# Cryogenic Orbital Testbed (CRYOTE) Development Status

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Abstract

High-performance space travel is enabled with propellants having a high specific impulse, and the highest specific impulse can be produced with hydrogen. The Cryogenic Orbital Testbed (CRYOTE) provides an in-space environment where the unique properties and fluid flow of hydrogen can be demonstrated in micro- or zero- gravity. With partnerships across industry and NASA, CRYOTE has developed a detailed concept of an in-flight core system (that can accommodate a variety of experiments). Development has included launch vehicle interface development for transfer of residual liquid hydrogen (LH2) from the launch vehicle to a development tank and an in-depth thermal analysis considering the orbital thermal environment and heat loads imparted on the thermal system.

This paper will describe the non-proprietary development to date, outline lessons learned in the development, and detail the plan moving forward with the CRYOTE project.

Abbreviations

| | | | |
|---|---|---|---|
| CCAM | Collision Contamination and Avoidance Maneuver | MLI | Multi-layer Insulation |
| CFM | Cryogenic Fluid Management | MMOD | Micro-Meteoroid and Orbital Debris |
| CPS | Cryogenic Propulsion Stage | PMD | Propellant Management Device |
| CRYOTE | Cryogenic Orbital Testbed | TVS | Thermodynamic Vent System |
| IMLI | Integrated MLI | VCS | Vapor Cooled Shield |
| LH2 | Liquid Hydrogen | ZBO | Zero Boiloff |
| LO2 | Liquid Oxygen | | |

## 1.0 Introduction – CRYOTE Overview

The Cryogenic Orbital Testbed (CRYOTE) is a project that brings together several NASA centers, several industry partners, and ULA toward a common goal – the advancement of Cryogenic Fluid Management (CFM) technologies. The testbed provides an in-space environment in which the fluid transfer, handling, and storage of liquid hydrogen (LH2) and/or liquid oxygen (LO2) can be demonstrated.[i]

Using extensive trades and discussions with experts from across ULA, NASA, and industry, the CRYOTE detailed concept provides a cost effective, flexible, and extensible method for flight demonstrating CFM technologies and integrated cryogenic systems. Results from CRYOTE can be used to anchor analytic models and applied directly to the design of cryogenic propulsion stages (CPS).

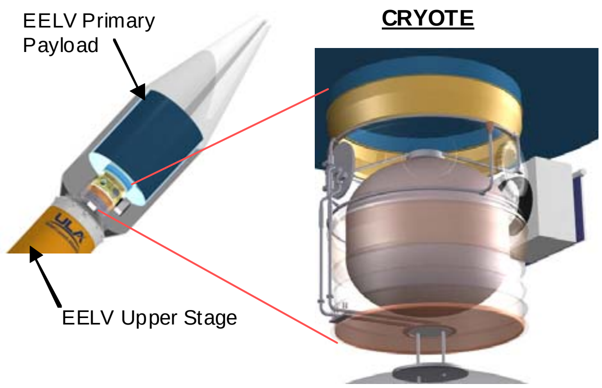


**Figure 1 – CRYOTE is affordable because it launches as an EELV secondary payload and utilizes residual upper stage propellant for the technology demonstration**

CRYOTE avoids the high costs of a dedicated launch vehicle by flying as a secondary payload on an Atlas V (Figure 1). CRYOTE is launched with empty tanks and is filled on-orbit from residual LH2 and LO2 in the Centaur tank following primary payload delivery. The transfer of LH2 and LO2 residual propellants from Centaur to CRYOTE demonstrates transfer out of an actual CPS (Centaur) into CRYOTE's tanks. Launching empty, CRYOTE demonstrates how future CPSs can be made ultra light weight with very low structural tank heating, enhancing the ability to support long duration missions.

With empty, ambient temperature tanks and dormant avionics, CRYOTE represents minimal risk to the primary payload, simplifying acceptance by the primary payload community. The primary payload community may have serious issues flying with a cryogenic secondary payload, especially if this cryogenic payload drives launch day requirements such as loading, venting, and recycle turn around duration. The CRYOTE approach of on-orbit cryogenic loading may be mandatory to gaining broad primary mission acceptance to flying a cryogenic secondary payload. Centaur's avionics bring CRYOTE to life after the primary payload is separated.

There are three distinct versions of CRYOTE designed to flexibly satisfy a broad range of mission objectives (Table 1):

- **CRYOTE Lite –** To save cost and schedule, CRYOTE Lite utilizes the existing Centaur avionics for power and control. Reliance on Centaur batteries limits the primary mission duration to <24 hours. CRYOTE Lite provides on-orbit demonstration with either LH2 or LO2 of system chilldown, liquid transfer, tank fill, transient boil-off, mass gauging, propellant management device, thermodynamic vent system and vapor cooling. With the addition of an independent battery-powered telemetry system, CRYOTE Lite can transmit limited cryogenic system performance (temperature, pressure) for a period of months.

- **CRYOTE Pup** – Expands CRYOTE Lite's capabilities with the addition of dedicated mission avionics including a flight computer, solar power, two-way communications and guidance enabling multi-month mission duration. CRYOTE Pup increases mission capability over CRYOTE Lite by incorporating closed loop control, multi-month mission, increased sensor count, active cooling, long term stratification, cryogenic fluid couplings, and integrated $GH_2$ propulsion attitude control.

- **CRYOTE Grande** – Enhances CRYOTE Pup by enabling both LH2 and LO2 in a single mission thanks to additional plumbing and extra tanks. This additional hardware provides the capability to perform numerous LH2 and LO2 transfers (settled and unsettled), demonstrate $H_2/O_2$ propulsion, zero LO2 boil-off storage, low and zero LH2 boil-off storage, and multiple tank designs, propellant management devices, and liquid acquisition devices on a single mission.

**Table 1 CRYOTE's Three Configurations are Designed to Flexibly Satisfy a Broad Range of Mission Objectives Enabling Testing of NASA, Academia and Industry Defined Experiments.**

| | **Lite** | **Pup** | **Grande** |
|---|---|---|---|
| Duration on-orbit | <24 Hours | >6 Months | >6 Months |
| Lead Time to ILC | 2 Years | 2+ Years | 2+ Years |
| Flight Computer | Centaur | CRYOTE Avionics | CRYOTE Avionics |
| System Control | Open Loop | Closed Loop | Closed Loop |
| Power | Centaur Batteries | Solar Arrays | Solar Arrays |
| Attitude Control | Centaur Hydrazine | Cold Gas Thrusters Using Vented $H_2$ | Cold Gas & $H_2/O_2$ Thrusters |
| Telemetry | Centaur | CRYOTE Antennas | CRYOTE Antennas |
| Upper Stage Launch Vehicle Separation | Remains Attached to Centaur | Remains Attached to Centaur | Remains Attached to Centaur |
| Cryogen | Centaur Residual LH2 or LO2 | Centaur Residual LH2 or LO2 | Centaur Residual LH2 & LO2 |
| Tank size | 1 * 1000L<br>1.2 m (48 in) diameter | 1 * 1000L<br>1.2 m (48 in) diameter | 1 * 1000L; 1.2 m dia<br>3 * 400L; 0.9 m (36") dia |

## 2.0 Select CRYOTE Details

***2.1 CRYOTE Core:*** The subsystem for all CRYOTE mission variants is called the CRYOTE Core and is shown in Figure 2. CRYOTE Core employs a custom, 1,000L LH2/LO2 compatible tank. Solenoid latching valves are employed to facilitate propellant transfer and control of multiple experiments, which are under development by Ball Aerospace and United Launch Alliance (ULA). CRYOTE core resides in an ESPA ring. Support of the tank is provided by low conductivity, Ball Aerospace flight heritage cryogenic struts, mounted in a hexapod arrangement. For initial missions, Ball Aerospace high performance cryogenic multi-layer insulation (MLI), integrated MLI (IMLI), or a combination of the two will be used to provide tank acreage insulation.

The tank design is based on Ball Aerospace heritage design and manufacturing processes. The tank can accommodate multiple internal experiments, and has external mounting provisions for experimental hardware. Provisions to the tank design have been included for the incorporation of multiple propellant management device (PMD) technologies as well as zero-g mass gauging sensors such as the NASA Glenn Research Center (GRC) radio frequency technologies and the Sierra Lobo CryoTracker.

***2.2 Cryogenic Propellant Transfer:*** At a minimum, any CRYOTE configuration demonstrates cryogenic propellant transfer: LH2 only, LO2 only, or both LH2 and LO2. This description will include both propellants.

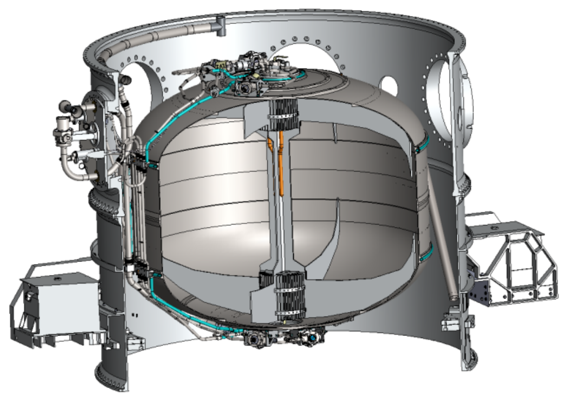

**Figure 2 – CRYOTE Core provides a flexible testbed for short and long term on-orbit cryogenic propellant storage and transfer experiments.**

Following launch and safe delivery of the primary payload, Centaur will perform a standard Collision Contamination and Avoidance Maneuver (CCAM) to ensure adequate separation from the primary payload and that Centaur is in an appropriate disposal orbit. During CCAM the initial chilldown of the CRYOTE plumbing and tanks commences. This is accomplished by flowing Centaur's cold hydrogen ullage gas through CRYOTE's LH2 tank and then venting the $GH_2$ overboard through a balanced vent system. During this venting Centaur's is settled to ensure acquisition and transfer of gaseous, not liquid, hydrogen.

A settling sequence including reverse settling and a Centaur transverse spin chills the system and prepares the Centaur upper stage for filling the CRYOTE tanks (Figure 3). A similar pulse/vent chilldown process has been demonstrated on past Centaur flights using both LH2 and LO2 to chill Centaur's feedlines and RL-10 pump housing.

Once the transfer lines and CRYOTE tanks have been chilled the transfer of Centaur residual LH2 and LO2 can commence. The LH2 and LO2 transfers are pressure fed. Centaur tank pressures ensure that the LH2 and LO2 will be sub-cooled. This sub-cooled LH2 and LO2 will enter their respective CRYOTE tanks, quenching the vapor and sucking in additional liquid. This "zero vent fill" transfer process is indifferent to the liquid-gas location inside the CRYOTE tanks, avoiding inadvertently venting liquid overboard which would represent wasted performance. This zero vent fill process has been ground-demonstrated to be very effective, attaining nearly 100% fill. This entire chill-and-fill process is designed to be accomplished in less than 30 minutes. 30 minutes represents the available time before Centaur's hydrogen tank pressure starts to approach structural limits forcing the LH2 to be resettled aft allowing for Centaur tank venting.


**Figure 3 The Use of Reverse Settling and Transverse Spin Will Reorient the LH2 to the Forward End of Centaur's LH2 Tank Enabling Bubble Free Liquid Acquisition.**

Following completion of the LH2 and LO2 transfer, Centaur's tanks are vented to vacuum, evacuating the majority of residual propellants, safing Centaur. Centaur's systems will then be turned off leaving CRYOTE avionics in control.

***2.3 Thermal modeling:*** In order to evaluate the transfer and storage performance of the CRYOTE Core[ii] subsystem, detailed thermal/fluidics models were developed that allowed parametric evaluation of the system level design. These models were developed to allow extensibility to other cryogenic propellant storage and delivery systems. A model was developed to predict the performance of the CRYOTE Ground Test Article to not only predict the performance of this experiment, but also to validate the CRYOTE Core model predictions with actual data.

### As can be seen in the analysis in

Figure 4, all aspects of the mechanical, thermal, and pneumatic design must be accounted for to optimize the results of a successful CRYOTE transfer. For the CRYOTE platform, propellant transfer is pressure fed based on a significant residual gas volume and subcooling of the liquid hydrogen within the Centaur hydrogen tank. The horizontal axis is the normalized design parameter for fill/vent line diameter, ESPA temperature, line K factor, vent line length, Centaur liquid supply pressure, Centaur liquid supply temperature, fill line length, valve K factor, and tank mass. The vertical axis is the fill time in minutes.

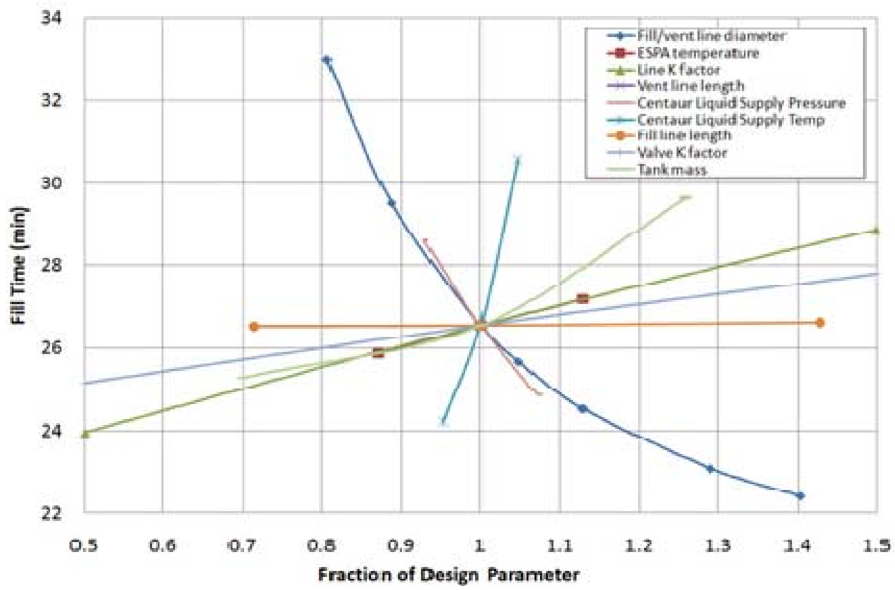


Figure 4 - Parametric analysis of CRYOTE tank cool down and fill design parameters

***2.4 Orbital Analysis:*** Another systems level goal of CRYOTE Pup/Grande is the ability to provide attitude control though the use of hydrogen boil-off in lieu of a hydrazine based attitude control system. Various operational orbits were analyzed, and optimization of attitude control requirements was performed (Figure 5).

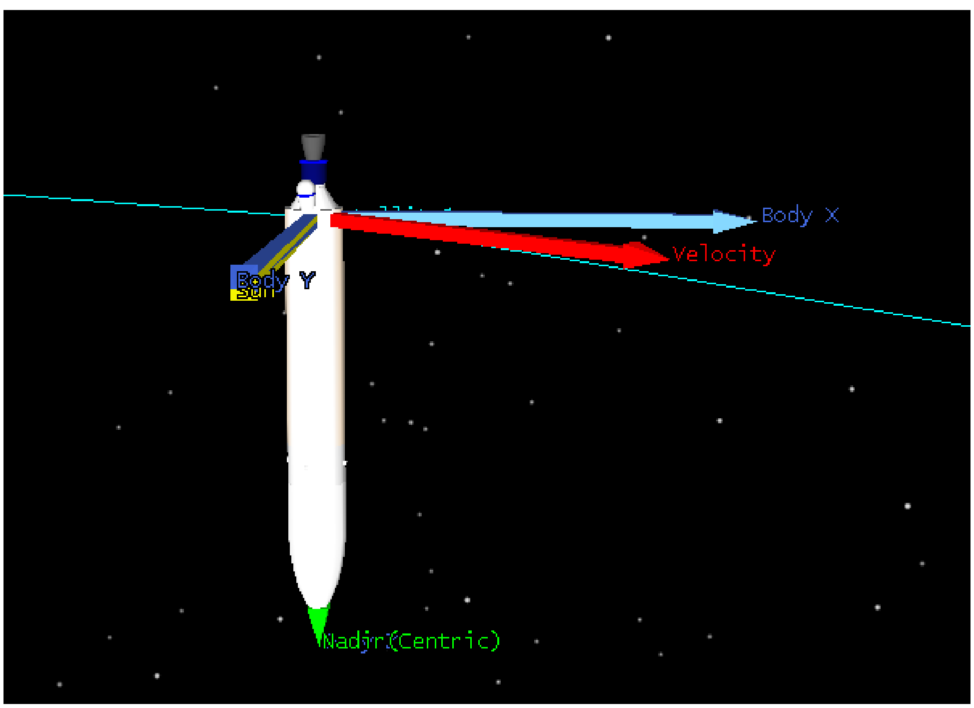


Figure 5 - CRYOTE orbital analysis was used to optimize the mission attitude control requirements

This analysis not only validated the ability to employ cold gas hydrogen thrusters for attitude control, but also evaluated the quantities of propellant required for various mission scenarios.

***2.5 Thermodynamic Vent System (TVS):*** **The system level thermal analysis shown in** Figure 4 incorporated both a TVS and a Vapor Cooled Shield (VCS) to maximize the passive storage duration for CRYOTE Core. A TVS can be used to provide significant cooling to stored, subcritical two-phase cryogenic propellants. Expansion and pressure drop of liquid (or two-phase fluid) propellant across a Joule Thompson (JT) orifice provides cooling that can be used to intercept system heat leaks, or cool the bulk gaseous or liquid stored in the propellant tank. The heat exchange process with the stored fluid can take place within the tank utilizing an internal heat exchanger within the tank, or by using fluid lines coupled to the tank wall.

For CRYOTE Core, the TVS is used primarily to intercept parasitic heat leaks from structural and plumbing penetrations though the Integrated Multi-Layer Insulation (IMLI) and into the tank. The TVS on the CRYOTE Lite/Pup/Grande programs was optimized to provide the maximum amount of cooling using duty cycled TVS operation, or TVS flow rates matched to the system level boil-off.

***2.6 Vapor Cooled Shield (VCS):*** **Also included in the** Figure 4 analysis was a VCS, imbedded in the IMLI, to intercept the broad area heat leak into the stored hydrogen. The analysis indicated that a significant increase in the LH2 storage life was achievable by the incorporation of the VCS. For the CRYOTE Core, the VCS is embodied as an aluminum shield embedded in the IMLI blanket. This shield is cooled by the gas exiting the TVS. The technology used to support this design is identical to that used on the Ball Aerospace Near Infrared Camera and Multi-Object Spectrometer (NICMOS) program for the Hubble Space Telescope, as well as on every Space Shuttle Power Reactant and Storage Distribution (PRSD) tank. Inclusion of the VCS layer within the IMLI further increases Micro-Meteoroid and Orbital Debris (MMOD) protection.

***2.7 Structural Heat Load:*** For cryogenic in-space stages such as the Saturn IVB, Centaur, and DCSS, structural supports account for a large fraction of the total heat load. This support structure heating is even more critical for long duration cryogenic stages where incorporation of high performance IMLI and integrated VCS substantially reduces the surface area heating. Substantially reducing the structural load path requires a combination of minimizing the load (e.g., launching tank empty when possible) and providing a structural interface designed for minimum heat transfer (e.g., struts). Ball cryogenic dewar strut technology (Figure 6***)*** is readily extensible to large propulsion stage architectures. Key elements include leveraging Ball flight heritage strut designs, as well as vapor cooling leveraged from flight programs such as Spitzer.

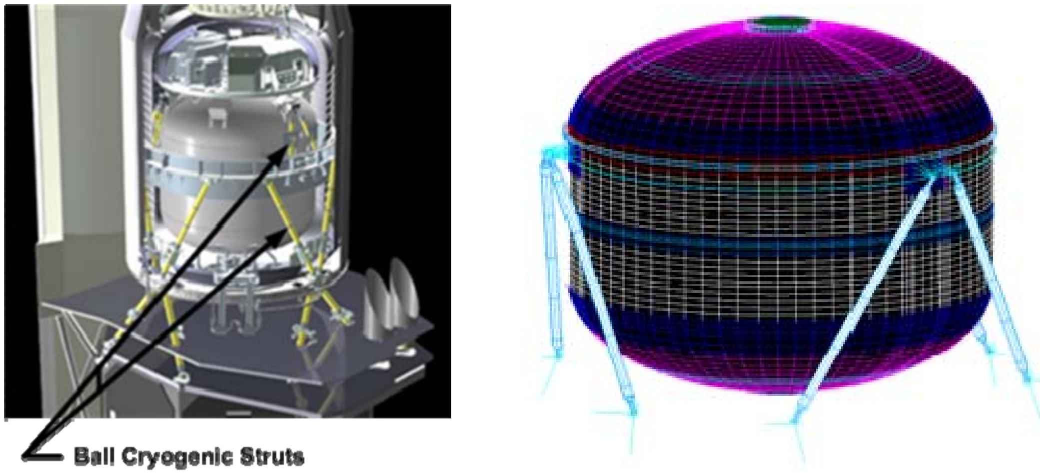


Figure 6 - Ball Aerospace flight heritage cryogenic strut technology has been optimized to meet the structural and thermal requirements of the CRYOTE missions

This hexapod strut technology has been tailored specifically for CRYOTE Core[iii] as shown in Figure 6. The hexapod arrangement is also based on flight heritage designs, and was examined in detail in the Cryogenic Propellant Storage and Delivery contract performed by Ball Aerospace for NASA GRC[iv]. This design was optimized to provide the best design solution for the CRYOTE mission by evaluating the structural, thermal, and coupled loads requirements for the mission.

***2.8 Integrated Multi-Layer Insulation (IMLI) for CRYOTE Ground Test Article:*** NASA, Quest, and Ball Aerospace have been developing advanced, cryogenic IMLI to enhance on-orbit storage of cryogenic propellants[v]. The cryogenic propellant storage and experimental tanks are shrouded in IMLI, incorporating radiation barriers and Micrometeoroid Orbital Debris (MMOD) protection. The various IMLI layers are separated by micro-molded polymer structures (Figure 7)**.** The polymer substructures promise to improve IMLI thermal and MMOD performance by providing precise, engineered layer spacing.

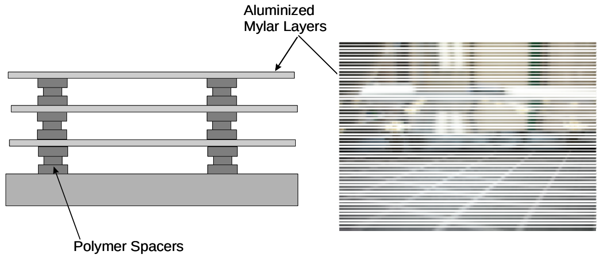


Figure 7 - Integrated MLI provides enhanced thermal and MMOD protection

A NASA-led study is currently underway to optimize the lay-up of IMLI for the CRYOTE Ground Test article, with extensibility to the flight application. An example of an optimized layup for this ground test is shown in Figure 8. This study is looking to optimize the application of IMLI technologies to various tank geometries.

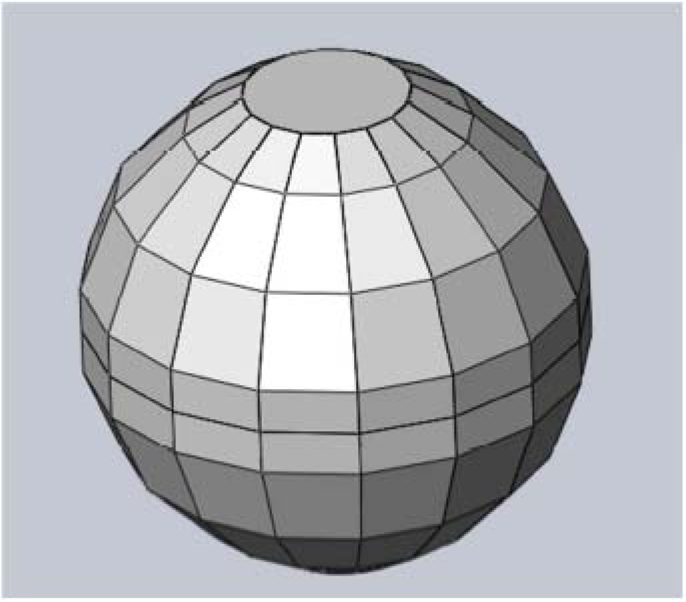

**Figure 8 - Optimization of CRYOTE IMLI layup (Credit: Quest)**

***2.9 Active Broad Area Cooling (BAC):*** As the CRYOTE Core concept matured, the experimental platform has also been designed to incorporate multiple NASA based technology demonstrations. One key goal of the current NASA technology roadmaps is the demonstration of zero boil off (ZBO) LO2 and LH2 propellant storage systems, which requires the use of active cooling. Active BAC on a cryogenic propellant tank simulator was demonstrated in a laboratory environment by NASA and Ball Aerospace (Figure 9)[vi]. For this testing, the BAC was embodied as a helium cooled shield imbedded within cryogenic Multi-Layer Insulation (MLI).

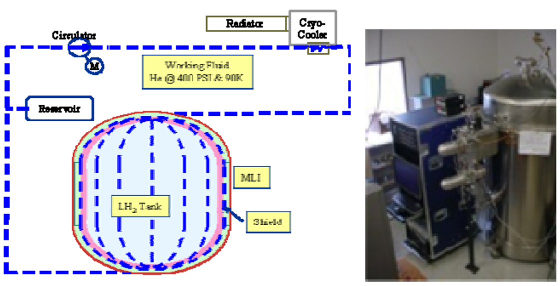


**Figure 9 - NASA/Ball Aerospace Broad Area Cooling test program**

For this program, a pumped helium circulation loop was employed to transfer heat from a 500 liter LN2 dewar shield to a cryocooler. Ball Aerospace built a novel system that uses the Stirling refrigerator's compressor to drive the circulating flow by means of valves in its transfer line, eliminating the need for a separate circulation pump. This technology demonstration is identical to that which could be employed on the CRYOTE Core to demonstrate ZBO.

Flying cryocooler technology on the CRYOTE Pup/Grande missions will validate the capability of cryocooler technology to extend the life of stored cryogenic propellants. With sufficient power and intelligent system design, ZBO for any cryogenic propellant is achievable. Ball Aerospace has designed, built, and delivered two flight cryocoolers, with one reaching seven years on-orbit with no performance degradation. Ball's current cryocooler focus is on higher capacity Stirling coolers with approximately 2 W at 35 K. In addition, circulation loops have been added to these Stirling coolers to produce very low temperatures and remote cooling.

## 3.0 Conclusion

CRYOTE is a customizable laboratory for demonstration a variety of CFM technologies, shown with multiple tanks and a long-duration avionics system in Figure 10. CRYOTE Lite provides an affordable first step toward enhanced CFM, providing the risk reduction flight test for more costly and demanding technology demonstration missions such as CRYOTE Pup and CRYOTE Grande.

Results from CRYOTE can provide the critical in-space CFM demonstration to allow selection of mission architectures that utilize on-orbit fueling, long duration cryo storage and development of cryo propulsion stages truly designed for in-space use that have higher mass fractions and reduced boil-off compared to current designs.

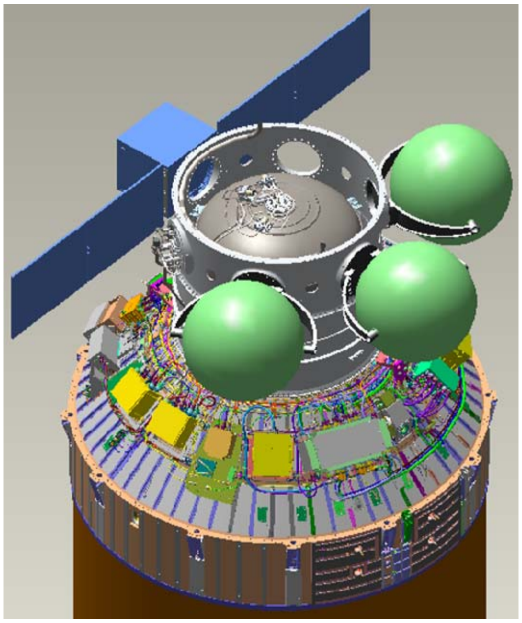

**Figure 10 CRYOTE Provides a Cost Effective Laboratory for Orbital Testing of CFM Technologies.**

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i Wollen, M. A., Gravlee, M., Johnson, W.L.; 'CRYOTE (Cryogenic Orbital Testbed) – Goals, Progress, and Potential', 2009 JANNAF Conference, Colorado Springs

ii Gravlee, M., Vera, C., Wollen, M., McLean, C., and Walls, L.; "Micro-gravity Cryogenic Experiment Opportunity," AIAA 2010-8838, AIAA Space 2010 Conference & Exposition, Anaheim, CA, 30 August – 2 September 2010

iii McLean, C.H., et al.; Simple, Robust Cryogenic Propellant Depot for near Term Applications", IEEE 2011-1044 IEEE Aerospace Conference, Big Sky, MT, January 2011

iv McLean, C., Mills, G., Riesco, M., Meyer, M., Plachta, D., Hurlbert, E.; "Long Term Space Storage and Delivery of Cryogenic Propellants for Exploration", Joint Propulsion Conference, AIAA-2008-4853, Hartford, CT, July 2008

v Dye, S.A., Kopelove, A.B., Mills, G.L.; "Integrated and Load Responsive Multilayer Insulation", Advances in Cryogenic Engineering. AIP Conference Proceedings, Volume 1218, pp. 946-953, 2010

vi Feller, J.R., Plachta, D.W., Mills, G., and McLean, C.; "Demonstration of a Cryogenic Boil-Off Reduction System Employing an Actively Cooled Thermal Radiation Shield," in Cryocoolers 16, edited by S.D. Miller and R.G. Ross, Jr., International Cryocooler Conference, Inc., Boulder, CO, 2011, pp. 601-609


 