Cryogenic Propellant Storage & Transfer (CPST) Project Technology Advancement

Presentation to the
NAC Technology and Innovation Committee
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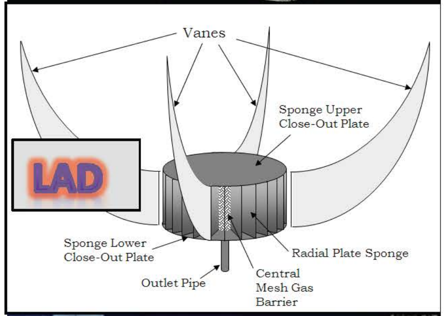
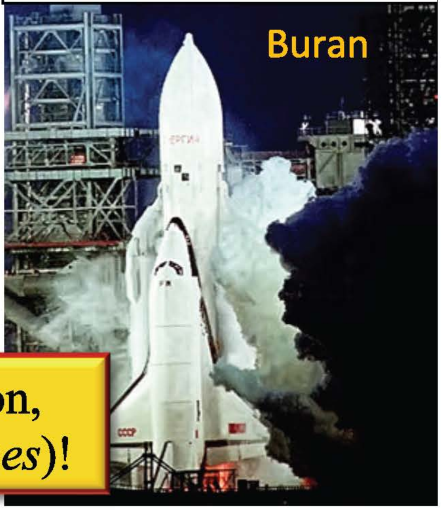
Last Time CPST Presented to NAC, November 2011

- Mission justification and challenges with cryogenic propulsion systems
- Mission concept studies
- Technology maturation plans
- Go Forward Plan
  - FY12 focus on technology maturation to TRL 5, ***completed October 2013***
    - LH2 storage tests and analyses to support reduced boil-off capability
    - LH2 liquid acquisition tests and analyses to provide the ability for unsettled acquisition
  - BAA mission studies, ***completed January 2012***
  - Build on Government POD Study results to develop a mission concept, ***completed December 2011***
    - 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, ***completed April 2012***
    - Value proposition of possible missions
    - Approval to proceed to Mission Definition
    - Acquisition strategy approved for in-house build of the cryogenic fluid system, procurement for the remainder of the mission

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



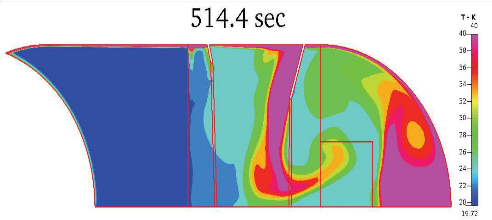


Note

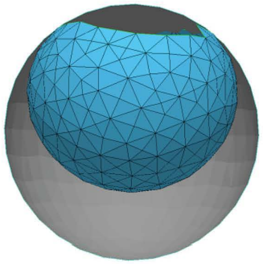
A flight demonstration with cryogenic propellant storage, expulsion, and transfer can remedy these problems (*and other more subtle ones*)!

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

Mapping of CFM Capability Advancement To Missions

Cryogenic Fluid Management Capability	Near Term Cryogenic Propulsion Stage (CPS)	Asteroid Mission CPS	Mars Transfer Stage (Chemical or NTP)	Cryogenic Propellant Depot	Commercial Launch Upper Stage Near Term	Commercial Propellant Tanker
Approximate In-Space Mission Duration	Days to a few weeks	Mutiple Months	~2 years	Multiple years	> 1 day	< 2 days
Oxygen Storage	Very Low Boil-off - Passive Thermal Control	Zero Boil-Off Active Thermal Control	Zero Boil-Off Active Thermal Control	Zero Boil-Off Active Thermal Control	Low Boil-Off Passive Thermal Control	Low Boil-Off Passive Thermal Control
Hydrogen Storage	Very Low Boil-off - Passive Thermal Control	Ultra-Low Boil-Off Active Thermal Control	Zero Boil-Off Active Thermal Control	Zero Boil-Off Active Thermal Control	Low Boil-Off Passive Thermal Control	Very Low Boil-Off Passive Thermal Control
Cryogen Transfer	Engine Supply	Engine Supply; Micro-g Tank-to-Tank may benefit	Micro-g Tank-to-Tank & Engine Feed	Micro-g Tank-to-Tank & Engine Feed	Engine Supply	Micro-g Tank-to-Tank & Engine Feed
Propellant Gauging	Micro-g gauging beneficial	Micro-g gauging required	Micro-g gauging required	Micro-g gauging required	Micro-g gauging beneficial	Micro-g gauging beneficial
Analytical Perf. Models	✔	✔	✔	✔	✔	✔

CPST Technology Development

Needs

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

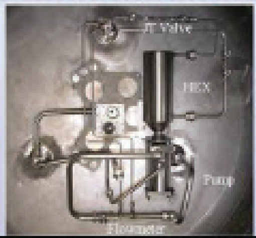
Goals

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)

Turbo Brayton cryocooler

LH2 /LO2 Storage

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

LH2 /LO2 Acquisition

Liquid Acquisition Devices (LADs)	4/5*

Screen Channel Capillary LAD

LH2 /LO2 Transfer

Transfer Valves	4/5*
Transfer Pump**	5
Line and Tank Chill-down	5

LH2 /LO2 Quantity Gauging

Advanced Wet-Dry Sensor	4/5*
Radio Frequency (settled/unsettled)	5

RF Gauge Test Rig

Flight and ground test program to mature technology
* Where TRL has two values they are for LH2/LO
** Ground test only

Summary of CPST FY12-13 Technology Maturation

Test Name	Objective
LH2 Active Cooling – Thermal Test (a.k.a. RBO I)	Demonstration of a flight representative active thermal control system for Reduced Boil-Off (RBO) storage of LH2 for extended duration in a simulated space thermal vacuum environment
LH2 Active Cooling – Broad Area Cooling Shield/MLI Structural Integrity (a.k.a.VATA I)	Assess the structural performance of an MLI / BAC shield assembly subjected to launch vibration loads
Active Thermal Control Scaling Study	Conduct study to show relevancy of CPST-TDM active thermal control flight data to full scale CPS or Depot application
(MLI) Penetration Heat Leak	Measurement of heat leak due to strut penetration integrated with MLI
Thick MLI Extensibility Study	Assess optimum approach for attachment of thick (40-80 layer) MLI to very large tanks
LAD Outflow & Line Chill	Quantify the LAD stability (no LAD breakdown) due to transfer line chill down transient dynamic pressure perturbations during outflow
Performance Modeling/Analytical Tools	Continue development and validation of tools to support design of CPST-TDM and future NASA exploration mission using cryogenic systems

Related Activities

LO2 Zero Boil-off	Demonstration of a flight representative active thermal control system for Zero Boil-off (ZBO) storage of LO2 (using LN2 as simulant)
Self-Supporting MLI	Validate new MLI concept (led by Game Changing Development w/ CPST support)
RF Mass Gauge	Long lead activities for radio frequency mass gauge
CFD Benchmarking	CFD Modeling assessment activity in partnership with CNES

Advancement of TRL by CPST

		CFM Technologies	InitialTRL LH2/LO2	Current TRL LH2/LO2	Projected Post CPST Flight TRL LH2/LO2**
Category	Subset	Specific			
Long Duration Propellant Storage	Passive Thermal Control	Tank Multilayer Insulation with Foam Substrate	(4/6)/(4/6)	(5/6)/(5/6)	6/6
		Low Conductivity Structure/Struts	(4/6)/(4/6)	(4/7)/(4/7)	(4/7)/(4/7)
		Vapor Cooled Shields	(5/9)/(N/A)	(5/9)/(N/A)	(5/9)/(N/A)
		Para to Ortho Conversion	5/(N/A)	5/(N/A)	5/(N/A)
		Densified Propellants	(4/5)/5	(4/5)/5	(4/5)/5
		Sacrificial Structures	4/4	4/4	4/4
		Solar Shield	4/4	4/4	4/4
	Active Thermal Control	Cryocooler Development (20K/90K)	2/6	3/6	3/6
		Cryocooler Integrated BAC	4/(N/A)	5/(N/A)	6/(N/A)
		BAC Shield -Tube-on-Tank	3/4	3/4	3/4
		BAC Shield - Tube-on-Shield	4/(N/A)	5/(N/A)	6/(N/A)
	Micro-g Pressure Control	TVS	5/5	4/4	6/6
		Fluid Mixer	5/5	5/5	6/6
Liquid Transfer	Settled/Unsettled	Micro-g Transfer Line ChillDown	4/4	5/5	7/7
		Micro-g Receiver Tank Chilldown	5/5	4/4	6/6
		Pressurization Systems	5/5	5/5	6/6
		Tank To Tank Transfer	5/5	5/5	6/6
		2-Phase Fluid Tolerant Transfer Pumps	3/3	3/3	3/3
		Automated Fluid Couplings	4/4	4/4	4/4
Liquid Supply	Unsettled Liquid Acquisition Devices	Bubble Point Pressure (BPP) Measurement	(4/5)/5	5/5	6/6
		LAD Outflow	4/5	5/5	6/6
	Propellant Positioning Using External Forces	Linear Acceleration	9/9	9/9	9/9
		Spacecraft Spin	6/6	6/6	6/6
		Magnetic Positioning	3/3	3/3	3/3
	Autogenous Pressurization	Heat source, heat exchanger, control logic	3/3	3/3	3/3
Instrumentation	Mass Gauging	Settled Mass Gauging: point sensors	9/9	9/9	9/9
		Unsettled Mass Gauging: RF Gauging	5/5	5/5	6/6
	Automated Leak Detection	Vacuum compatible distributed sensors	5/5	5/5	5/5
	2-Phase Mass Flow Meters		3/3	3/3	3/3
Fluid Handling	Slosh Control	Baffles	9/9	9/9	9/9
	Vanes		6/6	6/6	6/6

🟨 Indicates change due to Tech. Mat.

🟧 Non-CPST maturation or changed in assessment

Range of TRL indicates more than one technology approach

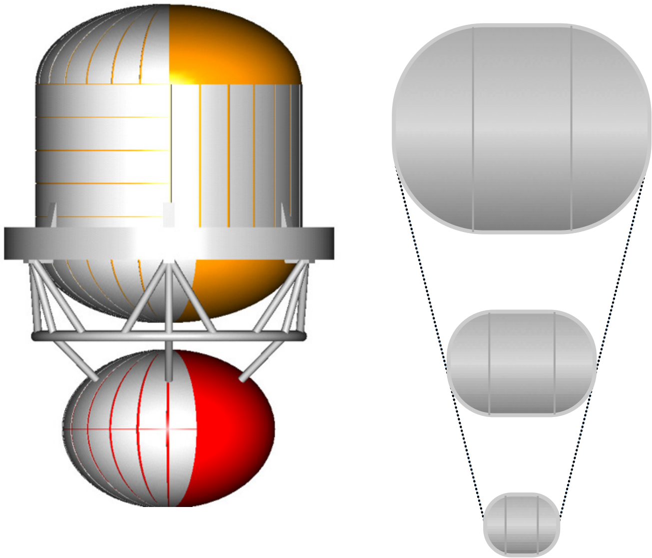
Technologies selected for flight demonstration

Today

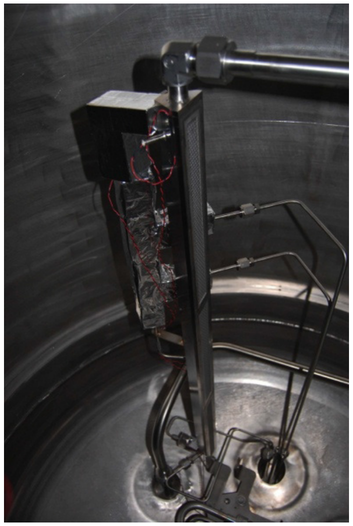
**Post CPST TRL assumes pre-reformulation mission concept.

CPST Technology Maturation in Pictures

LH2 Active Cooling–Thermal Test (RBO) and Acoustic Test (VATA)



Scaling Studies-MLI and Active Thermal Control



LAD Outflow Test

(MLI) Penetration Heat Leak Study

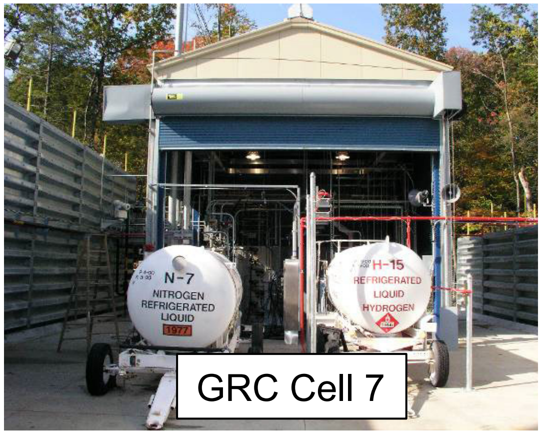
Slight Glass during Line Chilldown

RF Mass Gauging

Composite Strut Study

Key Agency Facilities Used by CPST

KSC Cryogenics Lab

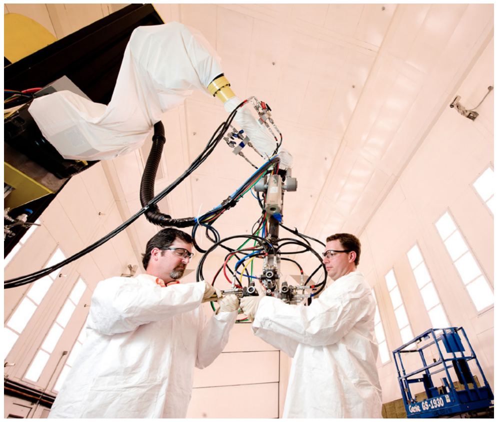


GRC Cell 7

GRC SMiRF

MSFC B4205

MSFC SOFI Dev. Center



MSFC B4619
Acoustic Chamber

CPST Technology Infusion

- ***Our goal is to maximize infusion of the demonstrated technologies to:***
  - future NASA mission architecture and vehicle development teams (CPS, propellant depots, NCPS)
  - US launch and in-space transportation industry
  - spin-off industry applications
- ***The primary pathways CPST will utilize to ensure infusion of the matured technologies are:***
  - Documentation & dissemination of the knowledge gained
  - Presentation and peer interaction
  - Transfer of performance models
  - Experienced project personnel
- ***Other supporting infusion pathways include:***
  - CPST residual hardware
  - Experienced vendors
  - Experienced NASA test facilities

CPST Technology Infusion - Industry Workshops

Date	Topics	Attendees (Non-NASA) In-Person	Virtual
May 22, 2013	CPST Technology & Maturation Overview Composite Strut Thermal Performance Multi- Layer Insulation (MLI) Penetration Heat Leak Study	11	13
June 5, 2013	Analytical Tools Performance Models	3	7
July 25, 2013	Liquid Acquisition Device (LAD) Outflow Line Chilldown Propellant Gauging	4	6
August 14-15, 2013	Active cooling thermal/structural studies Scaling Extensibility to large tanks	10	15

Attendees: Analytical Mechanics Associates, Ball Aerospace, Boeing Company, Boeing Phantom Works, Creare Inc., GE Healthcare, Lockheed Martin, Moog Inc., Northrop Grumman, Quest Thermal Group, Shackleton Energy, Sierra Lobo, United Launch Alliance and NASA GRC, MSFC, LaRC, KSC, and ARC.

Industry greatly appreciative of the data provided and the insight on cryogenic performance

Notable Results, Including "Firsts"

- Successful experimental evaluation of thermal losses associated with MLI and penetrations, including options to minimize degradation to the bulk MLI from the penetration.
- Successfully completed a "first of its kind" demonstration of flight-representative Reverse Turbo-Brayton Cycle (RTBC) cryocooler integrated with Broad Area Cooled (BAC) shield to reduce boil-off of a LH2 storage tank, including a direct coupling of the radiator to the RTBC.
- "First of its kind" to demonstrate a tank-applied integrated MLI and BAC shield configuration able to survive a worst-case acoustic launch environment, meeting all test Key Performance Parameters.
- Active Thermal Control Scaling study concludes that there are substantial mass savings for large cryogenic upper stages or depots faced with moderate loiter periods when including Reduced Boil Off (RBO) and Zero Boil Off (ZBO) systems.
- Successful demonstration of tank liquid acquisition with a screen channel device (LAD) and transfer line chill down technologies in liquid hydrogen.

Notable Results, Including "Firsts" (Cont.)

- Furthered the development and validation of fluid dynamics and thermodynamics analytical tools for design of TDM CPST and future NASA exploration missions using cryogenic systems.
- Completed environmental testing of prototype Radio Frequency Mass Gauge critical components, and developing custom circuit board for unsettled mass gauging.
- Demonstrated via testing a more effective (lower power input) settled LH2 wet-dry mass gauging using Cernox sensors.
- Successful collaboration with STMD Game Changing Development to utilize existing hardware assets to conduct thick MLI/Reduced Boil Off thermal and structural testing to gain directly comparable data for SSMLI vs. traditional MLI performance.

Summary

- A technological foundation of knowledge, skills, capabilities has been laid that:
  - Provides a backbone for embarking on the CPST flight to test and validate key cryogenic capabilities and technologies,
  - Opens up a much more capable architecture for large cryogenic propulsion stages and propellant depots to extend human and robotic presence throughout the solar system.

The Agency must fly a CPST Demo to push the TRLs and to enable infusion into mainstream applications. These technologies really are, as the NRC said, at a "Tipping Point", and CPST is the required push.