# Cryogenic Fluid Management Technologies Enabling for the Artemis Program and Beyond

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**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 [1]. 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 active and passive storage, transfer, and gauging technologies over the last decade plus primarily focused on ground development with a few small-scale microgravity fluid experiments. Recently, NASA created a Cryogenic Fluid Management (CFM) Technology Roadmap identifying the critical gaps requiring further development to reach a technology readiness level (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, collaborating with international partners, and leveraging Public Private Partnerships (PPPs) opportunities with US industry through the Tipping Point and Announcement of Collaborative Opportunities (ACO) solicitations. Once proven, these system capabilities will enable the high performing cryogenic propellant systems needed for the Artemis Program and beyond.**

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## I. Nomenclature

| | | |
|---|---|---|
| *g* | = | gravitational force |
| *K* | = | Unit of Temperature, Kelvin |
| *W* | = | Unit of Power, Watts |

## II. Introduction

Historically NASA has been a leader in the fundamental research and development of cryogenic fluid component and system technologies. Over the last decade NASA has focused on maturing cryogenic fluid management (CFM) technologies through the Space Technology Mission Directorate (STMD) via ground test campaigns as well as microgravity experiments to help enable future science and exploration missions using cryogenic propellants.  These CFM technology investments will be crucial to opening up potential architecture elements being considered for the Artemis Program, including sustainable cryogenic Human Landing Systems (HLS), refueling elements or cryogenic depots, Space Transportation Nodes (STNs) [2], Mars Transfer Vehicles (MTV), Nuclear Thermal Propulsion (NTP) stages, cryogenic upper stages, cryogenic fluid tankers, cryogenic descent elements, and liquefaction systems for In-Situ Resource Utilization (ISRU) on both the Moon and Mars. Infusion of these technologies into industry partner programs is likely to enable new commercial opportunities as well. This paper will provide a history of NASA CFM Projects, an in-depth look at recent investments related to liquefaction for ISRU applications under the Cryogenic Fluid In-Situ Liquefaction for Landers (CryoFILL) Project, development under the Evolvable Cryogenics (eCryo) Project, an overview of NASA's CFM technology roadmap, and how CFM fits within the current STMD priorities.

## III. Recent History of Cryogenic Fluid Management Projects in NASA

NASA has been developing CFM technologies since the 1960s.  Early developments focused on upper stages such as the Centaur and the Saturn IV-B stage [3].  By the late 60s, NASA was pursing technologies in support of the Mars Nuclear Vehicle [4].  As the need for cryogenic fluids for NASA's exploration goals became clear and obvious, NASA began the process of developing different options for the demonstration of long duration storage and transfer of cryogenic propellants (generally hydrogen and oxygen).  These efforts include Aerobee sub-orbital launches in the early 1960s, included various levels of testing on the early Atlas-Centaur flights, and evolved into full orbital demonstration proposals such as Project Thermo and Hydrodynamic Experiment Research Module in Orbit (THERMO) Phase B [5].  However, as the agency vectored to the Space Shuttle and studies were investigated reusable use tanks and tankers within the payload bay [6], the demonstration concepts also changed to look at a demonstration within the payload bay, including Cryogenic On-Orbit Liquid Depot Storage, Acquisition and Transfer (COLD-SAT), Cryogenic Orbital Nitrogen Experiment (CONE), and the Cryogenic Fluid Management Experiment (CFME) [5].  A liquid hydrogen free-flying satellite demonstrator, Cryogenic On-orbit Liquid Depot-Storage And Transfer (ColdSAT) completed multiple contractor conceptual studies [7]. Following the cancellation of the last of these experiments, NASA focused on operating the Space Shuttle along with Single Stage to Orbit (SSTO) concepts such as the National Aero-Space Plane (NASP) and the X-33. The agency focused mainly on the development of large-scale ground test beds to demonstrate the next generation of technology concepts such as densified propellants [8], Variable Density Multilayer Insulation (VD-MLI), and the Multi-purpose Hydrogen Test Bed (MHTB) [9].

With the creation of the Exploration Technology Development Program to explore the technologies required for a lunar return, orbital cryogenic technologies were once again a focus, first as a part of the Propulsion and Cryogenics Advanced Development (PCAD) project, and then with the startup of the Cryogenic Fluid Management (CFM) project [10,11]. These projects naturally flowed into the Cryogenic Storage and Transfer (CRYOSTAT) and then Cryogenic Propellant Storage and Transfer (CPST) projects that were funded under the new formation of the STMD within the Technology Demonstration Program [12]. After the mission concept review/systems requirements review of CPST, the project was redirected to develop a large-scale ground demonstration and fly the Radio Frequency Mass Gauge (RFMG) under the eCryo project [13]. At the same time the Robotic Refueling Mission 3 (RRM3) attempted to perform liquid methane transfer on orbit, however, after storage on orbit for four months (similar to how liquid helium has been stored for up to 2 years on Gravity Probe-B [14]), the cryocooler electronics failed and no transfers were completed. Now once again, in partnership with US industry and other Governments, NASA is exploring several options for the demonstration of CFM capabilities on orbit.

In parallel, with NASA's return the moon, the Human Landing Systems (HLS) Program has awarded contracts to three vendors: The Blue Origin-led team (Blue Origin, Northrop Grumman, Lockheed Martin, and Draper Laboratories) using liquid oxygen and liquid hydrogen for a Transfer Element and a Descent Element, SpaceX using liquid oxygen and liquid methane, and Dynetics using liquid oxygen and liquid methane [15].

As such, NASA and US industry has set itself, once again, along the fast path of demonstrating and incorporating cryogenic propellant in long duration storage and transfer in-space operations.

## IV. Cryogenic Fluid In-Situ Liquefaction for Landers (CryoFILL)

As more focus is put on ISRU [16-18], the CFM team has begun exploring the technologies needed for cryogenic fluid liquefaction, both on the earth or on orbit (either around the earth, in Cis-Lunar, or orbiting some other body). The need for the demonstration of liquefaction as might be scaled to Lunar or Martian applications became apparent and a team set out to develop such a demonstration.

Initial architecture level studies [19, 20] drove the team towards using tube-on-tank integration methods between the cryocooler and tank for liquefaction (in general assumed to be the lander tank). This drove the team to piece together an initial "Brassboard" test system to test out different liquefaction operations, fill levels, and transient behavior using liquid nitrogen [21]. Initial results suggested that the tank used could be filled to greater than 95% full with little degradation in liquefaction rate. Different transient testing situations were considered such as 12 hour on (at 2x flow rate) -12 hour off operations that may be driven by ISRU plant transient operations and power limitations. Little difference was seen between the rates of the operations, but the pressure swings during the flow on duration, especially at high fill levels were quite extreme (greater than 90 psia at 90% full). Similarly, different operations tested included a submerged injector vs. a direct ullage injector; the submerged injector reduced pressurization rates in transient operations considerably.

For Mars operations, the soft vacuum insulation system is a major technology gap that requires closure. Studies conducted showed that at a system level lightweight vacuum jacketed solutions can save several hundred kilograms of mass for a nominal lander design [22]. NASA has continued the internal development of these systems. Quest Thermal Group has begun developing their Mars Evacuated MLI (MEMLI) system using their patented discrete spacer system. Lockheed Martin is under contract for developing an evacuated system based on their previously developed flight science dewar solutions.

A "Prototype" system is under development for testing using liquid oxygen and a custom designed system with aluminum tank and tube-on-tank cryocooler integration. For initial testing, an industrial based cryocooler system was procured to provide 200W of heat removal capability at 90*K*. Testing on operations will be similar to the Brassboard testing. A follow-on test, with possible incorporation of 150W at 90*K* flight-like cryocooler systems currently under development is under consideration, which would allow for a more integrated system testing approach. This testing hardware will eventually be available for use in an integrated, end to end ISRU test.

The results of all the testing are fed into thermodynamic models that are developed to have the full system: tank, cryocooler, fluid, and integration. The models are verified and validated to the results, and the validated models can then be used to predict performance on systems beyond the scope and scale of the testing but based on the same thermo-fluid physics [23].

## V. Evolvable Cryogenics (eCryo) Project

From April 2014 through September 2020 the eCryo Project was executed to develop, integrate, and validate CFM technologies at a scale relevant to and meeting the mission needs for future NASA missions including the Space Launch System (SLS) Block 1B Exploration Upper Stage (EUS). The eCryo Project set out to mature CFM technologies from the component level to entire systems which were managed under the following project sub-elements: Development and Validation of Analytical Tools (DVAT), RFMG, Improved Fundamental Understanding of Super Insulation (IFUSI), and the Structural Heat Intercept, Insulation, Vibration Evaluation Rig (SHIIVER). The following paragraphs summarize each of the four subprojects.

Cryogenic fluid modeling was a critical emphasis area within the eCryo Project focused on developing and validating multi-node and Computational Fluid Dynamic (CFD) tools. DVAT was set up to develop tools capable of predicting thermodynamic and fluid behavior of settled and unsettled cryogenic fluid management systems. Prior to eCryo the CFD tools had little validation against test data for unsettled conditions, and multi-node tools were not compatible with unsettled cryogenic fluids. An extensive amount of tool development and validation occurred under DVAT against both 1-*g* and microgravity experiments using multi-node and CFD software. The multi-node modeling tools included SINDA FLUINT, Thermal Desktop, and General Fluid System Simulation Program (GFSSP), while the CFD modeling tools included Flow 3D, ANSYS FLUENT, and Star CCM. Ground 1-*g* experiments used to perform tool development and validation against included: SHIIVER, MHTB, K-Site, and Liquid Hydrogen (LH2) line chilldown experiment. Microgravity experiments used to perform tool development and validation against included: Zero Boiloff Test (ZBOT) experiment on the International Space Station (ISS), Tank Pressure Control Experiment (TPCE) from Space Shuttle mission Space Transportation System (STS) 52, RRM3, Japanese Aerospace Exploration Agency (JAXA) Suborbital Chilldown experiment, JAXA H-IIA Test Flight 1. Model validation against these various ground and flight experiments provided a great improvement in code capabilities through the development of User Defined Functions (UDFs) to capture the phenomena. A technical paper is in work to capture the recent modeling progress titled, "NASA's Recent

Development and Validation of CFD and Multi-node Predictive Modeling Tools for Cryogenic Fluid Management" [24].

IFUSI consisted of testing insulation blanket samples that were representative in construction to what may be applied to tanks. The tests obtained data that can be used in designing and fabricating multilayer insulation blankets for cryogenic tanks as large as 10 meters in diameter. The data from the testing was documented and published in a manner that increased the general understanding of insulation system design, fabrication, and analysis. IFUSI consisted of testing insulation blanket samples to provide future mission designers with performance data and models for MLI for large cryogenic tanks [25]. The IFUSI team performed thermal testing on seam configurations [26], hybrid MLI configurations [27, 28], low temperature transmissivity of typical MLI components [29], epoxy testing at cryogenic temperatures [30], repeatability testing on representative insulation systems [31, 32], and performance of MLI seams between 20*K* and 293*K* [33] (see Fig. 1 below). Testing at the sub-scale level under IFUSI helped inform the large-scale system design for the SHIIVER test article [34]. Data generated during the IFUSI testing was used to inform the design of the SHIIVER insulation system. A NASA Technical Paper (TP) is in work and planned to be published in 2021 [35] on low temperature MLI testing.


**Fig 1. IFUSI performed thermal characterization testing on MLI systems, epoxies for cryogenic tanks, and assessed thermal repeatability of MLI systems.**

The RFMG is a propellant quantity gauging technique developed at NASA for the purpose of gauging cryogenic propellant tanks in unsettled (low gravity) and settled environments (see Fig. 2 below). The RFMG operates by sensing several resonant electromagnetic modes of a tank and comparing the measured tank mode frequencies to a lookup table of results from several thousand numerical simulations. The numerical simulations are performed in advance in order to predict the electromagnetic eigenmode frequencies at different propellant fill levels, liquid configurations, and temperatures. A best match between measured and simulated eigenmode frequencies is used to gauge the fluid mass inside the tank. An RFMG instrument flew on the International Space Station (ISS) and was used to gauge the mass of liquid methane in a 50 L tank as part of the RRM3 payload operations. Analysis of the RFMG data collected during the 4 month on-orbit RRM3 cryogenic payload operations showed the RFMG produced a mean gauged value with a one-sigma error of ±2 percent of the full-scale mass. Results of the RFMG performance on RRM3 were published in a final RFMG technical report, *NASA/TP-20205000671*, as an export-controlled document available on the NASA Technical Report Server (NTRS) [36].

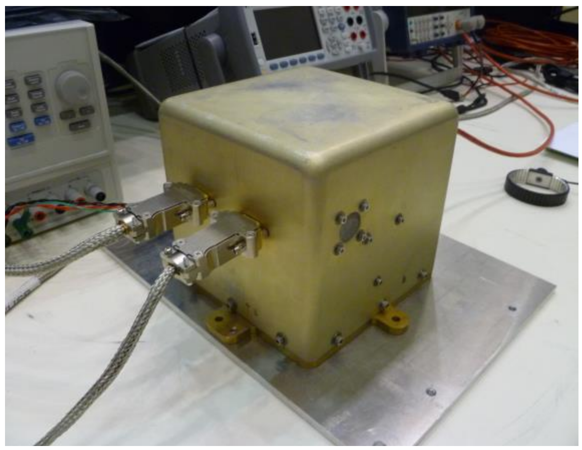

**Fig 2. The RFMG was developed to measure cryogenic propellant levels in microgravity and was successfully demonstrated on the RRM3 mission on the ISS.**

SHIIVER is a 4-meter American Society of Mechanical Engineers (ASME) code-stamped cryogenic ground test article made of 304L stainless steel with support structures (see Figure 3) including an aft and forward test skirts built as a scaled-down version of the Space Launch System's (SLS) Exploration Upper Stage (EUS). It was designed to have the ability to test with a variety of cryogenic fluids including LH2, Liquid Nitrogen (LN2), Liquid Oxygen (LOX), or Liquid Methane (LCH4). SHIIVER was built to assess potential performance benefits of incorporating advanced insulation systems and vapor-based heat intercept concepts for the SLS EUS, including adding MLI and a vapor cooling system on the forward skirt. The SHIIVER tank included a 1-inch thick layer of Spray-on Foam Insulation (SOFI), and was insulated with traditional MLI on the domes of the tank to mimic how the insulation could be infused to the SLS EUS stage. It does not include MLI on the barrel since traditional MLI would not survive the aero-acoustic loads of a launch environment, however, other novel systems could be investigated to further improve the thermal performance of the stage.

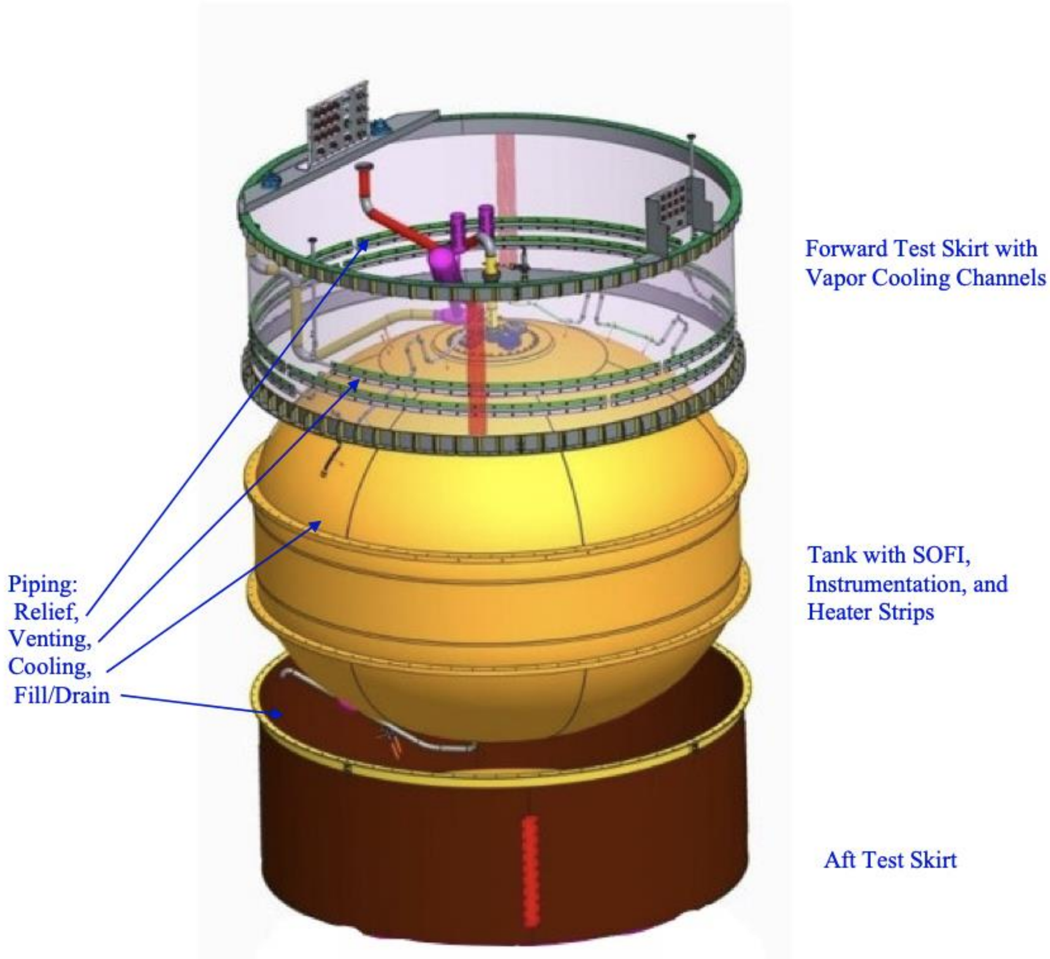


**Fig 3. SHIIVER Test Article**

The SHIIVER test campaign was performed between August 2019 through January 2020 including thermal vacuum testing at the Plum Brook Station's In-Space Propulsion (ISP) vacuum chamber and acoustic testing at Plum Brook Station's Reverberant Acoustic Test Facility (RATF) in the Space Environment's Complex (SEC). The test series started with a Baseline thermal vacuum test with only SOFI on the SHIIVER tank to record the baseline system performance using LH2 as the test fluid. For the Baseline Test the vapor cooling system was one of the control parameters that was turned on to assess its performance. Upon completion MLI was installed on the aft and forward tank domes in preparation for the Thermal Test 1 with LH2. A second Thermal Test 1 was also performed with LN2 to capture how the system performed at the LN2 temperature regime. After Thermal Test 1 was completed, the SHIIVER test article was transported into the RATF acoustic chamber where it underwent acoustic testing from 130 dB up to 144 dB. This acoustic test was performed to assess the survivability of the MLI system installed on a cryogenic tank through a flight-representative acoustic launch profile. After completing the acoustic test, the SHIIVER test article was transported back to the ISP facility to perform a post-acoustic thermal vacuum test of the system.

Results from the post-acoustic Thermal Test 2 show that no MLI performance degradation occurred after exposure to the acoustic loading associated with launch. The SHIIVER test campaign showed great benefit of using thick-layer MLI blankets paired with vapor cooling system. In general, the SHIIVER test showed that vapor cooling had a larger benefit at higher fill levels, where the heat load from the forward skirt enters the liquid in the tank via the flange. When the liquid level is below the flange, there is less benefit from vapor cooling. The benefit of vapor cooling on self-pressurization is very clear and equally important. For the Baseline and Pre-Acoustic tests, the reduction in the rate of pressure rise with vapor cooling is in excess of 50% and 33%, respectively. Complete results of the SHIIVER test campaign will be published in a final SHIIVER technical report as a NASA TP available on the NTRS [37].

## VI. Cryogenic Fluid Management Technology Roadmaps

NASA is focusing heavily on implementing reusable cryogenic systems to enable the agency's planned long duration missions. Cryogenic systems trade favorably over storable options as they offer higher propulsive performance and have the potential to make use of in-situ produced propellant on planetary surfaces. However, environmental heat loads introduce a significant challenge when considering cryogens for extended mission durations. When absorbing the external heat loads, cryogens increase in energy state causing propellant tank pressurization, which is generally mitigated by venting the tank, leading to propellant loss (boil-off). With the focus now on extended lunar surface missions, then eventually on to Mars, the required storage time for cryogens can be from sixty days on up to five years. Reusable systems require on-orbit refueling via propellant tankers or depots. Challenges arise with the acquisition of liquid and mass gauging in a micro-*g* environment due to the unsettled state of the cryogen. Considering the State-of-the-Art (SOA) for cryogen storage is fourteen hours and the challenges associated with refueling, near-term investments in advancing CFM technologies are necessary to enable NASA's planned missions.

NASA's STMD requested a strategic roadmap to layout the development path for CFM technologies. This roadmap will enable decision makers to identify the current state of the technologies, existing development efforts, and technology gaps.

A multi-center team of CFM experts across the agency assembled to develop a plan [38]. The team compiled a list of twenty-seven applicable technologies, all at various states of maturity. These are not all the possible technologies that could be used but represent a large majority of what NASA has investigated recently. Technologies evaluated and characterized were based on gravity dependence, fluid specificity, their respective Technology Readiness Levels (TRL) and are summarized in Table 1. Other items considered were risk associated with not developing the technology, sensitivity to scaling, and the path required to mature the technology to TRL 6 which is required for mission infusion at the Preliminary Design Review (PDR) per NASA Procedural Requirements (NPR) document 7120.5.

Technologies that are not considered gravity dependent to mature to TRL 6 can be advanced via ground testing, while gravity dependent technologies require a flight demonstration. Some technologies are fluid dependent and must be developed and demonstrated for a specific fluid. Others have no fluid specificity and are "cross cutting". Technologies at TRL 5 or greater are at a level of maturity where they can be demonstrated on a large-scale ground test or flight demonstration. Lower maturity level technologies (TRL 4 or less) require further technology development.

**Table 1. Twenty-Seven CFM Technologies Evaluated for the CFM Roadmap**

| 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 | Can achieve TRL 6 through ground testing. |
| High Vacuum Multilayer Insulation | 6 | 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 | 5 | No | Ground Test | Fluid Specific | |
| Composite Tanks | 6 | No | Ground Test | Fluid Specific | |
| Helium Pressurization of an Unsettled Tank | 5* | Yes | Flight Demo | Cross Cutting | Flight Demo required to achieve TRL 6. |
| MPS Line Chilldown | 5 | Yes | Flight Demo | Cross Cutting | |
| Pump Based Mixing | 5 | Yes | Flight Demo | Cross Cutting | |
| Termodynamic Vent System | 5 | Yes | Flight Demo | Cross Cutting | |
| Tube-On-Tank BAC | 5 | Yes | Flight Demo | Cross Cutting | |
| Unsettled Liquid Mass Gauging | 7 | Yes | Flight Demo | Cross Cutting | |
| Liquid Acquisition Devices | 5 | Yes | Flight Demo | Fluid Specific | |
| Advanced External Insulation | 3 | No | Ground Test | Can Be Both | Technology "Long Poles" Development is needed. |
| 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 | 4 | No | Ground Test | Cross Cutting | |
| Structural Heat Load Reduction | 3 | No | Ground Test | Cross Cutting | |
| Flowmeters | 4 | 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 | 3 | 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 | |
| Propellant Densification | 4 | No | Ground Test | Fluid Specific | |
| Autogenous Pressurization (non-traditional) in Micro-g | 4* | Yes | Flight Demo | Fluid Specific | |

While modeling is not specifically called out in the list of technologies, the modeling of the solutions to filling the technology gaps are critical. Validating different CFD and nodal tools with microgravity data is necessary to being able to routinely design in-space cryogenic systems, especially with the fluid dynamics and heat transfer being tightly coupled as in two phase cryogenic systems.

The CFM team evaluated architectures identified by the Mars Study Capabilities Team and by NASA's Artemis HLS Program. Architectures included the Nuclear Thermal Propulsion In-Space Stage, Propellant Depots, Tankers, Transfer Vehicles (or Tugs), and both lunar and Martian Landers and Ascent Vehicles. Some elements with short duration storage times can complete their mission with passive storage technologies only, while other long duration missions require a carefully designed suite of passive storage technologies coupled with active cooling systems (i.e. cryocoolers).

Each of the aforementioned architectural concepts were evaluated by the CFM team to determine the technologies believed necessary for mission closure. The current TRL of each of the technologies, path to TRL 6, and development efforts with the respective funding source were identified. Efforts planned but unfunded were identified as "technology gaps" enabling decision makers to determine where investments should be made.

Lower TRL technologies (TRL 4 or less) are considered "long poles" as further development is needed before they can be designed into a large-scale ground or flight demonstration. Currently, there are "long pole" development efforts funded through Small Business Innovation Research (SBIRs), Announcement of Collaborative Opportunities (ACO), STMD's Game Changing Development (GCD) Program, and Human Exploration and Operations Mission

Directorate's (HEOMD) Advanced Exploration Systems (AES) Program. The Cryo Fluid Technologies (CFT) portfolio is another GCD project focused on maturing 20*K* and 90*K* cryocooler technologies, developing cryogenic thermal coatings, and investigating cryogenic fluid transfer and tank chilldown techniques on the Reduced Gravity Cryogenic Transfer (RGCT) experiment via a parabolic flight opportunity. The latest progress of the CFT portfolio will be presented at the 2020 ASCEND conference titled "Enabling Extended Utilization of Cryogens in Space: Plans and Status of the Cryo Fluid Technologies Project under NASA's Game Changing Development Program" [39].

Among all of the architectures evaluated by the CFM teams, the most common "long pole" need was the High Efficiency, High Capacity 90*K* Cryocoolers. All architectures require liquid oxygen with the sole exception being NTP. However, NTP has baselined in their concept two-stage active cooling which utilizes a 90*K* cryocooler integrated with a Broad Area Cooling (BAC) Shield to intercept heat, and a 20*K* cryocooler integrated with BAC mounted directly to the propellant tank's exterior surface. There are currently two development paths going forward for the development of a 90*K* cryocoolers while only one for 20*K* cryocoolers.

The aforementioned CFM technology development roadmap [38] was presented to NASA STMD in July 2017. It has since brought to the forefront the urgency for advancing CFM technologies and the need for a flight demonstration. With NASA's previous focus being on the Crew to Mars Surface Mission and now lunar surface missions, and both looking to make use of in-situ produced propellant, the agency is now making significant investments toward CFM technology development. Through the HLS Program, US industry partners all proposed reusable cryogenic architectures to enable a 2024 lunar surface mission and all carry CFM as enabling technologies. In FY2021, the agency plans to award contract to one (or more) private companies to collaborate with NASA in building and flying a CFM flight demonstration advancing many technologies to TRL 6/7.

## VII. Space Technology Mission Directorate CFM Priorities

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. CFM is one of many capabilities that are being evaluated. As the STAR team studies their technology gaps across all space capabilities, they are reaching out to all segments of NASA (and beyond) into academia, industry and other government agencies to share their architectures and gaps that need to be closed in order to enable these proposed architectures. Once the gaps are identified and prioritized, then future investment will be guided by the prioritization of closing the technology gaps. More explicitly, the purpose of STAR is to accomplish the following:

1. Disseminate architecture information across NASA's mission directorate staff [STMD, HEOMD, Science Mission Directorate (SMD)], Program Executives, Program Technologists, System Capability Leadership Teams (SCLTs), supporting Center Representatives, Center Chief Technologists, and others to ensure the community is knowledgeable on the latest stakeholder architectures
2. Create and maintain Strategic Technology Plans (STPs) to drive investments moving forward.

- STPs must address gaps across all stakeholder architectures and recommend a comprehensive plan for transformative new technologies.
- STPs will directly inform the technology funding process.
- Prioritize and recommend investments
- Evaluate technology progress against STPs and recommend forward path

3. Provide open communication between stakeholders, STMD Headquarters (Level 1) and Programs (Level 2), Centers, Academia, Industry etc.

The STAR team meets on a regular basis. Representatives from HEOMD, SMD, US industry, and the US Department of Defense (DoD) are invited to discuss their respective architectures and the technology needs of these architectures with the STAR team. 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, shown in the Figure 4 below, 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.

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

**Fig. 4. STMD Thrust Areas**

CFM is a critical technology investment area within the STMD, with a prioritized emphasis on maturing long-duration CFM storage and transfer systems for microgravity environments through flight demonstrations, advancing integrated active and passive cooling system capabilities, and developing individual components and technologies for architectural elements in the Artemis Program. STMD is looking at a multitude of options to address these technology and capability gaps, including public-private partnerships through Tipping Point and ACO awards [40], NASA-led and international partnerships on flight system demonstrations, advanced cryocooler development for $20K$ and $90K$ systems, component and sub-system development, and ground test campaigns to mature systems for mission infusion. Flight demonstrations may include partnerships with US industry on microgravity flights, CFM free-flyer experiments, ISS CFM external platform experiments, as well as sub-orbital and parabolic flights experiments.

## VIII. Conclusion

Developing and demonstrating in-space long-duration cryogenic fluid storage and transfer system capabilities is a critical step to enabling cryogenic propulsion systems for the Artemis Program and beyond. Once available, these technologies could greatly enhance system performance for several key architecture elements utilizing cryogenic propellants including: Human Landing System cryogenic landers, cryogenic refueling depots, Nuclear Thermal Propulsion (NTP) stages, Mars Transfer Vehicles, etc. Over the last 60 plus years NASA has matured CFM technologies through ground test programs and through in-space flight demonstration projects and is now looking to further invest in CFM capabilities to open up high-performing system architectures using cryogenic propulsion systems.

The CryoFILL Project has made great progress in maturing liquefaction technologies for ISRU that will be valuable for both Lunar and Mars surface applications. The CryoFILL Project built up a "Brassboard" test system to test out different liquefaction operations, fill levels, and transient behavior using liquid nitrogen. Initial results suggested that the tank used could be filled to greater than 95% full with little degradation in the liquefaction rate. A "Prototype" system is under development for testing using liquid oxygen and a custom designed system with aluminum tank and tube-on-tank cryocooler integration. A follow-on test, with possible incorporation of the 150W at $90K$ flight-like cryocooler systems currently under development is under consideration, which would allow for a more integrated system testing approach.

Under the eCryo Project the team successfully completed the SHIIVER test campaign at NASA Glenn Research Center's Plum Brook Station that included a series of thermal vacuum and acoustic tests using the 4-meter SHIIVER test article with both LH2 and LN2. A series of sub-scale and component tests of insulation techniques, attachment methods, and epoxy use at cryogenic temperatures helped inform the SHIIVER test article design which will be applicable for other large-scale cryogenic tank systems. eCryo successfully demonstrated an RFMG system on the Robotic Refueling Mission 3 flown on the ISS and showed the ability to scale up the system for large tank applications through the SHIIVER test campaign. The eCryo Project focused on developing CFD and nodal modeling tools, and validated those codes against ground and flight experiments, greatly enhancing the team's ability to match the models to the observed phenomena. This will continue to be an important area to build on these capabilities to be able to accurately predict the cryogenic fluid behavior for in-space cryogenic tank applications.

To better understand the strategic technology gaps NASA created a CFM roadmap to identify key technologies needing further development and investment to be ready for infusion into in-space cryogenic propulsion systems. The CFM roadmaps was developed to capture the current technology TRL state, which technologies are gravity depending requiring flight demonstrations before mission infusion (to reach TRL 6), and whether they are fluid dependent.

The STMD formed the STAR team to identify and coordinate technology investment needs across NASA's exploration and science mission architectures, as well as understanding the broader need across the US Government and industry. Once the gaps are identified and prioritized, then future investment will be guided by the prioritization of closing the technology gaps. CFM has been identified as one of the key capability emphasis areas by the STAR team, since it has a broad applicability for enabling high-performance propulsion systems in support of the Artemis Program. STMD is looking at a multi-pronged approach to mature these CFM components and systems through partnerships with US industry via Tipping Point and ACO awards, free flyer CFM flight demonstrations, ISS experiments, sub-orbital and parabolic flight opportunities, as well as ground system and component test series. This provides diverse opportunities to buy down risks and strategically develop the in-space CFM system capabilities needed for the Artemis Program and beyond.

## Appendix A: Acronyms

ACO - Announcement for Collaborative Opportunities
AES – Advanced Exploration Systems
BAC – Broad Area Cooling
CFM – Cryogenic Fluid Management
CFME - Cryogenic Fluid Management Experiment
CFT – Cryo Fluid Technologies
COLDSAT - Cryogenic On-Orbit Liquid Depot Storage, Acquisition and Transfer
CONE - Cryogenic Orbital Nitrogen Experiment
CPST – Cryogenic Propellant Storage & Transfer
CryoFILL - Cryogenic Fluid In-Situ Liquefaction for Landers
CRYOSTAT - Cryogenic Storage and Transfer
DoD – Department of Defense
DVAT – Development and Validation of Analytical Tools
EUS – Exploration Upper Stage
GCD – Game Changing Development
GFSSP - General Fluid System Simulation Program
HEOMD – Human Exploration and Operations Mission Directorate
IFUSI – Improved Understanding of Super Insulation
ISP - In-Space Propulsion
ISRU - In-Situ Resource Utilization
ISS – International Space Station
JAXA - Japanese Aerospace Exploration Agency
LCH4 – Liquid Methane
LH2 – Liquid Hydrogen
LN2 – Liquid Nitrogen
LOX – Liquid Oxygen
MEMLI - Mars Evacuated MLI
MHTB - Multi-purpose Hydrogen Test Bed
MTV – Mars Transfer Vehicle

NASP - National Aero-Space Plane
NTP – Nuclear Thermal Propulsion
NTRS - NASA Technical Report Server
PCAD - Propulsion and Cryogenics Advanced Development
PDR - Preliminary Design Review
PPP – Public Private Partnerships
RATF – Reverberant Acoustic Test Facility
RFMG – Radio Frequency Mass Gauge
RGCT – Reduced Gravity Cryogenic Transfer
RRM3 – Robotic Refueling Mission 3
SBIR - Small Business Innovation Research
SCLT – System Capability Leadership Team
SEC - Space Environment's Complex
SHIIVER – Structural Heat Intercept, Insulation, Vibration Evaluation Rig
SLS – Space Launch System
SMD – Science Mission Directorate
SOA - State of the Art
SOFI - Spray-on Foam Insulation
SSTO – Single Stage To Orbit
STAR - Strategic Technology Architecture Roundtable
STMD – Space Technology Mission Directorate
STN – Space Transportation Node
STS – Space Transportation System
TDM – Technology Demonstration Mission
THERMO - Thermo and Hydrodynamic Experiment Research Module in Orbit
TRL – Technology Readiness Level
TP – Technical Paper
TPCE - Tank Pressure Control Experiment
VD-MLI - Variable Density MLI
ZBOT – Zero Boiloff Tank

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