

Cryogenic Fluid Technologies for Long Duration In-Space Operations

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Reliable knowledge of low-gravity cryogenic fluid management behavior is lacking and yet is critical in the areas of storage, distribution, and low-gravity propellant management. The Vision for Space Exploration mission objectives will require the use of high performance cryogenic propellants (hydrogen, oxygen, and methane). Additionally, lunar missions will require success in storing and transferring liquid and gas commodities on the surface. The fundamental challenges associated with the in-space use of cryogenics are their susceptibility to environmental heat, their complex thermodynamic and fluid dynamic behavior in low gravity and the uncertainty of the position of the liquid-vapor interface if the propellants are not settled. The Cryogenic Fluid Management (CFM) project is addressing these issues through ground testing and analytical model development, and has crosscutting applications and benefits to virtually all missions requiring in-space operations with cryogenics. Such knowledge can significantly reduce or even eliminate tank fluid boil-off losses for long term missions, reduce propellant launch mass and on-orbit margins, and simplify vehicle operations. The Cryogenic Fluid Management (CFM) Project is conducting testing and performing analytical evaluation of several areas to enable NASA's Exploration Vision. This paper discusses the content and progress of the technology focus areas within CFM.



Cryogenic Fluid Management (CFM) Project

Space Technology and Application International Forum
(STAIF)

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Presentation Objectives

- *Explain the use of cryogenic fluids in meeting Lunar Lander technology requirements and the U.S. Space Exploration Policy objectives.*
- *Explain the fundamental challenges associated with in-space use of cryogenic fluids.*
- *Provide CFM objectives and scope of work associated with meeting Agency objectives.*
- *Discuss progress of technology focus areas within the CFM Project*



Presentation Outline

- Project Objectives
- Architecture Benefit
- Risk Mitigation
- Technology Description
- Technology Maturity
- Team & Partnerships
- Conclusion



Cryogenic Fluid Management Project Objectives

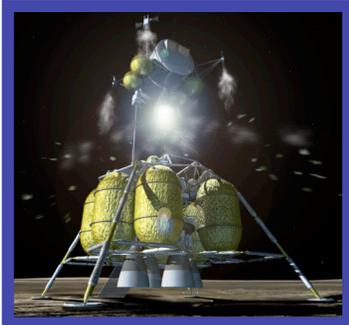
- To develop storage and distribution technologies for cryogenics that will support the enabling of high performance cryogenic propulsion systems, lunar surface systems and economical ground operations.
- CFM supports the long term U.S. Space Exploration Policy as outlined in NASA's Procedural Directives (NPD) 1001.0, *NASA Strategic Plan*.
 - Pg 37: NASA's vision for the next ten years is clear: return the Space Shuttle to flight; complete the International Space Station; launch robotic missions to the Moon for long-duration stays in preparation for robotic and human exploration of the solar system and the universe; **and return humans to the Moon's surface.**
 - **Strategic Goal 6:** Establish a lunar return program having the maximum possible utility for later missions to Mars and other destinations.

*“Transporting humans from Earth to the Moon and back in a sustainable, safe, and affordable manner will recapture the spirit of the Apollo program and ignite the Nation's excitement about space exploration as the United States takes the first major steps in preparing for future missions to Mars and beyond. However, missions to the Moon will be vastly different in this century. More crewmembers will **land on the lunar surface** with no limit on the location of the landing sites, and they will **remain on the lunar surface for longer periods of time**, exploring more of the lunar surface per trip than did their Apollo predecessors”*

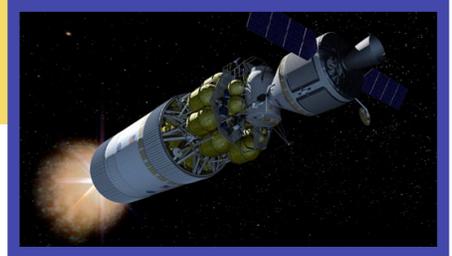
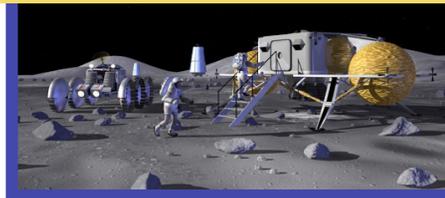


Cryogenic Fluid Management Project Objectives

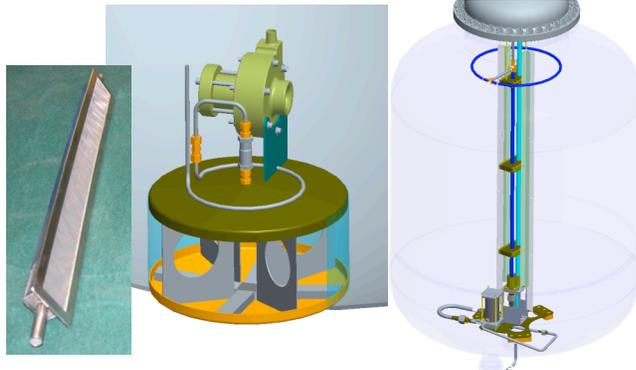
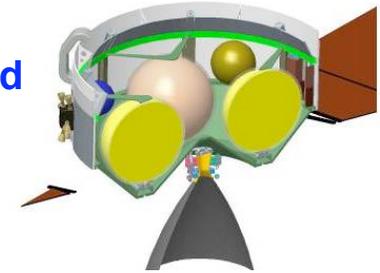
Project Objective: Develop **cryogenic fluid management** systems in support of all Exploration missions requiring in-space and surface operations with cryogenics



Customers:
Altair, Ares V, Ground Operations, Lunar Surface Systems

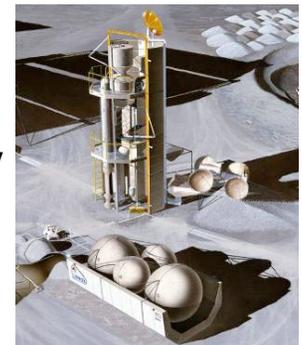


CFM Systems Technology: Evaluate and predict performance of **integrated CFM systems** using cryogenics, and evaluate the use of **common systems** for storage, transfer, and handling.



Propulsion Systems CFM Technology: Design and test advanced technology subsystems to **store** and **distribute** cryogenic propellants that will meet the need for high-performance propulsion systems on **long-duration missions**.

Surface Systems CFM Technology: Provide advanced development of technology required for **servicing** and **interfacing** with **surface assets** including **transfer** and handling of cryogenics on the **Earth** and **lunar surfaces**, or transferred in near lunar space.





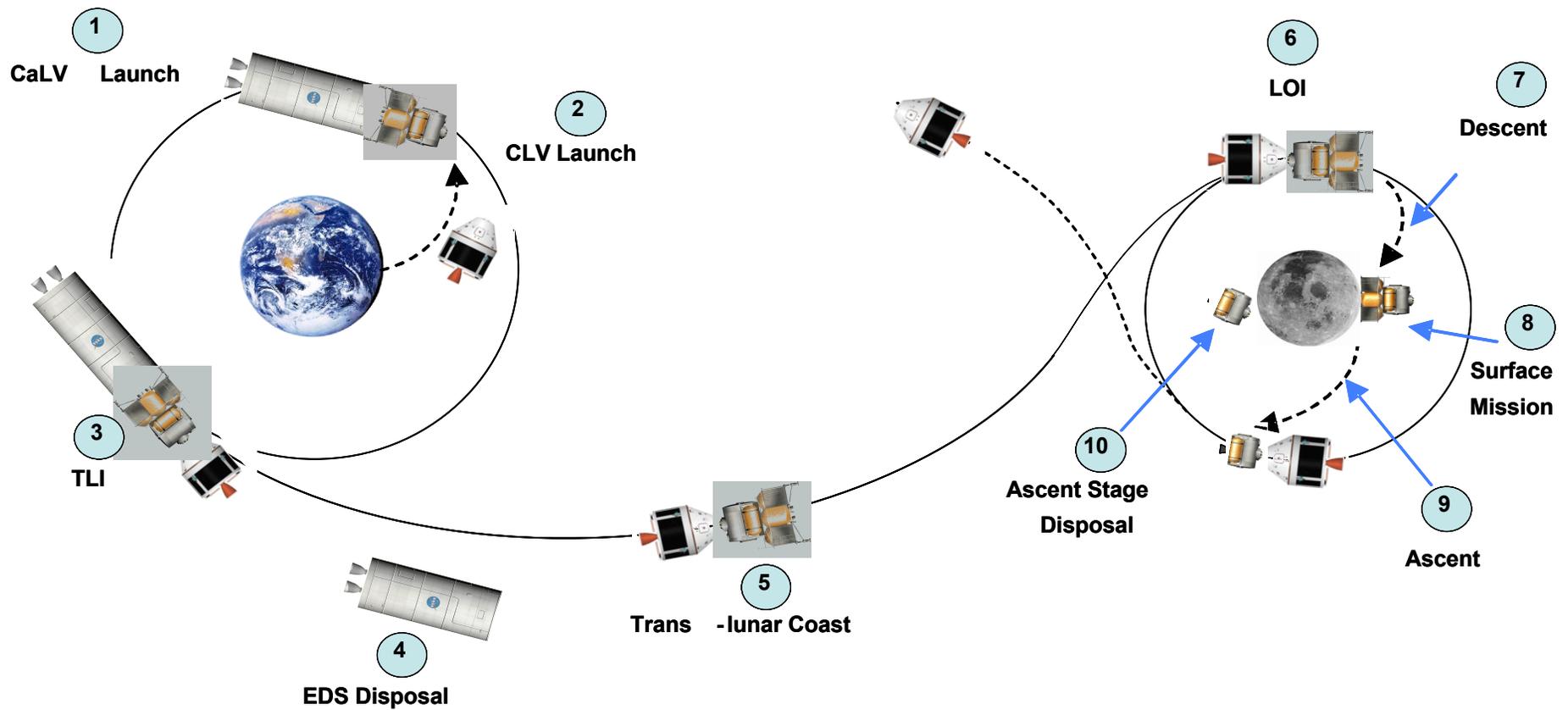
Cryogenic Fluid Management Project

Architectural Benefit

- The CFM project focuses on the development of cryogenic storage, low-gravity propellant management, and distribution technologies needed to support informed decisions on implementation of cryogenics into the Constellation architecture.
- Multiple engineering analyses and trades have indicated that the overall architecture goals require that the Lunar Lander Descent Module Main Propulsion System must utilize LOX/LH₂ propellants.
 - Because LOX/LH₂ propulsion has not previously been applied to Lander systems, multiple technology risks exist.
- LOX/LCH₄ is a promising option for the Lunar Ascent Module, due to potential savings in overall system mass.
 - LOX/LCH₄ propulsion for Lunar Lander Ascent Main and Ascent/Descent Reaction Control Propulsion is currently conceded a critical enhancing technology, due to the potential increase of lunar surface payload.
- Lunar surface operations require long-term cryogenic storage and fluid transfer between surface assets.



Cryogenic Fluid Management Project Mission Architecture





Cryogenic Fluid Management Project **Constellation Program Needs**

- Lunar Lander/Altair
 - Long term storage and transfer of cryogenes from descent to lunar ascent
 - Thermal protection
 - Low-g propellant management
- Ares V Project
 - Long term storage and transfer (feedline conditioning) of cryogenes from liftoff to after TLI
 - Challenging thermal protection (advanced techniques that minimize effects on the rest of the launch/space vehicle)
 - Low-g propellant mass gauging
 - CFM issues with composite cryogen tanks
- Lunar Surface Systems Project
 - Storage and transfer of cryogenes on the lunar surface
 - Consumables brought from earth
 - Consumables created through ISRU
- Ground Operations Project
 - Load and store densified and sub-cooled propellants.



Cryogenic Fluid Management Project

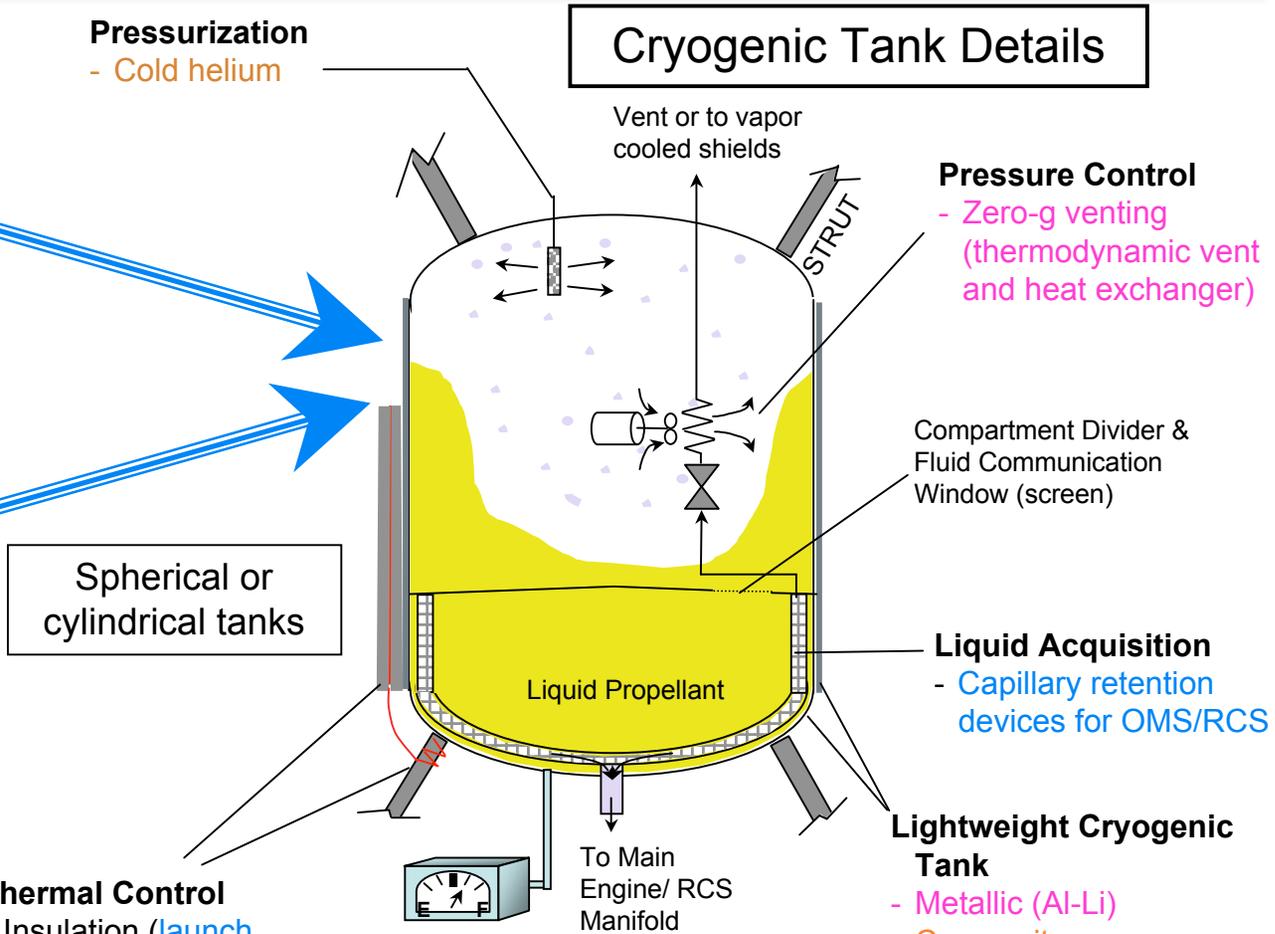
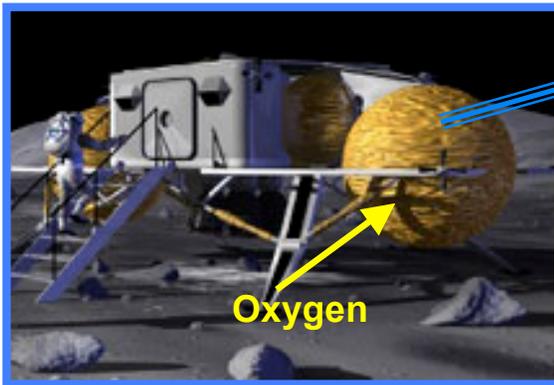
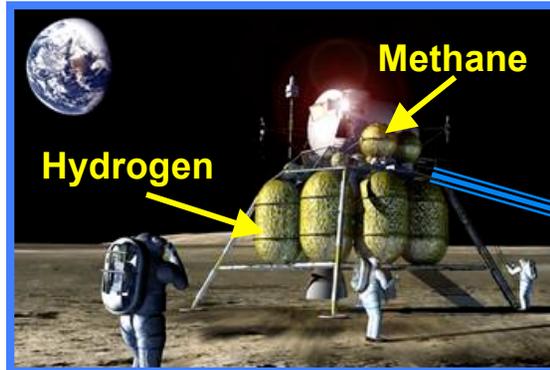
What does CFM do?

- CFM allows successful management of the entire cryogenic propellant delivery system to rocket engines, surface systems (power, ISRU, life support), and ground system end users
 - CFM system is the tanks, transfer lines, gauging devices, thermodynamic components, everything up to the valve interface
- The CFM Project has two main groups of products
 1. Hydrodynamic/Thermodynamic Knowledge: knowledge of the physics and the existing databases allow the development of analytical tools. These tools are then used to design CFM systems for the new space applications. There are gaps in the existing databases that require the acquisition of additional data.
 2. New/refined thermodynamic devices to better control the system/component thermodynamics
 - Pressure/thermal control devices for tanks and transfer lines
 - Improved insulation techniques
 - Improved gauging techniques



Cryogenic Fluid Management Project

Cryogenic Storage and Distribution



Spherical or cylindrical tanks

- Thermal Control**
- Insulation (launch environments and in-space)
 - Vapor cooled shields
 - Low conductivity/ cooled support structure

- Propellant Gauging**
- Settled propellant
 - Inventory (Bookkeeping)
 - Pressure-volume-temperature (PVT)
 - High accuracy zero-g techniques

Color Code for Text	
Pink	- flight or extensive ground demonstration
Blue	- key components ground tested
Orange	- technology development required



Cryogenic Fluid Management Project Team & Partnerships

Center	Lead Roles and Responsibilities	Supporting Roles and Responsibilities
GRC	<ul style="list-style-type: none"> • Project lead and management • Liquid Storage • Liquid Supply • Instrumentation • Education and Outreach 	<ul style="list-style-type: none"> • Feedsystem design and test • In-Situ CFM Technology • Ground Operations • Liquefaction and Storage
MSFC	<ul style="list-style-type: none"> • Project Management • CFM-Feedsystem Integrated Test • Life Support CFM Technology 	<ul style="list-style-type: none"> • Propellant Storage • Low-g Propellant Management • Liquid Acquisition design and test • Feedsystem design • In-Situ CFM Technology • Consumables Transfer • Ground Operations • Liquefaction and Storage • Education and Outreach
JSC	<ul style="list-style-type: none"> • Feedsystem design and test • ISRU POC • Surface Systems • In-Situ CFM Technology • Liquefaction and Storage 	<ul style="list-style-type: none"> • Propellant Storage • Ground Operations
ARC		<ul style="list-style-type: none"> • Propellant Storage
GSFC		<ul style="list-style-type: none"> • Propellant Storage
KSC	<ul style="list-style-type: none"> • Consumables Transfer • Ground Operations 	<ul style="list-style-type: none"> • In-Situ CFM Technology • Liquefaction and Storage



Cryogenic Fluid Management Project **Risk Mitigation**

Cryogenic Technical Risk Areas

- **Storage Technology**
 - Long-term storage of cryogenic propellants (LCH₄, LO₂, LH₂) in low-gravity and microgravity environments with minimal propellant losses.
 - Densification of LCH₄
- **Distribution Technology**
 - Maintain vapor-free liquid propellant between the tank outlet and the Main Engine/RCS engine inlet.
 - Minimal fluid loss in transfer on lunar surface
- **Low-g Propellant Management Technology**
 - Provide vapor-free liquid propellant from the tank outlet.
 - Enable accurate and reliable measurements of cryogenic liquid mass in low-gravity storage tanks without propellant settling, undue constraints on mission, or spacecraft subsystems.



Cryogenic Fluid Management Project **Technology Description**

System Technology

- Flow down the Exploration program applicable CFM technical requirements to the component/subsystem CFM technology developers
- Evaluate progress of CFM technology against a conceptual Lander CFM system and flow up to the relevant Exploration Project Offices the CFM advanced development technology products
- Direct CFM system trade studies to meet the requirements proposed by the Exploration program architecture studies
- Reduce program cost and accelerate CFM technology development by exploiting test hardware and test facility synergism between the CFM technology elements
- Conduct studies for future customers, such as Ares V, Surface Systems, and Ground Operations to determine technology needs and risk reduction approaches.



Cryogenic Fluid Management Project Technology Maturity

Accomplishments - CFM Systems Engineering Process

Objective:

- Collect, define and document Exploration program CFM technical requirements, identify collaborative testing opportunities between CFM technology elements and assist in Exploration CFM systems preliminary designs

Key Accomplishment/Deliverable/Milestone:

- Final report presentation of the “Delivery and Storage of Cryogenic Propellants for Exploration Missions” **thermal control conceptual design study** on August 8, 2007.
- Developed a **Liquid Acquisition Device (LAD) conceptual design** for LOX/LCH4 LSAM Ascent Stage, in support of LAT-2 Study
- Presented CFM papers at the 45th AIAA Aerospace Sciences Meeting (Reno, NV).
- Developed **approach to provide Lander data products for their SRR and PDR.**
 - Utilizing Integrated Product Teams (IPT)
- Continuing to **support EDS** Study Team.
- Developed and distributed to the CFM Project Team the first draft of the “LSAM Mission Derived Parameters for CFM”.
- Conducted analyses in support of LLPO to **examine lunar polar thermal environment and LEO loiter.** Showed uncertainty that exists in predicting lunar polar thermal environment and provided first order estimate of the length of LEO loiter for which lunar lander active thermal control appears to provide benefit.
- CFM project personnel organized, executed, and participated in the 2007 Space Cryogenics Workshop.
- Conducted a **CFM Workshop for Propulsion Systems** October 23-26, 2007.
- Conducted a **CFM Surface Systems Workshop**, January 15-16, 2008.



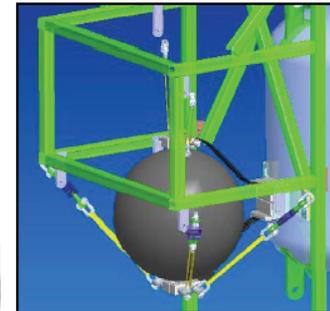
*Artist's Concept of the
Lunar Lander lowered into the
Space Propulsion Research Facility
(B-2) Chamber
For Thermal/Vacuum and Hot Fire
Testing*



Cryogenic Fluid Management Project Technology Description

Propellant Storage

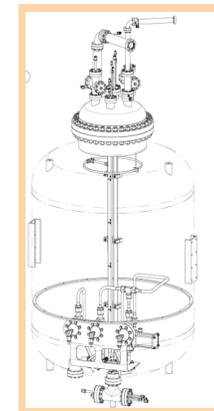
- **Develop and anchor computational models** to predict performance of tank thermal and pressure control subsystems in low gravity and microgravity for which flight data is unavailable.
- Conduct LCH₄, LO₂, and LH₂ **pressure control component tests** to confirm functional reliability
- Perform LCH₄ and LO₂ **pressure control subsystem tests** to evaluate the effectiveness of tank mixing and Thermodynamic Vent System (TVS) for pressure control.
- Conduct thermal control component tests
 - Demonstrate capability to **maintain cold gaseous helium (GHe)** in Composite Overwrapped Pressure Vessel (COPV) using a **passive thermal link** to the propellant tank
 - Design and demonstrate **GHe pressure regulator performance** at high pressure (6000psia) & LO₂ temperature for pressure fed system
 - Panel tests (tube-to-tank, tube-to-shield) to demonstrate effectiveness of **active thermal control**
- Conduct LCH₄ **lunar surface storage test** of thermal control concepts for lunar ascent tanks
- Conduct test of **tank-applied MLI** relevant to large scale tanks representative of EDS, applicable to on-orbit storage of LO₂ and LH₂
- Completed analysis and detailed design of **LO₂ Integrated Refrigeration and Storage (IRAS)** test system for liquefaction, zero boil off and densification of oxygen on the lunar surface.
- **Testing of heat exchanger performance of recuperators** using expanded carbon foam materials.



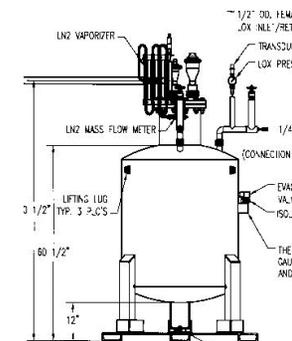
Test Setup -
Cold GHe COPV
Thermally Linked to
LN₂ Tank



Shuttle OMS
Pressure Regulator



Tank Assembly for
LO₂ Pressure Control
Subsystem Test



Integrated Refrigeration and
Storage System



Cryogenic Fluid Management Project Technology Maturity

Accomplishments - Storage - Current TRL = 4

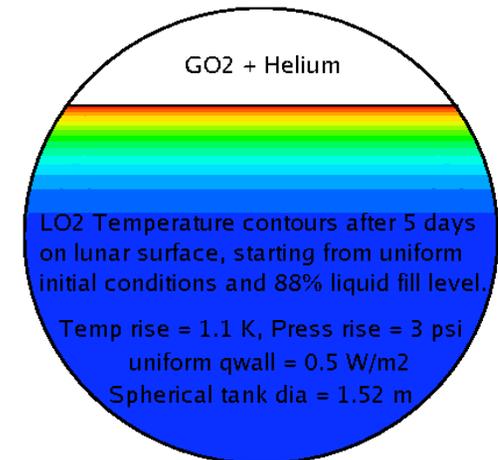
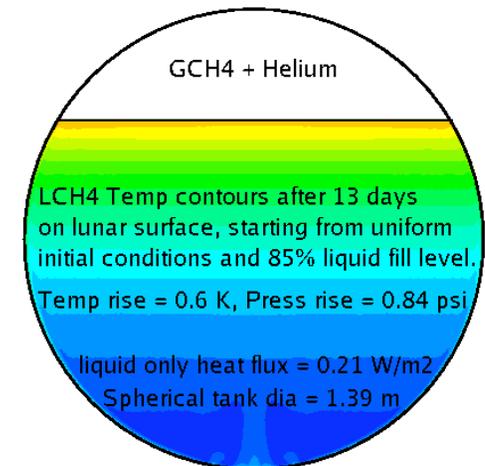
Objective:

- Provide technologies for long-term storage of cryogenic propellants (LCH₄, LO₂, LH₂) in low gravity environments with minimal propellant losses.

Key Accomplishment/Deliverable/Milestone:

Modeling:

- **Validated 1-g Fluent-based model** for pressurization **against K-site experimental data** for 5 cubic meter flightweight LH₂ tank at multiple fill levels. A paper, “Numerical & Experimental Comparisons of a Self-pressurizing LH₂ Tank in Normal Gravity,” was completed for submission to the Cryogenics Journal
- Simulated **modeling of low-g Saturn IVB flight experiment** LH₂ tank data pressure rise.
 - Presented CFM papers at the 43rd AIAA/ ASME/ SAE/ ASEE Joint Propulsion Conference..
- Completed preliminary Fluid Thermal **Model of Broad Area Cooling**. Model will be utilized to analyze active cooling approaches.
- Performed preliminary **CFD simulations for LO₂ and LCH₄ lunar ascent tanks** at sizes and conditions representative of a current LAT-II design (LCH₄ tank on top with cold spot and maximum estimated heat leak into tanks) to **assess temperature stratification in the liquid over a period of 210 days if no mixing is performed**. Up to 28 days simulated, with solutions extrapolated to 210 days for pressure and temperature rise in the LCH₄ and LO₂.



CFD simulations for LO₂ and LCH₄ lunar ascent tanks



Cryogenic Fluid Management Project Technology Maturity

Accomplishments - Storage - Current TRL = 4

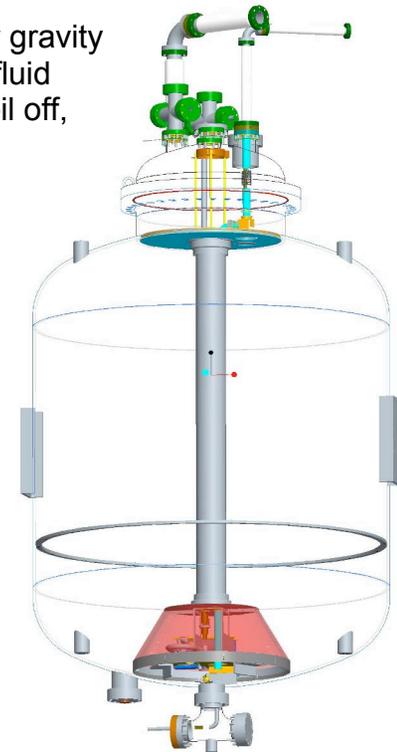
Objective:

- Provide technologies for long-term storage of cryogenic propellants (LCH₄, LO₂, LH₂) in low gravity environments with minimal propellant losses. Develop advanced technologies for cryogenic fluid storage on the lunar surface, including active integrated refrigeration for liquefaction, zero boil off, densification of oxygen, and miniature recuperative heat exchanger testing.

Key Accomplishment/Deliverable/Milestone:

Testing Activities:

- **Thermodynamic Vent System (TVS) tests** in GRC CCL-7 and SMiRF **to evaluate effects of LCH₄ and LO₂ trace contaminant freezing**.
 - Assess the performance of Viscojet Joule-Thomson device in LCH₄ and LO₂.
 - No clogging of the viscojets were detected under the test conditions
- Demonstrated at ARC that a bench test **Broad Area Cooling subsystem**, using a helium loop integrated with a cryo cooler **could efficiently remove heat**.
- Demonstrated in MSFC TS-300 **a large scale spray-bar TVS in LCH₄ with a GHe pressurant**.
 - Full pressure control achieved/ no TVS operational issues
 - Successfully used TVS to maintain subcooled LCH₄
 - Held Data review in April 2007. Presented and discussed MSFC, GRC, and JSC TVS data.
- Defined and documented **high-pressure cryogenic helium regulator preliminary requirements**.
- Performed **burst testing of Al-2219 lined Composite Overwrapped Pressure Vessels (COPVs)** at cryogenic temperatures.
- Completed **conceptual design of IRAS** test system. Awarded fabrication contract to Eden Cryogenics Inc.
- Awarded grant to the University of Central Florida for **testing of heat exchanger performance of recuperators** using expanded carbon foam materials. Literature review and preliminary design is complete.



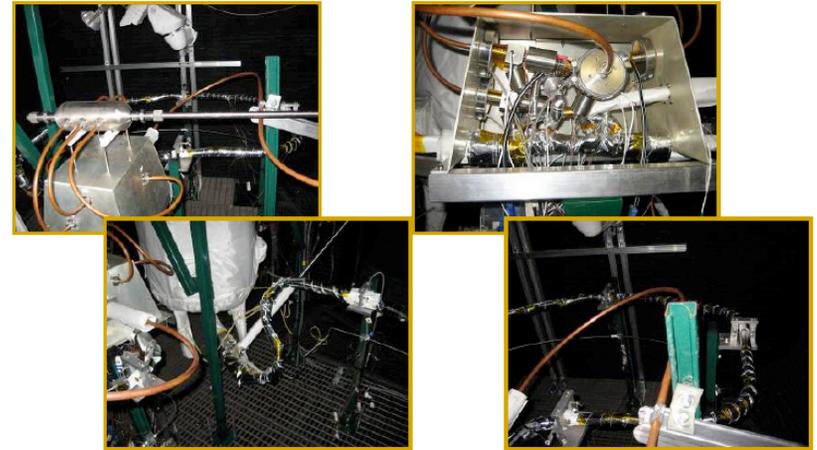
58 ft³ test tank configuration within SMiRF vacuum chamber that will support LO₂ OMG/ RF Mass Gauge and TVS testing



Cryogenic Fluid Management Project Technology Description

Propellant Distribution

- Propellant feed system component testing to demonstrate cryogenic life cycle capabilities.
 - **Piezoelectric tank isolation valve** tests in a simulated space environment and integrated with low fidelity subscale cryogenic propellant tank
- Propellant feed system integrated testing to demonstrate efficient propellant line conditioning and meet Lander RCS engine inlet requirements.
 - **Piezoelectric TVS valve** test integrated into cryogenic RCS feed system in a simulated space environment.
 - **High fidelity MLI blankets** installed on an integrated cryogenic RCS and feed system during RCS engine **hot fire testing** at altitude.
- **Consumables supply and distribution** strategy for lunar exploration
- **Dust tolerant liquid air quick disconnect (QD)** for Advanced EVA Systems.
- Develop dust tolerant umbilical systems integrated with cryogenic storage, liquefaction, and surface mobility elements for mobile lunar surface operations.



Subscale cryo propellant tank and feed system for piezoelectric iso-valve and TVS testing



Dust and Ice Proof Quick Disconnect and Umbilical Development



Cryogenic Fluid Management Project Technology Maturity

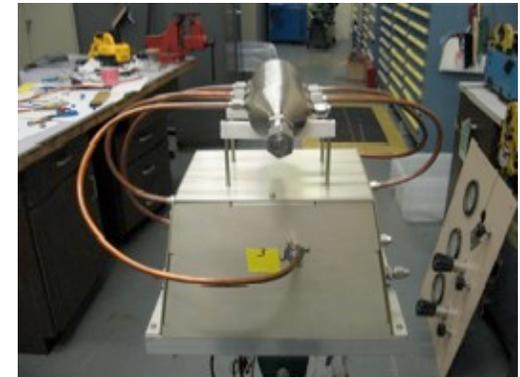
Accomplishments - Distribution - Current TRL = 5

Objective:

- Develop cryogenic, low-heat leak feed systems technologies to reduce/eliminate propellant loss during nominal RCS propellant usage. Develop and demonstrate a prototype standardized, modular consumable storage and distribution system capable of supporting multiple lunar surface elements.

Key Accomplishment/Deliverable/Milestone:

- Completed Cryogenic Feed System Phase I testing and distributed final report. The report describes testing in JSC's Energy Systems Test Area (ESTA) facility of a **Reaction Control System- scale Thermodynamic Vent System (TVS) that successfully maintained the required propellant conditions**, keeping feedline conditions in the sub-cooled region.
- Completed Phase II **cryogenic feed system engine simulator test**. The engine pod simulated the heat "soak back" from RCS thruster firings into the propellant manifold.
- Presented technical paper, "Cryogenic Feed-system Thermodynamic Vent System Design and Test," at JANNAF.
- The **paper**, "LOX/ LCH4 Propulsion System: Tank Stratification Model Using MATLAB," was **presented by undergraduate student Alex Rivas** at JANNAF.
- Completed study on consumables supply and distribution strategy for lunar exploration
- Completed study on recovery of Lunar Lander residual and reserve cryogenic propellants
- **Design and fabrication of a dust tolerant liquid air quick disconnect (QD)** for Advanced EVA Systems. QD was successfully **tested at Desert Rats** in September.
- Released **industry solicitation for development of dust tolerant gaseous oxygen quick disconnects** for EVA use.
- Completed design of dust tolerant telerobotic umbilical connector.



Engine simulator assembly for Phase II cryogenic feed system test in JSC ESTA Facility



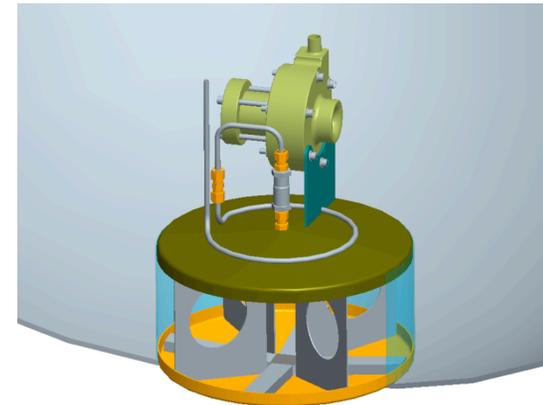
Cryogenic Feed System Set Up in Vacuum Chamber



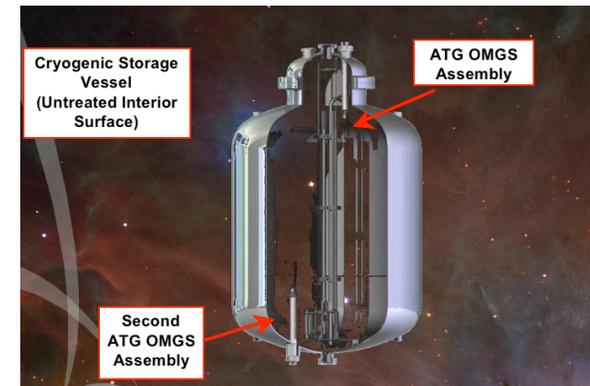
Cryogenic Fluid Management Project Technology Description

Low-g Propellant Management

- **Liquid Acquisition**
 - Perform **analytical modeling** to predict screen channel performance
 - Conduct **bubble point testing**, including subcooled conditions, to determine temperature effects on bubble point for screen channel LADs
 - Conduct Helium pressurization tests to **assess bubble point predictions at elevated temperature** conditions for LO2.
 - Perform **computational fluid dynamic modeling and testing to quantify heat entrapment** within screen channels and start baskets and develop technical approaches to mitigating it
 - Conduct tests at representative flow conditions for main engine burns, reaction control burns, and TVS systems to **assess pressure drop across the screen channel LAD** and to determine the breakthrough pressure at those conditions
- **Mass Gauge**
 - Develop **analytical models** to predict gauging accuracy and overall performance at various gravity levels and fluid conditions
 - Conduct **Pressure-Volume-Temperature (PVT) gauge tests** in LO2, LCH4, and LH2
 - Conduct **Radio Frequency (RF) gauge tests** in LO2 and LCH4
 - Conduct **Optical Mass Gauge (OMG) tests** in LO2 and LH2
 - Conduct LH2, LCH4, LO2 **settled gauging tests**



Screened Sump Conceptual Design for Lunar Lander Ascent Stage



LO2 Optical Mass Gauge Assemblies Shown in 58ft**3 Test Tank



Cryogenic Fluid Management Project Technology Maturity

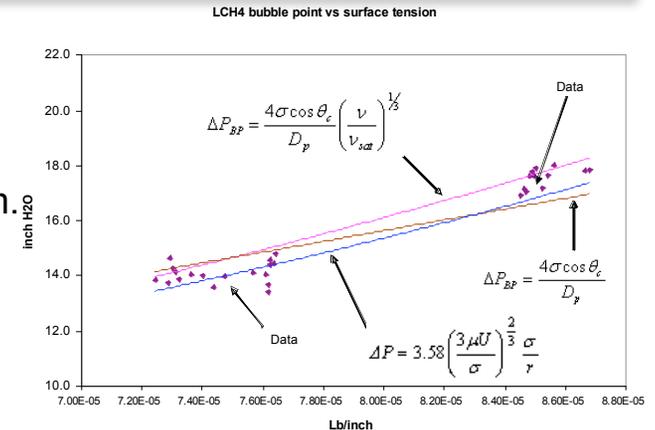
Accomplishments - Liquid Acquisition - Current TRL = 4

Objective:

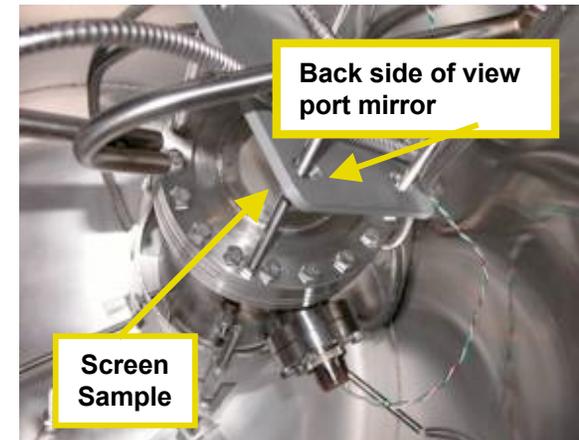
- Ensure that single phase fluid is delivered to the propellant feed system.

Key Accomplishment/Deliverable/Milestone:

- Completed **heat entrapment testing using water and LN2**. Testing with both water and liquid nitrogen has demonstrated that heat may be entrapped inside screen channels and start baskets.
- Test series at GRC Creek Road Complex cryogenic test facility (CCL-7) to **measure the bubble point (breakthrough) pressure for saturated and subcooled LCH4** were completed.
 - Two screen samples tested with both LN2 and LCH4.
- Presented technical paper, “Screen Channel Liquid Acquisition Device Testing Using Liquid Methane,” at JANNAF
- Presented technical paper, “Bubble Point Measurements with Liquid Methane of a Screen Capillary Liquid Acquisition Device,” at the Cryogenic Engineering Conference
- Formulated **Heat Entrapment Prevention and Mitigation Plan**. Plan utilizes a combined modeling and testing approach to quantify the conditions of heat entrapment and investigate technical approaches to resolving it.



Test data resulting in analytical model



GRC Creek Road Complex cryogenic test facility (CCL-7) to measure the bubble point pressure for LCH4, determine pressure drop across fine mesh screens during flow



Cryogenic Fluid Management Project Technology Maturity

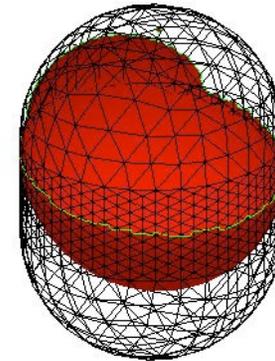
Accomplishments - Mass Gauge - Current TRL = 3

Objective:

- Enable measurement of cryogenic liquid mass in low-gravity without propellant settling.

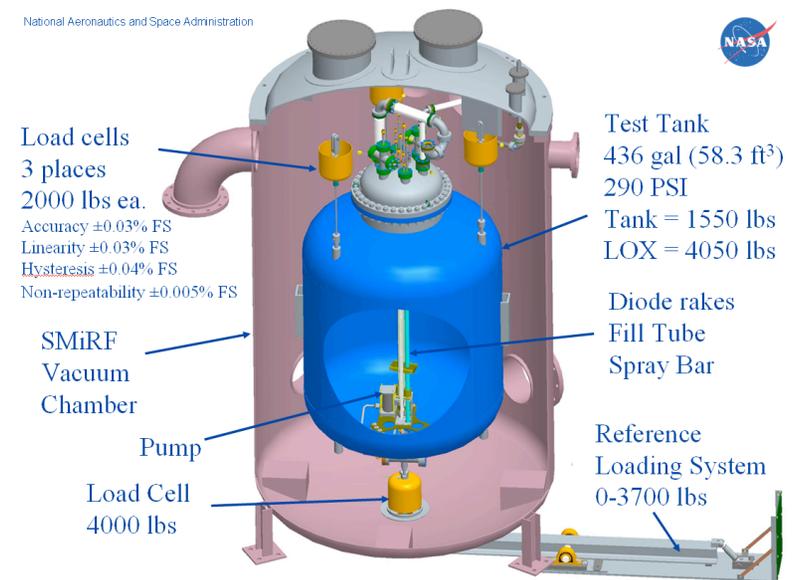
Key Accomplishment/Deliverable/Milestone:

- Developed Surface Evolver **model to investigate fluid configurations** in a specific tank geometry at various gravity levels and gravity vector directions.
- SMiRF (Small Multi-purpose Research Facility) Test Facility –
 - Completed the **LN2 test series for Pressure Volume Temperature (PVT) / Radio Frequency (RF) mass gauging**, and Joule-Thomson Expansion Device plugging.
 - Completed **LO2 PVT and RF Mass Gauging**. A real-time Pressure Volume Temperature (PVT) gauging in a completely cryogenic test configuration has been demonstrated. The Radio Frequency (RF) mass gauge has demonstrated accurate real-time settled gauging in LOX using a complex tank spectra.
- Presented technical paper, “Propellant Gauging for Exploration,” at JANNAF
- ATG **Optical Mass Gauge (OMG) for LO2** delivered 12-3-07.
- Fluid sampling during the LN2 PVT tests to **analyze helium solubility** has shown very **good agreement with modeling** of solubility.



Preliminary Surface Evolver results for simple tank geometry

National Aeronautics and Space Administration



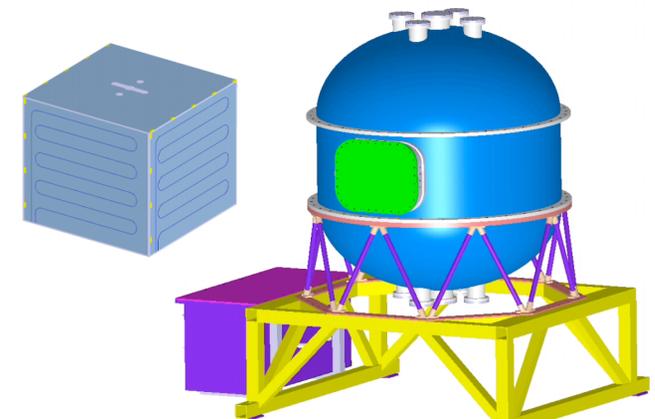
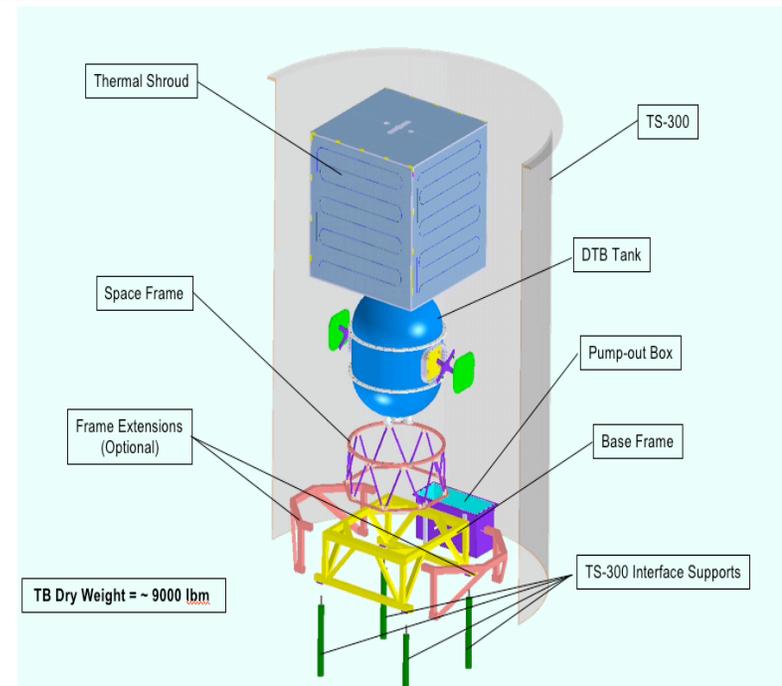
58 ft³ test tank within SMiRF vacuum chamber that supported LO2 OMG/ RF Mass Gauge and TVS testing



Cryogenic Fluid Management Project Technology Description

Integrated CFM-Feed-system Test

- Evaluate the effect of significant variations in the tank fluid state properties, thermal environments and fluid dynamics (mixing, outflow and level) on the CFM technologies within a LCH₄ filled tank, which could compromise individual CFM component and/or subsystem performance.
 - Development of a Cryogenic Test Bed (CTB)
 - Prototype CFM elements - Integrated CFM-Feed-system Test (ICFMFST) components delivered
- Characterize the combined influence of the CFM subsystems on component performance in a fully integrated system test.



CTB Assembly and Hardware Elements



Cryogenic Fluid Management Project

Conclusion

- CFM is set-up to meet requirements throughout the Constellation architecture
- CFM is acquiring data and developing models to help Constellation flight projects meet key decision points.
- The CFM program is robust to changes in the exploration architecture
 - Major CFM technology drivers
 - Cryogenic fluid storage duration
 - Environmental conditions (gravity level/heat flux)
 - Fluid storage temperature and pressure
- Exploration architecture has changed from initial ESAS study and the CFM technology program has mimicked the changes
 - System integration models developed for any storage duration and thermal environment in low-g or reduced gravity environments and include both passive and active thermal control options
 - Ground test programs developed for fluid conditions from subcooled to “warm” temperatures, to 250 psia operating pressures for LO2 and LCH4 (FY09)
 - CFD models validated with 1-G ground test data, extrapolated to low-g and validated with Saturn 2 test flight video
 - Propellant mass gauging development includes low-g and settled gauging techniques
- Technology is extensible to Mars
 - Cryogenic storage, distribution, low gravity propellant management is critical for getting to and from Mars, even if nuclear thermal propulsion is baselined.
 - Mars surface systems requires CFM