National Aeronautics and Space Administration

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Cryogenic Fluid Management for the Artemis Program and Beyond

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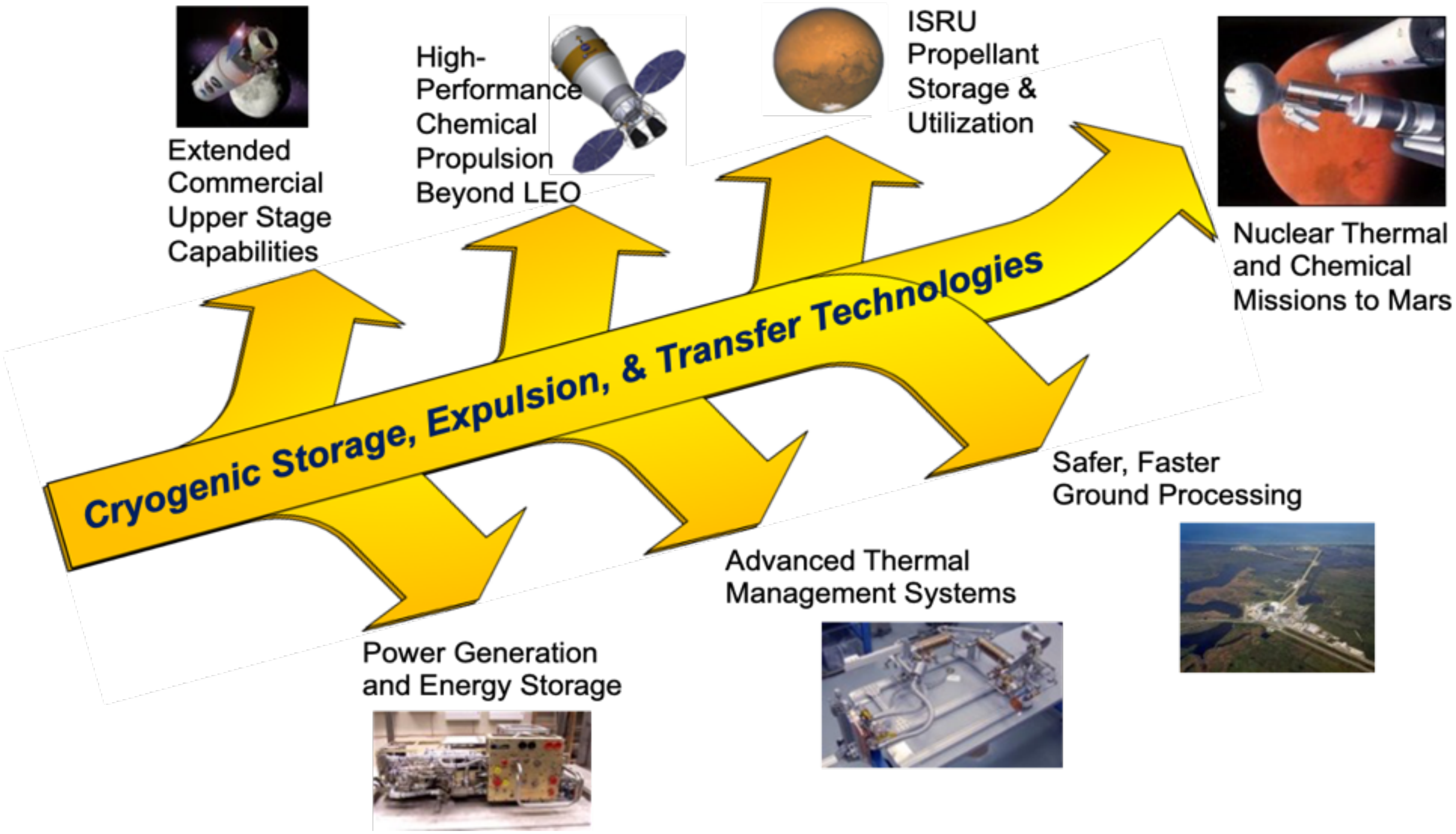
Overview

- **Introduction**
- **Recent History of CFM Projects in NASA**
- **CFM Technology Roadmap**
- **STMD CFM Priorities**
- **CryoFILL**
- **Evolvable Cryogenics Project (eCryo)**
- **Conclusions**

Introduction

- **NASA is endeavoring on an ambitious return to the Moon and eventually on to Mars through the Artemis Program leveraging innovative technologies to establish sustainable exploration architectures collaborating with US commercial and international partners.**
  - Future NASA architectures have baselined cryogenic propulsion systems to support lunar missions and ultimately future missions to Mars
- **NASA has been investing in maturing CFM storage, transfer, and gauging technologies over the last decade plus.**
  - Recently, NASA created a Cryogenic Fluid Management (CFM) Technology Roadmap identifying the critical gaps requiring further development to reach a TRL of 6 prior to infusion to flight applications.
- **To address the technology gaps the Space Technology Mission Directorate (STMD) strategically plans to invest in a diversified CFM portfolio approach through ground and flight demonstrations**
  - Plan to leverage Tipping Point and Announcement of Collaborative Opportunities with US Industry, and explore mutually beneficial partnerships with International Agencies
  - Once proven, these system capabilities will enable the high performing cryogenic propellant systems needed for the Artemis Program and beyond.

Cryogenic Propellant Technology Cross-Cutting Benefits



CFM Development Mitigates Risks for Multiple Architecture Elements and Systems

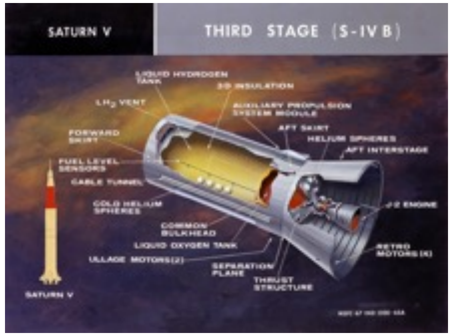
Recent History of CFM Projects at NASA

- **NASA has been developing CFM technologies since the 1960s.**
  – Early developments focused on upper stages, Centaur and the Saturn IV-B stage.
  – Late 1960s, NASA was pursing technologies in support of the Mars Nuclear Vehicle.
  – Aerobee sub-orbital in the early-mid 1960s as well as Atlas-Centaur Flights

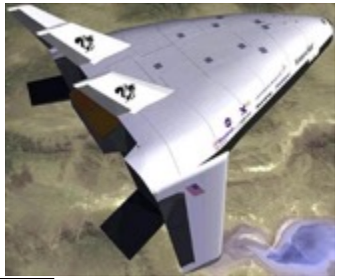
- **Space Shuttle - use of reusable tanks and tankers within the payload bay**
  – Cryogenic On-Orbit Liquid Depot Storage, Acquisition and Transfer (COLD-SAT)
  – Cryogenic Orbital Nitrogen Experiment (CONE)
  – Cryogenic Fluid Management Experiment (CFME)

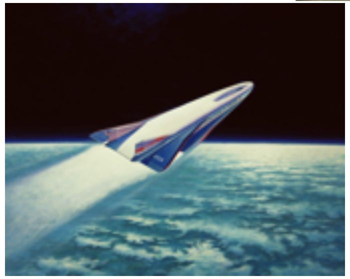
- **Single Stage to Orbit (SSTO)**
  – National Aero-Space Plane (NASP) and the X-33.

- **Large-scale ground test beds to demonstrate the next generation of technology concepts such as densified propellants**
  – Variable Density Multilayer Insulation (VD-MLI)
  – Multi-purpose Hydrogen Test Bed (MHTB)



Saturn IV-B Stage


X-33

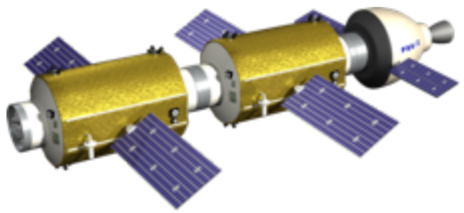

NASP, X-30


MHTB

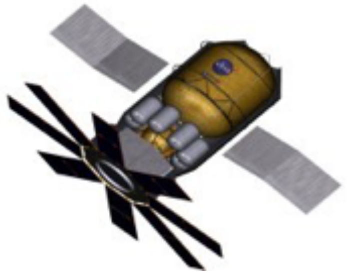
Recent History of CFM Projects at NASA

- **2000s: Exploration Technology Development Program – Return to the Moon, orbital cryogenic technologies were once again a focus**
  – Propulsion and Cryogenics Advanced Development (PCAD) Project
  – Cryogenic Fluid Management (CFM) Project
  – Cryogenic Storage and Transfer (CRYOSTAT)

- **2010s under STMD:**
  – Cryogenic Propellant Storage and Transfer (CPST)
    - Completed Mission Concept and System Requirements Reviews
  – Evolvable Cryogenics (eCryo)
    - CFM Modeling, Radio Frequency Mass Gauge (RFMG), and large-scale ground demonstration of insulation and vapor cooling on the SHIIVER Test Rig.
  – Robotic Refueling Mission 3 (RRM3)
  – Cryo Fluid Technologies (CFT) Portfolio
    - High Capacity Cryocooler Development (20W/20K & 150W/90K), Reduced Gravity Cryo Transfer (RGCT), Cryogenic Thermal Coatings (Solar White)

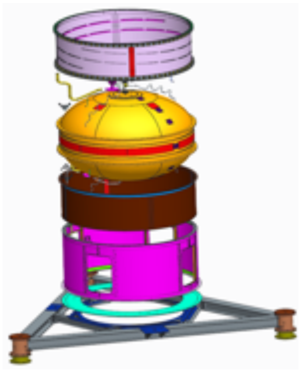


CRYOSTAT



CPST

RRM3



SHIIVER

CFM Technology Roadmaps

CFM Elements				
Technologies	Current TRL	Gravity Dependant (Y/N)	Path to TRL 6	"Cross Cutting" or "Fluid Specific"
Low Conductivity Structures	6	No	Ground Test	Cross Cutting
High Vacuum Multilayer Insulation	6	No	Ground Test	Cross Cutting
Sun Shields (deployment mechanism)	5	No	Ground Test	Cross Cutting
Tube-On-Shield BAC	5	No	Ground Test	Cross Cutting
Valves, Actuators & Components	5	No	Ground Test	Cross Cutting
Vapor Cooling	6	No	Ground Test	Fluid Specific
Propellant Densification	5	No	Ground Test	Fluid Specific
Unsettled Liquid Mass Gauging	7	Yes	Flight Demo	Cross Cutting
Helium Pressurization of an Unsettled Tank	5*	Yes	Flight Demo	Cross Cutting
MPS Line Chilldown	5	Yes	Flight Demo	Cross Cutting
Pump Based Mixing	5	Yes	Flight Demo	Cross Cutting
Thermodynamic Vent System	5	Yes	Flight Demo	Cross Cutting
Tube-On-Tank BAC	5	Yes	Flight Demo	Cross Cutting
Liquid Acquisition Devices	5	Yes	Flight Demo	Fluid Specific
Advanced External Insulation	4	No	Ground Test	Can Be Both
Automated Cryo-Couplers	4	No	Ground Test	Cross Cutting
Cryogenic Thermal Coating	4	No	Ground Test	Cross Cutting
High Capacity, High Efficiency Cryocoolers 90K	4	No	Ground Test	Cross Cutting
Soft Vacuum Insulation	3	No	Ground Test	Cross Cutting
Structural Heat Load Reduction	3	No	Ground Test	Cross Cutting
Propellant Tank Chilldown	4	Yes	Flight Demo	Cross Cutting
Transfer Operations	4	Yes	Flight Demo	Cross Cutting
High Capacity, High Efficiency Cryocoolers 20K	4	No	Ground Test	Fluid Specific
Liquefaction Operations (MAV & ISRU)	4	No	Ground Test	Fluid Specific
Para to Ortho Cooling	4	No	Ground Test	Fluid Specific
Cryogenic Flow Meter	4	Sometimes	Flight Demo	Can Be Both
Autogenous Pressurization in Micro-g	4*	Yes	Flight Demo	Fluid Specific

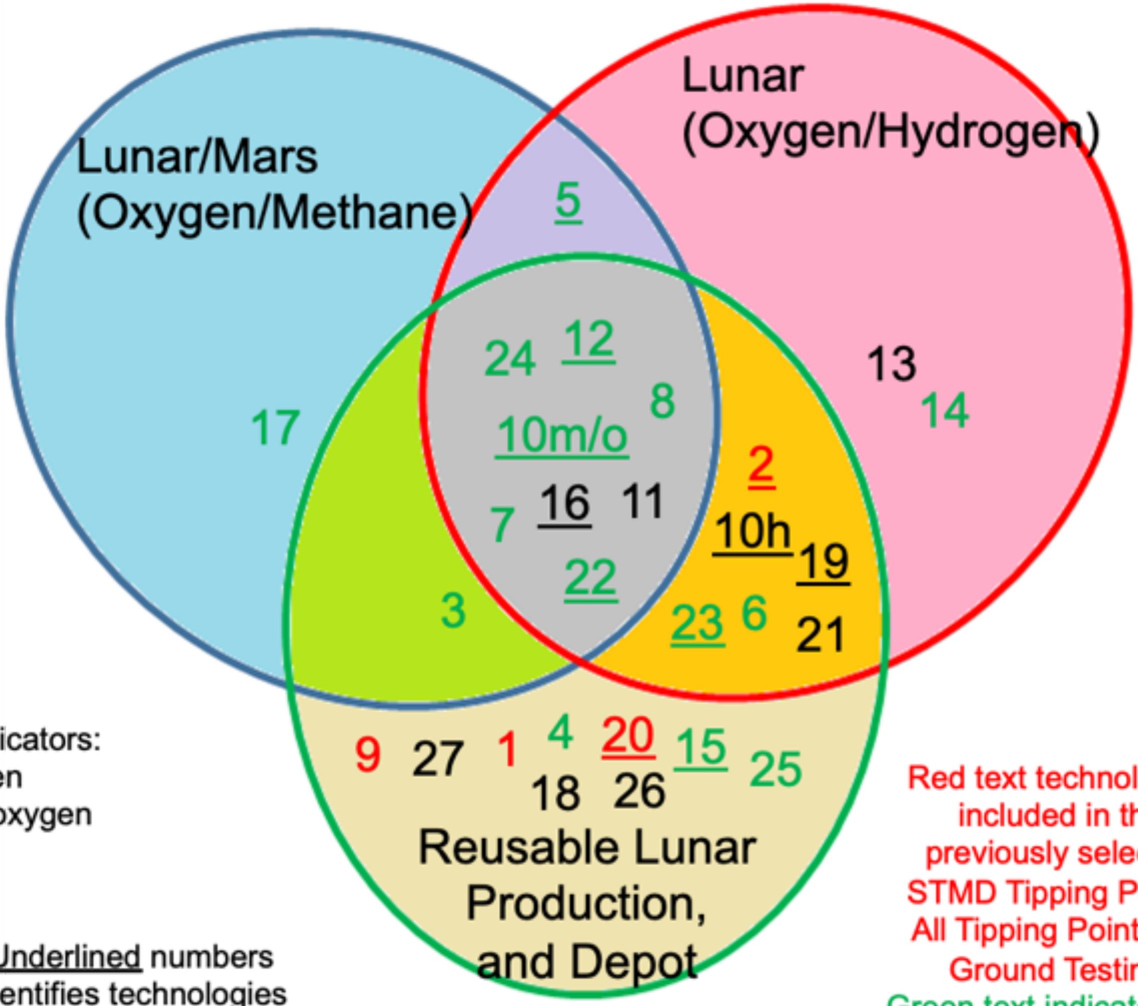
Can achieve TRL 6 through ground testing

Flight Demo required to reach TRL 6

Technology ”Long-Poles” Development is needed.

*Traditional pressurization methods, helium and autogenous, have flown for years and are TRL 9

Cryogenic Fluid Management Across Multiple Lander Architectures



Fluid Specific indicators:
h – hydrogen
m/o – methane/oxygen

Underlined numbers identifies technologies requiring flight demonstration to realize TRL 6.

Red text technologies included in the previously selected STMD Tipping Points. All Tipping Points are Ground Testing.
Green text indicate other STMD/AES active Funding.

Technology	No
Advanced External Insulation	1
Autogenous Pressurization	2
Automated Cryo-Couplers	3
Cryogenic Thermal Coating	4
Helium Pressurization	5
High Capacity, High Efficiency Cryocoolers 20K	6
High Capacity, High Efficiency Cryocoolers 90K	7
High Vacuum Multilayer Insulation	8
Liquefaction Operations	9
Liquid Acquisition Devices	10
Low Conductivity Structures (Materials)	11
Line Chilldown	12
Para to Ortho Cooling	13
Propellant Densification	14

Technology	No
Propellant Tank Chilldown	15
Pump Based Mixing	16
Soft Vacuum Insulation	17
Structural Heat Load Reduction (Active)	18
Thermodynamic Vent System	19
Transfer Operations	20
Tube-On-Shield BAC	21
Tube-On-Tank BAC	22
Unsettled Liquid Mass Gauging	23
Valves, Actuators & Components	24
Vapor Cooling	25
2 Phase Flow Meter	26
Sun Shields	27

Strategic Architecture Roundtable (STAR)

- **The Strategic Technology Architecture Roundtable (STAR) is an effort that started within NASA's STMD to establish strong communication and synchronization of technologies across the Spaceflight continuum.**
  - Representatives from HEOMD, SMD, US industry, and the US Department of Defense (DoD) provide inputs on architectures and the technology needs within the STAR team.
  - If interested in participating in the STAR process, please contact Art Maples at arthur.b.maples@nasa.gov.

- **The Moon to Mars architecture under the Artemis Program is the primary driving force for many Agency technology investments, however, it is not the only architecture where technology infusion will be needed.**
  - Other CLPS providers, HLS Providers, Gateway, SMD Decadal Missions (Earth Science, Helio-physics, Planetary, Astrophysics) and Transportation of Crew and Cargo are all architectures in their own right, in addition to Lunar Surface exploration/habitation and part of the much larger Moon to Mars architecture.
  - STMD decisions are primarily driven by the Lead/Go/Land/Live/Explore Strategic Framework, illustrating the major thrust areas and capabilities. STMD will tie its technology investment strategy to NASA and industry human exploration and science architectures to increase focus on technology infusion paths.

STMD CFM Priorities

LEAD	THRUSTS	OUTCOMES	CAPABILITIES
Ensuring American global leadership in Space Technology • Lunar Exploration building to Mars • Robust national space technology engine to meet national needs • U.S. national and regional economic growth for space industry • Expanded commercial enterprise in space	**Go** *Rapid, Safe, & Efficient Space Transportation*	• Enable Human Earth-to-Mars Round Trip mission durations less than 750 days. • Enable rapid, low cost delivery of robotic payloads to Moon, Mars and beyond. • Enable reusable, safe launch and in-space propulsion systems that reduce launch and operational costs/complexity and leverage potential destination based ISRU for propellants.	• Cryogenic Fluid Management & Propulsion • Advanced Propulsion
	Land *Expanded Access to Diverse Surface Destinations*	• Enable Lunar and Mars Global Access with ~20t payloads to support human missions. • Land Payloads within 50 meters accuracy while also avoiding local landing hazards.	• Human & Robotic Entry, Descent and Landing • Precision Landing
	Live *Sustainable Living and Working Farther from Earth*	• Conduct Human/Robotic Lunar Surface Missions in excess of 28 days without resupply. • Conduct Human Mars Surface Missions in excess of 365 days without resupply. • Provide greater than 90% of propellant and water/air consumables from local resources for Lunar and Mars missions. • Enable Surface habitats that utilize local construction resources. • Enable Intelligent robotic systems augmenting operations during crewed and uncrewed mission segments.	• Sustained human life support systems • Operate in Extreme Environments • Sustainable Power • In-situ Propellant and Consumable Production • Intelligent/Resilient Systems & Advanced Robotics • Advanced Materials and Structures
	Explore *Transformative Missions and Discoveries*	• Enable new discoveries in Lunar/Mars surface and other extreme locations. • Enable next generation space data processing with higher performance computing, communications and navigation in harsh deep space environments. • Enable potential new architectures and approaches for in-space servicing, assembly and manufacturing and other missions.	• Extreme Access • Small Spacecraft Technologies • Advanced Avionics • Advanced Communications and Navigation • Servicing, Assembly and Manufacturing

- **The CFM capability Team has identified the following focus areas to assist in technology gap closures.**
  - Priority 1 – Collect CFM Transfer & Storage data from flight experiments using Cryogenic propellants.
  - Priority 2 – Stimulate investment in Flight-rated, high-power Cryo-cooler Development to enable active cooling on a large scale.
  - Priority 3 – Continue investments in critical CFM support technologies for the Artemis Program

STMD Tipping Point and ACO Awards

- **FY19 Awards**
  - Blue Origin
    - A ground demonstration of hydrogen and oxygen liquefaction and storage, representing rocket and spacecraft propellant that could be produced on the Moon. The demonstration could help inform a large-scale propellant production plant suitable for the lunar surface.
  - Skyre Inc.
    - Skyre, also known as Sustainable Innovations, along with partner Meta Vista USA LLC, will develop a system to make propellant from permanently frozen water located at the Moon's poles, including processes to separate the hydrogen and oxygen, keep the product extremely cold and use hydrogen as a refrigerant to liquefy oxygen.
  - SpaceX
    - SpaceX will collaborate with Marshall Space Flight Center to develop and test coupler prototypes – or nozzles – for refueling spacecraft such as the company's Starship vehicle. A cryogenic fluid coupler for large-scale in-space propellant transfer is an important technology to aid sustained exploration efforts on the Moon and Mars.
    - SpaceX will work with Glenn and Marshall to advance technology needed to transfer propellant in orbit, an important step in the development of the company's Starship space vehicle.
- **FY18 Awards**
  - Paragon Space Development Corporation
    - Proposal: Cryogenic Encapsulating Launch Shroud and Insulated Upper Stage (CELSIUS)
      CELSIUS is a system that can be installed on the surface of the cryogenic upper stage tank of a space launch vehicle to provide enhanced insulation capabilities and protection from meteoroids and debris.

STMD Tipping Point and ACO Awards

- **Cryogenic Fluid Management Technology Demonstration**
  - NASA and industry partners have developed and tested numerous technologies to enable long-term cryogenic fluid management, which is essential for establishing a sustainable presence on the Moon and enabling crewed missions to Mars. Implementation of the technologies in operational missions requires further maturation through in-space demonstrations.

- **New FY20 Awards**
  - **Eta Space** of Merritt Island, Florida, $27 million
    - Small-scale flight demonstration of a complete cryogenic oxygen fluid management system. As proposed, the system will be the primary payload on a Rocket Lab Photon satellite and collect critical cryogenic fluid management data in orbit for nine months.
  - **Lockheed Martin** of Littleton, Colorado, $89.7 million
    - In-space demonstration mission using liquid hydrogen – the most challenging of the cryogenic propellants – to test more than a dozen cryogenic fluid management technologies, positioning them for infusion into future space systems.
  - **SpaceX** of Hawthorne, California, $53.2 million
    - Large-scale flight demonstration to transfer 10 metric tons of cryogenic propellant, specifically liquid oxygen, between tanks on a Starship vehicle.
  - **United Launch Alliance (ULA)** of Centennial, Colorado, $86.2 million
    - Demonstration of a smart propulsion cryogenic system, using liquid oxygen and hydrogen, on a Vulcan Centaur upper stage. The system will test precise tank pressure control, tank-to-tank transfer, and multi-week propellant storage.

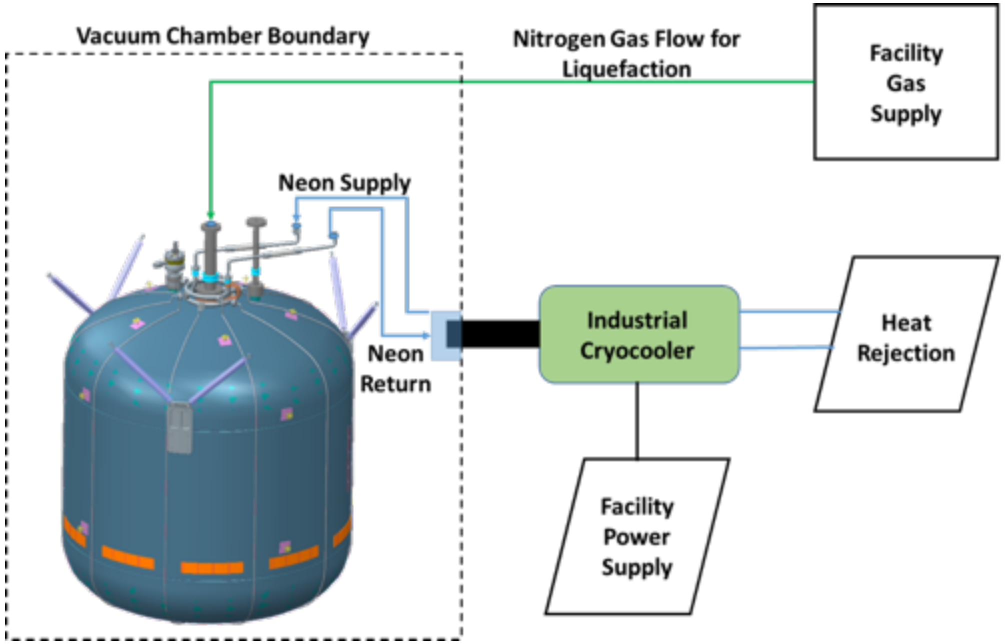
Cryogenic Fluid In-situ Liquefaction for Landers (CryoFILL) Overview

CryoFILL Project is funded by HEOMD's Advanced Exploration Systems (AES) Program

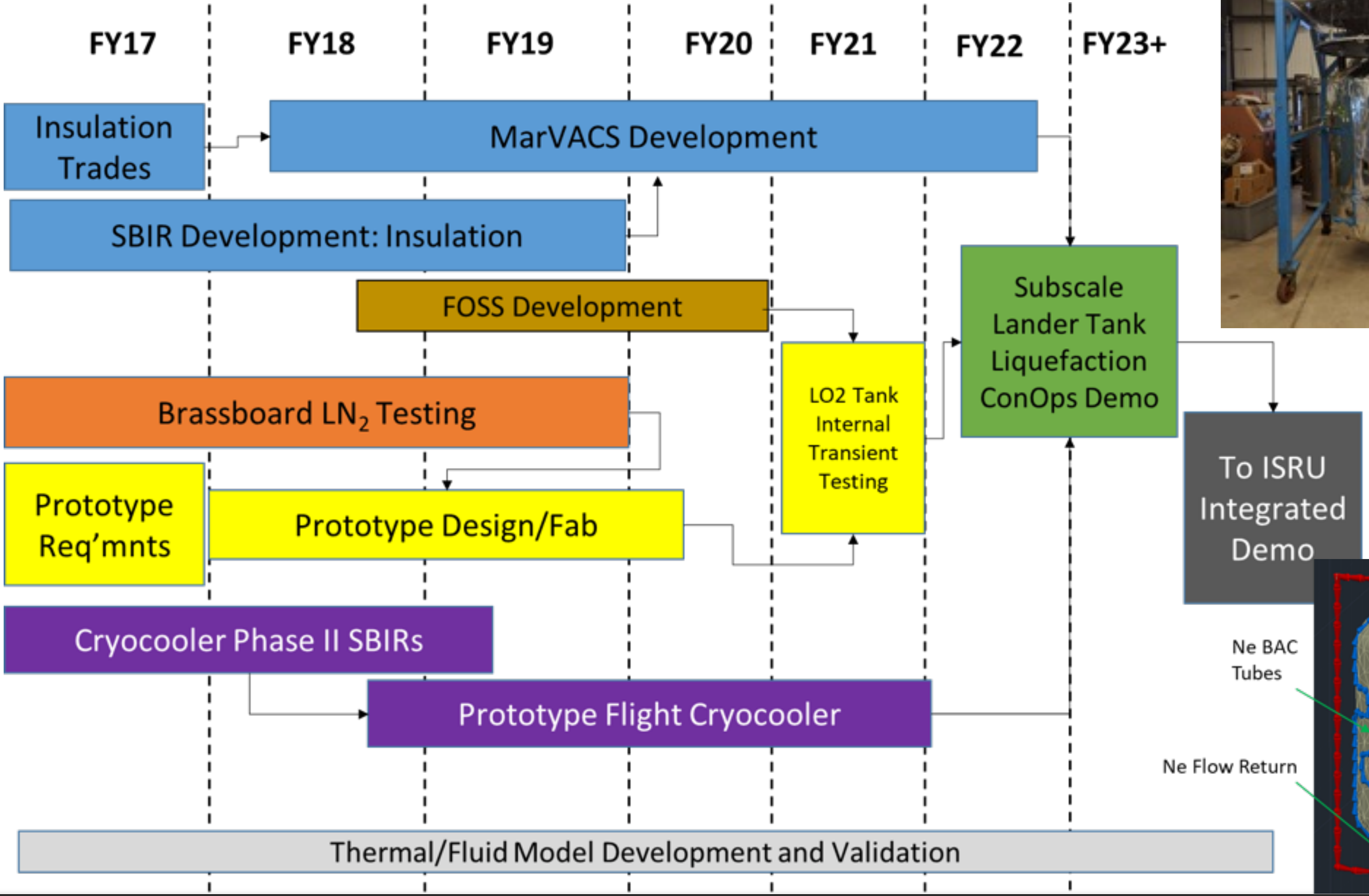
– Demonstrate liquefaction capabilities for In-Situ Resource Utilization (ISRU) at a relevant scale, in a relevant environment for use in ISRU End to End tests.

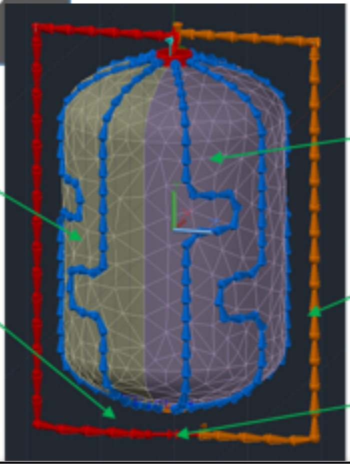
Goals

1. Deliver a prototypical ISRU Liquefaction system to the ISRU team for End to End testing.
   - The ISRU team plans to conduct a system level testing in the mid-2020's to better understand subsystem interactions and top level performance. Liquefaction is a desired part of this demonstration
2. Demonstrate liquefaction processes in a relevant environment.
   - A relevant environment test of a prototype increases the TRL to 6. It also builds confidence that the system will operate as designed during end-to-end testing.
3. Verify/validated models associated with the liquefaction system operations.
   - Validated models and modeling approaches are needed to justify scaling relations, support system design, and predict performance during non-tested transient operations.



CryoFILL Development





Evolvable Cryogenics (eCryo) Project

Develop, integrate, and validate cryogenic fluid management technologies (CFM) at a scale relevant to and meeting the mission needs for NASA missions and SLS/Stages

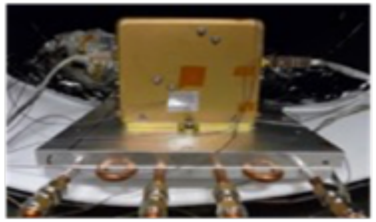
Themes:

- Technology development for extended missions focused on the needs of the SLS Exploration Upper Stage (EUS).
- Evolutionary development of new CFM technologies demonstrating near term gains which are shared with industry.
- Increase capabilities of analysis tools to perform predictive simulations for missions with in-space cryogenic systems.

Technology Demonstrations:

- Use existing Agency assets and infrastructure to mature cryogenic propellant technologies
  - Testing ranges from components to entire systems
  - Scale of testing will be limited only by facility capabilities.
- Subsystem tests and system tests need not use flight-like components

SHIIVER Test Article



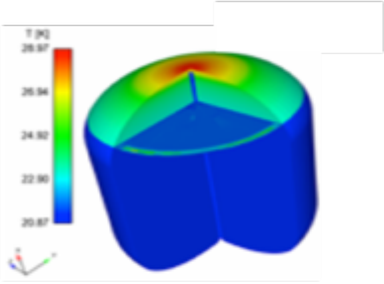
RFMG for ISS Demonstration

Team:

GRC (lead), MSFC
Industry Partners: ULA (on IVF)
International Partners: CNES, JAXA, DLR

Products:

- **COMPLETED: Structural Heat Intercept Insulation Vibration Evaluation Rig (SHIIVER):** Implement vapor cooling and multilayer insulation onto a large liquid hydrogen tank that is representative of a cryogenic stage.
- **COMPLETED: Development & Validation of Analysis Tools (DVAT):** Advancement of numerical tools to model cryogenic fluids in both settled/unsettled conditions.
- **COMPLETED: Radio Frequency Mass Gauge (RFMG):** Test and demonstrate RFMG technology on the International Space Station.
- **COMPLETED: Improved Fundamental Understanding of Super Insulation (IFUSI):** Improve the capability of designing cryogenic multilayer insulation (MLI) blankets for large cryogenic upper stages.
- **COMPLETED: Integrated Vehicle Fluids (IVF):** Evaluate the extensibility of the IVF concept for use on the SLS Exploration Upper Stage (EUS).
- **COMPLETED: Large Scale Leakage Fixture (LSLF):** Demonstrate valve seat technology for long duration storage applications.

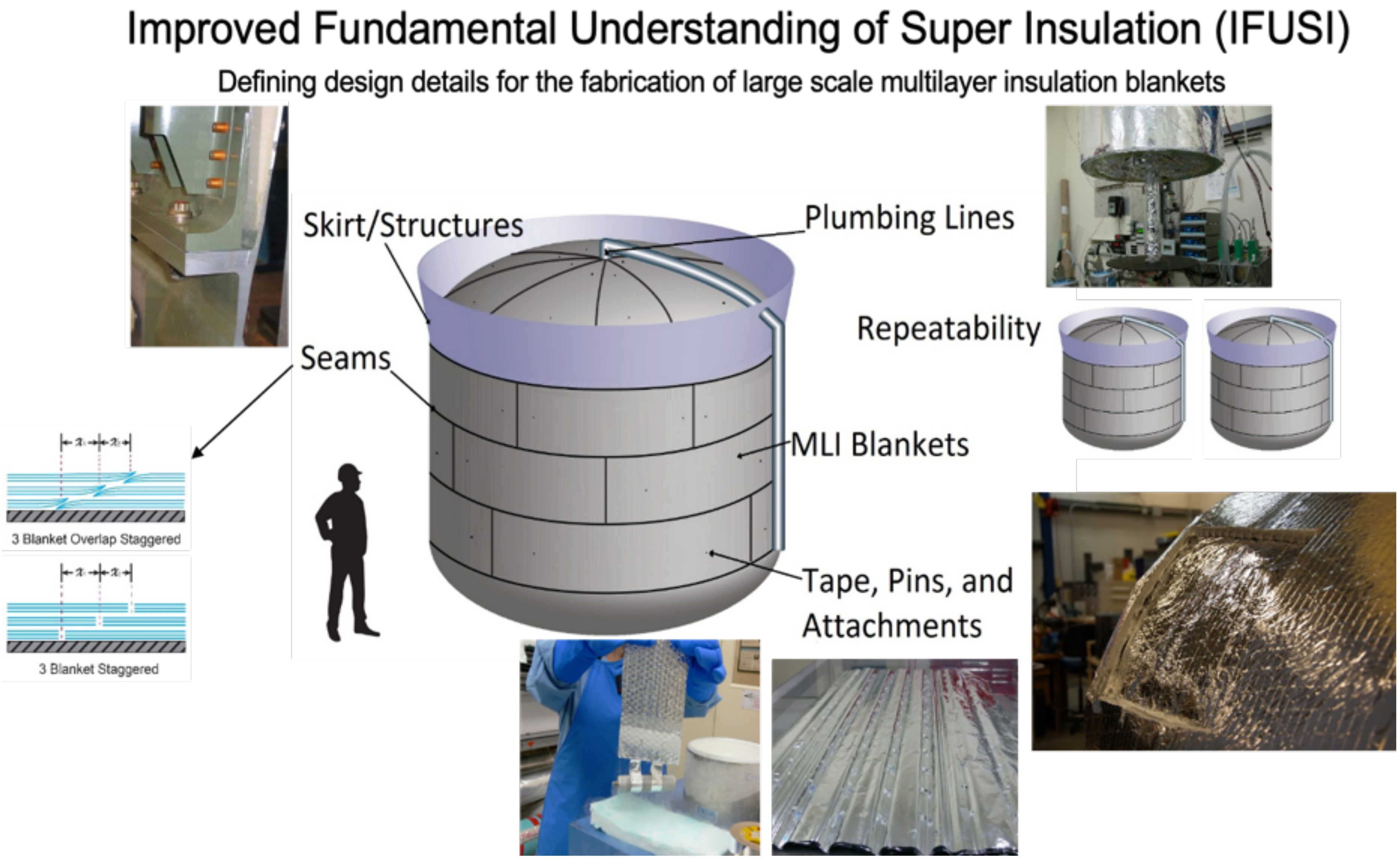


DVAT: CFM Analysis

IFUSI: MLI Testing

SLS/Stages

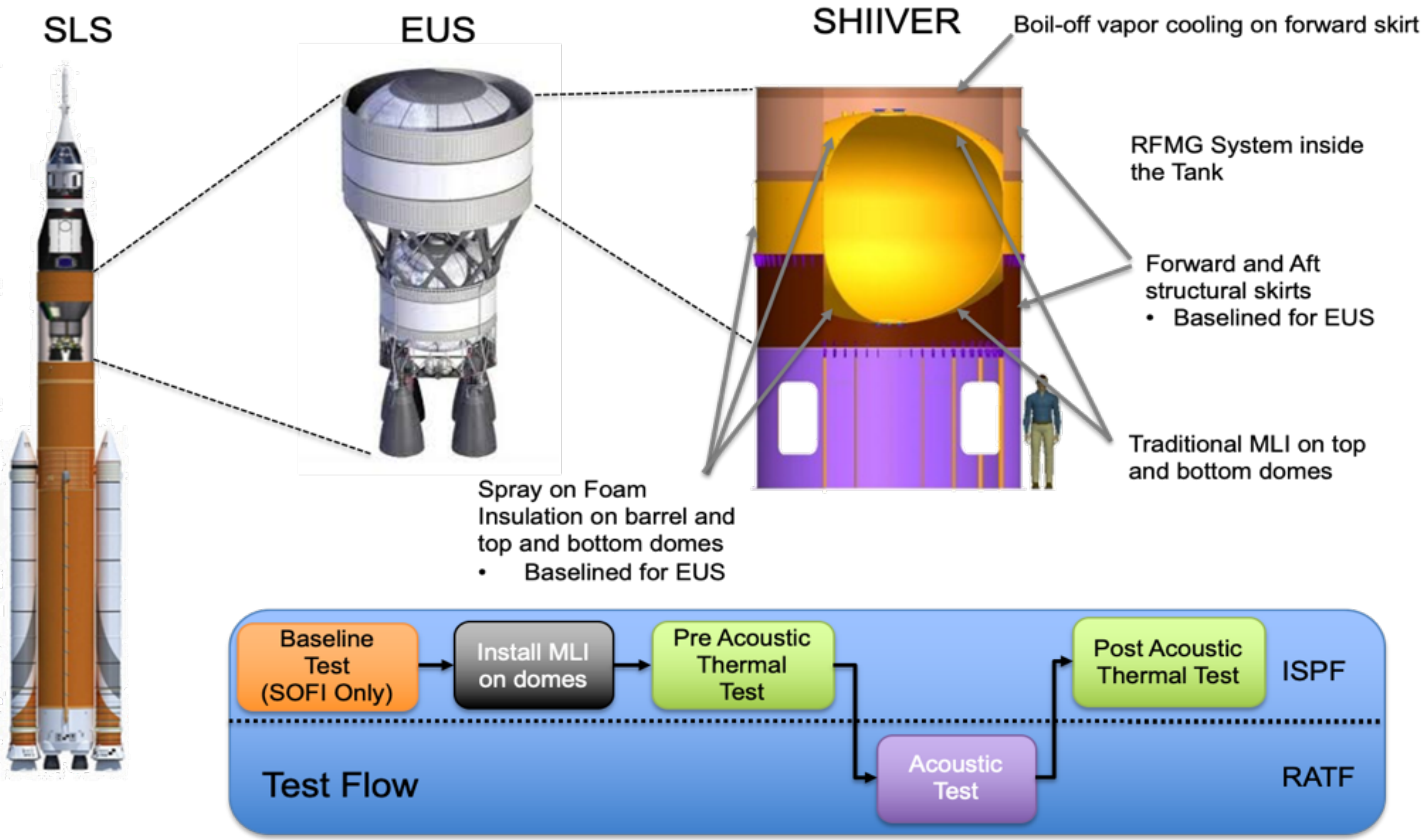
Improved Fundamental Understanding of Super Insulation (IFUSI)



Testing Completed under IFUSI:

- Hybrid MLI
- Transmissivity Testing
- MLI Repeatability
- 20K/300K MLI Seams Testing
- SHIIVER MLI Coupon Test
- Seaming Techniques on Low Temp MLI Performance
- Low Temp MLI Heat Transfer Testing

SHIIVER Testing Overview

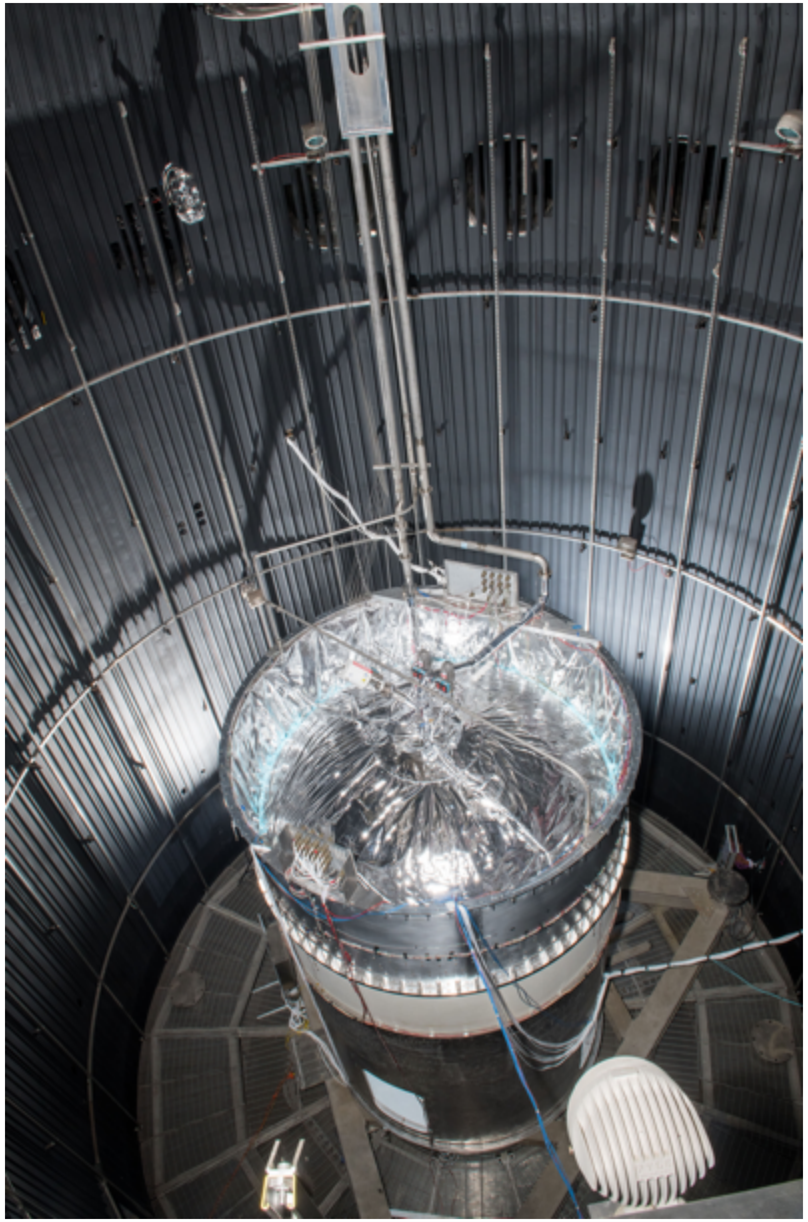


SHIIVER Testing Summary

- **SHIIVER Testing Campaign Complete:**
  - Baseline Test: August 23-30, 2019
  - Thermal Test #1 with LH2: September 23-October 1, 2019
  - Thermal Test #1 with LN2: October 3-12, 2019
  - Acoustic Test: November 4-5, 2019
  - Thermal Test 2 with LH2: January 20-26, 2020

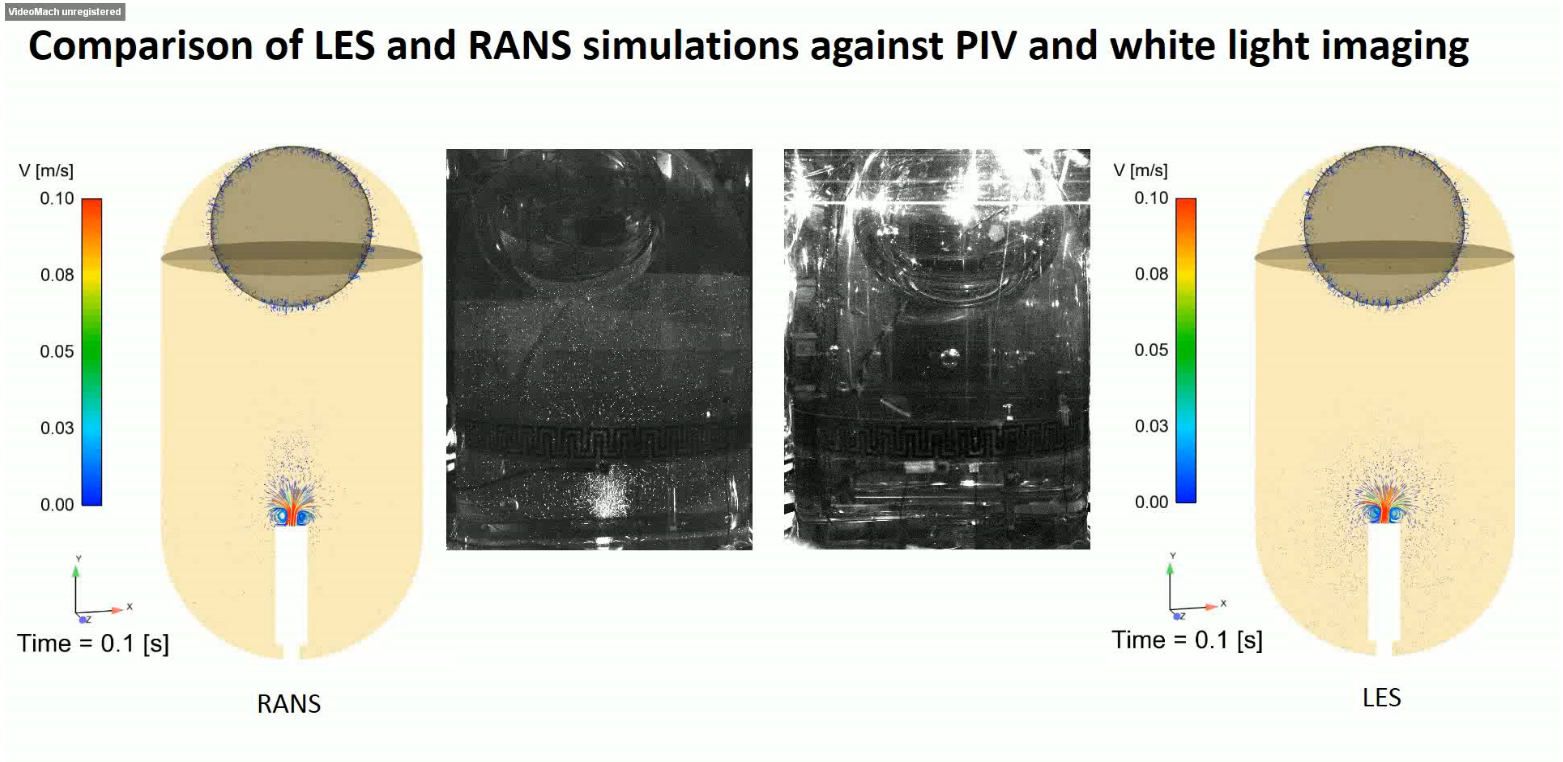
- **Testing Observations/Accomplishments:**
  - MLI consistently reduced heat load into the tank with greatest reduction at lowest fill levels.
  - Heat loads reductions were not directly proportional to boiloff reduction.
  - Vapor cooling (VC) had greatest benefit at high fill-levels near forward skirt where the cooling was applied.
  - For the Baseline and Pre-Acoustic tests, the reduction in the rate of pressure rise with VC is in excess of 50% and 33%, respectively.

High Vacuum MLI and Vapor Cooling increased TRL from 5 to 6.
SHIIVER Final Report to be published as a NASA TP.



Development and Validation of Analytical Tools

- **Completed model development and validation with CFD and Nodal Tools against microgravity and 1-G**
  - Micro-G: Zero Boiloff Tank Experiment (ZBOT), Robotic Refueling Mission 3 (RRM3), Tank Pressure Control Experiment (TPCE), JAXA H-IIA Test Flight 1, JAXA LN2 Suborbital Chilldown Experiment
  - 1-G Ground: Structural Heat Intercept, Insulation, Vibration Evaluation Rig (SHIIVER), K-Site, Multipurpose Hydrogen Testbed (MHTB), JAXA LN2 Slosh

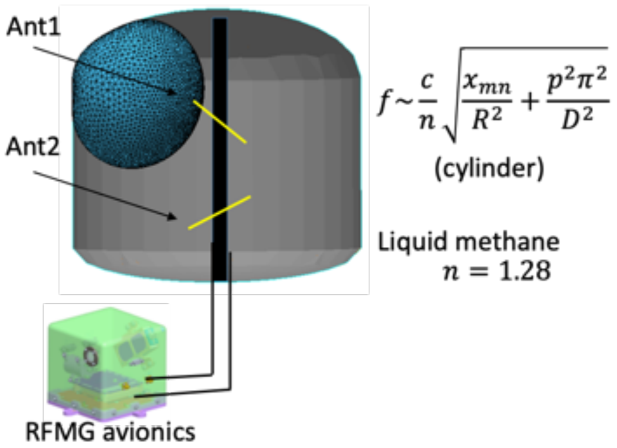


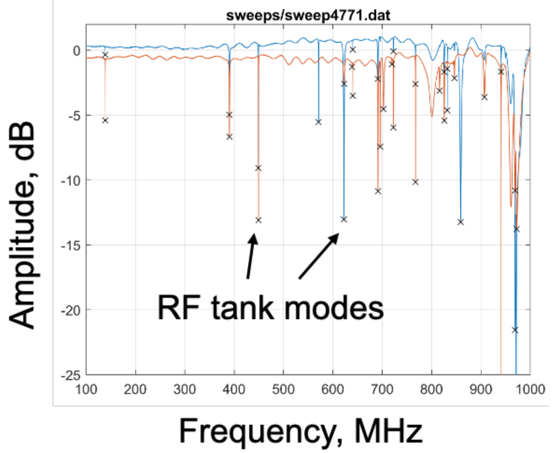
DVAT team identified roadmap and gaps for model development for future system uses.

Radio Frequency Mass Gauge

RFMG Operational Overview

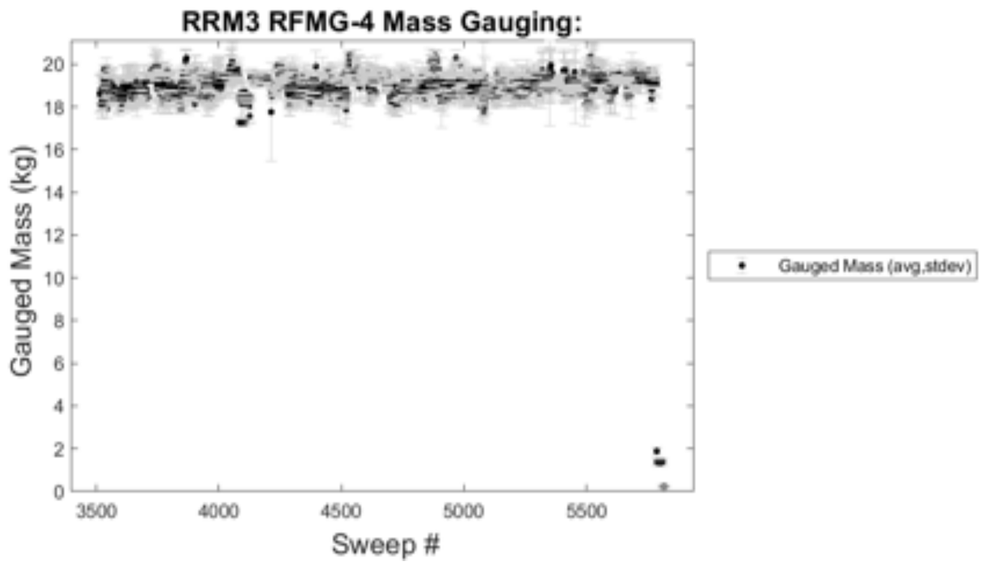
- RF antennas broadcast and receive the reflected RF signal
- Tank RF spectrum is measured and recorded by RFMG avionics
- Spectrum changes with fluid fill level and liquid configuration
- Compare spectrum with simulation database, find best match to gauge mass





RFMG was successfully demonstrated on the RRM3 mission on ISS launched in 2018

- Analysis of the data shows the RFMG produced a mean gauged mass of 19.0 kg, in agreement with the expected value, with a one-sigma error of ±2% of the full-scale mass.



RFMG System Prototype was successfully demonstrated on RRM3, increasing TRL to 7.
RFMG-RRM3 Final Report (Export Controlled) is archived (*NASA/TP-20205000671)*

Conclusions

- **NASA is embarking on an ambitious return to the Moon with an eye to Mars through the Artemis Program looking to establish sustainable exploration architectures.**
  - Future NASA architectures have baselined cryogenic propulsion systems to support lunar missions and ultimately future missions to Mars.

- **NASA has developed CFM technologies and Flight Experiment Concepts since the 1960s.**
  - Recent investments primarily focused on ground development and small-scale microgravity fluid experiments.
  - CryoFILL Project is demonstrating end-to-end Brassboard and Prototype Liquefaction Systems for ISRU.
  - eCryo Project matured high vacuum MLI and vapor cooling systems to TRL 6 for large-scale tanks, developed and validated CFM modeling capabilities for 1-g and μ-g, and demonstrated RFMG Prototype on ISS (TRL 7).

- **NASA created a CFM Technology Roadmap identifying the critical gaps requiring further development to reach a TRL of 6 prior to infusion to flight applications.**
  - STMD established the Strategic Architecture Roundtable (STAR) to align and prioritize technology investments needed across multiple architecture in NASA, US Industry, and Other US Government Agencies based on technology infusion path.
  - STMD is planning a diversified approach to mature CFM technologies for mission infusion through Flight and Ground Demonstrations with US Industry (Tipping Point and ACO calls) and international partnerships.

Backup

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