Cryogenic Propellant Long-term Storage With Zero Boil-off

A. HEDAYAT
Sverdrup Technology, Inc. MSFC Group
Hunstville, AL

L. J. HASTINGS and C. BRYANT
NASA, Marshall Space Flight Center
Huntsville, AL

D. W. PLACHTA
NASA, Glenn Research Center
Cleveland, OH

ABSTRACT

Significant boil-off losses from cryogenic propellant storage systems in long-duration space mission applications result in additional propellant and larger tanks. The potential propellant mass loss reductions with the Zero Boil-off (ZBO) concept are substantial; therefore, further exploration through technology programs has been initiated within NASA. A large-scale demonstration of the ZBO concept has been devised utilizing the Marshall Space Flight Center (MSFC) Multipurpose Hydrogen Test Bed (MHTB) along with a cryo-cooler unit. The ZBO concept consists of an active cryo-cooling system integrated with traditional passive thermal insulation. The cryo-cooler is interfaced with the MHTB and spraybar recirculation/mixer system in a manner that enables thermal energy removal at a rate that equals the total tank heat leak. The liquid hydrogen (LH2) is withdrawn from the tank, passed through a heat exchanger, and then the chilled liquid is sprayed back into the tank through a spraybar. The test series will be performed over a 20-30 day period. Tests will be conducted at multiple fill levels to demonstrate concept viability and to provide benchmark data to be used in analytical model development. In this paper the test set-up and test procedures are presented.

INTRODUCTION

Delivery of large payloads over great distances in future space missions, requires high-energy cryogenic upper stages. Many advanced propulsion systems use hydrogen as a working fluid for long duration missions. Advancements in Cryogenic Fluid Management (CFM) particularly, reduction or elimination of the boil-off in cryogenic storage applications pose challenges in long-term space programs. MSFC has initiated an advanced development/technology program to broaden the CFM experience and database. Due to the cost of, and limited opportunities for, orbital experiments, ground testing is being employed to the fullest extent possible. Therefore, a major objective of the MSFC program has been to perform ground based advanced development testing on CFM systems for space transportation applications. The MHTB is a MSFC advanced development effort directed at addressing technology issues associated with CFM needs for future space transportation applications. The approach taken was to build a test bed with enough versatility such that it could be used for both component and subsystem level testing of various CFM devices.

One of the current efforts at MSFC is involved with ZBO concept that may provide a solution in eliminating propellant loss associated with long-term storage. The ZBO testing involves testing of a Heat Removal System (HRS) that uses a cryo-cooler, a propellant pump, and the Optical Mass Gauge Sensor (OMGS) test that will evaluate the ability to determine the liquid mass contained within the MHTB tank at various fill levels. The data collected will be used to evaluate the ability of the HRS concept to control tank pressures and to eliminate cryogenic fluid boil-off over an extended storage period. Initially, boil-off tests will be performed to calculate the total heat leak and to establish consistent initial conditions for the HRS hardware. Following that, zero boil-off tests will be conducted at multiple fill levels. Furthermore, the information gained will validate system-level HRS models. Moreover, the objective of the OMGS test is to obtain experimental data demonstrating that the optical sensor can accurately measure tan propellant mass in a flight scale tank. In the present work, the OMGS set up and measurements are not discussed, so the ZBO testing and HRS are mainly presented. The ZBO test set up and test procedures are presented in the following sections.

ZERO BOIL-OFF TESTING

It has long been known that, by thoroughly mixing the contents of a propellant tank, the thermal energy contained in the ullage gas can be distributed throughout the liquid phase. This mixing results in both an immediate reduction in ullage pressure and an overall reduction in tank pressurization rate. Left unconstrained, the liquid bulk temperature will rise until its saturation pressure equilibrates to the ullage pressure. Once the propellant is in this fully saturated condition, a method for removing the thermal energy is required to properly control the ullage pressure.

One method that has been proposed is an active cryo-cooler that reduces the bulk liquid temperature and, consequently, its vapor pressure. The integrated MHTB and HRS configuration utilized in ZBO testing is shown in Figure 1. The HRS is comprised of spray bar, pump, flow meter, and cryo-cooler. Propellant is routed to the cryo-cooler with a pump through its inlet at the bottom of the tank. The cryo-cooler exchanges heat with the propellant and routes the propellant to a spray bar. The spray bar, mounted vertically inside the tank, is equipped with a series of orifices located along its length. These orifices inject the cooled propellant radially into the tank, providing bulk mixing and counterbalancing the heat leak into the tank. The descriptions of major components of the test are presented in the following subsections.

MHTB Tank

Figure 2 illustrates the MHTB tank layout. The tank is fabricated from 5083-Aluminum. It has a diameter of 3.05m (10 ft), a height of 3.05m (10 ft) and a total internal volume of

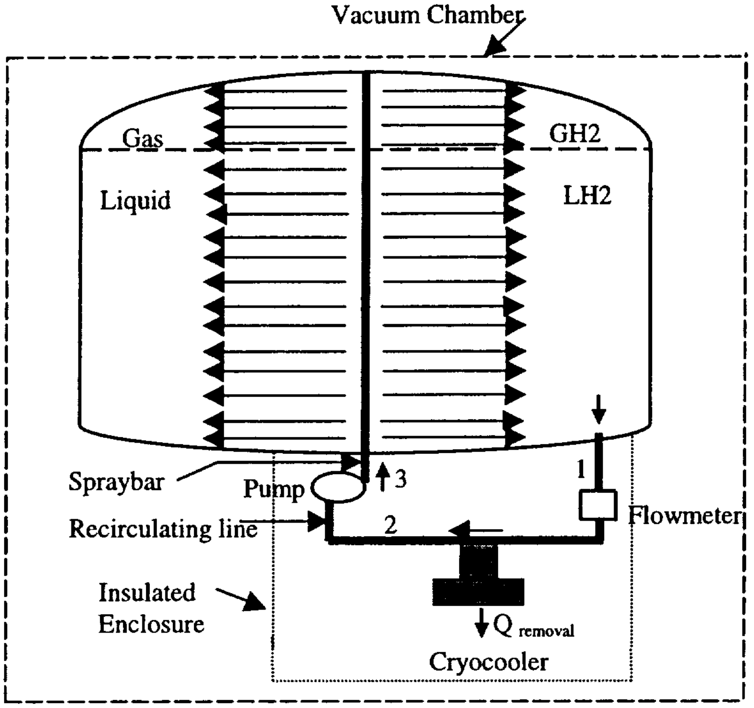

Figure 1. Zero Boil-off Testing Setup.

18.09m^3 (639 ft^3). The tank is supported by four low-heat-leak composite legs and has a variety of penetrations and access ports to accommodate future potential test configurations. The test bed is enclosed in an environmental shroud which is used to provide thermal conditioning and purge capability under both vacuum and ambient environments. Two insulation systems are used on the MTHB. The first is a layer of Spray-On Foam Insulation (SOFI) (sprayed directly on the tank skin) that provides a barrier to convective heat transfer under atmospheric conditions. The second is a variable-density, aluminized mylar Multilayer Insulation (MLI) blanket (installed on top of the SOFI layer) that provides a barrier to radiation heat transfer under vacuum conditions. The combined effects of the SOFI and MLI variable density and installation technique resulted in substantial performance improvements as reported by Hastings and Martin[1].

Spraybar

A longitudinal spraybar is used to achieve both liquid bulk and ullage gas thermal destratification through mixing. During the mixing process, fluid is withdrawn from the tank by a pump and flows back into the tank through the spraybar positioned along (or near) the tank longitudinal axis. The fluid is expelled radially back into the tank through 45 spray bar orifices, which forces circulation and mixing of the tank contents, assuring destratification

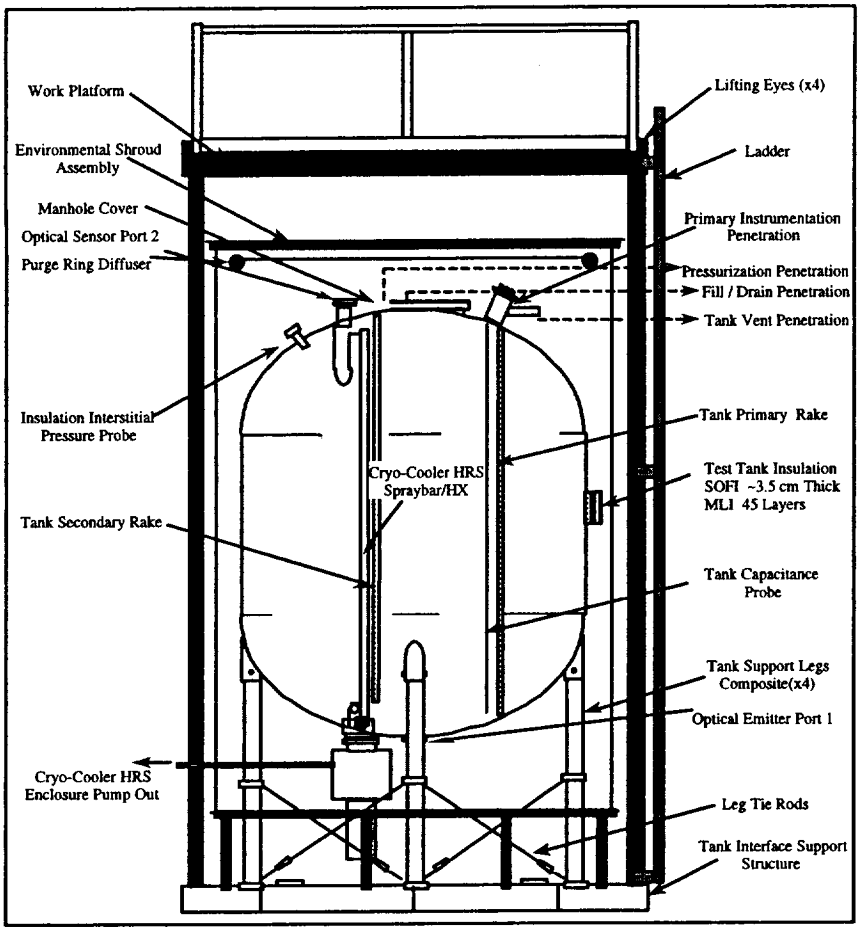

Figure 2. MHTB layout.

and minimum pressure rise rate. For missions lasting from a few days to weeks, depending on the insulation performance, liquid spray injection into the ullage may be sufficient to control the tank pressure with no propellant loss. The spary bar is made of stainless steel tubes with an outside diameter of 0.5 inch and wall thickness of 0.028 inch. The orifices have diameters of 0.055-0.086 inch. Detailed description of this spraybar is provided by Flachbart[2].

Cryo-cooler

The Cryomech GB37 cryorefrigerator is used in the ZBO testing. The GB37 is a two-stage Gifford-McMahon (G-M) cycle Refrigerator[3,4]. Essential to the operation of the GB37 Cryorefrigerator is a compressor system. The compressor system supplies helium to the cold head through stainless steel flexible lines. The GB37 Cryorefrigerator achieved the G-M cycle by expanding the high pressure helium to the low pressure. Integration of the cryo-cooler with the MHTB tank is shown in Figure 3. The heat removal capability of the cryo-cooler varies with the cold head temperature and is depicted in the Figure 4.

Figure 3. Integration of Cryo-cooler with MHTB Tank.

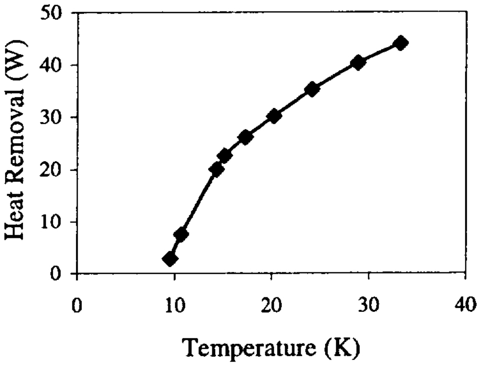

Figure 4. Cryo-cooler Heat Removal Vs. Cold Head Temperature.

Pump

A Barber-Nichols BNHP-08 centrifugal cryogenic pump is utilized for the LH2 recirculating process. The pump data is presented in Table 1.

Flow (GPM)	Frequency (Hz)	Pump Power (Watts)	Motor Input Power (Watts)	Delta P (mBar)
5	18	0.040	0.44	0.9
10	37	0.330	1.77	3.9
15	55	1.10	3.47	8.6
20	73	2.70	6.51	15.2
30	110	9.00	16.75	34.5
40	147	21.00	37.3	61.3

Table 1. LH2 Pump Data.

Vacuum Chamber

Testing is performed at the MSFC East Test Area thermal vacuum facility, Test Stand 300. The vacuum chamber is cylindrical and has usable internal dimensions of 5.5 m in diameter and 7.9 m in height. The chamber pumping train consists of a single-stage GN2 ejector, three mechanical roughing pumps with blower, and two 1.2m-diameter oil diffusion pumps. Liquid nitrogen (LN2) cold walls surrounded the usable chamber volume providing cryopumping and thermal conditioning. Combination of test facility and test article shroud systems enabled simulation of orbital conditions (vacuum level as low as 10^{-6} torr).

TEST PROCEDURES

The zero boil-off/OMGS test series consists of a number of independent tests performed over an interval expected to last between 20 and 30 days. Each of these tests establishes initial conditions prior to a component test, or evaluates a particular component performance. After the tank is chilled, it will be filled to a specific liquid level and a reading will be taken using optical sensor at different fill levels in the MHTB. The tank will continue to be filled until the next specified level, and another reading will be taken. This will continue until the tank is 95% full. At this point, a boiloff test will be performed to calculate the total heat leak and to establish consistent initial conditions for the HRS hardware. Then, a zero boiloff test will be initiated. Following that, another zero boil-off test will be conducted at 25 % fill level to demonstrate concept viability. Table 2 outlines the test series matrix.

Boiloff testing is conducted to determine the ambient heat leak into the MHTB tank and to set up consistent initial conditions for each test. The ambient heat leak is expressed as an energy balance across the tank boundary where the boil-off heat transfer is equal to the sum of the heat transfer through the insulation, the tank penetrations, and the rate of energy storage, if any, as seen in the following equation:

$$q_{boil\text{-}off} = q_{insulation} + q_{penetrations} + dU_{system/dt}$$

The terms $q_{\text{boil-off}}$ and $q_{\text{pentrations}}$ were defined using the test data. Specific calculation of these parameters can be found in Reference 4. The thermal storage term, dUsystem/dt, represents the energy flow into or out of the tank wall, insulation, and fluid mass. It is driven by the fluid saturation temperature, which varies as ullage pressure varies. Since the ullage pressure is held within a tight control band, this term is considered negligible. The $Q_{\text{insulation}}$ term can be determined using the defined quantities described above.

Pre-test heat leak predictions are as follow:

1) $q_{\text{insulation}} + q_{\text{pentrations}} = 8.33$ W, estimated from previous test data[2].
2) $q_{\text{cooler-off}} = 4.3$ W, a calculated value heat leak (conduction) through cooler in cooler-off mode.

Therefore, during the boil-off test, $q_{\text{total}} = 12.3$ W is estimated.

As shown in Figure 1, states 1, 2, and 3 represent tank outlet, cryo-cooler exit, and tank inlet, respectively. The tank is divided into liquid (LH2) and ullage (GH2) regions. To predict the ullage pressure during the ZBO testing, a mathematical model based on the following four regions is considered: 1) Recirculating line across cryo-cooler (1-2); 2) Recirculating line across pump (2-3); 3) Liquid region; and 4) Gaseous region. The test results and mathematical model will be presented in later date.

REFERENCES

1. Hastings, L. J. and Martin, J. J., "Experimental Testing of a Foam/Multilayer Insulation (FMLI) Thermal Control System (TCS) for use on a Cryogenic Upper stage," Space Technology & Applications International Forum, 1st Conference on Orbital Vehicles, Albuquerque, NM, Jan. 25-28, 1998.

2. Flachbart, R.H., Hastings, L.J., and J.J. Martin, "Testing of a Spray Bar Zero Gravity Cryogenic Vent System for Upper Stages," AIAA paper No. AIAA-99-2175, 35th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Los Angeles, CA, 20-24 June, 1999.

3. Walker, G., "Cryocoolers, Part 1: Fundamentals,"Plenum Press, New York, 1983, pp. 237-263.
4. Gifford, W.E., "The Gifford-McMahon Cycle," Advances in Cryogenic Engineering, V. 11, 1966, pp. 152-159.

Test	Scope	Estimated Duration	Description
1	LH_2 OMGS reading @ 0%	30 min	Establish a baseline reading for OMGS.
2	LH_2 OMGS reading @ 10%	1hour	Fill MHTB with LH_2 to 10% fill level and record an OMGS reading.
3	LH_2 OMGS reading @ 20%	1hour	Fill MHTB with LH_2 to 20% fill level and record an OMGS reading.
4	LH_2 OMGS reading @ 25%	30 min.	Fill MHTB with LH_2 to 25% fill level and record an OMGS reading.
5	LH_2 OMGS reading @ 30%	1hour	Fill MHTB with LH_2 to 30% fill level and record an OMGS reading.
6	LH_2 OMGS reading @ 40%	1hour	Fill MHTB with LH_2 to 40% fill level and record an OMGS reading.
7	LH_2 OMGS reading @ 50%	1hour	Fill MHTB with LH_2 to 50% fill level and record an OMGS reading.
8	LH_2 OMGS reading @ 60%	1hour	Fill MHTB with LH_2 to 60% fill level and record an OMGS reading.
9	LH_2 OMGS reading @ 70%	1hour	Fill MHTB with LH_2 to 70% fill level and record an OMGS reading.
10	LH_2 OMGS reading @ 80%	1hour	Fill MHTB with LH_2 to 80% fill level and record an OMGS reading.
11	LH_2 OMGS reading @ 90%	1hour	Fill MHTB with LH_2 to 90% fill level and record an OMGS reading.
12	LH_2 Heat Leak test @ 90-95%	4 Days	Initial LH_2 boiloff used to assess heat leak and setup initial conditions (Ullage pressure controlled and boiloff measured @ boundary temperature of 165 K).
13	Ullage Pressure Trend @ 90% - 95% fill	12 hours	Establish of heat leak/ullage pressure trends with cooler on/heater off.
14	Ullage pressure/heat balance @ 90% - 95% fill	1 Day	Establish constant average ullage pressure/heat balance conditions with cooler on/control system on.
15	LH_2 HRS @ 90% - 95% fill	5 Days	Assess HRS performance
16	LH_2 OMGS reading @ 80%	1hour	Drain MHTB with LH_2 to 80% fill level and record an OMGS reading.
17	LH_2 OMGS reading @ 70%	1hour	Drain MHTB with LH_2 to 70% fill level and record an OMGS reading.
18	LH_2 OMGS reading @ 60%	1hour	Drain MHTB with LH_2 to 60% fill level and record an OMGS reading.
19	LH_2 OMGS reading @ 50%	1hour	Drain MHTB with LH_2 to 50% fill level and record an OMGS reading.
20	LH_2 OMGS reading @ 40%	1hour	Drain MHTB with LH_2 to 40% fill level and record an OMGS reading.
21	LH_2 OMGS reading @ 30%	1hour	Drain MHTB with LH_2 to 30% fill level and record an OMGS reading.
22	Ullage pressure/heat balance @ 25% - 30% fill	1 Day	Establish constant average ullage pressure/heat balance conditions with cooler on/control system on.
23	LH_2 HRS @ 25 - 30% fill	5 Days	Assess HRS performance
24	LH_2 OMGS reading @ 40%	1hour	Fill MHTB with LH_2 to 40% fill level and record an OMGS reading.
25	LH_2 OMGS reading @ 50%	1hour	Fill MHTB with LH_2 to 50% fill level and record an OMGS reading.
26	LH_2 OMGS reading @ 60%	1hour	Fill MHTB with LH_2 to 60% fill level and record an OMGS reading.
27	LH_2 OMGS reading @ 70%	1hour	Fill MHTB with LH_2 to 70% fill level and record an OMGS reading.
28	LH_2 OMGS reading @ 80%	1hour	Fill MHTB with LH_2 to 80% fill level and record an OMGS reading.
29	LH_2 OMGS reading @ 90%	1hour	Fill MHTB with LH_2 to 90% fill level and record an OMGS reading.
30	LH_2 HRS test # 3	6 days	Conduct Test #3 TBD
31	LH_2 OMGS reading @ 80%	1hour	Drain MHTB with LH_2 to 80% fill level and record an OMGS reading.
32	LH_2 OMGS reading @ 70%	1hour	Drain MHTB with LH_2 to 70% fill level and record an OMGS reading.
33	LH_2 OMGS reading @ 60%	1hour	Drain MHTB with LH_2 to 60% fill level and record an OMGS reading.
34	LH_2 OMGS reading @ 50%	1hour	Drain MHTB with LH_2 to 50% fill level and record an OMGS reading.
35	LH_2 OMGS reading @ 40%	1hour	Drain MHTB with LH_2 to 40% fill level and record an OMGS reading.
36	LH_2 OMGS reading @ 30%	1hour	Drain MHTB with LH_2 to 30% fill level and record an OMGS reading.
37	LH_2 OMGS reading @ 20%	1hour	Drain MHTB with LH_2 to 20% fill level and record an OMGS reading.
38	LH_2 OMGS reading @ 10%	1hour	Drain MHTB with LH_2 to 10% fill level and record an OMGS reading.
	Total Days of Test =	24 days	

Table 2. The ZBO Test Matrix