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Large-Scale Demonstration of Liquid Hydrogen Storage With Zero Boiloff for In-Space Applications

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LIST OF ACRONYMS, SYMBOLS, AND ABBREVIATONS

ACS	automated control system
AFRL	Air Force Research Laboratory
ARC	Ames Research Center
CFM	cryogenic fluid management
CO_2	carbon dioxide
Cu	copper
DSU	data systems unit
GH_2	gaseous hydrogen
GHe	gaseous helium
GN_2	gaseous nitrogen
GRC	Glenn Research Center
H_2O	water
He	helium
HRS	heat removal system
HX	heat exchanger
J-T	Joule-Thompson
LH_2	liquid hydrogen
LN_2	liquid nitrogen
MGA	missile-grade air
MHTB	multipurpose hydrogen test bed
MLI	multilayer insulation
MSFC	Marshall Space Flight Center
N_2	nitrogen
NI DAQ	National Instruments data acquisition

LIST OF ACRONYMS AND SYMBOLS (Continued)

O_2	oxygen
OMGS	optical mass gauging sensor
RGA	residual gas analysis
SCRAMNet	shared common random access memory network
SLPM	standard liters per minute
SOFI	spray-on foam insulation
TC	thermocouple
TS300	test stand 300
TVS	thermodynamic vent system
ZBO	zero boiloff

TECHNICAL PUBLICATION

LARGE-SCALE DEMONSTRATION OF LIQUID HYDROGEN STORAGE WITH ZERO BOILOFF FOR IN-SPACE APPLICATIONS

1. INTRODUCTION

The extension of cryogenic propellant storage periods to months and years has become increasingly important within NASA, especially with the current emphasis on manned space exploration beyond Earth orbit. Furthermore, the advancement of cryocooler and passive insulation technologies in recent years has substantially improved the prospects for long-term, in-space storage of cryogenics with zero-boiloff (ZBO) losses. The ZBO weight benefits for long-term missions are substantial, particularly because the tank size and insulation weight grow with mission duration extension in a passive storage concept, but not with ZBO.[1] Additionally, mission flexibility is significantly enhanced because delays in operations and transient space environments can be accommodated without jeopardizing propellant mass margins; i.e., cryogenics can be treated like storable propellants. ZBO involves the use of a cryocooler/radiator system to balance incoming and extracted thermal energy such that boiloff and the necessity for venting are precluded. A cryocooler—with a power supply, radiator, and controls—is integrated into a traditional orbital cryogenic storage subsystem, which includes passive thermal insulation, a destratification mixer, instrumentation, and controls.

A cooperative effort (fig. 1) by NASA's Ames Research Center (ARC), Glenn Research Center (GRC), and Marshall Space Flight Center (MSFC) was implemented to develop and demonstrate ZBO concepts for in-space storage of cryogenics, particularly liquid hydrogen (LH_2) and oxygen. ARC leads the development of flight-type cryocoolers, GRC the subsystem development and small-scale testing,[2] and MSFC the large-scale and integrated system-level testing. Because of constrained opportunities for orbital experiments, ground testing must be employed to the fullest extent possible. The early ground-based concept demonstrations are performed with low-cost available hardware, followed by increasingly flight-like hardware. Described herein is one element of the cooperative program, a large-scale ZBO system demonstration using the MSFC multipurpose hydrogen test bed (MHTB) along with a commercial cryocooler unit.

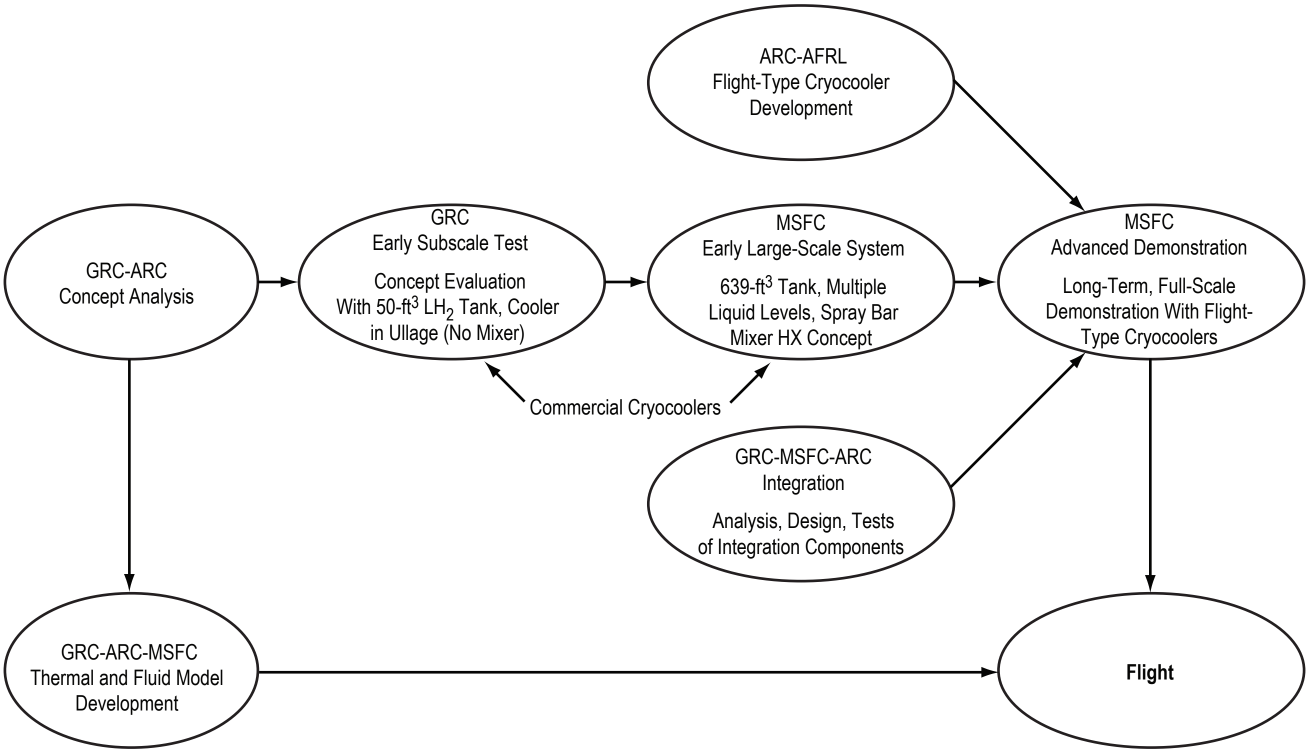


Figure 1. NASA's cooperative effort on ZBO storage.

2. TEST ARTICLE ELEMENTS

2.1 Multipurpose Hydrogen Test Bed

The MHTB 5083 aluminum tank is cylindrical in shape with a height of 3.05 m (10 ft), a diameter of 3.05 m (10 ft), and 2:1 elliptical domes (figs. 2 and 3). It has an internal volume of 18.09 m^3 (639 ft^3) and a surface area of 35.74 m^2 (379 ft^2), with a resultant surface area-to-volume ratio of 1.92 m^{-1} (0.58 ft^{-1}) that is reasonably representative of a full-scale vehicle LH_2 tank; e.g., a manned lunar lander. The tank is an American Society of Mechanical Engineers pressure vessel coded for a maximum operational pressure of 344 kPa (50 psid) and was designed to accommodate various cryogenic fluid management (CFM) technology and advanced concepts as updated versions become available. Major accommodations include a 60.9-cm-diameter (24-in-diameter) manhole; pressurization and vent ports; a fill/drain line (through the top of the tank); 15.24 and 7.5 cm (6 and 3 in) general purpose penetrations with flanges on top; the zero-gravity pressure control subsystem (thermodynamic vent subsystem) penetration provisions on the tank bottom (one each 5.08-, 3.81-, and 1.27-cm tube) and an enclosure external to the tank; a 7.62-cm-diameter (3-in-diameter) drain at the tank bottom for future growth; a continuous liquid level capacitance probe; two vertical temperature rakes; wall temperature measurements at selected locations; ullage pressure sensors; pressure control/relief safety provisions; internal mounting brackets for future equipment and structural ‘hard points’ for a temporary scaffolding and ladder; and low-heat-leak composite structural supports. Each of the penetrations is equipped with a heat guard to intercept heat leak, thereby enabling more accurate measurement of the tank insulation performance; however, the heat guards were not activated in this test series.

Fluid connections are welded wherever possible and all mechanical seals are the knife-edge/copper (Cu) gasket (Conflat®) design. The exception is the primary manhole cover design, which incorporates a soft, crushable indium wire as a seal material and Invar® expansion collars on the stainless steel bolts to offset thermal expansion effects. The secondary manhole cover is equipped with a pumpout port (fig. 4) so that any primary seal leakage can be intercepted and routed to a facility vacuum pump. Appendix A contains an MHTB tanking table with information regarding fill height, percent liquid/ullage volume, and LH_2 mass.

The MHTB tank is enclosed within an environmental shroud (fig. 5) that simulates a ground hold conditioning purge (similar to that in a payload bay) and enables the imposition of a range of uniform temperatures on the multilayer insulation (MLI) external surfaces. The shroud is 4.57 m (15 ft) high by 3.56 m (12 ft) in diameter and contains a purge ring for distributing gaseous nitrogen (GN_2). The shroud heater strips/cooling loops can impose either constant or time-dependent boundary temperatures ranging from 80 to 320 K (144 to 576 °R).

The MHTB insulation concept consists of a foam/multilayer combination. The foam element enables the use of a payload bay-type GN_2 purge during ground hold periods. The 45-layer, double aluminized mylar MLI provides thermal radiation protection while at vacuum conditions on orbit.

Figure 2. MHTB test article.

As reported in reference 3, which describes the insulation in more detail, the combined effects of the MLI variable density, large vent hole pattern, and installation technique resulted in substantial performance improvements over conventional insulation configurations. However, in this application, the insulation system performance was compromised by the thermodynamic vent system hardware installation and by degradation due to exposure to multiple test environments over a 15-yr period.

2.2 Cryocooler

ARC selected and procured a commercial Cryomech, Inc. GB37 cryocooler unit for the MHTB testing (fig. 6). The Cryomech unit, a two-stage Gifford-McMahon cycle refrigerator[4,5] was then delivered to GRC for bench testing and the design of a heat exchanger (HX) and structure for MHTB integration. The cryocooler rated capacity is 30 W at 20 K and requires 350 W of power input per watt of cooling for a 4% Carnot cycle efficiency. The first stage provides 50 W of cooling at 80 K. Unlike a flight-type unit, the compressor system is positioned outside the vacuum chamber and is linked to the cryocooler with stainless steel helium (He) lines penetrating the chamber walls, as shown in figure 7. The cryocooler integration procedure is described in appendix B.

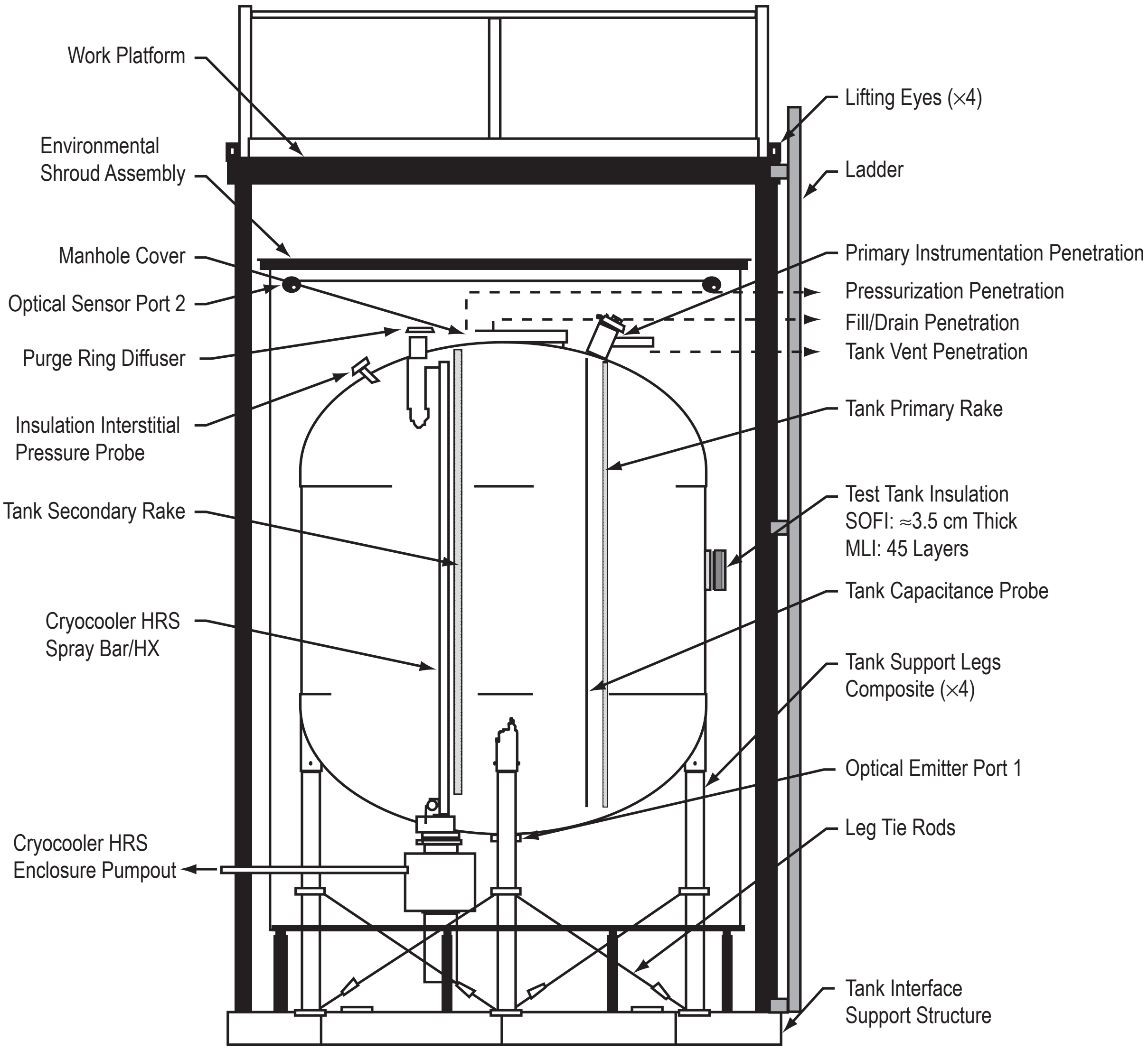


Figure 3. MHTB schematic.

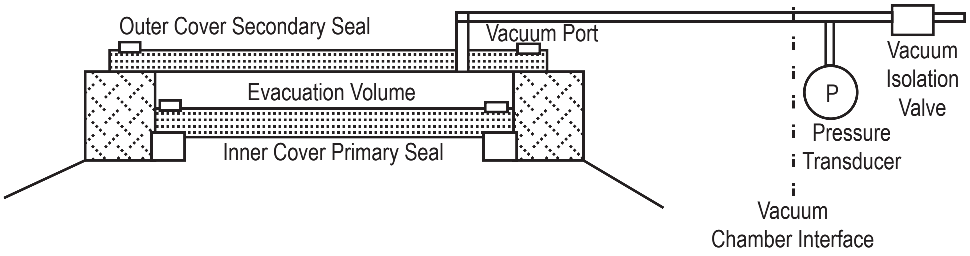


Figure 4. Manhole cover.

Figure 5. Environmental shroud assembly.

2.3 Cryocooler Integration

The cooler integration concept involves connecting the second-stage cooling head to a HX inserted into an existing 5-cm-diameter recirculation line that, in turn, interfaces with the pump and spray bar mixer system (figs. 8–11). The spray bar recirculation system shown in figures 12 and 13 is designed to provide destratification independent of ullage and liquid positions in a zero-gravity environment.[6] During the mixing process, fluid is withdrawn from the tank by a pump and flows through the spray bar positioned along, or near, the tank longitudinal axis. The fluid is then expelled radially back into the tank through 180 spray bar orifices 0.17 cm (0.067 in) in diameter, or a standard 51 drill size. The orifice diameter was selected to produce relatively uniform injection velocities for the design condition of a half-full tank in a normal gravity environment. If the liquid is settled in the upper half of the tank, then the pump can be shut down and the ullage cooled directly, thereby controlling tank pressure.

The inline HX is shown in diagram and schematic form in figures 8 and 9, respectively, and in pictorial form in figure 10. It transfers thermal energy from the fluid to the cryocooler and was

Figure 6. Cryocooler.

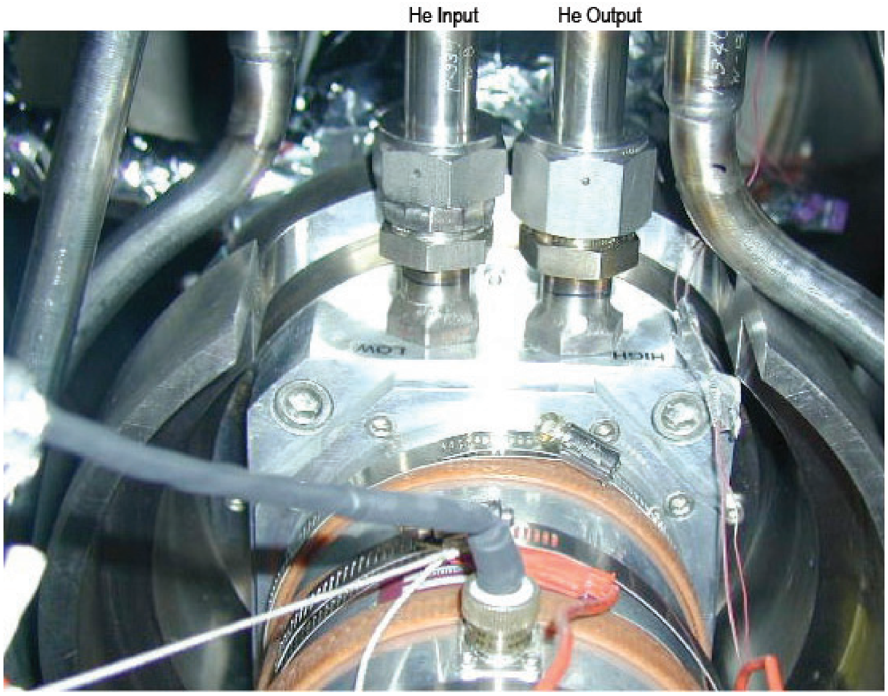


Figure 7. Interfacing He lines.

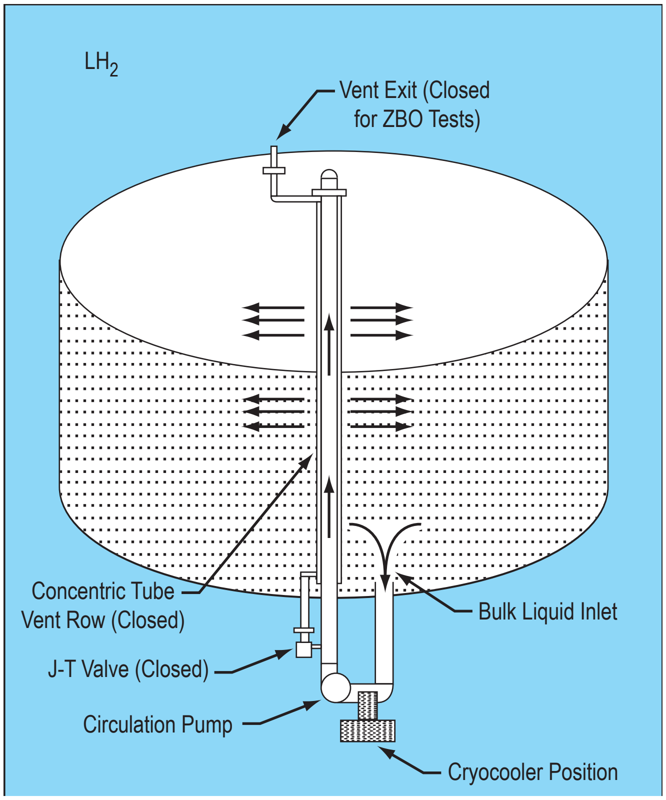


Figure 8. Spray bar integration with cryocooler.

designed by GRC to minimize cryocooler size and power requirements. Further details regarding the GRC testing are presented in section 4.1.

A Barber-Nichols, Inc. BNHP-08 centrifugal cryogenic pump was used for the recirculation process. The pump delivers 18 and 37.8 L/min with an estimated power input to the liquid of 0.04 and 0.3 W, respectively. The pump power input versus flow rate, which must be considered in the tank heat leak computations, is presented in table 1. The recirculation line, pump, and cryocooler assembly (fig. 11) were contained within an enclosure attached to the tank bottom, as shown in figures 8 and 9, so that any leakage could be entrapped and pumped out without compromising the chamber vacuum levels. Such an enclosure would not be required in an actual application.

2.4 Instrumentation and Controls

The environmental shroud instrumentation details are shown in figure 14 and the instrumentation arrangement for each primary test article segment is summarized in this section. (A list of all instrumentation is presented in app. E.) The test article instrumentation consists primarily of thermocouple (TC) and silicon diodes to measure insulation, fluid, and tank wall temperatures. Typically, silicon diode (Lakeshore type DT-470-11A) temperature transducers are positioned in the areas of lowest temperatures because of their higher accuracy as compared with TCs. MLI temperature profiles or gradients are measured at seven positions with one silicon diode and four TCs placed at each of the seven measurement positions. The MLI interstitial pressure is measured at the foam/

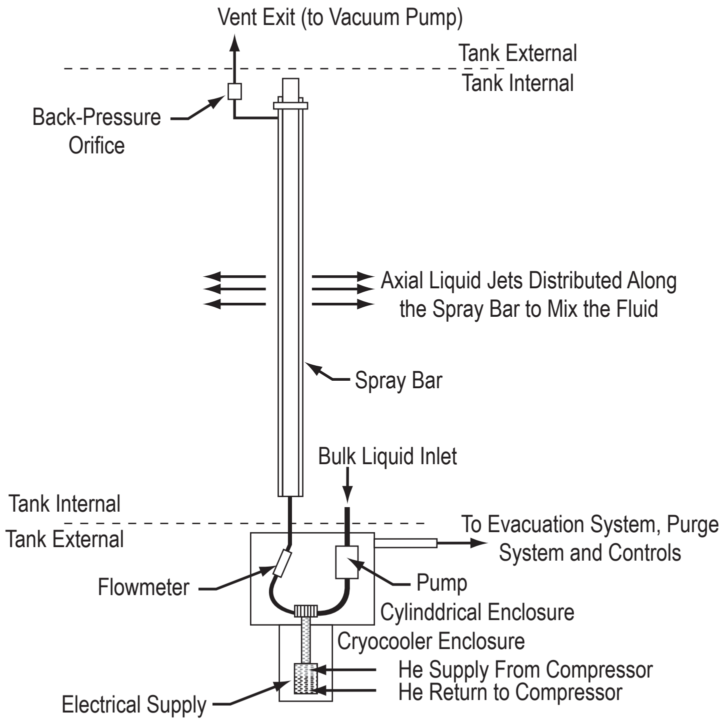


Figure 9. Test facility/spray bar/cryocooler integration.

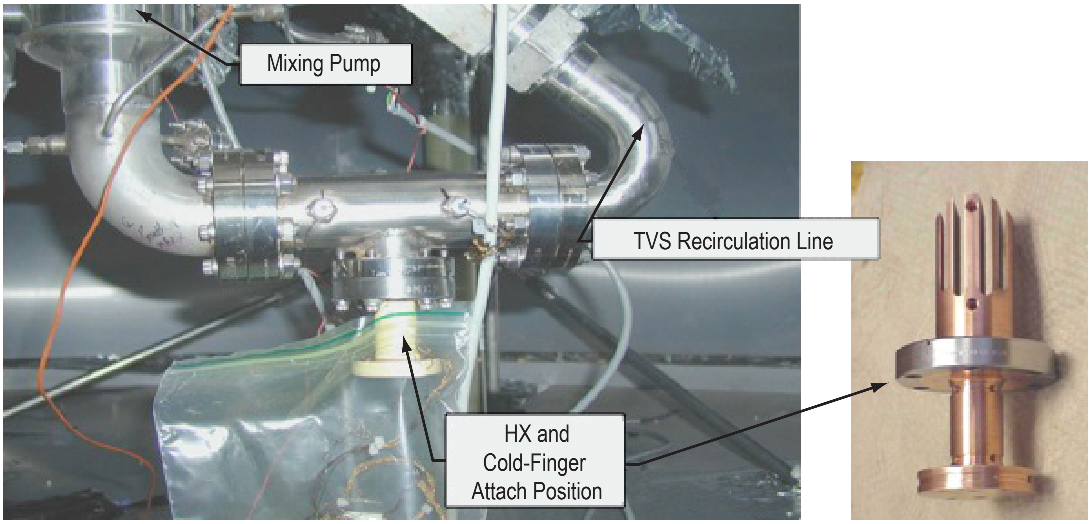


Figure 10. Cryocooler integration with MHTB.

MLI interface, and a sampling port for both dewpoint level and gas species is provided. The environmental shroud is composed of 17 individual panels, each equipped with a minimum of two TCs attached to the inner surfaces and placed beneath the electrical heating strips. These TCs are used with a closed-loop control system to regulate each shroud panel temperature.

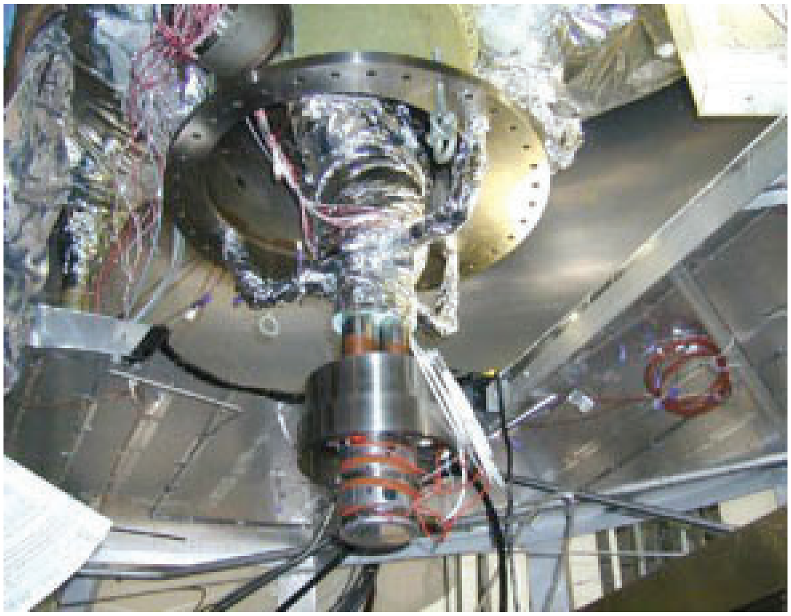


Figure 11. Installed cryocooler.

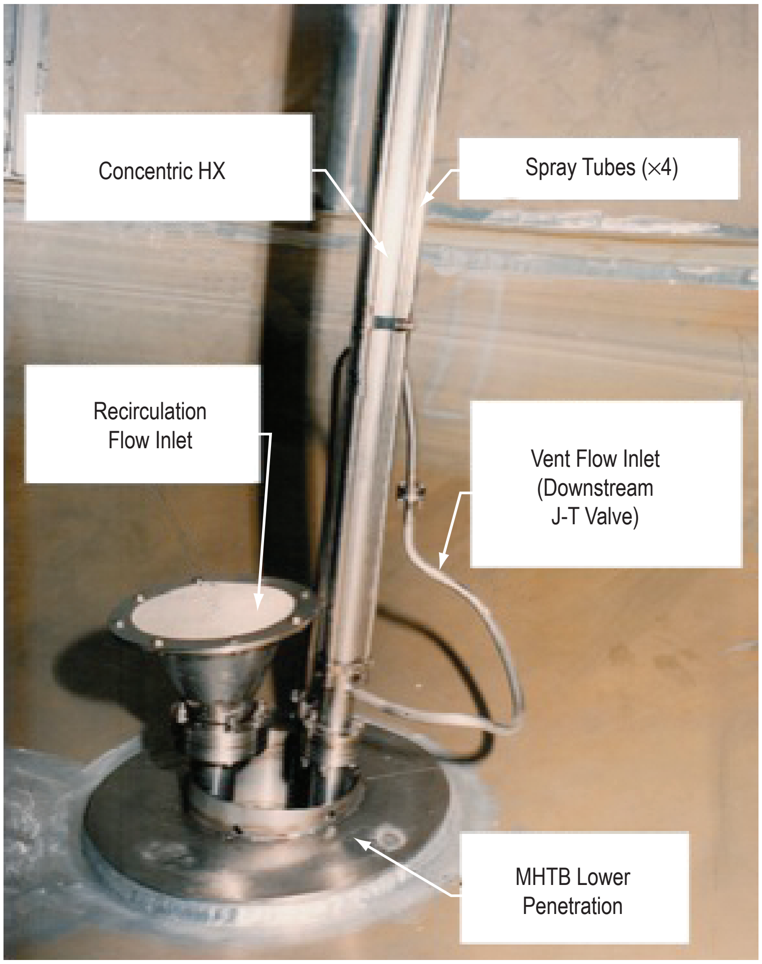


Figure 12. Spray bar at tank bottom.

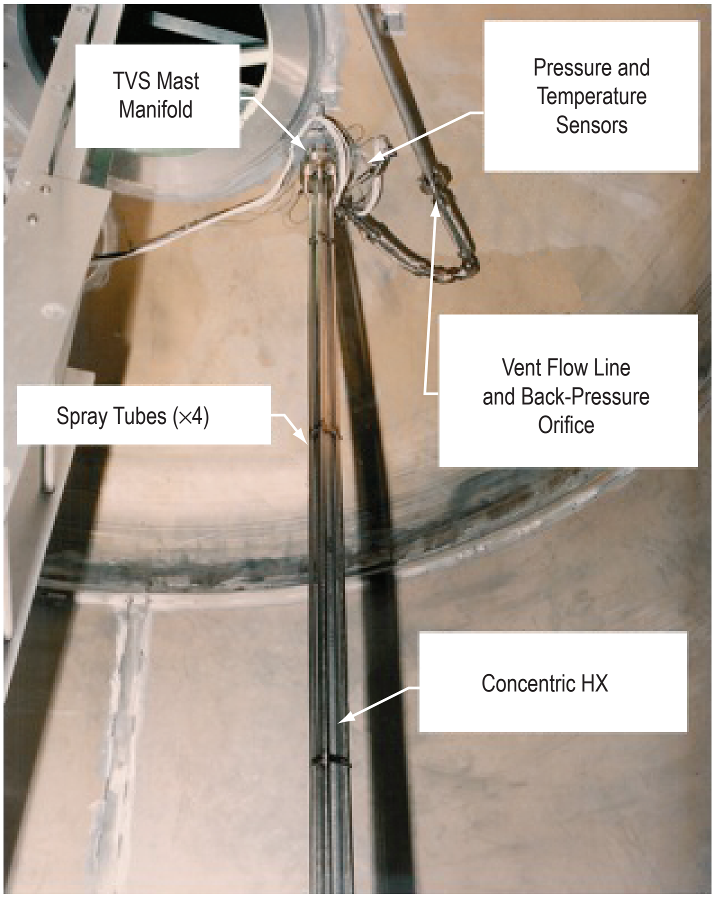
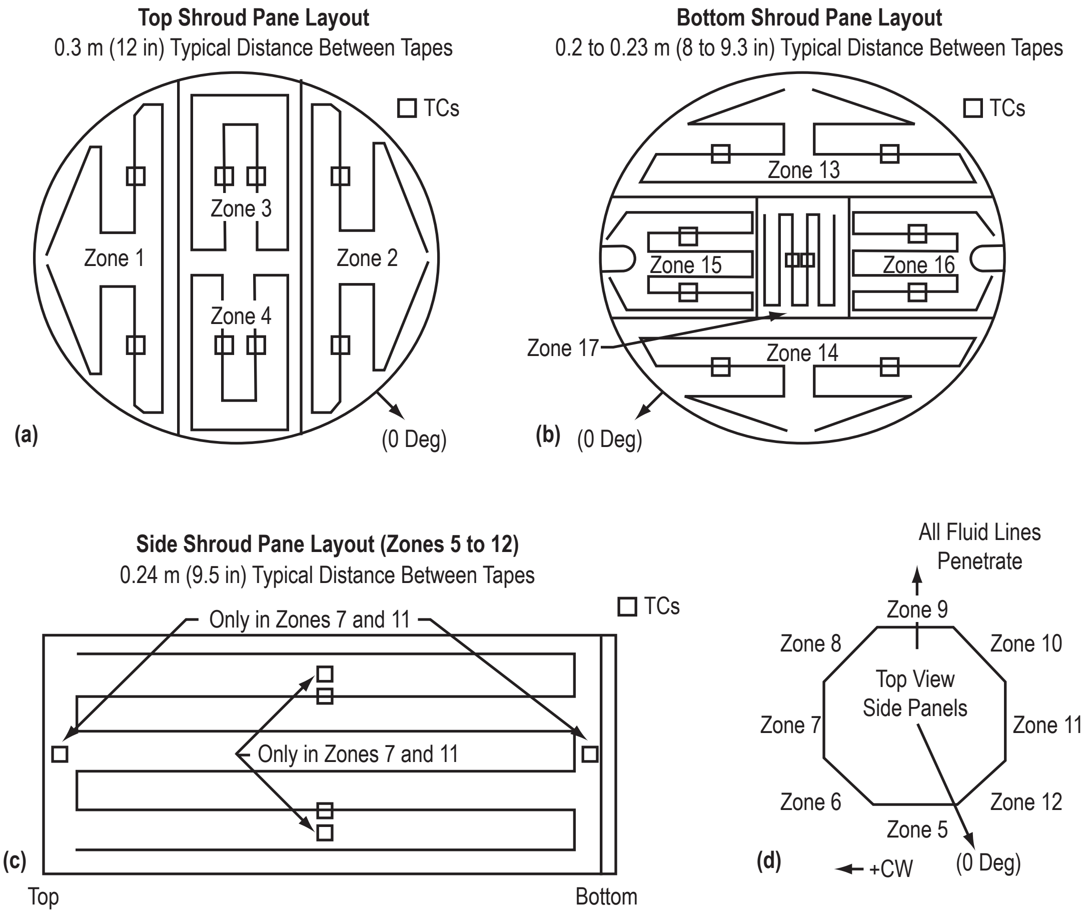


Figure 13. Spray bar recirculation system.

Table 1. Pump power input versus flow rate.

Flow		Frequency (Hz)	Pump Power (W)	Motor Input Power (W)	ΔP (mBar)
(L/min)	(gpm)				
19	5	18	0.040	0.44	0.9
38	10	37	0.330	1.77	3.9
57	15	55	1.10	3.47	8.6
76	20	73	2.70	6.51	15.2
118	30	110	9.00	16.75	34.5
151	40	147	21.00	37.3	61.3

As shown in figure 15, the tank is internally equipped with two instrumentation rakes and a capacitance liquid level probe, all supported from the top of the tank. The following should be noted:



(Based on Original Design, Modifications will be Implemented During Assembly Based on Pretest Checkouts)

Figure 14. Environmental shroud layout: (a) Top panel, (b) bottom panel, (c) side panel (zones 5–12), and (d) top view side panels.

- Diode rake 2 was relocated inside the MHTB to accommodate mass gauge testing.* Rake 2 is in a vertical position with the uppermost diode (TD13) located 24.77 cm (9.75 in) from the bottom surface of the inner manway flange.

- The LH_2 heaters are installed such that the top of each heater is located ≈224 cm (≈88 in) from the bottom surface of the inner manway flange. This also places the top of each heater ≈11.4 cm (≈4.5 in) below the 25% point level sensor.

- The Sierra Lobo instrument is installed with one diode at the 61.1% location—the TD5 diode—with the second Sierra Lobo diode located 22.86 cm (9 in) above the 61.1% location.*

The rakes, constructed from a fiberglass epoxy channel section, are equipped with silicon diodes attached at 22.9 cm (9 in) intervals using nylon rod offsets and cryogenic epoxy. The instrumentation rakes provide temperature-gradient measurements within both the ullage and liquid, in

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*Piggy-Back Testing"—not a part of ZBO testing.

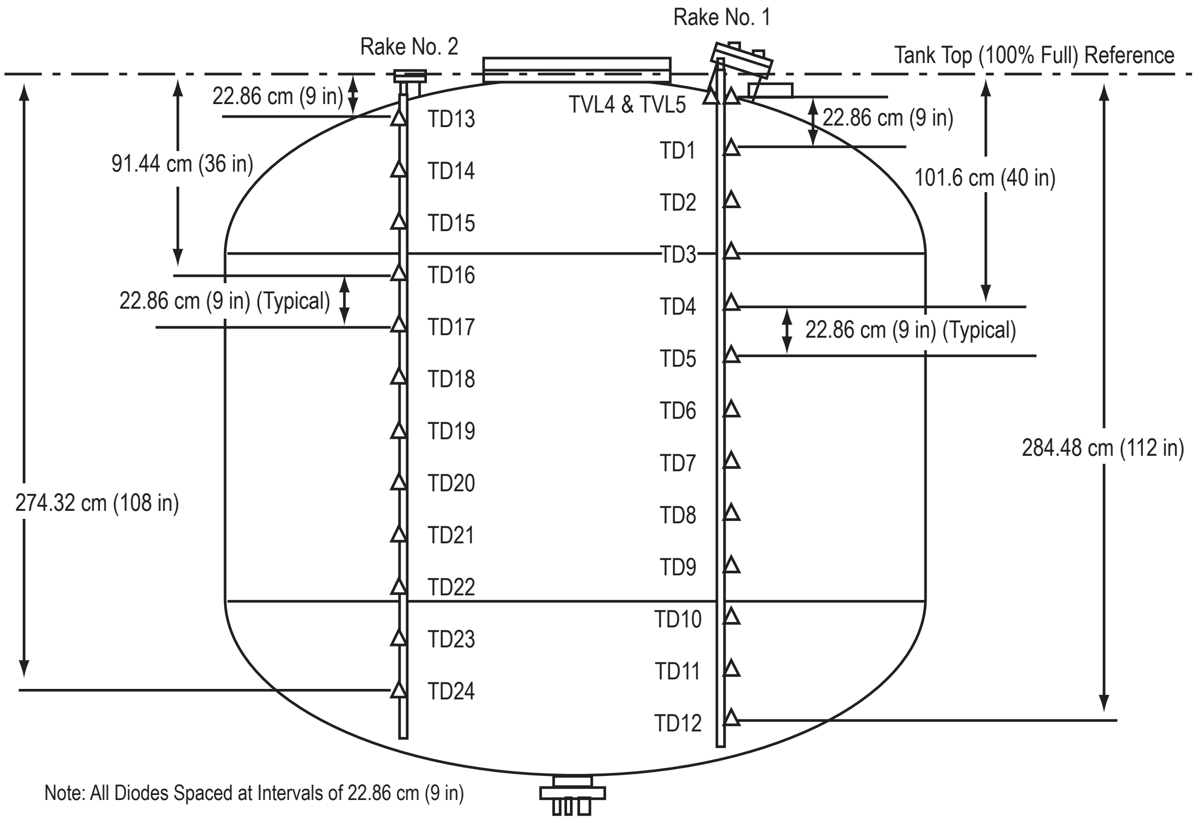


Figure 15. MHTB internal instrumentation rakes.

addition to providing a backup to the continuous liquid level capacitance probe. Two of the four composite legs, the vent, fill/drain, pressurization, pressure sensor probe, and manhole pumpout penetrations are instrumented to determine the solid conduction component of heat leak.

In a flight application, the cooler would be designed to vary the thermal extraction rate with the storage system heat leak. However, the thermal extraction rate of the commercial cooler could not be varied. Therefore, to enable balancing the total tank heat leak with the cooler extraction rate more precisely and efficiently, two graphite heaters were installed below the 25% fill level such that the heaters always remained submerged in liquid. Because graphite electrical resistance increases with decreasing temperature, the heaters were especially suited for cryogenic applications. Each heater provided zero to 50 W of power (two for redundancy) and were adjustable in increments of <1 W. Details on the heater bench testing are presented in appendix C.

The controller task was to maintain the tank heat leak at a value that matched the heat extraction capability of the cryocooler. As described earlier, the controller basically added thermal energy to the LH_2 via submerged heaters as required to achieve constant ullage pressure and corresponding liquid saturation conditions. To check out the control system logic, the controller was exercised during both pretest simulation/checkout and real-time test operations to eliminate version differences. As detailed in appendix D, the 'acquire data' block read data from the TS300 data acquisition computer using a shared common random access memory network (SCRAMNet).

SCRAMNet was used to provide a low-latency, low-overhead, and high-bandwidth network for the transfer of large quantities of data between separate data acquisition and control computers. Control was applied to the heater using a National Instruments data acquisition (NI DAQ) board installed in the control computer. Specialized C-language software was written to transfer data from the data acquisition computer onto the SCRAMNet, from this network into the control computer, and finally from the heater power command to the NI DAQ board. This command was presented to a power supply (Agilent) that controlled the carbon heaters' voltage. Before testing, the resistance of three carbon heaters was calibrated at LH_2 temperatures (app. C). Two heaters were selected for installation in the MHTB LH_2 tank that had the nearest match in calibration (heaters 1 and 2). The basic control law was a proportional-integral-derivative controller with simplified Kalman filters (pink blocks) used to estimate the ZBO measurements that were fed into two thermodynamic/fluid system models (blue blocks) of the MHTB LH_2 system. The two models—ZBO recirculation line model and ZBO ullage model—are included in appendix D, as well as the MHTB thermal performance worksheet, which provided the 'real time' heat leak into the MHTB LH_2 tank. Although the tank heat leak was a manual input, the control system could have interacted directly with the MHTB thermal model. The upper portion of this MATLAB/Simulink block diagram was used primarily for simulation but was active during test operations for 'health' monitoring the control system state. The lower portion implemented the control law and predicted the ullage pressure rise rate, which was displayed with the measured rise rate, and calculated the heater power command, which was displayed with the measured heater power.

Three benefits resulted from using this control scheme:

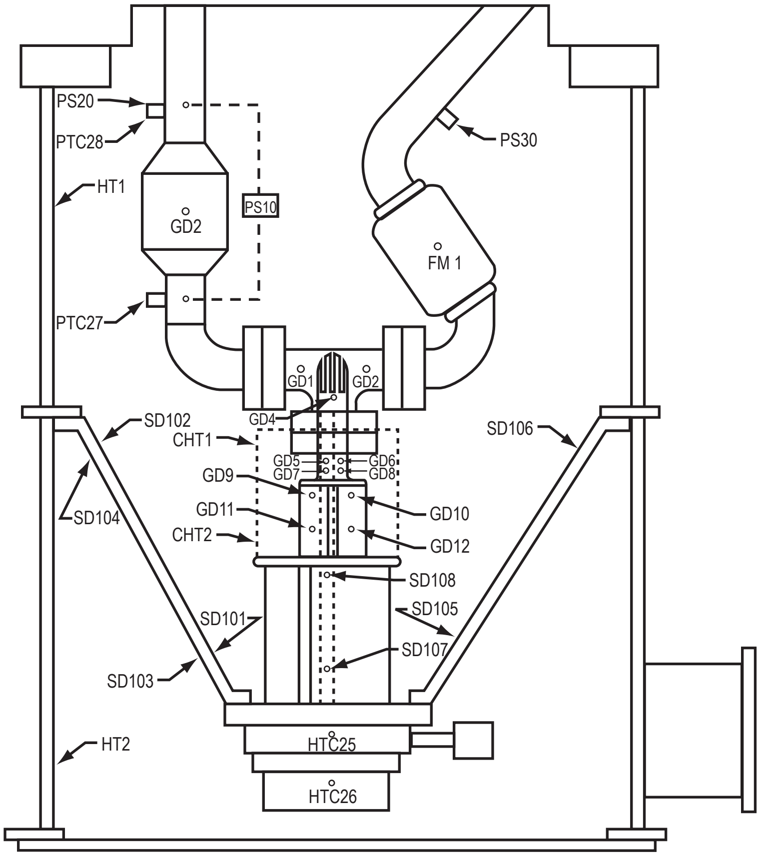
(1) Highly accurate pressure control was obtained from 'standard' pressure gauges.

(2) Significant time reductions to reach a stable liquid saturation point were achieved. Pressure control ±0.0003 kPa was achieved using a pressure gauge with a range of 5,000 psig, instead of having to use the more expensive delta pressure system. The latter can also be very time consuming to set near the saturation point of the LH_2. Pretest planning indicated that many hours would be needed to reach saturation using a manual control procedure. Using this controller, saturation was reached in a matter of 30 min. Many hours of setup time were turned into useful test time and allowed testing at several saturation points that were not in the initial test matrix.

(3) Interfacing the control system directly with thermal and thermodynamic analytical models enabled the use of real-time predictions to guide the controller. For future testing applications, the significance of successfully integrating 'real time' thermal/thermodynamic analytical modeling into the control system should not be overlooked.

During the ZBO performance testing, the bulk liquid temperature relative to the ullage saturation conditions was monitored using silicon diode TD23 on rake 2 and ullage pressure sensor P1 (see sec. 2.5). TD23 is at the 11.5% fill level or 53.3 cm (21 in) above the tank bottom and was assumed to be representative of the bulk liquid temperature. The TD23 temperature output was converted to an equivalent saturation pressure (termed PSA1) and compared with ullage pressure sensor P1. P1 is an MKS Instruments, Inc. Baratron zero to 133 kPa (zero to 19 psia) absolute pressure transducer with an accuracy of ±0.02%.

MHTB instrumentation added specifically to support ZBO is presented in figure 16.



Cryocooler Intrumentation

MID	Description	Range
GD1	Gallium diode	15/310
GD2	Gallium diode	15/310
GD4	Gallium diode	15/310
GD5	Gallium diode	15/310
GD6	Gallium diode	15/310
GD7	Gallium diode	15/310
GD8	Gallium diode	15/310
GD9	Gallium diode	15/310
GD10	Gallium diode	15/310
GD11	Gallium diode	15/310
GD12	Gallium diode	15/310
SD101	Silicon diode	15/310
SD102	Silicon diode	15/310
SD103	Silicon diode	15/310
SD104	Silicon diode	15/310
SD105	Silicon diode	15/310
SD106	Silicon diode	15/310
SD107	Silicon diode	15/310
SD108	Silicon diode	15/310
HTC25	Motor heater temperature top	15/310
HTC26	Motor heater temperature bottom	15/310
PTC28	Pump M 1 inlet temperature	15/310
PTC27	Pump M 1 outlet temperature	15/310
PS10	Pump M 1 ΔP	0/0.2 psid
PS20	Pump M 1 inlet pressure	0/50 psig
PS30	Flowmeter FM 1 outlet pressure	0/50 psig
FM 1	Flowmeter	15/150 gpm
CHT1	Copper HSG surface temperature top	15/310
CHT2	Copper HSG surface temperature bottom	15/310
HT1	Cryocooler HSG wall temperature top	15/310
HT2	Cryocooler HSG wall temperature bottom	15/310

Figure 16. MHTB instrumentation specific to ZBO.

Further details on all test instrumentation are presented in appendix E. The red line values used to protect the facility test article and test objectives are defined in table 2.

2.5 Test Facility and Procedures

2.5.1 Facility Description

Testing was performed at the MSFC east test area thermal vacuum facility, test stand 300 (TS300). The vacuum chamber, shown in figure 17, is cylindrical in shape and has usable internal dimensions of 5.5 m (18 ft) in diameter and 7.9 m (26 ft) in height. Personnel access is through a small side-entry door, but the chamber lid is removable for the installation of large test articles. The chamber pumping train consists of a single-stage GN_2 ejector, three mechanical roughing pumps (rated at 140 L/s (300 ft^3/min) each) with blowers (rated at 610 L/s (1,300 ft^3/min) each), and two 1.2-m (48-in) oil diffusion pumps (rated at 95,000 L/s (200,000 ft^3/min) N_2 each). Liquid nitrogen (LN_2) cold walls provide cryopumping and thermal conditioning capability and are composed

Table 2. ZBO red line values.

Red Line	Value	Red Line Type	MID No.
Ullage pressure increase	1 psi over set pressure	Alarm	P1
Ullage pressure decrease	1 psi under set pressure	Alarm	P1
Ullage high pressure cut	>45 psid	Automated	P2
Recirculation Line Temperature			
Recirculation line low temperature	<15 K	Alarm	GD1
Mixing pump			
Pump ΔP	0 psi	Alarm	PS10
Pump flow stabiliation	Set flow 5 gpm	Alarm	FM1
Compressor			
Compressor cooling water	<2 gpm	Alarm	F16
Compressor ΔP low	<210 psid	Alarm	P3143–P3144
Compressor ΔP high	>270 psid	Alarm	P3143–P3144
Heat Exchanger			
HX high temperature	GD4>GD2	Alarm	GD4 and GD2
HX low temperature	<7 K	Alarm	GD4
HX motor high temperature	>105 °F	Alarm	HTC26
HX motor low temperature	<45 °F	Alarm	HTC26
HX enclosure pressure	1 atm	Alarm	TBD
Heater Shroud			
HX low temperature	<159 K	Alarm	Controller
HX high temperature	>169 K	Alarm	Controller
20-ft Vacuum Chamber			
Chamber high pressure	>0.001 torr	Alarm	VP3010
Chamber Cold Walls			
Chamber high temperature	>85 K	Alarm	TBD
Manway Pressure			
Manway pumpout flow	TBD	Alarm	F8

of five parallel zones that totally surround the usable chamber volume with a surface emissivity of ≈0.95. The facility systems in combination with the test article shroud enable simulation of orbit environmental conditions by providing vacuum levels of 10^{-8} torr and a temperature range of 80 to 320 K (140 to 576 °R).

A fluid flow schematic shown in figure 18 depicts the integration of the MHTB, with its ZBO hardware, into the TS300 vacuum chamber facility.

A vacuum-jacketed fill and drain system provides cryogenic fluid servicing to and from the test article. All facility lines have welded construction to assure that vacuum conditions are not compromised by leakage. During the heat leak measurement phases of the testing, conditions within the MHTB were controlled using the following facility subsystems:

Figure 17. TS300 vacuum chamber.

- A tank pressure control subsystem was used to maintain the MHTB ullage pressure at the required steady-state conditions during the boiloff or heat leak measurement phase of testing. The system was composed of several flow control valves (located in the vent line), each of which 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 and the desired set point. An MKS Instruments, Inc. Baratron zero to 133 kPa (zero to 19 psia) absolute pressure transducer (accuracy of ±0.02%) and an MKS delta pressure (ΔP) 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 system successfully maintained set points ranging from 110 to 124 kPa (16 to 18 psia) with a tolerance of ±0.00689 kPa (±0.001 psi) for the boiloff or simulated orbital heat leak test conditions.

- The LH_2 boiloff flow instrumentation was located in the vent downstream of the flow control valves. During the on-orbit heat leak simulations, one of three mass flowmeters (MKS model 258C, Hastings model 200, and Hastings model H-3MS) was used. These meters spanned flow ranges of zero to 280, zero to 50, and zero to 1 SLPM with accuracies of ±0.8%, ±1%, and ±1% of full scale, respectively. To prevent ambient temperature effects on measurement accuracy, the flowmeter system was placed within a containment box and equipped with a temperature-controlled purge, which maintained the box interior at a constant temperature, typically 306 K (550 °R). This facility element was only used to establish a baseline heat leak magnitude and was deactivated during the ZBO phase of testing.

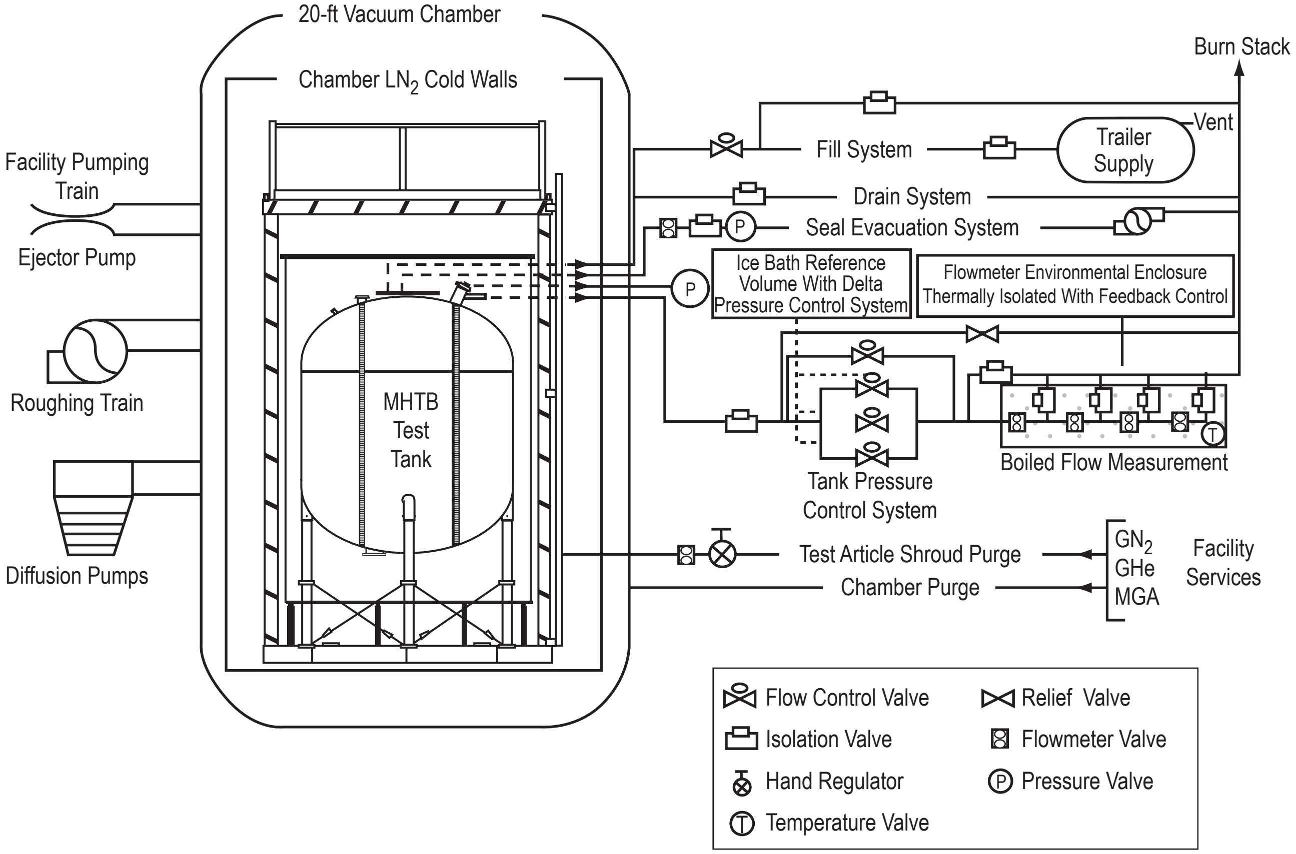


Figure 18. TS300 facility flow diagram.

- A seal evacuation system, MKS model 258 with a range of zero to 61 standard in^3/min, captured and measured any gases leaked past the 61 cm (24 in) primary tank seal (fig. 4). As described earlier, this was used as required to prevent vacuum-level degradation; i.e., maintained a seal volume pressure at or below 133 Pa (1 torr). During boiloff testing, however, seal leakage is typically avoided by maintaining tank pressures at moderate level; i.e., in the 105 to 140 kPa (15 to 20 psi) range.

2.5.2 Test Facility Procedures

The procedures and approaches used for test preparations, heat leak measurement, and post-test operations are summarized in sections 2.5.2.1 through 2.5.2.3.

2.5.2.1 Pretest Operations. Before testing, the vacuum chamber and environmental shroud were purged at a trickle rate with dry GN_2 for ≈5 days while the chamber and MLI dewpoint was maintained. Before tanking, the environmental shroud purge ring was operated at a GN_2 flow rate of 5 kg/min (11.2 lb/min) with a dewpoint not to exceed –54 °C (–65 °F). Also, the seal evacuation system was activated and held steady at a level of 2×10^{-2} torr or less. About 2 hr before tanking, dry GN_2 (followed by gaseous hydrogen (GH_2)) with a dewpoint of –54 °C (–65 °F) was used for the internal purge/conditioning operations of the test tank, fill/drain line, and vent line. This purge and conditioning process was accomplished using charge-vent cycles during which the tank was pressurized to ≈103 kPa (≈15 psig) with GH_2, held for ≈1 min, and then vented back down to near atmospheric pressure. This sequence was typically repeated 15–20 times before loading LH_2 into the MHTB. The test tank is designed to withstand an internal vacuum against external atmospheric pressure, enabling vacuum cycling with GH_2 pressurization, a much more efficient method of conditioning. However, the vacuum cycling approach was not implemented during this test program.

The vacuum chamber was pumped down to a steady-state vacuum level (10^{-6} torr or less), and the MLI allowed time to evacuate before initiating tank fill. The test article was then filled with LH_2 to the 85% level while maintaining the ullage pressure ≈103.4 torr (≈2 psi) above the required set point pressure. Completion of fill to the 95% level was then accomplished with the automated pressure control subsystem activated to control the ullage ≈25.8 torr (≈0.5 psi) above the set point. Once filling was completed, the transition to the test set point pressure occurred over a period of 10–20 min. Several hours were required to saturate and equilibrate the tanked LH_2 at the set point pressure.

2.5.2.2 Tank Heat Leak Testing. Boiloff testing was conducted to determine the ambient heat leak into the MHTB tank and to set up consistent initial conditions for each of the ZBO tests. Also, the additional ZBO hardware added heat leak. The heat leak test procedures are summarized herein and further details are presented in reference 3.

Steady-state vacuum and thermal conditions within both the chamber and MLI were achieved before the on-orbit heat leak test phase. The four criteria, which had to occur simultaneously, for steady-state thermal conditions were as follows:

(1) A vacuum chamber pressure of 10^{-6} torr or less was required to ensure an adequate vacuum within the insulation.

(2) Insulation temperatures (MLI and spray-on foam insulation (SOFI)) had to be in a steady-state condition with the MLI surface temperature at the prescribed set point imposed by the environmental shroud. Insulation equilibrium was assumed to exist once temperature transients of no more than 0.55 K in 6 hr occurred in any section of the insulation system.

(3) Thermal equilibrium of the LH_2 had to be maintained through precise ullage pressure control during the heat leak measurement test phase. Ullage pressure was maintained at a set point in the range of 110.316 to 124.106 kPa (16 to 18 psia) with a tolerance of ±0.00689 kPa (0.001 psi). The boiloff rate was recorded for 6 hr after steady state was achieved.

(4) The vented ullage gas temperature had to increase with time (have a positive slope), indicating that the tank dome is in thermal equilibrium; i.e., is not cooling and contributing to the vented gas enthalpy.

When performing the heat leak cryogenic storage testing, either a loss of ullage pressure control or the chamber vacuum can significantly increase unproductive test time. Each 6.89 kPa (1 psi) of LH_2 subcooling, due to a sudden reduction in ullage pressure, requires 30 hr for recovery to saturation (due to the low heat leak conditions). Similarly, a sudden increase in vacuum chamber pressure (10^{-4} torr or above) can dramatically alter the MLI temperatures, necessitating several days to recover the steady-state temperature profile. Therefore, great care was taken to ensure tight control of the tank ullage and vacuum chamber pressures.

A residual gas analysis (RGA) system was used to periodically record vacuum chamber and MLI interstitial gas composition during steady-state orbit hold periods. RGA sampling intervals varied, depending on the vacuum chamber pressure stability, and assisted in determining the source of any chamber pressure variations; e.g., test article or chamber leakage, or outgassing. Species possibilities included H_2O, N_2, O_2, CO_2, and the foam-blowing agent CFC-11 (CCL_3F molecular weight of 137.4).

2.5.2.3 Post-Test Operations. Chamber repressurization conditions after the ZBO tests were selected primarily to protect the test article and facility. Also, following a test, the MHTB was not held under vacuum conditions for needlessly long periods. The chamber and test article were warmed and repressurized within 8 to 12 hr after testing was concluded. Chamber repressurization occurred slowly (≈30 min) with dry GN_2 (dewpoint –54 °C (–65 °F)) in the 4 to 27 °C (40 to 80 °F) temperature range. To prevent H_2O condensation, repressurization was initiated only after the vacuum chamber cold walls and all test article insulation (SOFI/MLI) had reached ≈15.5 °C (≈60 °F).

Dry GN_2 with a dewpoint of –54 °C (–65 °F) was used to accomplish purge and inerting operations for the test article volume and all service lines. These operations were designed so that the test article was not subjected to a positive differential pressure in excess of 344 kPa (50 psid). Typically, the GN_2 shield purge remained on for 24 hr after completion of testing.

3. PREDICTIONS AND TEST APPROACH

The strategy was to first use the MHTB environmental shroud to establish an insulation warm boundary temperature of 164 K and, before turning the cooler on, to ensure a tank heat leak below the cooler thermal extraction capability (27 W expected). A tank heat leak of 12.9 W was predicted with the pump operating (table 3). About 8.3 W was expected through the insulation and penetrations, excluding the nonoperating cooler. An additional heat leak of 4.3 W was calculated for the nonoperating cooler using a model based on bench testing the MHTB cryocooler hardware. The pump was expected to add ≈0.3 W at 37.8 L/min. Then, during subsequent ZBO testing with the cooler operating, one of the internal heaters could be adjusted, based on the measured tank pressure transients, to balance the tank heat load and achieve steady-state pressure conditions. By integrating a simplified MHTB thermal/fluid analytical model into a control system algorithm (see sec. 2.5), the measured ullage pressure response and real-time thermal data could be used to automatically provide a constant tank pressure condition. Although the control scheme was necessitated by the cooler's constant output design, the control system challenges were similar to those that will be encountered in actual missions. The MHTB test request sheet is presented in appendix G.

Table 3. Predicted heat leak distribution.

Source	Heat Leak (W)
Tank with penetrations	8.3
Nonoperating cooler	4.3
Operating pump	0.3
Total	12.9

4. COMPONENT AND SUBSYSTEM TEST RESULTS

4.1 Multipurpose Hydrogen Test Bed/Cryocooler Assembly Bench Test

As mentioned earlier, the inline HX was designed to transfer thermal energy from the fluid to the cryocooler in a manner that minimized cryocooler size and power requirements. Besides having a high conductivity, the HX design had to allow for welding to a stainless steel flange and have the strength to accommodate piping stress. GRC conducted a series of bench tests to verify that the design would perform as expected and that the assembly could be successfully integrated into the MHTB.

The HX was fabricated from high-conductivity Cu and then integrated with the stainless steel piping tee. The HX, composed of five fins, has an overall height and a base diameter of ≈17 and ≈3 cm, respectively. The measured conductivity was ≈23 W/cm·K, which limits the temperature increase along the HX to just 2 K and mitigates thermal integration losses. This limited temperature increase, compared to the predicted difference of 3.5 K, improved the overall system efficiency and limited the thermal integration losses.

The GRC bench testing proved to be very worthwhile and enabled avoidance of last-minute issues that would have otherwise been encountered. The testing resulted in a measured conductivity that was higher than expected which minimized the temperature increase between the cooler ‘cold finger’ and the LH_2 end of the HX. The measured conductivity of ≈23 W/cm·K limited the temperature increase to just 2 K, compared to the predicted difference of 3.5 K, thereby reducing losses and improving the overall system efficiency. Furthermore, the bench testing assured that the cryocooler subsystem structural support and electrical and mechanical fittings would be easily accommodated by MSFC’s MHTB and test facility interfaces.

4.2 Heater Testing

Each of the carbon heater elements was secured in a fixture and solid Cu feedthrough wires were attached to the heating elements, as shown in figure 19. The baseline resistance of each element with the solid Cu wires attached was measured before and after installation in the cryostat. After cryostat fill, voltage and current readings were taken periodically as the power level was slowly increased to a maximum of 50 W. Table 4 presents a representative set of data for one of the three heater elements. The following could be concluded:

- As expected, the heater element resistance increased with decreasing temperature.

- LH_2 exposure did not adversely affect the heater operation.

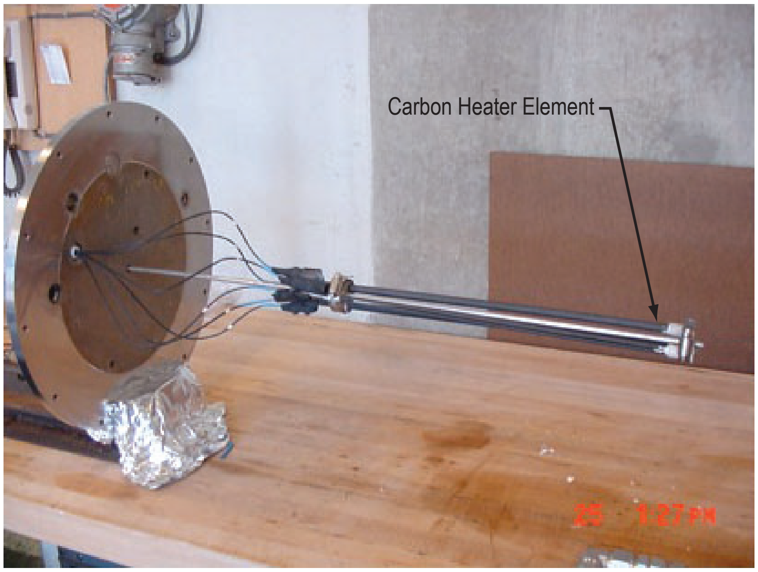


Figure 19. LH_2 heater test fixture.

Table 4. Representative set of data for one heater element.

Applied Volts	Current (A)	Power (W)
1	0.8	0.8
2	1.7	3.4
3	2.6	7.8
4	3.5	14.0
5	4.4	22.0
6	5.3	31.8
7	6.2	43.4
7.5	6.6	49.5

4.2.1 First Zero-Boiloff Test Series

The ZBO testing consisted of two test series—one during the summer and a second during the fall of 2001. The first series (see table 5), conducted with a 95% fill level, was compromised by a larger-than-predicted heat leak from the component enclosure positioned around the recirculation line and cooler assembly. Based on measured parameters, the cryocooler net energy extraction rate from the LH_2 was established to be 24 W. However, the internal heat generated by the cooler motor operation resulted in an enclosure assembly heat leak addition of 17 W. Thus, the enclosure heat leak combined with a measured tank heat leak of 9.5 W (including the recirculation pump input of 0.3 W) totaled 26.5 W, exceeding the cooler extraction capability by 2.5 W. Therefore, testing was

Table 5. ZBO testing matrix summary—summer 2001.

Test	Scope	Description
1	Establish thermal control subsystem heat leak < cooler capacity @ 90%–95% fill with boiloff vent open	Steady-state boiloff with cooler and mixer off to baseline heat leak prior to ZBO test; correlate predictions
2	Assure that cooler capacity > heat leak @ 90%–95% fill with cooler and mixer on, vent closed	Baseline ullage pressure trend (decrease expected); correlate predictions
3	Establish constant average ullage pressure @ 90%–95% fill with cooler, mixer, and heater on	Add and adjust heater input to balance total heat leak with cooler energy removal; evaluate auto pressure control
4	Sustain ZBO conditions for 4 days @ 90%–95% fill	Allow automatic controls to maintain constant average ullage pressure; verify ZBO concept
5	Check heat leak conditions @ 25%–30% fill	Perform abbreviated heat leak test
6	Repeat tests 1 and 2 @ 25%–30% fill	Ullage pressure rise rate slower with larger ullage, assess effect on controls
7	Repeat test 1 and 2 @ 50%; then impose off-nominal conditions	Abbreviated ZBO test @ 50% followed by assessing effects of off-nominal conditions on ullage pressure and system controls

Note: Total test duration of 25 to 30 days including optical mass gauge testing.

suspended so that LN_2 cooling coils could be installed around the component enclosure, shown in figure 20, and reduce the heat leak to acceptable levels. (Such an enclosure would not be needed in an actual space application.)

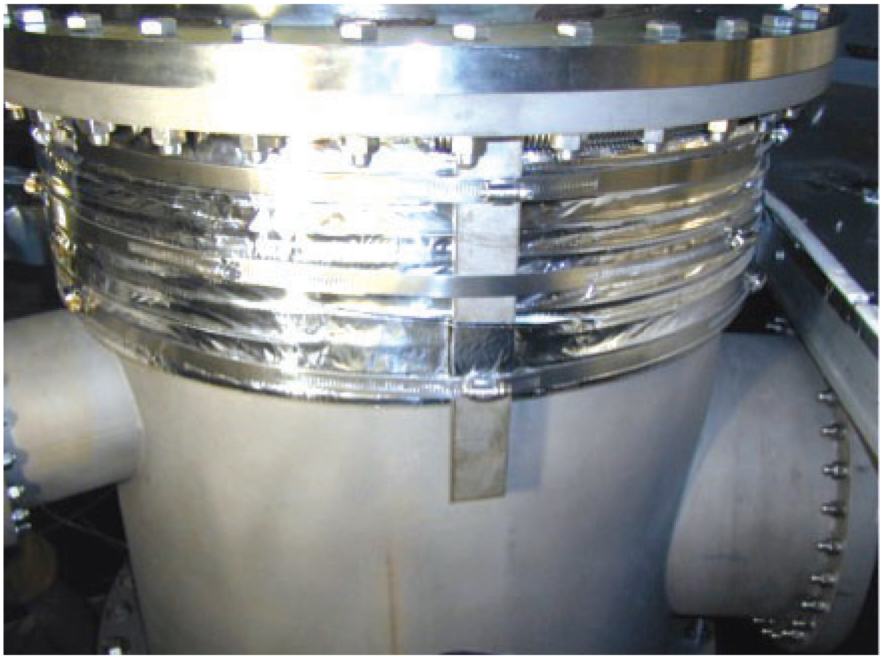


Figure 20. Component enclosure with coils.

In spite of the limitations, the first series was successfully used to evaluate various system elements and adjust operational procedures. Both intermittent and continuous pump operations at various flow rates were tested to evaluate impacts on pressure control and cryocooler performance.

The intermittent pump operations compromised the cryocooler heat extraction process because the colder liquid that accumulated between operations reduced the cooler efficiency, did not benefit destratification and ullage pressure control, and added operational complexity. As the pump flow rate was reduced, erratic flow rate and ΔP across the pump indicated unstable, two-phase flow began at flow rates below ≈37.8 L/min. Because the pump was designed for operation at 114 L/min, the pump efficiency began to rapidly degrade below 38 L/min and an increased percentage of the power input was thermally transferred to the fluid. Ultimately, it was concluded that continuous pump operation at ≈38 L/min was optimal for the MHTB ZBO hardware arrangement. A substantial advancement was that thermal/fluid analytical modeling of the MHTB system was successfully integrated into the control system algorithm. Measured thermal and thermodynamic parameters were used to quantify the various heat leak sources, anchor real-time analytical modeling, and establish confidence in the automated control system (ACS) algorithm.

4.2.2 Second Test Series

Using LN_2 cooling coils and structural temperature sensors on the component enclosure, it was established that the assembly heat leak was reduced from 17 to 3.5 W (figs. 20–22). Also, boiloff testing confirmed that the total MHTB tank heat leak, including the operating pump, was reduced to 13 W, well within the measured 24 W cryocooler energy extraction rate. Testing was conducted primarily at fill levels of 95% and 50%, with limited testing at 25%.

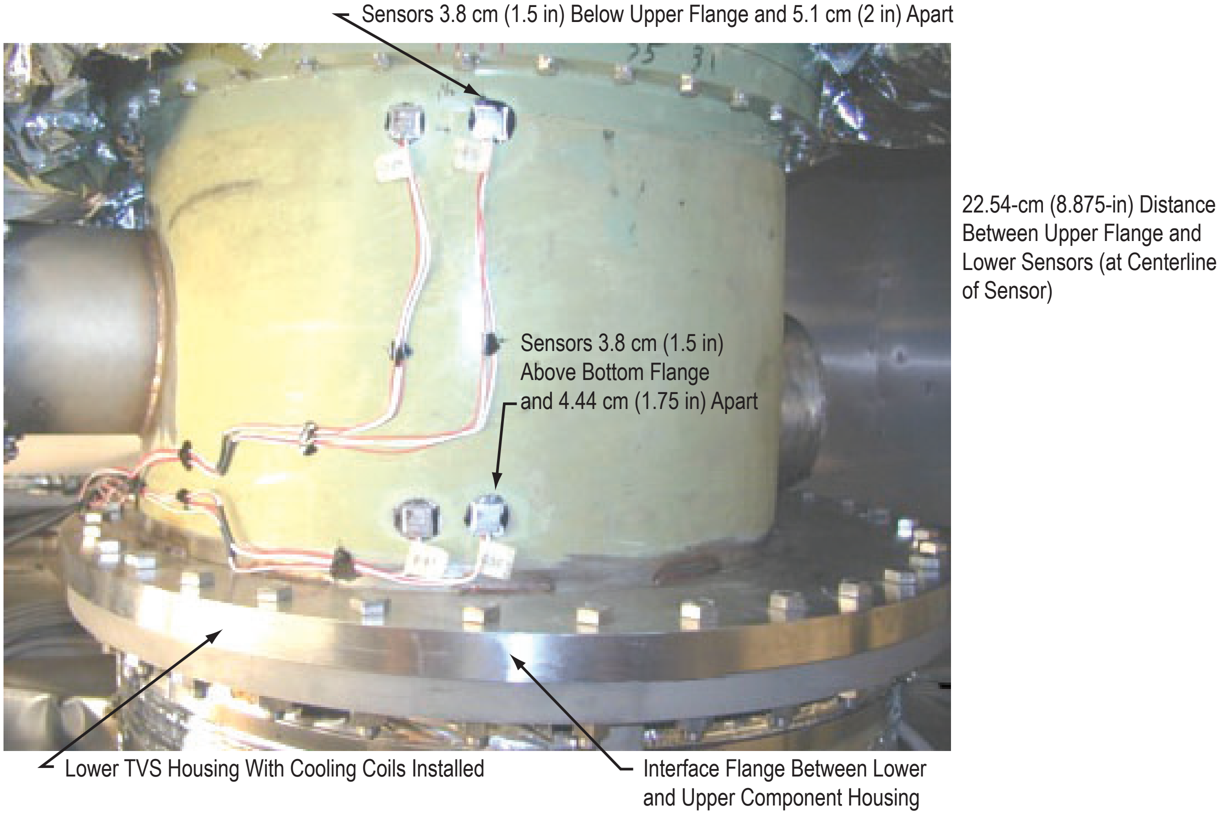


Figure 21. Upper enclosure with instrumentation—sensors 3.8 cm (1.5 in) below upper flange.

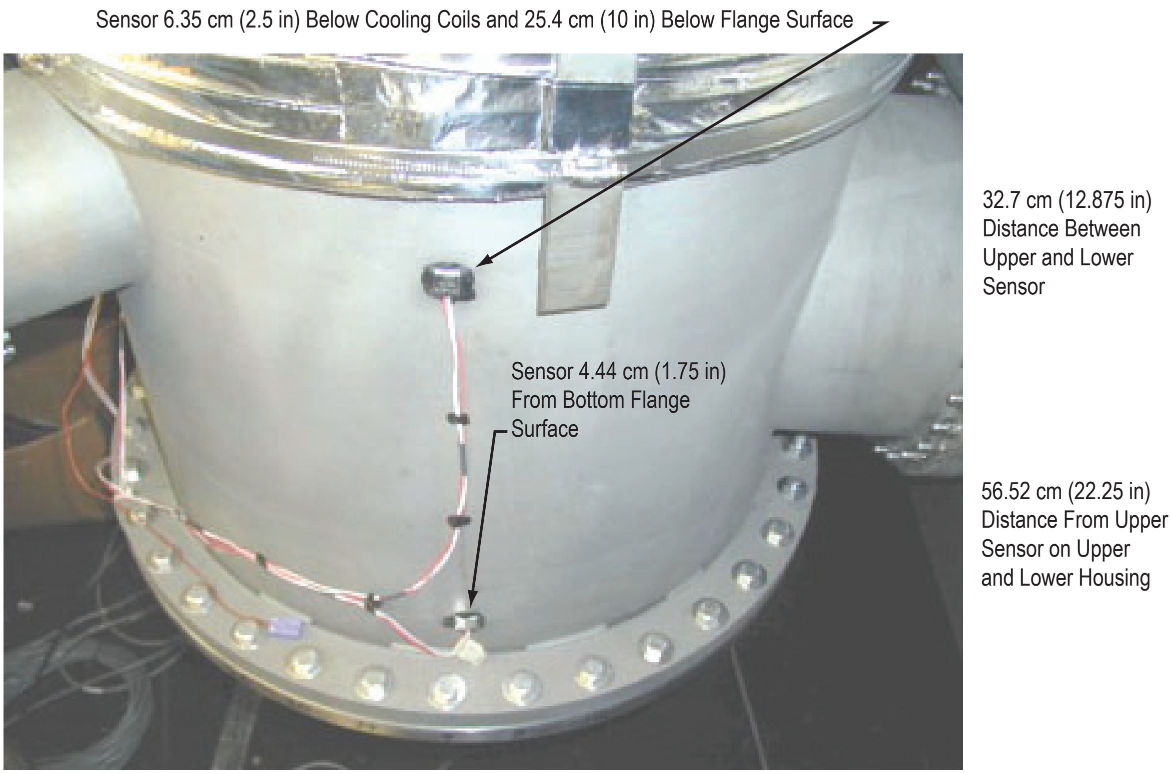


Figure 22. Upper enclosure with instrumentation—sensors 6.35 cm (2.5 in) below cooling coils.

The transition to ZBO conditions is illustrated in figure 23, in which the measured boiloff rate versus time at the 95% fill level is presented. The boiloff rate peaked shortly after tanking. Then, the transition to steady-state temperature profiles within the MLI was expedited by injecting a small amount of He into the chamber. This technique accelerated the transition to stable boiloff conditions by several days. Steady-state boiloff began at ≈150,000 s, and ≈100,000 s (28 hr) later, the cryocooler was turned on and the transition to ZBO began and was achieved within ≈30,000 s (8.3 hr). The corresponding ullage pressure versus time data presented in figure 24 demonstrate the transition from constant pressure (steady-state boiloff) at 117.3 kPa to a gradual drop in pressure when ZBO conditions began at ≈230,000 s, and to a constant 114.8 kPa after the heater control algorithm was activated at 670,000 s. The ACS thereafter maintained the ullage pressure within ±0.003 kPa for over 50 hr and could have continued indefinitely. The total ZBO period was over 156 hr at the 95% fill level.

The automated interaction between the ullage pressure and heater input is illustrated in figure 25 for the 50% fill level. The cooler was initially operated without heater input; the ullage pressure therefore decreased at the beginning. As the pressure dropped below the pressure control point of 114.8 kPa at 20,000 s, the heater was activated; then, when the pressure increased to the set point, the heater was deactivated. The ACS then locked on the set point and thereafter controlled the ullage pressure to within ±0.003 kPa for the remaining 89 hr of testing. The total ZBO period was ≈114 hr at the 50% fill level. Short-duration testing conducted at the 25% fill level indicated similar trends. The test durations were considered sufficient to demonstrate that the ZBO condition could have been sustained for the operating life of the cryocooler and mixer pump.

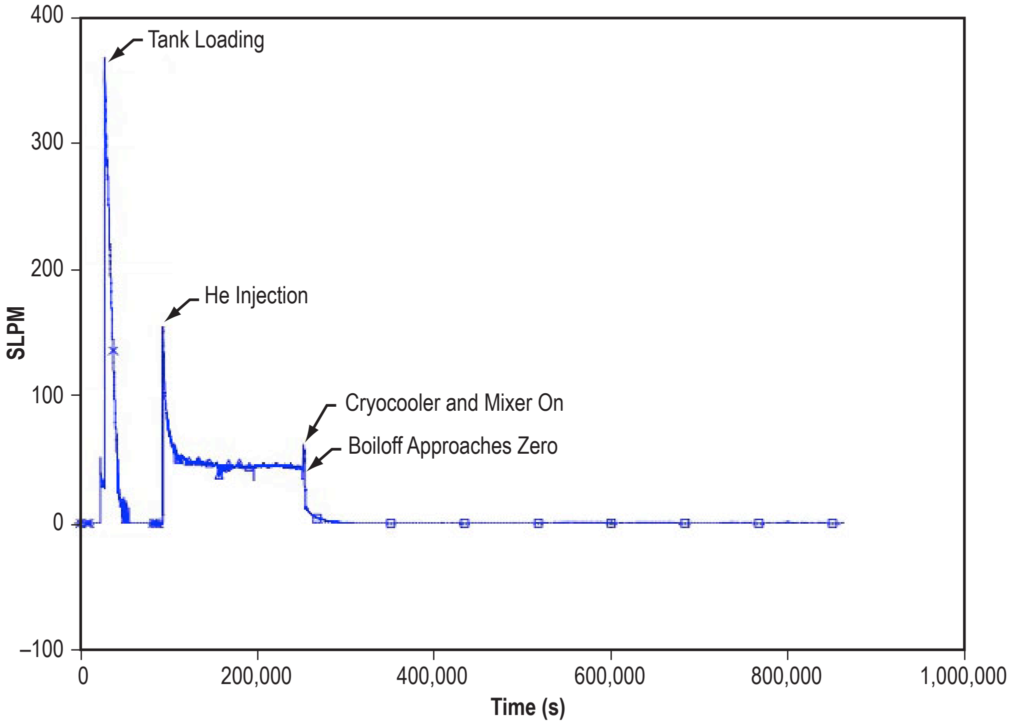


Figure 23. Boiloff flow rate transition to ZBO at 95% fill level.

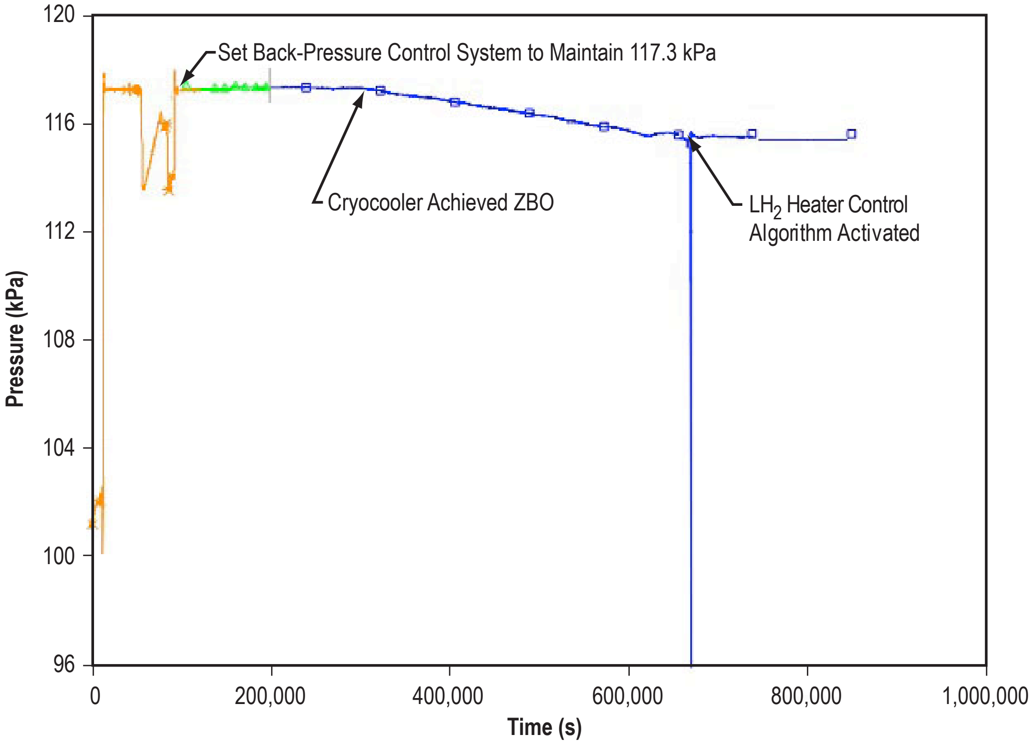


Figure 24. Ullage pressure transition at 95% fill level.

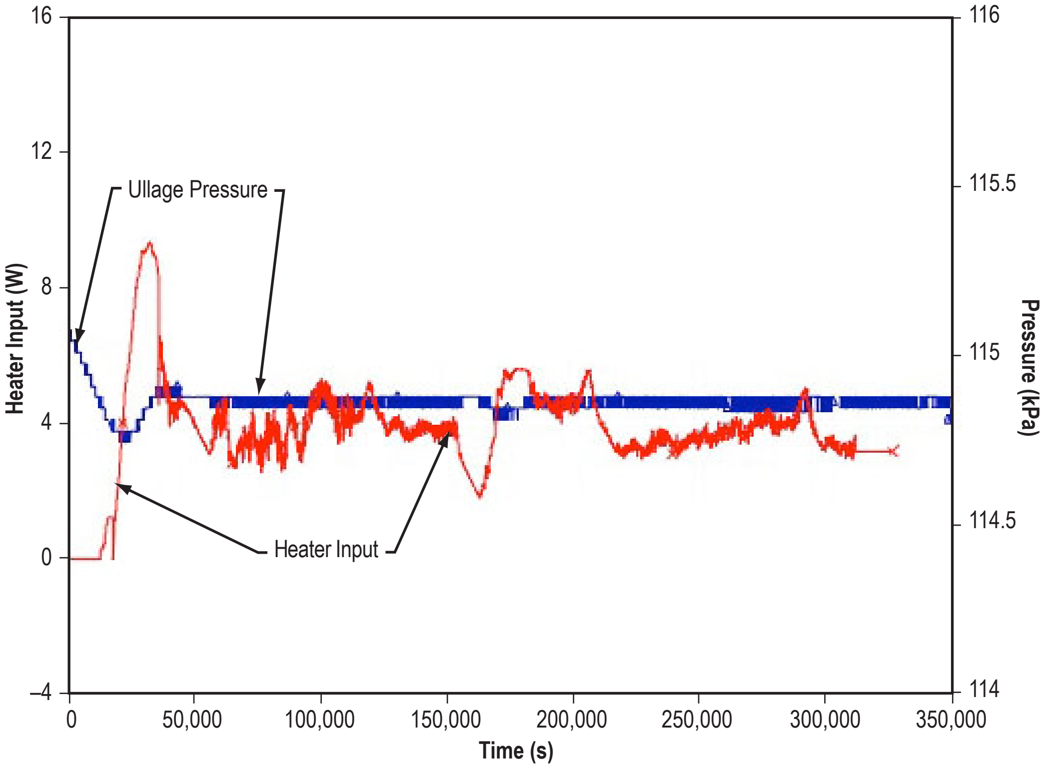


Figure 25. Ullage pressure at 50% fill level.

5. ANALYTICAL CORRELATIONS

A transient, one-dimensional analytical model was formulated by modifying an existing thermodynamic vent system (TVS) computer program to characterize integrated performance of the spray bar recirculation, cryocooler, and heaters within the MHTB. The integrated system performance formulation comprises three combined thermal/fluid models, including the spray manifold and injector tubes, the recirculation pump, and the tank. The spray manifold and injection tube model determines the pressure drops within the manifold and tubes along with the spray flow rates and velocities leaving the injection orifices. The recirculation pump model calculates the pump head increase from the pump speed and the head coefficient curve provided by the pump manufacturer. The tank model is a lumped model consisting of three control volumes—the ullage, the tank wall, and the bulk liquid. A more detailed description of the TVS analytical model, developed by H. Nguyen, Rockwell Aerospace, is presented in reference 7.

With the continuous spray bar and cooler operation, the thermal energy input and energy extraction rates could be balanced, and the ullage and liquid were homogenous or destratified. Therefore, the single-node analytical representations of the ullage and liquid proved to be accurate. Analytical modeling correlations for test periods with ACS set point pressure control are presented in figures 26 and 27 for the 95% and 50% fill levels, respectively. The analytically modeled ullage pressures correlated almost perfectly with the measured data.

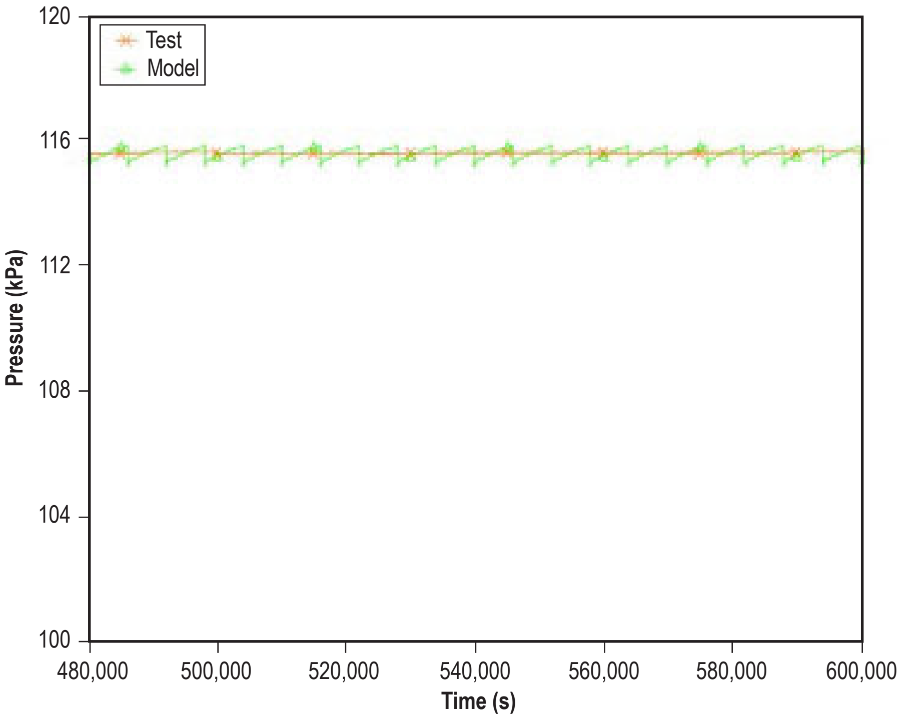


Figure 26. Ullage correlations at 95% fill level.

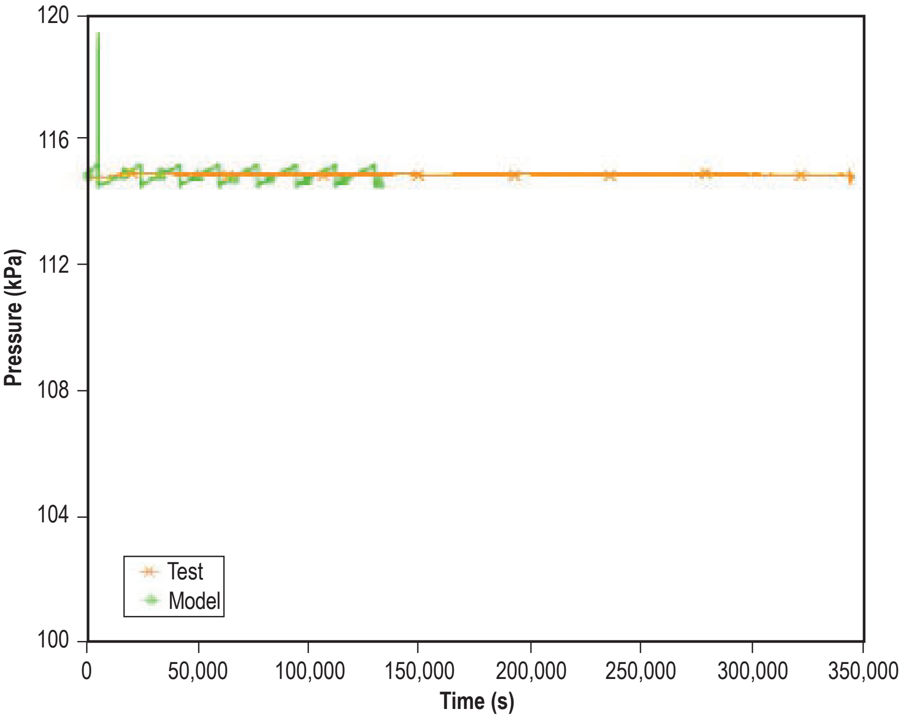


Figure 27. Ullage correlations at 50% fill level.

6. CONCLUSIONS AND RECOMMENDATIONS

ZBO involves using a cryocooler/radiator system to intercept and reject cryogenic storage system heat leak such that boiloff and the necessity for venting are precluded. A cooperative effort by ARC, GRC, and MSFC was implemented to develop and demonstrate ZBO hardware and concepts for in-space storage of cryogenic propellants. The MHTB, a large-scale LH_2 test article, was modified at MSFC for the integrated operation of a commercial cooler with passive insulation, a propellant recirculation subsystem, and pressure control subsystems. The cooler was a Cryomech GB37 unit with a rated cooling capacity of 30 W at 20 K. Because the cooler thermal extraction rate could not be directly controlled, the test procedure strategy was to first establish a heat leak below the thermal extraction capability of the cooler. Then an automated control algorithm was used to adjust an internal heater, based on the measured tank pressure to achieve steady-state pressure conditions; i.e., the incoming and extracted thermal energy were continually balanced.

Both intermittent and continuous pump operations at various flow rates were tested to evaluate impacts on pressure control and cryocooler performance. However, the intermittent pump operations compromised the cryocooler heat extraction process because the colder liquid that accumulated between operations reduced the cooler efficiency, did not benefit destratification and ullage pressure control, and added operational complexity. Because the pump was designed for operation at 114 L/min, the pump efficiency began to rapidly degrade below 38 L/min and an increased percentage of the power input was thermally transferred to the fluid. Ultimately, it was concluded that continuous pump operation at ≈38 L/min was optimal for the MHTB ZBO hardware arrangement.

The MHTB/cryocooler arrangement successfully demonstrated that hydrogen can be stored within a large-scale vessel without boiloff losses and with tight pressure control limits. A substantial advancement was achieved with the successful integration of a thermal/fluid analytical model into an ACS algorithm. Measured thermal and thermodynamic parameters were used in real time to quantify the various heat leak sources, anchor analytical modeling, and perform troubleshooting. The control algorithm maintained the ullage pressure within ±0.003 kPa. The test durations at 90% and 50% fill levels (156 and 114 hr, respectively) were sufficient to demonstrate that the ZBO condition could have been sustained for the operating life of the cryocooler and mixer pump. Limited testing at a 25% fill level indicated similar trends. Also, excellent correlation of measured ullage pressures was achieved with a simplified analytical model. In conclusion, cryogenic storage technology in space entered a new era wherein hydrogen and other cryogens can eventually be stored in space on the order of years as opposed to a few weeks or months.

APPENDIX A—MULTIPURPOSE HYDROGEN TEST BED TANKING

The liquid hydrogen fill height versus fill volume, ullage and liquid percent, and liquid mass for the MHTB tank is presented in table 6.

Table 6. MHTB tanking.

Height*		Volume**		Ullage	Liquid	Liquid Mass	
(in)	(cm)	(ft^3)	(m^3)	(%)	(%)	(lbm)	(kg)
0.00	0.00	0.00	0.0000	100.00	0.00	0.00	0.0000
0.50	1.27	0.05	0.0015	99.99	0.01	0.24	0.1087
1.00	2.54	0.22	0.0061	99.97	0.03	0.95	0.4324
1.50	3.81	0.48	0.0137	99.92	0.08	2.13	0.9673
2.00	5.08	0.85	0.0242	99.87	0.13	3.77	1.7098
2.50	6.35	1.33	0.0375	99.79	0.21	5.86	2.6560
3.00	7.62	1.90	0.0537	99.70	0.30	8.38	3.8025
3.50	8.89	2.57	0.0727	99.60	0.40	11.34	5.1453
4.00	10.16	3.33	0.0944	99.48	0.52	14.73	6.6809
4.50	11.43	4.19	0.1187	99.34	0.66	18.53	8.4055
5.00	12.70	5.15	0.1457	99.20	0.80	22.74	10.3154
5.50	13.97	6.19	0.1753	99.03	0.97	27.35	12.4068
6.00	15.24	7.32	0.2073	98.85	1.15	32.36	14.6762
6.50	16.51	8.54	0.2419	98.66	1.34	37.74	17.1198
7.00	17.78	9.85	0.2788	98.46	1.54	43.51	19.7338
7.50	19.05	11.23	0.3181	98.24	1.76	49.64	22.5146
8.00	20.32	12.70	0.3597	98.01	1.99	56.13	25.4585
8.50	21.59	14.25	0.4035	97.77	2.23	62.97	28.5618
9.00	22.86	15.88	0.4495	97.52	2.48	70.15	31.8207
9.50	24.13	17.58	0.4977	97.25	2.75	77.67	35.2316
10.00	25.40	19.35	0.5480	96.97	3.03	85.52	38.7907
10.50	26.67	21.20	0.6003	96.68	3.32	93.68	42.4943
11.00	27.94	23.12	0.6546	96.38	3.62	102.16	46.3388
11.50	29.21	25.10	0.7109	96.07	3.93	110.94	50.3204
12.00	30.48	27.16	0.7690	95.75	4.25	120.01	54.4354
12.50	31.75	29.28	0.8290	95.42	4.58	129.37	58.6801
13.00	33.02	31.46	0.8907	95.08	4.92	139.00	63.0509
13.50	34.29	33.70	0.9542	94.73	5.27	148.91	67.5439
14.00	35.56	36.00	1.0193	94.37	5.63	159.08	72.1556
14.50	36.83	38.36	1.0861	94.00	6.00	169.50	76.8821
15.00	38.10	40.77	1.1545	93.62	6.38	180.16	81.7198

Table 6. MHTB tanking (Continued).

Height*		Volume**		Ullage	Liquid	Liquid Mass	
(in)	(cm)	(ft^3)	(m^3)	(%)	(%)	(lbm)	(kg)
15.50	39.37	43.24	1.2243	93.24	6.76	191.06	86.6650
16.00	40.64	45.76	1.2957	92.84	7.16	202.19	91.7140
16.50	41.91	48.32	1.3684	92.44	7.56	213.55	96.8630
17.00	43.18	50.94	1.4425	92.03	7.97	225.11	102.1084
17.50	44.45	53.60	1.5179	91.62	8.38	236.88	107.4464
18.00	45.72	56.31	1.5946	91.19	8.81	248.84	112.8734
18.50	46.99	59.06	1.6724	90.76	9.24	261.00	118.3856
19.00	48.26	61.85	1.7515	90.33	9.67	273.33	123.9794
19.50	49.53	64.68	1.8316	89.88	10.12	285.83	129.6510
20.00	50.80	67.55	1.9128	89.43	10.57	298.50	135.3967
20.50	52.07	70.45	1.9949	88.98	11.02	311.32	141.2128
21.00	53.34	73.39	2.0780	88.52	11.48	324.29	147.0957
21.50	54.61	76.35	2.1620	88.06	11.94	337.40	153.0415
22.00	55.88	79.35	2.2469	87.59	12.41	350.64	159.0467
22.50	57.15	82.37	2.3325	87.12	12.88	364.00	165.1074
23.00	58.42	85.42	2.4188	86.64	13.36	377.48	171.2200
23.50	59.69	88.49	2.5059	86.16	13.84	391.06	177.3808
24.00	60.96	91.59	2.5935	85.67	14.33	404.74	183.5861
24.50	62.23	94.71	2.6818	85.19	14.81	418.51	189.8321
25.00	63.50	97.84	2.7705	84.70	15.30	432.36	196.1152
25.50	64.77	100.99	2.8598	84.20	15.80	446.29	202.4317
26.00	66.04	104.16	2.9494	83.71	16.29	460.28	208.7778
26.50	67.31	107.34	3.0394	83.21	16.79	474.32	215.1498
27.00	68.58	110.53	3.1298	82.71	17.29	488.42	221.5441
27.50	69.85	113.73	3.2204	82.21	17.79	502.56	227.9569
28.00	71.12	116.93	3.3112	81.71	18.29	516.73	234.3845
28.50	72.39	120.15	3.4021	81.21	18.79	530.92	240.8233
29.00	73.66	123.36	3.4932	80.70	19.30	545.14	247.2695
29.50	74.93	126.58	3.5843	80.20	19.80	559.36	253.7193
30.00	76.20	129.80	3.6755	79.70	20.30	573.58	260.1718
30.50	77.47	133.02	3.7666	79.19	20.81	587.80	266.6225
31.00	78.74	136.23	3.8577	78.69	21.31	602.02	273.0731
31.50	80.01	139.45	3.9489	78.19	21.81	616.24	279.5237
32.00	81.28	142.67	4.0400	77.68	22.32	630.47	285.9743
32.50	82.55	145.89	4.1311	77.18	22.82	644.69	292.4250
33.00	83.82	149.11	4.2222	76.68	23.32	658.91	298.8756
33.50	85.09	152.33	4.3134	76.17	23.83	673.13	305.3262
34.00	86.36	155.54	4.4045	75.67	24.33	687.35	311.7768
34.50	87.63	158.76	4.4956	75.17	24.83	701.57	318.2275
35.00	88.90	161.98	4.5868	74.66	25.34	715.79	324.6781

Table 6. MHTB tanking (Continued).

Height*		Volume**		Ullage	Liquid	Liquid Mass	
(in)	(cm)	(ft^3)	(m^3)	(%)	(%)	(lbm)	(kg)
35.50	90.17	165.20	4.6779	74.16	25.84	730.01	331.1287
36.00	91.44	168.42	4.7690	73.66	26.34	744.24	337.5793
36.50	92.71	171.63	4.8601	73.15	26.85	758.46	344.0300
37.00	93.98	174.85	4.9513	72.65	27.35	772.68	350.4806
37.50	95.25	178.07	5.0424	72.15	27.85	786.90	356.9312
38.00	96.52	181.29	5.1335	71.64	28.36	801.12	363.3818
38.50	97.79	184.51	5.2247	71.14	28.86	815.34	369.8325
39.00	99.06	187.73	5.3158	70.64	29.36	829.56	376.2831
39.50	100.33	190.94	5.4069	70.13	29.87	843.78	382.7337
40.00	101.60	194.16	5.4980	69.63	30.37	858.00	389.1843
40.50	102.87	197.38	5.5892	69.13	30.87	872.23	395.6350
41.00	104.14	200.60	5.6803	68.62	31.38	886.45	402.0856
41.50	105.41	203.82	5.7714	68.12	31.88	900.67	408.5362
42.00	106.68	207.03	5.8626	67.62	32.38	914.89	414.9868
42.50	107.95	210.25	5.9537	67.11	32.89	929.11	421.4375
43.00	109.22	213.47	6.0448	66.61	33.39	943.33	427.8881
43.50	110.49	216.69	6.1359	66.11	33.89	957.55	434.3387
44.00	111.76	219.91	6.2271	65.60	34.40	971.77	440.7893
44.50	113.03	223.13	6.3182	65.10	34.90	986.00	447.2400
45.00	114.30	226.34	6.4093	64.60	35.40	1,000.22	453.6906
45.50	115.57	229.56	6.5005	64.09	35.91	1,014.44	460.1412
46.00	116.84	232.78	6.5916	63.59	36.41	1,028.66	466.5918
46.50	118.11	236.00	6.6827	63.09	36.91	1,042.88	473.0425
47.00	119.38	239.22	6.7738	62.58	37.42	1,057.10	479.4931
47.50	120.65	242.43	6.8650	62.08	37.92	1,071.32	485.9437
48.00	121.92	245.65	6.9561	61.58	38.42	1,085.54	492.3943
48.50	123.19	248.87	7.0472	61.07	38.93	1,099.76	498.8450
49.00	124.46	252.09	7.1384	60.57	39.43	1,113.99	505.2956
49.50	125.73	255.31	7.2295	60.07	39.93	1,128.21	511.7462
50.00	127.00	258.53	7.3206	59.56	40.44	1,142.43	518.1968
50.50	128.27	261.74	7.4117	59.06	40.94	1,156.65	524.6475
51.00	129.54	264.96	7.5029	58.56	41.44	1,170.87	531.0981
51.50	130.81	268.18	7.5940	58.05	41.95	1,185.09	537.5487
52.00	132.08	271.40	7.6851	57.55	42.45	1,199.31	543.9993
52.50	133.35	274.62	7.7763	57.05	42.95	1,213.53	550.4500
53.00	134.62	277.83	7.8674	56.54	43.46	1,227.76	556.9006
53.50	135.89	281.05	7.9585	56.04	43.96	1,241.98	563.3512
54.00	137.16	284.27	8.0496	55.54	44.46	1,256.20	569.8018
54.50	138.43	287.49	8.1408	55.03	44.97	1,270.42	576.2525
55.00	139.70	290.71	8.2319	54.53	45.47	1,284.64	582.7031
55.50	140.97	293.93	8.3230	54.03	45.97	1,298.86	589.1537

Table 6. MHTB tanking (Continued).

Height*		Volume**		Ullage	Liquid	Liquid Mass	
(in)	(cm)	(ft^3)	(m^3)	(%)	(%)	(lbm)	(kg)
56.00	142.24	297.14	8.4142	53.52	46.48	1,313.08	595.6043
56.50	143.51	300.36	8.5053	53.02	46.98	1,327.30	602.0550
57.00	144.78	303.58	8.5964	52.52	47.48	1,341.53	608.5056
57.50	146.05	306.80	8.6875	52.01	47.99	1,355.75	614.9562
58.00	147.32	310.02	8.7787	51.51	48.49	1,369.97	621.4068
58.50	148.59	313.23	8.8698	51.01	48.99	1,384.19	627.8575
59.00	149.86	316.45	8.9609	50.50	49.50	1,398.41	634.3081
59.50	151.13	319.67	9.0521	50.00	50.00	1,412.63	640.7587
60.00	152.40	322.89	9.1432	49.50	50.50	1,426.85	647.2093
60.50	153.67	326.11	9.2343	48.99	51.01	1,441.07	653.6600
61.00	154.94	329.33	9.3254	48.49	51.51	1,455.29	660.1106
61.50	156.21	332.54	9.4166	47.99	52.01	1,469.52	666.5612
62.00	157.48	335.76	9.5077	47.48	52.52	1,483.74	673.0118
62.50	158.75	338.98	9.5988	46.98	53.02	1,497.96	679.4625
63.00	160.02	342.20	9.6900	46.48	53.52	1,512.18	685.9131
63.50	161.29	345.42	9.7811	45.97	54.03	1,526.40	692.3637
64.00	162.56	348.63	9.8722	45.47	54.53	1,540.62	698.8143
64.50	163.83	351.85	9.9633	44.97	55.03	1,554.84	705.2650
65.00	165.10	355.07	10.0545	44.46	55.54	1,569.06	711.7156
65.50	166.37	358.29	10.1456	43.96	56.04	1,583.29	718.1662
66.00	167.64	361.51	10.2367	43.46	56.54	1,597.51	724.6168
66.50	168.91	364.73	10.3278	42.95	57.05	1,611.73	731.0675
67.00	170.18	367.94	10.4190	42.45	57.55	1,625.95	737.5181
67.50	171.45	371.16	10.5101	41.95	58.05	1,640.17	743.9687
68.00	172.72	374.38	10.6012	41.44	58.56	1,654.39	750.4193
68.50	173.99	377.60	10.6924	40.94	59.06	1,668.61	756.8700
69.00	175.26	380.82	10.7835	40.44	59.56	1,682.83	763.3206
69.50	176.53	384.03	10.8746	39.93	60.07	1,697.06	769.7712
70.00	177.80	387.25	10.9657	39.43	60.57	1,711.28	776.2218
70.50	179.07	390.47	11.0569	38.93	61.07	1,725.50	782.6725
71.00	180.34	393.69	11.1480	38.42	61.58	1,739.72	789.1231
71.50	181.61	396.91	11.2391	37.92	62.08	1,753.94	795.5737
72.00	182.88	400.13	11.3303	37.42	62.58	1,768.16	802.0243
72.50	184.15	403.34	11.4214	36.91	63.09	1,782.38	808.4750
73.00	185.42	406.56	11.5125	36.41	63.59	1,796.60	814.9256
73.50	186.69	409.78	11.6036	35.91	64.09	1,810.82	821.3762
74.00	187.96	413.00	11.6948	35.40	64.60	1,825.05	827.8268
74.50	189.23	416.22	11.7859	34.90	65.10	1,839.27	834.2775
75.00	190.50	419.43	11.8770	34.40	65.60	1,853.49	840.7281
75.50	191.77	422.65	11.9682	33.89	66.11	1,867.71	847.1787
76.00	193.04	425.87	12.0593	33.39	66.61	1,881.93	853.6293

Table 6. MHTB tanking (Continued).

Height*		Volume**		Ullage	Liquid	Liquid Mass	
(in)	(cm)	(ft^3)	(m^3)	(%)	(%)	(lbm)	(kg)
76.50	194.31	429.09	12.1504	32.89	67.11	1,896.15	860.0800
77.00	195.58	432.31	12.2415	32.38	67.62	1,910.37	866.5306
77.50	196.85	435.53	12.3327	31.88	68.12	1,924.59	872.9812
78.00	198.12	438.74	12.4238	31.38	68.62	1,938.82	879.4318
78.50	199.39	441.96	12.5149	30.87	69.13	1,953.04	885.8824
79.00	200.66	445.18	12.6061	30.37	69.63	1,967.26	892.3331
79.50	201.93	448.40	12.6972	29.87	70.13	1,981.48	898.7837
80.00	203.20	451.62	12.7883	29.36	70.64	1,995.70	905.2343
80.50	204.47	454.83	12.8794	28.86	71.14	2,009.92	911.6849
81.00	205.74	458.05	12.9706	28.36	71.64	2,024.14	918.1356
81.50	207.01	461.27	13.0617	27.85	72.15	2,038.36	924.5862
82.00	208.28	464.49	13.1528	27.35	72.65	2,052.58	931.0368
82.50	209.55	467.71	13.2440	26.85	73.15	2,066.81	937.4874
83.00	210.82	470.93	13.3351	26.34	73.66	2,081.03	943.9381
83.50	212.09	474.14	13.4262	25.84	74.16	2,095.25	950.3887
84.00	213.36	477.36	13.5173	25.34	74.66	2,109.47	956.8393
84.50	214.63	480.58	13.6085	24.83	75.17	2,123.69	963.2899
85.00	215.90	483.80	13.6996	24.33	75.67	2,137.91	969.7406
85.50	217.17	487.02	13.7907	23.83	76.17	2,152.13	976.1912
86.00	218.44	490.23	13.8819	23.32	76.68	2,166.35	982.6418
86.50	219.71	493.45	13.9730	22.82	77.18	2,180.58	989.0924
87.00	220.98	496.67	14.0641	22.32	77.68	2,194.80	995.5431
87.50	222.25	499.89	14.1552	21.81	78.19	2,209.02	1,001.9937
88.00	223.52	503.11	14.2464	21.31	78.69	2,223.24	1,008.4443
88.50	224.79	506.33	14.3375	20.80	79.20	2,237.46	1,014.8949
89.00	226.06	509.54	14.4286	20.30	79.70	2,251.68	1,021.3456
89.50	227.33	512.76	14.5198	19.80	80.20	2,265.90	1,027.7962
90.00	228.60	515.98	14.6108	19.30	80.70	2,280.12	1,034.2433
90.50	229.87	519.19	14.7019	18.79	81.21	2,294.33	1,040.6895
91.00	231.14	522.41	14.7929	18.29	81.71	2,308.52	1,047.1282
91.50	232.41	525.61	14.8837	17.79	82.21	2,322.69	1,053.5559
92.00	233.68	528.81	14.9743	17.29	82.71	2,336.83	1,059.9687
92.50	234.95	532.00	15.0646	16.79	83.21	2,350.93	1,066.3630
93.00	236.22	535.18	15.1546	16.29	83.71	2,364.98	1,072.7350
93.50	237.49	538.35	15.2443	15.80	84.20	2,378.97	1,079.0811
94.00	238.76	541.50	15.3335	15.30	84.70	2,392.89	1,085.3976
94.50	240.03	544.63	15.4223	14.81	85.19	2,406.74	1,091.6807
95.00	241.30	547.75	15.5105	14.33	85.67	2,420.51	1,097.9267
95.50	242.57	550.84	15.5982	13.84	86.16	2,434.19	1,104.1320
96.00	243.84	553.92	15.6852	13.36	86.64	2,447.78	1,110.2928
96.50	245.11	556.97	15.7716	12.88	87.12	2,461.25	1,116.4054

Table 6. MHTB tanking (Continued).

Height*		Volume**		Ullage	Liquid	Liquid Mass	
(in)	(cm)	(ft^3)	(m^3)	(%)	(%)	(lbm)	(kg)
97.00	246.38	559.99	15.8572	12.41	87.59	2,474.61	1,122.4661
97.50	247.65	562.99	15.9420	11.94	88.06	2,487.85	1,128.4713
98.00	248.92	565.95	16.0260	11.48	88.52	2,500.96	1,134.4171
98.50	250.19	568.89	16.1091	11.02	88.98	2,513.93	1,140.3000
99.00	251.46	571.79	16.1913	10.57	89.43	2,526.75	1,146.1161
99.50	252.73	574.66	16.2724	10.12	89.88	2,539.42	1,151.8618
100.00	254.00	577.49	16.3526	9.67	90.33	2,551.92	1,157.5334
100.50	255.27	580.28	16.4316	9.24	90.76	2,564.26	1,163.1272
101.00	256.54	583.03	16.5095	8.81	91.19	2,576.41	1,168.6394
101.50	257.81	585.73	16.5861	8.38	91.62	2,588.37	1,174.0664
102.00	259.08	588.40	16.6615	7.97	92.03	2,600.14	1,179.4044
102.50	260.35	591.01	16.7356	7.56	92.44	2,611.71	1,184.6498
103.00	261.62	593.58	16.8084	7.16	92.84	2,623.06	1,189.7988
103.50	262.89	596.10	16.8797	6.76	93.24	2,634.19	1,194.8478
104.00	264.16	598.57	16.9496	6.38	93.62	2,645.09	1,199.7930
104.50	265.43	600.98	17.0179	6.00	94.00	2,655.76	1,204.6307
105.00	266.70	603.34	17.0847	5.63	94.37	2,666.18	1,209.3572
105.50	267.97	605.64	17.1498	5.27	94.73	2,676.34	1,213.9689
106.00	269.24	607.88	17.2133	4.92	95.08	2,686.25	1,218.4619
106.50	270.51	610.06	17.2751	4.58	95.42	2,695.88	1,222.8327
107.00	271.78	612.18	17.3350	4.25	95.75	2,705.24	1,227.0774
107.50	273.05	614.23	17.3932	3.93	96.07	2,714.31	1,231.1924
108.00	274.32	616.22	17.4494	3.62	96.38	2,723.09	1,235.1740
108.50	275.59	618.14	17.5037	3.32	96.68	2,731.57	1,239.0185
109.00	276.86	619.99	17.5560	3.03	96.97	2,739.73	1,242.7221
109.50	278.13	621.76	17.6063	2.75	97.25	2,747.58	1,246.2812
110.00	279.40	623.46	17.6545	2.48	97.52	2,755.10	1,249.6921
110.50	280.67	625.09	17.7005	2.23	97.77	2,762.28	1,252.9510
111.00	281.94	626.64	17.7444	1.99	98.01	2,769.13	1,256.0543
111.50	283.21	628.11	17.7860	1.76	98.24	2,775.62	1,258.9981
112.00	284.48	629.49	17.8253	1.54	98.46	2,781.75	1,261.7790
112.50	285.75	630.80	17.8622	1.34	98.66	2,787.51	1,264.3930
113.00	287.02	632.02	17.8967	1.15	98.85	2,792.90	1,266.8366
113.50	288.29	633.15	17.9288	0.97	99.03	2,797.90	1,269.1060
114.00	289.56	634.19	17.9583	0.80	99.20	2,802.51	1,271.1974
114.50	290.83	635.15	17.9853	0.66	99.34	2,806.72	1,273.1073
115.00	292.10	636.01	18.0097	0.52	99.48	2,810.52	1,274.8319
115.50	293.37	636.77	18.0313	0.40	99.60	2,813.91	1,276.3675
116.00	294.64	637.44	18.0503	0.30	99.70	2,816.87	1,277.7103
116.50	295.91	638.01	18.0665	0.21	99.79	2,819.40	1,278.8567
117.00	297.18	638.49	18.0799	0.13	99.87	2,821.48	1,279.8030

Table 6. MHTB tanking (Continued).

Height*		Volume**		Ullage	Liquid	Liquid Mass	
(in)	(cm)	(ft^3)	(m^3)	(%)	(%)	(lbm)	(kg)
117.50	298.45	638.86	18.0904	0.08	99.92	2,823.12	1,280.5455
118.00	299.72	639.12	18.0979	0.03	99.97	2,824.30	1,281.0804
118.50	300.99	639.28	18.1025	0.01	99.99	2,825.01	1,281.4041
119.00	302.26	639.34	18.1040	0.00	100.00	2,825.25	1,281.5128

*Height is measured from the bottom of the tank.
**Total Tank Volume: 18.10 m^3 (639.34 ft^3).
***LH_2 Density: 70.786 kg/m^3 (4.419 lbm/ft^3).

APPENDIX B—INTEGRATION OF THE CRYOMECH GB37 CRYO-REFRIGERATOR INTO THE MULTIPURPOSE HYDROGEN TEST BED THERMODYNAMIC VENT SYSTEM

Prepared by
E. Johnson/TD71

Revised 02/27/01

General Notes:

(1) Cryo-refrigerator specs:
Cryomech model GB37 w/CP25 compressor (Cryo-Refrigerator S/N GB37-500047)
Refrigerator capacity of 25 W @ 20 K.

(2) Reference GRC drawing 58444M70A000 for cryo-refrigerator assembly and integration into the existing MHTB TVS plumbing.

(3) This procedure will be performed after installation of the HX spool piece (tee) drawing reference number A009.

(4) Exercise caution with delicate instrumentation wiring at all times during installation and especially when handling the HX which is heavily instrumented.

(5) During installation of fasteners, cross-torque patterns will be repeated until no movement is observed.

(6) MHTB instrumentation PTC27 and PTC28 to be replaced prior to installing cryo-refrigerator housing.

(7) Cleanliness:

– Clean all surfaces prior to installation with 190 proof alcohol or other engineering approved solvent only. Use lint-free cloth to wipe surfaces.

– Use lint-free gloves at all times when handling hardware.

Installation Procedure:

(1) Insulate MHTB tank bottom (within TVS enclosure) and TVS plumbing as directed by engineering.

(2) Install diode probes (GD1 and GD2) into spool piece A009 and tighten as follows: Verify that the probe end is at the centerline of the flow stream. Initially hand tighten Swagelok nuts. Scribe the nuts at the 6:00 position. Tighten the nuts 1¼ turn while holding the fitting body steady. The scribe mark on the nut will be in the 9:00 position when tight. (Verify the upstream and downstream diode are labeled and traceable back to the individual calibration curves for each diode.)

(3) Instrumentation engineer verify that the HX instrumentation is installed and checkout is complete.

(4) Use lint-free gloves to clean all residue from the HX using alcohol as required. Take extra precaution not to damage delicate wiring on HX.

(5) Using Loctite primer and threadlock on the Conflat bolts, install HX (A010) onto spool piece (A009). Verify that the HX fins are installed such that the LH_2 will flow through the fins and the threaded plugs are on the downstream end of the fins. Torque bolts to 144 in-lb using cross-torque pattern. (Note: Temporarily secure instrumentation wiring as required to prevent damage during mechanical installation.)

Note: An ambient leak check will be performed on the MHTB at this time to verify the integrity of all sealing surfaces including the TVS connections. Cryo-refrigerator installation will continue after this initial leak check is completed. Proceed to next step only after ambient leak check is completed.

(6) Verify PTC28 and PTC27 have been replaced (upstream and downstream of the MHTB LH_2 pump, respectively).

(7) Install TVS component box A001 onto the MHTB using 0.0625-in-diameter indium wire. Verify orientation of A001 in accordance with drawing 58444M70A000. Torque housing bolts to 144 in-lb using cross-torque pattern.

(8) Route instrumentation from HX through 8-in flange on TVS housing A001. (Note: Instrumentation wiring will be connected to flange feedthrough connectors at a later date.)

(9) Verify thermocouples HTC25 and HTC26 are installed onto cryo-refrigerator motor per drawing 58444170S000.

(10) Using lint-free gloves, clean all cryo-refrigerator surfaces with alcohol, paying special attention to the first- and second-stage surfaces.

Caution: Take precautions to prevent moving the cryo-refrigerator once bolted to the HX in the following step. Movement could overstress the bolted joint.

(10A) Verify spring retainer collar (A005) is properly bolted to the cryo-refrigerator. Verify that bolts are tight. (Note: Cryo-refrigerator arrived from GRC with spring retainer collar attached.)

(11) Install cryo-refrigerator (A006) onto HX (A010) using indium foil between the two mating surfaces. Support the cryo-refrigerator weight during and after installation to reduce stress on

bolted joint. Torque 0.635-cm (0.250-in) bolts to 140 in-lb and 0.164-in bolts to 5 in-lb using cross-torque pattern. (Note: Verify clocking of the cryo-refrigerator onto the HX before bolting to confirm that He supply and return lines are oriented correctly relative to the He line interface flange A008.)

(11A) Install temporary cryo-refrigerator support as directed by engineering to prevent lateral movement of cryo-refrigerator.

(12) Using lint-free gloves, insulate cryo-refrigerator as directed by engineering. (Reference insulation sketch provided by D. Plachta dated 02/12/01.)

(13) Install the three instrumented Cu HX straps per drawing 58444M70A000 using indium foil between the mating surfaces. Insulate over the Cu straps as directed by engineering. (Note: Indium foil is the preference but conductive grease supplied by GRC may be substituted if an adequate quantity of indium foil is not available.)

(14) Install two heater strips onto the cryo-refrigerator motor as indicated by drawing 58444170S000. (Note: Verify the location of the seals within the cryo-refrigerator motor with the Cryomech manual to ensure that the heater strips are properly located.) Route thermocouple wiring, heater wiring, and the motor power cable to 8-in outlet flange through the gap in the spring retainer collar (A005) bearing in mind that the spring (A007) will be installed directly over the wiring. Place a tight layer of aluminized mylar directly over the heater strips and secure with mylar tape. Further insulate cryo-refrigerator motor as directed by engineering.

(15) Verify that MHTB LH_2 pump and flowmeter wiring is routed to 20.36-cm (8-in) flange as required. (Note: Wiring to be connected to flange feedthrough connector at a later date.)

(16) Instrumentation perform final verification that all wiring is routed to outlet flange as required. Instrumentation wiring will be difficult to access once cryo-refrigerator cover A002 is installed.

(17) Remove temporary supports from the cryo-refrigerator and install the cryo-refrigerator cover (A002) onto the component box (A001), ensuring that the dowel pin aligns between the two mating surfaces. Use 0.159-cm (0.0625-in-) diameter indium wire gasket material. Torque cryo-refrigerator cover bolts to 500 in-lb using a cross-torque pattern. Provide additional temporary support of the cryo-refrigerator after the cover (A002) is installed and prior to connecting the He lines in the following step.

(18A) (Note: Helium supply and return line tubing which connects to refrigerator is pre-charged with 1,378 kPa (200 psi) He.) Check alignment of He supply and return lines (A14) from the refrigerator to the He interface flange (A008) by initially engaging only enough threads to hold lines in place on refrigerator. Place He line interface flange into position on housing cover (A002) to verify alignment of tubing connections. Reference drawing 58444M70A000 to verify proper installation.

(18B) After initial alignment is completed, install the He supply and return lines (A14) onto the cryo-refrigerator. Verify proper installation and alignment prior to tightening connections. Take precaution not to apply torque to cryo-refrigerator housing while tightening connections.

(19) (Note: The 1.9-cm (0.75-in) tubing with Aeroquip fittings is precharged with 1,378 kPa (200 psi) He. Proper alignment of the Aeroquip fittings before tightening is critical. Set the housing flange (A008) containing ¾-in tubing near the mating flange on the housing and adjust length of ¾-in tubing as required to interface with the ¾-in Aeroquip fittings inside the housing. Tighten Aeroquip fittings first to ensure proper alignment and then install bolts for flange A008. Torque Aeroquip connection to 46 ft-lb and torque A008 flange bolts to 312 in-lb using cross-torque pattern. Caution: If tubing connections within the housing do not align, do not bend tubing while attached to cryo-refrigerator as overstress of upper bolted joint may occur.

(20) Verify that all insulation is installed per engineering direction. Clean all accessible surfaces with alcohol and lint-free cloth.

(21) Temporarily install TVS housing flange (A003) and spring (A007) to the TVS housing as shown in drawing 58444M70A000. (Note: Do not use indium wire at this time as cover will be removed after LH_2 coldshock.)

Note: An LN_2 and LH_2 coldshock of the MHTB will be performed to verify the integrity of the connections when thermally cycled. The cryo-refrigerator will not be operated during this coldshock. Proceed to next step only after LH_2 coldshock is successfully completed.

(22) After coldshock and leak check are completed, carefully remove housing cover (A003) and spring (A007). Install temporary transportation support per engineering direction.

(23) Verify MHTB and cryo-refrigerator hardware are properly secured for removal from the test cell and transportation to TS300.

Note: The following steps to be performed after MHTB has been relocated to TS300:

(24) Remove temporary shipping support from the cryo-refrigerator. Install the housing cover (A003) and spring (A007) using 0.159-cm (0.0625-in) indium wire gasket. Torque flange bolts to 500 in-lb using cross-torque pattern.

(25) When feedthrough connectors for instrumentation and controls are installed in TVS housing flanges, make final connections at the connectors. Perform checkouts as required to ensure that connections to feedthrough pins match instrumentation/controls drawings.

(26) Verify Conax flange feedthrough connector on flange A008 is tight. Perform seal weld of Conax fittings as directed by engineering.

APPENDIX C—LIQUID HYDROGEN HEATER ELEMENT TESTING FOR MULTIPURPOSE HYDROGEN TEST BED ZERO-BOILOFF DEMONSTRATION

C.1 Background

These graphite heater elements were installed in the MHTB LH_2 tank to assist in maintaining the total heat load at a constant value. The test objectives were to (1) demonstrate that the heater elements would survive and operate effectively in LH_2 and (2) calibrate the electrical resistance of the three heater assembly elements before and during LH_2 exposure.

C.2 Test Setup

This test was performed in the LH_2 cryostat located in test cell 15 of Building 4628. The three heater elements were installed in fixturing to hold them in place inside the cryostat (fig. 19). Six strands of 14-gauge, solid Cu wire with Kapton insulation were passed through a sealed port in the lid of the cryostat. The solid Cu wire was attached to the connecting wires on the furnace elements using screw-type connectors. Stranded 14-gauge Cu wire was attached to the solid Cu wires passing through the lid of the cryostat. These stranded wires were run to the control room adjacent to the test cell where the furnace power supply was located. The power supply used was a Lambda model LLS9040 capable of outputting zero to 40 V dc at 20 A.

The amount of LH_2 in the cryostat was measured using two thermocouples placed above the height of the heater elements. The thermocouples detected when the LH_2 covered the heater elements. This was accomplished by monitoring the readout from the TCs and watching for stabilization on the readout that represented LH_2 temperatures. When the TC readout stabilized at LH_2 temperatures, this indicated that the LH_2 was covering the heater elements.

C.3 Test Procedures

The heater elements were installed in a fixture to hold them in place while in the cryostat and solid Cu feedthrough wires were attached to the heating elements (fig. 19). The baseline resistance of each element with the solid Cu wires attached was measured prior to installing in the cryostat. The fixture with the heating elements was installed in the cryostat and stranded Cu wires were attached to the solid Cu feedthrough wires. The resistance of each furnace/wire assembly was measured to determine the total initial resistance of the assemblies at room temperature. When the electrical connections were verified and the resistance measurements made, the lid was installed on the cryostat. The resistance measurements are provided in table 7.

LH_2 was added to the cryostat until the fill level thermocouples indicated the heater elements were covered. The pressure supplied by the LH_2 Dewars was reduced and a constant flow of $LH_2$was

Table 7. Resistance measurements for each element.

	Resistance (Ω) of Heater Elements		
	1	2	3
Baseline	6.039	0.815	0.780
With lead wire	0.766	0.945	0.929
In LH_2 before power	1.190	1.214	1.534
In LH_2 after power	1.190	1.216	1.535
In LH_2 after 90-min soak	–	1.219	1.541
In LH_2 after 105-min soak	–	1.214	1.536
At 133 °F after test	0.743	0.909	0.889

maintained to keep the cryostat full. This test was performed with ≈27.6 kPa (≈4) psig back-pressure applied to the cryostat because of a check valve and the water pressure in the boiloff tank on the vent line.

When the cryostat was full, resistance measurements were taken for each heater element. The power leads for one heater element were connected to the power controller. Power was slowly added to the heater element to a maximum of 50 W. Voltage and current readings were taken periodically as the power level was being increased (see table 8). While power was being added to the heating element, pressure in the cryostat was monitored carefully to ensure that the vent system could handle the volume of hydrogen boiled off and pressure did not exceed 103 kPa (15 psig). This turned out not to be an issue because pressure inside the cryostat never increased during the application of power. The maximum power level was held on the heater element for 60 s and then the power was shut off. The remaining heater elements were connected to the power controller one at a time and the test procedure repeated.

Table 8. Data for element 1 at different voltage settings.

Applied Volts	Current (A)	Power (W)
1	0.8	0.8
2	1.7	3.4
3	2.6	7.8
4	3.5	14.0
5	4.4	22.0
6	5.3	31.8
7	6.2	43.4
7.5	6.6	49.5

Heating elements 2 and 3 were evaluated after soaking 90 and 105 min in LH_2 by applying 3 and 7 V to each element and measuring the associated current and comparing it to the initial readings. These data are provided in table 9. Resistance measurements were also taken at the same time and compared to the initial measurements. These readings are provided in table 7.

Table 9. Current measurements for each element.

	Applied Volts	Element 1 (A)	Element 2 (A)	Element 3 (A)
Initial run	3	2.6	2.5	2.0
Initial run	7	6.2	6.0	4.7
After 90-min soak	3	–	2.5	2.0
After 90-min soak	7	–	6.0	4.7
105-min soak	3	–	2.5	2.0
105-min soak	7	–	6.0	4.7

After the LH_2 test was completed, the LH_2 was boiled off and the cryostat purged with He gas. When the temperature of the cryostat and heating elements had stabilized at room temperature, heated He gas was flowed through the cryostat to bring the temperature of the heating elements up to 133 °F and the resistance of each element was measured again. These resistance readings are provided in table 7.

C.4 Conclusions

The following conclusions can be reached:

- The resistance of the heater elements increased with decreased temperature.

- The LH_2 environment did not adversely affect the operation of the heater elements.

- The heater elements were not degraded by the short-term LH_2 exposure as indicated by consistent current measurements from the three readings taken at different time intervals.

APPENDIX D—CONTROL SYSTEM FOR MULTIPURPOSE HYDROGEN TEST BED ZERO-BOILOFF DEMONSTRATION

The control system used to maintain the tank heat leak at a value that matched the tank heat extraction capability of the cryocooler is presented.

D.1 Zero-Boiloff Model

The ZBO cooler dynamics schematic is shown in figure 28, the recirculation line model schematic in figure 28a, and the ullage model schematic in figure 28b.

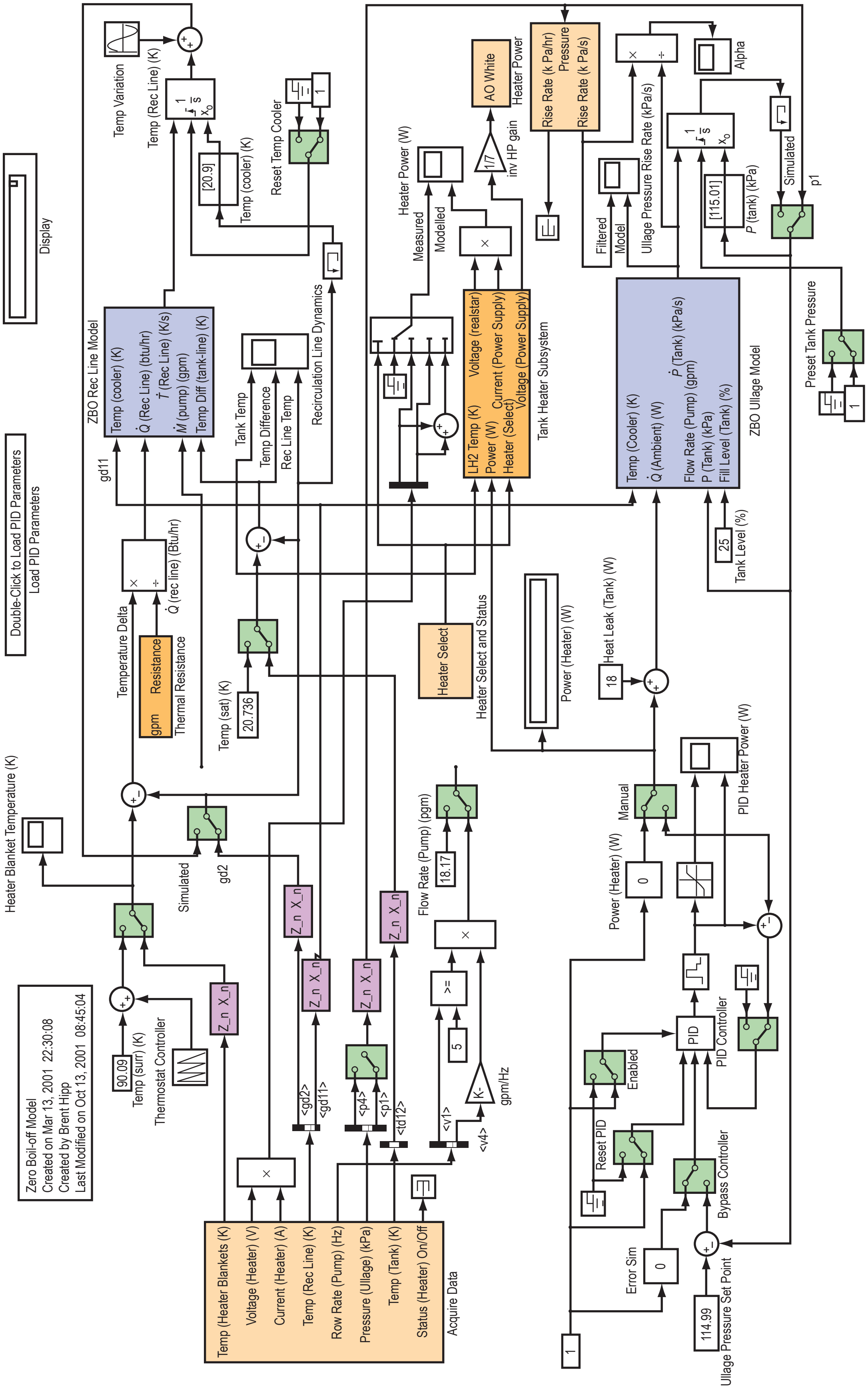


Figure 28. Schematic of control system ZBO model.

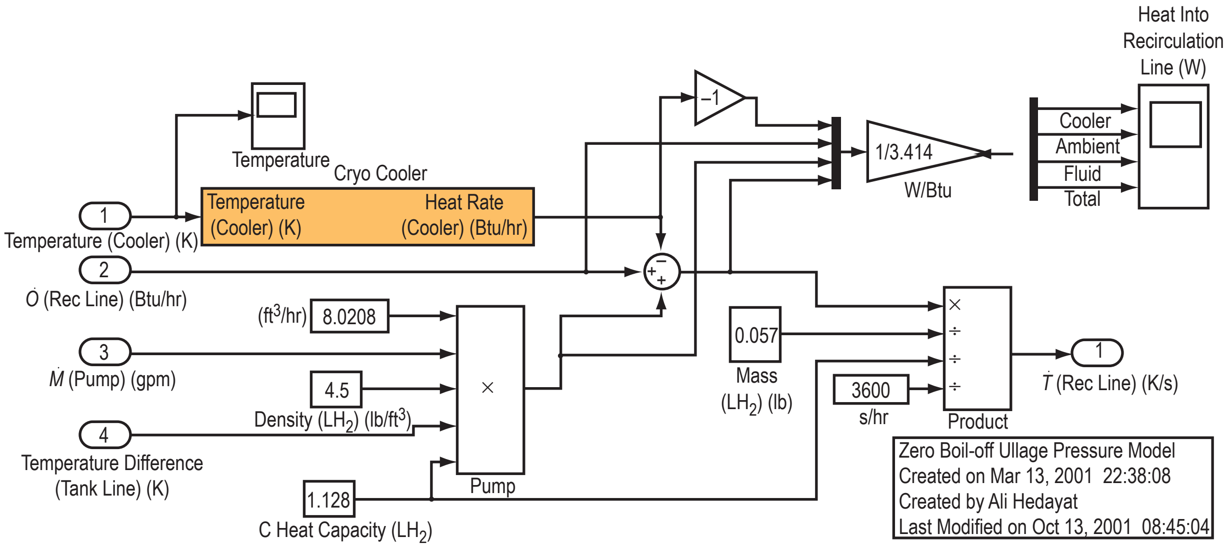


Figure 28a. Schematic of ZBO recirculation line model.

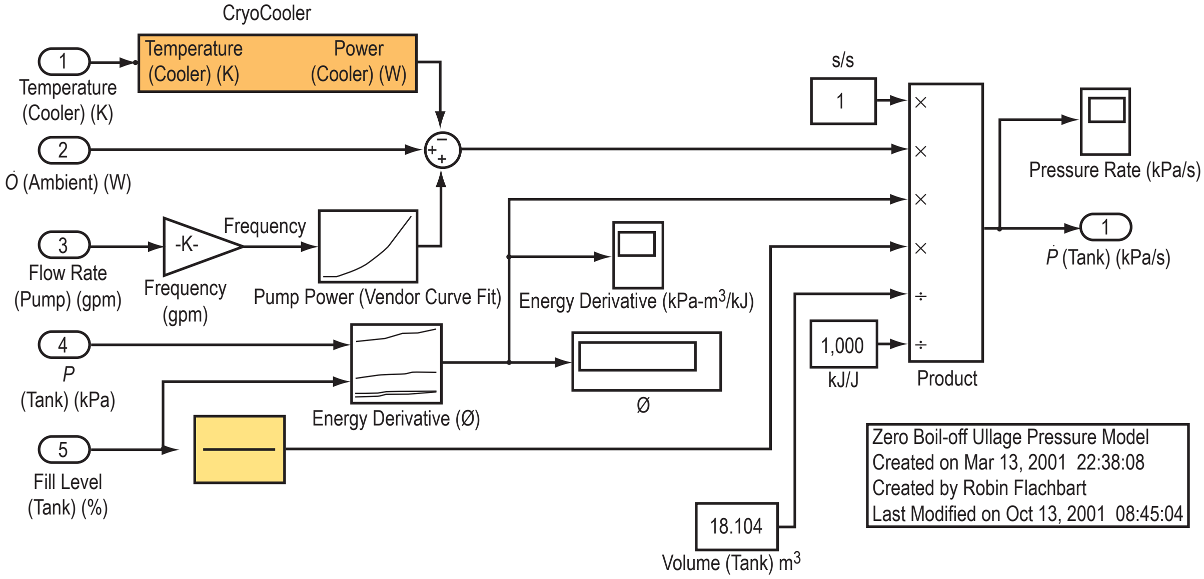


Figure 28b. Schematic of ZBO ullage model.

D.2 Multipurpose Hydrogen Test Bed Thermal Purformance

Table 10 is used to perform real time MHTB heat leak computations, which was input to the control system. The example data included were obtained during a representative boiloff test with a 305 K boundary condition imposed on the MLI external surface under high vacuum conditions.

Table 10. MHTB thermal performance spreadsheet.

MHTB Penetration Heat Leak Worksheet

Test #	**P263952H.300**
Phase	**Orbit Hold: Hot Boundary set to 305K**

DSU Time 0.0 sec to 35000 sec

Variable Input List

Fill/Drain Line

TFD2	33.9	K
HG6	41.51	K
TFD3	46.78	K
TFD4	50.13	K
HG6	41.51	K

Vent Line

TVL2	33.15	K
HG7	35.99	K
TVL6	60.66	K
TVL7	68.81	K
HG7	35.99	K

Interstitial Pressure Probe

IPP1	231.09	K
IPP2	267.1	K

Tank Leg #3

TSL3	85.62	K
TSL4	143.11	K
TSL15	201.4	K

Pressurization Line

TPL1	75.17	K
TPL2	99.42	K
TPL3	75.98	K
TPL4	127.58	K
HG5	138.08	K

Ullage Pressure Line K

TUP1	55.7	K
TUP2	71.25	K

Tank Manhole Pumpout K

TCP1	82.39	K
TCP2	84.17	K

Tank Leg #1

TSL1	81.96	K
TSL2	136.7	K
TSL19	59.67	K
TSL18	102.14	K
HG1	167.75	K
TSL14	180.18	K

Flow Meter Press/Temp

P3113	0.28	KPa G
T3227	306.51	K

Tank Ullage Vent Temp

TVL4	23.11	K
TVL5	23.25	K

Ref Volume Press

P3	113.7700777	KPa

Tank Ref Delta Press

DP1	66.36	Pa

Flow Meters		**Used (0 or 1)**
F1 (alpm)	0	0
F2 (alpm)	0	0
F3 (slpm)	16.12	0
F4 (slpm)	19.31	1
F5 (sccm)	0	0

Heat Leak Summary

Penetrations				
Fill/Drain	0.067885622	W	0.231635248	BTU/Hr
Vent	0.054455715	W	0.185810523	BTU/Hr
Int. Press	0.064030617	W	0.218481428	BTU/Hr
Legs (all 4)	1.449055468	W	4.944380126	BTU/Hr
Pressurization	0.706067782	W	2.409202123	BTU/Hr
Ullage	0.042407458	W	0.144700183	BTU/Hr
Manhole	0.001469353	W	0.005013639	BTU/Hr

Total Penetration Heat Leak

2.385372016	W
8.139223269	BTU/Hr

Total Tank Heat Leak Based on Boiloff (Including Penetrations)

13.0954942	W	44.68365956	BTU/Hr	0.097063453	kg/Hr
0.376907324	W/m2	0.119475026	BTU/Hr-ft2	0.21398803	#/hr

Total Tank Heat Leak Based on Boiloff (Penetrations Subtracted)

10.71012218	W	36.54443629	BTU/Hr
0.308242902	W/m2	0.097712397	BTU/Hr-ft2

Table 10. MHTB thermal performance spreadsheet (Continued).

MHTB Fill/Drain Penetration Heat Leak Worksheet

Test #	**P263952H.300**	Note: TFD1 failed (high reading). Replaced with HG6.
Phase	**Orbit Hold: Hot Boundary set to 305K**	

Silicion Diodes on Stainless Steel

ID	**Location From Tank Boundary (cm)**	**Temperature (K)**	**Tube Diameter (cm)**	**Tube Thickness (mm)**
TFD2	6.98	33.9	2.54	1.65
HG6	13.97	41.51		

Thermocouples on SOFI Surface

ID	**Location From Tank Boundary (cm)**	**Temperature (K)**	**SOFI Avg Circum (cm)**	**SOFI Avg Thick (cm)**
TFD3	6.98	46.78	49.53	6.6
TFD4	13.97	50.13		
HG6	13.97	41.51		

Heat Leak Due to Stainless Steel

Delta Temp	7.61	(K)		
Average Temp	37.705	(K)		
Average K	4.006483354	(W/m-K)		
Length	0.0699	(m)		
Cross-sectional Area	0.000123111	(m2)		
Heat Leak (Power)	**0.053699209**	**(W)**	**0.183229219**	**(BTU/hr)**

Heat Leak Due to PDL Foam

Avg Temp High	45.82	(K)		
Avg Temp Low	40.34	(K)		
Avg Delta Temp	5.48	(K)		
Avg High/Low Temp	43.08	(K)		
Average K	0.009521395	(W/m-K)		
Length	0.0699	(m)		
Cross-sectional Area	0.019005034	(m2)		
Heat Leak (Power)	**0.014186414**	**(W)**	**0.048406029**	**(BTU/hr)**

Total Heat Leak (Power)	**0.067885622**	**(W)**
	0.231635248	**(BTU/hr)**

Table 10. MHTB thermal performance spreadsheet (Continued).

MHTB Ullage Line Penetration Heat Leak Worksheet

Test #	**P263952H.300**
Phase	**Orbit Hold: Hot Boundary set to 305K**

Silicion Diodes on Stainless Steel

ID	Location From Tank Boundary (cm)	Temperature (K)	Tube Diameter (cm)	Tube Thickness (mm)
TUP1	11.43	55.7	1.27	1.25
TUP2	21.59	71.25		

Thermocouples on SOFI Surface

ID	Location From Tank Boundary (cm)	Temperature (K)	SOFI Avg Circum (cm)	SOFI Avg Thick (cm)
---	6.98	0	0	0
---	13.97	0		
---	13.97	0		

Heat Leak Due to Stainless Steel

Delta Temp	15.55	(K)		
Average Temp	63.475	(K)		
Average K	6.162267499	(W/m-K)		
Length	0.1016	(m)		
Cross-sectional Area	4.4964E-05	(m2)		
Heat Leak (Power)	**0.042407458**	**(W)**	**0.144700183**	**(BTU/hr)**

Heat Leak Due to PDL Foam

Avg Temp High	0	(K)		
Avg Temp Low	35.625	(K)		
Avg Delta Temp	-35.625	(K)		
Avg High/Low Temp	17.8125	(K)		
Average K	0.007591261	(W/m-K)		
Length	0.0699	(m)		
Cross-sectional Area	0	(m2)		
Heat Leak (Power)	**0**	**(W)**	**0**	**(BTU/hr)**

Total Heat Leak (Power)	**0.042407458**	**(W)**
	0.144700183	**(BTU/hr)**

Table 10. MHTB thermal performance spreadsheet (Continued).

MHTB Leg #1 Penetration Heat Leak Worksheet

Test #	**P263952H.300**
Phase	**Orbit Hold: Hot Boundary set to 305K**

Silicion Diodes on Fibre - Glass Epoxy

ID	**Location From Tank Boundary (cm)**	**Temperature (K)**	**Tube Diameter (cm)**	**Tube Thickness (mm)**
TSL1	2.54	81.96	7.9375	1.58
TSL2	7.62	136.7		

Thermocouples on SOFI Surface

ID	**Location From Tank Boundary (cm)**	**Temperature (K)**	**SOFI Avg Circum (cm)**	**SOFI Avg Thick (cm)**
TSL19	-5.08	59.67	48.26	3.81
TSL18	2.54	102.14		
HG1	13.97	167.75		

Thermocouple on SOFI Internal to Leg

ID	**SOFI Plug Len. (cm)**	**Temp (K)**	**SOFI Plug Dia. (cm)**
TSL14	10.16	180.18	7.62

Heat Leak Due to Fibre - Glass Epoxy

Delta Temp	54.74	(K)		
Average Temp	109.33	(K)		
Average K	0.359138188	(W/m-K)		
Length	0.0508	(m)		
Cross-sectional Area	0.000386152	(m2)		
Heat Leak (Power)	**0.149437965**	**(W)**	**0.50990326**	**(BTU/hr)**

Heat Leak Due to Exterior SOFI			**Interior SOFI**	
Avg Temp High	92.05	(K)	180.18	(K)
Avg Temp Low	43.835	(K)	28	(K)
Avg Delta Temp	48.215	(K)	152.18	(K)
Avg High/Low Temp	67.9425	(K)	104.09	(K)
Average K	0.011420592	(W/m-K)	0.014181827	(W/m-K)
Length	0.0762	(m)	0.1016	(m)
Cross-sectional Area	0.013826697	(m2)	0.004560363	(m2)
Heat Leak External	**0.099915815**	**(W)**	**0.34092675**	**(BTU/hr)**
Heat Leak Internal	**0.096871385**	**(W)**	**0.330538728**	**(BTU/hr)**

Total Heat Leak (Power)	**0.346225166**	**(W)**
	1.181368737	**(BTU/hr)**

Table 10. MHTB thermal performance spreadsheet (Continued).

MHTB Pressurization Line Penetration Heat Leak Worksheet
Test # **P263952H.300**
Phase **Orbit Hold: Hot Boundary set to 305K**

Silicion Diodes on Stainless Steel

ID	Location From Tank Boundary (cm)	Temperature (K)	Tube Diameter (cm)	Tube Thickness (mm)
TPL1	3.81	75.17	2.54	1.65
TPL2	7.62	99.42		

Thermocouples on SOFI Surface

ID	Location From Tank Boundary (cm)	Temperature (K)	SOFI Avg Circum (cm)	SOFI Avg Thick (cm)
TPL3	7.62	75.98	38.1	3.56
TPL4	15.24	127.58		
HG5	15.24	138.08		

Heat Leak Due to Stainless Steel

Delta Temp	24.25	(K)		
Average Temp	87.295	(K)		
Average K	7.949508229	(W/m-K)		
Length	0.0381	(m)		
Cross-sectional Area	0.000123111	(m2)		
Heat Leak (Power)	**0.622908267**	**(W)**	**2.125450213**	**(BTU/hr)**

Heat Leak Due to PDL Foam

Avg Temp High	132.83	(K)		
Avg Temp Low	87.7	(K)		
Avg Delta Temp	45.13	(K)		
Avg High/Low Temp	110.265	(K)		
Average K	0.014653523	(W/m-K)		
Length	0.0762	(m)		
Cross-sectional Area	0.009582074	(m2)		
Heat Leak (Power)	**0.083159515**	**(W)**	**0.283751909**	**(BTU/hr)**

Total Heat Leak (Power)	**0.706067782**	**(W)**
	2.409202123	**(BTU/hr)**

Table 10. MHTB thermal performance spreadsheet (Continued).

MHTB Manhole Pump-Out Line Penetration Heat Leak Worksheet

Test #	**P263952H.300**
Phase	**Orbit Hold: Hot Boundary set to 305K**

Silicion Diodes on Stainless Steel

ID	Location From Tank Boundary (cm)	Temperature (K)	Tube Diameter (cm)	Tube Thickness (mm)
TCP1	106.68	82.39	2.083	0.254
TCP2	121.92	84.17		

Thermocouples on SOFI Surface

ID	Location From Tank Boundary (cm)	Temperature (K)	SOFI Avg Circum (cm)	SOFI Avg Thick (cm)
---	6.98	0	0	0
---	13.97	0		
---	13.97	0		

Heat Leak Due to Stainless Steel

Delta Temp	1.78	(K)		
Average Temp	83.28	(K)		
Average K	7.662086394	(W/m-K)		
Length	0.1524	(m)		
Cross-sectional Area	1.64189E-05	(m2)		
Heat Leak (Power)	**0.001469353**	**(W)**	**0.005013639**	**(BTU/hr)**

Heat Leak Due to PDL Foam

Avg Temp High	0	(K)		
Avg Temp Low	42.085	(K)		
Avg Delta Temp	-42.085	(K)		
Avg High/Low Temp	21.0425	(K)		
Average K	0.007837994	(W/m-K)		
Length	0.0699	(m)		
Cross-sectional Area	0	(m2)		
Heat Leak (Power)	**0**	**(W)**	**0**	**(BTU/hr)**

Total Heat Leak (Power)	**0.001469353**	**(W)**
	0.005013639	**(BTU/hr)**

Table 10. MHTB thermal performance spreadsheet (Continued).

MHTB Leg #3 Penetration Heat Leak Worksheet

Test #	**P263952H.300**
Phase	**Orbit Hold: Hot Boundary set to 305K**

Silicion Diodes on Fibre - Glass Epoxy

ID	Location From Tank Boundary (cm)	Temperature (K)	Tube Diameter (cm)	Tube Thickness (mm)
TSL3	2.54	85.62	7.9375	1.58
TSL4	7.62	143.11		

Thermocouples on SOFI Surface

ID	Location From Tank Boundary (cm)	Temperature (K)	SOFI Avg Circum (cm)	SOFI Avg Thick (cm)
---	2.54	0	0	0
---	10.16	0		
---	13.97	0		

Thermocouple on SOFI Internal to Leg

ID	SOFI Plug Len. (cm)	Temp (K)	SOFI Plug Dia. (cm)
TSL15	10.16	201.4	7.62

Heat Leak Due to Fibre - Glass Epoxy

Delta Temp	57.49	(K)		
Average Temp	114.365	(K)		
Average K	0.370017233	(W/m-K)		
Length	0.0508	(m)		
Cross-sectional Area	0.000386152	(m2)		
Heat Leak (Power)	**0.161699555**	**(W)**	**0.551741521**	**(BTU/hr)**

Heat Leak Due to Exterior SOFI			**Interior SOFI**	
Avg Temp High	0	(K)	201.4	(K)
Avg Temp Low	71.555	(K)	28	(K)
Avg Delta Temp	-71.555	(K)	173.4	(K)
Avg High/Low Temp	35.7775	(K)	114.7	(K)
Average K	0.008963572	(W/m-K)	0.014992304	(W/m-K)
Length	0.0762	(m)	0.1016	(m)
Cross-sectional Area	0	(m2)	0.004560363	(m2)
Heat Leak External	**0**	**(W)**	**0**	**(BTU/hr)**
Heat Leak Internal	**0.116687198**	**(W)**	**0.398153055**	**(BTU/hr)**

Total Heat Leak (Power)	**0.278386753**	**(W)**
	0.949894576	**(BTU/hr)**

Table 10. MHTB thermal performance spreadsheet (Continued).

MHTB Vent Penetration Heat Leak Worksheet

Test #	**P263952H.300**	Note: Problems with TVL1swapped with HG7
Phase	**Orbit Hold: Hot Boundary set to 305K**	

Silicion Diodes on Stainless Steel

ID	**Location From Tank Boundary (cm)**	**Temperature (K)**	**Tube Diameter (cm)**	**Tube Thickness (mm)**
TVL2	7.62	33.15	5.08	1.65
HG7	15.24	35.99		

Thermocouples on SOFI Surface

ID	**Location From Tank Boundary (cm)**	**Temperature (K)**	**SOFI Avg Circum (cm)**	**SOFI Avg Thick (cm)**
TVL6	7.62	60.66	59.69	6.98
TVL7	15.24	68.81		
HG7	15.24	35.99		

Heat Leak Due to Stainless Steel

Delta Temp	2.84	(K)		
Average Temp	34.57	(K)		
Average K	3.728467236	(W/m-K)		
Length	0.0762	(m)		
Cross-sectional Area	0.000254775	(m2)		
Heat Leak (Power)	**0.035403865**	**(W)**	**0.120802943**	**(BTU/hr)**

Heat Leak Due to PDL Foam

Avg Temp High	52.4	(K)		
Avg Temp Low	46.905	(K)		
Avg Delta Temp	5.495	(K)		
Avg High/Low Temp	49.6525	(K)		
Average K	0.010023455	(W/m-K)		
Length	0.0762	(m)		
Cross-sectional Area	0.026357668	(m2)		
Heat Leak (Power)	**0.01905185**	**(W)**	**0.06500758**	**(BTU/hr)**

Total Heat Leak (Power)	**0.054455715**	**(W)**
	0.185810523	**(BTU/hr)**

Table 10. MHTB thermal performance spreadsheet (Continued).

MHTB Interstitial Pressure Probe Penetration Heat Leak Worksheet

Test #	**P263952H.300**
Phase	**Orbit Hold: Hot Boundary set to 305K**

Silicion Diodes on Stainless Steel

ID	**Location From Tank Boundary (cm)**	**Temperature (K)**	**Tube Diameter (cm)**	**Tube Thickness (mm)**
IPP1	3.81	231.09	5.08	0.0381
IPP2	8.89	267.1		

Thermocouples on SOFI Surface

ID	**Location From Tank Boundary (cm)**	**Temperature (K)**	**SOFI Avg Circum (cm)**	**SOFI Avg Thick (cm)**
---	6.98	0	0	0
---	13.97	0		
---	13.97	0		

Heat Leak Due to Stainless Steel

Delta Temp	36.01	(K)		
Average Temp	249.095	(K)		
Average K	14.86674607	(W/m-K)		
Length	0.0508	(m)		
Cross-sectional Area	6.07592E-06	(m2)		
Heat Leak (Power)	**0.064030617**	**(W)**	**0.218481428**	**(BTU/hr)**

Heat Leak Due to PDL Foam

Avg Temp High	0	(K)		
Avg Temp Low	133.55	(K)		
Avg Delta Temp	-133.55	(K)		
Avg High/Low Temp	66.775	(K)		
Average K	0.011331409	(W/m-K)		
Length	0.0699	(m)		
Cross-sectional Area	0	(m2)		
Heat Leak (Power)	**0**	**(W)**	**0**	**(BTU/hr)**

Total Heat Leak (Power)	**0.064030617**	**(W)**
	0.218481428	**(BTU/hr)**

Table 10. MHTB thermal performance spreadsheet (Continued).

MHTB Penetration Heat Leak Summary

Test #	**P263952H.300**
Phase	**Orbit Hold: Hot Boundary set to 305K**

Fill/Drain Line	0.067885622 W 0.231635248 BTU/Hr
Pressurization Line	0.706067782 W 2.409202123 BTU/Hr
Vent Line	0.054455715 W 0.185810523 BTU/Hr
MLI Interstitial Pressure Probe	0.064030617 W 0.218481428 BTU/Hr
Tank Manhole Pump-Out Line	0.001469353 W 0.005013639 BTU/Hr
Ullage Pressure Line	0.042407458 W 0.144700183 BTU/Hr
Support Leg #1	0.346225166 W 1.181368737 BTU/Hr
Support Leg #3 **(Only Fibre-Glass Epoxy Component)**	0.278386753 W 0.949894576 BTU/Hr
Average Leg Heat Leak For All 4 Legs	1.449055468 W 4.944380126 BTU/Hr
Total MHTB Tank Heat Leak	2.385372016 W 8.139223269 BTU/Hr

Table 10. MHTB thermal performance spreadsheet (Continued).

MHTB Boiloff Heat Leak Evaluation Worksheet

Test # **P263952H.300**

Phase **Orbit Hold: Hot Boundary set to 305K**

Flow Meter Data

Meter ID	**Used (0 or 1)**	**Flow Rate**	**Units**	**Flow Rate (kg/hr)**	**English Units**	
F1	0	0	ALPM	0	0	#/hr
F2	0	0	ALPM	0	0	#/hr
F3	0	16.12	SLPM	0	0	#/hr
F4	1	19.31	SLPM	0.097063453	0.21398803	#/hr
F5	0	0	SCCM	0	0	#/hr
		Total Flow Rate(kg/hr)		0.097063453	0.21398803	#/hr

Flow Meter Press	P3113	0.28	KPa Gauge	0.04061064	psid
Flow Meter Temp	T3227	306.51	K	551.718	R
Tank Ullage Vent Temp	TVL4	23.11	K	41.598	R
Tank Ullage Vent Temp	TVL5	23.25	K	41.85	R
Average Tank Ullage Vent Temp		23.18	K	41.72	R
Flow Meter Line Pressure		101605	Pa Absolute	14.74	psia
GH2 Density at Flow Meters based on P and T		0.080361212	kg/m3		
GH2 ideal gas constant		4125	(N-m)/(kg-K)	766.67	lb-ft/#-R
GH2 standard density		0.0837765	kg/m3	0.00523	#/ft3
Reference Volume Pressure	P3	113.7700777	KPa Absolute	0.01650	psia
Delta P tank to reference vol	DP1	66.36	Pa	0.00962	psi
Tank Ullage pressure (calculated)		113836.4377	Pa Absolute	16.51	psia

LH2/GH2 Calculated Properties (from curve fits)				
Density of Saturated Vapor	1.48250406	kg/m3	0.09	#/ft3
Density of Saturated Liquid	70.34763604	kg/m3	4.39	#/ft3
Enthaply of Saturated Vapor	191806.3494	J/kg	82.46	BTU/#
Enthaply of Vent Gas (use temps TVL4&5)	224045	J/kg	96.32	BTU/#
Latent Heat of Vaporization	443905.7234	J/kg	190.85	BTU/#

Heat Leak Component Calculations

mdot*hfg*(densatliq/ (densatliq-densatvap))		**mdot*(hvent-hsatvap)**		**Total Tank Heat Leak**	
44014.58436	J/hr	3129.194744	J/hr	47143.7791	J/hr
12.22627343	W (J/sec)	0.869220762	W (J/sec)	13.0954942	W (J/sec)
				0.376907324	W/m2
41.71775663	BTU/hr	2.965902932	BTU/hr	44.68365956	BTU/hr
				0.119475026	BTU/hr-ft2

APPENDIX E—INSTRUMENTATION LIST FOR THE MULTIPURPOSE HYDROGEN TEST BED TANKING ZERO-BOILOFF DEMONSTRATION

Table 11 shows the facility instrumentation list and table 12 shows the test article measurements for the MHTB ZBO testing. The MHTB test article list is further subdivided into the standard MHTB test instrumentation and specifically added for the ZBO demonstration.

Table 11. MHTB ZBO instrumentation list.

20-FT CHAMBER FACILITY MEASUREMENTS									
MID	LINK	SIU CH	J-BOX	Measurement Description	Xducer	Serial No.	Range	UNITS	CAL DUE
CFA2	1	6		Chamber temp 3 m above floor	Type E		15 / 310	KELVIN	NONE
CFA3	1	7		Chamber temp 4.6 m above floor	Type E		15 / 310	KELVIN	NONE
DEW1	1	8		MLI gas system dew point	Endress Hauser		-80 / 20	CELCIUS	NONE
DEW2	1	9		Heater shroud dew point	Endress Hauser		-80 / 20	CELCIUS	NONE
	1	10							
	1	11							
F1	1	12		LH2 Vent flow rov 20-671	Flow Tech	2402000	593 / 5410	ALPM	2/3/03
F2	1	13		LH2 Vent flow rov 20-672	Flow Tech.	1606628	519 / 1688	ALPM	2/3/03
F3	1	14		LH2 Vent flow rov 20-673	Hastings-Ray.	10879	14 / 550	SLPM	2/13/03
F4	1	15		LH2 Vent flow rov 20-674	MKS 179A	226281	0 / 61.9	SLPM	3/5/03
F5	1	16		LH2 Vent flow rov 20-675	MKS 179A	396971	0 / 1000	SCCM	3/3/03
F8	1	17		Manway pump out flow	MKS 179A		1.08 / 8.573	SLPM	3/13/03
P3105	1	18		LN2 PUMP LINE PRESSURE	TABER 226	860548	0 / 2068.43	KPAG	5/19/02
IP1	1	19		MLI interstitial pressure	HPS 953	107261	10-3 to 1000	TORR	3/5/03
IP2	1	CALC		MLI interstitial pressure - semi-log scale	HPS 953	107261	-2 to -8 log	TORR	3/5/03
IP4	1	20		MLI interstitial pressure	MKS 390	M62375	0 / 1000	TORR	5/11/03
IPC2	1	21		MLI interstitial pressure - millivolt reading	HPS 953	107261	0 / 6000	MV	3/5/03
IPD2	1	CALC		MLI interstitial pressure - linear scale	HPS 953	107261	0 / 10,000	UTORR	3/5/03
F16	1	22		CRYOMECH CP25 COMP. COOLING H2O	COX 8-6	50001	2.3 / 17.29	LPM	8/23/02
F17	1	23		TVS ENCLOSURE PUMP-OUT LINE FLOW	MKS 179A	92108	0 / 5000	SCCM	
D1	1	24		MILLIVOLTS DPP1	CSPV0002030001	93861-G	(-48) / (24)	MV	NONE
PP1	1	25		MILLIVOLTS PPA1	CSPV0002030001	93861-D	(0) / (300)	MV	NONE
PS1	1	26		MILLIVOLTS PSB1	CSPV0002030001	93861-E	(-3) / (267)	MV	NONE
DPP1	1	CALC		TVS PUMP DELTA PRESSURE				KPAD	NONE
PPA1	1	CALC		TVS PUMP INLET PRESSURE				KPA	NONE
PSB1	1	CALC		TVS FLOWMETER PRESSURE				KPA	NONE
PSA1	1	CALC		MHTB TANK LIQ. VAPOR PRESS. SAT				KPA	NONE
	1	27							
	1	28							
	1	29							
	1	30							
P3097	1	31		2nd stage firex	STATHAM PG347	15	0 / 6894.76	KPAG	5/17/02
P3104	1	32		LN2 Tank pressure	TABER 254	931251	0 / 689.47	KPAG	5/17/02
BAD CH	1	33							
P3107	1	34		GN2 Supply pressure	MB ELECTRONICS 151	41029	0 / 689.476	KPAG	5/17/02

Table 11. MHTB ZBO instrumentation list (Continued).

20-FT CHAMBER FACILITY MEASUREMENTS									
MID	LINK	SIU CH	J-BOX	Measurement Description	Xducer	Serial No.	Range	UNITS	CAL DUE
P3108	1	35		Air manifold	TABER 2105	888102	0 / 34,473.8	KPAG	5/18/02
P3109	1	36		Repress stage two	DYNISCO PT119	27686	0 / 10,342	KPAG	5/19/02
P3110	1	37		Repress stage one	TABER 226	930869	0 / 6894.76	KPAG	5/19/02
P3111	1	38		LH2 F/D trailer fill	TABER 254	880705	0 / 689.476	KPAG	5/17/02
P3112	1	39		LH2 Vent sytem	TABER 254	781316	0 / 689.476	KPAG	5/17/02
P3113	1	40		LH2 Vent sytem @ pressure control valves	TABER 254	931250	0 / 689.476	KPAG	5/17/02
P3114	1	41		LN2 Supply system rov 20-1700	TABER 254	891412	0 / 689.476	KPAG	5/17/02
P3115	1	42		GH2 Upstream DLR - 803	TABER2105	932076	0 / 41,368.6	KPAG	5/18/02
P3116	1	43		GH2 Downstream DLR - 803	STELLAR TECH GT200	941210	0 / 6,894.8	KPAG	5/17/02
P3117	1	44		GH2 Feed line	TABER 226	950379	0 / 3,447.4	KPAG	5/19/02
P3120	1	45		GN2 Downstream DLR-2082	TABER 226	890938	0 / 13,789.5	KPAG	5/19/02
P3140	1	46		Tank pressurization	TABER 226	890934	0 / 13,789	KPAG	5/19/02
T3226	1	47		LH2 VENT LINE @ CHAMBER PENETRAT	TYPE E		15 / 310	KELVIN	NONE
T3247	1	48		LN2 RETURN ROV 20-1707	TYPE E		15 / 310	KELVIN	NONE
T3248	1	49		LN2 RETURN ROV 20-1706	TYPE E		15 / 310	KELVIN	NONE
T3205	1	50		LN2 RETURN LINE TEMP.	TYPE E		15 / 310	KELVIN	NONE
T3206	1	51		LN2 Cold wall zone 1A	Type E		33.15 / 300	KELVIN	NONE
T3207	1	52		LN2 Cold wall zone 1B	Type E		33.15 / 300	KELVIN	NONE
T3208	1	53		LN2 Cold wall zone 2A	Type E		33.15 / 300	KELVIN	NONE
T3209	1	54		LN2 Cold wall zone 2B	Type E		33.15 / 300	KELVIN	NONE
T3210	1	55		LN2 Cold wall zone 3A	Type E		33.15 / 300	KELVIN	NONE
T3211	1	56		LN2 Cold wall zone 3B	Type E		33.15 / 300	KELVIN	NONE
T3212	1	57		LN2 Cold wall zone 4A	Type E		33.15 / 300	KELVIN	NONE
T3213	1	58		LN2 Cold wall zone 4B	Type E		33.15 / 300	KELVIN	NONE
T3214	1	59		LN2 Cold wall zone 5A	Type E		33.15 / 300	KELVIN	NONE
T3215	1	60		LN2 Cold wall zone 5B	Type E		33.15 / 300	KELVIN	NONE
T3217	1	61		Diff pump #1 water outlet	Type K		200 / 533	KELVIN	NONE
T3219	1	62		Diff pump #2 water outlet	Type K		200 / 533	KELVIN	NONE
T3220	1	63		Diff pump #1oil	Type K		200 / 533	KELVIN	NONE
T3221	1	64		Diff pump #2 oil	Type K		200 / 533	KELVIN	NONE
T3222	1	65		LH2 F/D rov 20-601	Type E		15 -310	KELVIN	NONE
T3227	1	66		LH2 Vent line flow box	Type E		15 -310	KELVIN	NONE
T3249	1	67		LN2 heat exchanger rov 20-1704	Type E		15 -310	KELVIN	NONE
T3250	1	68		LN2 supply rov 20-1700	Type E		15 -310	KELVIN	NONE
T3252	1	69		LH2 vent heat xchr water discharge temp	Type E		15 -310	KELVIN	NONE

Table 11. MHTB ZBO instrumentation list (Continued).

20-FT CHAMBER FACILITY MEASUREMENTS									
MID	LINK	SIU CH	J-BOX	Measurement Description	Xducer	Serial No.	Range	UNITS	CAL DUE
T3253	1	70		Tank pressurization line temperature	Type E		15 -310	KELVIN	NONE
T3254	1	71		Flowbox temperature - feedback	Type E		15 -310	KELVIN	NONE
T3255	1	72		Ice bath reference pressure vessel temp	Type E		15 -310	KELVIN	NONE
T3256	1	73		DP1 hoffman box temperature	Type E		15 -310	KELVIN	NONE
T3265	1	74		Tank pressurization ROV20-1809	Type E		15 / 310	KELVIN	NONE
	1	75							
TPT1	1	76		TEMP. PRESSURE TRANSDUCER TVS	TYPE E		15 / 310	KELVIN	NONE
TD23	1	77		RAKE 2 11.5% FILL	DT-470-BO-11A		15 / 310	KELVIN	NONE
	1	78							
	1	79							
VP3000	1	80		Manway pump out 2nd level	MKS390	G85195	0 / 1000	TORR	2/22/03
VP3003	1	81		15 Foot Chamber foreline	GP275	none	10-3 /760	TORR	3/3/03
VP3004	1	82		LN2 TANK VACUUM JACKET	GP275	none	10-3 / 760	TORR	3/3/03
VP3005	1	83		LH2 F/D vac jacket @ rov 1502	GP275	25210	10-3 / 760	TORR	3/3/03
VP3007	1	84		Chamber wall box	MKS 390	73995-2A	0 / 1000	MICRONS	3/22/03
VP3008	1	85		Chamber wall box	MKS 122A	M645228	0 / 1000	TORR	3/15/03
VP3009	1	86		Pump one foreline (outside pump house)	GP275	25211	10-3 / 760	TORR	3/15/03
VR3010	1	87		MILLIVOLTS FOR VP3010	MKS 290	94081226A	300 / 5300	MV	3/15/03
VR3011	1	88		MILLIVOLTS FOR VP3011	VARIAN BA2C	4003	2000 / 8000	MV	3/15/03
VR3012	1	89		MILLIVOLTS FOR VP3012	GP303	482	1000 / 7000	MV	3/15/03
VR3014	1	90		MILLIVOLTS FOR VP3014	VARIAN BA2C	4002	2000 / 8000	MV	3/15/03
VP3010	1	CALC		Internal chamber pressure			.01 / 1000	UTORR	NONE
VP3011	1	CALC		Chamber wall box			.01 / 1000	UTORR	NONE
VP3012	1	CALC		Internal chamber pressure			.01 / 1000	UTORR	NONE
VP3014	1	CALC		RGA Pressure			.01 / 1000	UTORR	NONE
VP3015	1	91		Chamber wall box - pirani	HPS 953	107263	10-3 / 1000	Torr	3/15/03
BAD CH	1	92							
VP3016	1	93		CHAMBER WALL BOX-COLD CATHODE-mv	HPS 953	107263	0/6000	MV	3/15/03
VP3018	1	94		20 Foot chamber foreline	GP275		10-3 / 760	Torr	3/303
VP3019	1	95		TVS enclosure pressure 3rd level	GP275		10-3 / 760	Torr	3/3/03
VPC3016	1	CALC		Chamber wall box - cold cathode - semi-log	HPS 953	107263	10-8 / 10-2	Torr	NONE
VPD3016	1	CALC		Chamber wall box - cold cathode - lin.scale	HPS 953	107263	.01 / 1000	uTorr	NONE
T3266	1	96		JUSTAK SIGHT GLASS VENT TEMP.	TYPE E		15 / 310	KELVIN	NONE
T3267	1	97		PRESSURANT SUPP. TEMP,E10 FLANGE	TYPE E		15 / 310	KELVIN	NONE
T3268	1	98		HEATER SHROUD LN2 SUPPLY	TYPE E		15 / 310	KELVIN	NONE

Table 11. MHTB ZBO instrumentation list (Continued).

20-FT CHAMBER FACILITY MEASUREMENTS									
MID	**LINK**	**SIU CH**	**J-BOX**	**Measurement Description**	**Xducer**	**Serial No.**	**Range**	**UNITS**	**CAL DUE**
T939	1	99		COMPRESS DISCHARGE WATER TEMP.	TYPE E		15 / 310	KELVIN	NONE
P3143	1	100		CRYO-COOLER HELIUM SUPPLY	TABER 226	810917	0 / 3,447.3	KPAG	
P3144	1	101		CRYO COOLER HELIUM RETURN	TABER 226	810922	0 / 3,447.3	KPAG	
DP4344	1	CALC		P3143 / P3144 DELTA PRESSURE			0 / 3,447.3	KPAD	NONE
P3145	1	102		PRESSURANT SUPP.PRESS. E10 FLANG	TABER 226	890893	0 / 1,378.9	KPAG	
VP3020	1	103		TVS PUMP-OUT D/S ROV 20-1500	GP275		10-3 / 760	TORR	3/3/03
VR3021	1	104		MILLIVOLTS FOR VP3021	GP375		0 / 7000	MV	3/35/03
VP3021	1	CALC		TVS PUMP-OUT LVL-2			10-3 / 760	TORR	NONE
VP3022	1	105		CRYO COOLER HELIUM PANEL	GP275		10-3 / 760	TORR	3/3/03
VP3024	1	106		MHTB MANWAY PUMP-OUT PRESS	GP275		10-3 / 760	TORR	3/3/03

NOTES:
6/1/01 - Added T3247, T3248, T3205, F17
6/11/01 - Deleted: VAV3, VAV4, VAV5, VAV6, VAV7, T3269, VP3017. Added: T939, T3226.
6/12/01 - Added: V1, V2, V3, V4, E1, ,E2, I1, I2, I5, I6, I7.
6/14/01 - Moved V1, V2, V3, V4, E1, E2, I1, I2, I5, I6, I7 to Real Star, SIU-0. Added calculated measurements DPP1, PPA1, PSB1, PSA1, and associated inputs, PP1, PS1, TPT1, TD23.
Moved D1 to another CH.
6/15/01 - Deleted F12, no longer used, not used on last MHTB Test, not a requirement. Moved P3105, VP3016 due to bad CH.
6/18/01 - Changed VP3010 to VR3010, VP3011 to VR3011, VP3012 to VR3012, VP3014 to VR3014, and made VP3010, VP3011, VP3012, VP3014 to calculated measurements.
7/2/01 - DP1, P1, P2, P3, P4, Moved to Real Star System. Added DP4344, VR3021.

Table 12. MHTB ZBO test article measurements.

TEST ARTICLE MEASUREMENTS									
MID	LINK	SIU CH	J-BOX	Measurement Description	Xducer	Serial No.	Range	UNITS	CAL DUE
HG1	0	0		Heat guard leg #1	Diode		15 / 310	Kelvin	None
HG3	0	1		Heat guard leg #3	Diode		15 / 310	Kelvin	None
HG5	0	2		Heat guard pressurization line	DT-470-BO-11A	D02247	15 / 310	Kelvin	None
HG6	0	3		Heat guard fill/drain line	DT-470-BO-11A	D02256	15 / 310	Kelvin	None
HG7	0	4		Heat guard vent line	DT-470-BO-11A	D02258	15 / 310	Kelvin	None
HS18	0	5		Inner volume 0.6 m above bottom	Type E		15 / 310	Kelvin	None
HS19	0	6		Inner volume 1.2 m above bottom	Type E		15 / 310	Kelvin	None
HS20	0	7		Inner volume 1.8 m above bottom	Type E		15 / 310	Kelvin	None
HS21	0	8		Inner volume 2.4 m above bottom	Type E		15 / 310	Kelvin	None
HS22	0	9		Inner volume 3 m above bottom	Type E		15 / 310	Kelvin	None
	0	10							
	0	11							
HS75	0	12		Zone 7 4 cm right of HS74A	Type E		15 / 310	Kelvin	None
HS76	0	13		Zone 7 8 cm right of HS74A	Type E		15 / 310	Kelvin	None
HS77	0	14		Zone 7 12 cm right of HS74A under cooling	Type E		15 / 310	Kelvin	None
HS78	0	15		Zone 7 12 cm left of HS711B under cooling	Type E		15 / 310	Kelvin	None
HS79	0	16		Zone 7 8 cm left of HS711B	Type E		15 / 310	Kelvin	None
	0	17							
HS114	0	18		Zone 11 12 cm right of HS113B	Type E		15 / 310	Kelvin	None
HS116	0	19		Zone 11 bottom center	Type E		15 / 310	Kelvin	None
HSA1	0	20		Zone 1 top panel under heater	Type E		15 / 310	Kelvin	None
HSA2	0	21		Zone 2 top panel under heater	Type E		15 / 310	Kelvin	None
HSA3	0	22		Zone 3 top panel under heater	Type E		15 / 310	Kelvin	None
HSA4	0	23		Zone 4 top panel under heater	Type E		15 / 310	Kelvin	None
HSA5	0	24		Zone 5 left 22.5 deg	Type E		15 / 310	Kelvin	None
HSA6	0	25		Zone 6 left 67.5 deg	Type E		15 / 310	Kelvin	None
HSA74	0	26		Zone 7 left side under heater	Type E		15 / 310	Kelvin	None
BAD CH	0	27							
HSA9	0	28		Zone 9 left under heater	Type E		15 / 310	Kelvin	None
HSA10	0	29		Zone 10 left under heater	Type E		15 / 310	Kelvin	None
HSA111	0	30		Zone 11 left side under heater	Type E		15 / 310	Kelvin	None

Table 12. MHTB ZBO test article measurements (Continued).

TEST ARTICLE MEASUREMENTS									
MID	**LINK**	**SIU CH**	**J-BOX**	**Measurement Description**	**Xducer**	**Serial No.**	**Range**	**UNITS**	**CAL DUE**
HSA12	0	31		Zone 12 left under heater	Type E		15 / 310	Kelvin	None
HSA13	0	32		Zone 13 under heater	Type E		15 / 310	Kelvin	None
HSA14	0	33		Zone 14 under heater	Type E		15 / 310	Kelvin	None
HSA15	0	34		Zone 15 under heater	Type E		15 / 310	Kelvin	None
HSA16	0	35		Zone 16 under heater	Type E		15 / 310	Kelvin	None
HSB1	0	36		Zone 1 top panel under heater	Type E		15 / 310	Kelvin	None
HSB2	0	37		Zone 2 top panel under heater	Type E		15 / 310	Kelvin	None
HSB3	0	38		Zone 3 top panel under heater	Type E		15 / 310	Kelvin	None
HSB4	0	39		Zone 4 top panel under heater	Type E		15 / 310	Kelvin	None
HSB5	0	40		Zone 5 right 22.5 deg	Type E		15 / 310	Kelvin	None
HSB6	0	41		Zone 6 right 67.5 deg	Type E		15 / 310	Kelvin	None
HSB7	0	42		Zone 7 right side under heater	Type E		15 / 310	Kelvin	None
HSB8	0	43		Zone 8 right under heater	Type E		15 / 310	Kelvin	None
HSB9	0	44		Zone 9 right under heater	Type E		15 / 310	Kelvin	None
HSB10	0	45		Zone 10 right under heater	Type E		15 / 310	Kelvin	None
HSB11	0	46		Zone 11 right side under heater	Type E		15 / 310	Kelvin	None
	0	47							
HSB13	0	48		Zone 13 under heater	Type E		15 / 310	Kelvin	None
HSB14	0	49		Zone 14 under heater	Type E		15 / 310	Kelvin	None
HSB15	0	50		Zone 15 under heater	Type E		15 / 310	Kelvin	None
HSB16	0	51		Zone 16 under heater	Type E		15 / 310	Kelvin	None
HSA17	0	52		Zone 17 under heater	Type E		15 / 310	Kelvin	None
	0	53							
IPP1	0	54		Interstitial penet. 3.8 cm from SOFI surface	Type E		15 / 310 K	Kelvin	None
IPP2	0	55		Interstitial penetration 5 cm from IPPT1	Type E		15 / 310 K	Kelvin	None
ISS1	0	56		Leg #1 interface support structure	Type E		15 / 310 K	Kelvin	None
ISS3	0	57		Leg #3 interface support structure	Type E		15 / 310 K	Kelvin	None
LL1	0	58		Tank liquid level	Cryomagnetics		0-2.75	Meters	None
V1	0	59		TVS pump on/off status	DISCRETE VDC		0/28 VDC	Vdc	None
V2	0	60		Tank heater element #1, on/off	DISCRETE VDC		0/28 VDC	Vdc	None

Table 12. MHTB ZBO test article measurements (Continued).

TEST ARTICLE MEASUREMENTS									
MID	LINK	SIU CH	J-BOX	Measurement Description	Xducer	Serial No.	Range	UNITS	CAL DUE
V3	0	61		Tank heater element #2, on/off	DISCRETE VDC		0/28 VDC	Vdc	None
V4	0	62		TVS pump controller set point	ANALOG VOLTS		2 / 10 VDC	Hz	None
E1	0	63		Heater voltage				Vdc	None
E2	0	64		Heater voltage				Vdc	None
PUP1	0	65		TVS pump on/off	indication		0 / 1000	ofn	None
HSA8	0	66		Zone 8 left under heater	TYPE E		15 / 310	Kelvin	None
TL19	0	67		Leg #1 45TH MLI layer	TYPE E		15 / 310	Kelvin	None
TM4	0	68		MLI Shield 1 Profile 4	TYPE E		15 / 310	Kelvin	None
TMI2	0	69		MLI Shield 10 Profile 2	TYPE E		15 / 310	Kelvin	None
TMO7	0	70		MLI Shield 45 Profile 7	TYPE E		15 / 310	Kelvin	None
I1	0	71		Heater current				Amps	None
I2	0	72		Heater current				Amps	None
I5	0	73		TVS pump phase current				Amps	None
I6	0	74		TVS pump phase current				Amps	None
TD1	0	75		Rake 1 95.4% fill	DT-470-BO-11A		15 / 310	Kelvin	None
TD2	0	76		Rake 1 88.1% fill	DT-470-BO-11A		15 / 310	Kelvin	None
TD3	0	77		Rake 1 79.2% fill	DT-470-BO-11A		15 / 310	Kelvin	None
TD4	0	78		Rake 1 70.1% fill	DT-470-BO-11A		15 / 310	Kelvin	None
TD5	0	79		Rake 1 61.1% fill	DT-470-BO-11A		15 / 310	Kelvin	None
TD6	0	80		Rake 1 52.0% fill	DT-470-BO-11A		15 / 310	Kelvin	None
TD7	0	81		Rake 1 42.9% fill	DT-470-BO-11A		15 / 310	Kelvin	None
TD8	0	82		Rake 1 33.9% fill	DT-470-BO-11A		15 / 310	Kelvin	None
TD9	0	83		Rake 1 24.8 % fill	DT-470-BO-11A		15 / 310	Kelvin	None
TD10	0	84		Rake 1 15.8% fill	DT-470-BO-11A		15 / 310	Kelvin	None
TD11	0	85		Rake 1 7.6 % fill	DT-470-BO-11A		15 / 310	Kelvin	None
TD12	0	86		Rake 1 1.8 % fill	DT-470-BO-11A		15 / 310	Kelvin	None
TD13	0	87		Rake 2 98.0% fill	DT-470-BO-11A		15 / 310	Kelvin	None
TD14	0	88		Rake 2 92.0% fill	DT-470-BO-11A		15 / 310	Kelvin	None
TD15	0	89		Rake 2 83.7% fill	DT-470-BO-11A		15 / 310	Kelvin	None
TD16	0	90		Rake 2 74.6% fill	DT-470-BO-11A		15 / 310	Kelvin	None

Table 12. MHTB ZBO test article measurements (Continued).

TEST ARTICLE MEASUREMENTS									
MID	LINK	SIU CH	J-BOX	Measurement Description	Xducer	Serial No.	Range	UNITS	CAL DUE
TD17	0	91		Rake 2 65.6% fill	DT-470-BO-11A		15 / 310	Kelvin	None
TD18	0	92		Rake 2 56.5% fill	DT-470-BO-11A		15 / 310	Kelvin	None
TD19	0	93		Rake 2 47.5% fill	DT-470-BO-11A		15 / 310	Kelvin	None
TD20	0	94		Rake 2 38.4% fill	DT-470-BO-11A		15 / 310	Kelvin	None
TD21	0	95		Rake 2 29.3% fill	DT-470-BO-11A		15 / 310	Kelvin	None
TD22	0	96		Rake 2 20.3% fill	DT-470-BO-11A		15 / 310	Kelvin	None
I7	0	97		TVS pump phase current				Amps	None
TD24	0	98		Rake 2 4.3 % fill	DT-470-BO-11A		15 / 310	Kelvin	None
TFD1	0	99		Fill/Drain penetration 2.54 cm from tank wall	DT-470-SD-11A	D01845	15 / 310	Kelvin	None
TFD2	0	100		Fill/Drain penetration 7cm from TFD1	DT-470-SD-11A	D01844	15 / 310	Kelvin	None
TFD3	0	101		Fill/Drain penetration on SOFI above TFD2	Type E		15 / 310	Kelvin	None
TFD4	0	102		Fill/Drain penetration on SOFI above HG6	Type E		15 / 310	Kelvin	None
TM7	0	103		MLI Shield 1 Profile 7	Type E		15 / 310	Kelvin	None
	0	104							
TL13	0	105		Leg 1 1st MLI layer	Type E		15 / 310	Kelvin	None
TL14	0	106		Leg #1 45th MLI layer	Type E		15 / 310	Kelvin	None
TL15	0	107		Leg #1 10th MLI layer	Type E		15 / 310	Kelvin	None
TL16	0	108		Leg #1 18th MLI layer	Type E		15 / 310	Kelvin	None
TL17	0	109		Leg #1 25th MLI layer	Type E		15 / 310	Kelvin	None
TL18	0	110		Leg #1 36th MLI layer	Type E		15 / 310	Kelvin	None
BAD CH	0	111							
TLA18	0	112		Leg #1 36th MLI layer	Type E		15 / 310	Kelvin	None
TLB1	0	113		Leg #1 Boundary	Type E		15 / 310	Kelvin	None
TLB3	0	114		Leg #3 Boundary	Type E		15 / 310	Kelvin	None
TM1	0	115		MLI Shield 1 Profile 1	Type E		15 / 310	Kelvin	None
TM2	0	116		MLI Shield 1 Profile 2	Type E		15 / 310	Kelvin	None
TM3	0	117		MLI Shield 1 Profile 3	Type E		15 / 310	Kelvin	None
BAD CH	0	118							
TM5	0	119		MLI Shield 1 Profile 5	Type E		15 / 310	Kelvin	None
TM6	0	120		MLI Shield 1 Profile 6	Type E		15 / 310	Kelvin	None

Table 12. MHTB ZBO test article measurements (Continued).

TEST ARTICLE MEASUREMENTS									
MID	LINK	SIU CH	J-BOX	Measurement Description	Xducer	Serial No.	Range	UNITS	CAL DUE
BAD CH	0	121							
TMH1	0	122		Manhole outer flange (180) by TMH1	Type E		15 / 310	Kelvin	None
TMH2	0	123		Manhole outer flange (0) opp. TCMH1	Type E		15 / 310	Kelvin	None
TMI1	0	124		MLI Shield 10 Profile 1	Type E		15 / 310	Kelvin	None
BAD CH	0	125							
TMI3	0	126		MLI Shield 10 Profile 3	Type E		15 / 310	Kelvin	None
TMI4	0	127		MLI Shield 10 Profile 4	Type E		15 / 310	Kelvin	None
TMI5	0	128		MLI Shield 10 Profile 5	Type E		15 / 310	Kelvin	None
TMI6	0	129		MLI Shield 10 Profile 6	Type E		15 / 310	Kelvin	None
TMI7	0	130		MLI Shield 10 Profile 7	Type E		15 / 310	Kelvin	None
TMM1	0	131		MLI Shield 25 Profile 1	Type E		15 / 310	Kelvin	None
TMM2	0	132		MLI Shield 25 Profile 2	Type E		15 / 310	Kelvin	None
TMM3	0	133		MLI Shield 25 Profile 3	Type E		15 / 310	Kelvin	None
TMM4	0	134		MLI Shield 25 Profile 4	Type E		15 / 310	Kelvin	None
TMM5	0	135		MLI Shield 25 Profile 5	Type E		15 / 310	Kelvin	None
TMM6	0	136		MLI Shield 25 Profile 6	Type E		15 / 310	Kelvin	None
TMM7	0	137		MLI Shield 25 Profile 7	Type E		15 / 310	Kelvin	None
TMN1	0	138		Manhole 0 deg	Diode		15 / 310	Kelvin	None
TMN3	0	139		Manhole 90 deg	Diode		15 / 310	Kelvin	None
	0	140							
TMO1	0	141		MLI Shield 45 Profile 1	Type E		15 / 310	Kelvin	None
TMO2	0	142		MLI Shield 45 Profile 2	Type E		15 / 310	Kelvin	None
TMO3	0	143		MLI Shield 45 Profile 3	Type E		15 / 310	Kelvin	None
TMO4	0	144		MLI Shield 45 Profile 4	Type E		15 / 310	Kelvin	None
TMO5	0	145		MLI Shield 45 Profile 5	Type E		15 / 310	Kelvin	None
TMO6	0	146		MLI Shield 45 Profile 6	Type E		15 / 310	Kelvin	None
BAD CH	0	147							
	0	148							
	0	149							
TPL1	0	150		Pressurization line 3.8 cm from tank	CY7 - SD1	D03906	15 / 310	Kelvin	None

Table 12. MHTB ZBO test article measurements (Continued).

TEST ARTICLE MEASUREMENTS									
MID	LINK	SIU CH	J-BOX	Measurement Description	Xducer	Serial No.	Range	UNITS	CAL DUE
TPL2	0	151		Pressurization line 7.6 cm from tank	CY7 - SD1	D03907	15 / 310	Kelvin	None
TPL3	0	152		Pressurization Line SOFI above TPL2	Type E		15 / 310	Kelvin	None
TPL4	0	153		Pressurization line SOFI above HG5	Type E		15 / 310	Kelvin	None
	0	154							
	0	155							
	0	156							
	0	157							
TSF1	0	158		#1 (90) 1.25” on foam pressurization	DT-470-SD-11A		15 / 310	Kelvin	None
	0	159							
TSF3	0	160		#3 (90) barrel midplane	DT-470-SD-11A		15 / 310	Kelvin	None
TSF4	0	161		#4 (210) barrel midplane	DT-470-SD-11A		15 / 310	Kelvin	None
TSF5	0	162		#5 (330) barrel midplane	DT-470-SD-11A		15 / 310	Kelvin	None
	0	163							
	0	164							
TSL1	0	165		Leg # 1 1” below tank leg adapter	Diode		15 / 310	Kelvin	None
TSL2	0	166		Leg # 1 3” below tank leg adapter	Diode		15 / 310	Kelvin	None
TSL3	0	167		Leg # 3 1” below tank leg adapter	Diode		15 / 310	Kelvin	None
TSL4	0	168		Leg # 3 3” below tank leg adapter	Diode		15 / 310	Kelvin	None
TSL5	0	169		Leg #1 comp profile 20.8 cm from socket	Type E		15 / 310	Kelvin	None
TSL6	0	170		Leg #1 comp profile 25.4 cm from socket	Type E		15 / 310	Kelvin	None
TSL7	0	171		Leg #1 comp profile 30.48 cm from socket	Type E		15 / 310	Kelvin	None
TSL8	0	172		Leg #1 comp profile 35.56 cm from socket	Type E		15 / 310	Kelvin	None
TSL9	0	173		Leg #1 comp profile 40.64 cm from socket	Type E		15 / 310	Kelvin	None
TSL10	0	174		Leg #1 comp profile 45.72 cm from socket	Type E		15 / 310	Kelvin	None
TSL11	0	175		Thin SOFI by zero g vent penetration	Type E		15 / 310	Kelvin	None
TSL12	0	176		Thick SOFI by lower trunoin	Type E		15 / 310	Kelvin	None
TSL14	0	177		Leg #1 interior below SOFI	Type E		15 / 310	Kelvin	None
TSL15	0	178		Leg #3 interior below SOFI	Type E		15 / 310	Kelvin	None
TSL17	0	179		Leg #1 SOFI profile 10.2 cm from socket	Type E		15 / 310	Kelvin	None
TSL18	0	180		Leg #1 SOFI profile 2.54 cm from socket	Type E		15 / 310	Kelvin	None

Table 12. MHTB ZBO test article measurements (Continued).

TEST ARTICLE MEASUREMENTS									
MID	LINK	SIU CH	J-BOX	Measurement Description	Xducer	Serial No.	Range	UNITS	CAL DUE
TSL19	0	181		Leg #1 SOFI profile -5.08 cm from socket	Type E		15 / 310	Kelvin	None
TSS1	0	182		Temperature support structure	Type E		15 / 310	Kelvin	None
TSS2	0	183		Temperature support structure	Type E		15 / 310	Kelvin	None
TSS3	0	184		Temperature support structure	Type E		15 / 310	Kelvin	None
TSS4	0	185		Temperature support structure	Type E		15 / 310	Kelvin	None
TTB1	0	186		Inner MLI tank bottom	Type E		15 / 310	Kelvin	None
TTB2	0	187		Outer MLI Ttank bottom	Type E		15 / 310	Kelvin	None
TUP1	0	188		Ullage pressure line	Type E		15 / 310	Kelvin	None
TUP2	0	189		Ullage pressure line	Type E		15 / 310	Kelvin	None
	0	190							
	0	191							
TVL1	0	192		Vent line penetration 3”	CY7 - SD1	D03908	15 / 310	Kelvin	None
TVL2	0	193		Vent line penetration 2”	CY7 - SD1	D03910	15 / 310	Kelvin	None
TVL3	0	194		Vent line penetration top flange	DT-470-BO-11A	D02257	15 / 310	Kelvin	None
TVL4	0	195		Rake 1 99.2% fill	DT-470-SD-11A		15 / 310	Kelvin	None
TVL5	0	196		Rake 1 99.2% fill	DT-470-SD-11A		15 / 310	Kelvin	None
TVL6	0	197		Vent line penetration SOFI above TVL2	Type E		15 / 310	Kelvin	None
TVL7	0	198		Vent line penetration SOFI 15 cm from TVL6	Type E		15 / 310	Kelvin	None
TW1	0	199		T. wall barrel 255 98.9% ullage	DT-470-SD-11A		15 / 310	Kelvin	None
TW2	0	200		T. wall barrel 255 83.7% ullage	DT-470-SD-11A		15 / 310	Kelvin	None
TW3	0	201		T. wall barrel 255 63.6% ullage	DT-470-SD-11A		15 / 310	Kelvin	None
TW4	0	202		T. wall barrel 255 43.5% ullage	DT-470-SD-11A		15 / 310	Kelvin	None
TW5	0	203		T. wall barrel 255 23.3% ullage	DT-470-SD-11A		15 / 310	Kelvin	None
	0	204							
PL25	0	205		Liquid level 25% fill	118CPS		0/10 VOLTS	Volts	None
PL50	0	206		Liquid level 50% fill	118CPS		0/10 VOLTS	Volts	None
PL1	0	207		Sierra Lobo pt. Lvl. sensor 61.1%	DT470SD-11A		15 / 310	Kelvin	None
PL2	0	208		SIERRA LOBO PT. LVL.SENSOR TOP	DT470SD-11A		15 / 310	Kelvin	NONE

Table 12. MHTB ZBO test article measurements (Continued).

TEST ARTICLE MEASUREMENTS									
MID	LINK	SIU CH	J-BOX	Measurement Description	Xducer	Serial No.	Range	UNITS	CAL DUE
CRYOCOOLER (ZBO-Specific) INSTRUMENTATION									
GD1	0	209		Gallium diode	TP022SQNO04	10093	15 / 310	Kelvin	
GD2	0	210		Gallium diode	TP022SQNO04	10094	15 / 310	Kelvin	
GD4	0	211		Gallium diode	TG120P	10031	15 / 310	Kelvin	
GD5	0	212		Gallium diode	TG120P	10024	15 / 310	Kelvin	
GD6	0	213		Gallium diode	TG120P	10025	15 / 310	Kelvin	
GD7	0	214		Gallium diode	TG120P	10026	15 / 310	Kelvin	
GD8	0	215		Gallium diode	TG120P	10027	15 / 310	Kelvin	
GD9	0	216		Gallium diode	TG120P	10028	15 / 310	Kelvin	
GD10	0	217		Gallium diode	TG120P	10029	15 / 310	Kelvin	
GD11	0	218		Gallium diode	TG120P	10032	15 / 310	Kelvin	
	0	219							
	0	220							
SD102	0	221		Silicon diode	DT-470	D30429	15 / 310	Kelvin	None
SD103	0	222		Silicon diode	DT-470	D30430	15 / 310	Kelvin	None
SD104	0	223		Silicon diode	DT-470	D30431	15 / 310	Kelvin	None
SD105	0	224		Silicon diode	DT-470	D30432	15 / 310	Kelvin	None
SD106	0	225		Silicon diode	DT-470	D30433	15 / 310	Kelvin	None
SD107	0	226		Silicon diode	DT-470	D30434	15 / 310	Kelvin	None
SD108	0	227		Silicon diode	DT-470	D30435	15 / 310	Kelvin	None
HTC25	0	228		Motor heater temp. top	TYPE E		15 / 310	Kelvin	None
HTC26	0	229		Motor heater temp. bottom	TYPE E		15 / 310	Kelvin	None
	0	230							
TPT2	0	231		Temp. press. Transducer TVS - backup	TYPE E		15 / 310	Kelvin	None
TPA1	0	232		Tvs pump inlet temp.	TYPE E		15 / 310	Kelvin	None
TPA2	0	233		Tvs outlet temp.	TYPE E		15 / 310	Kelvin	None
TCP1	0	234		Manway pumpout line temp.	TYPE E		15 / 310	Kelvin	None
TCP2	0	235		Manway pumpout line temp.	TYPE E		15 / 310	Kelvin	None
	0	236							
FM1	0	237		Flowmeter	FT24AESWLAAS	2402088	15/150 GPM		None

Table 12. MHTB ZBO test article measurements (Continued).

TEST ARTICLE MEASUREMENTS									
MID	**LINK**	**SIU CH**	**J-BOX**	**Measurement Description**	**Xducer**	**Serial No.**	**Range**	**UNITS**	**CAL DUE**
CHT1	0	238		Copper hsg surface temp. top	DT470SD-11A		15 / 310	Kelvin	None
CHT2	0	239		Copper hsg surface temp. bot	DT470SD-11A		15 / 310	Kelvin	None
HT1	0	240		Cryo cooler hsg wall temp. top	TYPE E		15 / 310	Kelvin	None
HT2	0	241		Cryo cooler hsg wall temp. bot	TYPE E		15 / 310	Kelvin	None
DP1	0	242		Ullage differential pressure	MKS 698	95256248A	0 / 133.332	PAD	4/20/03
P1	0	243		Ullage pressure	MKS 390	59135-4B	0 / 133.332	KPAA	2/26/03
P2	0	244		Ullage pressure	TABER 254	781298	0 / 350	KPAG	2/16/03
P3	0	245		Reference pressure vessel	MKS 690	92150128A	0/ 133.332	KPAA	3/24/03
P4	0	246		Ullage pressure	MKS 390	19551-3B	0 /34.473	MPAA	4/5/03

NOTES:
6/11/01 - Deleted: P501, P502, PJ1, PJ2, PUP2, PV2, T601, T602, T603, T604, T605, TCP1, TCP2, TJT1, TJT2, TSA1, TSA2, TVA1, TVA2.
6/11/01 - Corrected typo HSA74, HSA111
6/12/01 - Deleted: TSF2, TSF6, TSF7, TW6 Damaged unable to repair at this time. added HSA17. Moved HSA8, TL19, TM4, TMI2, TMO7 due to bad SIU CH.
6/14/01 - Moved calculated measurements to SIU-1, DPP1, PSA1, PPA1, PSB1, and associated inputs TPT1, TD23, PP1, PS1. Deleted PS10, PS20, PS30, T1, T2, PTC28, PTC27. Added V1, V2, V3, V4, E1, E2, I1, I2, I5, I6, I7.
7/2/01 - Deleted HS72, HS73, HS112, HSB12, (OPEN T/C beads), TMN4, (unable to locate), GD12, SD101, (grounded silicon diode to facility). Added DP1, P1, P2, P3, P4. Deleted PVA2, not used no transducer found.
7/6/01 - Added TCP1, TCP2.

APPENDIX F—FLUID SYSTEM FOR THE MULTIPURPOSE HYDROGEN TEST BED TANKING ZERO-BOILOFF DEMONSTRATION

Figure 29 is a schematic of the MHTB test article system and figure 30 is the cryo-refrigerator He system schematic.

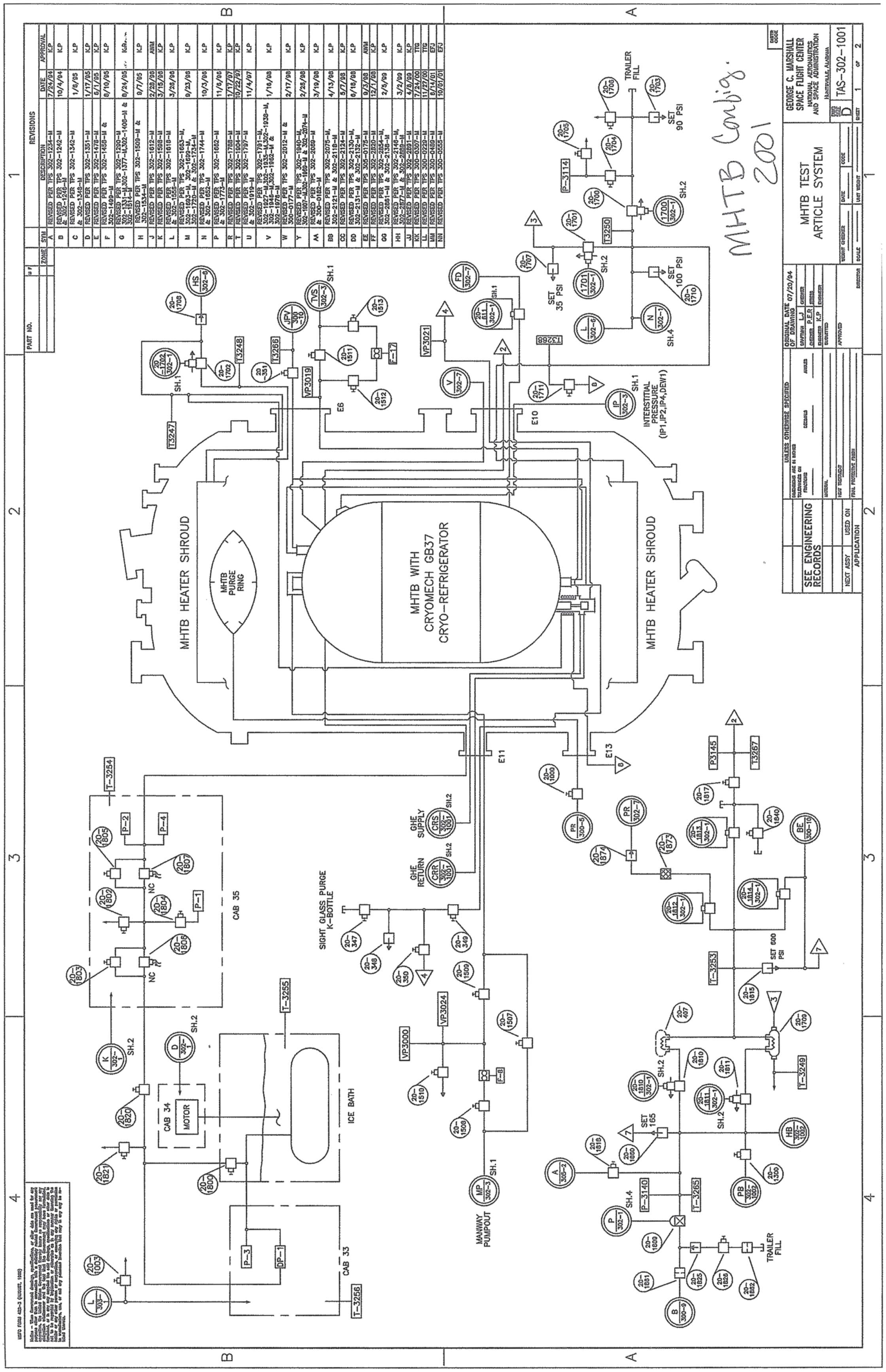


Figure 29. Schematic for MHTB ZBO demonstration.

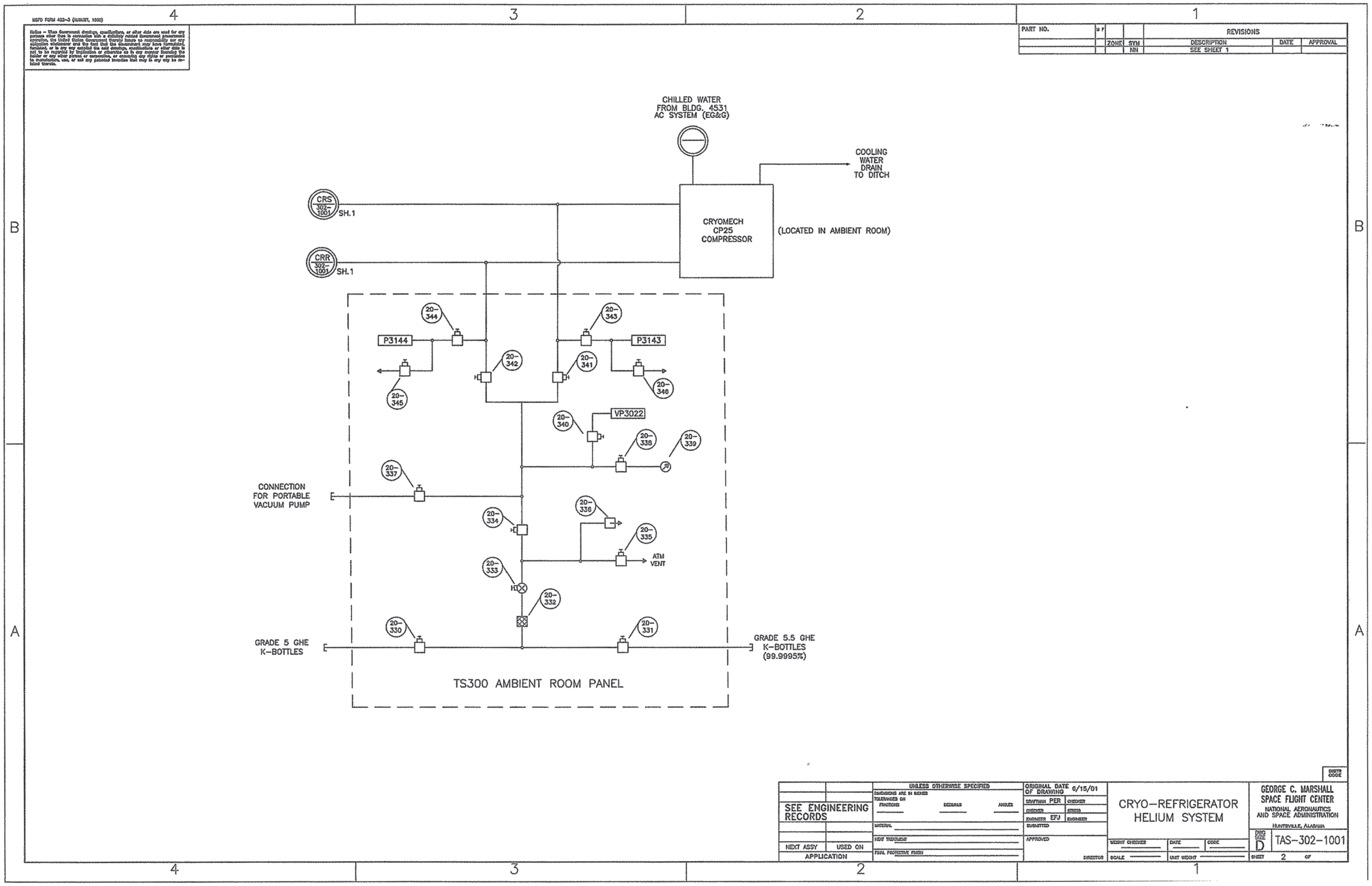


Figure 30. Schematic for cryo-refrigerator He system.

APPENDIX G—MULTIPURPOSE HYDROGEN TEST BED TEST REQUEST SHEET

G.1 Zero-Boiloff Cryogenic Storage/Optical Mass Gauging Sensor Testing

Test Name: Multipurpose Hydrogen Test Bed Heat Removal System (HRS)
and Optical Mass Gauging Sensor (OMGS) Test

Test Project ID: P2111 Test Requester: Leon Hastings/Chad Bryant

Test Date: 7/21/01 Test Conductor: Ed Johnson

Test Objectives:

- Demonstrate the flexibility, repeatability, and baseline the accuracy of the OMGS.

- Demonstrate the capability of the Sierra Lobo Cryotracker liquid level sensor.

- Measure steady-state boiloff to assess baseline insulation performance. These tests will also serve to set up the initial fluid conditions for HRS operations.

- Demonstrate and quantify the performance of ‘zero-gravity’ tank pressure control concepts in the 18 m^3 (640 ft^3) MHTB tank under normal gravity but in a simulated space thermal environment. This concept includes a radial flow HRS (equipped with a spray bar, HX, cryocooler, pump, and LH_2 heater).

Test Fluid: LH_2

Approximate Test Duration: 600 hr (25 days)

Data System Unit (DSU) Sampling Rate: High: One sample per second (used during system changes)
Low: One sample per 60 s (used during system monitoring)
(Note: Sampling rates can be adjusted by test engineer’s discretion.)

Sampling Start/End Time: ½ hr before chill/fill through test completion

Vacuum Chamber/Pump Operation: Orbit simulation—hard vacuum condition 10^{-6} torr range or better (evacuate chamber 24 hr before tanking)

Vacuum Chamber Purge: Dry GN_2 (dewpoint –54 °C) initiate 3 days before test

Vacuum Chamber Coldwalls: LN_2 at ≈80 K

Tank Pressure Control: Set up ice bath and constant pressure volume (set ref. vessel @ ≈17 psia)/ ice bath 2 days before testing to obtain steady-state environment. Check ice bath at 1- to 2-hr intervals. Fill or pack as needed to prevent temperature drift. Document all operations in the test log.

Other Vacuum Systems: Pump down HRS enclosure and test article manhole annulus before testing. Document all operations in the test log.

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

Camera Operation: Not required

Test Article Internal Purge: Holding: Dry (dewpoint –54 °C) missile grade air or GN_2
Pretest: Dry GH_2 or GHe
Post-test: Dry GHe (when tank is below 100 K)
Dry GN_2 (when tank is above 100 K)
Dry missile-grade air (MGA) (when tank is at ambient temperature)

Test Article Fill Level:		
	≈90+%	First test condition (LH_2)
	≈25%	Second test condition (LH_2)
	≈50%	Third test condition (LH_2)

Test Article Shroud Purge: May be required as needed

Test Article Shroud: Heating: Start/Stop: Continuous throughout test
Settings: 159–169 K
Cooling: As required to maintain temperature of 164 K

Test Article Ullage Pressure Control: Setting: 117.2 kPa (17 psia) or near
(used for boiloff testing only) Tolerance: Orbit ± 0.007 kPa (0.001 psi)
Duration: Steady-state boiloff interval

Chamber Pressurization: Minimum temperature of facility/test article: 85 K
Purge gas type: Dry GN_2 or MGA (dewpoint –54 °C)
Pressurization rate: 30-min repressurization
Maximum time test article left at vacuum after test: 48 hr

Specific Test Hardware Parameters: Real-time adjustments of some of the parameters listed below may be required based on actual measured MHTB heat leak. Document all operations in the test log.

Radial Flow HRS Inputs:
- Psat = calculated from TD23
- Pmax = 124.106 kPa (18 psia)

- Pmin = 110.316 kPa (16 psia)
- PSA1 = 117.211 kPa (17 psia)
- Pump flow rate = 37.854 L/min (10 gal/min)
- Initial fluid saturation pressure = ≈110.32 kPa (≈16 psia)
- Use active control logic to operate LH_2 heater

Additional General Instructions:

- Document file names and time stamps for all events in figure 31.

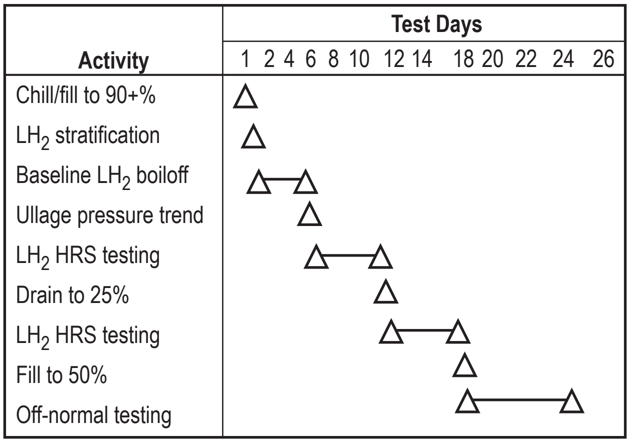


Figure 31. Test matrix timeline.

- Spray bar: After tanking is completed, the pump/motors shall be calibrated to determine the operational frequency for a flow rate of 37.854 L/min (10 gal/min). This value shall be noted in the test logbook and used for system operation.

- Steady-state criteria for boiloff: Real-time judgment is necessary to determine the onset of steady-state conditions; hence, discussion between the test requester and test engineer is critical to overall test success. (This approach has been used during past testing of this type quite successfully.) Basic parameters will include the following:

  – MLI shield temperature change of 0.15 K/hr, averaged over a 6-hr timespan.
  – Boiloff flow has stabilized to a change of <0.5 % per hour, averaged over a 6-hr timespan.
  – Vacuum chamber and MLI interstitial pressure stable in the 10^{-6} torr range.
  – Minimum 6 hr test data should be recorded past the onset of steady-state conditions (if time permits).

- General HRS operation: Real-time judgment is necessary to determine when sufficient component cycles have occurred; hence, discussion between the test requester and test engineer is critical to overall test success. (This approach has been used during past testing of this type quite successfully.) Basic parameters will include the following:

  - Combined pump and cryocooler operation and multiple LH_2 heater cycles.
  - Potential for real-time changes in PSA1, Pmin, Pmax, and pump flow rate.

- Facility power outage/DSU and RS off-line: During any condition requiring that the DSU/RS or other systems be off-line (i.e., tape changes, power outages), tank pressure control must be maintained to prevent subcooling of the LH_2. All facility systems related to the tank pressure control system and the tank vent must use an uninterruptible power supply. Subcooling of the tanked LH_2 will have a disastrous effect on the overall test timeline.

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14. ABSTRACT

Cryocooler and passive insulation technology advances have substantially improved prospects for zero-boiloff cryogenic storage. Therefore, a cooperative effort by NASA's Ames Research Center, Glenn Research Center, and Marshall Space Flight Center (MSFC) was implemented to develop zero-boiloff concepts for in-space cryogenic storage. Described herein is one program element—a large-scale, zero-boiloff demonstration using the MSFC multipurpose hydrogen test bed (MHTB). A commercial cryocooler was interfaced with an existing MHTB spray bar mixer and insulation system in a manner that enabled a balance between incoming and extracted thermal energy.

15. SUBJECT TERMS
orbital cryogenic fluid management, orbital cryogenic storage, zero-gravity cryogenic pressure control, zero-boiloff cryogenic storage

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