The Cryogenic Propellant Storage and Transfer Technology Demonstration Mission: Progress and Transition

Michael L. Meyer
William J. Taylor
Carol A. Ginty
Matthew E. Melis

NASA Glenn Research Center

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• Motivation for an in-space demonstration
• Early mission concept formulation
• External input (Broad Area Announcement contracts)
• Mission overview & redirection
• Technology maturation overview
  • Thermal control technologies
  • Propellant transfer
  • Propellant gauging
  • Analytical modeling
• Summary
CPST Demonstration Cross-Cutting Benefits

- Extended Commercial Upper Stage Capabilities
- High-Performance Chemical Propulsion Beyond LEO
- ISRU Propellant Storage & Utilization
- Nuclear Thermal Missions to Mars
- Safer, Faster Ground Processing
- Advanced Thermal Management Systems
- Power Generation and Energy Storage
- Cryogenic Storage, Expulsion, & Transfer Technologies

CPST Demonstration Mitigates Risks for Multiple Architecture Elements and Systems

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Purpose of CFM Demo: Support Future Missions

Cryogenic Fluid Management
Flagship Demonstration

- Active Long Duration Cryo Storage
- Passive Long Duration Cryo Storage
- Quantity Gauging
- Leak Detection
- Thermal Isolation of Structures
- Microgravity Fluid Transfer
- Propellant Conditioning for Transfer
- Automated Fluid Coupling
- Other AR&D Technologies
- Small O2/CH4 Thrusters
- Zero-G Cryogenic Fluid Acquisition

Propellant Management Systems

Cryogenic Propellant Depots
(ULA concept)

- Passive Long Duration Cryo Storage
- Quantity Gauging
- Leak Detection
- Thermal Isolation of Structures

Cryogenic Propellant Transfer

Automated Rendezvous & Docking

Large Propellant Stages

Cryogenic Thruster Systems

Lox/CH4 Spacecraft Propulsion

- Large Science and Robotic Exploration Missions
- Human Exploration Beyond Low-Earth-Orbit
- Oxygen and Water Resources Platform
- Propellant Depot “Gas Station”
- Industrial / Manufacturing Platform
- Lunar Orbit / L2 / Mars Orbit Depots (from in-situ resources)
- Reusable / Refuelable Upper Stages
- Satellite Refueling and Servicing
- Orbital Transfer Vehicle Platform
- Large and Maneuverable Defense Systems
- Asteroid Exploration Mining and Defense
- Space Resources Utilizations

Missions
(Commercial & Government)

Discipline Technologies

Capability Technologies

Mission Technologies

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Cryogenic Propellant Depot CFM Technologies

Liquid Propellant Notional Depot

Cryogenic Depot Tank Details

Pressurization
- Storage/compression
  - Helium
  - Autogenous

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

Thermal Control
- Insulation (launch environments and in-space, MMOD protection)
- Vapor/cryocooler cooled shields
- Sun shades
- Low conductivity/ cooled support structure

Pressure Control
- Low-g mixing/venting (thermodynamic vent and heat exchanger)

Liquid Acquisition
- Capillary retention devices for low-g
- Settling thrust

Lightweight Cryogenic Tank
- Metallic (Al-Li)
- Composite

Liquid Transfer
- Line/tank chilldown
- Pumps
- Leak-free coupling

Leak Detection

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Early Mission Concept Formulation

Methane-Oxygen Concept

Hydrogen-Oxygen Concept

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• BAA Intended to get Industry input on technology objectives, mission concepts
  – 4 Contracts awarded (AMA, Ball, Boeing, Lockheed Martin)
  – 1 Space Act Agreement implemented (ULA)
• BAA requested
  – Mission Justification and Prioritized Objectives
  – Technology recommendations and maturation plans
  – Technology extensibility arguments
  – Mission Concept
  – Cost Estimate
• BAA Mission Concept Constraints
  – Target Mission Cost - $200M (not including Government requirements)
    • Allowed to propose up to $300M if significant added benefit identified
  – ATP in 2012 or 2013 if Technology Maturation identified as required
  – Flight 3 years from ATP
  – ~6 month mission duration
BAA Mission Objectives

- **Cryogenic Fluid Storage**
  - Demonstrate approach for zero boil-off storage of liquid oxygen in microgravity.
  - Demonstrate approach for minimal boil-off storage, with a goal of zero boil-off, of liquid hydrogen in microgravity.

- **Cryogenic Propellant Acquisition**
  - Demonstrate approach for acquisition and bubble-free flow of liquid oxygen and liquid hydrogen in microgravity.

- **Cryogenic Fluid Transfer**
  - Demonstrate approach for transfer of liquid oxygen and liquid hydrogen in microgravity (settled and unsettled conditions).

- **Cryogenic Fluid Quantity Gauging**
  - Demonstrate approach for mass gauging of liquid oxygen and liquid hydrogen in microgravity.

- **Instrumentation**
  - Demonstrate approach for leak detection of liquid oxygen and liquid hydrogen in microgravity.
  - Demonstrate approach for flow measurement of liquid oxygen and liquid hydrogen in microgravity.

- **Tank Pressurization Methods**
  - Demonstrate approach for cryogenic tank pressurization and pressure control of liquid oxygen and liquid hydrogen in microgravity.
BAA Summary

- 5 Diverse Concepts Developed
  - 1 Single Fluid (H2) Concept
  - 1 Propellant Scavenged Concept
  - 1 DragonLab Concept
- All concepts met constraints
- General consensus on objectives and priorities
- All identified need for Technology Maturation Effort before proceeding to flight demonstration development

BAA responses in conjunction with NASA Point of Departure Study were basis for Mission Concept Review and satisfaction of KDP A

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• CPST Project successfully conducted an SRR / MDR in September of 2013
• Concept was based on study of DragonLab mission identified in the reformulation studies
• Based on SRR/MDR results, CPST project proceeded to KDP B in December of 2013
Extending human reach into deep space by advancing cryogenic propellant storage and transfer technologies to meet the needs of both NASA exploration systems and commercial launch providers.

**Passive Storage, Transfer, and Gauging Demo**

- **Launch 2017**
  - Demonstrate long-duration storage
  - Demonstrate in-space transfer
  - Demonstrate in-space, accurate gauging

**Dock to ISS**

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DragonLab Concept (Launch Orientation)

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Payload SRR/MDR Concept

SSMLI/MLI

CNES Tank (green)

Press System (warm side)

CNES Component Panel

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Payload Assembly Breakdown

- Vent Panel (cold)
- Cold Gas Tank (blue)
- GHe Tank W/MLI & Protective Covers
- TVS Vent Panel
- Transfer/AJ Panel
- Press Panel (cold) SOFI and SSMLI removed
- Press Panel (warm side)
- Press Panel (warm side)
- CNES Tank (green)
- Vent Panel (warm side)
- CNES Panel (warm side)
SPACEX PROVIDED USABLE VOLUME

DRAGONLAB UMBILICAL INTERFACE

PAYLOAD CONCEPT IN DRAGONLAB TRUNK

CPST Payload installed in Dragon Trunk

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Technology Maturation Phase Overview

**Purpose:**
Conduct tests, analytical modeling, and studies to mature technologies which were planned for the CPST demonstration flight in order to reduce the risk to cost and schedule for system development.

**Scope:**
The technology maturation phase addressed the following cryogenic fluid management technology areas:
- Thermal Control
  - “Thick” Multi-layer insulation (MLI) blanket penetration thermal losses
  - Reduced hydrogen boil-off with active thermal control
  - “Thick” Multi-layer insulation (MLI) for large scale tanks
  - Zero Boil-off oxygen storage
- Zero-g acquisition of cryogenic liquid for propellant transfer
- Chill-down of a propellant line for tank-to-tank transfer
- Zero-g propellant gauging
- Development and validation of analytical tools for thermal and fluid dynamic prediction of cryogenic propellant system storage performance

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**Objective:**
- Quantify thermal losses involving integrating MLI into real situations.

**Approach:**
- Test different integration methods & develop models specifically focused on the effects of penetrations (including structural attachments, electrical conduit/feedthroughs, and fluid lines) through MLI.

**Results:**
- Developed test method for measuring degradation of MLI around a penetration
- Measure heat load degradation and radius of thermally effected zone
- Determined the integration is best done with microfiberglass blankets
- Built & validated detailed thermal model of penetrations
**Objective:**
Validate concept to reduce boil-off of LH2 by integrating a ~90K cryocooler to intercept heat in the MLI and conductive loads.
- Address both thermal and structural concerns

**Approach:**
Constructed identical subscale tank test articles with broad area cooling (BAC) shields inside a thick MLI blanket.
- Thermal test article integrated with a reverse turbo Brayton cryocooler.
- Structural test article exposed to launch representative acoustic environment
- Self supporting MLI evaluated in Phase II of testing

**Results:**
- Acoustic tests resulted in no damage to MLI/BAC system
- Thermal testing demonstrated ~60% reduction in boil-off
Thermal Control: Oxygen Zero Boil-off

**Objectives**
Quantify the system performance integrating a flight representative reverse turbo-Brayton cycle cryocooler for Zero Boil-Off (ZBO) storage of Liquid Oxygen (LO2) for extended duration in a simulated space environment.

**Approach**
- Liquid Nitrogen was used as a surrogate fluid for LO2 to eliminate risks/costs associated with testing with LO2; testing conducted at elevated pressure to simulate LO2 storage temperature.
- Test article included the following:
  - Flight representative test tank with circulator tubing stitch welded and epoxied to test tank; thick (74 layer) traditional MLI.
  - Simulated space vacuum and thermal environment.

**Results**
- Success in ground demonstration of active thermal control technologies that achieve ZBO of LO2.
  - ZBO achieved at two storage tank fill levels: ~90% and ~25% full.
Cryogenic Propellant Transfer: Transfer Line Chill-down

**Objectives**
Evaluate efficient methods of pre-chilling a (tank-to-tank) transfer line of size representative of the CPST mission hardware.

**Approach**

- Construct a LH2 supply test tank with a transfer line of suitable diameter and length to roughly simulate the CPST system
- Test article included the following:
  - Vertical flow
  - Variable flow rates
  - Downstream flow visualization
  - Simulated space vacuum and thermal environment

**Results**

- Successfully collected data on chill-down of the line varying several parameters.
- Compared temperature and pressure data to visual flow quality.
- Used data to develop simplified chill-down models.

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Propellant Transfer: Transfer line Chill-down Visualization

LH$_2$ Gas to Droplet

LH$_2$ Wavy Annular Flow

LH$_2$ Bubbly Flow

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**Objective:**
Continued maturation of a gauge technology capable of measuring the amount of liquid cryogenic propellant in the tanks of a vehicle in space without accelerating to settle the propellant

**Approach:**
- Apply system developed in ground-based testing to a tank with a simulant fluid on an aircraft flying parabolic arcs for “zero-g”
- Mature electronics used for excitation and analysis of RF signal to enable a flight system.

**Results:**
- Successfully obtained microgravity data through multiple parabolic arcs and multiple configurations

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Analytical Model Development Example
Fluent Validation against LH2 Axial Jet Mixing

- Dia\_tank = 2.2 m, Dia\_jet = 2.21 cm
- 10 hrs self-pressurization simulated before axial jet is turned on (using uniform Wall Heat Flux= 4.2 W/m\(^2\))

Temperature contours “clipped” in ullage to show stratification in liquid

CFD grid
2D-axisymmetric

36000 grid cells.

Pump & nozzle

10 sec of mixing
150 sec of mixing

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The Cryogenic Propellant Storage and Transfer Technology Demonstration mission is being reformulated into a ground test activity.

The Technology Maturation Phase of the mission was highly successful in raising the maturity of key technologies to reduce the risk of developing these systems for a flight demonstration. Advancements were made in:

- Thermal control
- Propellant transfer
- Propellant gauging

In addition, advancements were incorporated into NASA’s analytical modeling for cryogenic fluid management systems.

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