Cryogenic Propellant Storage & Transfer (CPST) Technology Demonstration Mission

Presentation to the
NAC Technology and Innovation Committee
November 18, 2011

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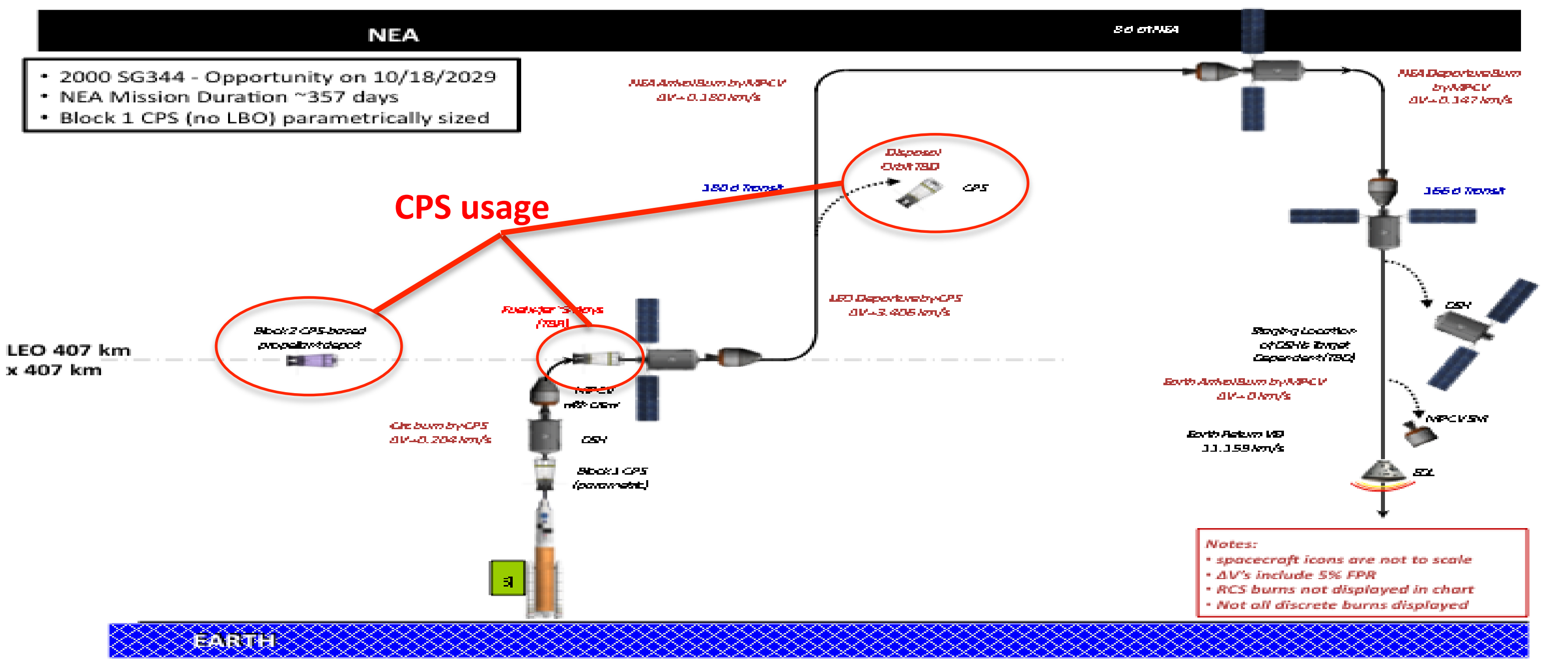
Presentation Outline

- **CPST Project Technology Infusion and Mission Justification**
- Technology Maturation
- Project Overview
- Conclusion

CPST Project Customer Infusion

- Human Exploration and Operations Mission Directorate (HEOMD) is a primary customer requiring cryogenic propellant storage and transfer technology to perform future missions.
- The initial HEOMD infusion customer is the Cryogenic Propulsion Stage (CPS)
  - CPST technologies are needed for the development of a CPS; CPS is part of the HAT architecture and is required to perform all beyond LEO exploration missions
  - CPST technologies are under examination for SLS and commercial upper stages
  - CPST technlogies also support architectures using depots in conjunction with SLS.



Cryo-Propulsion Stage – Block 1

Design Constraints/Parameters

Propellants	O2/H2
Stage Diameter	7.5 m
Stage Length	13 m
# Engines / Type	2 / RL10 Derived
Engine Thrust (100%)	30,000 lbf
Engine Isp (100%)	465 sec
RCS Propellant	NTO/MMH
# RCS Thruster / Type	16 / Press-fed
RCS Thruster Isp	300 sec

Passive Thermal Control of Propellants
0.7% per day H2 Boiloff (0.4 days)
0.25% per day O2 Boiloff (0.4 days)

Lithium Ion Batteries (100% DoD)

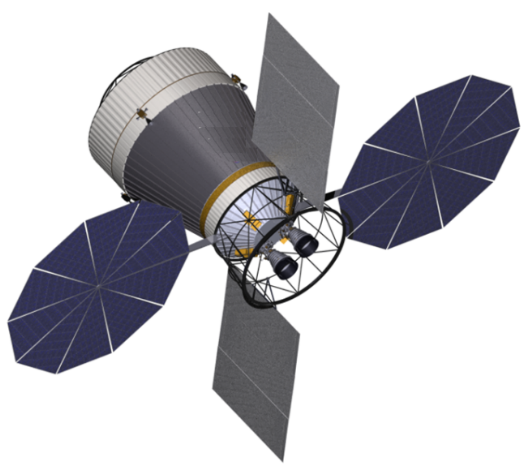
Category	Mass, kg
Structure	3,600
Protection	-
Propulsion	2,550
Control	-
Power	170
Avionics	420
ECLSS/Thermal	760
Other	-
Growth (30%)	2,250
Dry Mass	9,750
Non-Cargo	-
Cargo	-
Inert Mass	9,750
Non-Propellant	160
Propellant	70,500
Total Wet Mass	80,410

Description

The Block 1 Cryo Propulsion Stage (CPS-B1) is delivered to a -47 x 130 nmi insertion orbit by the launch vehicle, where the CPS is then responsible for raising and circularizing itself and any payload to an orbit of 220 nmi. The non-reusable CPS-B1 utilizes passive thermal control techniques to limit cryogenic propellant boiloff during its operation. The CPS-B1 includes avionics, propulsion, and attitude control for automated rendezvous and docking.

NOTE: The propellant inventory is based on the GEO mission inventory.

Cryo-Propulsion Stage – Block 2



Design Constraints/Parameters

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Stage Diameter	7.5 m
Stage Length	13 m
# Engines / Type	2 / RL10 Derived
Engine Thrust (100%)	30,000 lbf
Engine Isp (100%)	465 sec
RCS Propellants	NTO/MMH
# RCS Thrusters / Type	16 / Press-fed
RCS Thruster Isp	300 sec

Active Thermal Control of Propellants
0.5% per month H2 Boiloff
0% per month O2 Boiloff

2 x UltraFlex Arrays (26.7 kW total power)

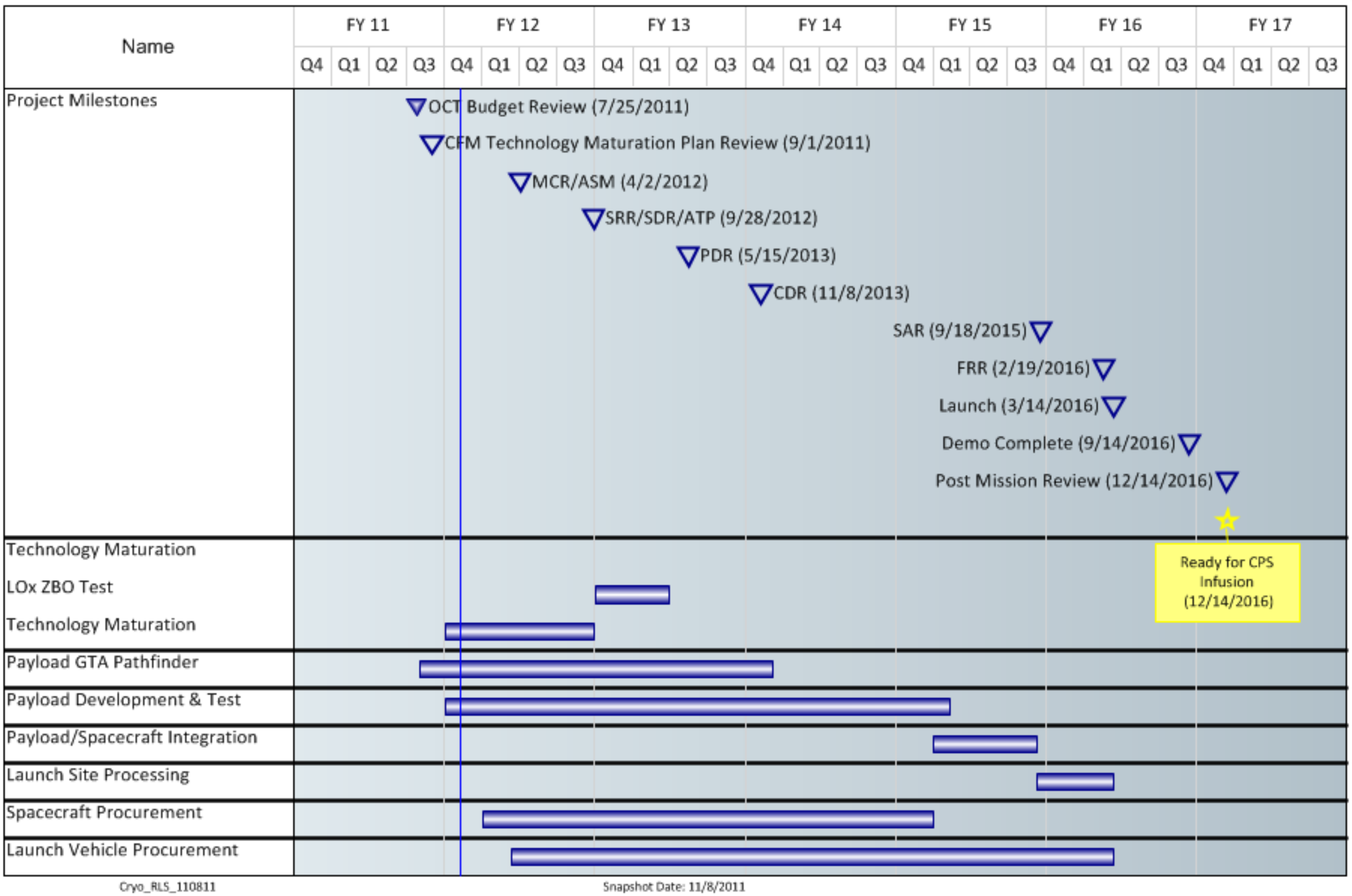
Category	Mass, kg
Structure	3,700
Protection	380
Propulsion	2,710
Control	-
Power	1,110
Avionics	590
ECLSS/Thermal	5,780
Other	-
Growth (30%)	4,280
Dry Mass	18,550
Non-Cargo	-
Cargo	-
Inert Mass	9,750
Non-Propellant	170
Propellant	52,540
Total Wet Mass	71,260

Description

The Block 2 Cryo Propulsion Stage (CPS-B2) builds upon the Block 1 CPS but includes a long duration cryogenic fluid management system that reduced propellant boiloff to 0.5%/month liquid hydrogen loss (by mass), and 0%/month liquid oxygen loss. The CPS-B2 also includes a long duration power system as well as avionics, propulsion, and attitude control for automated rendezvous and docking.

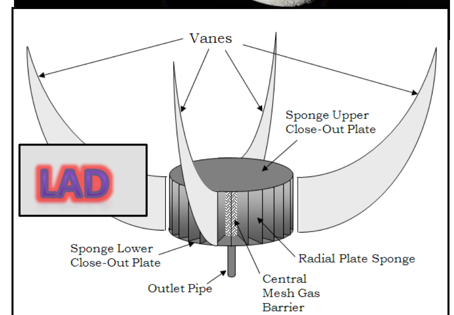
NOTE: The propellant inventory is mission specific, determined by mission duration, number of engine burns, and other mission parameters. The propellant tanks are sized by the Block 1 GEO mission, therefore the tanks are off-loaded for Block 2 NEO mission by 30.8%.

CPST Project Summary Schedule Customer Infusion



Present Challenges for In-Space Cryogenic Systems

- We have no demonstrated capability to store cryogenic propellants in space for more than a few hours
  - SOA is Centaur's 9 hours with boil-off rates on the order of 30% per day
- We have no demonstrated, flight-proven method to gauge cryogenic propellant quantities accurately in microgravity
  - Need to prove methods for use with both settled and unsettled propellants
- We have no proven way to guarantee we can get gas-free liquid cryogens out of a tank in microgravity
  - Gas-free liquid is required for safe operation of a cryo propulsion system
  - Need robust surface-tension **liquid acquisition device (LAD)** analogous to those in SOA storable propulsion systems
  - Only known experience in the world is the single flight of the Russian Buran single flight (liquid oxygen reaction control system)
- We have no demonstrated ability to move cryogenic liquids from one tank (or vehicle) to another in space



Note: A flight demonstration with cryogenic propellant storage, expulsion, and transfer can remedy these problems (*and other more subtle ones*)!

HAT Requires CPST Technologies

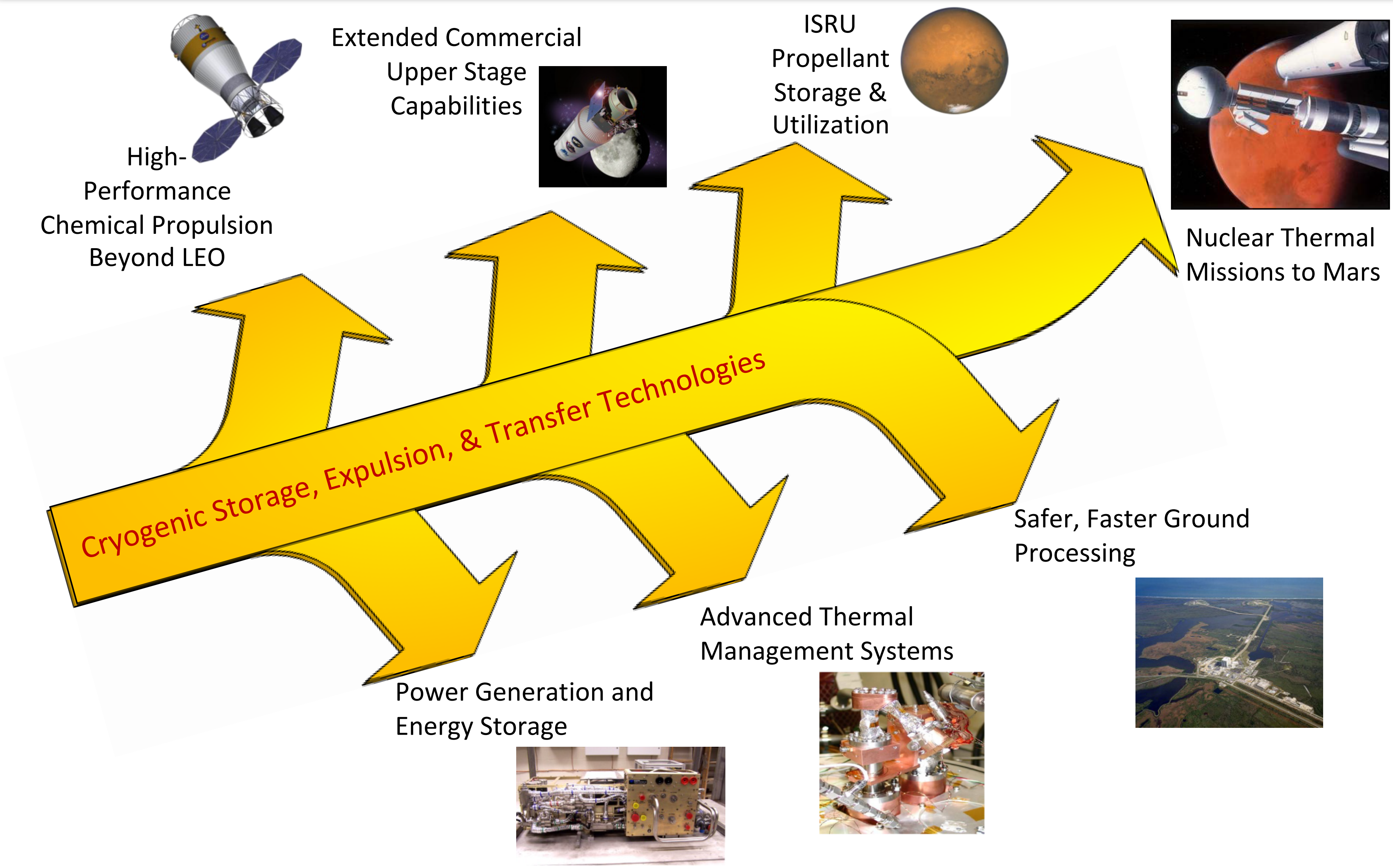
Technology Applicability for Future Destinations[1]		Destination									
		LEO		Beyond LEO	Moon		NEA		Mars		
		LEO	Adv. LEO	Cis-Lunar	Lunar Surface Sortie	Lunar Surface GPOD	Min NEA	Full NEA	Mars Orbit	Mars Moons	Mars Surface
Technology Need	LO2/LH2 reduced boiloff flight demo	N/A	N/A	May be required	Required	Required	Required	Required	Required	Required	Required
Technology Need	LO2/LH2 reduced boiloff & other CPS tech development	N/A	N/A	May be required	Required	Required	Required	Required	Required	Required	Required
Technology Need	LO2/LH2 Zero boiloff tech development	N/A	N/A	N/A	N/A	May be required	May be required	May be required	Probably Required	Probably Required	Probably Required

[1] *Adapted from chart 26 of HEFT Final Briefing dated 1/18/2011, posted at: http://www.nasa.gov/pdf/511089main_HEFT_Final_Brief_508_20110111.pdf*

Note

Almost all HAT missions beyond LEO *require* CPST's storage and expulsion technologies.

CPST Offers Cross-Cutting Benefits

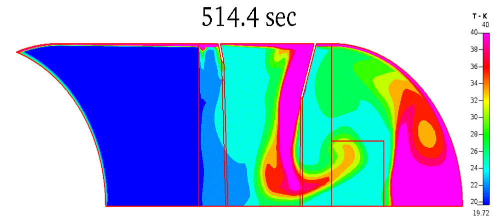


Why Is Microgravity Required for CPST?

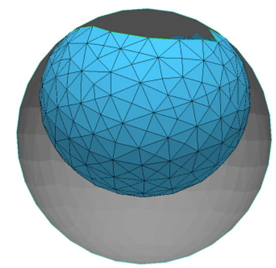
- Passive and active thermal control performance is unknown due to effects of acceleration level and propellant orientation.
  - Mixing of liquid (and heat transfer) inside the tanks
  - Low-g effects on internal convection and on thermal gradients
  - Analytical models for cryogenic storage tanks must be correlated to low-g data

- Liquid Acquisition Device (LAD) only works when surface tension forces are greater than gravity/acceleration forces.
  - Need long-duration microgravity to demonstrate LAD robustness across range of conditions and operating scenarios.

- Propellant Mass Gauging must be demonstrated in microgravity in an actual tank across a range of propellant orientation scenarios and fill levels.



CFD Model of Ullage Temperature of Saturn IV-B in Microgravity



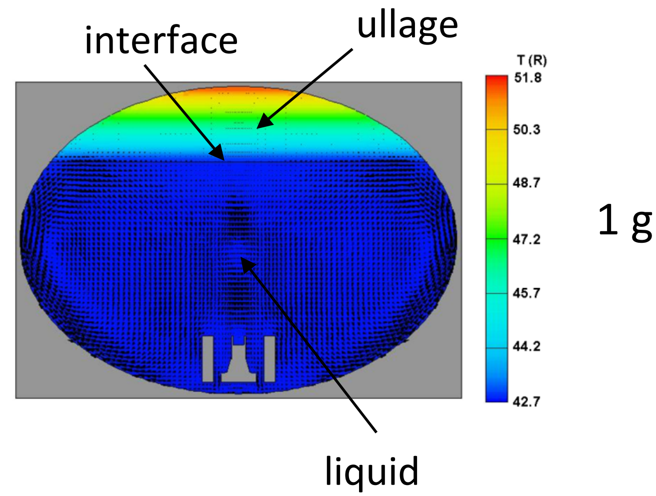
Fluid interface at 30 micro-g settling thrust in a 36" diameter LH2 tank at 50% fill (CPST POD transfer tank). A level sensor in the center of the tank would incorrectly read around 27% fill.

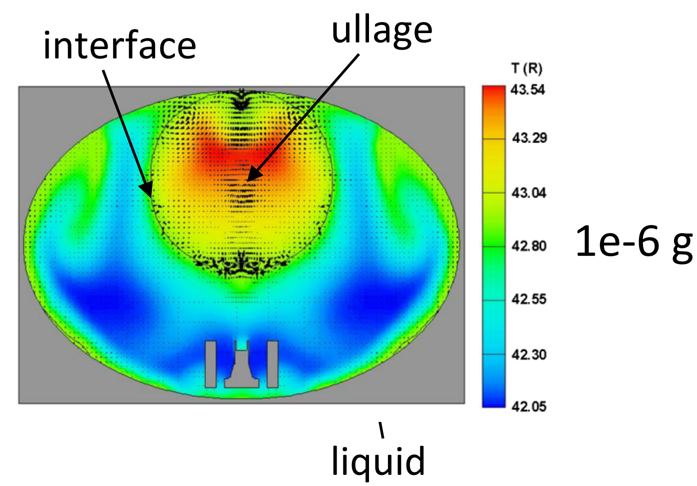
Mass Gauging Low-g aircraft test

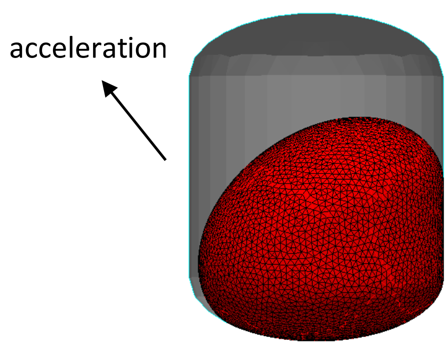
Why Storage Tests in Microgravity are Needed

Acceleration direction and magnitude → affects liquid shape and position
→ affects wall wetting and liquid/ullage interface area

- Primary heat source is through tank penetrations
- Wall wetting → determines heat into liquid and ullage
- Heat into liquid → affects temperature stratification
- Heat into ullage → affects pressure rise rate & stratification
- Liquid/ullage interface shape and area → affects heat and mass transfer across interface → affects pressure rise rate and temperature stratification
- Liquid and Ullage location → affects performance of mixers, such as axial jet or spray bar since ullage may not be "centered" in the tank

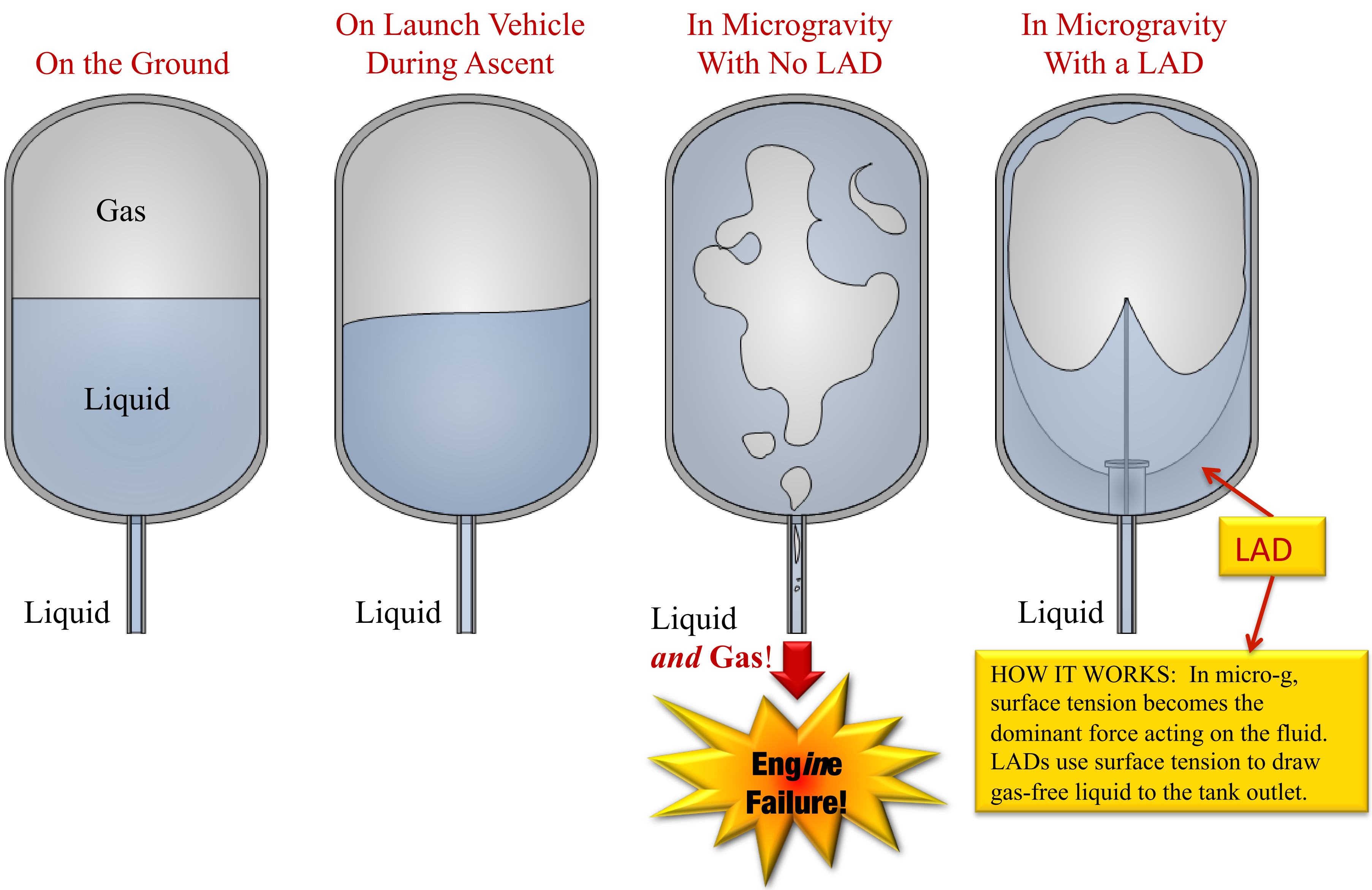






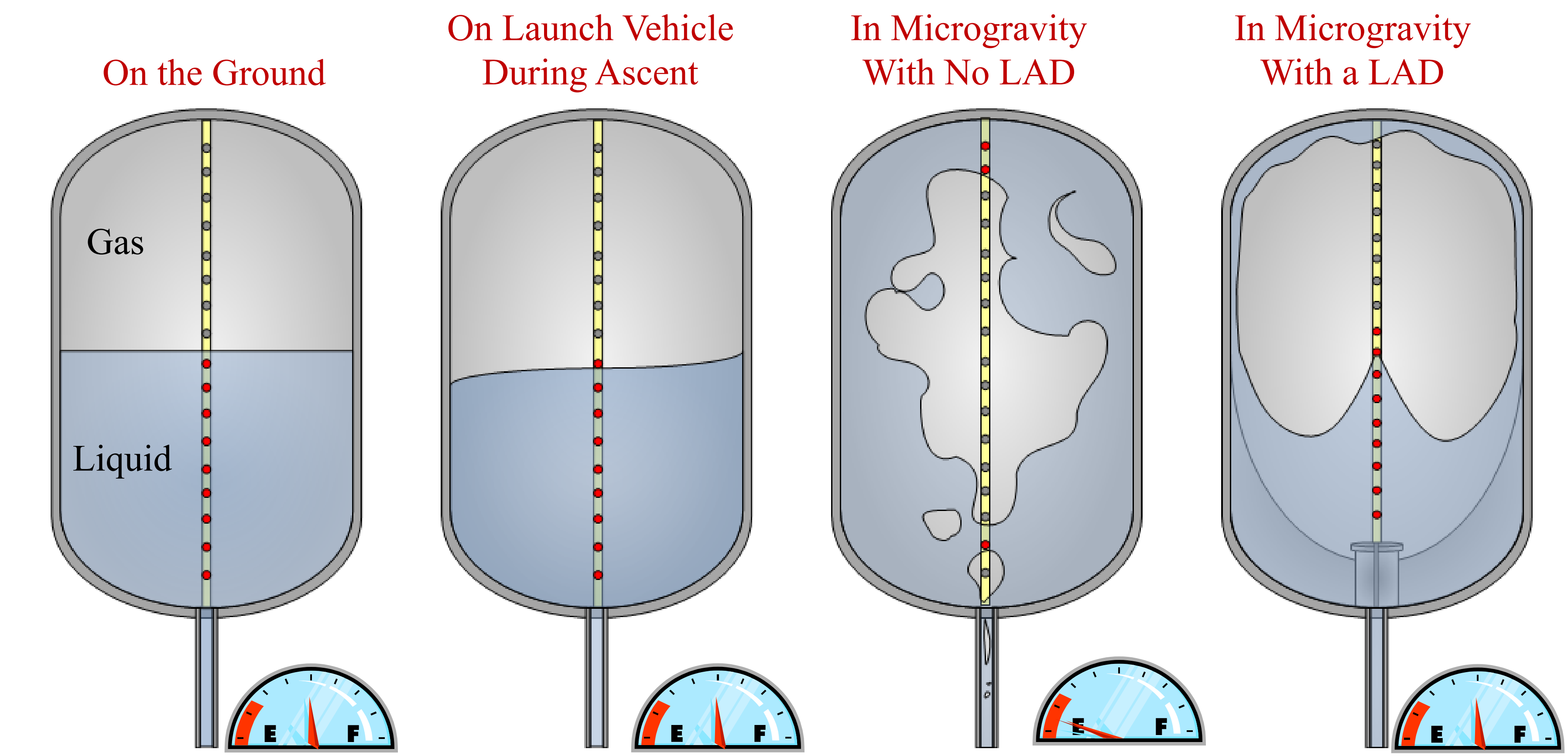
Why Liquid Acquisition Devices (LADs) Are Needed

Propellant Tanks



Why Probe-Type Gauges Aren't Sufficient

Probe-Type Gauges



Accuracy: Very good | Very good | Terrible | CPST Demonstration Needed

Probes work best when liquid is ***settled!***

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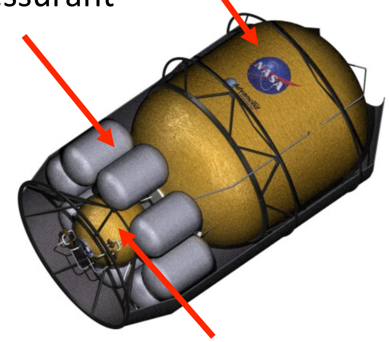
Cryogenic Propellant Storage and Distribution

Hydrogen Storage

Pressurant

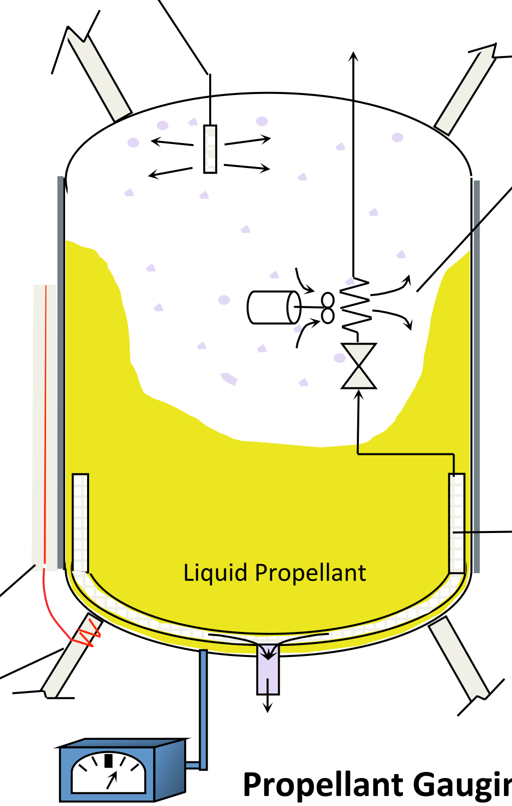


Receiver Tank

Cryogenic Tank Details

Pressurization
- Cold helium
- Autogenous

Pressure Control
- Thermodynamic Vent System



Liquid Acquisition
- Capillary retention devices

Thermal Control
- Insulation
- Vapor or actively cooled shields
- Low conductivity/ cooled support structure

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

Passive Thermal Control: Cryogenic Insulation for Thermal Control

Technology development goal: Demonstrate high performance cryogenic insulation to minimize heat leak through large areas of tanks and lines.

Spray-On Foam Insulation (SOFI)
- Extensive heritage
- Mitigates convection from the atmosphere
- Prevents condensation of air and prevents ice buildup
- Supports launch pad operations and ascent phase of mission
- TRL = 9

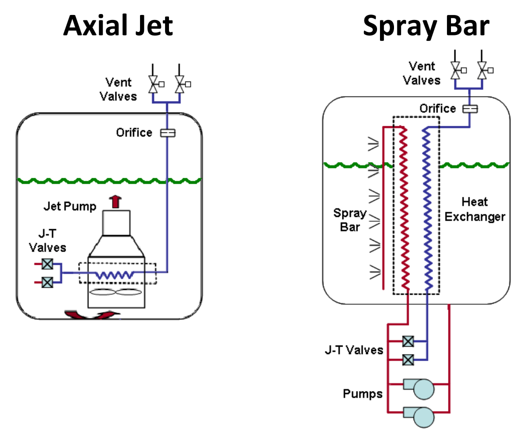
Thick Multi-Layer Insulation
- Radiation shields with low thermal conductance seperators between the shields
- Support of blanket for large area tanks, high number of layers, seams, and blanket penetrations are challenges
- Supports in-space phases of the mission
- TRL = 4

Active Thermal and Pressure Control for Long Duration Storage

Technology development goal: Develop active thermal and pressure control systems to achieve reduced or zero boil-off for a cryogenic propellant

Efficient Low-g Venting

- Thermodynamic Vent System (TVS) ensures that only gas phase is vented in low gravity without using settling thrusters.
- De-stratifies propellant tank contents, with mixer
- TRL = 5



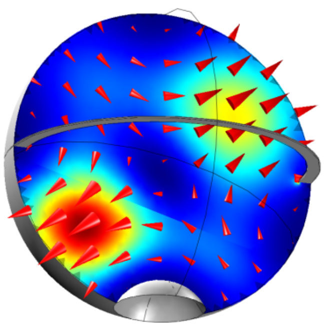
Cut away of pulse tube type cryocooler

Reduced Boil-off Technologies

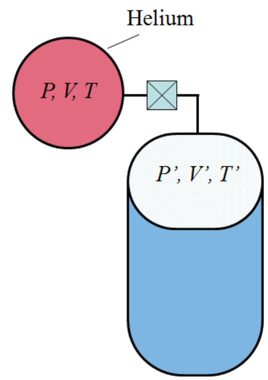
- Eliminate heat leak into the storage tank, re-condense vapor, or potentially sub-cool propellant
- 90 K cryocoolers to achieve reduced boil off for CPS
  - TRL = 6
  - Current CPS concept does not use 90k cryocoolers
  - If used, 90k cryocoolers (~5% efficiency) removing 20 Watts of heat each sized as:
    - Approximate input power per cooler = ~500 W
    - Approximate mass per cooler = ~500 W
- 20 K cryocoolers to achieve zero boil-off (ZBO) for CPS
  - TRL = 2
  - Current CPS assumption uses seven 20k cryocoolers (~1% efficiency), removing 20 watts of heat each.
    - Approximate CPST input power per cooler = ~2000 W
    - Approximate mass per cooler = ~280 kg

Low-g Cryogenic Liquid Mass Gauging

Technology development goal: Develop propellant quantity (mass) gauges that work in zero-g, and/or under low settling thrust (<0.001g)

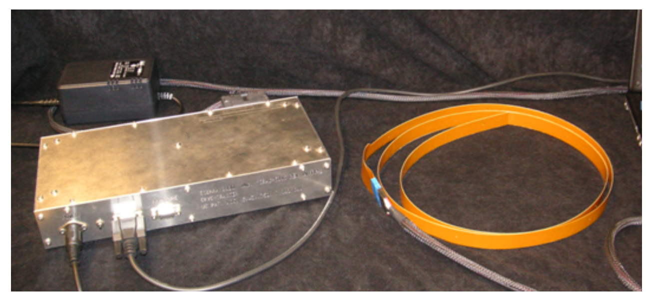


RF Mass Gauge
- GRC technology
- tested on low-g aircraft
- tested in LH2, LOX
- zero-g or settled
- TRL = 5



Pressure-Volume-Temperature Gauge
- requires helium
- tested in LOX
- zero-g or settled
- TRL = 5

Compression Mass Gauge
- developed by SwRI
- tested in small LN2 tank
- zero-g or settled
- TRL = 4



CryoTracker - Sierra Lobo
- wet/dry level sensors
- requires settled liquid
- TRL = 5

Low-g Cryogenic Propellant Liquid Acquisition

Technology development goal: Develop liquid acquisition system to provide transfer of vapor free liquid cryogenic propellant.

Liquid Acquisition Devices

- Multiple contoured tubes with fine pore wicking screen windows
- Liquid wets screen and fills tubes
- GRC ground tested screen channels with LN2, LO2, LH2, and LCH4 (bubble point and outflow)
- TRL = 4

Vane-Type LAD integration into a tank

Breadboard screen-channel LAD for outflow testing

Vane Type Devices

- Multiple contoured solid plates
- Liquid transferred along interior corners
- Used on monopropellant systems
- TRL = 5

Total communication propellant management devices (PMDs) have not been used yet in cryogenic propulsion applications.

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Cryogenic Propellant Storage and Transfer (CPST) Overview

Description: Space flight mission to demonstrate a single fluid (LH2), passive/active cryogenic propellant storage, transfer, and gauging systems for infusion into future extended in-space missions.

TRL Advance: 5 to 7

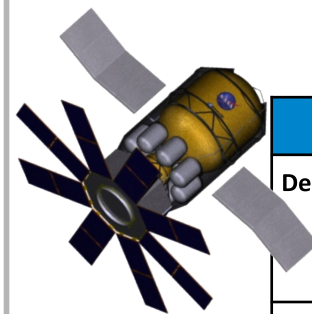
Benefits

Support exploration beyond LEO

- Demo long duration in-space storage of cryogenic propellants.
- Demo in-space transfer of cryogenic propellants.

Cost Guidance: No more than $300M

Flight System Concept Option



Flight System Characteristics	
Demonstrations	Single Fluid (LH2) Passive Storage Active Storage 2 Transfer Cycles
Launch Vehicle	Medium Class

Mission Architecture Description:

CFM technologies include

- Passive Cryogenic Propellant Storage
- Active Cryogenic Propellant Storage
- Tank Thermal & Pressure Control
- Liquid Acquisition
- Mass Gauging

Mission Duration - 6 months

Ground Tech Maturation (to TRL 5)

- Structural and thermal performance of passive and active cooling systems
- Thermal performance of composite struts
- LAD out flow and transfer line chill down (LH2)

Team:

Project Manager/Lead Center: Susan Motil/GRC

Team: MSFC, GSFC, KSC, ARC

Near term Milestones:

- Technology maturation complete thru 2013
- BAA Mission Studies Complete: 01/2012
- CPST Mission Concept Review Complete: 05/2012
- System Requirements: 09/2012

Concept Definition Process

Government Pre-Phase A Study

- **Mission Justification**
- **Technology Identification and Technology Development Ground Test Plan**
  - Candidate Demonstration Technologies
  - Technology Maturation Plan
  - Analysis and Design Tools
  - Technology Gaps and Residual Risks
- **Mission Concept**
  - Mission Concept of Operations
  - Launch Vehicle Considerations
  - Mission Performance Factors
  - Integrated Conceptual Design
- **Demonstration Flight System**
  - Flight System Performance Analysis
  - Cryogenic Fluid System Definition
  - Supporting Subsystem Definition
- **Project Formulation**
  - Mission Cost Estimate
  - Project Schedule
  - Government – Industry Partnerships
  - Project Risks
- **Supporting Technical Products**

Mission Assessments and Synthesis of New Government/ Industry Mission Concept

BAA Industry A Studies

BAA Industry B Studies

BAA Industry C Studies …

CPST MCR
~April 2012

MCR Products

- Concept of Operations
- Mission Requirements
- CPST Architecture Requirements
- Technology Development Requirements
- Test and Verification Strategy
- Risk Management Plan
- Evaluation of Alternative Mission Concepts
- Project Planning Documentation

Approach enables infusion of best ideas from Industry and Government

Concept Option: Technology Development

Needs

Create the innovative new space technologies for our exploration, science, and economic future

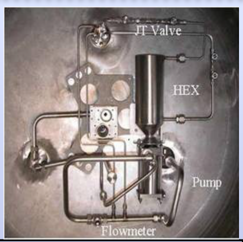
Goals

Advance cryogenic propellant systems technologies for infusion into future extended in-space mission

Objectives

- Store cryogenic propellants in a manner that maximizes their availability for use regardless of mission duration
- Efficiently transfer conditioned cryogenic propellant to an engine or tank situated in a microgravity environment
- Accurately monitor and gauge cryogenic propellants situated in a microgravity environment

Technologies



TVS components (installed in test tank)

Pulse-tube cryocooler

LH2 Storage	
Active thermal control: Broad Area Cooling (tubes on tank or tubes on shield)	4
Active thermal control: cryo-coolers (90K)	6
Passive storage: reduced penetration heat leak through MLI	4
Passive storage: low conductivity structural attachments	4
Tank Pressure Control: thermodynamic vent system (TVS)	5
Tank Pressure Control: mixing pumps	5

LH2 Acquisition	
Liquid Acquisition Devices (LADs)	4

Screen Channel Capillary LAD

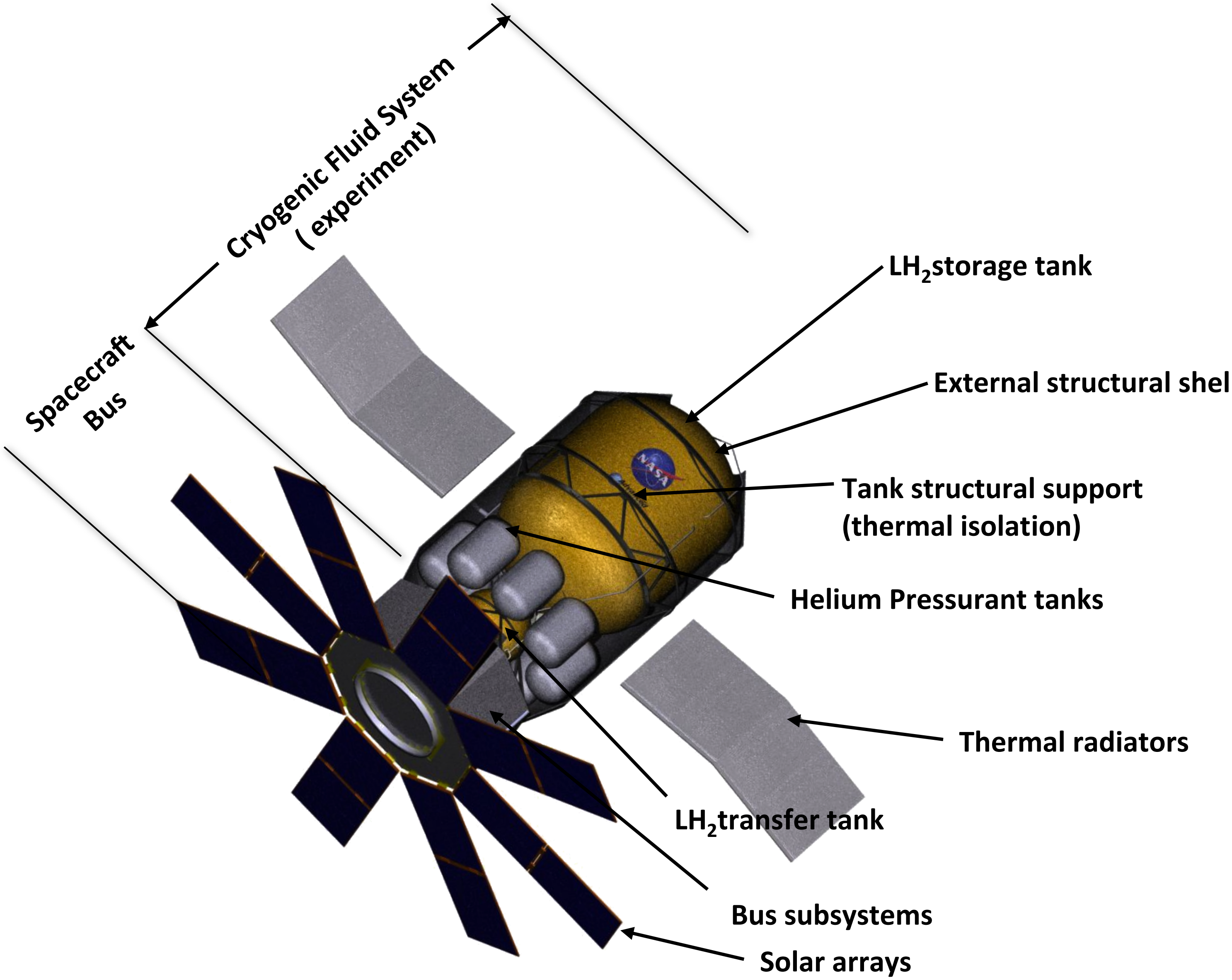
LH2 Transfer	
Transfer Value	4
Transfer Pump	5
Line and Tank Chill-down	5

LH2 Quantity Gauging	
Capacitance Probe	4
Wet-Dry Sensor (Cryotracker)	5
Radio Frequency (settled/ unsettled)	5

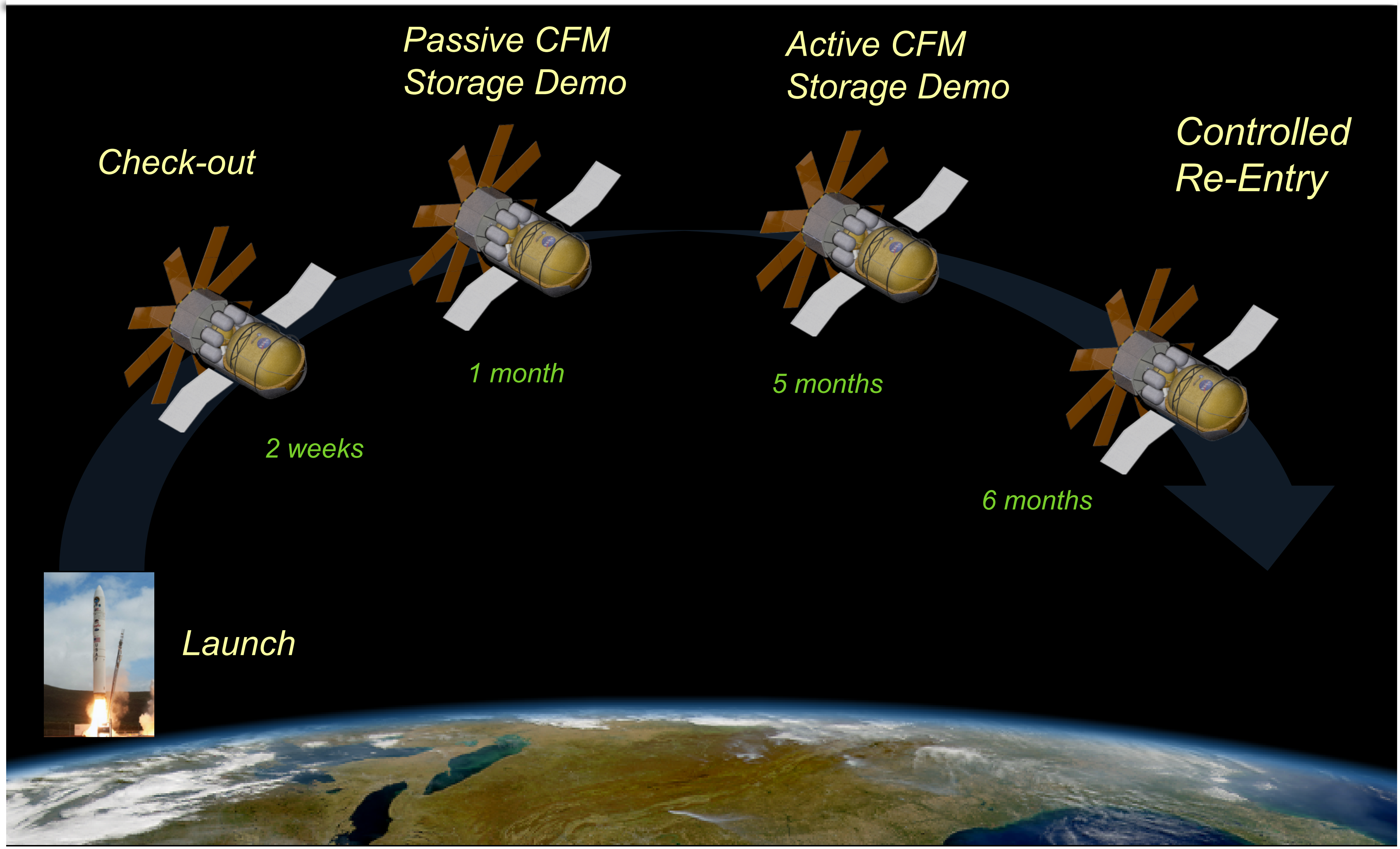
RF Gauge Test Rig

Assessment of Technology Readiness at Pre-Flight Demonstration

Concept Option: CPST Demonstration Architecture



Concept Option: 6-Month Mission Profile



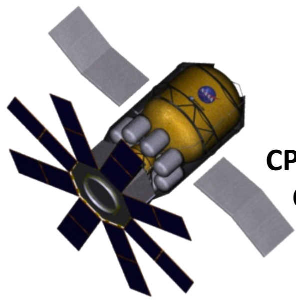
Concept Option: Scenario for a CPST Mission Architecture

Cryogenic Fluid System
- LH2 Storage
- CFM management
- Transfer Demonstration System
- Data Recording

Six Month Orbital Mission (500 km altitude/38^{O} Inclination Orbit)

Mission Demonstration`	Month					
	1	2	3	4	5	6
Spacecraft & CFM Demo Systems Checkout						
LH2 Storage Tank Passive CFM Demo						
LH2 Storage Tank Active CFM Demo						
LH2 Transfer Demos						

Spacecraft Bus
- Attitude Control
- Communications
- Propulsion



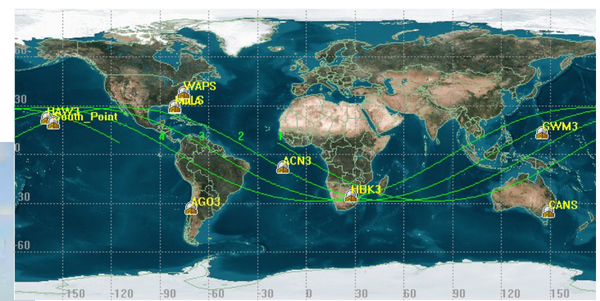
CPST Operational Configuration

Technology Developments:
- **Tank Thermal Control**
- **Tank Pressure Control**
- **Cryogenic Fluid Transfer**
- **Liquid Acquisition**
- **Mass Gauging**
- **Leak Detection**

Controlled Reentry & Disposal

Eastern Launch Site: TBR

Mission Operations



Communications: Near Earth Network

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FY12 CPST Go Forward

- FY12 focus will be on technology maturation to TRL 5
  - LH2 storage tests and analyses to support reduced boil-off capability
  - LH2 liquid acquisition tests and analyses to provide the ability for unsettled acquisition
- Complete BAA mission studies
- Build on Government POD Study results to develop a mission concept
  - Review industry BAA concepts and begin mission concept synthesis
  - Finalize POD based on in-house study and BAA mission studies
  - Define system concept of operations
- Prepare for Mission Concept Review in FY12
  - Includes system requirements and acquisition strategy
  - budget and schedule recommendation based on a system concept

Flight Demonstration Closes CFM Technology Gaps

- Primary motivation for the CPST technology demonstration mission is to enable long duration beyond LEO human exploration missions (Moon, NEA & Mars)
  - A Cryogenic Chemical (LOX/LH2) Propulsion Stage (CPS), capable of storing and transferring cryogenic propellants is considered **required** for all such missions.
- Closing the technology gaps *requires* microgravity environment and opens the trade space for future missions.
  - **Required** to demonstrate thermal and pressure control performance for long duration storage
  - **Required** to demonstrate LAD performance for vapor-free liquid acquisition and transfer
  - **Required** to validate microgravity mass gauging systems
- Propulsion applications require a flight demo to address *both* storage & transfer.
  - Must repeatedly get liquid (not pressurant gas) out of the tanks in space
  - Must verify that fluids leaving the tank are gas-free liquids
  - Verify quantities of fluids on orbit, settled or unsettled

A flight demonstration is the only way to close CFM technology gaps and ready the Cryogenic Propulsion System for future in-space applications.