

Propulsion System High Pressure Gaseous Helium (GHe) Vessels at Cryogenic Temperatures

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Nomenclature

°C	=	degrees Celsius
CEV	=	Crew Exploration Vehicle
CFM	=	Cryogenic Fluid Management
COPV	=	composite overwrapped pressure vessel
°F	=	degrees Fahrenheit
GHe	=	gaseous helium
ISRU	=	In-Situ Resource Utilization
JSC	=	Johnson Space Center
LCH ₄	=	liquid methane
LH ₂	=	liquid hydrogen
LN ₂	=	liquid nitrogen
LO ₂	=	liquid oxygen
LSAM	=	Lunar Surface Access Module
LM	=	Lunar Module
MDP	=	maximum design pressure
MLI	=	multilayer insulation
MMH	=	monomethyl hydrazine
MPa	=	megapascal
NASA	=	National Aeronautics and Space Administration
NTO	=	nitrogen tetroxide
PCAD	=	Propulsion and Cryogenic Advanced Development
psia	=	pounds per square inch absolute
RCS	=	reaction control system
TC	=	thermocouple

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Abstract

The Propulsion Systems Branch at the National Aeronautics and Space Administration (NASA) Johnson Space Center (JSC) in Houston, Texas is conducting research and development work for reaction control propulsion systems using cryogenic propellants such as liquid oxygen (LO₂) and Liquid Methane (LCH₄). The propellants for these systems are supplied to the engines using high pressure gaseous helium (GHe) to pressurize the propellant tanks. The objective for using cryogenic propulsion systems at JSC is to support future missions to the moon and Mars for ascent vehicles. A major benefit of cryogenic propellants versus hypergolic propellants, such as monomethyl hydrazine (MMH) and nitrogen tetroxide (NTO), for space exploration is that technology exists to create cryogenic liquids based on In-Situ Resource Utilization (ISRU) efforts for habitat power systems. The creation of propellants on the moon provides significant advantages for plans to use the moon as a stepping stone for future exploration. For these advanced propulsion systems, high pressure GHe will be stored in composite overwrapped pressure vessels (COPVs) at 4500 to 6000 psia (31 to 41 MPa) and will be regulated down to 350 to 500 psia (2.4 to 3.4 MPa) for the inlets to propellant tanks. The challenges in using high pressure GHe for cryogenic propulsion systems are: getting the high pressure GHe down to cryogenic temperatures to maximize storage efficiency and minimizing the heat transfer into the tanks to maintain cryogenic temperatures, preventing boil-off of the propellants. A Cryogenic Fluid Management (CFM) test bed has been created at JSC using liquid nitrogen (LN₂) to simulate the LO₂ or LCH₄ in order to demonstrate long-term storage of cold GHe and cryogenic propellants. Major components including pressure vessels, valves, and feed lines have been assembled inside a thermal vacuum chamber for system testing and development. The purpose of this paper is to present the results of testing efforts to obtain cryogenic temperatures for high pressure GHe stored in COPVs.

I. Introduction

NASA Johnson Space Center in Houston, Texas has been performing design, development, and testing of cryogenic propulsion systems under the Propulsion and Cryogenic Advanced Development (PCAD) and Cryogenic Fluid Management (CFM) projects. The major effort in cryogenic propulsion system development for future exploration missions includes the use of propellants such as liquid oxygen (LO₂), liquid hydrogen (LH₂), and liquid methane (LCH₄), which can be produced in-situ from resources available on the surface of the moon and Mars. A notional schematic of a cryogenic propulsion system using LO₂ and LCH₄ is shown in Figure 1. This system is being proposed for NASA's Constellation program that will take a Lunar Surface Access Module (LSAM), which is called the 'Altair,' to the moon. Altair, which is similar in design, but much larger than the Apollo Lunar Module (LM), will consist of two stages: a descent stage, which will house the majority of the fuel, power supplies, and breathing oxygen for the crew, and an ascent stage, which will house the astronauts, life support equipment, and fuel for the ascent stage motor and steering rockets.¹ The cryogenic propellants are fed to the reaction control system (RCS) thrusters and the ascent engine in a liquid state using a cold GHe pressurization subsystem. An artist's conception of the Altair aboard the Ares V launch vehicle is shown in Figure 2. The schematic in Figure 1 represents the ascent stage for Altair.

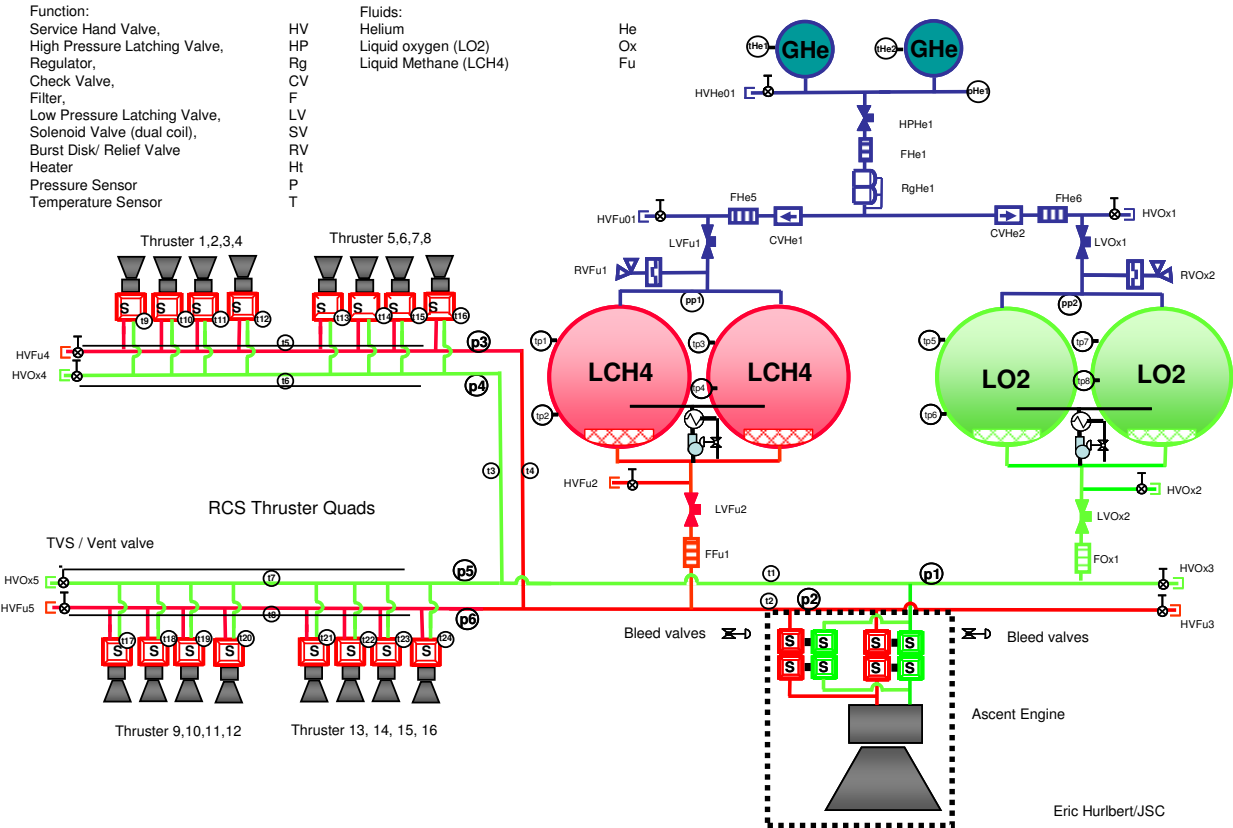


Figure 1. Notional LO2 and LCH4 Propulsion System Schematic for the Altair ascent stage²

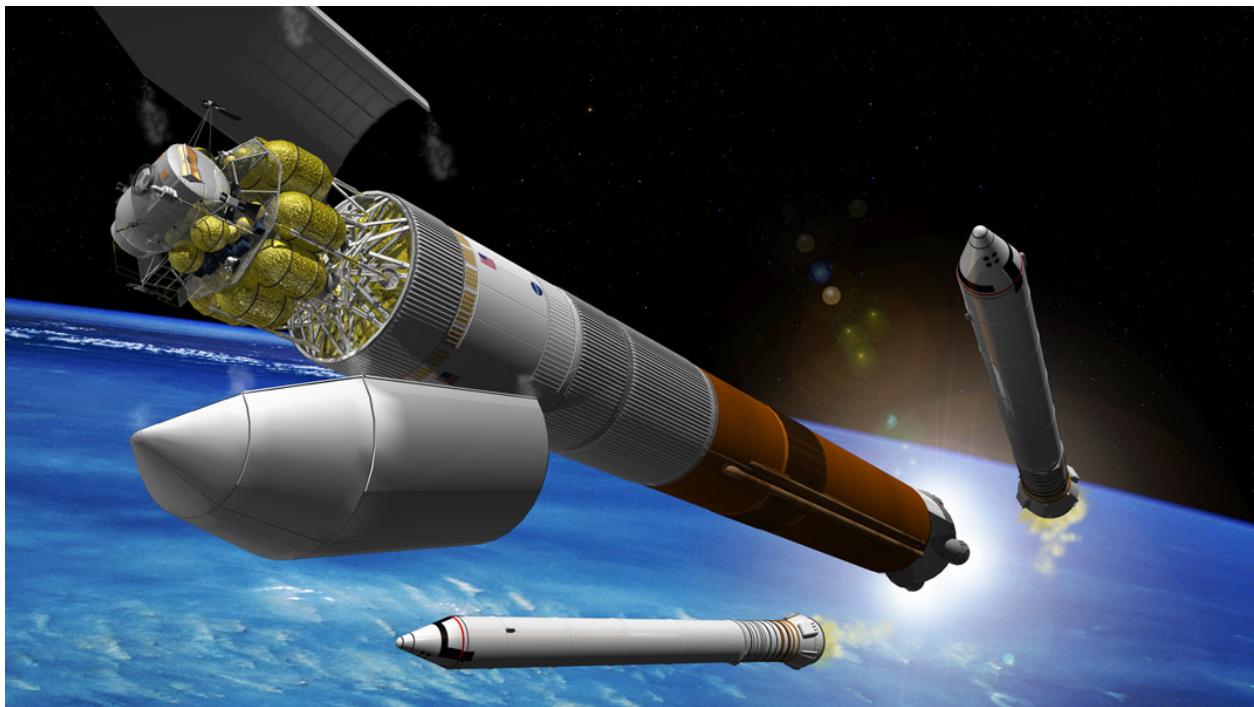


Figure 2. Altair aboard the Ares V Launch Vehicle

Figure 3 shows a description of Constellation's lunar mission profile using the Ares I and Ares V launch vehicles. First, Ares I launches the Orion Crew Exploration Vehicle (CEV), which consists of a Crew Module and a Service Module, to low Earth orbit. This is followed by the launch of Altair aboard the Ares V launch vehicle to low Earth orbit. Orion then docks with Altair and the Earth departure stage, which is used for trans-lunar injection. Once in low lunar orbit, Altair descends to the lunar surface. The ascent stage of Altair is used in the mission profile to launch the crew off the lunar surface to rendezvous and dock with Orion before returning to Earth.

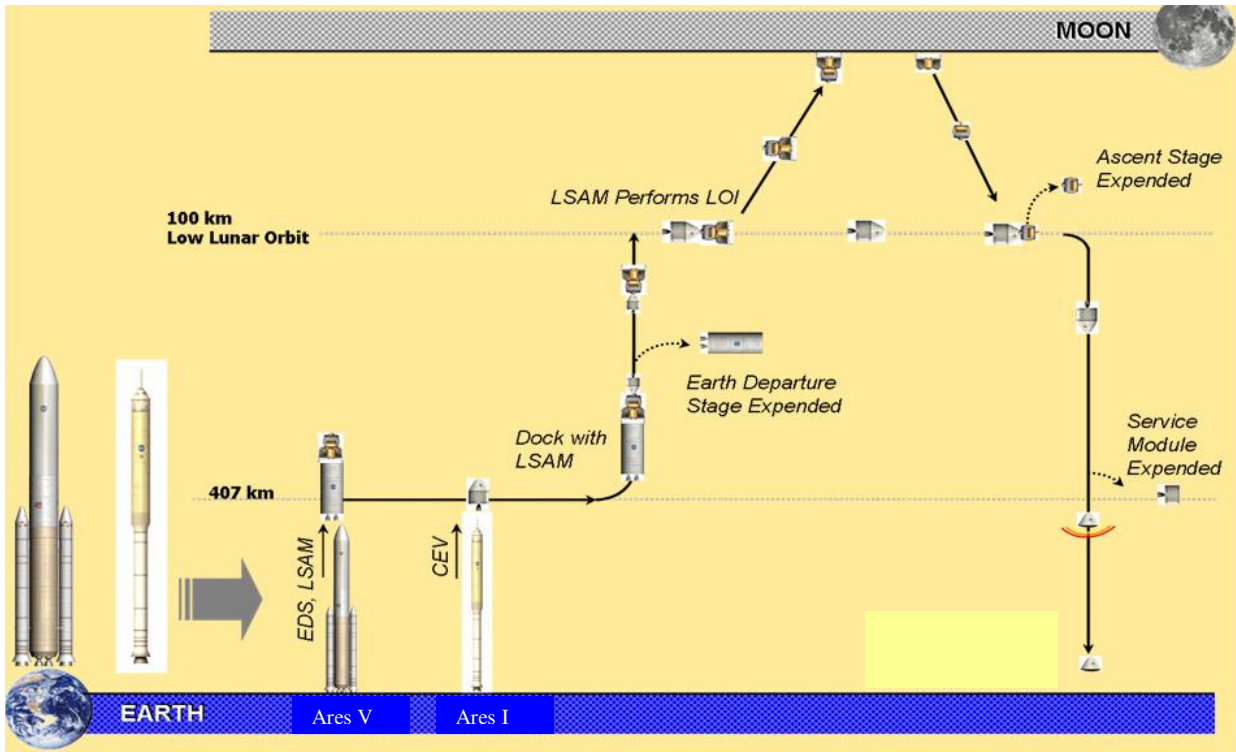


Figure 3. Constellation Mission Profile

One objective of this test program is to determine if GHe COPVs can be charged up to required storage pressures while maintaining cryogenic temperature so that storage efficiency can be maximized and boil-off and loss of propellants is minimized, ultimately leading mass savings.

II. Test Description

A simplified schematic of the test setup is shown in Figure 4. The test articles are inside a thermal vacuum chamber in order to test the system in a relevant space vacuum environment. The test components are assembled to represent a flight-like configuration. A picture of the test articles inside the vacuum chamber is shown in Figure 5. One major challenge is to develop techniques to chill down the GHe as it is loaded and stored in a vehicle on the pad prior to launch. A spherical COPV has been chosen for the GHe pressurization system instead of a cylinder since spheres provide better performance for low blowdown pressures at cryogenic temperatures, and it has a lower surface area to volume ratio, which minimizes the amount of heat transfer to the tank. A picture of the GHe COPV used in this test program (Ardé Part No. D4971) is shown in Figure 6. Burst tests following thermal and pressure cycles on these vessels performed with Ardé, Inc. showed that their required performance at cryogenic conditions is exceeded.² The GHe COPV used in this test program has an Al-2219 liner and is wrapped with a Toray T-1000 carbon fiber and Ardé 31-43B resin composite. The T-1000 fiber has been selected since it currently has the best fiber strength to weight ratio.³ A conductive thermal strap is connected from each boss section of the COPV to the LN2 storage tank to maintain cryogenic GHe temperatures by using the LN2 tank's very large thermal mass compared to the GHe tank as a heat sink to counteract heat leaks into the COPV.

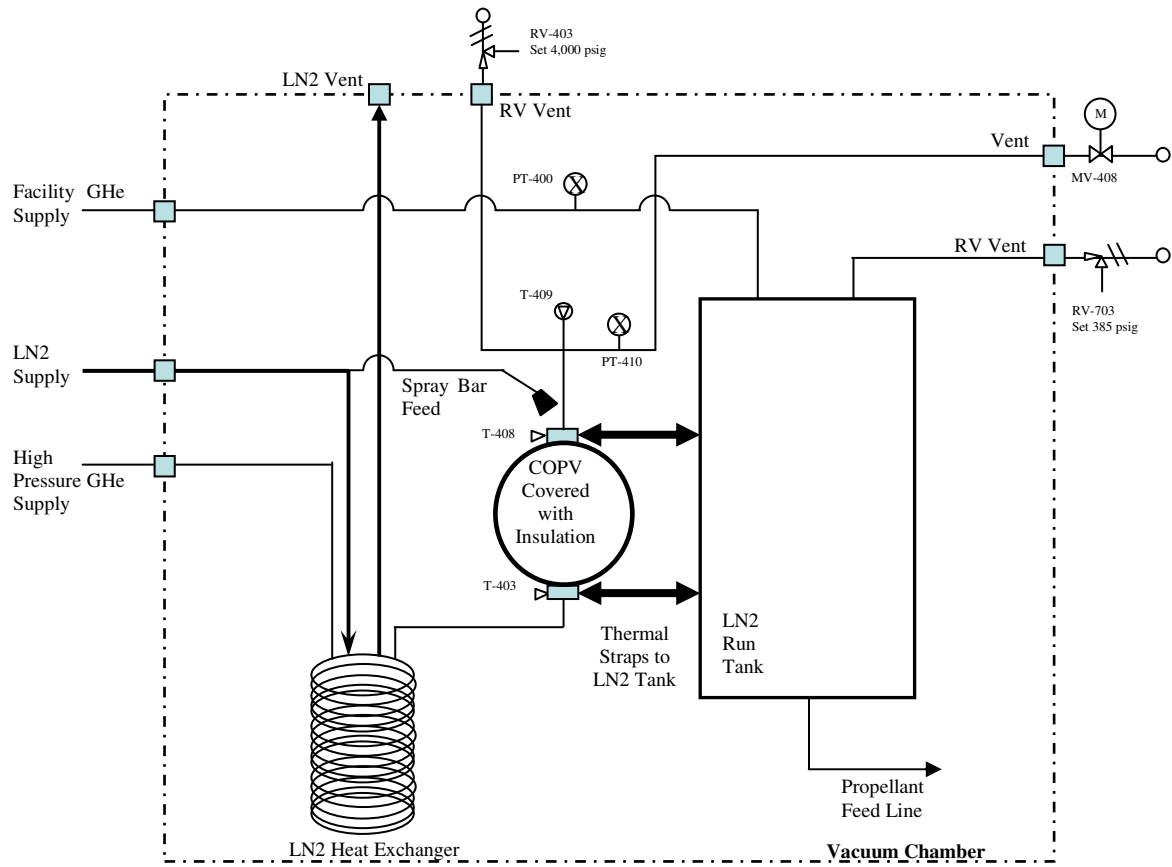


Figure 4. Simplified GHe Cold Charge Test Schematic

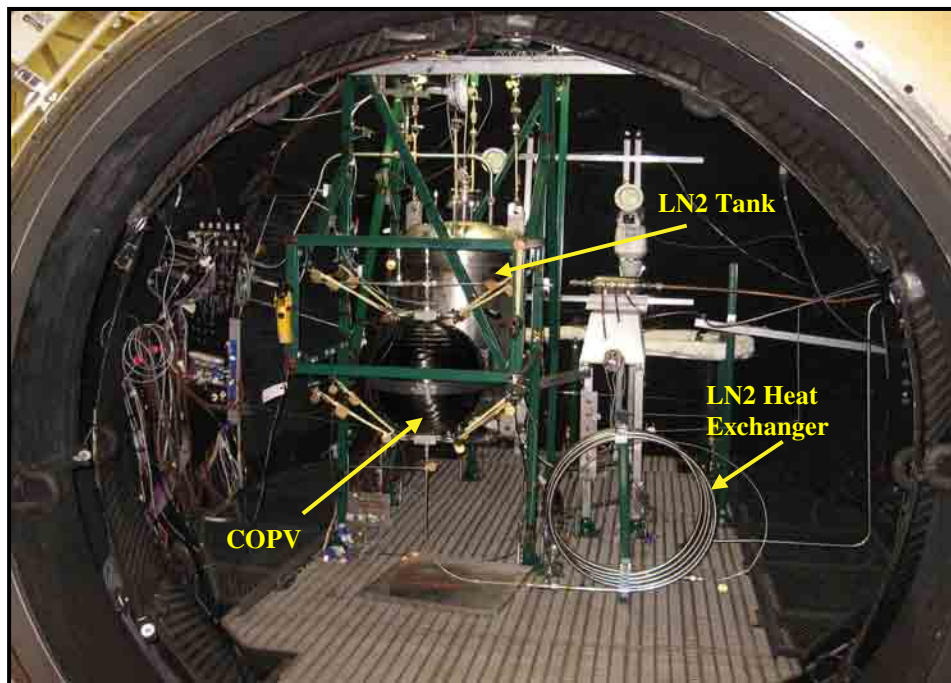


Figure 5. Test Components Inside Thermal Vacuum Chamber

In order to charge the COPVs with cold GHe, various techniques were tested during this test program. One option is to use a tube-in-tube LN2 heat exchanger to chill down high pressure GHe. In order to offset temperature rise due to compressive heating once cold gas is introduced into the COPV, the heat exchanger option can be used in combination with a series of partial blowdown and refill cycles. Once the target pressure is reached within the COPV, the vessel can be partially vented to take advantage of the isentropic cooling process associated with blowdown. This test implemented a ΔP limit of 25% of the tank's maximum design pressure (MDP) during these blowdown cycles so as to not induce additional pressure cycles on the COPV, as defined in the American National Standard ANSI/AIAA S-081A-2006, Space Systems - Composite Overwrapped Pressure Vessels (COPVs).⁴ A close-up picture of the LN2 heat exchanger is shown in Figure 7. Another option is to use an LN2 spray bar over one boss section to cool the tank liner directly as gas is introduced. The spray bar can be used by itself as warm gas is introduced to the COPV, or it can be used in conjunction with the heat exchanger as cold gas is introduced and subsequently heated due to compression inside the tank. A close-up picture of the LN2 spray bar over the aluminum block that is connected to the boss section of the COPV and the thermal strap is shown in Figure 8. Figure 9 shows a picture of the thermal straps from the COPV to the LN2 tank. The spray bar is also visible in Figure 9. All of these cold charge options can be complemented by pre-chilling the COPV liner internally by filling and draining the COPV with LN2. The COPV and the LN2 tank are both covered with multilayer insulation (MLI) blankets to prevent radiation heat transfer in a vacuum environment to maintain cryogenic temperatures.



Figure 6. Picture of Ardé Part No. D4971 During LN2 Thermal Cycle



Figure 7. Tube-in-tube LN2 Heat Exchanger



Figure 8. LN2 Spray Bar over Aluminum Support Block

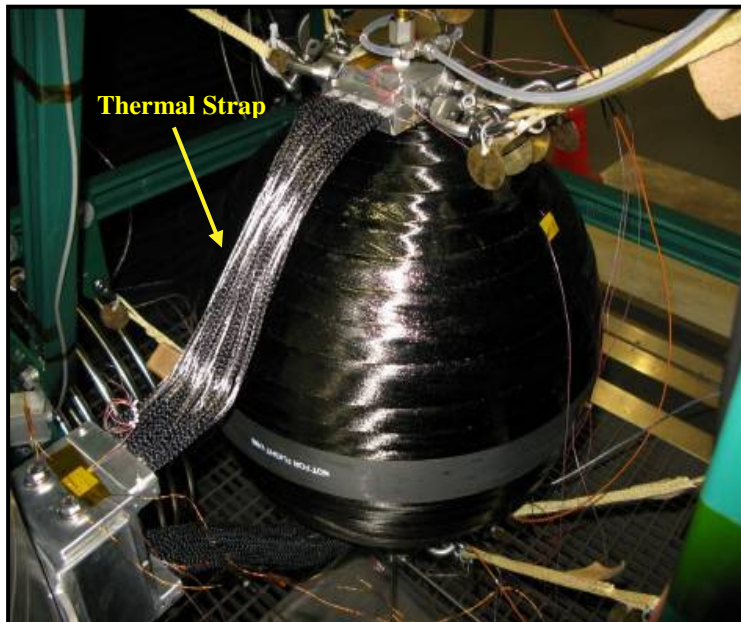


Figure 9. Thermal Straps from COPV to LN2 Tank

Separate facility feed lines are used to provide working fluids to the test components. A liquid nitrogen Dewar is used to supply the run tank, as well as the tube-in-tube heat exchanger and the spray bar. The LN2 feed line to the run tank is not shown in Figure 4 for clarity. Helium K-bottles are used to pressurize and subcool the LN2 run tank so that cryogenic heat sink temperatures can be maintained throughout the test run.

III. Test Procedures

The following are the basic test procedures that were used to chill down high pressure GHe for long-term storage inside the COPV.

1. Fill the run tank with LN2.
2. Pressurize the run tank with helium from the facility helium supply.

3. Fill the COPV with LN2 and drain it.
4. Purge through the COPV, feed lines, and components with GHe
5. Initiate heat exchanger and/or spray bar operations based on the various cold charge options while introducing GHe to the COPV to determine optimal results.
6. Once at maximum pressure, vent the COPV from the target pressure of 3600 psia (25 MPa) down to approximately 2500 psia (17 MPa) to take advantage of blowdown cooling, if using the partial blowdown option. This pressure drop range allows for staying within the 25% maximum design pressure cycle limit for COPVs as specified in ANSI/AIAA S-081A-2006 Space Systems - Composite Overwrapped Pressure Vessels (COPVs).⁴
7. Continue to supply GHe until the final conditions of 3600 psia (25 MPa) and the desired temperature are reached.

IV. Test Results

Several test runs were performed to chill down high pressure GHe to various target temperatures. Discussed here are the results of each of the two main cold charge techniques for the test runs with the lowest target temperatures. The data shown are representative of all test runs performed. Figure 10 shows the temperature and pressure results for GHe in the COPV by using the LN2 heat exchanger option with the use of partial blowdown cycles.

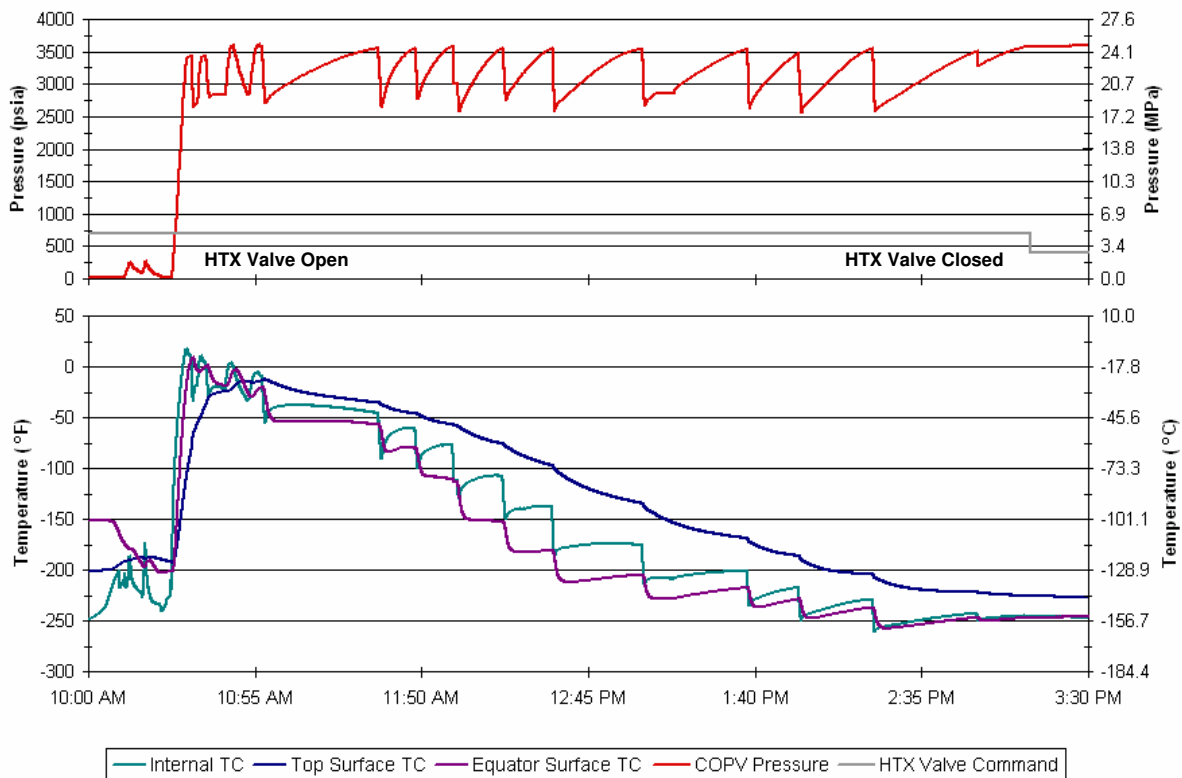


Figure 10. LN2 Heat Exchanger Cold Charge with Partial Blowdown Cycles

Figure 11 shows the results of the temperature and pressure for the GHe in the COPV by using the LN2 spray bar option.

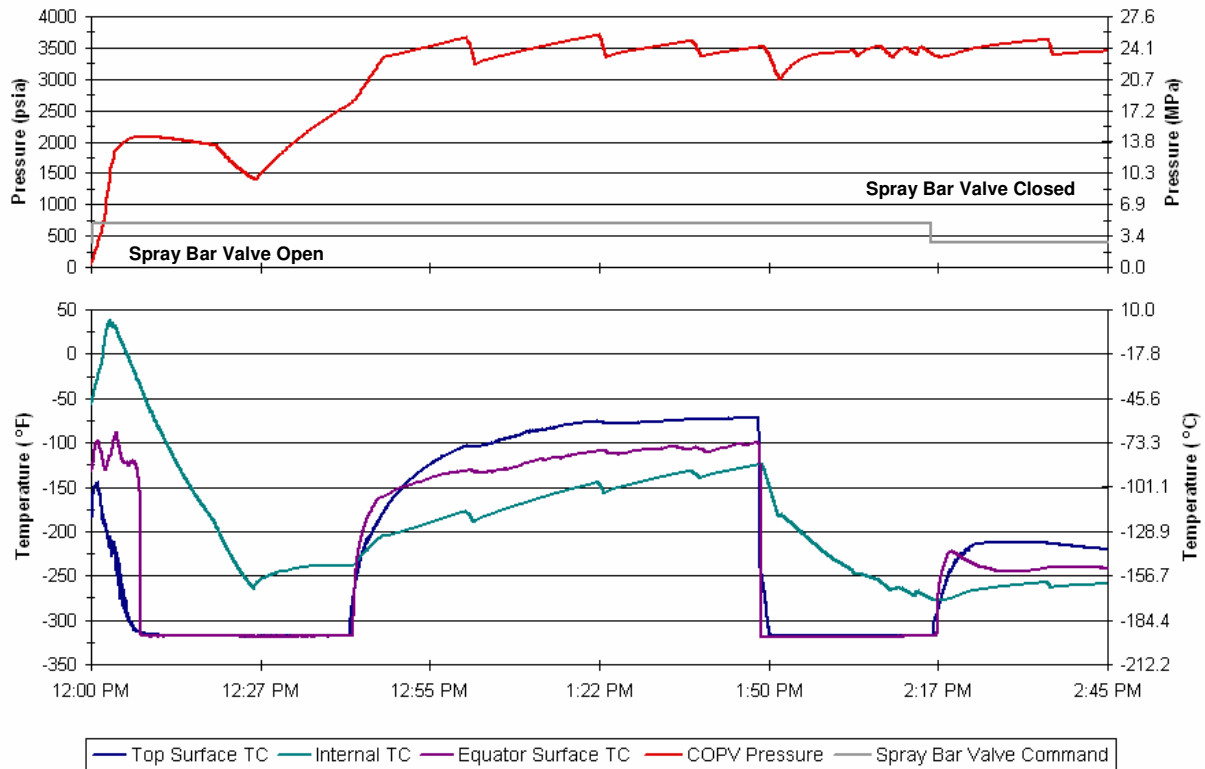


Figure 11. LN2 Spray Bar Cold Charge

Both Figures 10 and 11 show the conditions of the GHe inside the COPV for pressure and temperature versus time. The temperature traces vary based on the location of the thermocouple (TC). The internal TC is a temperature probe that protrudes approximately halfway into the COPV. The top surface TC is located on the aluminum block, shown in Figure 8, which is attached to the COPV and thermal strap. Finally, the equator surface TC is on the overwrap at the girth weld location. The data in Figure 10 for the LN2 heat exchanger show that the blowdown technique that was used cycled the pressure between approximately 2500 and 3600 psia (17 to 25 MPa), using cold gas from the heat exchanger to charge the COPV. It is this cycling blowdown that is needed to counteract the compressive heating of the GHe as pressure is increased from ambient up to 3600 psia (25 MPa). It must be noted that the starting condition for the temperature from the internal TC shows approximately -250 °F (-157 °C) due to the internal LN2 pre-chill of the COPV liner. The temperature then increases to above 0 °F (-18 °C) as the pressure is increased to 3500 psia (24 MPa), and multiple blow-down cycles must be used to chill down to the target temperature at high pressure. The data in Figure 11 for the LN2 spray bar show that temperature rise rates due to compressive heating are not nearly as substantial as in Figure 10. It must also be noted that the GHe introduced to the COPV during the LN2 spray bar test was at ambient temperature, as opposed to cryogenic temperatures as done during the LN2 heat exchanger test. This suggests that the spray bar is providing a much higher net cooling effect than the heat exchanger plus partial blowdown cycles. Furthermore, the spray bar cold charge process took place in approximately half the time as the option with the heat exchanger in combination with partial blowdown cycles.

V. Conclusion

The LN2 spray bar operated much more efficiently than anticipated. The LN2 heat exchanger operated as designed, providing gas at liquid nitrogen temperatures at the inlet of the COPV, but compressive heating within the COPV made it difficult to reach the target GHe pressure and temperature end conditions. When used with the LN2 heat exchanger, partial blowdown cycles were only useful in achieving temperatures in the -250 °F (-157 °C) range, after which a point of diminishing returns is reached. Therefore, the benefits of a heat exchanger for ground loading are questionable. This is based on the amount of LN2 that would need to be expended for a launch vehicle that will have a larger GHe pressurization vessel, and the amount of time required for this process. The amount of LN2 used for the spray bar option is considerably less than the LN2 for the heat exchanger option, as well as being more time

efficient. The spray bar option is also better than the heat exchanger since there is no venting of the GHe to achieve lower temperatures by using the blowdown technique. It was also determined that the spray bar worked so effectively that it rendered the internal pre-chill of the COPV liner with LN2 an unnecessary step. The spray bar can pre-chill the entire COPV, including the liner and the overwrap, without the need for additional GHe purges of the system.

Additional chilling options are being pursued such that there would be a flow path for the LN2 through the Aluminum support block as opposed to spraying it over the surface. This way, cryogenic propellant can possibly be used on a vehicle as its propellants are being loaded. There are also further design challenges regarding application of insulation for the ground loading procedures to prevent heat transfer while on the launch pad since MLI is not effective in the atmospheric pressure environment. One potential solution is a hybrid foam that is being developed to add to the COPV to prevent heat leaks on the launch pad. MLI integrated with other materials such as Dacron netting, silk, and aerogel cloths are being investigated and analyzed for preventing heat leaks. An assessment of the potential for long-term storage of cold helium for a cryogenic propulsion system and thermal strap performance assessments will be made as soon as additional testing, including the baseline heat leak test, are performed. Going into space for long-term missions is a very challenging scenario for propulsion systems. NASA Johnson Space Center will continue design and development efforts as required to properly support space exploration to the moon and beyond.

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⁴ American National Standard, *ANSI/AIAA S-081A-2006 Space Systems-Composite Overwrapped Pressure Vessels (COPVs)*, July 24, 2006, pg. 22.