Cryogenic Fluid Management (CFM) Portfolio Project

EXPL-05: NASA CFM Portfolio Project - 2023 Accomplishments and Highlights

Progress on Flight Demos and Large CFM Demonstration (LCD)

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Cryogenic Fluid Management (CFM) Portfolio Project Office

Objective: Mature CFM technologies essential to NASA's future missions in science and exploration which utilize both chemical and nuclear in-space propulsion, landers, and in-situ resource utilization

CFMP is a TDM portfolio project comprised of twenty-four individual CFM technology development activities, spread across four portfolio areas
Technology entrance minimum of TRL 4, with project end state objective of TRL 7

CFMPP was established to consolidate management and integration of TDM CFM technology development activities
NASA MSFC partnering with GRC for management and execution of the portfolio project

System Demonstration Complexity →

Technologies Portfolio

Scope: Design, development, testing, and evaluation of critical-need cryogenic components enabling long-duration CFM storage and propellant transfer

Major Activities:

Hydrogen low-leakage valves and cryo-couplers

Radio Frequency Mass Gauge (RFMG)

Next-generation FOSS (fiber optics sensing system)

Solar White thermal coatings

Subsystems Portfolio

Scope: Design, development, and testing of complex systems of technologies to address technical challenges for specific CFM mission needs

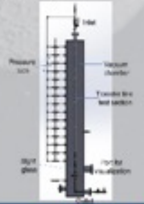
Major Activities:

20W/20K Cryocooler

90W/150K Cryocooler

Cryocooler Electronics and alternate generic 20W Cryocooler

Reduced Gravity Cryogenic Transfer (RGCT)



Demonstrations Portfolio

Scope: Design, build, and test integrated flight and ground systems comprised of multiple CFM subsystems, enabling TRL 5 - 7 maturation for many technologies

Major Activities:
Large CFM Demonstration
Concept Planning
Tipping Point Contract Demonstrations

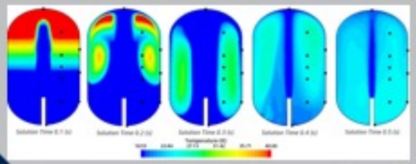
Two-Stage Cooling Demonstration

CryoFILL Liquefaction Demonstration

Modeling Portfolio

Scope: Develop, enhance, validate, and demonstrate Computational Fluid Dynamics (CFD) and Nodal tools to address capability gaps for predicting cryogenic fluid behavior in 1-G and microgravity environments for use as design tools for future NASA missions

Testing and demo activities across the CFMP portfolio are used within modeling tools to predict CFM behavior at a flight vehicle scale in a relevant environment including microgravity



System Validation →

2020 TIPPING POINT CONTRACTS – 'RIDESHARE CFM FLIGHT DEMOS'

SpaceX

On-Orbit Large-Scale Cryogenic Propellant Management and Transfer Demonstration

Overview: Demonstration of large-scale on-orbit cryogenic fluid transfer (up to 10 metric tons) between tanks on a Starship in orbit and management to provide a basis for operational use of in-space refueling technology.

Mission Overview:

- Demonstration conducted as part of a Starship flight
- Active settling maneuver
- Settled transfer between main propellant tank and header tank located in the nosecone.
- ~1 day mission duration

Projected Flight: 2024

Starship Launch Vehicle

ULA

Cryogenic (H_2/O_2) Smart Propulsion Flight Demonstration

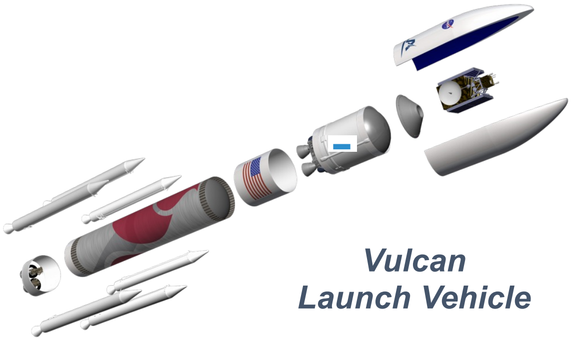
Overview: Flight demonstration of key CFM technologies:

- passive thermal control,
- tank pressure control,
- tank-to-tank propellant transfer

Mission Overview:

- Demonstration occurs after primary spacecraft is separated; demonstration hardware integrated with Centaur V
- ~1 day on-orbit duration

Projected Flight: 2025



Vulcan Launch Vehicle

2020 TIPPING POINT CONTRACTS – ‘PAYLOAD CFM FLIGHT DEMOS’

Eta Space

Liquid Oxygen Flight Demonstration (LOXSAT-1)

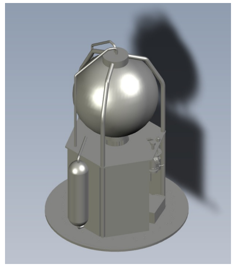
Overview: Develop, launch and fly a technology demonstration payload designed to test multiple CFM technologies necessary for creating practical propellent depots.

Mission Overview:

- Flight demonstration based on:
    - Zero fluid loss storage in LEO environment
    - Control of fluid position and thermodynamic state
    - Control of tank pressure using autogenous and helium pressurization
    - Tank-to-tank fluid transfer
- LOXSAT 1 hosted on a dedicated Rocket Lab Photon satellite bus
- ~ 9 month mission

Projected Flight: 2025

Rocket Lab Electron Launch Vehicle



Eta Space LOXSAT-1 Payload

Lockheed Martin

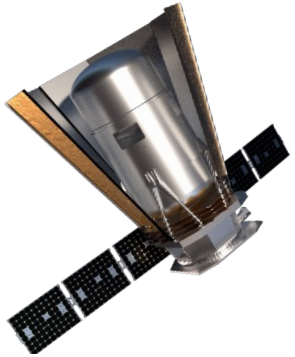
Cryogenic Demonstration Mission (CDM)

Overview: Ground testing and flight demonstration of cryogenic LH2 transfer and long duration storage in space. CDM incorporates CFM technologies into a single system that demonstrates the transfer, storage, and pressure control of LH2 through ground testing and flight demonstration.

Mission Overview:

- Demonstrate passive and active LH2 storage
- Demonstrate transfer of LH2 between a storage tank and receiver
- Up to 2 month mission demonstration

Projected Flight: 2025



Lockheed Martin CDM Payload

CFMPP – STAKEHOLDERS, MISSIONS AND ACTIVITY TIMELINES*

STMD | ESDMD | SMD | STMD Pre-Formulation | ESDMD Pre-Formulation | CFM Technology Maturation Impacts Being Refined / Updated

CY2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2030+

CFMPP Ground Developments for Storage, Transfer, and Mass Gauging Technologies
- 2-Stage Cooling and CryoFILL / 2019 Tipping Point Liquefaction Demonstrations
- High Capacity 90K & 20K Cryocooler Technologies
- Transfer and Chilldown Operations
- Component Development for Valves, Cryo-Couplers, RFMG

ISRU O2 Pilot Plant*

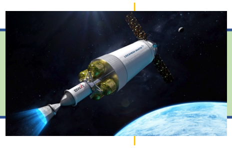
Surface Systems for Lunar and Mars*

CFMPP Flight Demonstrations
- 2020 Tipping Points

Integrated CFM Demonstration Mission (Launch 2032)

Currently in Study Phase

DRACO NTP Demonstration with DARPA



Mars Missions* Propulsion Systems – NTP, NEP-Chem, SEP-Chem, All-Chem (2039+)

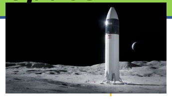
SMD Flight Experiments Supporting CFM Technologies / Modeling
- ZBOT, FBCE, CLPS

Artemis III

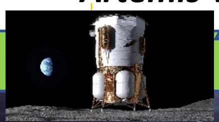
Artemis IV

Artemis V

HLS – SpaceX Initial Crewed Mission and Sustaining Demonstrations (Appendix H, Options A and B)



HLS – Blue Origin Sustaining Demonstration (Appendix P)



HLS Sustaining Missions*

**All Dashed Missions are Currently in Development*

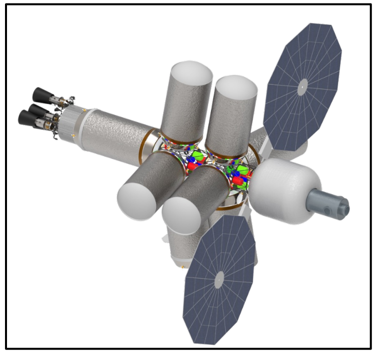
CFMPP – FLIGHT DEMONSTRATION OPPORTUNITIES IDENTIFICATION APPROACH

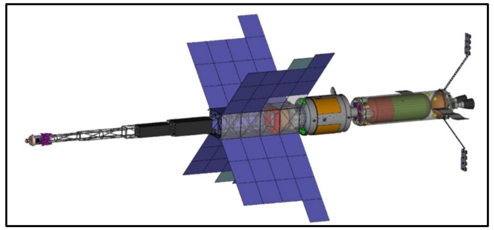
- Identify, evaluate, and mature Integrated CFM flight demonstration approaches, separate from the 2020 Tipping Point contracts, to meet the Demonstration Need / Goals / Objectives. These approaches will include, but are not limited to:
  - Development of a single government reference mission concept designated the Large CFM Demo (LCD).
  - Identification of existing / future NASA (e.g., HLS) and non-NASA (DARPA / DRACO)flight missions which can provide technology gap closure consistent with the Demonstration NGOs.

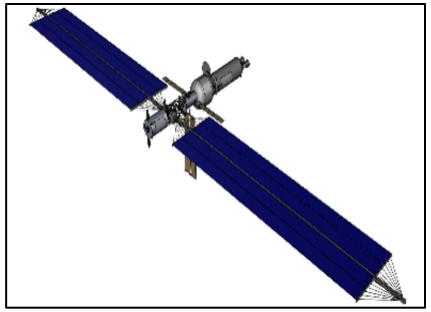
- Use the government reference mission concept, LCD, to define Flight Demonstration Needs / Goals / Objectives to compare against other awarded flight missions. Comparisons and LCD concept refinement, occurring through 2023 and 2024

- Demonstration Need
  - There is a need to mature CFM technologies and integrated system operations, utilizing an orbital flight test in a microgravity environment, that enable in-space cryogenic propellant automated storage and transfer operations required for future mission applications.

CFMPP – FLIGHT DEMONSTRATION OPPORTUNITIES – DEMONSTRATION GOALS







- Demonstration Goals
  - Primary goal: To demonstrate enabling CFM technologies for hydrogen-based in-space mission applications, prioritizing those applications supporting Mars Transportation systems.
  - Secondary goal: To demonstrate enabling CFM technologies for non-hydrogen based in-space mission applications, including those applications supporting Mars Transportation systems.
  - Tertiary goal: To demonstrate enhancing CFM technologies for In-space chemical applications of Lander Systems, in-situ resource utilization (ISRU) systems, surface systems, and In-space chemical depot / refueling systems.
- Chemical and Nuclear Transportation systems include:
  - Nuclear Thermal Propulsion (NTP) Vehicle – Liquid Hydrogen (LH2) based system
  - Nuclear Electric Propulsion (NEP) / Chemical Vehicle – Liquid Oxygen (LO2) / Liquid Methane (LCH4) boost stage
  - Solar Electric Propulsion (SEP) / Chemical Vehicle – Liquid Oxygen (LO2) / Liquid Methane (LCH4) boost stage
  - All Chemical Vehicle & In Space Chemical Depot – can be some combination of LH2, LO2, and LCH4 systems

CFMPP – FLIGHT DEMONSTRATION OPPORTUNITIES – DEMONSTRATION OBJECTIVES

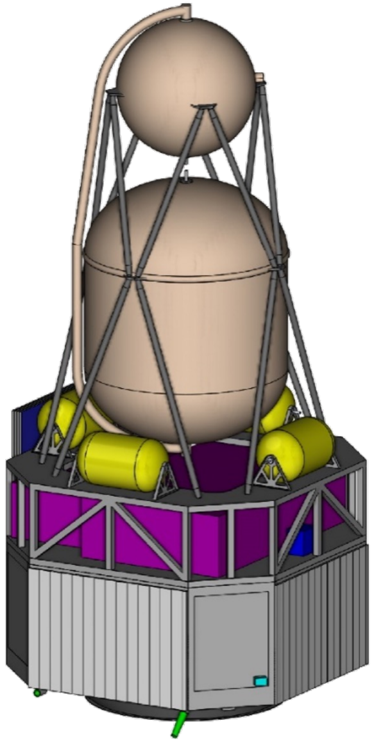
- Demonstration Objectives
  - <u>Primary Objective:</u> Demonstrate and collect, within a representative microgravity environment, flight performance data for LH2 integrated subsystem(s):
    - Long Duration Storage Operations
    - Automated Propellant Mass, State, and Stratification Measurements with Command Feedback Operations
    - Transfer Operations
  - <u>Secondary Objective:</u> Mature predictive CFM modeling capabilities through flight prediction model validation
  - <u>Tertiary Objective:</u> Mature domestic capability needed for In-space cryogenic flight hardware in the areas of:
    - cryogenic hardware design, manufacturing, test, and integration
    - launch vehicle ground servicing and orbit delivery of cryogenic payloads

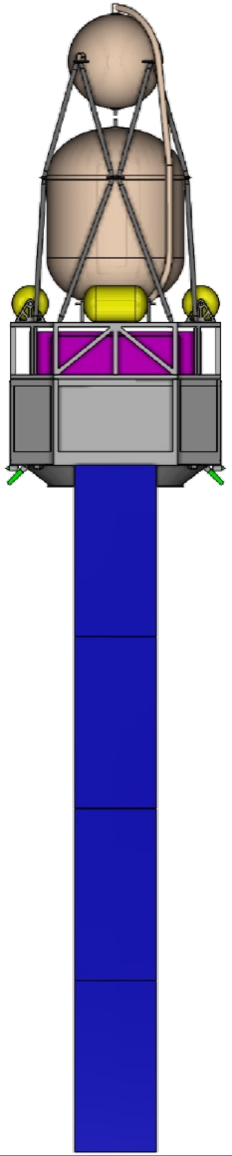
CFMPP – FLIGHT DEMONSTRATION OPPORTUNITIES – COMPARISON METRICS

- Flight demonstration approach evaluation will include the following metrics:
  - Technology Demonstration is Conducted within an Integrated System and in a Microgravity Environment
    - *Does the mission concept demonstrate technologies in a microgravity environment, relevant to future NASA Mars Transportation systems, in an integrated system to satisfy TRL 6 or greater requirements?*
  - Technology Demonstration is of Appropriate Scale and Provides Sufficient Data
    - *Is the mission concept conducted with physical dimensions, fluid-thermal operating conditions, and steady-state operation duration(s), such that technology demonstration data collected will be directly scalable to envision full scale flight mission applications?*
  - Technology Demonstration Data Results are Available to Both Government and Private Sector Users
    - *Does the mission approach have any data rights restrictions such that technology demonstration data cannot be infused into domestic users, either by direct data or validated model dissemination?*

CFMPP – GOVERNMENT REFERENCE CONCEPT (FY2022)

- Large LH_2 Active Cryogenic Storage Demonstrator, Class D Mission
- Mission: Up to 8 Months, ELV launch to 500 km SS 6am or 6pm orbit (full sun for 8 months), Orbit life < 25 years
  - Primary LCD system mass to orbit requirements will allow ELV to carry secondary payloads
- Zero Boil-Off Storage Experiment
  - 200 kg LH_2, 1.5 m D x 2 m Al Tank with SOFI, MLI (32 layers)
  - 20K / 90K combined Broad Area Cooling with 20K and 90K cryocoolers
- Cryogenic Transfer Experiment
  - 1.05m spherical, passive cooled receiver tank (25 layers MLI)
  - Receiver tank cooled with LH_2 from storage tank
  - Unsettled and settled transfers (3 total transfers)
- Spacecraft: 'OTS' bus
  - Power: ~2.4 kWe from single solar array, minimal battery (no shadow when using cryocoolers)
  - Thermal: ~ $5.4 m^2$ of body mounted radiators, fed by heat pipes
  - AD&CS: Simple gravity gradient with magnetic torquers, sun and horizon sensors
  - Propulsion: Cold Gas N_2 to provide tip-off, up to 46 ~864 sec settling burns for experiment and six settled chilldown burns
  - C&DH: control bus and experiment, store ALL 8 months of data 1 TB
  - Comms: S-Band, 10 Mbps for 8-minute passes over NEN sites (Svalbard), 10-15 passes a day
  - Mechanical: Simple bus structure, Long E-Glass struts to hold LH_2 storage and receiver tanks to minimize heat leak to cryo tank





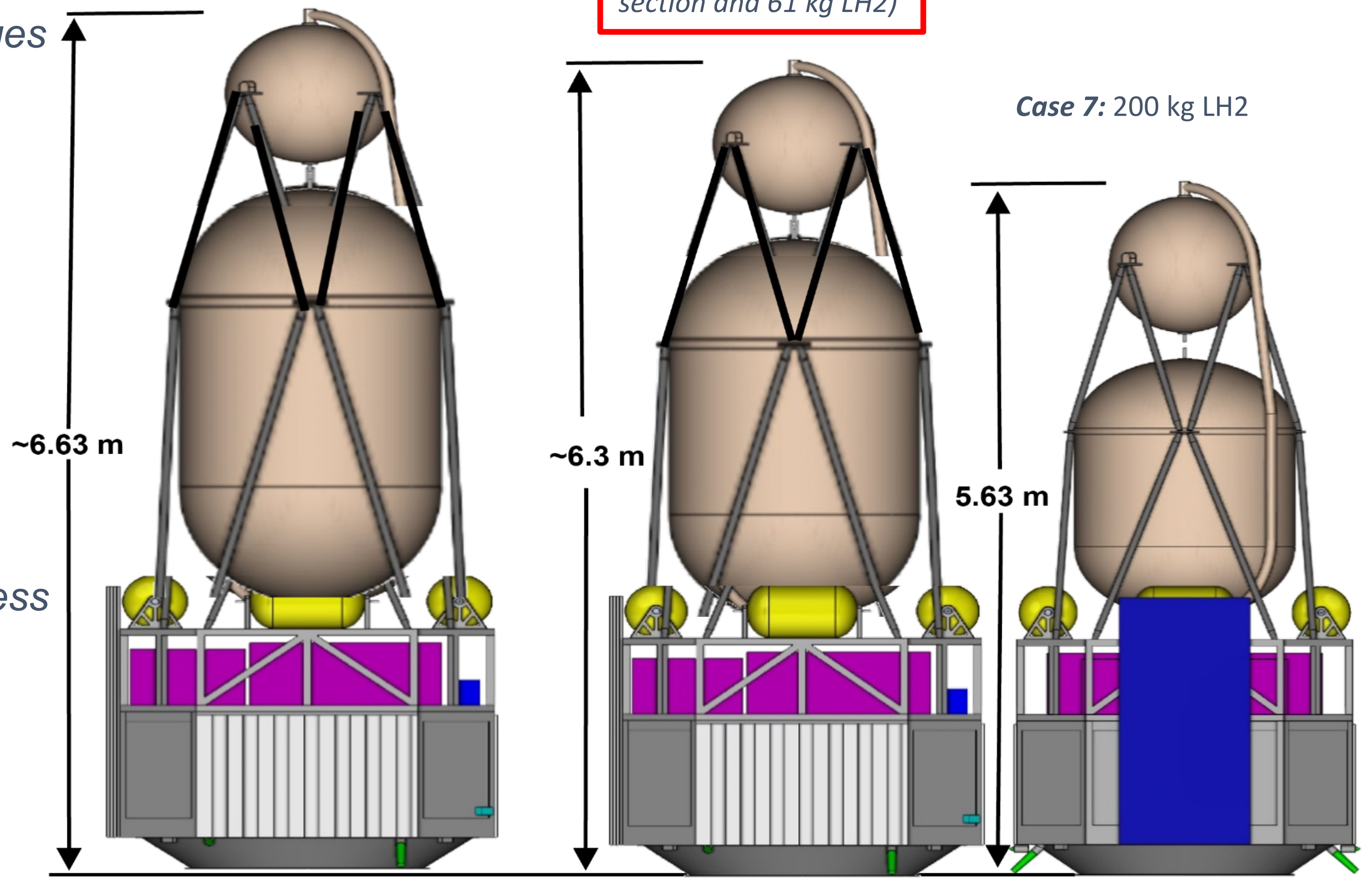
CFMPP – GOVERNMENT REFERENCE CONCEPT PLANNED UPDATES (FY2023)

- Planned Concept Trades for DAC3
  - *Increasing storage tank sizes*
  - *Cryocooler/BAC operations during mission phases*
  - *20K-only cryocooler stage versus 20K + 90K stages*
- Planned Updates
  - *Reference launch vehicle (e.g., Antares 330)*
  - *Number of propellant transfers and transfer operations*
  - *Autogenous pressurization capability*
- Concept Study Cases
  - *Case 5: 300 kg LH2 Transfer with autogenous press*
  - *Case 6: 260 kg LH2 Transfer with autogenous press, fits Antares 231 fairing*
  - *Case 7: 200 kg LH2 Transfer FY2022 Reference Case, no autogenous press*

Case 5*: Add 100 kg LH2, 1m longer barrel, Struts even longer (less heat leak), tank aspect ratio is representative of flight tanks*

Case 6: *Max fit for Antares 330 (adds 67 cm longer barrel section and 61 kg LH2)*

Case 7: 200 kg LH2



CFMPP – GOVERNMENT REFERENCE CONCEPT (UPDATED FY2023)

- Large LH_2 Active Cryogenic Storage Demonstrator, Class D Mission
- Mission: Up to 8 Months, ELV launch to 500 km SS 6am or 6pm orbit (full sun for 8 months), Orbit life < 25 years
  - Primary LCD system mass to orbit requirements will allow ELV to carry secondary payloads
- Zero Boil-Off Storage Experiment
  - ~260 kg LH2, 1.5 m D x 2.67 m Al Tank with SOFI, MLI (45 layers)
  - 20K / 90K combined Broad Area Cooling with 90K and 20K cryocoolers lifting ~11.5Wth and ~3.8Wth heat leak respectively. ~7.3 Wth for the 20K only case.
- Cryogenic Transfer Experiment
  - 1.05m spherical, passive cooled receiver tank (25 layers MLI)
  - Receiver tank cooled with LH2 from storage tank
  - Unsettled and settled transfers (5 total, with less 'top offs')
  - Both He and Autogenous pressurization systems
- Spacecraft: 'OTS' bus similar to Leostar or equivalent (see RSDO catalog)
  - Power: ~3 kWe from single solar array, minimal battery (no shadow when using cryocoolers)
  - Thermal: ~ 6m2 of body mounted radiators, fed by heat pipes
  - AD&CS: Simple gravity gradient with magnetic torquers, sun and horizon sensors
  - Propulsion: Cold Gas N2 to provide tip-off, up to 46 ~864 sec settling burns for experiment and six settled chilldown burns
  - C&DH: control bus and experiment, store ALL 8 months of data 1 TB
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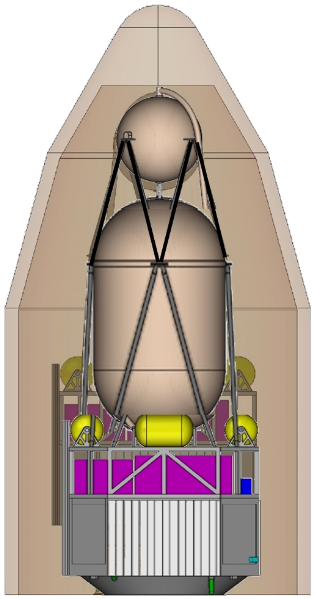
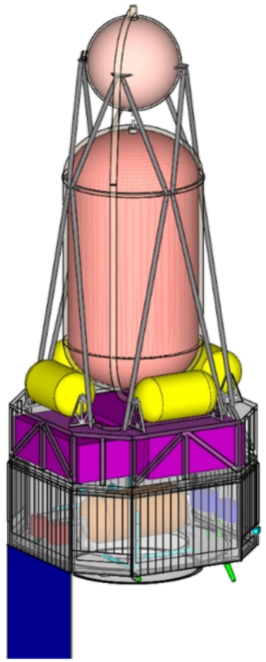
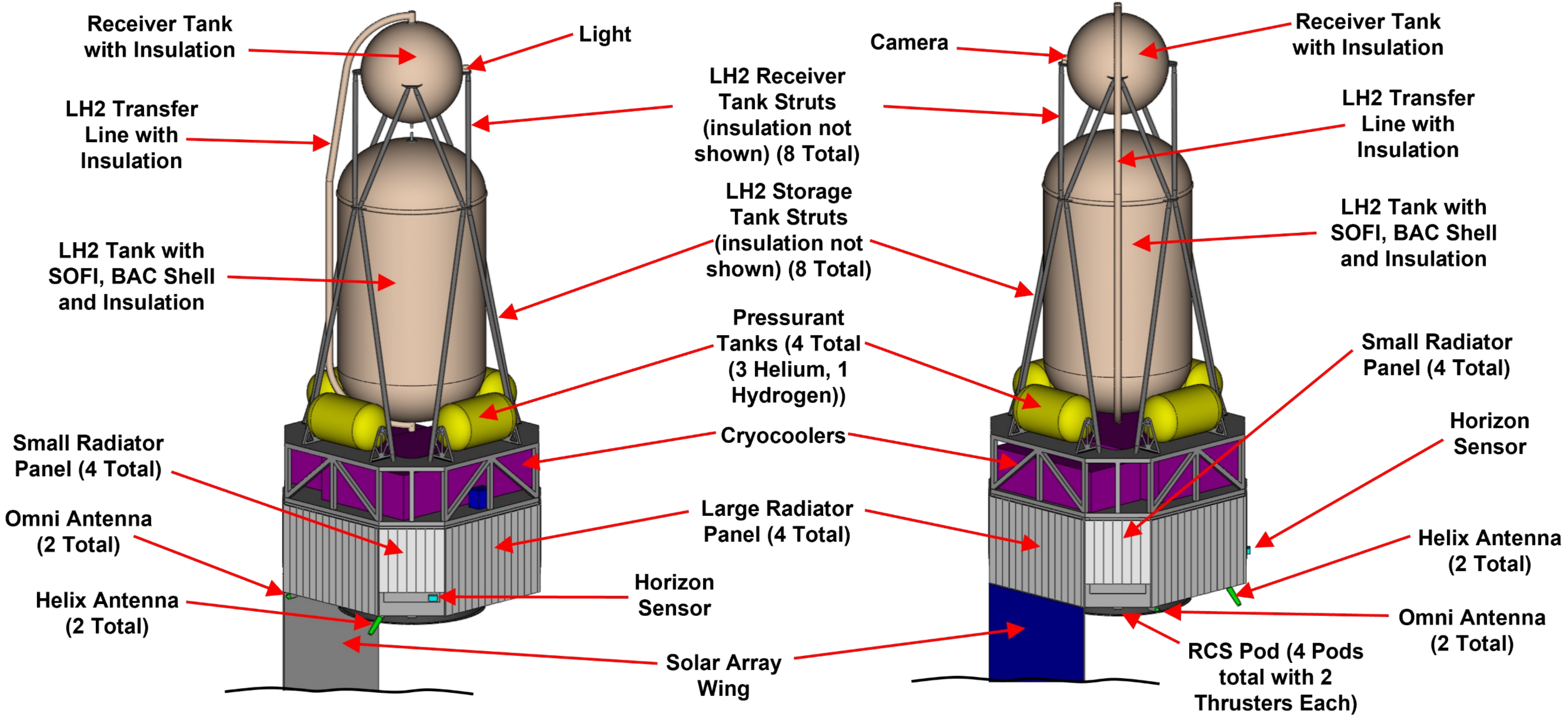




CFMPP – GOVERNMENT REFERENCE CONCEPT (UPDATED FY2023)



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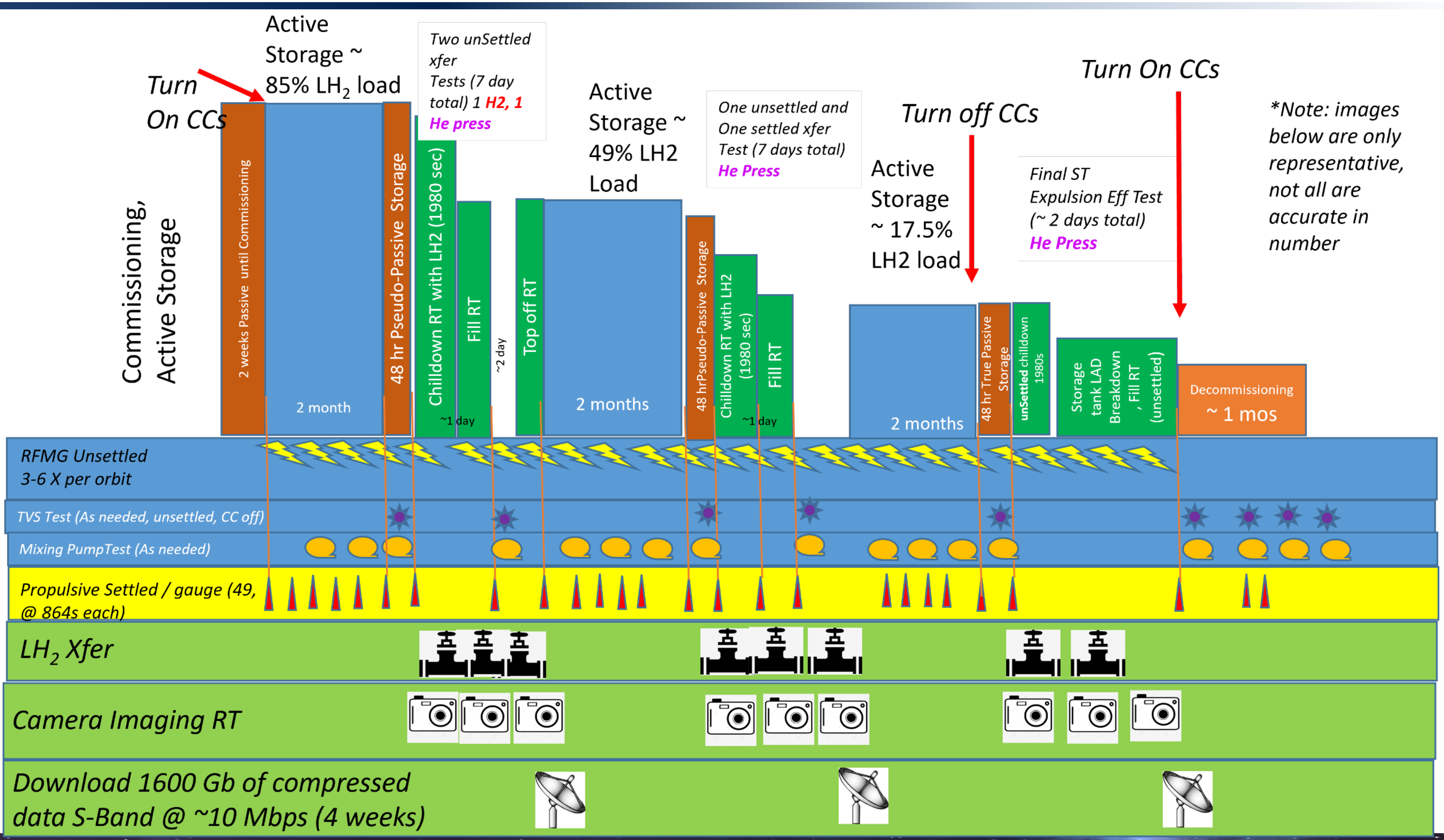
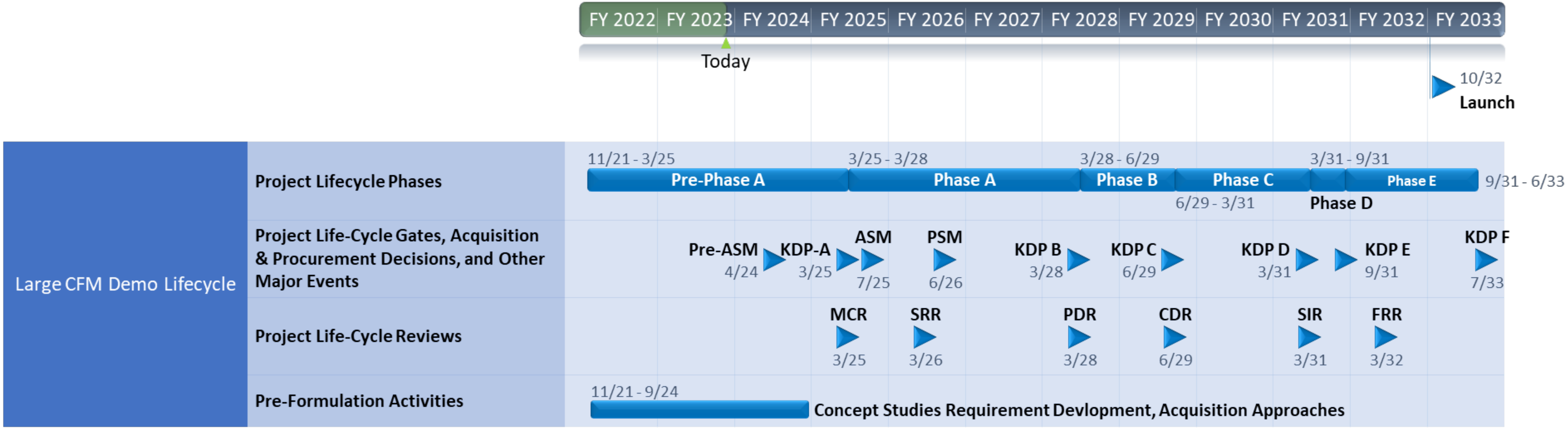


CFMPP – GOVERNMENT REFERENCE CONCEPT SCHEDULE (FY2023)

- **Assuming KDP-A on 03/2025, Launch date is 10/2032 with ~1 year margin incorporated**
  - Mission Ops + Final Reporting = +1 year after Launch date
  - Nominal launch date is 10/2031 (~6.5 year duration)
    - Acquisition process between ASM and PSM assumed to be 1 year, allowing for SRR to be completed by Government
  - Concept elements for future schedule refinement: Bus acquisition timeline; Launch Vehicle LH2 loading development
    - Industry RFIs could inform schedule estimates



CFMPP – FLIGHT DEMONSTRATION OPPORTUNITIES – FORWARD WORK (FY2024)

- Completing the Integrated CFM Flight Demonstration Opportunity Assessments
- Refining relationships with Stakeholders / increasing information exchange
- Developing, Executing, and Summarizing Industry Spacecraft Bus, Launch Vehicle LH2 Loading, System RFIs
    - Make vs Buy? Data Rights? Government Resources (Facilities, personnel, etc.) Used?
    - Refine the acquisition approach and schedule between MCR, Procurement activities, and SRR
- Updating Lifecycle Schedule, Cost, and Cost Phasing projections
- Conducting Design/Analysis Cycle #4 for LCD single mission refinement to support Government Point of Departure Review
    - Incorporate technology advancements as applicable (e.g., cryocoolers, transfer operations, etc.)
    - Expand launch vehicle options to include recently awarded missions (e.g., DRACO -> Vulcan, HLS Blue Origin -> New Glenn)
- Continuing Programmatic and Technical Management Product Maturation

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BACKUP

TECHNOLOGY DEVELOPMENT TO MISSION ARCHITECTURE MAPPING

ESDMD Mission Functions	*STMD Technology Development*	*Mars Architecture System Implementation*
In-Space Chemical Stage Design, Development, Test, & Evaluation (DDTE) Domestic Capabilities Needed	***Key CFM Technology Areas / Operations Needing Demonstration***	***Integrated Architecture Propellant and Propulsion Systems***
Cryogenic System Hardware Design, Procurement, Manufacturing, and Integration	*General design, fabrication, and integration activities*	*Development of Domestic Public and Private Capabilities*
Cryogenic System Ground Servicing and Orbit Delivery	*Payload-Launch Vehicle Integration, Servicing, and Payload to orbit delivery operations*	*Cryogenic loading ground and launch vehicle infrastructure*
Propellant Storage throughout Mission	*Passive Storage, High Efficiency / Capacity 90K & 20K Cryo-Cooling, BAC applications, 2-Stage Cooling, OLAF* Valves, TVS & Injector*	*Pressure Control Design & Operations Passive Thermal Control Design & Operations Active Thermal Control Design & Operations*
Propellant Transfer throughout Mission	*Unsettled Fluid Acquisition (LAD), Autogenous Pressurization, OLAF* Cryo-Couplers, Transfer Operations*	*Storage to Receiver Tank Transfer Design & Operations Receiver Tank Flow / Fluid Measurement Design & Operations*
Automated Stage Operations during Mission	*Fluid mass gauging and state / stratification determination throughout mission operations*	*Unsettled Mass Gauging Design & Operations Integrated propellant measurement systems and automated avionics*

CFM – LCD INTEGRATED SYSTEMS

LCD Primary Objective: ***Demonstrate and collect, within a representative microgravity environment, flight performance data for LH2 integrated subsystem(s):***

1. **Long Duration Storage Operations**
2. **Automated Propellant mass, state, and stratification measurements with System Feedback Operations**
3. **Transfer Operations**

[TRL assumed at LCD Payload PDR]

Long Duration Storage Operations

- *Pressure Control Design & Operations*
  - Liquid Acquisition Device (LAD) [4-5]
  - Mixing Pump [5]
  - Thermodynamic Vent System [5]
  - Venting Hardware and Operations [5]
- *Passive Thermal Control Design & Operations*
  - Multi-Layer Insulation (MLI) [6]
  - Spray On Foam Insulation [9]
  - Low Conductivity Structures [6]
- *Active Thermal Control Design & Operations*
  - 20W / 20K Cryocooler [5-6]
  - BAC / Tube-to-Tank [5]
  - 15W / 90K Cryocooler [6]
  - BAC / Tube-to-Shield [5]
  - Cryocooler thermal rejection [6]

Automated Propellant…Measurements with System Feedback Operations

- *Unsettled Mass Gauging Design & Operations*
  - Storage / Receiver Tank RFMG Antenna System [7]
  - Mass Gauging Data Reduction and Measurement Electronics [6]

Transfer Operations

- *Storage to Receiver Tank Transfer Design & Operations*
  - Receiver Tank Thermodynamic Vent System [5]
  - Storage to Receiver Tank Transfer Line with Valves [4-5]
  - Receiver Tank and Transfer Line Chill down Operations using Charge / Hold / Vent (CHV) [5]
- *Receiver Tank Flow / Fluid Measurement Design & Operations*
  - Receiver Tank Camera and Light [6]
  - 2-Phase Flowmeter [5-6]

- ***LCD Mission Objectives prioritize demonstrating multiple storage, gauging, and transfer subsystems, not just advancing TRL for singular components.***
- ***Flight performance data collected will advance subsystem design modeling approaches leveraging multiple CFM Technologies, strategically reducing risk for early DDT&E lifecycle designs with in-space cryogenic systems.***