NASA MARSHALL SPACE FLIGHT CENTER IN-SPACE CRYOGENIC PROPULSION CAPABILITIES AND APPLICATIONS TO HUMAN EXPLORATION:

SPACE PROPULSION 2024
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Thomas M. Brown (1), Michel Fazah (2), Michael Allison (3), Hunter Williams (4)

(1) NASA Marshall Space Flight Center, Huntsville, AL, U.S.A., Thomas.M.Brown@NASA.GOV
(2) NASA Marshall Space Flight Center, Huntsville, AL, U.S.A., Mike.Fazah@NASA.GOV
(3) NASA Marshall Space Flight Center, Huntsville, AL, U.S.A., Michael.A.Allison@NASA.GOV
(4) NASA Marshall Space Flight Center, Huntsville, AL, U.S.A., Hunter.Williams@NASA.GOV

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ABSTRACT:
The current focus on lunar exploration and future human missions to Mars is driving in-space propulsion system requirements toward higher performance cryogenic systems with long-duration storage and operational capabilities. Not only do these systems offer higher performance than storable propellant options, but they also enable the potential for in-situ propellant production. Future Mars transit systems are envisioned to utilize either high-thrust nuclear thermal propulsion (with liquid hydrogen propellant), or hybrid systems with both cryogenic chemical systems (likely LOX/CH_4) for high acceleration manoeuvres and nuclear electric systems for long duration high Isp manoeuvres. Exploration architectures based on either of these options require the use of high-performance cryogenic propellants with long-duration storage capabilities for both in-space transportation as well as planetary descent and ascent functions. Current efforts focusing on lunar exploration also rely on cryogenic propellants (either LOX/LCH_4 or LOX/LH_2) for lunar transit and descent/ascent transportation functions.

In-space cryogenic propulsion systems pose numerous technology challenges with respect to long-duration propellant storage and usage, including advanced insulation, tank stratification and pressure management, cryogenic refrigeration to reduce propellant loss through boil off, low leakage cryogenic valves, low temperature liquid acquisition, and cryogenic propellant transfer. NASA has invested in technology development efforts, demonstrating individual technologies and systems-level operations. NASA Marshal Space Flight Center has also invested in multiple test facilities and modular test rigs that allow ground demonstration of numerous integrated technologies and systems concepts of operations. Additional investments have been made to mature analytical capabilities and design tools. These capabilities (both test/demonstration & engineering design/analysis) are available to support both internal efforts and industrial partners in the development of exploration and science mission systems.

With this increased interest, it is critical to understand the current state of in-space cryogenic propulsion technology, determine risks to its successful application to human exploration, and prepare the engineering, test, and evaluation capabilities to support the ambitious plans for future systems. This paper provides a survey of recent developments in in-space cryogenic propulsion and cryogenic propellant management technologies, as well as facilities and engineering/analytical capabilities ready to support current and future exploration efforts.

1. INTRODUCTION

1.1. NASA In-Space Transportation Direction

Human exploration space transportation systems currently under development, and future concepts rely on cryogenic propellants to improve performance and enable the possibility for in-situ resource utilization. The current NASA Human Landing Systems (HLS) program has chosen SpaceX and Blue Origin as providers of lunar landing systems [1]. Both systems utilize cryogenically stored propellants (either liquid methane or liquid hydrogen fuels with liquid oxygen oxidizer).

Figure 1 is an artist conception of the SpaceX Lunar Lander element which utilizes liquid methane and liquid oxygen as primary propellants. Figure 2 is an artist conception of the Blue Origin lunar lander element which utilizes liquid hydrogen and liquid oxygen as primary propellants.

Figure 1. Artist's rendering of SpaceX Starship human lander design [1]

In both cases the lunar lander elements are pieces of broader transportation architectures which will (between the two providers) apply many of the passive and active in-space cryogenic fluid management technologies that have been under development years at NASA and across the aerospace community.

Figure 2. Artist's rendering of Blue Origin human lander design [1]

Future Mars transit propulsion could use chemical propulsion like current lunar architectures, or significantly higher performing nuclear thermal or nuclear electric based propulsion. These higher performance space transportation systems would also utilize cryogenic propellants. Nuclear thermal concepts typically use liquid hydrogen as a working fluid and the nuclear electric concepts being investigated utilize higher thrust chemical systems (e.g. liquid methane and liquid oxygen) for high thrust at the beginning and end of transit trajectories. NASA is currently partnering with the Defense Advanced Research Programs Administration on the Demonstration Rocket for Agile Cislunar Operations, or DRACO, program. Figure 3 depicts an artist's rendering of the DRACO spacecraft.

Figure 3. Artist's rendering of the DRACO spacecraft [2]

While DRACO will demonstrate nuclear thermal rocket operation in cis-lunar space, the technology advancement will be directly applicable to NASAs human Mars exploration goals. The flight demonstration will also mitigate challenges related to flight certification and launch approval of a new class of nuclear mission.

1.2. Cryogenic Fluid Management Portfolio Project

The NASA Cryogenic Fluid Management (CFM) Portfolio Project has been working to advance the Technology Readiness Level (TRL) of numerous CFM technologies [3]. These technologies include but are not limited to advanced Multi-Layer Insulation (MLI) systems, Thermodynamic Vent Systems (TVS), flight weight high power 90K and 20K flight design cryo-coolers for active cooling, two stage cooling methodologies, vapor cooled shields, low conductivity structural supports/struts, and others. In addition, the project is conducting three in-space flight demonstrations conducted by SpaceX, Lockheed Martin, and Eta Space. The engineering capabilities outlined in this paper as well as those at the NASA Glenn Research Center have been applied in support of the CFM Portfolio Project and in several cases these capabilities have been augmented or evolved through investments from the project.

1.3. Introduction to Capabilities

The NASA Marshall Space Flight Center (MSFC) has long been known for excellence in engineering development and operations of cryogenic propulsion systems. While MSFC is most known for its previous experience related to Earth to orbit, launch system propulsion, in-space cryogenic technologies and their application to high performance long duration space transportation systems has also been an area of interest for many years [4]. MSFC cryogenic propulsion capabilities are now being applied to human and robotic space transportation systems for Lunar and Mars exploration.

Propulsion engineering capabilities at the MSFC are made up of three general categories. The first is the corporate knowledge of the engineers and Subject Matter Experts (SMEs) who have conducted numerous broad engineering development and technology efforts over the years. These people and the knowledge they possess is the core of the engineering capabilities. The second category is analytical capabilities. These analytical approaches, tools, and numerical models provide the ability to model or simulate component/system-performance and evaluate the impact of individual technologies on overall system performance. The third category is hardware related demonstration test and evaluation capabilities. This third category is made up of modular rigs, laboratories, and test areas/stands. The philosophy is to use laboratories and rigs to evaluate and demonstrate component level designs/technologies. Modular rigs can be easily transported between labs and more capable test areas/stands for full-scale testing and subsystem level demonstrations. Finally, multiple rigs and demonstration capabilities may be combined to perform full system demonstrations, and demonstrations of full Concepts of Operation (Con Ops).

2. SYSTEMS & COMPONENT MODELLING

2.1. Component and Functional Modelling

MSFC's Liquid Propulsion Systems Modelling and Simulation organization has a wide array of experience utilizing numerous tools for modelling and analysing cryogenic propulsion systems and associated components, technologies, and processes. Models can range from one-dimensional fluid lump and thermal node models for simplified analyses up to three-dimensional mesh models for more complex and detailed efforts. Tools such as Thermal Desktop (TD), as well as MSFC's in-house tools Generalized Fluid System Simulation Program (GFSSP) and TankSIM, have been used for a number of applications in both 1-g and low-g conditions, to include:

- Liquefaction processes
- Modelling of Joule-Thompson devices with spray bars or axial jets
- Line and tank chill-down analyses
- Zero boil-off
- Self-pressurization
- Mixing
- Thermodynamic vent systems (TVS)

These models and analyses have been compared and anchored to available test data. Many of these models have historically been stand-alone, but recent efforts have been made to combine these component and sub-system models into full-integrated system level models using model-based engineering tools.

2.2. Generalized Fluid Systems Simulation Program (GFSSP)

GFSSP has been developed to perform nodal analysis of Liquid Propulsion Systems [5]. GFSSP discretizes a flow system into nodes and branches. The nodes are interconnected by branches. The pressures and temperatures are computed at the nodes whereas the flowrates are computed at the branches. A pressure based finite volume formulation is used to solve mass, momentum, and energy conservation equations in conjunction with the thermodynamic equation of state to calculate pressure, flowrate, and resident mass in the node. These equations are solved simultaneously by the Newton-Raphson (N-R) iterative method. The energy equation is decoupled from the thermo-hydraulic equations by solving outside of the N-R loop, and thermodynamic properties are evaluated from computed pressure and enthalpy.

Solid nodes are added to the flow circuit when solid to fluid heat transfer is critical (i.e., conjugate heat transfer). In addition to solving the energy conservation equation for the fluid, GFSSP also solves an energy equation for the solid, and the two separate equations communicate with each other through a source term which calculates solid to fluid heat transfer.

GFSSP has a graphical user interface which uses the paradigm of 'point and click' to construct the flow circuit consisting of nodes, branches, and conductors, supply geometrical properties, and initial and boundary conditions. GFSSP uses a plotting software, WINPLOT, developed at NASA/Marshall Space Flight Center to display results of unsteady simulations.

2.3. Model Based Engineering & Model Based Systems Engineering

Multiple Model-Based Engineering (MBE) models for various Cryogenic Fluid Management (CFM) technology applications have been developed by

MSFC. The MBE models were built by utilizing a large collection of existing validated CFM models developed on a variety of modelling platforms. Mission related to HLS, Space Nuclear Propulsion, Gateway, and Mars exploration all require long-term in-space storage of cryogens, reliable methods of mitigating cryogen loss, mitigation of risk to crew and mission (by guaranteeing sufficient margins on cryogenic commodities), and assurance of safe operation for CFM systems. Specifically, NASA's recent efforts to return to the moon have led to a need to integrate legacy CFM models into an environment that enables rapid aggregate modelling of CFM systems. Recent work at NASA has addressed this by coupling these legacy CFM models, and through Python wrappers to enable models from different platforms to pass parameters to one another. Furthermore, collecting and wrapping legacy models in this manner is a promising knowledge retention method to mitigate the risk of losing organizational expertise due to older members retiring from the workforce. The future work planned for this effort includes development of: 1). MBE models for additional CFM technologies; and 2). An integrated CFM model library to simulate systems of CFM technologies, and to optimize the CFM system for mass, power, and overall cost reduction.

3. DETAILED FOUNDATIONAL MODELLING

3.1. Thermal Analysis

MSFC's Thermal Analysis organization produces detailed thermal analyses in support of in-space cryogenic propulsion. Thermal analysis of propellant management systems, liquid engine systems and components can range from detailed component modelling (e.g., reverse Turbo-Brayton cryocooler) to detailed sub-system and system modelling (e.g., lunar exploration lander, on-orbit cryogenic storage depot systems for in-space fueling, launch vehicle upper stages, etc.). The thermal engineering team supports various long duration cryogenic fluid management storage and transfer technology development activities and model validation efforts. These assessments often require conjugate thermal/fluid modelling to encompass the thermodynamics and fluid mechanics aspects in addition to heat transfer. Some of the primary thermal software tools utilized for heat transfer are Thermal Desktop and ANSYS Mechanical. To produce conjugate thermal/fluids results, GFSSP or FloCAD Thermal Desktop module are utilized for 1-D fluid integration. If higher fidelity is required, there is coordination with MSFC's Fluid Dynamics branch for mapping between tools.

IN-SPACE THERMAL ANALYSIS

For in-space cryogenic systems, thermal analysis is critical to characterizing the sources of heat load from the in-space thermal environments, including direct incident heating from solar, albedo and planetary infrared sources as well as indirect heat sources from a vehicle's interfaces to the cryogenic tanks, lines and components via the structural attachment and radiation interfaces. MSFC utilizes Thermal Desktop to simulate orbital heating radiative environments (e.g., solar heating, planetary albedo and infrared heating) and analyze thermal control coatings/finishes to determine absorbed radiative heat loads for the cryogenic tanks and components (see Figure 4).

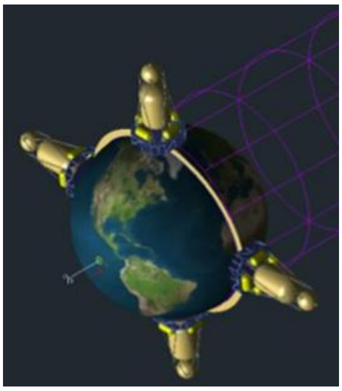

Figure 4. NTP Cryo Demo Orbital Heating

MSFC has also developed methodologies to analyze surface planetary thermal environments, such as lunar landing sites that includes specific terrain effects on solar illumination and varying infrared 'backload' as well as the interaction with the lunar regolith as a function of solar angles (see Figure 5). MSFC led the cross-agency development of the HLS thermal analysis guidebook, HLS-UG-001 [6], that documents the rigorous methodologies and assumptions developed for these complex lunar analyses. The agency's interest in the polar regions and longer duration that will cross seasons makes the thermal environment range much more extreme than the Apollo era missions.

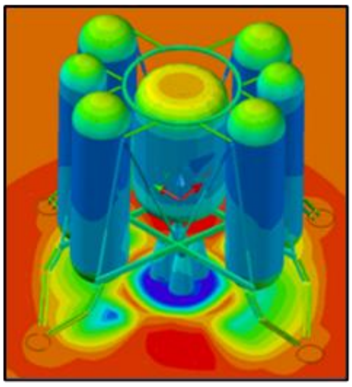

Figure 5. Example Lunar Lander Thermal Environment Analysis

In addition to the absorbed heating from incident radiant sources, the actual heat load to the cryogenic tanks and components includes representation of the insulation systems utilized to minimize the heating, such as Spray-On Foam Insulations (SOFI) and multi-layer insulation (MLI). Examples are shown from the CPST Engineering Development Unit testing at MSFC (see Figure 6) [7].

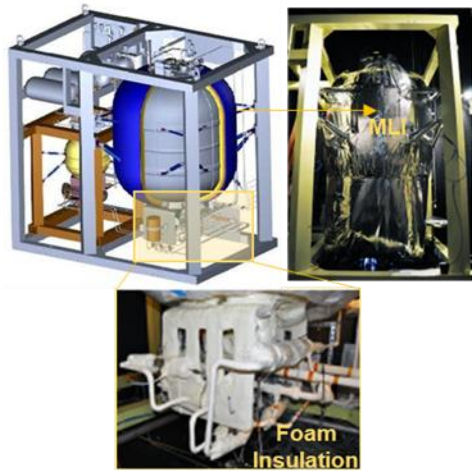

Figure 6. CPST Thermal Insulation Systems

CFM TECHNOLOGY THERMAL ANALYSIS
MSFC is supporting many CFM technology development activities and collaborative analyses for demonstration flight missions. Example CFM technology areas and demonstration missions:

- Reverse Turbo-Brayton Cycle Cryocooler
- Broad Area Cooling (BAC) Shields
- Tube-on-Tank Cooling
- Integrated MLI (IMLI) with polymer spacers
- On-orbit cryogenic transfer demonstration
- 2-Stage Cooling (see Figure 7)
- Modelling/Validation
- Large Cryogenic Demonstrator
- Tipping Point Demonstration Flights

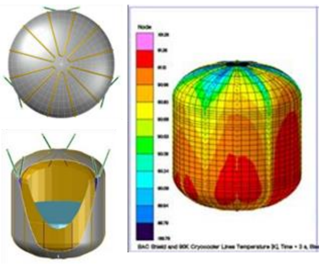

Figure 7. Two-Stage Cooling Experiment

These technology tasks have been supported with Thermal Desktop and FloCAD and GFSSP.

3.2. Fluid Dynamics Analysis

The MSFC Fluid Dynamics branch uses multiple levels of modelling fidelity to provide analyses of tank slosh dynamics and CFM operations for launch vehicles, spacecraft, and landers. Engineering models may be used for bounding CFM assessments with the assumption of homogenous thermodynamics, while initial estimates of linear regime slosh dynamics in normal or high-g conditions are constructed using analytical and semi-empirical methods. For in-space applications with reduced or zero gravity, engineering and nodal models cannot necessarily predict the fluid position in the tank or the thermal stratification and mixing of the cryogenic propellant. In this case, multiphase computational fluid dynamics (CFD) simulations are used to either directly model the problem of interest or perform detailed simulations of system components to extract data to improve engineering or nodal models. For CFM and tank dynamics simulations, the MSFC Fluid Dynamics branch uses the Loci/STREAM CFD software with a volume of fluid (VOF) model to represent the gas/liquid interface. The VOF model provides a high-fidelity representation of the interface shape, including wave breakup and formation of droplets, while also capturing heat and mass transfer due to liquid-vapor phase change.

SLOSH DYNAMICS
The large propellant masses carried on liquid fuel rockets induce loads on the vehicle both during engine operation and long-duration coasts whenever the propellant is in motion. As a result, any change in vehicle attitude is met with attitude error. MSFC supports slosh modelling and mitigation efforts for high-g mission phases including vehicle tip-over assessment at landing. Quantification of reaction control system consumable mass budgets needed to offset attitude error during coast is performed by coupling fluid dynamics analysis with vehicle control system simulation (see Figure 8). Propellant loads during docking maneuvers inform coupled vehicle attitude dynamics and coupling hardware requirements.

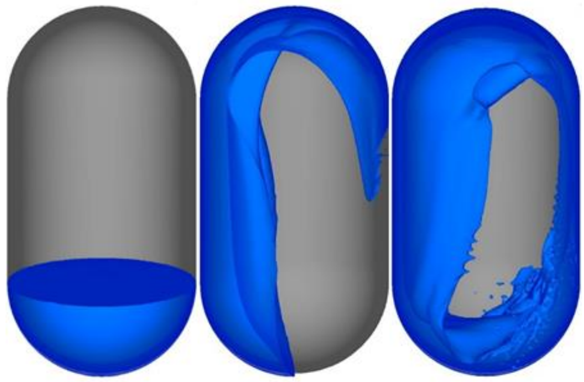

Figure 8. Propellant Unsettling Following a Slew (Time Increases Left to Right)

TANK PRESSURIZATION AND CONTROL
Conditioning cryogenic propellants is critical to maintaining propellant in a usable form for propulsion. MSFC evaluates both autogenous and non-condensable pressurization of propellant tanks to define pressurant mass budgets needed to condition propellant prior to and during engine burns. Self-pressurization of cryogens from radiant heating in low-g fluid states is analysed to quantify propellant boil-off and define tank venting

schedules. Ullage collapse assessment is performed for a wide array of manoeuvres to further define pressurant mass budgets and pressurant system requirements to keep propellant in the engine run box. (See Figure 9)

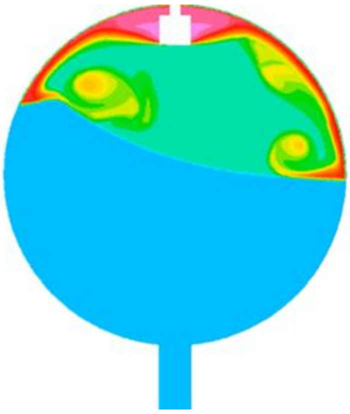

Figure 9. Hot Gas Pressurization During Slosh (Cold Cryogenic Liquid Shown in Blue)

PROPELLANT FILL AND TRANSFER
Increasing mission durations for cryogenic propulsion stages has forced spacecraft mission design to include in-space propellant transfer. A variety of transfer methods are analysed to optimize efficient propellant filling of a vehicle. Quantification of vapor ingestion onset and propellant mass residual in supply tanks is used to optimize spacecraft refuelling operations. Assessment of tank thermal conditioning, heat transfer correlations, and tank pressure transients is conducted to trade propellant injection methods and operations ensuring maximum fill levels are achieved in receiver tanks.

CONOPS DESIGN
Cryogenic propellants are sensitive to how a spacecraft manoeuvres and conditions the propellant. This dependency can have a profound impact on the order and method of conducting in-space operations. Low-g propellant dynamics are assessed to prevent liquid venting, which could freeze valves, when trying to decrease tank pressure. Propellant settling maneuver design and corresponding reaction control system mass budget quantification ensures efficient positioning of liquid propellants during in-space operations. Development of strategies to mitigate vapor in feedlines, originating from long-duration heat leaks, prior to engine firing ensures a smooth engine restart. (see Figure 10)

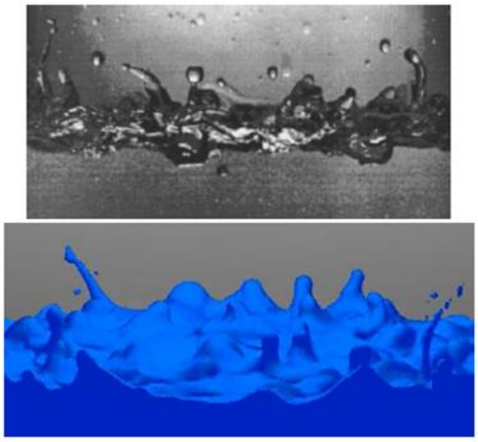

Figure 10. Propellant Surface Under Pulsed Settling (Top: Ground Test / Bottom: CFD Analysis)

4. LABORATORIES AND RIGS

4.1. Component Development Area (CDA)

The Component Development Area (CDA), in MSFC Building 4656, provides a unique propulsion system component technology advancement, hardware assessment, anomaly investigation, troubleshooting, and repair capability, primarily focused on reliability, operability, and safety of valves (see Figure 11). Rocket engine and main propulsion system valves have historically proven to be problematic and costly in vehicle development programs. To help NASA address this, the CDA was established in 2001 specifically to support propulsion fluid component technology development activities. The CDA was specifically designed to bridge the gap between engineering design/development phases and full-scale testing in MSFC's East and West Test Areas. The lab environment serves as an engineering development tool, which enables rapid, real-time hardware modification and assessment. High-risk technologies that the industrial base is unwilling or unable to investigate can be studied. Investigation and development of new valve design concepts, valve seal types and materials, valve bearing types and materials, actuator concepts, and valve manufacturing improvements, are among the primary functions of the CDA. Typically, between twenty and thirty active research and development activities are being conducted in parallel.

The CDA provides a unique combination of capabilities necessary for the efficient operation of such a technology development area. Pressurized gas flow, liquid flow, leak tests, burst tests, and electrical tests can be performed. Available fluid test media include helium, gaseous and liquid nitrogen, water, and missile grade air. Smaller quantities of hydrogen, oxygen, methane and even the newer green propellants can also be used for testing. The facility operates three bunkers, two of with are blast rated for 11 lbm equivalent TNT, making them ideal locations for pressurized testing of components. Pressures with various media up to 5,000 psi can be obtained and higher pressure up to 17,000 psig can be achieved for burst tests.

Figure 11. Cryogenic Valve Flow Testing

The CDA has several fabrication capabilities onsite including welding machines, an orbital tube welder (Figure 12), tube benders and flaring machines, saws, overhead cranes, and multiple lathes and mills. The machine shop also operates two CNC turning stations. The facility employs a dozen full-time technicians that are certified welders, electricians, and machinists. Most valve prototypes and any special test equipment required can be manufactured in-house.

Figure 12. Orbital Tube Welder

The CDA implements high-speed real-time controls and data acquisition systems that utilize National Instruments or Dewesoft Systems for data acquisition and National Instruments hardware paired with Labview software for controls. Numerous channels of data can be sampled at rates from 1 Hz to 100kHz. Control systems have demonstrated repeatable valve/thruster control to within +/- 2 msec and redline capability to detect and cut a test within 2 msec. The facility houses multiple water flow loops that have traditionally been used to characterize flow coefficient of valves and to investigate flow induced vibration of flex hoses or metal bellows. Two loops with flows up to 2,200 psig and 220 GPM are housed withing the primary highbay. Higher pressures and flows can be achieved with nearby run tanks if needed. Those run tanks are rated for either water or liquid nitrogen storage and can achieve pressure up to 5,000 psig. The CDA operates two heaters, a 520-kW electric model and a 1.5-MW propane powered unit for performance assessments of hot-gas valves and main propulsion system tank diffusers (see Figure 13). Proximity to the contractor operated MSFC Valve and Component Shop (Building 4653), and to the East and West Test Areas, provides additional capability and resources when needed.

Figure 13. Heaters for Hot-Gas Valve and Propellant Tank Diffuser Testing

The CDA vacuum chamber and ejector system can provide an initial vacuum < 2 Torr (.039 psia) and capability of sustained vacuum level < 26 Torr (0.5 psia) while firing thrusters up to 100 lbf. The ejector system consists of two stages, each fed with GN2 regulated to 500 psig and a total mass flow rate of 21 lbm/sec. The system can provide test durations up to 20 minutes. There is also an existing GN2 gas load system allowing simulated testing of thruster exhaust effects on vacuum level and run times. The vacuum chamber is a 3-ft. diameter x 16 ft. long chamber with multiple feed-through ports for propellants and purge gas. There are numerous electrical feed-though flanges for instrumentation and DC power. For video of hot-fire testing, the chamber has optical and IR compatible viewports for infrared footage of test articles. There are also existing feed systems for green propellant (compatible with LMP-103S and AF-M315), gaseous oxygen, and gaseous hydrogen/methane.

4.2. Cryogenic Fluid Management Lab

The Exploration Systems Test Facility (ESTF) located within the Propulsion Research and Development Laboratory (PRDL) at Marshall Space Flight Center (MSFC) houses unique capabilities for CFM hardware concept development and performance assessments. The facility includes a 9 ft vacuum chamber, multiple test beds, and propellant tanks allowing for quick turnaround testing of CFM technologies and hardware with liquid nitrogen (LN2). Activities in the ESTF are focused on CFM technology investigations supporting varied customers and projects in concept development, prototyping, evaluation and trades/analysis of components & systems to address various architectures, e.g., in-space propulsion, human lander systems, on-orbit propellant storage & transfer, cryocooler development.

4.3. Modular Assembly for Testing Cryogenic Hardware (MATCH)

MSFC has a variety of test stands of differing capacities and capabilities for testing cryogenic systems, and the Modular Assembly for Testing Cryogenic Hardware (MATCH) is intended to seamlessly leverage different stand operations for a single test article. MATCH is essentially an interface stand for cryogenic subsystems, which boasts flow control and metering via its three vacuum jacketed supply lines. A given test article can be installed into MATCH, have all instrumentation and power wired into its patch panels, and then be transported to one or more tests areas via a standard flatbed truck for integration into their test stand. In practice, a test article can be installed in a lab, transported to a test stand for nitrogen testing and checkouts, then be transported into the test area for a hydrogen test without ever having the test article be uninstalled. This greatly streamlines the installation process and enables time at each test stand to be better utilized. MATCH is mounted on a 4’x8’ skid and has panel interfaces for a variety of common instrumentation used in cryogenic systems. MATCH’s vacuum jacketed fluid supply lines come in three sizes, 0.5”, 1”, and 2”, to support different fluid delivery needs to test articles. MATCH will be able to support testing of liquid nitrogen, oxygen, and hydrogen. Assembly is currently ongoing, and the first test is set to be executed in mid-2024.

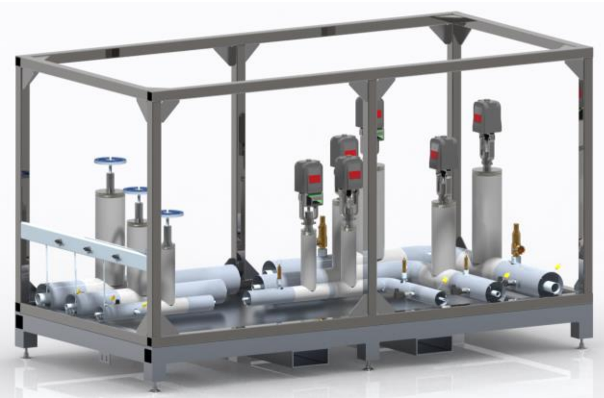

Figure 14. MATCH CAD Rendering

4.4. Integrated Reaction Control System

Integrated Reaction Control Systems (iRCS) are considered an enabling technology for future human exploration of the solar system. An iRCS uses the same fuel and oxidizer as the main propulsion system, allowing for increased performance and simplified cryogenic fluid management operations. In contrast to accumulator and gasifier designs, the recirculation loop design is less massive and can provide large, sustained flowrates to the thruster inlet.

The iRCS team at MSFC developed a ground testbed to evaluate iRCS systems utilizing a combination of pumps and pressure-regulation devices in a recirculation loop to provide a constant flow of conditioned LN2 propellant simulant to a thruster bank during operation. The test was successful in demonstrating the closed loop concept and much of the infrastructure remains intact for future system-level demos.

4.5. Cryo-Coupler Rig

NASA and its industry partners consider cryogenic couplers for in-space fluid transfer a technology gap. Heritage launch vehicle quick disconnects exist but are typically mated slowly and carefully with finely controlled procedures as part of ground processing. Additionally, design factors such as connection seal friction, weight, and cycle life set couplers apart from traditional quick disconnect designs. New designs will have to be developed to address these requirements and accommodate long-term missions requiring propellant transfer. MSFC is proactively addressing this gap by building the Cryogenic Coupler Test Apparatus, a fixture designed specifically for mate and de-mate testing of new couplers concepts. The fixture is composed of two, rail-mounted plates that can easily accommodate both halves of any type of coupler. The plate positions are controlled by large, hydraulic actuators which allow for repeated coupler mate and de-mate cycles for life-cycle testing. Load cells are mounted in series with the hydraulic actuators for evaluating seal frictional forces during mate and de-mate, a critical parameter for couplers that could drive vehicle docking mechanism design. Both radial and angular misalignments can be induced through offsetting or shimming the stationary plate during the mate process. This will allow for possible misalignments expected at the vehicle level to be intentionally induced and investigated during cycle testing on the ground. Load cells will also be able to measure structural loads these misalignments drive back into the vehicle structure. The driving actuators are hydraulically controlled, meaning mate and de-mate speed can be precisely controlled to mimic two stages coming together in space. Relative movement of the couplers is enabled by flex hoses or bellows between the test article and facility tankage. This provides the capability to cycle the couplers while chilled to cryogenic temperatures or to investigate external leakage while chilled. All controls are operated remotely and off-nominal or unexpected operations such as de-mating while pressurized can be investigated safely. In addition to cryogenic couplers, the test stand is capable of testing traditional propellant, pressurant, or electrical quick disconnects. The fixture is portable and can be relocated to any MSFC test position to accommodate testing with either ambient or cryogenic fluids.

5. TEST STANDS AND FACILITIES

The Test Laboratory at MSFC is home to multiple test facilities that possess unique testing capabilities, infrastructure, and expertise required to perform testing on various cryogenic propulsion hardware ranging from full scale structural tests to component and system level propulsion tests. The Test Laboratory is made up of a highly skilled work force that includes engineers, analysts, technicians, and trades. Each test facility provides unique capabilities with certified technicians experienced with working around hazardous high pressure and cryogenic systems. The Test Lab also provides multiple in-house fabrication capabilities which include a machine shop, pipe fabrication shop, millwright shop, and many more. The Test Laboratory possesses the resources needed to efficiently test a wide range of experimental, developmental, and flight ready hardware with minimal buildup. Multiple facilities mentioned below are working diligently to test and evaluate in-space cryogenic propulsion technologies in support of lunar exploration and future missions to Mars.

5.1. Test Facility 4527

Test Facility 4527 is a multipurpose test facility capable of testing full scale cryogenic fluid vehicles and specializes in low pressure (<120 psig) medium to large scale cryogenic component developmental testing. Test Facility 4527 possesses multiple test capabilities which include a 21-ft diameter by 45-ft tall vertical test structure for full scale vehicle testing, closed loop hydrogen cold flow testing, and internal and external component leakage testing. Test Facility 4527 is the ideal facility for testing engine subsystem components, high performance boost pumps, low leakage cryogenic valves, and full-scale cryogenic tanks (see figure 15)

The test facility has multiple propellant feed systems which a include a 120,000-gal liquid hydrogen storage sphere, a 14,000-gal run tank, and a 26,500-gal liquid nitrogen storage tank. The 14,000-gal run tank is configured for multiple propellants which include liquid hydrogen, liquid methane, and liquid nitrogen. The 120,000-gal liquid hydrogen storage sphere is used to supply the 14,000-gal run tank and can also be used to supply liquid to large full scale test articles. Liquid hydrogen can flow from the 14,000-gal run tank through the test article back to the 120,000-gal sphere recapturing much of the liquid hydrogen propellant used during testing. Liquid methane and liquid nitrogen, when used in the run tank, are discharged to one of three 8-inch burn stacks. Cross country feed systems supply multiple gases to Test Facility 4527. These include helium, hydrogen, and nitrogen all supplied at 4000 psig. Two 700 ft^3 hydrogen bottles at 4,000 psig are located at the stand. A secondary hydrogen/helium/nitrogen gas supply system can be used if required. Up to five gas trailers at 5,000 psig can be integrated into a high-pressure reduction system as needed to meet customer flow requirements. All test article piping is designed and fabricated in-house. Test article piping is integrated into 6-inch facility supply and drain lines and can be modified to meet customer interface requirements. Liquid propellant and gases available at Test Facility 4527 are summarized in Table 1.

Table 1. Test Facility 4527 Liquid and Gas Capabilities

Media	Quantity	Maximum Pressure	Maximum Flowrate
LH2	120,000-gal LH2 Sphere	60 psig	68 lb/s at 45 psig
	14,000-gal Run Tank	120 psig	108 lb/s at 100 psig
LCH4	14,000-gal Run Tank	120 psig	260 lb/s at 100 psig
LN2	26,500-gal Storage Tank	90 psig	313 lb/s at 75psig
	14,000-gal Run Tank	120 psig	368 lb/s at 100 psig
GH2	1,400 ft^3	4,000 psig	-
GN2	3-inch line	4,000 psig	-
GHe	3-inch line	4,000 psig	-

Test Facility 4527 utilizes high performance Emerson Rx3i programmable logic controllers (PLC) to execute test sequencing and command valve positions. WonderWare communicates with the PLC for HMI user interfacing. Low speed data acquisition systems utilize the Pacific Instruments (PI) 6000 data system. Up to 1024 channels can be sampled at rates from 1Hz to 100Hz. Typical hardware configuration provides channels for 256 pressure measurements, 272 thermocouples (type K and E), 160 RTD temperature measurements, and 48 voltage inputs. The high-speed data system utilizes a separate PI system with fewer channels (64 channels) but higher sampling rates (up to 100kHz).

Figure 15. Aerial view of Test Facility 4527

5.2. Test Stand 300

Test Stand 300 (TS300) is a thermal vacuum test facility used for testing CFM technologies and in-space cryogenic system demonstrations. TS300 has three active vacuum chambers which include a 20-ft vertical chamber, a 15-ft vertical chamber, and a 12-ft horizontal chamber (see figure 16). TS300 specializes in conducting hazardous test operations using liquid hydrogen and liquid methane propellants in medium to high vacuum test environments. TS300 provides multiple unique capabilities necessary to advance the development of numerous CFM technologies. Liquid propellant and gases available at Test Stand 300 are summarized in Table 2,

Table 2, Test Stand 300 Capabilities

Media	Quantity
LH2/LCH4	Offload to test articles from government owned trailers, 12,000-gals
	33,000-gal LH2 storage tank at 95 psig
LN2	20,000-gal Storage Tank at 90 psig
GH2	3-inch line at 4,000 psig
GN2	3-inch line at 4,000 psig
GHe	1.5-inch line at 4,000 psig
MGA	1.5-inch line at 3,500 psig
Industrial Water	150 psig

The 20-ft chamber located at TS300 is a 20-ft diameter by 35-ft tall vertical chamber primarily used for cryogenic fluid management developmental studies. The chamber has a removable lid to allow for installation of large test articles and a 50,000-lb test article support structure. The test volume of the chamber is 18-ft diameter by 25-ft tall. The pumping system on the 20-ft chamber consists of three 1722 mechanical pumps with blowers and two 52-inch diffusion pumps with baffles that can achieve a baseline vacuum level of <1x10^-7 Torr. The chamber has multiple capabilities which include a residual gas analyzer, a liquid nitrogen thermal shroud, a rapid pump down high pressure GN2 ejector to simulate rapid ascent launch profiles, test article thermal vent system (TVS), dual stage cryocooler (20K and 80K), and two separate zero boiloff heat load measurement systems that can be utilized on individual tanks in parallel. The 20-ft chamber also has multiple propellant feed systems into the chamber that include liquid hydrogen, liquid helium, liquid nitrogen, and liquid methane. Fuel propellants can be transferred into test articles during testing from government-owned trailers. A 20,000-gal liquid nitrogen storage tank is used to feed the thermal shroud and a 33,000-gal liquid hydrogen facility storage tank can be utilized as needed. The 20-ft chamber has a 1000 channel data system which consists of type "K" and type "E" thermocouples, pressure transducers, RTD temperature measurements, and 300 channels of silicon diodes with "wet or dry" operations.

Figure 16. 20-ft chamber – TS300

The 15-ft chamber has an operational test volume of 15-ft diameter by 15-ft vertical (see figure 17). The chamber is primarily used to support cryogenic fluid management studies performed in the 20-ft chamber and has recently been used to perform physics focused plume surface interaction studies. The 15-ft chamber is utilized as an accumulator for the 20-ft thermal vent system (TVS). The pumping system consists of two 1722 mechanical pumps and blowers and two 36-inch diffusion pumps that can achieve a baseline vacuum of 10 mTorr. The 15-ft chamber has hydrogen, helium, and nitrogen gas available at 4,000 psig and high purity air at 3500 psig. The chamber utilizes a 256-channel data acquisition system.


Figure 17. 15-ft chamber – TS300

The 12-ft chamber is the smallest chamber located at TS300. The chamber is primarily used for hazardous cryogenic component testing and high heat flux testing (see Figure 18). The chamber has multiple unique capabilities which include a rapid ascent launch profile simulator, a 450kW IR quartz lamp array (up to 20 BTU/FT-SEC), and a thin film heater control system. The chamber has a liquid hydrogen, liquid methane, liquid helium, and liquid nitrogen cryogenic control feed system. The 12-ft chamber utilizes a 512-channel data acquisition system which includes calorimeters and IR temp sensors.


Figure 18. 12-ft chamber – TS300

6. CONCLUSIONS

Future long duration high performance space transportation systems for human and robotic exploration will utilize high performance cryogenic propellants. Cryogenic propellants provide increased performance and are compatible with the use of in-situ propellant manufacturing. While the benefits are clear, these propellants also bring complexities due to challenges of log duration storage, boil-off, and general propellant management. NASA has been advancing the required CFM technologies for years and has also invested in engineering capabilities for design/development, test, evaluation and demonstration of these complex high-performance components and systems. MSFC cryogenic propulsion capabilities (focused on propellant storage, management, feed, and pressurization systems) have been developed and are currently being applied to future human and robotic exploration systems.

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