NASA's Developments in Cryogenic Fluid Management Technology

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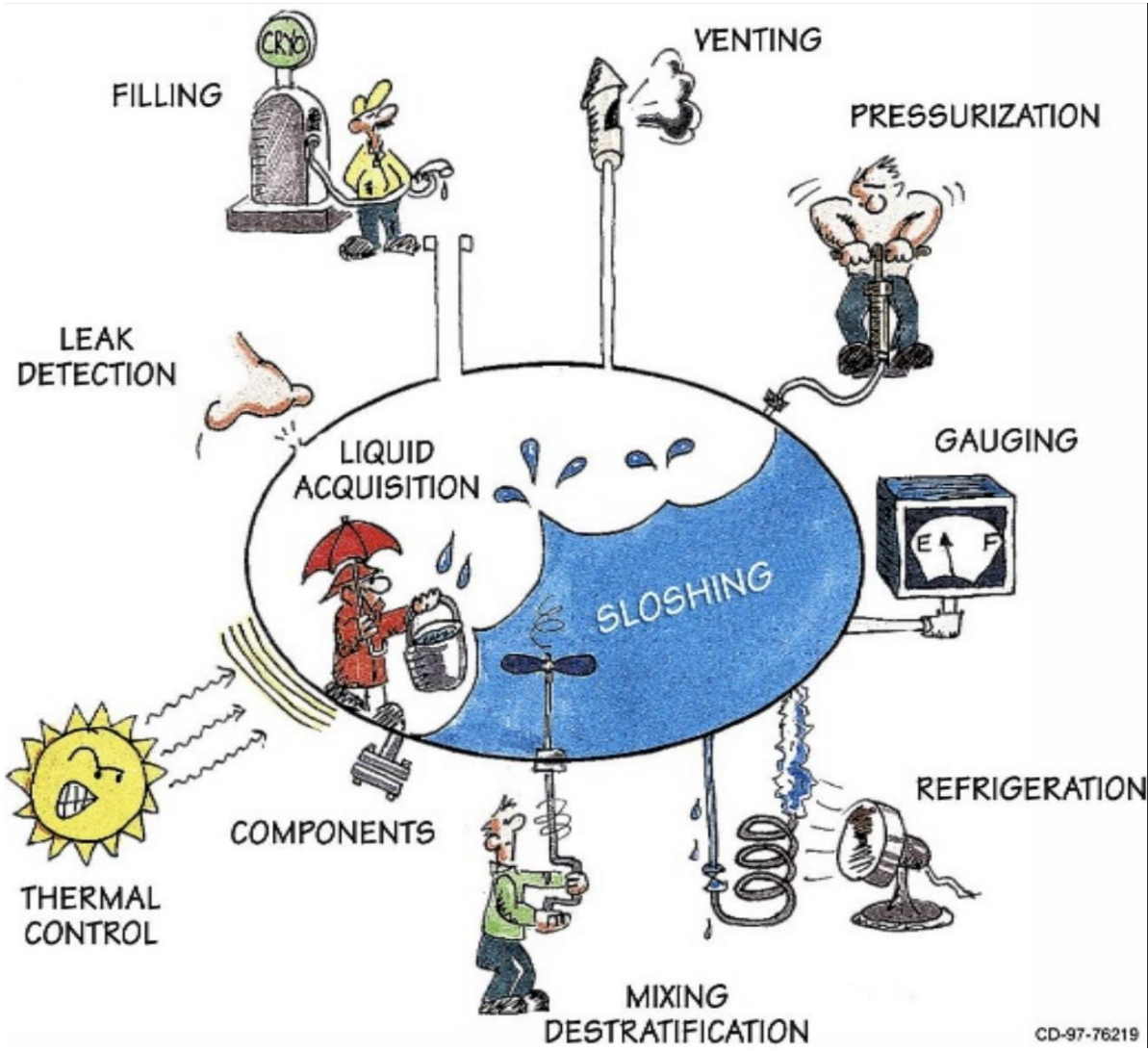
Cryogenic Fluid Management (CFM) at NASA

- **Cryogenic Fluid Management:** Suite of technologies that enable the storage, transfer, and measurement of cryogenic fluids
- **NASA has *60+ years* of expertise in CFM component and system development and execution**
  - Completed through partnerships across NASA centers
  - Pursuing both NASA in-house and partnerships for future development
- **Interest for cryogenic propulsion systems is nearing an all-time high across both the government and industry**
  - Both in-space and terrestrial applications (i.e. hydrogen aircraft)



Cryogenic Fluid Management Technology Pulls

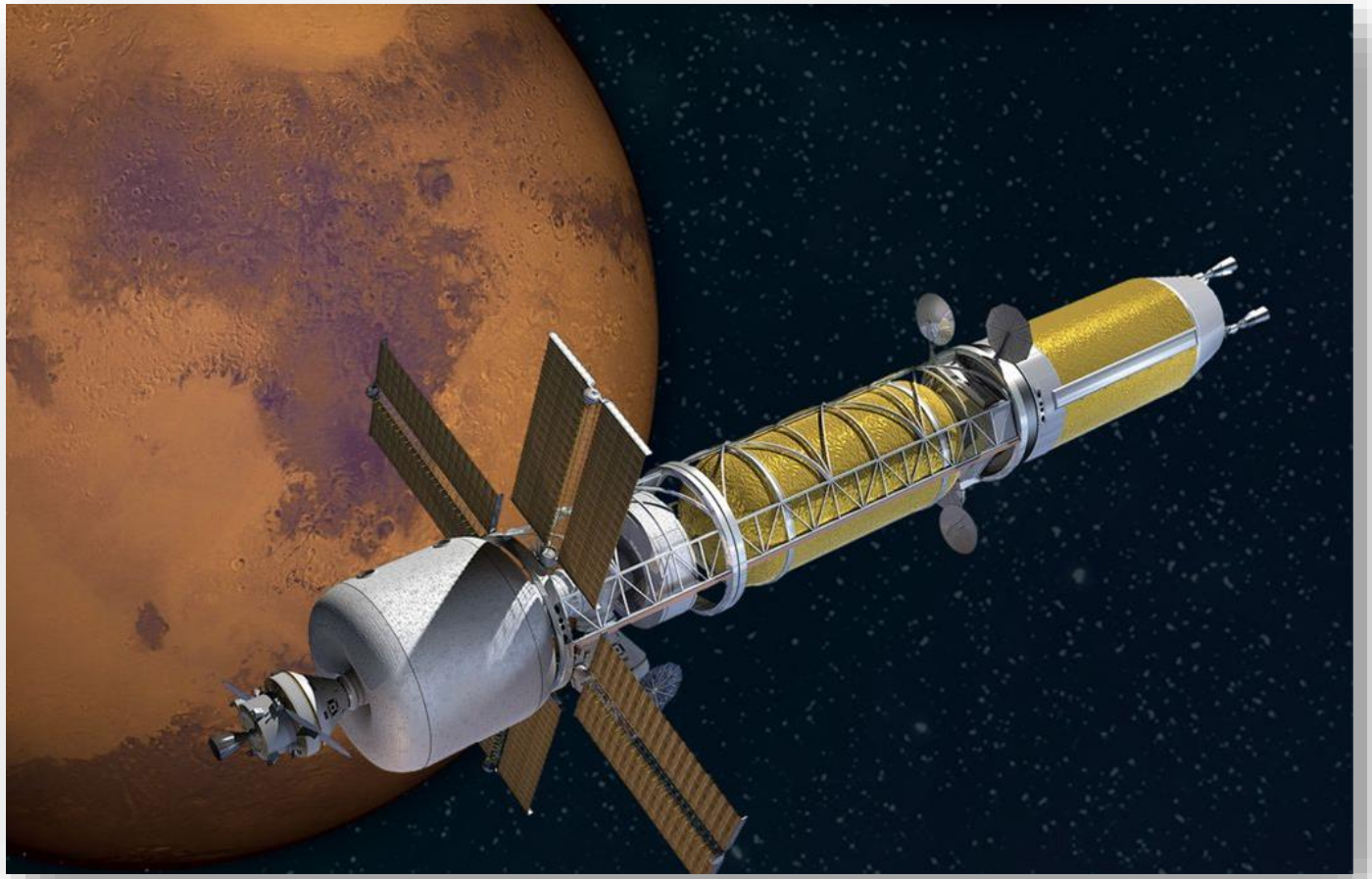
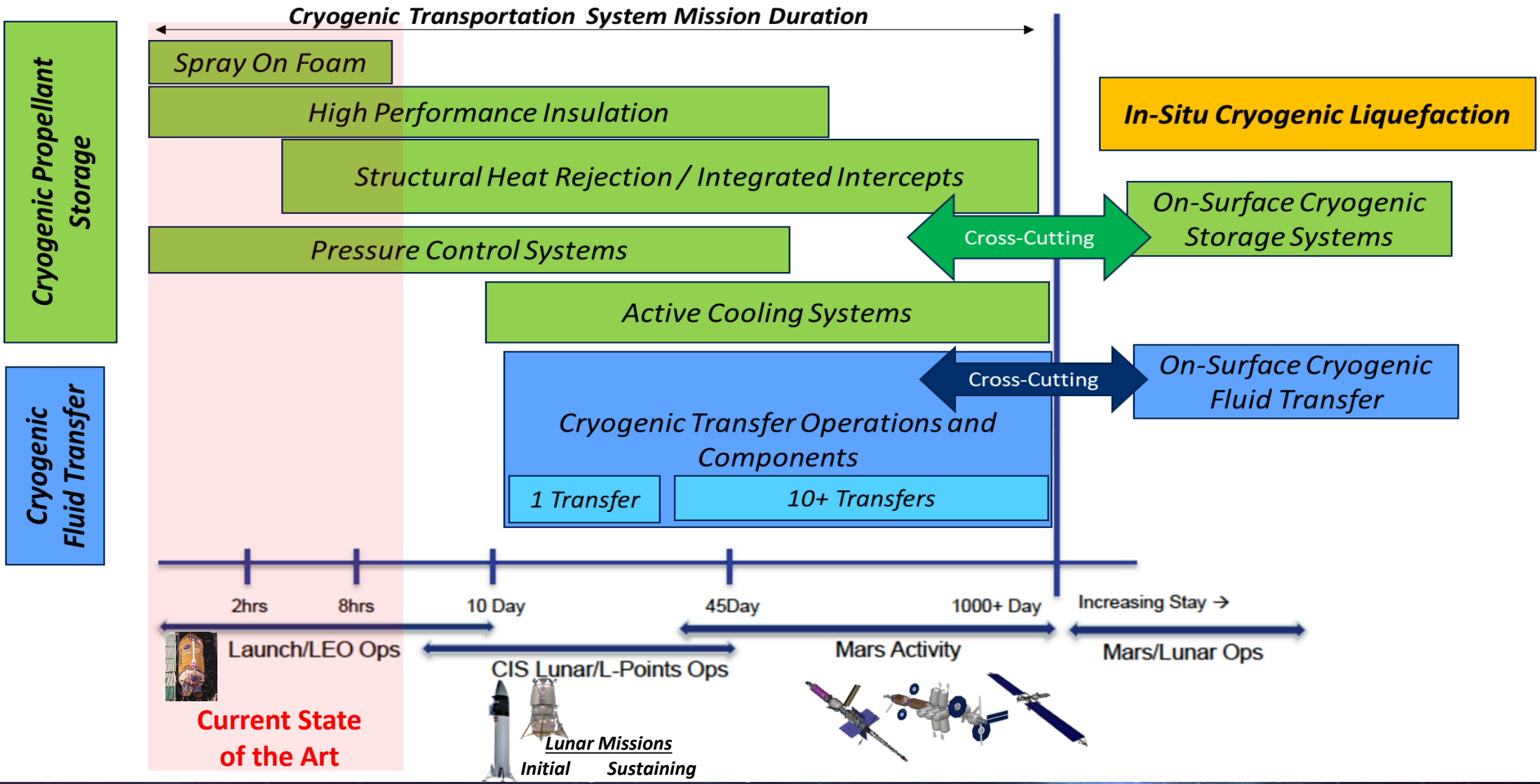


Photo Credit: NASA

- **Moon2Mars will push cryogenic mission durations from months to years**
- **Enabling cryogenic fluid management technologies at a TRL ≥ 6 for Mars and Cis-lunar transportation, ISRU, and Surface Systems operations are required for the Moon2Mars Campaign**
  - Advanced cryogenic propellant storage and transfer, operable in microgravity environments is required for **all** proposed mission architectures
- **Increasing cryogenic mission duration drives the need for more advanced CFM technology**
  - Current CFM capabilities support missions on the order of days

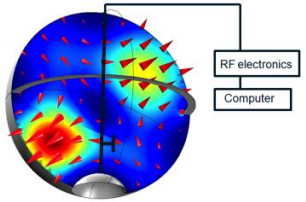
CFM Technology Current Capabilities



NASA Cryogenic Fluid Management Programs (Last ~20 years)

2001-2003: Next Generation Launch Technology (NGLT) support for CFM technology development

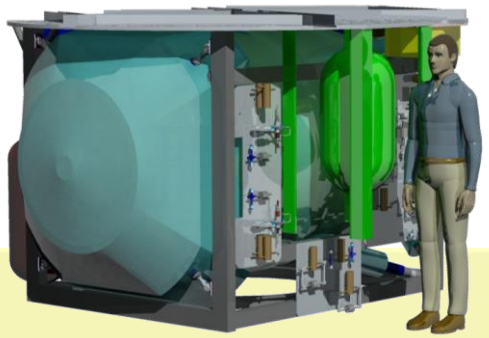
1996-2001: X-33 Propellant Densification



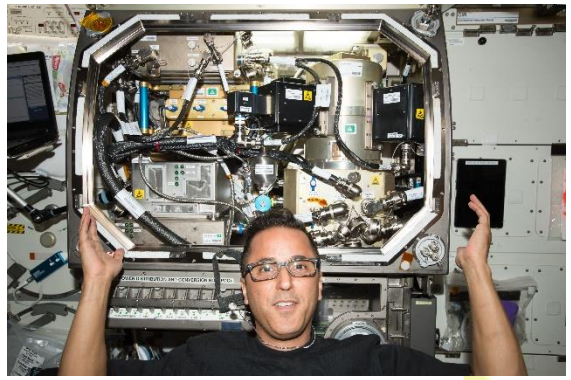
2004-2005: Propellant Depot Technology Development Project

2005-2010: LOX-Methane Project Propulsion and Cryogenic Advanced Development

2010-2014: Cryogenic Propellant Storage and Transfer (CPST) Mission



2014-2020: Evolvable Cryogenics (eCryo)



2010-Present: Zero Boil-off Tank (ZBOT) ISS Flight Experiments

2021-Present: Cryogenic Fluid Management Portfolio Project

Modeling and Simulation Development and Validation

CFM Portfolio Project (CFMPP)

- ***Project 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**
- **Space Technology Mission Directorate (STMD) portfolio project comprised of over twenty individual CFM technology development activities**
  - Includes non-flight demo related activities related to Lunar/Mars surface system applications (ex. ISRU liquefaction)
- **Partnered leadership and execution by NASA's Marshall Spaceflight Center and Glenn Research Center**
- **CFMPP aims to close technology gaps development, with focus on integrated CFM systems development and demonstration, to advance the national goals of landing on the Moon and Mars**
- **Technology entrance minimum of TRL 4, with project end state objective of TRL 7 (Flight Demonstration)**
  - CFMPP has developed and implemented a rigorous TRL assessment and advancement process
- **CFMPP leverages Agency-wide mission developments and expertise for prioritization of activities**

To mature CFM technologies critical for space flight applications, CFM flight demonstrations are required. Flight demonstrations must be of appropriate scale, utilize integrated systems, and be performed in extended microgravity and thermal environments

Cryogenic Fluid Management Portfolio Project (CFMPP)

CRYOGENIC FLUID MANAGEMENT PORTFOLIO PROJECT

System Demonstration Complexity

Technologies Portfolio

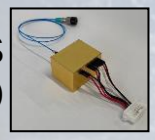
Scope: Design, development, testing, and evaluation of critical-need cryogenic components enabling long-duration CFM storage and propellant transfer

Major Activities:

Hydrogen low-leakage valves and cryo-couplers

Radio Frequency Mass Gauge (RFMG)

Next-generation FOSS (fiber optics sensing system)

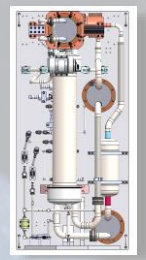


Solar White thermal coatings

Subsystems Portfolio

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

Major Activities:



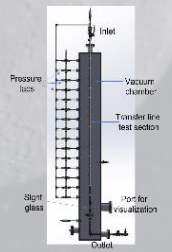
20W/20K Cryocooler

90W/150K Cryocooler

Cryocooler Electronics

Alternate Cryocooler Studies

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+ maturation for many technologies

Major Activities:

Integrated CFM Flight Demo
Tipping Point Contracts
Ground System Demonstrations

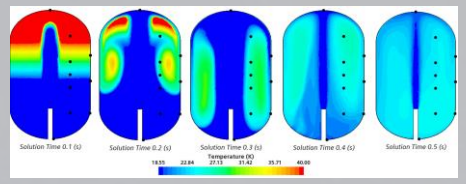
Two-Stage Cooling Demonstration

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

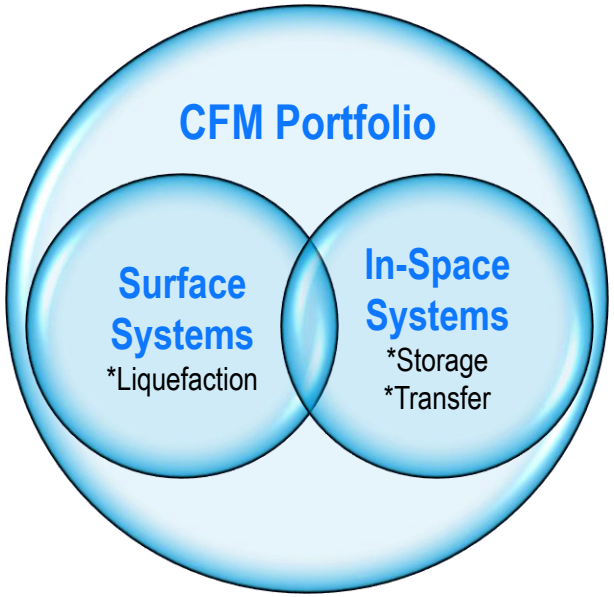
Testing and demo activities <u>across the CFMP portfolio</u> used within modeling tools to predict CFM behavior at a flight vehicle scale in a relevant microgravity environment



System Validation

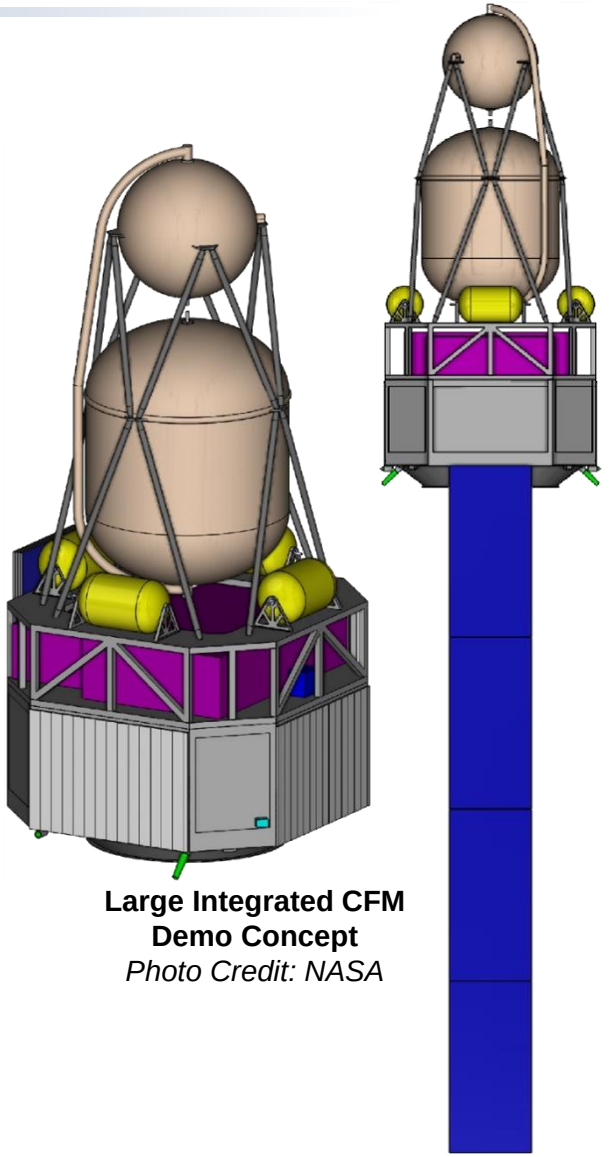
Capability Shortfalls

- **Numerous CFM capability shortfalls exist for both in-space transportation and Lunar/Mars surface system applications.**
  - Due to microgravity dependent nature of technology gaps, must be closed via integrated flight demonstrations
- **Identified Enabling CFM Technologies/Capabilities with Shortfalls:**
  - Active Cooling Systems using high-efficiency, high-capacity cryocoolers
  - Unsettled cryogen transfer systems
  - Low-leakage hydrogen fluid components (cryo-valves and cryo-couplers)
  - Cryogenic propellant mass gauging systems
  - Flight-proven passive thermal systems (advanced MLI, coatings, etc.)
- **Activities within CFMPP office directly map to path for shortfall closure**
- **CFMPP has two approaches for integrated flight demonstrations:**
  - Four 2020 Tipping Point flight contracts
  - Government Reference Integrated CFM Demo Mission
- **CFMPP-developed analysis and simulation capabilities are essential and cross-cutting**
  - Flight demonstrations validate modeling tools for use in design and operations of future missions



CFMPP Approach for Integrated Flight Demonstration

- **Since 2021, CFMPP has been formulating the gov't reference concept mission programmatic and technical requirements supporting remaining technology gap closure**
  - Flight demonstration must be conducted within an integrated system and in a microgravity environment
  - Data results (measured flight data and validated models) would be available to both Government and Private Sector Users
- **Flight demonstration is of appropriate scale, operational duration, and provides sufficient data for TRL 6+ maturation**
  - CFMPP has baselined LH2 cryogen for demonstration → maximized cross-cutting technology gap closure to LO2/LCH4 systems
- **Concept Highlights:**
  - 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)
  - Zero Boil-Off Storage Experiment
    - 261 kg LH_2, 20K / 90K combined Broad Area Cooling with 20K and 90K cryocoolers
  - Cryogenic Transfer Experiment
    - Unsettled and settled transfers (3 total transfers)
    - Both He and H2 Autogenous pressurization systems



Large Integrated CFM Demo Concept
Photo Credit: NASA

CFM Notional Near-Term Roadmap

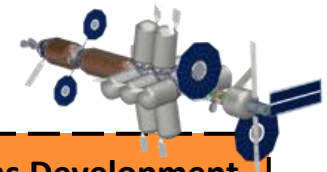
CY2024	2025	2026	2027	2028	2029	2030	2031+

CFM technology infused to enable storage and transfer capability needs in future NASA missions

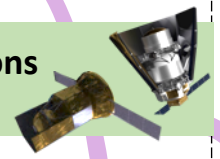
CFMPP Ground Developments for Storage, Transfer, and Mass Gauging Technologies
- 2-Stage Cooling and CryoFILL / 2019 Tipping Point Liquefaction Demos
- High Capacity 150W / 90K & 20W / 20K Cryocooler Technologies
- Transfer and Chilldown Operations
- Component Development for Valves, Cryo-Couplers, RFMG

ISRU Subscale Demo 1 → **ISRU Subscale Demo 2**

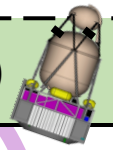
Surface Systems for Lunar and Mars



CFMPP Flight Demonstrations
- 2020 Tipping Points



Integrated CFM Demonstration Mission (Launch 2030+)



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

DRACO NTP Demonstration with DARPA

Initial Human Landing System (HLS)

Artemis 3 ▲ SpaceX Uncrewed Demo

Artemis 4 ▲

Artemis 5 ▲

HLS Sustained Capability Demonstration

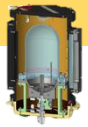
▲ Blue Origin Uncrewed Demo

HLS Sustaining Missions

Advanced In-Space CFM Model Development
- Physics based, high fidelity, flight data validated

SMD Flight Experiments Supporting CFM Technologies / Modeling

CLPS ZBOT-NC ZBOT-DP ZBOT-FT



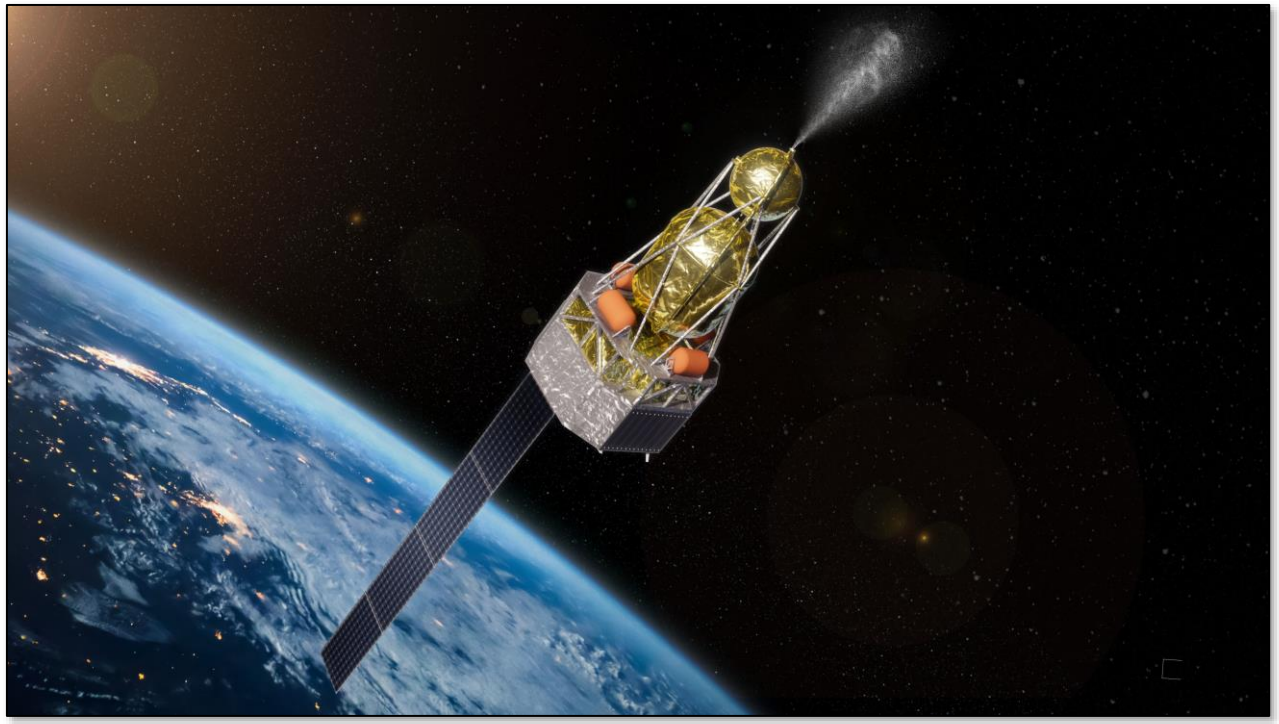
Images: Blue Origin; Eta Space; Lockheed Martin; NASA, SpaceX

STMD | ESDMD | SMD | SMD/STMD Collab. | Pre-Formulation

Arrows indicate cross-project/program integration.
Curved – delivery of data for model development/validation
Straight - technology and validated models infused to enabling system development

Summary and Forward Work

- NASA through the CFM Portfolio Project is seeking and leveraging infusion opportunities to advance US goals of landing on the Moon and Mars
- CFMPP refining the government reference Large Integrated CFM Flight Demonstration concept
- Near-term forward work includes study of acquisition approaches for key developments within the CFM Portfolio Project Office and pursuit of potential mission partnerships



Large Integrated CFM Demo Concept
Photo Credit: NASA

Pursuing both NASA in-house and industry/international partnerships for future developments