# NASA MARSHALL SPACE FLIGHT CENTER IN-SPACE CRYOGENIC PROPULSION

# CAPABILITIES AND APPLICATIONS TO HUMAN EXPLORATION

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# Introduction

- Lunar exploration and future human missions to Mars are driving in-space propulsion systems toward higher performance cryogenic propellants with long-duration storage and operational capabilities.
- These systems offer higher performance and the potential for in-situ propellant production.
- NASA Marshal Space Flight Center has 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 internal efforts and industrial partners in the development of exploration and science mission systems.

# Introduction

- The NASA Human Landing Systems (HLS) program has chosen SpaceX and Blue Origin as providers of lunar landing systems.
- Both systems utilize cryogenically stored propellants – either liquid methane or liquid hydrogen fuels with liquid oxygen oxidizer.
- In both cases lander elements are pieces of broader transportation architectures.
- HLS architectures utilize both active and passive Cryogenic Fluids Management (CFM) technologies.

*Artist's rendering of Blue Origin human lander design*

*Artist's rendering of SpaceX Starship human lander design*

# Introduction

- Future Mars Architectures concepts use liquid Hydrogen for Nuclear Thermal Systems, LOX/CH4 for Nuclear Electric/Chemical Hybrid Systems, or LOX/CH4 for all chemical approaches.
- Mars Landers may use LOX/CH4 propellants enabling potential in-situ propellant production.
- NASA has partnered with the Defense Advanced Programs Agency on the Demonstration Rocket for Agile Cislunar Operations (DRACO).
- DRACO will demonstrate nuclear thermal rocket operation in cis-lunar space, and the technology advancement will be directly applicable to NASAs human Mars exploration goals.

*Artist’s rendering of the DRACO spacecraft*

# 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.
- These technologies include but are not limited to the following:
  - Multi-Layer Insulation (MLI) systems
  - Thermodynamic Vent Systems (TVS)
  - flight weight high power 90K and 20K cryo-coolers for active cooling,
  - two stage cooling methodologies,
  - vapor cooled shields
  - low conductivity structural supports/struts, **and many others**
- The project is conducting in-space flight demonstrations performed by SpaceX, Lockheed Martin, United Launch Alliance and ETA Space.
- Engineering capabilities outlined here, 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.

# **Capabilities:** What is a Capability?

**Capability = Competency + Analytical Tools & Simulation + Demonstration & Test**

- MSFC has unmatched experience and expertise in cryogenic propulsion systems
- MSFC cryogenic test facilities continue to adapt to meet the needs of a growing market
- The coupling of the engineering competency, test infrastructure, and analytical toolbox make MSFC a <u>one-stop-shop</u> for industry partners and other government agencies

Comprehensive Cryogenic Propulsion Capability

**Design & Analysis**

- Conceptual Design and Architecture Studies
- Systems and Physics Model Development (MBSE, MBE, Structural/Fluid/Thermal, etc.)
- Systems Integration and Management

**Component & System Development**

- Integrated Cryogenic Propulsion Systems (CFM, HLS, SNP, Mars-Class Landers, etc.)
- Component Design & Development (Low-Leakage Valves, Cryo-Couplers, etc.)

**Development & Qualification Testing**

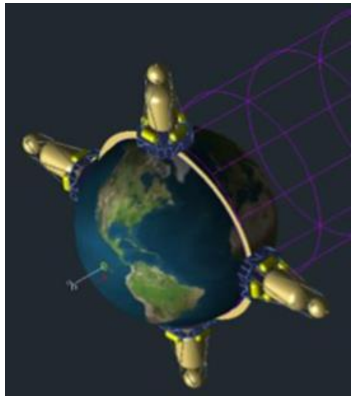
- Proof of Concept and System Demonstration
- Model Validation
- Internal Project Risk Reduction
- Industry and Other Government Agency Partnerships

**MSFC is a world-class cryogenic propulsion engineering and test capability**

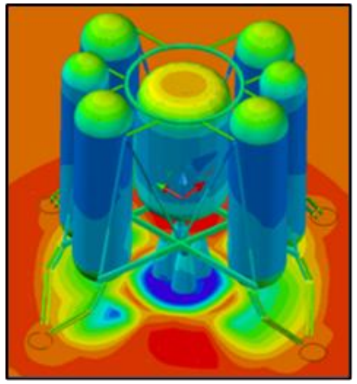
# System and Component Modeling

- MSFC's Propulsion Systems Department has a wide array of experience utilizing numerous tools to simulate cryogenic propulsion systems and components.
- Tools such as Thermal Desktop (TD), and in-house tools Generalized Fluid System Simulation Program (GFSSP) and TankSIM, have been successfully used for several applications including:
  - Liquefaction processes
  - Modelling of Joule-Thompson devices with spray bars or axial jets
  - Line and tank chill-down analyses
  - Zero boil-off, and Self-pressurization
  - Thermodynamic vent systems (TVS)
- GFSSP has been developed to perform nodal analysis of Liquid Propulsion Systems.
  - GFSSP discretizes a flow system into nodes and branches.
  - Pressures and temperatures are computed at the nodes whereas the flowrates are computed at the branches.
- MBSE -- 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.

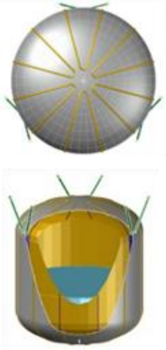
# Detailed Foundational Modeling: Thermal

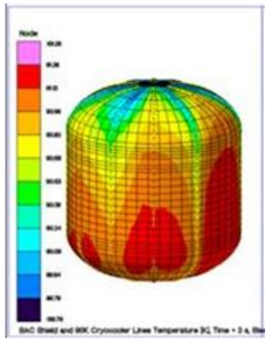


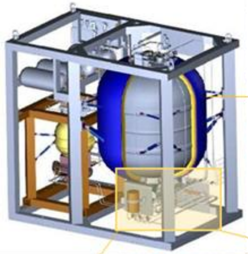
- The thermal engineering team supports various long duration cryogenic fluid management storage and transfer technology development activities and model validation efforts.
  - These assessments often require conjugate thermal/fluid modelling
  - Primary thermal software tools utilized are Thermal Desktop and ANSYS Mechanical

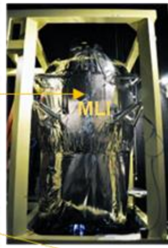


- GFSSP or FloCAD Thermal Desktop provide 1-D fluid integration for conjugate thermal/fluids modeling.
- If higher fidelity fluids modeling is required, work is coordination with MSFC’s Fluid Dynamics branch.
- MSFC is supporting many CFM technology development activities and collaborative analyses for demonstration flight missions (including):
  - 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
  - Tipping Point Demonstration Flights



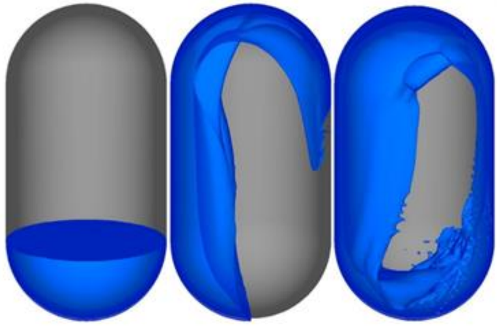


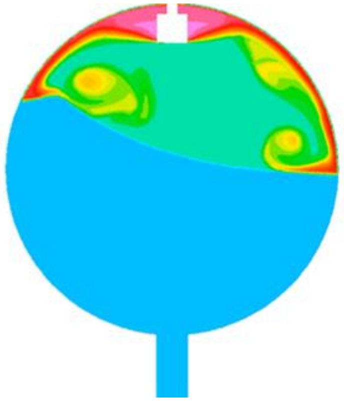


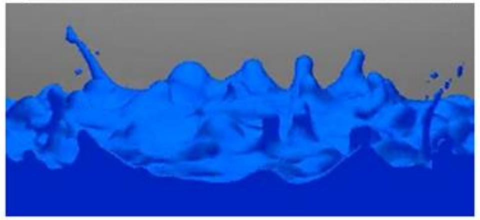



# **Detailed Foundational Modeling:** Fluid Dynamics

- The MSFC Fluid Dynamics branch uses multiple levels of modelling fidelity to provide analyses of tank slosh dynamics and CFM operations.
- Multiphase computational fluid dynamics (CFD) simulations are used directly model complex low gravity environments.
- Detailed simulations of system components are also performed to extract data to improve engineering or nodal models,
- 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.





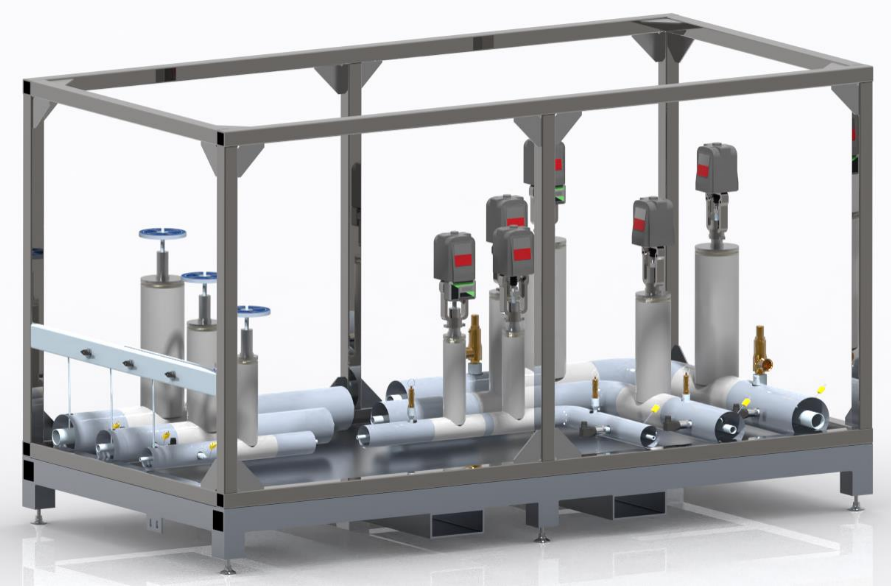


# **Laboratories and Rigs:** Laboratories

- Component Development Area (CDA)
  - Rapid hardware assessment, manufacturing, and modification capability
    - Valve prototyping (art-to-part)
    - Special test equipment
  - Valve technology development and test
    - 20-30 concurrent test and evaluation projects on average
    - Multiple gas and liquid flow capabilities with working fluid pressures up to 5-kpsi and burst test pressures up to 17-kpsi
    - DAQ with 1-100kHz data sampling rates
    - Thruster Vacuum test capability (26 torr)
- Cryogenic Fluid Management Lab
  - Exploration Systems Test Facility
    - 9-ft vacuum chamber ($10^{-8}$ torr); 24./7 operational capability
    - Multipurpose Hydrogen Test Bed
    - Cryogenic Testbeds (CTB-1 & CTB-2)

# Laboratories and Rigs: Modular Rigs

- Modular Assembly for Testing Cryogenic Hardware (MATCH)
  - Low-cost test article interface
    - Lowers cost by reducing test stand integration costs
    - Standardized interfaces (power, data, fluids)
  - Modular and Mobile
    - Interfaces with multiple MSFC test facilities
    - LOX, LH2, and LN2 capable
- Integrated Reaction Control System
  - Recirculation-type feed system
  - Pump-fed with dynamic back pressure regulation
  - Used to test pulse-mode and constant thrust combustion devices in an integrated Main Propulsion System (fed from main tanks)
- Cryo-Coupler Test Apparatus
  - Fixture designed for fast-acting mate/de-mate operations testing, including misalignments
  - Can be used to assess seal friction forces



# Test Stands and Facilities: Test Facility 4527

- Multipurpose Test Facility
  - Full-scale cryo component, subsystem and system-level development testing
  - 21-ft Diameter, 45-ft tall test structure
  - Specializes in low-pressure medium to large components
    - Stage test heritage
  - Configurations exist for high pressure tests like pump tests as well
    - Nuclear propulsion system pump test heritage
  - 120k-gal LH2 storage tank with 14-k gal run tanks
    - Recirculation configuration can be used to maximize commodities

| 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 | 1400 $ft^3$ | 4,000 psig | - |
| GN2 | 3-inch line | 4,000 psig | - |
| GHe | 3-inch line | 4,000 psig | - |

# Test Stands and Facilities: Test Stand 300

- Thermal Vacuum Test Facility
  - 20-ft chamber
    - 18 ft diameter, 25 ft tall test volume
    - $10^{-7}$ torr
    - Thermal shroud
    - Can simulate rapid ascent profiles
    - Zero boil-off measurement
  - 15-ft chamber
    - 15 ft diameter, 25 ft tall test volume
    - 10 mTorr
    - Used as an accumulator for the thermal shroud in the 20-ft chamber
    - Served as a test facility for lunar plume surface interaction studies
  - 12-ft chamber
    - Used for hazardous component testing and rapid ascent profile simulations

| 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 4000 psig |
| GN2 | 3-inch line at 4000 psig |
| GHe | 1.5-inch line at 4000 psig |
| MGA | 1.5-inch line at 3500 psig |
| Industrial Water | 150 psig |

# Summary and Conclusions

- Future high performance space transportation systems for human and robotic exploration will utilize high performance cryogenic propellants.

- 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 (both internal NASA efforts and through Industry partnerships).