	619.99	17.556	3.03	96.97	2739.73	1242.7221
109.5	278.13	621.76	17.6063	2.75	97.25	2747.58	1246.2812
110	279.4	623.46	17.6545	2.48	97.52	2755.1	1249.6921
110.5	280.67	625.09	17.7005	2.23	97.77	2762.28	1252.951
111	281.94	626.64	17.7444	1.99	98.01	2769.13	1256.0543
111.5	283.21	628.11	17.786	1.76	98.24	2775.62	1258.9981
112	284.48	629.49	17.8253	1.54	98.46	2781.75	1261.779
112.5	285.75	630.8	17.8622	1.34	98.66	2787.51	1264.393
113	287.02	632.02	17.8967	1.15	98.85	2792.9	1266.8366
113.5	288.29	633.15	17.9288	0.97	99.03	2797.9	1269.106
114	289.56	634.19	17.9583	0.8	99.2	2802.51	1271.1974
114.5	290.83	635.15	17.9853	0.66	99.34	2806.72	1273.1073
115	292.1	636.01	18.0097	0.52	99.48	2810.52	1274.8319
115.5	293.37	636.77	18.0313	0.4	99.6	2813.91	1276.3675
116	294.64	637.44	18.0503	0.3	99.7	2816.87	1277.7103
116.5	295.91	638.01	18.0665	0.21	99.79	2819.4	1278.8567
117	297.18	638.49	18.0799	0.13	99.87	2821.48	1279.803
117.5	298.45	638.86	18.0904	0.08	99.92	2823.12	1280.5455
118	299.72	639.12	18.0979	0.03	99.97	2824.3	1281.0804

Table 3. Tanking table (Continued).

Height		Volume		Ullage	Liquid	Liquid Mass	Liquid Mass
(in)	(cm)	(ft^3)	(m^3)	(%)	(%)	(lbm)	(kg)
118.5	300.99	639.28	18.1025	0.01	99.99	2825.01	1281.4041
119	302.26	639.34	18.104	0	100	2825.25	1281.5128

APPENDIX B—CHILL/FILL INSTRUMENTATION LIST

The ASUS facility measuring statistics are listed in table 4.

Table 4. Instrumentation list.

MID	Description	Low	High	Units	SIU	CH	Manufac-turer	Model No.	S/N	RTD Info	CAL Due	FAP	NASA CAL	MRCF#
31P039	Test Article Inlet Pressure	0	200	PSIG	0	1	SENSOTEC	134MB250D	18772	2.5”	03/11/01	07/05/00	M626678	3,8,
31T037	Test Article Inlet Tem-perature	-424	100	DEG F	0	2	RTD, ROSE-MONT	150BD32	2549	4”	03/14/01	07/10/00	M636743	2,8,
31P042	Test Article Ullage Pressure	0	50	PSIG	0	5	STELLAR	GT200-50G-104	930257		05/11/02	07/05/00	M631362	8,
31P003	Test Article Vent Pressure	0	50	PSIG	0	3	TELEDYNE TABER	254	781295		02/08/01	06/22/00	M641701	8,
31T041	Test Article Vent Line Temperature	-424	100	DEG F	0	4	RTD, ROSE-MONT	150BD48	2734	6”	04/12/01	07/10/00	M624861	2,
31P008	Test Article Drain Line U/S VPV-3107	0	200	PSIG	0	8	STELLAR	GT200-200G-115	986776		10/15/00	06/22/00		8,
31T009	Test Article Drain Line U/S VPV-3107	-424	100	DEG F	0	9	ROSE-MOUNT ENG.	150HF32	3261	4”	07/29/00	07/10/00	M629619	8,9,
31P010	Fill Line Filter F-3104	0	5	PSID	0	10	STATHAM	PM385TC+5-350	93		09/15/00	07/05/00	M640319	8,
31T011	Down Stream ROV3119 Temperature	-424	100	DEG F	0	11	OMEGA	TYPE “E” T/C, 6X1/8	N/A	4”x6” VJ	N/A	07/05/00	N/A	8,
31P012	Down Stream ROV3119 Pressure	0	200	PSIG	0	12	STELLAR	GT200-200G-115	986769		10/15/00	07/05/00		8,
31P017	Storage Tank Drain Line U/S ROV-31161 Pressure	0	200	PSIG	0	17	TELEDYNE TABER	226	890898		11/16/00	06/22/00	M625310	8,
31T018	Storage Tank Drain Line U/S ROV-31161 Tem-perature	-424	100	DEG F	0	18	OMEGA	TYPE “E” T/C 6X1/8	N/A	1” tubing	N/A	07/05/00	N/A	8,
31P024	T8 Storage Tank Ullage Pressure	0	200	PSIG	0	22	STELLAR	GT200-200G-115	986775		10/15/00	07/05/00	M640036	8,
35P001	Test Article Pressurant Supply	0	200	PSIS	0	24	TELEDYNE TABER	226	890946		10/22/00	06/22/00	M640397	8,
35P002	T8 Storage Tank Pressurant Supply	0	1000	PSIG	0	25	STELLAR	GT200-1000G-115	986806		03/30/02	07/05/00	M640793	1,8,
36P001	Environmental Enclosure Purge	0	1000	PSIG	0	26	STELLAR	GT200-1000S-115	951770		09/14/01	07/05/00	M630581	8,
36P006	GN2 Panel Supply Pressure	0	5000	PSIS	0	31	TELEDYNE TABER	2105	902145		04/04/02	06/22/00	M635988	8,
31P031	Test Article Vent Pressure	0	50	PSIS	0	37	TELEDYNE TABER	254	781248		05/11/02	07/12/00	M638034	6,9,
T4630	SIU Room Temperature - B4630	32	100	DEG F	0	40	OMEGA	TYPE “E” T/C, 6X1/8	N/A		N/A	07/20/00	N/A	10,
31T036	Test Article Inlet Tem-perature	-424	100	DEG F	0	41	RTD, ROSE-MONT	134MB250D	18770	2.5”	03/11/01	07/10/00	M626699	1,3,8,

Table 4. Instrumentation list (Continued).

MID	Description	Low	High	Units	SIU	CH	Manufac-turer	Model No.	S/N	RTD Info	CAL Due	FAP	NASA CAL	MRCF#
31T033	Flowmeter D/S Temperature	-424	100	DEG F	0	42	RTD, ROSE-MONT	150BD48	2188	6”	03/16/01	07/10/00	M627372	1,8,
31T051	T8 Storage Outlet Temperature	-424	100	DEG F	0	44	RTD, OMEGA	PR-13-2-100-24-E		24”	09/07/01	09/27/00	M646957	
31T049	MHTB Drain Line Temperature	-424	100	DEG F	0	45	OMEGA	Type ‘E’ T/C		1” tubing		07/20/00		10,
FM3125	Facility Flowmeter	95	1300	GPM	0	46	Flow Technology	FT-64CINW-LHA-2021	640558		09/28/00	07/25/00	M642757	10,
31P050	T8 Storage Tank Delta Pressure	0	2	PSID	0	47	STELLAR	DT400-2BD-101	941217		07/28/01	08/03/00	M628186	
31P035	Flowmeter D/S Pressure	0	200	PSIG	0	48	SENSOTEC	Z/C438-02	633692		05/03/02	07/05/00	M645599	1,8,
31P034	Flowmeter U/S Pressure	0	200	PSIG	0	49	SENSOTEC	Z/C438-02	633674		05/03/02	07/05/00	M645595	1,8,
31P038	Test Article Inlet Pressure	0	200	PSIG	0	50	SENSOTEC	Z/C438-02	633694		05/04/02	07/06/00	M645601	1,8,
31P046	OR-31114 U/S Pressure	0	50	PSIS	0	51	Taber	254	921152		07/26/01	09/14/00	M623259	1,8,
31P048	OR-31114 Delta Pressure	0		PSID	0	52								
31P047	OR-31114 D/S Pressure	0	50	PSIS	0	53	TELEDYNE TABER	254	781293		07/26/01	09/14/00	M628975	1,8,
31T045	OR-31114 D/S Temperature	-424	100	DEG F	0	55	ROSE-MOUNT ENG.	134RN68	20709	8.5”	03/24/01	09/12/00	M622427	1,9,
31T052	Vent Line Surface Temperature	-424	100	DEG F	0	56	OMEGA	Type ‘E’ T/C Skin Temp	N/A		N/A	07/20/00	N/A	10,
31T053	Vent Line Surface Temperature	-424	100	DEG F	0	57	OMEGA	Type ‘E’ T/C Skin Temp	N/A		N/A	07/21/00	N/A	10,
31T016	GH2 Vent Line (near HCF)	-424	100	DEG F	0	58	OMEGA	Type ‘E’ T/C 6”x3/16	N/A		N/A	07/21/00	N/A	10,
31T040	Test Article Vent Temperature	-424	100	DEG F	0	59	RTD, ROSE-MONT	150BD48	2209	6”	04/12/01	07/10/00	M624855	1,8,
36P007	GN2 Tube Trailer Supply Pressure	0	6000	PSIG	0	60	STELLAR	GT200-6000G-115	962926		04/09/01	07/05/00	M633036	1,8,
36P008	GN2 Tube Trailer Reg Panel Outlet Pressure	0	200	PSIG	0	61	STELLAR	GT200-200G-115	986773		08/17/02	09/26/00	M640821	1,8,
31P019	Test Article Differential Pressure	0	2	PSID	0	62	STATHAM	TP-A-1064-EX	91		04/24/02	07/05/00	M629981	1,8,
31P043	Test Article Ullage Pressure	0	50	PSIS	0	63	TELEDYNE TABER	254	761560		07/26/01	07/12/00	M643345	6,9,
Dew1	Dewpoint	-68	78	DEG F	0	64	VAISALA	DMP248			06/15/01	07/14/00	N/A	4,9,
35T003	Storage Tank Pressurant Supply Temperature	32	100	DEG F	0	6	OMEGA	TYPE “E” T/C, 6X1/8	N/A		N/A	07/20/00	N/A	1,10,
31T054	RV31111 DownStream Skin Temperature	-424	100	DEG F	0	14	OMEGA	Type”E” T/C Skin Temp	N/A		N/A	07/20/00	N/A	3,10,
31T055	RV31111 DownStream Skin Temperature	-424	100	DEG F	0	15	OMEGA	Type”E” T/C Skin Temp	N/A		N/A	07/20/00	N/A	3,4,10,
31T056	RV31061 DownStream Skin Temperature	-424	100	DEG F	0	16	OMEGA	Type”E” T/C Skin Temp	N/A		N/A	07/20/00	N/A	3,4,10,
31V3107	Control Feedback Voltage Parameter	0	100	PCNT	0	28	N/A	N/A	N/A		N/A	07/27/00	N/A	4,14,
31V3126	Control Feedback Voltage Parameter	0	199	PCNT	0	29	N/A	N/A	N/A		N/A	07/27/00	N/A	4,14,
35V3513	Control Feedback Voltage Parameter	0	100	PCNT	0	30	N/A	N/A	N/A		N/A	07/27/00	N/A	4,5,14,

Table 4. Instrumentation list (Continued).

MID	Description	Low	High	Units	SIU	CH	Manufac-turer	Model No.	S/N	RTD Info	CAL Due	FAP	NASA CAL	MRCF#
31L022	Control Feedback Voltage Parameter	0	100	PCNT	0	32	N/A	N/A	N/A		N/A	07/27/00	N/A	4,14,
31P028	Control Feedback Voltage Parameter	0	50	PSIG	0	34	N/A	N/A	N/A		N/A	07/27/00	N/A	4,14,
31P029	Control Feedback Voltage Parameter	0	50	PSIG	0	35	N/A	N/A	N/A		N/A	07/27/00	N/A	4,14,
31P030	Control Feedback Voltage Parameter	0	100	PCNT	0	36	N/A	N/A	N/A		N/A	07/27/00	N/A	4,14,
31V3112	Control Feedback Voltage Parameter	0	100	PCNT	0	38	N/A	N/A	N/A		N/A	07/27/00	N/A	4,14,
35V3510	Control Feedback Voltage Parameter	0	100	PCNT	0	39	N/A	N/A	N/A		N/A	07/27/00	N/A	4,5,14,
31C3107	Control Feedback Voltage Parameter	0	100	PCNT	0	19	N/A	N/A	N/A		N/A	07/27/00	N/A	5,14,
31C3112	Control Feedback Voltage Parameter	0	100	PCNT	0	20	N/A	N/A	N/A		N/A	07/27/00	N/A	5,14,
31C3126	Control Feedback Voltage Parameter	0	100	PCNT	0	21	N/A	N/A	N/A		N/A	07/27/00	N/A	5,14,
35C3510	Control Feedback Voltage Parameter	0	100	PCNT	0	65	N/A	N/A	N/A		N/A	07/27/00	N/A	5,14,
35C3513	Control Feedback Voltage Parameter	0	100	PCNT	0	23	N/A	N/A	N/A		N/A	07/27/00	N/A	5,14,
36T003	Test Article Press. Sys. Temp.	-425	100	DEG F	0	124	OMEGA	Type"E" T/C 6x1/8	N/A		N/A	07/05/00	N/A	7,10,
31P023	Control Feedback Voltage Parameter	0	50	PSIG	0	67	N/A	N/A	N/A		N/A	07/27/00	N/A	14,
36T009	Test Article External Purge Temperature	-424	100	DEG F	0	68	OMEGA	Type "E" T/C 6x3/16	N/A		N/A	07/25/00	N/A	10,
36P004	L/C Purge U/S Pressure	0	200	PSIS	0	69	STATHAM	PG752TC-200-350	59		09/10/00	07/25/00	M627128	10,
31V3105	Control Feedback Voltage Parameter	0	100	PCNT	0	125	N/A	N/A	N/A		N/A	08/10/00	N/A	11,14,
31C3105	Control Feedback Voltage Parameter	0	100	PCNT	0	126	N/A	N/A	N/A		N/A	08/10/00	N/A	11,14,

APPENDIX C—INSTRUMENTATION IN THE MULTIPURPOSE HYDROGEN TEST BED UPPER DOME REGION

The MHTB test article was established primarily for vacuum chamber testing of various cryogenic fluid management technologies involving in-space propulsion and storage. Although the MHTB instrumentation is primarily arranged to address in-space cryogenic fluid management (CFM) issues, a substantial portion of the instrumentation could be adapted to the chill/fill testing. Therefore, the descriptions provided herein include all the instruments that were available in the MHTB upper dome region, i.e., not only the instruments that directly supported the current chill/fill program. The instrumentation that directly supported the chill/fill data evaluation is highlighted in the following discussions. Table 4 in appendix B contains additional information regarding the instruments.

C.1 Vent Penetration Instrumentation

The MHTB tank internal volume is vented through a 2-in- (5.08-cm-) diameter tube connected to a 8-in (20.32-cm) tank penetration (Conflat-type flange) as illustrated in figure 20. The vent tube transitions to a vacuum jacketed pipe assembly approximately 12 in (30.48 cm) from the tank penetration. The penetration and tube are closed out with foam extending out over the vacuum jacketed pipe section approximately 16 in (40.64 cm) from the tank penetration. Average thickness of this foam based on the measured circumference is 2.75 in (6.98 cm). Three silicon diodes are place along the length of the tube for determination of heat input (TVL1 and TVL2) and evaluation of the heat guard (HG7) operation. The vent tube foam surface is instrumented with two TCs (TVL6 and TVL7) to assist in evaluation of heat input through the foam. The vent penetration top flange contains a tank ullage pressure measurement port and 0.5-in- (1.27-cm-) diameter sampling tube equipped with two TCs (TUP1 and TUP2). The surface temperature of the top flange is measured by a silicon diode (TVL3). Internal to the tank, the vent flange supports a capacitance probe (CAP1) and an instrumentation rake. Two diodes (TVL4 and TVL5) are supported by the rake at the 99.4% tank fill location. These diodes are positioned just below the vent penetration (inside the test tank) and provided a measurement of temperatures in the upper dome area.

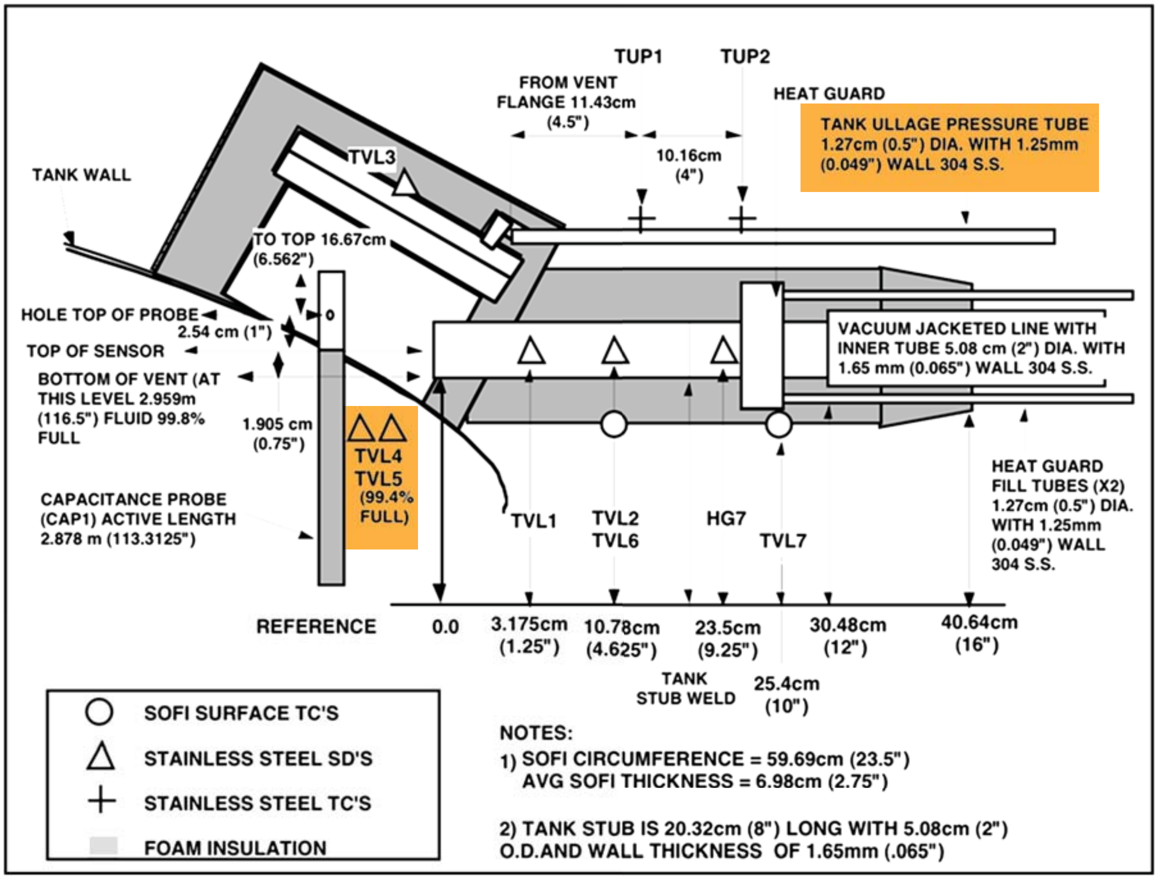

Figure 20. Measurement positions in upper dome area—TVL4, TVL5, and ullage pressure.

C.2 Manhole Cover and Pump-Out Port Instrumentation

The MHTB tank is equipped with two manhole covers (inner and outer) to control potential leakage during vacuum chamber testing. Figure 21 illustrates the manhole cover setup. The inner cover is equipped with two silicon diodes (TMN3 and TMN4) adhesively bonded to its inner surface with cryogenic epoxy (Lake Shore Stycast). The outer manhole cover exterior surface is equipped with a silicon diode (TMN2) bonded to its center with a single diode (TMN1) and two TCs (TMH1 and TMH2) bonded to its flange area. These temperature measurements were used to assess the total thermal capacitance carried by the massive tank manhole system. The gas volume trapped between the inner and outer manhole covers is connected to a stainless steel evacuation line (flex hose) which is used to intercept potential leakage from the inner cover if it should occur. This flex line is equipped with two TCs (TCP1 and TCP2) attached to determine heat input. The spatial distance between the TCs is 2 in (5.08 cm); however, the flex hose has a 3:1 contraction ratio yielding a material length of 6 in (15.24 cm). The entire surface of the outer manhole cover is covered with foam insulation at an approximate thickness of 1.25 in (3.175 cm). The evacuation line is routed along the vent line and, as such, is buried beneath the vent line foam insulation.

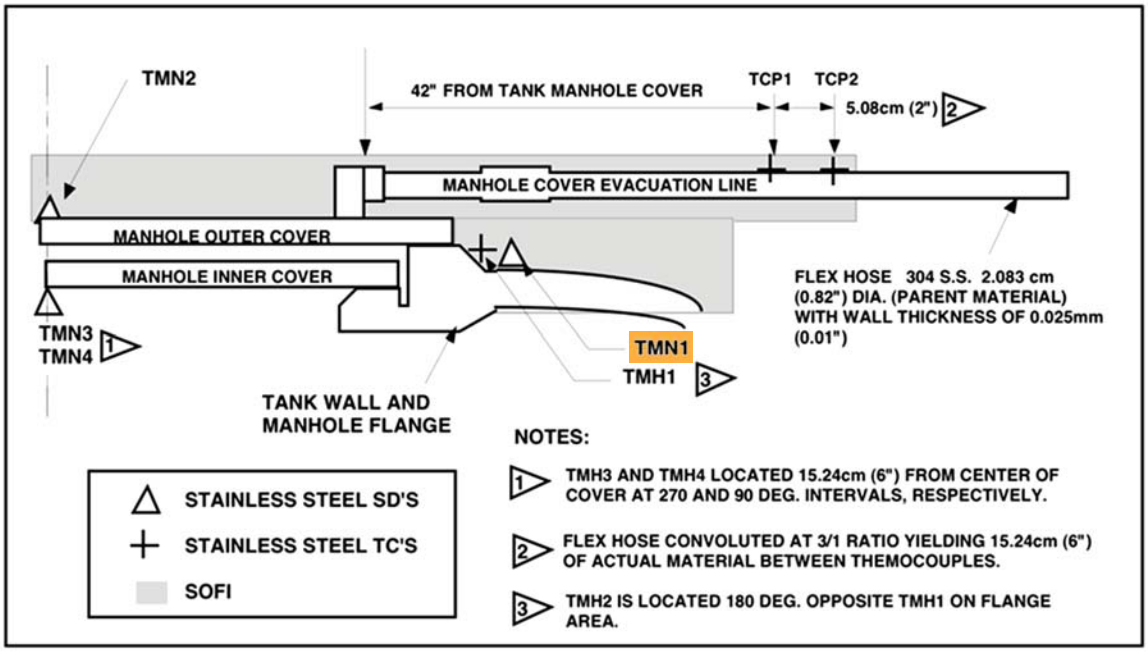

Figure 21. MHTB manhole cover area instrumentation.

APPENDIX D—CHILL/FILL TEST FACILITY REQUIREMENTS

The facility purge systems will be used to provide specific gas types (GN_2 and air) and pressure and temperature conditions to the internal facility volume. These conditions will be used to establish a safe environment and uniform initial conditions for the test article. Uninsulated MHTB tank surfaces and lines will be bagged and purged to prevent local condensation.

D.1 Facility Pretest Conditions

The facility pretest conditions are as follows:

- The facility shall be purged with dry GN_2 until an adequate number of atmosphere volume changes have occurred to establish a GN_2 atmosphere within the enclosure volume.

- The MHTB shroud purge ring shall be used for this purge.

- An adequate number (as determined by the test project engineer) of volume changes shall be completed prior to starting a test.

- Internal facility temperature, dew point, and relative humidity shall be measured and recorded at least once per hour on the day of a test to insure no condensation will occur once propellant tanking begins.

- The test article go-for-test shall be given when the facility internal environmental conditions preclude any condensation on the MHTB.

D.2 Purging/Inerting Requirements

The purging/inerting requirements are as follows:

- A dry GH_2 purge shall be used following each test until the tank walls are warm enough to preclude condensing GN_2 on the tank inner walls.

- Electrically heated, dry GN_2 shall be used as an inerting operation for the test article volume and to condition the MHTB tank initial temperature.

- The GN_2 purge shall be followed by a dry GH_2 purge to remove the condensable GN_2.

- A cycle purge shall be used.

- Data shall be recorded throughout the entire purge and inerting operation to baseline the initial instrument and test article condition.

- Sample rates shall be set to the low setting specified in the test request sheet (TRS).

- To avoid resetting the mechanical relief valve setting, the tank internal pressure shall be no greater than 35 psig (241.3 kPa) during purging and inerting.

D.3 Chill/Fill Requirements

The chill/fill requirements are as follows:

- The feed system between the test position and the storage tank shall be well insulated.

- The facility fill system shall be equipped with a bypass valve as close to the MHTB interface as possible so that LH_2 can be used to precondition the majority of the facility feed system.

- The facility shall be capable of delivering a maximum LH_2 flow rate of 1,100 gpm (4,160 L/m).

- The flow rate of LH_2 specified in the TRS shall be established through the bypass line prior to opening the MHTB prevalve.

- LH_2 temperature, measured at the outlet of the storage tank, shall be no greater than 40 °R (22 K) throughout the chill and fill process.

- A mechanical relief valve shall be used to restrict the test article to a maximum pressure of 35 psig (241.3 kPa).

- An automatic redline cutoff shall be programmed to terminate LH_2 flow (and to open the vent valve, if applicable) when the MHTB ullage pressure reaches 32 psig.

D.4 Vent Flow Measurement Requirements

Vent flow measurement requirements are as follows:

- The vent system shall measure vented propellant flow rate.

- The vent system shall be insulated with SOFI and chilled prior to testing.

- The measurement system shall be capable of handling a transient maximum 1,100 gpm (4,160 L/m) flow rate of nearly saturated GH_2 without large pressure losses.

D.5 Tank Environmental Conditions Requirements

The temperature, heat load, and pressure requirements are as follows:

- Temperature: Initial tank average temperature shall be 530 ± 10 °R (294 ± 5.6 °K) and shall be met prior to GH_2 cycle purging.

- Heat load: No external heat loading will be required.
- Pressure: The facility shall maintain a positive pressure to prevent air ingestion.

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R.H. Flachbart (retired), A. Hedayat, K.A. Holt, J. Sims, E.F. Johnson, L.J. Hastings,* and T. Lak (retired)**

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Prepared by the Propulsion Systems Department, Engineering Directorate
*Alpha Technology Inc., Huntsville, AL **The Boeing Company, Huntington Beach, CA

14. ABSTRACT
Cryogenic upper stages in the Space Shuttle program were prohibited primarily due to a safety risk of a 'return to launch site' abort. An upper stage concept addressed this concern by proposing that the stage be launched empty and filled using shuttle external tank residuals after the atmospheric pressure could no longer sustain an explosion. However, only about 5 minutes was allowed for tank fill. Liquid hydrogen testing was conducted within a near-ambient environment using the multipurpose hydrogen test bed 638.5 ft^3 (18 m^3) cylindrical tank with a spray bar mounted longitudinally inside. Although the tank was filled within 5 minutes, chilldown of the tank structure was incomplete, and excessive tank pressures occurred upon vent valve closure. Elevated tank wall temperatures below the liquid level were clearly characteristic of film boiling. The test results have substantial implications for on-orbit cryogen transfer since the formation of a vapor film would be much less inhibited due to the reduced gravity. However, the heavy tank walls could become an asset in normal gravity testing for on-orbit transfer, i.e., if film boiling in a nonflight weight tank can be inhibited in normal gravity, then analytical modeling anchored with the data could be applied to reduced gravity environments with increased confidence.

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STI Help Desk at email: help@sti.nasa.gov

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STI Help Desk at: 443–757–5802

National Aeronautics and
Space Administration
IS20
George C. Marshall Space Flight Center
Huntsville, Alabama 35812