National Aeronautics and
Space Administration

Space Technology Mission Directorate

Cryogenic Fluid Management Investments Overview

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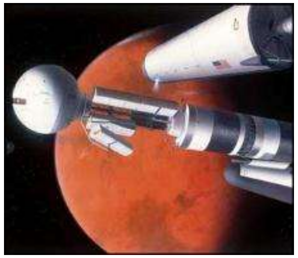
18 Nov 2016

Cross-Cutting Benefits of Cryofluid Management Technologies

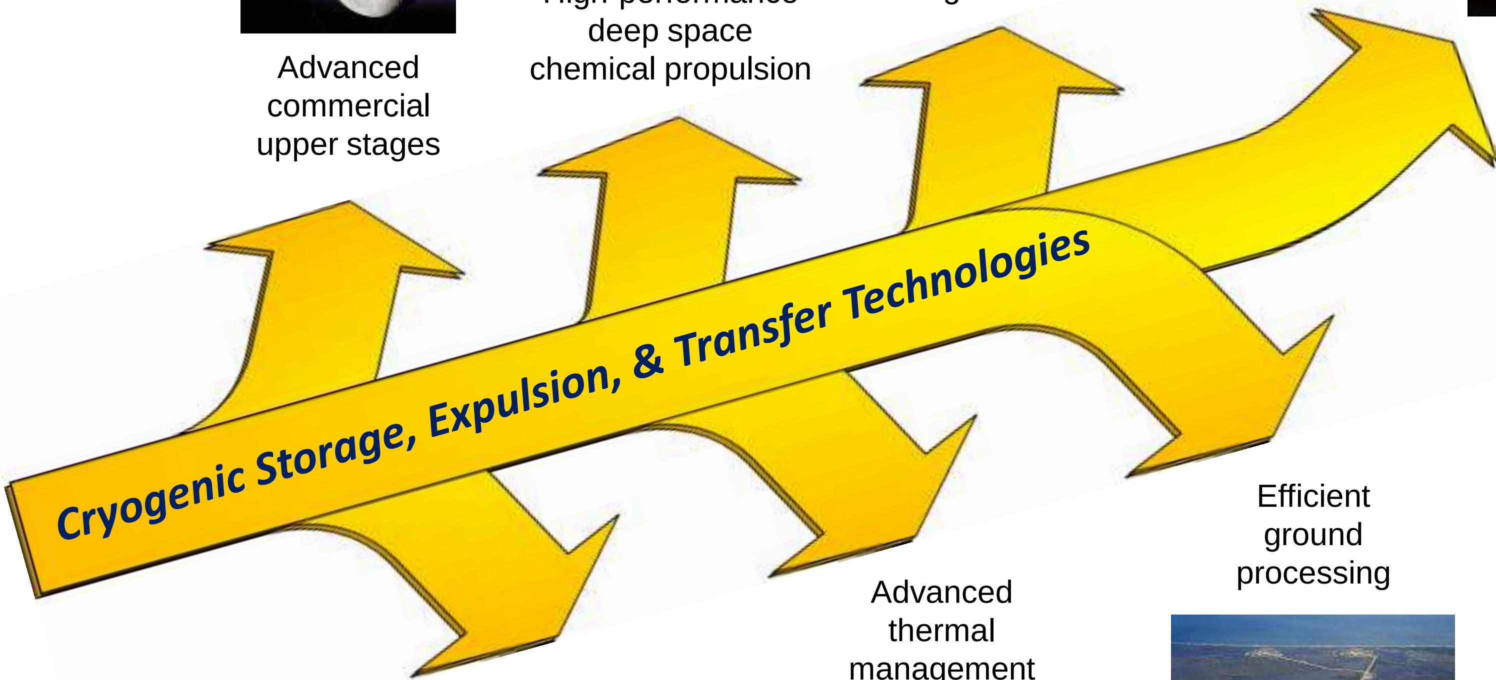
Advanced commercial upper stages

High-performance deep space chemical propulsion

ISRU propellant storage & utilization



Nuclear thermal propulsion



Power distribution & transmission

Advanced thermal management

Efficient ground processing

CFM Status & Needs
Circa 2009

From the "Cross-Cutting Systems" section of *Human Exploration of Mars – Design Reference Architecture 5.0* (NASA-SP-2009-566):

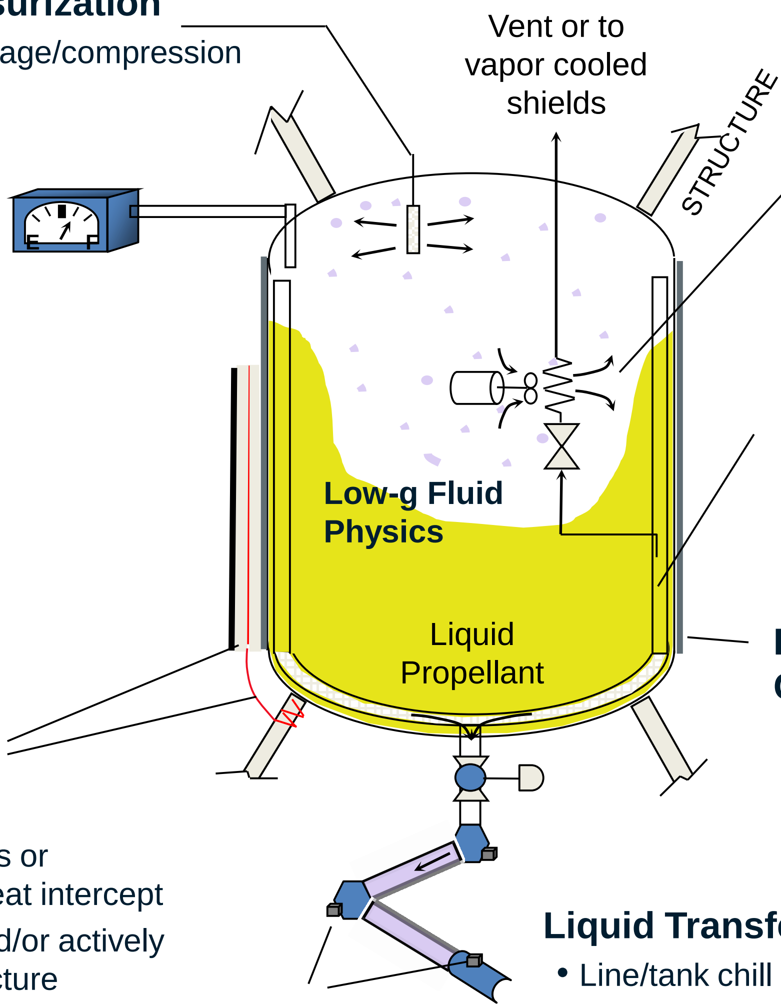
- CFM is a critical technology area that is needed for successful development of Mars architectures
- The first and foremost challenge is storage of liquid H_2, CH_4, and O_2 propellants for long durations
  - The longest flight of stored cryogenic propellants to date is 9 hr on Titan Centaur-5
- Venting or active cooling must be utilized to prevent propellant tank overpressurization
  - Venting would cause unacceptable propellant losses for long-duration missions
- Certain long-term space cryogenic storage technologies have been developed mainly for thermal management of scientific instruments for telescopes and other applications
  - Thick multilayer insulation systems have been applied to cryogenic dewars and active cooling components such as cryocoolers have been utilized in lieu of dewars
- These developments have not been applied to cryogenic propellant storage at the scale needed for the Mars architecture
- Other CFM technologies that would ensure safe and reliable cryogenic storage and supply to the propulsion systems include liquid acquisition and transfer and mass gauging
- Advanced cryogenic storage systems, including large flight-rated cryocoolers, would also benefit ISRU and power systems

Major CFM Technology Elements

Pressurization
- Storage/compression

Propellant Gauging
- Propellant inventory
- Pressure / volume / temperature
- High accuracy micro-g techniques

Thermal Control
- Insulation
- Vapor-cooled shields or cryocooler-based heat intercept
- Low conductivity and/or actively cooled support structure
- Sun shades



Leak Detection

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

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

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

Liquid Transfer
- Line/tank chill down
- Pumps
- Leak-free couplings

Cryogenic Propellant Storage & Transfer Flight Demo Project (2010-2014)

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Cryogenic Propellant Storage and Transfer 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 missions

Objectives

- Store cryogenic propellants to maximize 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

Reverse turbo Brayton cryocooler

Cryogenic testing in Small Multipurpose Research Facility (SMiRF)

LH_2/LO_2 Storage

- Passive storage: thick multilayer insulation (MLI) and reduced penetration heat leak
- Passive storage: low-conductivity structural attachments
- Tank pressure control: thermodynamic vent system (TVS)
- Tank pressure control: mixing pumps
- Active thermal control: broad area cooling (tubes on tank or tubes on shield)
- Active thermal control: cryocoolers (90 K)

LH_2/LO_2 Acquisition and Transfer

- Liquid acquisition devices (LADs)
- Pressurization
- Transfer valves
- Line and tank chilldown

Screen channel capillary LAD

LH_2/LO_2 Unsettled Gauging

- Radiofrequency mass gauge (RFMG)

Low-g aircraft testing of RFMG with simulant fluid

www.nasa.gov

CPST Project History

The cryogenic propellant storage and transfer demo project existed in various forms from early-2010 to mid-2014:

- CRYOSTAT Flagship Technology Demonstration managed by MSFC (Mar-Jul 2010)
  - Two flight vehichles demonstrating cryogenic propellant storage & transfer technologies, autonomous rendezvous & docking technologies, and LOX/CH_4 propulsion technologies

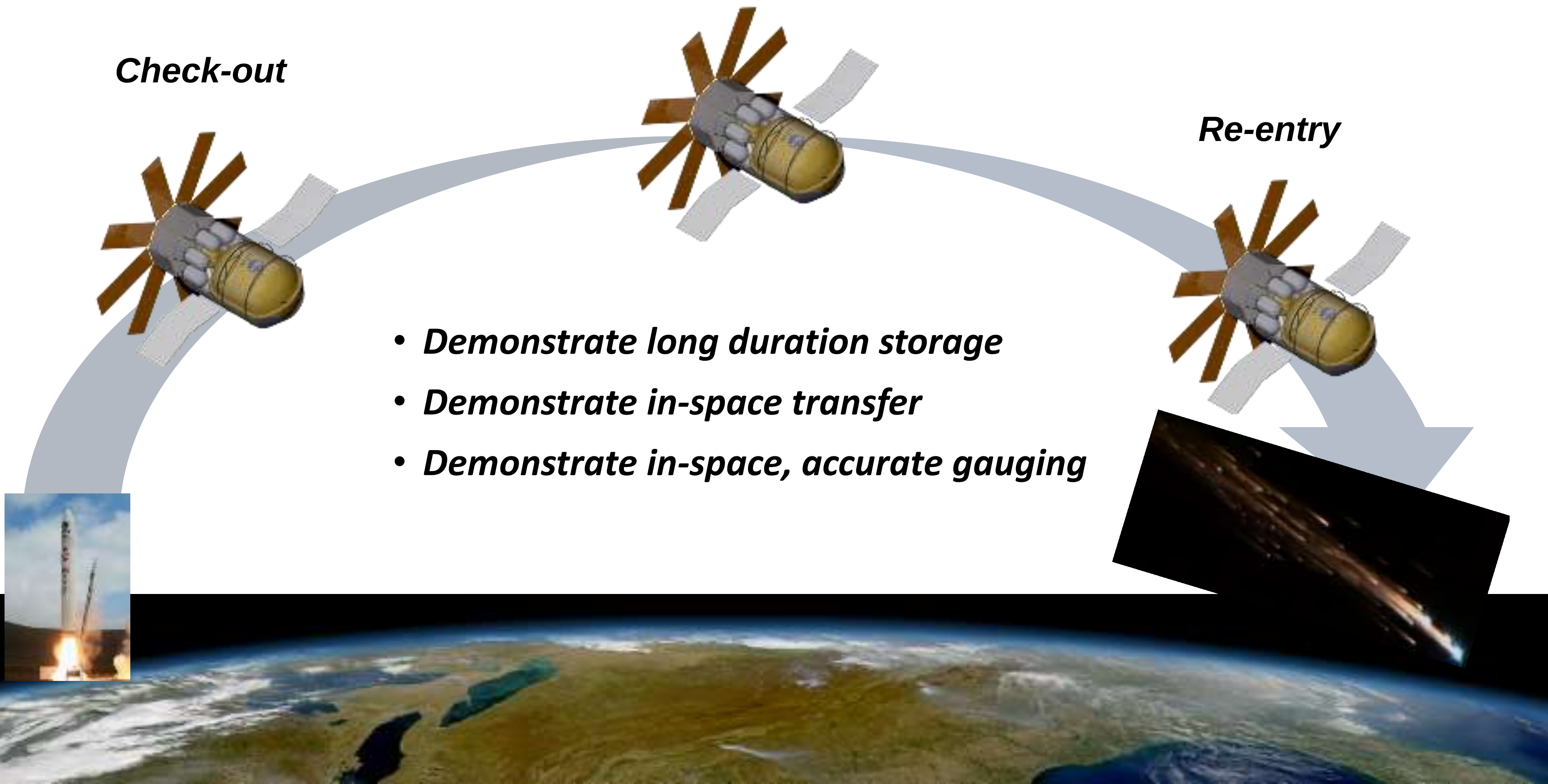
- CRYOSTAT Flagship Technology Demonstration managed by KSC (Jul 2010 – Mar 2011)
  - Single vehicle flight demonstration of cryogenic propellant storage & transfer technologies

- CPST flight demonstration in STMD managed by GRC (Apr 2011 – Feb 2014)
  - Single vehicle flight demonstration of cryogenic propellant storage & transfer technologies

- CPST technology maturation project in STMD managed by GRC (Feb 2014 – Sep 2014)
  - Completion of extensive CFM technology maturation efforts pursued by CPST throughout its life cycle

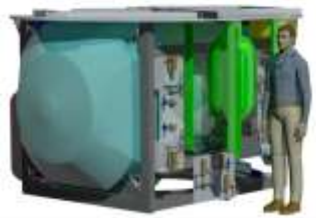
A new ground demonstration project called Evolvable Cryogenics, or eCryo, began formulation in mid-2014 and replaced CPST in FY15

CPST Demo: Free Flyer Concept

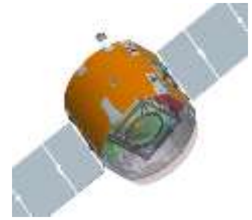


- ***Demonstrate long duration storage***
- ***Demonstrate in-space transfer***
- ***Demonstrate in-space, accurate gauging***

CPST Demo: Dragon Trunk Concept

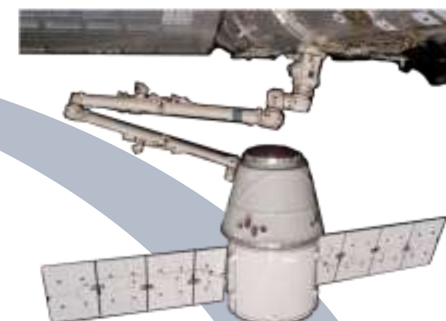


Passive Storage, Transfer, and Gauging Demo



Check-out

Dock to ISS

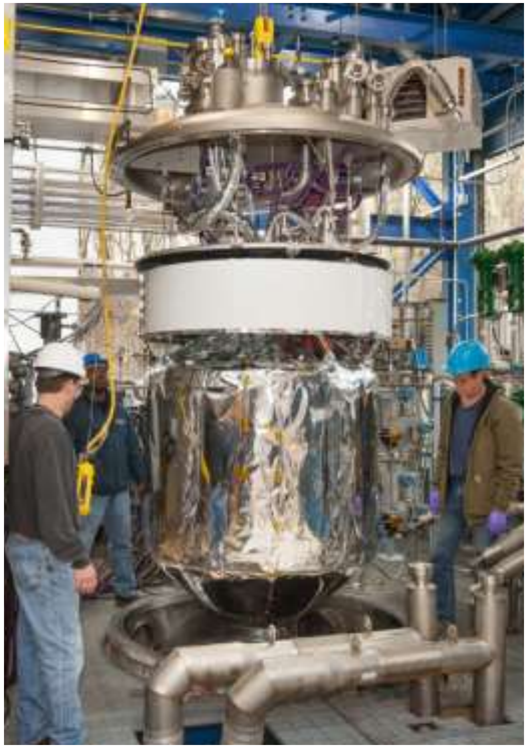


- *Demonstrate long duration storage*
- *Demonstrate in-space transfer*
- *Demonstrate in-space, accurate gauging*

CPST Major Accomplishments
(1 of 2)

The CPST project had a robust technology maturation element to bring relevant CFM technologies to a point of readiness for flight demonstration

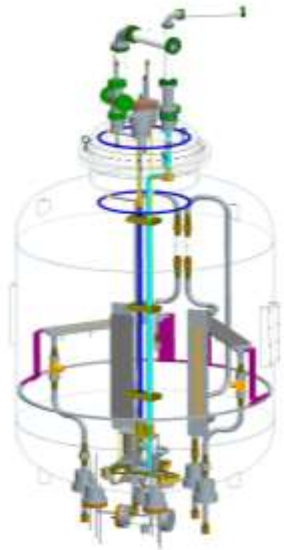
- **Liquid oxygen zero boil off testing**
  - Advanced to TRL 6 a suite of technologies that enable space systems to store 70 mt of LOX for 400 d with zero boil off
  - Flight representative cryocooler integrated to broad area cooled shield and radiator
  - Demonstrated robust tank pressure control using excess cryocooler capacity
  - Zero loss propellant storage was demonstrated



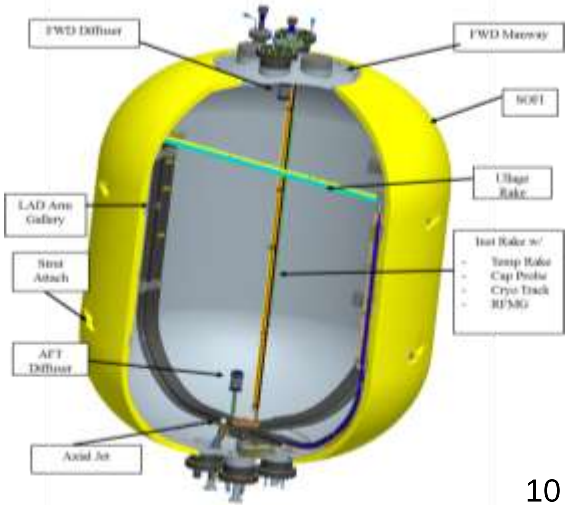
- **Liquid hydrogen reduced boil off testing**
  - Quantified system performance of flight-representative reduced boil off storage of LH_2
  - Broad area cooled shield embedded in both traditional and load-bearing MLI with a flight-representative cryocooler
  - Load-bearing MLI reduced inner MLI heat by 26% compared to traditional MLI
  - Load-bearing MLI supported the broad area cooled shield and withstood vibroacoustic loading of a simulated launch ascent sequence

CPST Major Accomplishments
(2 of 2)

The CPST project had a robust technology maturation element to bring relevant CFM technologies to a point of readiness for flight demonstration



- **Liquid acquisition device (LAD) development & testing**
  - Fluid transfer for propellant storage systems in microgravity is driven largely by surface tension forces
  - LADs are fine mesh screens that exploit surface tension forces to provide single phase fluid transfer (liquid with no gas bubbles)
  - LAD characterization testing was performed on multiple designs at various pressures and flow rates with liquid N_2, CH_4, O_2, and H_2
  - Thermodynamic vent system cooled LADs showed superior performance



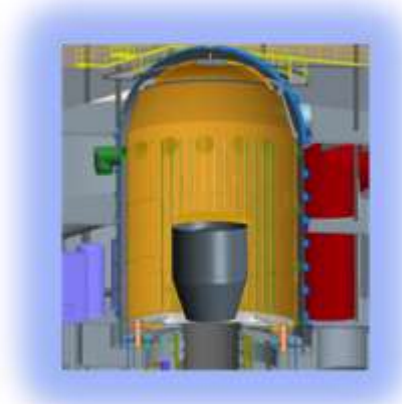
- **Engineering development unit testing**
  - EDU was a proof-of-manufacturing and proof-of-performance test unit for a passive LH_2 storage flight demonstration payload
  - Heavily instrumented tank with four types of integrated mass gauges, mixing pump with adjustable flow rates, axial jet thermodynamic vent system, gallery LAD arms, lightweight struts, SOFI & MLI
  - Largely successful testing conducted in vacuum chamber to simulate ascent and measure boil off after "ascent" and then after several days (steady state conditions)

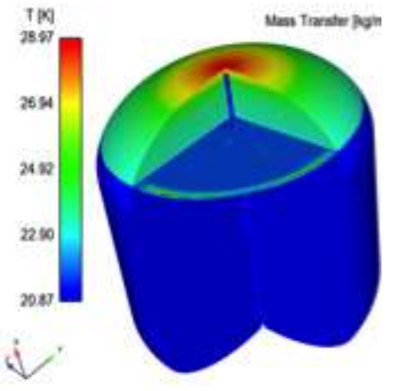
Evolvable Cryogenics (eCryo) Project Overview

The Evolvable Cryogenics (eCryo) project was formulated in mid-FY14 as a ground demonstration replacement and extension of CPST

The major objective is to develop, integrate, and validate CFM technologies at a scale relevant to SLS and NTP stages

- **Project elements:**
  - **Structural heat intercept insulation vibration evaluation rig (SHIIVER)** -- Implement vapor cooling and multilayer insulation on a large liquid hydrogen tank that is representative of a cryogenic stage
  - **Integrated vehicle fluids (IVF)** -- Evaluate the extensibility of the ULA IVF concept for use on the SLS upper stage
  - **Radiofrequency mass gauge (RFMG)** -- Test and demonstrate RFMG technology on ISS
  - **Improved fundamental understanding of super insulation (IFUSI)** -- Improve the capability for designing MLI blankets for large cryogenic upper stages
  - **Development & validation of analysis tools (DVAT)** -- Advance numerical tools to model cryogenic fluids in both settled and unsettled conditions





SHIIVER Project Element

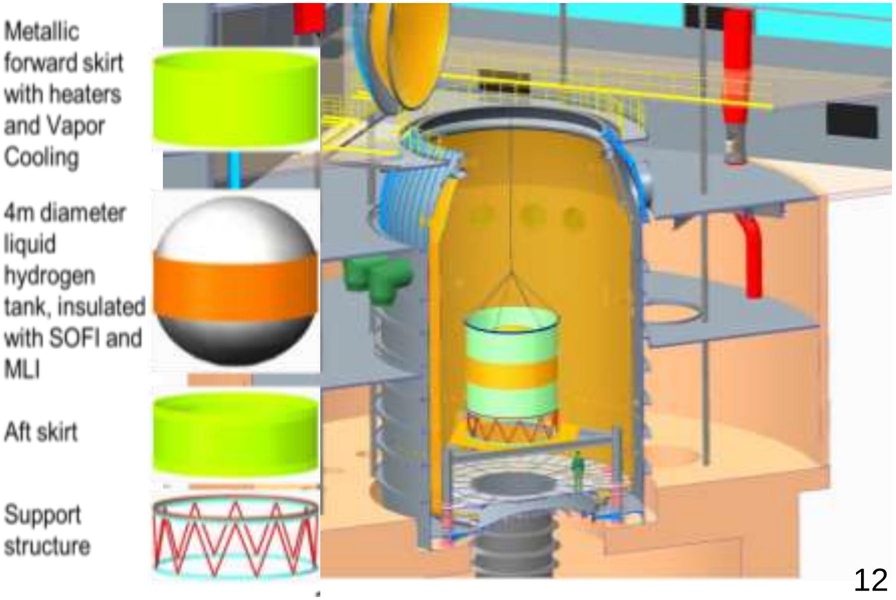
The SHIIVER project element will determine the baseline thermal performance for existing upper stages and those with CFM technology enhancements

Major SHIIVER objectives:

- Perform subscale engineering development to ensure that heat intercept approaches for the large-scale rig are stage representative
- Build large stage-representative rig capable of testing CFM technologies
- Perform test of large rig under mission representative environmental conditions using one possible stage-like heat intercept configuration; advance large-scale multilayer insulation and vapor cooling to TRL 6

Status:

✓Concept review: Aug 2015
✓MLI contract award: Sep 2016
✓Tank contract award: Oct 2016
- Complete subscale vapor cooling testing: Feb 2017
- Receive large tank: May 2017
- SOFI installation complete: Aug 2017
- Large scale testing begins: Mar 2018
- Large scale testing complete: Feb 2019
- Final report: Sep 2019



IVF Project Element

The Integrated Vehicle Fluids project element will evaluate the extensibility of the ULA-developed IVF concept for use on SLS upper stages

IVF uses boiled off O_2 and H_2 that would typically be vented for electrical power generation, tank pressurization, propellant settling thrust, and attitude control thrusters

Major IVF objectives:

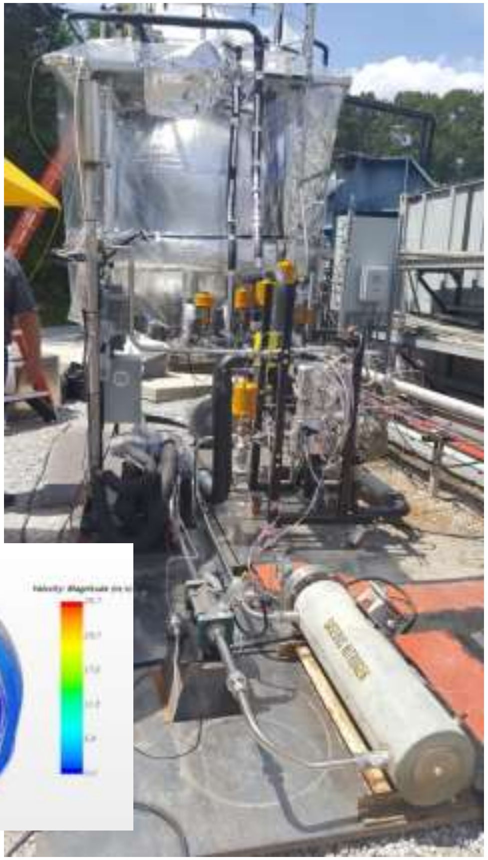
- Determine whether IVF can be scaled to meet SLS upper stage needs
- Determine whether IVF can be integrated into an SLS upper stage

SLS program is examining:

- IVF human rating approach
- IVF safety, reliability, and performance payoff

Status:

✓ Tank stratification testing complete: Feb 2016
✓ Simulated IVF system testing complete: Jun 2016
- Complete tesing of IVF system incorporated into test hardware: Dec 2016
- Deliver final report to SLS program: Apr 2017



RFMG Project Element

The Radiofrequency Mass Gauge project element will deliver a RFMG flight unit to measure LCH_4 propellant mass on Robotic Refueling Mission 3 (planned ISS demo)

RFMG is capable of propellant mass gauging in micro-g without settling burns

- Natural electromagnetic modes of the tank are excited via an RF signal from two small antennas mounted in the tank
- The mode frequencies of the measured RF power spectrum are compared to a large database of simulations and the fill level associated with the best match is reported as the gauged fill level.

Major RFMG objectives:

- Develop and deliver an RFMG instrument for use on the RRM3 demo
- Quantify the accuracy of the RFMG measurements
- Advance RFMG technology to TRL 6

Status:

✓ Flight hardware built
✓ Avionics box environments testing completed
✓ Antenna cold shock and vibration testing completed
- Pre-ship review: Dec 2016
- Flight hardware shipment: Dec 2016

IFUSI Project Element

The Improved Fundamental Understanding of Super Insulation project element will test insulation samples to provide performance data and models of MLI for large cryo tanks

Major IFUSI objectives:

- Perform thermal testing on seam configurations
- Perform thermal testing on hybrid MLI configurations
- Perform thermal testing to determine low temperature transmissivity of MLI components
- Perform thermal repeatability testing on representative insulation systems
- Perform structural testing on attachment mechanisms

Schedule:

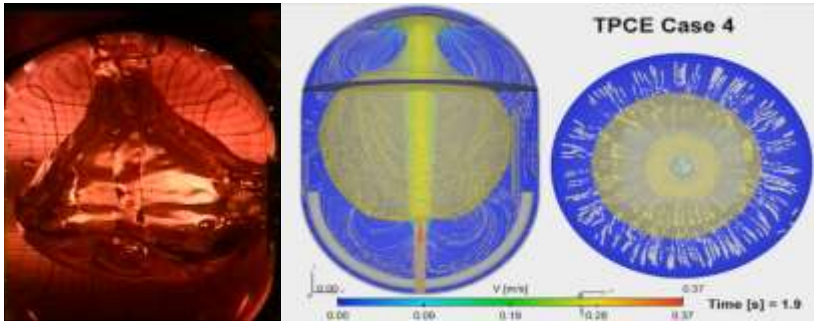
- Test seam configurations between 300 K & 20 K: Dec 2016
- Test seam configurations between 90 K & 20 K: Sep 2017
- Test SHIIVER insulation coupons: May 2017
- Complete repeatability testing: Jun 2017
- Complete structural epoxy testing: Jul 2017

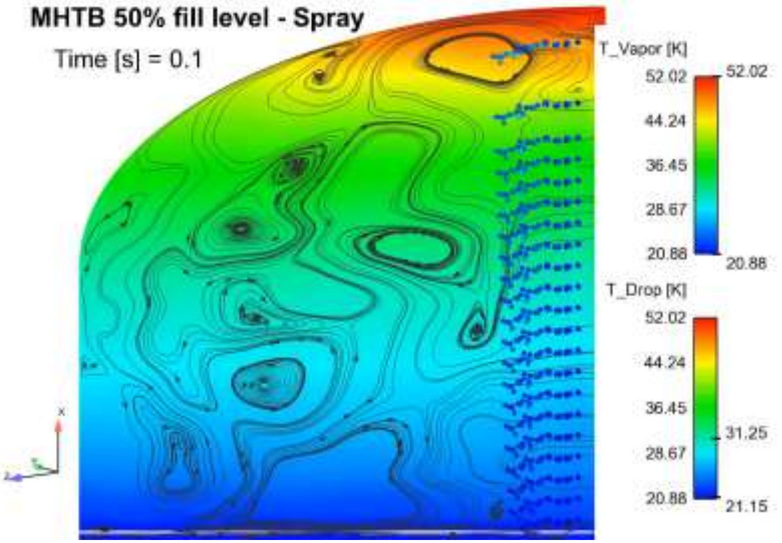
DVAT Project Element

The Development and Validation of Analytical Tools project element will develop or enhance tools for predicting thermodynamic and fluid behavior of CFM systems

Major DVAT objectives:

- Conduct CFD benchmark collaboration with Centre national d'études spatiales (France)
- Extend multinode analysis tools to unsettled conditions
- Validate multinode and CFD tools against 1-g experimental data
- Validate multinode and CFD tools against micro-g experimental data





Schedule:

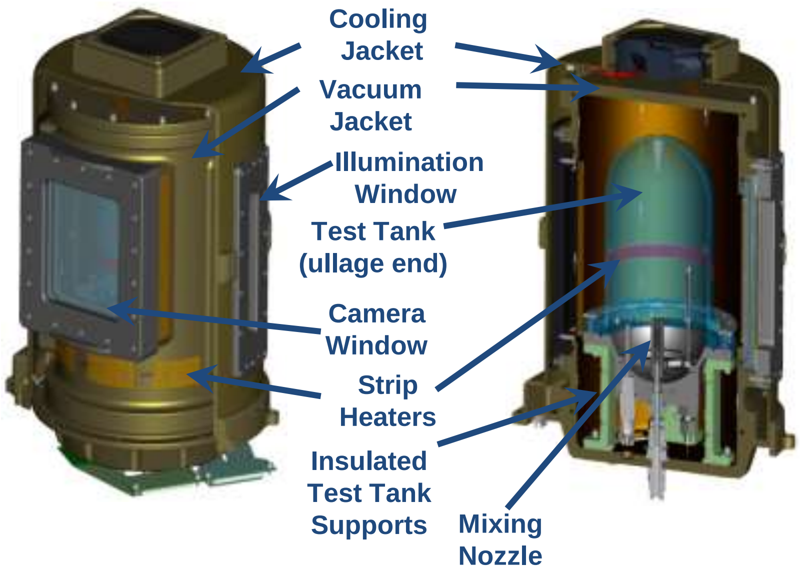
- Validation of multinode predictions against line chill down data: FY17
- Conduct zero boil off tank experiment: Sep 2017
- JAXA benchmarking collaboration: FY17-FY19
- SHIIVER data validation: FY19
- Validation of multinode predictions with moving ullage: FY17-FY18

Zero Boil Off Tank (ZBOT) Experiments

The Zero Boil Off Tank experiments are a series of three small-scale simulant fluid (perfluor-n-pentane, C_5F_{12}) tests in the ISS Microgravity Science Glovebox

Major ZBOT Objectives:

- Gain a fundamental understanding of the phase change and transport phenomena associated with tank pressurization and pressure control (ZBOT-1)
- Determine the time constants associated with pressurization, mixing, destratification, and pressure reduction for different gravitational environments (ZBOT-1)
- Determine the effects of noncondensables on evaporation, condensation, and transport phenomena (ZBOT-2)
- Delineate the micro-g transport & phase change mechanisms associated with various mixing/cooling strategies such as droplet spray bar, axial jet mixing, broad area cooling (ZBOT-3)
- Investigate the nature of micro-g superheating and the effect on boil-off (ZBOT-3)
- Validate and verify a state-of-the-art two-phase CFD model for cryogenic storage that can be used to design full-scale storage tanks (all three ZBOTs)



SBIR/STTR Projects on CFM Technologies

Selected relevant recent projects in the SBIR & STTR programs:

- 20 Watt 20 Kelvin cryocooler for thermal control of space-based liquid hydrogen **(project in Game Changing Development program with co-funding from SBIR program)**
- A reliable, efficient cryogenic propellant mixing pump with no moving parts
- Parahydrogen-orthohydrogen catalytic conversion for cryogenic propellant passive heat shielding
- Innovative Stirling-cycle cryocooler for long-term in-space storage of cryogenic liquid propellants
- Bubble-free cryogenic liquid acquisition device
- Thermally insulative structural connection for cryogenic propellant tanks
- Lightweight, high-flow, low-connection-force, in-space cryogenic propellant coupling
- A high efficiency cryocooler for in-space cryogenic propellant storage
- Thin aerogel as a space in multilayer insulation for cryogenic space applications
- Lightweight non-compacting aerogel insulation for cryotanks
- Manufacture of novel cryogenic thermal protection materials
- Aerogel-filled foam core insulation for cryogenic propellant storage
- Hybrid aerogel-MLI insulation system for cryogenic storage in space applications
- And so on …

Early Stage Projects on CFM Technologies

Relevant recent projects in the Space Technology Research Grants program:

- Innovations in understanding & modeling cryogenic propellants for long-duration spaceflight (ESI 2013)
- A new experiment for determining evaporation & condensation coefficients of cryogenic propellants and development of an efficient computational model of cryogenic propellants (ESI 2013)
- Design and development of a next-generation, high-capacity, lightweight 20 K pulse tube cryocooler for active thermal control on future space exploration missions (ESI 2012)
- Experimental, numerical, and analytical characterization of slosh dynamics applied to in-space propellant storage, management, and transfer (NSTRF 2014)
- Hydrogen-helium mixtures: fundamental measurements, neutral droplet buoyancy, evaporation, and boiling (NSTRF 2014)

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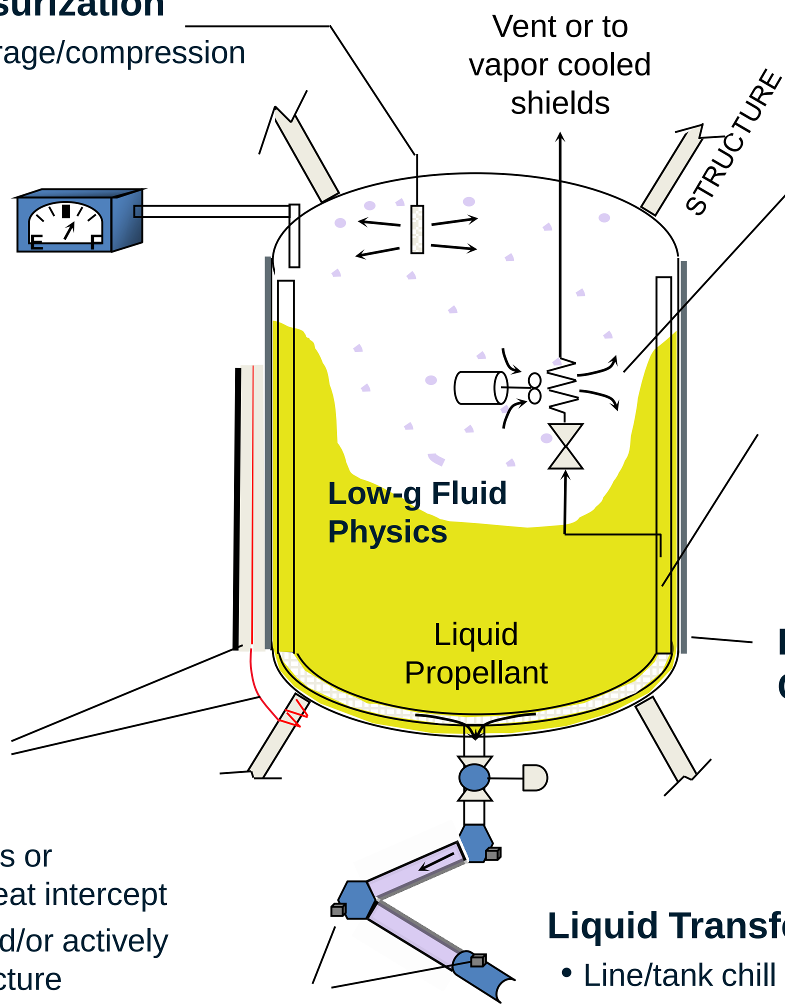

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- Low conductivity and/or actively cooled support structure
- Sun shades

Leak Detection

Liquid Transfer
- Line/tank chill down
- Pumps
- Leak-free couplings

Key CFM Technology TRL Assessments

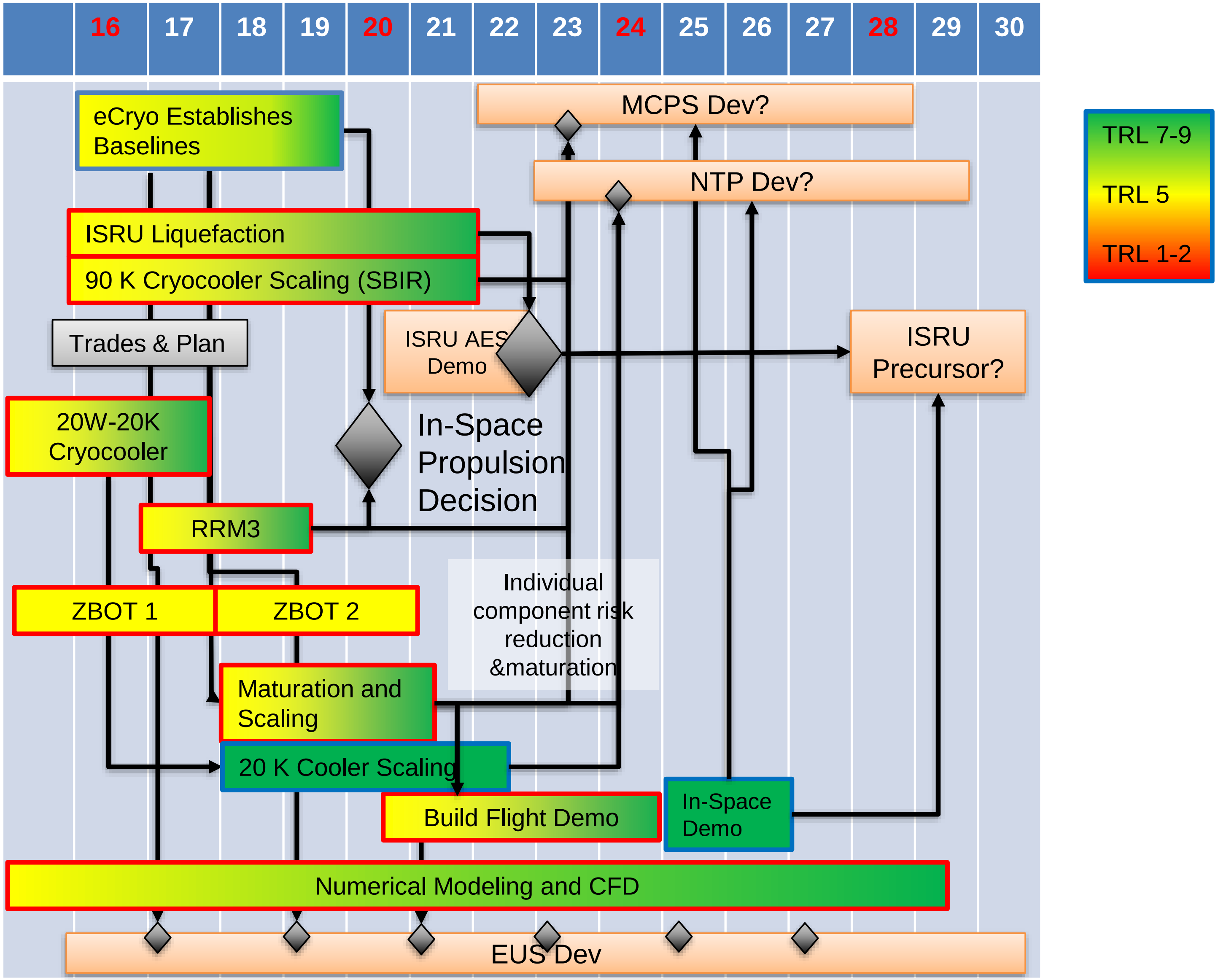
Technology	TRL	Path to TRL 6
Tank MLI	5	Scale up to large implementations and perform ground or flight demo on integrated flight-like system
Low conductivity structure	5	Perform ground or flight demo on integrated flight-like system
90 K cryocooler (high thermal lift)	4	Scale up to large implementations and perform ground or flight demo on integrated flight-like system
Broad area cooled shield (tube on tank)	5	Perform **flight demo** on integrated flight-like system
Thermodynamic vent system	5	Perform **flight demo** on integrated flight-like system
Fluid mixing pump	4	Develop lightweight, low-voltage pump and perform **flight demo** in integrated flight-like system
Transfer line chill down in microgravity	5	Perform **flight demo** on integrated flight-like system
Pressurization system	5	Perform **flight demo** on integrated flight-like system
Valve	4	Develop low leakage valves and perform ground or flight demo on integrated flight-like system
Liquid acquisition device	5	Perform **flight demo** on integrated flight-like system
Radiofrequency mass gauge	5	Scale up to large implementations and perform **flight demo** on integrated flight-like system

CFM Technologies Requiring Flight Demonstration

Flight demonstration in the microgravity environment is required to validate several key CFM technologies:

- **Broad area cooled shield (tube on tank)**
  - Possible reliance on convection in tank / elimination of hot spots
- **Thermodynamic vent system**
  - Pressure rise rate / convection in tank and bubble dynamics during spray for destratification in microgravity
- **Transfer line chill down in microgravity**
  - Gravitational effects of flow boiling
- **Pressurization system**
  - Bubble formation and bubble dynamics due to injection in microgravity
- **Liquid acquisition device**
  - Operation in surface tension dominated environment with heat transfer
- **Mass Gauging**
  - Effects of fluid dynamics/curvature and ullage placement

Notional Strategy for CFM Technology Development & Demonstration



Summary

Cryogenic fluid management (CFM) technology development & demonstration has been and continues to be a significant emphasis area for STMD investment

STMD is developing the key CFM technologies required for long-term space storage of cryogenic propellants

STMD is performing extensive technology maturation and risk reduction testing for key CFM technologies, laying the groundwork for eventual mission infusion

A system-level spaceflight demonstration that integrates the major CFM technologies will be necessary prior to mission infusion for cryogenic propulsion stages