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Micro-gravity Cryogenic Experiment Opportunity

Mari Gravlee[1] and Chris Vera[2]
United Launch Alliance, Centennial, CO

Mark Wollen[3]
Innovative Engineering Solutions, Murrieta, CA

Chris McLean[4]
Ball Aerospace, Boulder, CO

Laurie Walls[5]
NASA Kennedy Space Center, FL

Demonstrating cryo-fluid management (CFM) technologies in space is critical for advancing current space technologies in order to develop the capability for longer duration in-space missions. The capability to perform long duration in-space missions is a near term vision for most of the space community. Currently, space-based cryogenic propulsion does not support the capability to perform for the hours, weeks to years needed for space exploration and space science. The Cryogenic Orbital Testbed (CRYOTE) provides an affordable low-risk environment to demonstrate a broad array of critical CFM technologies that cannot be tested in Earth's gravity.

United Launch Alliance has partnered with Innovative Engineering Solutions, the National Aeronautics and Space Administration (NASA), and others in the development of a ground test article of CRYOTE to be tested and used as a baseline for a flight article of the testbed. CRYOTE has been developed to fly as a secondary payload between the primary payload and the Centaur upper stage on an Atlas V rocket. The testbed provides minimal risk to the primary payload by launching with dormant avionics and empty of any cryogens. Flying as a secondary payload allows the testbed to be an affordable, cost-effective method to demonstrate several CFM technologies—which include but are not limited to propellant transfer, pressure control, active cooling, and long-term storage.

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[1] Sr. Mechanical Engineer, Advanced Programs, United Launch Alliance, Centennial, CO 80112, AIAA Member

[2] Engineering Intern, Advanced Programs, United Launch Alliance, Centennial, CO 80112

[3] Vice President, Innovative Engineering Solutions, Murrieta, CA 92562, AIAA Member

[4] Senior Engineer, Spacecraft Systems, Ball Aerospace and Technologies Corp., Boulder, CO 80301, AIAA Member

[5] Thermal/Fluids Group, NASA Launch Services Program, Kennedy Space Center, FL 32899, AIAA Senior Member

I. Introduction

United Launch Alliance (ULA), in partnership with the National Aeronautics and Space Administration (NASA) and industry, is developing an affordable CRYogenic Orbital TEstbed (CRYOTE) to demonstrate a broad array of critical cryogenic fluid management (CFM) technologies in space. These technologies include: system chilldown, transfer, handling, health management, mixing, pressure control, active cooling and long-term storage. Testing and validation in the micro-gravity environment is essential for developing improved mission capabilities using cryogenics. Results from CRYOTE experiments can aid in the development of enhanced upper stages, Earth Departure Stage (EDS), lunar lander, cryogenic propulsion modules, propellant depots, solar thermal and nuclear thermal propulsion systems, small satellite hydrogen propulsion, and cryogenic science applications.

CRYOTE is an affordable, long-duration in-space laboratory, shown in Figure 1, containing a tank filled with liquid hydrogen (LH2)[1] that is transferred from the Atlas V upper stage Centaur after the primary payload is separated.

CRYOTE separates from Centaur to become its own independent, orbiting laboratory, shown in Figure 2. A non-separating version of CRYOTE called CRYOTE Lite can be launched as early as December 2012. CRYOTE Lite remains attached to Centaur, relies primarily on Centaur for power and flight computer, and has a life of 8-20 hours. The free-flying version of CRYOTE contains independent avionics equipped with a solar array, enabling a system life of weeks to months.

CRYOTE defers dedicated launch costs by flying as a secondary payload on an Evolved Expendable Launch Vehicle (EELV), as shown in Figure 1. CRYOTE is required to negligible risk to the primary payload which is achieved by launching CRYOTE with an empty tank and dormant avionics. Centaur's avionics bring CRYOTE to life after the primary payload is separated. CRYOTE's backbone structure includes the EELV Secondary Payload Adapter (ESPA) ring that has been flight-proven on the STP-1 and LRO/LCROSS missions.

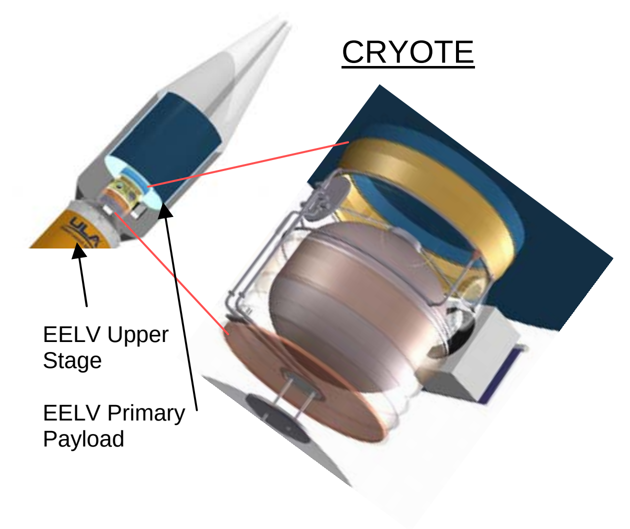


Figure 1 - Cryogenic Orbital Testbed

II. Status

The CRYOTE project is expected to conduct a ground test by the end of calendar year 2010. A CRYOTE prototype designed and manufactured by Innovative Engineering Solutions (IES) and shown in Figure 3 was insulated with Multi-Layer Insulation (MLI) at NASA Kennedy Space Center (KSC). The ground test article consists of a 28-inch titanium tank donated by NASA Jet Propulsion Laboratory (JPL) attached to an ESPA ring with a conical composite skirt. The ground test will use liquid nitrogen (LN2) to demonstrate the chilldown, propellant transfer, and steady-state boiloff rate of a cryogenic flight system under vacuum. This ground test is unique from others because it utilizes a tank with flight wall thickness, and data from this test will support the sequencing of a flight article. NASA has several vacuum chambers at NASA MSFC, JSC, and GRC that fulfill the specifications for the CRYOTE ground test, and the location where the ground test will be performed is influenced by the NASA center that acquires funding.

A ground test design review was held in July 2010 and was attended by 25 people from NASA KSC, Marshall Space Flight Center (MSFC), Glenn Research Center (GRC), and Johnson Space Center (JSC), ULA, Ball Aerospace, Yetispace, and Sierra Lobo. The ground test article design and instrumentation details were reviewed, and the test facility plans and test sequence developed by MSFC/Yetispace were discussed.

The two days after the design review, NASA KSC hosted CRYOTE Industry Days where NASA Centers and interested industry partners were invited to learn more about CRYOTE and share their inputs on applications of the testbed in the context of NASA's space technology roadmap. Breakout sessions allowed smaller groups to discuss in detail CRYOTE objectives, concepts, and technology advancement opportunities.

To ensure that CRYOTE and CRYOTE Lite's designs are copacetic with the Centaur upper stage, risk mitigation tasks focusing on structure, pressure control, sequencing, and avionics are being led by ULA, funding by ULA IRAD, NASA Innovative Partnerships Program (IPP), and KSC. For structure, the clocking of shelves holding CRYOTE Lite batteries, valves, and avionics boxes is being designed to not interfere with ground support equipment required for stacking the launch vehicle on the launch pad. For pressure control and sequencing, analysis is being conducted to determine reverse settling requirements and venting constraints for system chilldown and propellant transfer in space. An avionics risk mitigation task determining avionics requirements will enable an assessment of a low-cost avionics capability. To minimize cost for CRYOTE Lite, avionics control is provided by Centaur avionics and an auxiliary avionics box developed by Design Net Engineering, LLC. The box is a low cost option to enhance avionics capability for CRYOTE because most of its development was funded by a different ULA IRAD project to provide an interface between secondary payloads and Centaur avionics.

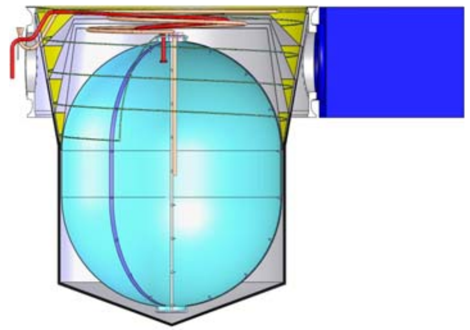


Figure 2 – CRYOTE Free Flyer (Credit: IES)

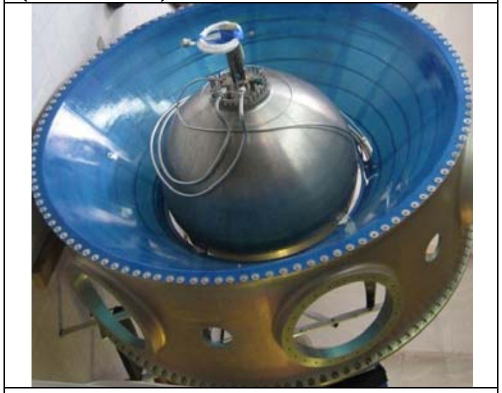


Figure 3 – CRYOTE Ground Test Article (Credit: IES)

ULA consistently monitors the performance excess of EELV missions to determine what missions are candidates for secondary payloads. Currently a prime candidate mission for CRYOTE Lite is a commercial mission scheduled to launch in late 2012. The commercial mission is welcoming secondary payloads to utilize its excess performance.

III. Cryogenic Applications

The CRYOTE and CRYOTE Lite experimental test beds provide a unique, long term environment for validating the numerous technologies required for the long term storage and delivery of cryogenic propellants. Though some ground testing has been performed evaluating various mixing, venting, insulation, propellant quantity gauging, and other supporting technologies, actual testing of these subsystems in a micro- or zero-g environment has been limited to subscale testing in reduced gravity aircraft, if at all.

In any CRYOTE configuration, transfer of residual LH2 from Centaur to the CRYOTE tank will demonstrate transfer of cryogenic propellants on orbit required for propellant depots and flagship missions Several smaller-scale technologies can also be brought to a Technology Readiness Level (TRL) 9 including the Sierra Lobo CryoTracker™ advanced technology propellant mass gauging system[2], a passive Thermo-dynamic Vent System (TVS) to augment thermal isolation of the stored cryogen, Ball Aerospace advanced technology integrated Multi-layer Insulation (IMLI)[3], other MLI designs, and Liquid Acquisition Device (LAD)/Propellant Management Device (PMD) technology with cryogenic propellants.

CRYOTE can be a first step in the roadmap for advanced (CFM) technologies. Because CRYOTE Lite can launch as early as 2012 with sufficient funding, the CRYOTE team is actively looking for partners from industry and government agencies that would assist in the development of this testbed. Potential partners and sponsors of CRYOTE could use this first step as a means of enhancing their current technologies to become Centers of Excellence in long-duration, high-performance space flight. Partners willing to fund some development of CRYOTE are likely to include experiments on the flight article beneficial to their interests.

Several high-level projects can be supported through the advancement of CFM technologies to a high TRL. The next few sections outline CRYOTE's benefits to LOX/LH2 Propulsion, Propellant Depots, LOX/methane propulsion, EELV advanced upper stages, and Lunar Landers.

A. LOX/LH2 Propulsion

Figure 4 – Concept image of the Ares V EDS in orbit, shown with Orion docked with the Lunar Lander. (Credit: NASA)

NASA's current vision is to launch crew and cargo beyond low earth orbit (LEO) using a first stage rocket booster and the EDS, shown in Figure 4. The EDS is responsible for getting the payload to an earth escape velocity and into lunar orbit. Because of the high performance of LOX/LH2 systems, a probable EDS design uses LH2 and LOX propellants[4].

The purpose of CRYOTE is to better understand the storage and handling of cryogenics, such as LH2, in a micro-gravity environment. Improving our understanding of how to store, gauge, and acquire cryogens for long durations in a tank when placed in zero or low-gravity environments will help to enhance the capability of all in-space cryogenic propulsion systems including the EDS or Altair.

B. Propellant Depots[5]

The weight of space-bound payloads is constrained by the amount of propellant required to achieve its desired orbit. If an upper stage could be topped off or filled in LEO from a propellant depot, the payload capacity of a given launch vehicle could greatly increase. Any launch vehicle, such as Atlas V, Delta IV, or Ares V, would be able to use propellant depots to refuel in space and then continue on to their destination. This ability to refuel has a amplifying effect. For example, an Atlas 401 using propellant depots could provide the same Trans-Mars capacity as an Atlas 551. Alternatively, Ares V's lunar surface payload is doubled.

One main function of CRYOTE is to demonstrate the capability to store and transfer cryogens in space while maintaining minimal boiloff, a mandatory capability for functioning propellant depots. CRYOTE is an end-to-end demonstration of a propellant depot and the first step in developing the capability to fulfill these requirements of propellant depots.

C. LOX/Methane Propulsion[6]

The original design of CRYOTE uses residual LH2 from the launch vehicle upper stage, but that is not its only capability. CRYOTE could also be filled from Centaur's LOX tank. LOX experiments in micro and zero gravity would be directly applicable to propellant management concepts for a LOX/Methane propulsion system. This eliminates the need to store LOX in the spacecraft on the launch pad simplifying ground processing and reducing payload mass. An intriguing option would be to actually fuel small propulsion systems with LOX on orbit.

D. Advanced Upper Stages

The ability to increase launch vehicle capability and versatility while still maintaining cost effectiveness is a near term goal for the aerospace community. The advancement of CFM technologies allows current upper stages to increase efficiency and perform for longer durations. These advanced upper stages could then accommodate heavier payloads and perform more demanding missions while becoming more cost-effective.

CRYOTE also becomes a natural platform on which to demonstrate small high performance thrusters that utilize upper stage main propellants. Currently, most upper stages utilize a LOX/LH2 for primary propulsion while relying on a separate hydrazine system for RCS. The demonstration of LH2/LOX thrusters sized for upper stage attitude control can facilitate the development of a system that eliminates the need for hydrazine, an additional propellant and a toxic one, on advanced upper stages. Should bi-propellant thrusters be demonstrated on CRYOTE, a relatively small tank of oxygen could be loaded and carried along, or it is conceivable that a future version of CRYOTE could also use liquid oxygen transferred from Centaur, thereby maintaining the highly safe, inert characteristics of the baseline CRYOTE concept.

Simple, heated hydrogen thrusters, using either electrical or direct solar energy, can yield high specific impulse values due to the low molecular weight of hydrogen. An optimized insulation design allows a spacecraft powered by electrical or solar heating to utilize LH2 over a long period of time, beneficial due to the limited power output provided by these propulsion systems. Electrical or direct solar heating will yield limited power output, but with good insulation the spacecraft can facilitate a large orbital change when days or weeks are available to make this transfer. More advanced thrusters (ion, etc.) could also, of course, be employed.

E. Lunar Lander

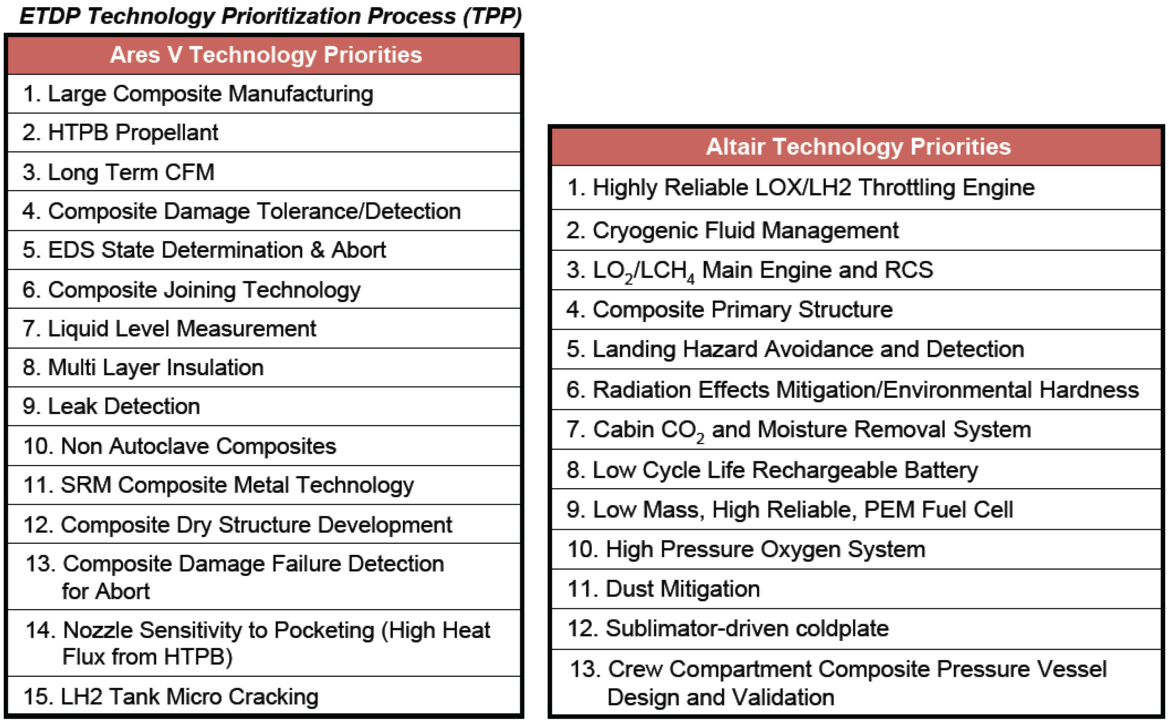
A lunar lander based on operational upper stage technology minimizes development and recurring costs while increasing crew safety and reliability[7]. Because of the high performance provided by LO2/LH2 propulsion and the possibility of in-situ resource utilization, NASA may choose to use an LH2/LOX lander to support sending the next humans to the moon. CRYOTE can demonstrate the CFM technologies needed for this advanced spacecraft, bringing the TRLs of these technologies to comfortably high levels.

IV. Advantages of CFM Technologies

One of the most critical technology areas requiring maturation that was identified during the development of the NASA Exploration architecture was CFM. Three major subsystems, the EDS, the Altair descent and the Altair ascent stages required major leaps in in-space cryogenic propellant storage and delivery technologies in order to meet the mission requirements of returning men to the moon. As an example, the initial Exploration Systems Architecture Study (ESAS) placed the EDS/Altair stack in orbit for up to 90 days before launch and docking of the Orion manned vehicle. As the Exploration architecture design progressed, the duration of the EDS/Altair stack in LEO was reduced from 90 to 4 days due to excessive boil-off from the EDS[8]. From the 2008 NASA Exploration Technology Development Program (ETDP) Altair and Ares V studies, CFM was noted to be the third highest risk for Ares V Altair and the second highest risk for Altair, shown in Figure 5.

As the focus of Exploration has shifted away from the lunar mission focus to LaGrange Point, Mars, Near Earth Objects (NEOs), and other deep space manned missions, the requirement for long term cryogenic depots has come to the forefront of NASA’s advanced technology focus, illustrated in Figure 6.

The same cryogenic propellant storage and delivery technologies identified as critical for development during the lunar architecture studies are just as relevant for long term propellant depots. The CRYOTE and CRYOTE Lite platforms provide a relatively inexpensive, fast turn-around test bed to advance critical CFM technologies. The development and implementation of these test beds will have a short lead time due to the use of well-understood technologies that have already supported long-duration spacecraft. Using these well-understood technologies as a foundation, CRYOTE can provide a low cost method to validate and advance CFM technologies for Exploration.



ETDP Technology Prioritization Process (TPP)

Ares V Technology Priorities
1. Large Composite Manufacturing
2. HTPB Propellant
3. Long Term CFM
4. Composite Damage Tolerance/Detection
5. EDS State Determination & Abort
6. Composite Joining Technology
7. Liquid Level Measurement
8. Multi Layer Insulation
9. Leak Detection
10. Non Autoclave Composites
11. SRM Composite Metal Technology
12. Composite Dry Structure Development
13. Composite Damage Failure Detection for Abort
14. Nozzle Sensitivity to Pocketing (High Heat Flux from HTPB)
15. LH2 Tank Micro Cracking

Altair Technology Priorities
1. Highly Reliable LOX/LH2 Throttling Engine
2. Cryogenic Fluid Management
3. LO_2/LCH_4 Main Engine and RCS
4. Composite Primary Structure
5. Landing Hazard Avoidance and Detection
6. Radiation Effects Mitigation/Environmental Hardness
7. Cabin CO_2 and Moisture Removal System
8. Low Cycle Life Rechargeable Battery
9. Low Mass, High Reliable, PEM Fuel Cell
10. High Pressure Oxygen System
11. Dust Mitigation
12. Sublimator-driven coldplate
13. Crew Compartment Composite Pressure Vessel Design and Validation

Figure 5 - Top risk identified by NASA for Altair included CFM[9]

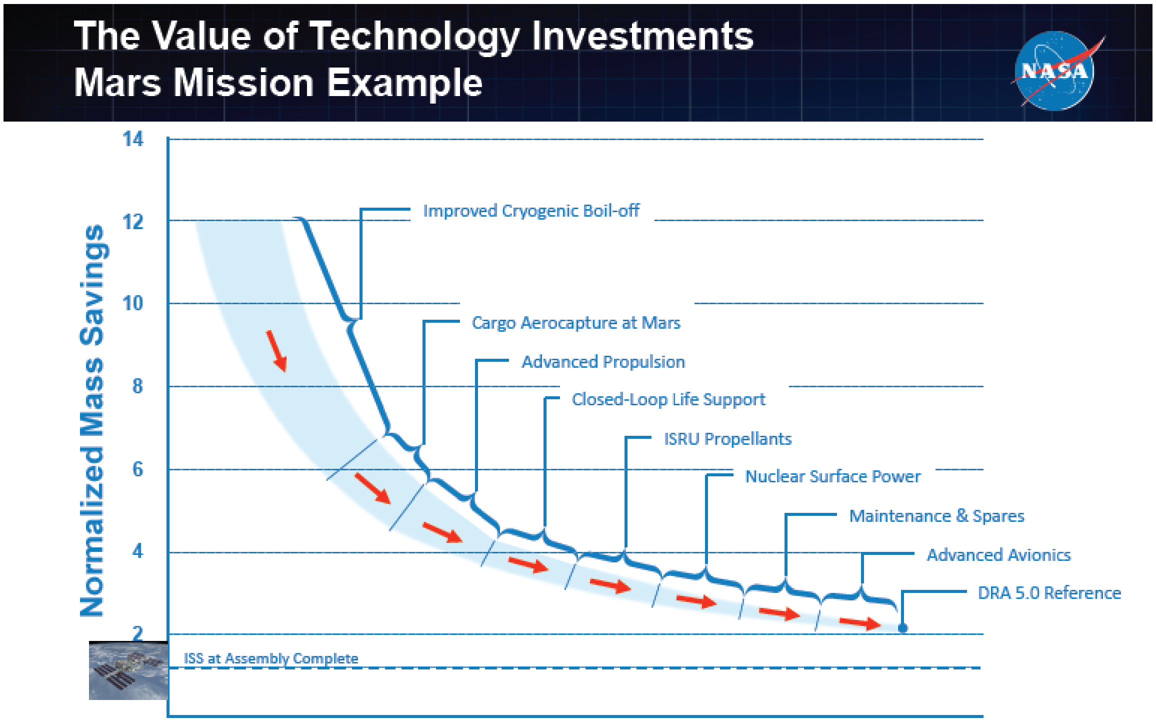


Figure 6 - NASA ESMD Mars mission shows dramatics impact of increasing in-space cryogenic propellant storage technologies[10]

V. Rideshare

ULA consistently monitors the performance excess of EELV missions to determine what missions are candidates for secondary payloads. Candidate missions for CRYOTE require at least 1000 lbs of performance excess, at least 29 inches of height within the payload fairing, and an orbit around earth to maximize telemetry duration. CRYOTE must also not preclude any disposal requirements necessary for the primary mission. Although NASA and Department of Defense (DoD) missions are considered, the most promising first flight Rideshare opportunity for CRYOTE Lite is a commercial mission scheduled to launch at the end of 2012. This mission has a height constraint much larger than 29 inches, which will allow the use of an ESPA ring and a large tank (~48" dia).

CRYOTE itself can be a carrier for additional secondary payloads due to its ESPA ring backbone structure that contains six 15" dia mounting ports. Once an autonomous CRYOTE platform is operational, the evolution into a versatile small, secondary payload delivery vehicle is straightforward. CRYOTE avionics and hardware will only occupy 2 of the 6 available payload ports on the ESPA ring, leaving the remaining 4 ports available for experiments, propulsion system hardware, and small payloads.[11] With maneuvering capability, the secondary payloads can be maneuvered to a variety of orbits prior to release. With high performance thrusters and modest weight reduction efforts, CRYOTE could potentially send secondary payloads to very high or even Earth escape and lunar transfer trajectories.

VI. Conclusion

CRYOTE can be the first step to the advancement of CFM technologies, enabling a high performance space transportation architecture. This testbed is a near term opportunity to demonstrate key CFM technologies in space while maintaining affordability and low-risk. Its affordability is achieved through its capability to fly as a secondary payload, deferring dedicated launch costs for the testbed.

Currently the CRYOTE project is focused on an upcoming ground test, flight concept risk mitigation tasks for a 4Q2012 launch with a commercial satellite, and the pursuit of full funding for the flight. In partnership with Innovative Engineering Solutions, NASA, Sierra Lobo, and others a ground test article of CRYOTE has been assembled. The ground test will take place inside of a vacuum chamber to simulate the thermal conditions of propellant transfer and storage. Yetispace at Marshall Space Flight Center is currently designing a schematic to simulate CRYOTE sequencing and conditions in the ground test. The components are in place to perform a ground test in 2010.

CRYOTE has the ability to advance the TRL numbers of technologies to supoprt propellant depots, NASA exploration spacecraft, and advanced upper stages, and thereby can directly contribute to the future of space flight. With CRYOTE as a first step, the CFM technology roadmap can be jumpstarted to support a versatile, high performance space transportation architecture utilizing cryogenic propellants and propellant depots. The future of space flight is bright but the first step is critical—CRYOTE.

Nomenclature

CFM	Cryo-Fluid Management	LAD	Liquid Acquisition Device
CRYOTE	Cryogenic Orbital Testbed	LEO	Low Earth Orbit
DoD	Department of Defense	LH2	Liquid Hydrogen
EDS	Earth Departure Stage	LN2	Liquid Nitrogen
EELV	Evolved Expendable Launch Vehicle	LOX	Liquid Oxygen
ESAS	Exploration Systems Architecture Study	MLI	Multi-Layer Insulation
ESPA	EELV Secondary Payload Adapter	MSFC	Marshall Space Flight Center
GRC	Glenn Research Center	NEO	Near-Earth Object
IMLI	Integrated Multi-Layer Insulation	PMD	Propellant Management Device
IPP	Innovative Partnerships Program	Rideshare	Launch as a secondary payload
JPL	Jet Propulsion Laboratory	TRL	Technology Readiness Level
JSC	Johnson Space Center	TVS	Thermo-dynamic Vent System
KSC	NASA Kennedy Space Center	ULA	United Launch Alliance

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