National Aeronautics and Space Administration
Marshall Space Flight Center

Cryogenic Fluid Management

Technology Development Roadmaps

NASA Pathways Beyond Low Earth Orbit
In-Space Chemical Propulsion
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CFM Technology Development Roadmaps

OBJECTIVE(S):

- Outline a CFM Technology development path to support the long duration missions envisioned by the agency.
- Identify which CFM elements are likely to be needed:
  - Based on the 2020 Decision Point to determine the In-Space Stage Architecture
  - Lander & Ascent Vehicle Architectures
- Identify technology development “long poles”
- Identify which technologies require a flight demonstration to achieve TRL 6
- Path to TRL 6 to support the In-Space Stage PDR which is tentatively scheduled for 2023
- Identify which development efforts are currently funded and the state of technology maturation once the effort is complete.
- Effort includes the CFM communities at GRC and MSFC including personnel from STMD
- Provide final product in the form of a White Paper to AES, STMD, etc

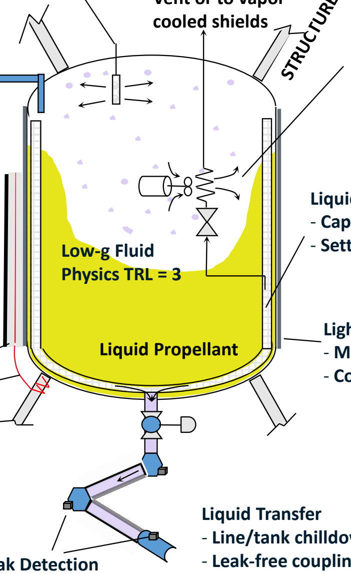
CFM Technology Development Roadmaps

BACKGROUND:

- Advancement in Cryogenic Fluid Management (CFM) Technologies is essential for achieving NASA's future long duration missions.
- Current State Of the Art (SOA) CFM technologies enable cryogenic propellants to be stored for several hours. However, some envisioned mission architectures require that cryogens to be stored for two years or longer.
- All functions are required to perform both with and without the presence of a gravitational field or acceleration.
- Which CFM technologies are required is a function of the cryogens used, mission architecture, vehicle design and propellant tank size.

What are the Fundamental CFM Responsibilities?

- <u>Store propellant</u>: Reduce heat leak and gauge propellant level
  - Tank and structure insulation
  - Passive and active cooling
  - Liquid level and mass gauging instrumentation
- <u>Control pressure</u>: Ameliorate effect of heat leak
  - Venting
  - Mixing
  - TVS / Active Cooling (Cryocoolers)
- <u>Deliver propellant</u>: Provide liquid or vapor conditioned as required
  - Start and run box conditioning
  - Settled transfer
  - LADs & PMDs
  - No-vent fill



Pressurization
- Storage/compression
- Helium TRL= 9
- Autogenous TRL = 3

Propellant Gauging
- Settled propellant TRL = 9
- Inventory (Bookkeeping)
- Pressure-volume-temperature (PVT) TRL = 5
- High accuracy low-g techniques TRL = 3/4

Vent or to vapor
cooled shields

Pressure Control
- Low-g venting (mixing and heat exchanger) TRL = 5

Liquid Acquisition
- Capillary devices for low-g TRL = 4/5
- Settling thrust TRL = 9

Lightweight Cryogenic Tank
- Metallic (Al-Li)
- Composite

Thermal Control
- Insulation (launch environments and in-space, MMOD protection) TRL = 5
- Vapor/cryocooler cooled shields
- Sun shades
- Low conductivity/ cooled support structure

Leak Detection
TRL = 3/4

Liquid Transfer
- Line/tank chilldown TRL = 4
- Leak-free coupling TRL = 3

Courtesy of Yetispace, Inc.

Definitions / References

**“<u>Cross Cutting</u>”- Term used to define a technology that is applicable for all cryogens.
Examples include most insulation concepts, settled / unsettled liquid level mass gauging and helium pressurization systems.**

“<u>Fluid Specific</u>”- Defines a technology that is only applicable for a specific fluid. Examples include autogenous pressurization, LADs, PMDs, and Cryocoolers.

“<u>Hard Cryogens</u>” – LH2

“<u>Long Duration</u>” – A mission requiring cryogens to be stored for extended periods of time requiring Active Cooling via Cryocoolers. Examples include In-Space NTP, and Mars and Lunar Ascent/Decent Vehicles.

“<u>Settled</u>” – The location of the liquid interior to the propellant tank is driven by the presence of a gravitational field.

“<u>Short Duration</u>” – A mission requiring cryogens to be for a short enough period of time that Active Cooling via Cryocoolers is not required (typically a few hours to ~ 30 days). Examples include SLS EUS and Centaur.

“<u>Soft Cryogens</u>”- Essentially any cryogens other than LH2. Examples include LOX, LCH4 and LNG.

“<u>Unsettled</u>” – Liquid propellant is attached to the tank inner walls with the ullage taking a spherical shape at the tanks center. In micro-g, surface tension effects dominate gravitational forces.

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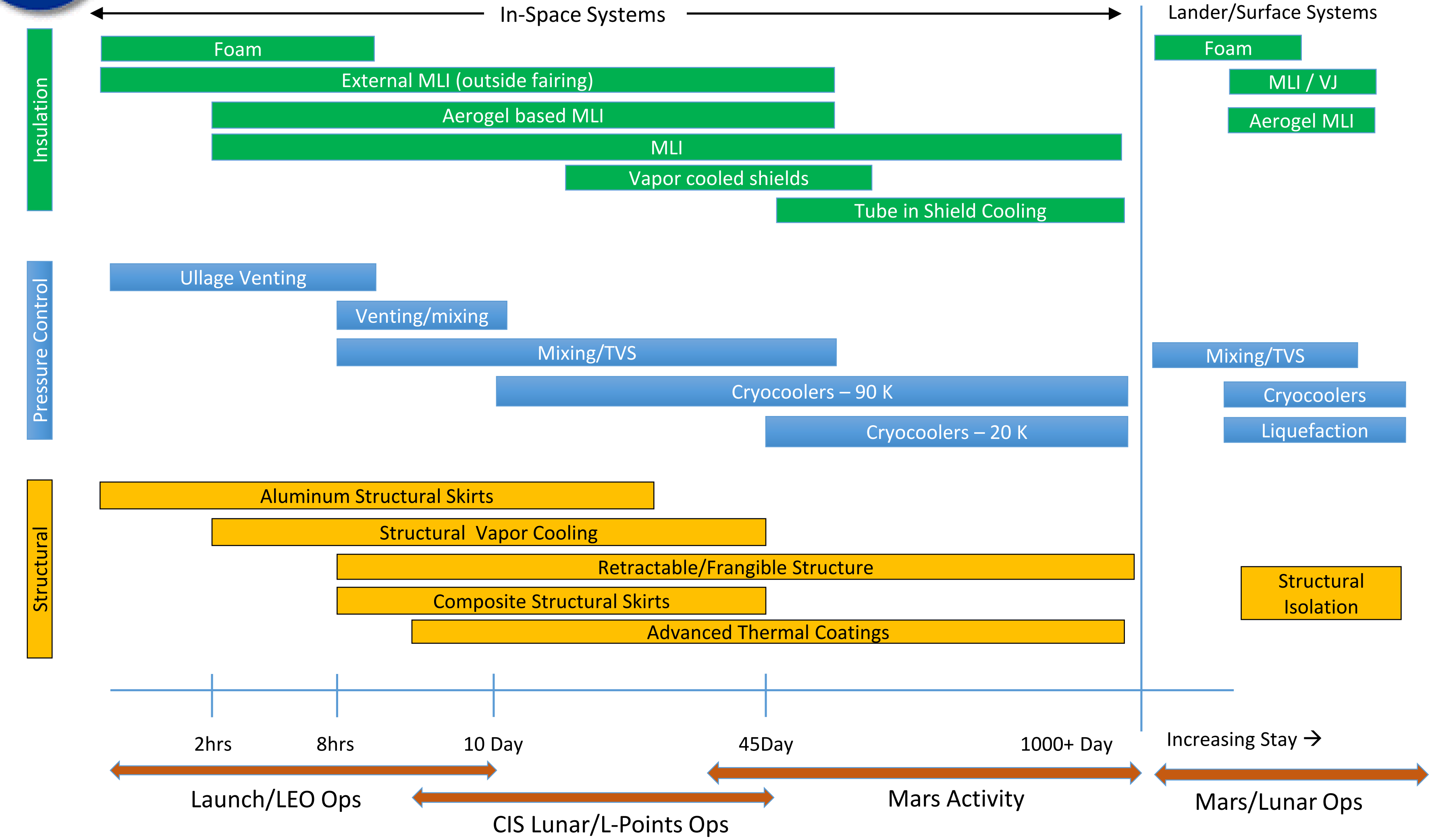
Technology Application for Thermal Management of Cryogenic Fluids



In-Space Systems

Lander/Surface Systems

Insulation

Foam

External MLI (outside fairing)

Aerogel based MLI

MLI

Vapor cooled shields

Tube in Shield Cooling

Foam

MLI / VJ

Aerogel MLI

Pressure Control

Ullage Venting

Venting/mixing

Mixing/TVS

Cryocoolers – 90 K

Cryocoolers – 20 K

Mixing/TVS

Cryocoolers

Liquefaction

Structural

Aluminum Structural Skirts

Structural Vapor Cooling

Retractable/Frangible Structure

Composite Structural Skirts

Advanced Thermal Coatings

Structural Isolation

2hrs

8hrs

10 Day

45Day

1000+ Day

Increasing Stay →

Launch/LEO Ops

CIS Lunar/L-Points Ops

Mars Activity

Mars/Lunar Ops

Other CFM Technologies:

Mass Gauging - Independent of mission time – as needed operationally (settled or unsettled)
Pressurization - Independent of mission time – as needed for fluid transfer or engine operation can be provided by IVF
Liquid Acquisition - Independent of mission time – as needed for RCS or fluid transfer (settling can minimize the need for this technology)
Fluid Transfer - Independent of mission time – as needed depending on operations/depot usage/ISRU/Refueling/Landers

CFM Technologies Requiring Maturation

There are a total of eighteen CFM technologies identified to support an In-Space Stage and a Lander/Ascent Vehicle, six of which require further development <u>before a flight demonstration</u> and are considered “*gaps needing development*”.

CFM Elements				
Technologies	Current TRL	Gravity Dependant (Y/N)	Path to TRL 6	"Cross Cutting" or "Fluid Specific"
Multilayer Insulation	5	No	Ground Test	Cross Cutting
Low Conductivity Structure	5	No	Ground Test	Cross Cutting
Tube-On-Shield BAC	5	No	Ground Test	Cross Cutting
Tube-On-Tank HTX	5	Yes	Flight Demo	Cross Cutting
Termodynamic Vent System	5	Yes	Flight Demo	Cross Cutting
MPS Line Chill	5	Yes	Flight Demo	Cross Cutting
Helium Pressurization	5	Yes	Flight Demo	Cross Cutting
Unsettled Liquid Mass Gauging	5	Yes	Flight Demo	Cross Cutting
Pump Based Mixing	5	Yes	Flight Demo	Cross Cutting
Autogenous Pressurization	5	Yes	Flight Demo	Fluid Specific
Liquid Acquisition Devices	5	Yes	Flight Demo	Fluid Specific
Advanced External Insulation	3	No	Ground Test	Can Be Both
High Capacity, High Efficiency Cryocoolers 90K	3	No	Ground Test	Cross Cutting
Soft Vacuum Insulation	3	No	Ground Test	Cross Cutting
Valves, Actuators & Components	3	No	Ground Test	Cross Cutting
High Capacity, High Efficiency Cryocoolers 20K	3	No	Ground Test	Fluid Specific
Liquefaction Efficiencies (MAV & ISRU)	4	No	Ground Test	Fluid Specific
Vapor Cooling	4	No	Ground Test	Fluid Specific

Can achieve TRL 6 through ground testing.

Flight Demo required to achieve TRL 6.

Technology “Long Poles” Development is needed. Can achieve TRL 6 through ground testing.

EMC system CFM Technology Priorities

Based on initial review of the EMC architecture (landers and stages), the following technologies are prioritized:

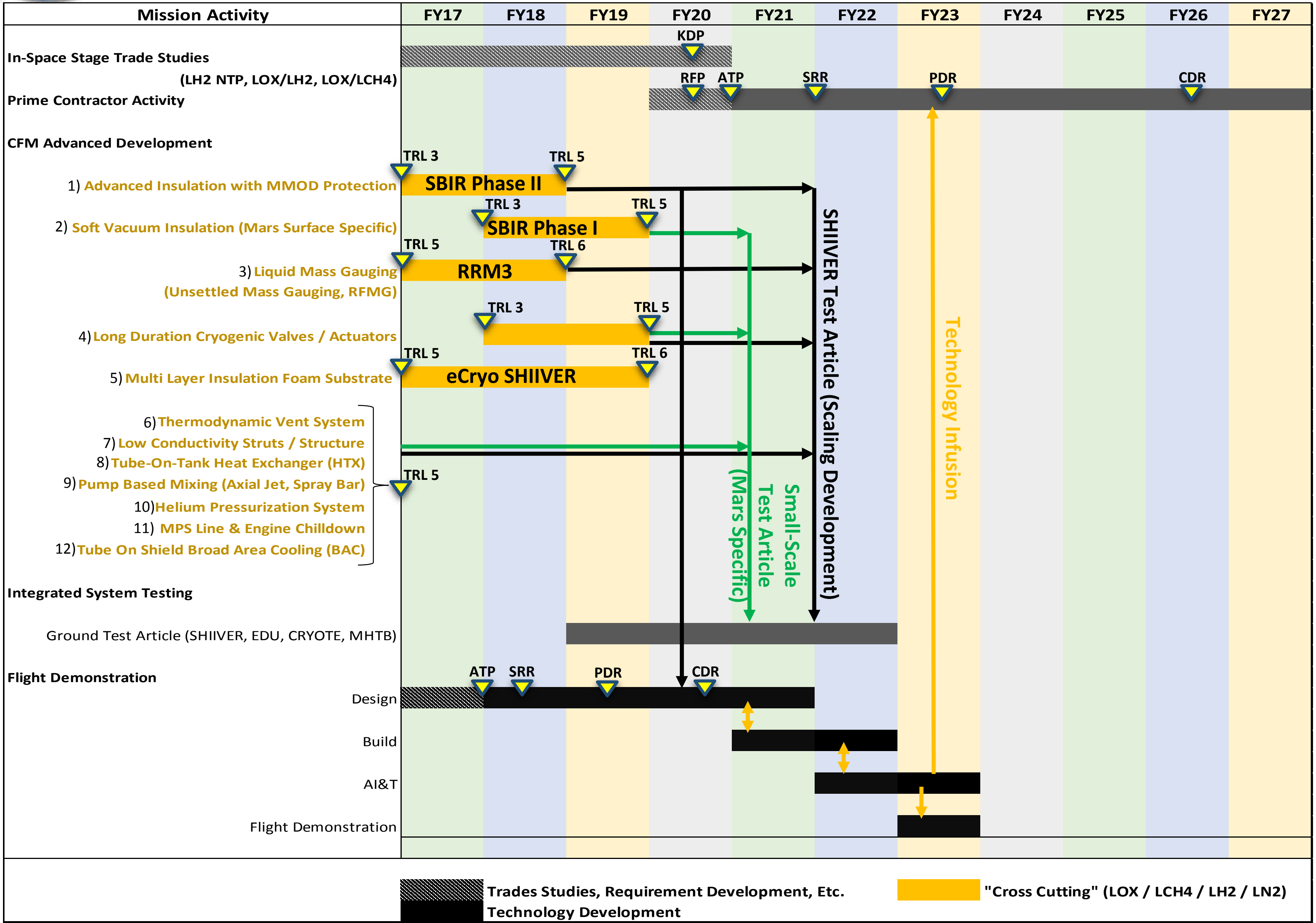
- **Stages (Split Architecture, Methane Cryogenic Propulsion Stage):**
    - **High capacity cryocoolers (~100 W @ 90 K) integrated into a single tank cooling distribution system**
    - **Pressure Control (TVS, mixing)**
    - **Mass Gauging (settled is baselined)**
    - **Valves to meet flow, heat load, and leakage requirements**
    - **Helium Conditioning/Storage and Pressurization**
- **Landers (Ascent and Descent Stages, All Architectures)**
    - **High capacity cryocoolers (~100 W @ 90 K) integrated across multiple tank cooling and oxygen liquefaction systems**
    - **Insulation systems for the surface of Mars (5 Torr)**
    - **Pressure Control (TVS, mixing)**
    - **Mass Gauging (settled and unsettled)**
    - **Low-g propellant acquisition**

NTP & Aggregation / Depot System CFM Technology Priorities

- Nuclear Thermal Propulsion
  - 20 K Cryocoolers (up to 225 W lift needed) – need to compare 20 K only and 20 K + 90 K rejection scenarios
  - Autogenous pressurization
  - External MLI outside fairing (assuming in-line tanks)
  - Quick Disconnects/Automated Couplings for engine feedlines
  - Transfer between tanks (multiple drop tanks and refueling tanks), currently assuming settled

- Lunar Aggregation/Depot Scenarios
  - Assumed ZBO storage, didn’t size storage system (production starts 2030)
  - Fluid transfer (large quantities) in lunar and Martian orbits (autogenous)
  - Autogenous couplings
  - Lots of reuse and common sizing

CFM Development Roadmap – “Cross Cutting”



Mission Activity | FY17 | FY18 | FY19 | FY20 | FY21 | FY22 | FY23 | FY24 | FY25 | FY26 | FY27

In-Space Stage Trade Studies
(LH2 NTP, LOX/LH2, LOX/LCH4)
KDP

Prime Contractor Activity
RFP ATP SRR PDR CDR

CFM Advanced Development

1) Advanced Insulation with MMOD Protection
TRL 3 — SBIR Phase II — TRL 5

2) Soft Vacuum Insulation (Mars Surface Specific)
TRL 3 — SBIR Phase I — TRL 5

3) Liquid Mass Gauging
(Unsettled Mass Gauging, RFMG)
TRL 5 — RRM3 — TRL 6

4) Long Duration Cryogenic Valves / Actuators
TRL 3 — TRL 5

5) Multi Layer Insulation Foam Substrate
TRL 5 — eCryo SHIIVER — TRL 6

6) Thermodynamic Vent System
7) Low Conductivity Struts / Structure
8) Tube-On-Tank Heat Exchanger (HTX)
9) Pump Based Mixing (Axial Jet, Spray Bar)
10) Helium Pressurization System
11) MPS Line & Engine Chilldown
12) Tube On Shield Broad Area Cooling (BAC)
TRL 5

Small-Scale Test Article (Mars Specific)

SHIIVER Test Article (Scaling Development)

Technology Infusion

Integrated System Testing

Ground Test Article (SHIIVER, EDU, CRYOTE, MHTB)

Flight Demonstration

Design
ATP SRR PDR CDR

Build

AI&T

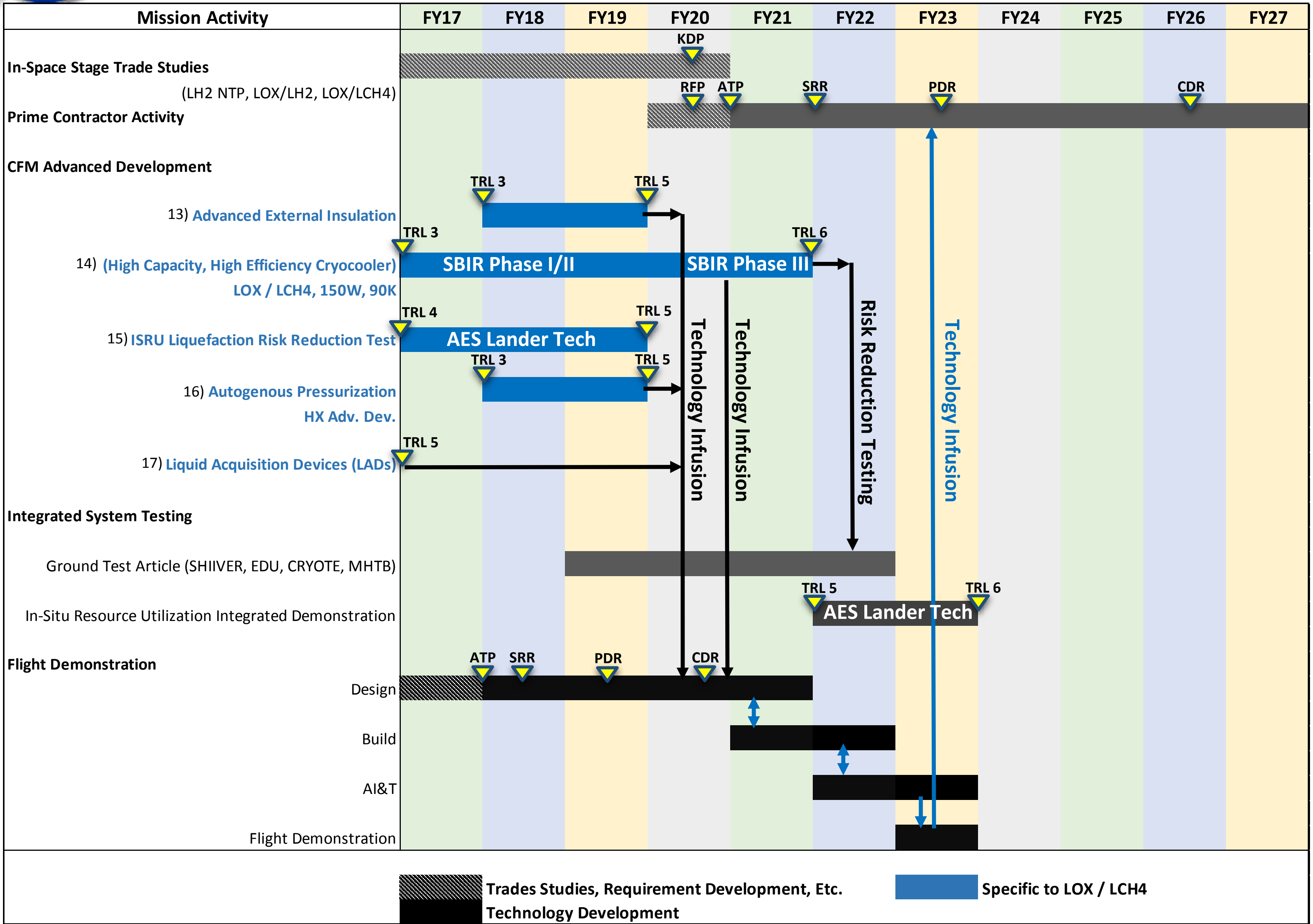
Flight Demonstration

▨ **Trades Studies, Requirement Development, Etc.**

■ **Technology Development**

🟨 **"Cross Cutting" (LOX / LCH4 / LH2 / LN2)**

CFM Development Roadmap – Fluid Specific - LOX/LCH4



Mission Activity

FY17 FY18 FY19 FY20 FY21 FY22 FY23 FY24 FY25 FY26 FY27

In-Space Stage Trade Studies
(LH2 NTP, LOX/LH2, LOX/LCH4)

KDP

Prime Contractor Activity

RFP ATP SRR PDR CDR

CFM Advanced Development

13) Advanced External Insulation — TRL 3, TRL 5

14) (High Capacity, High Efficiency Cryocooler) LOX / LCH4, 150W, 90K — TRL 3, SBIR Phase I/II, SBIR Phase III, TRL 6

15) ISRU Liquefaction Risk Reduction Test — TRL 4, AES Lander Tech, TRL 5

16) Autogenous Pressurization HX Adv. Dev. — TRL 3, TRL 5

17) Liquid Acquisition Devices (LADs) — TRL 5

Technology Infusion

Technology Infusion

Risk Reduction Testing

Technology Infusion

Integrated System Testing

Ground Test Article (SHIIVER, EDU, CRYOTE, MHTB)

In-Situ Resource Utilization Integrated Demonstration — TRL 5, AES Lander Tech, TRL 6

Flight Demonstration

Design — ATP, SRR, PDR, CDR

Build

AI&T

Flight Demonstration

▨ Trades Studies, Requirement Development, Etc.

■ Technology Development

🟦 Specific to LOX / LCH4

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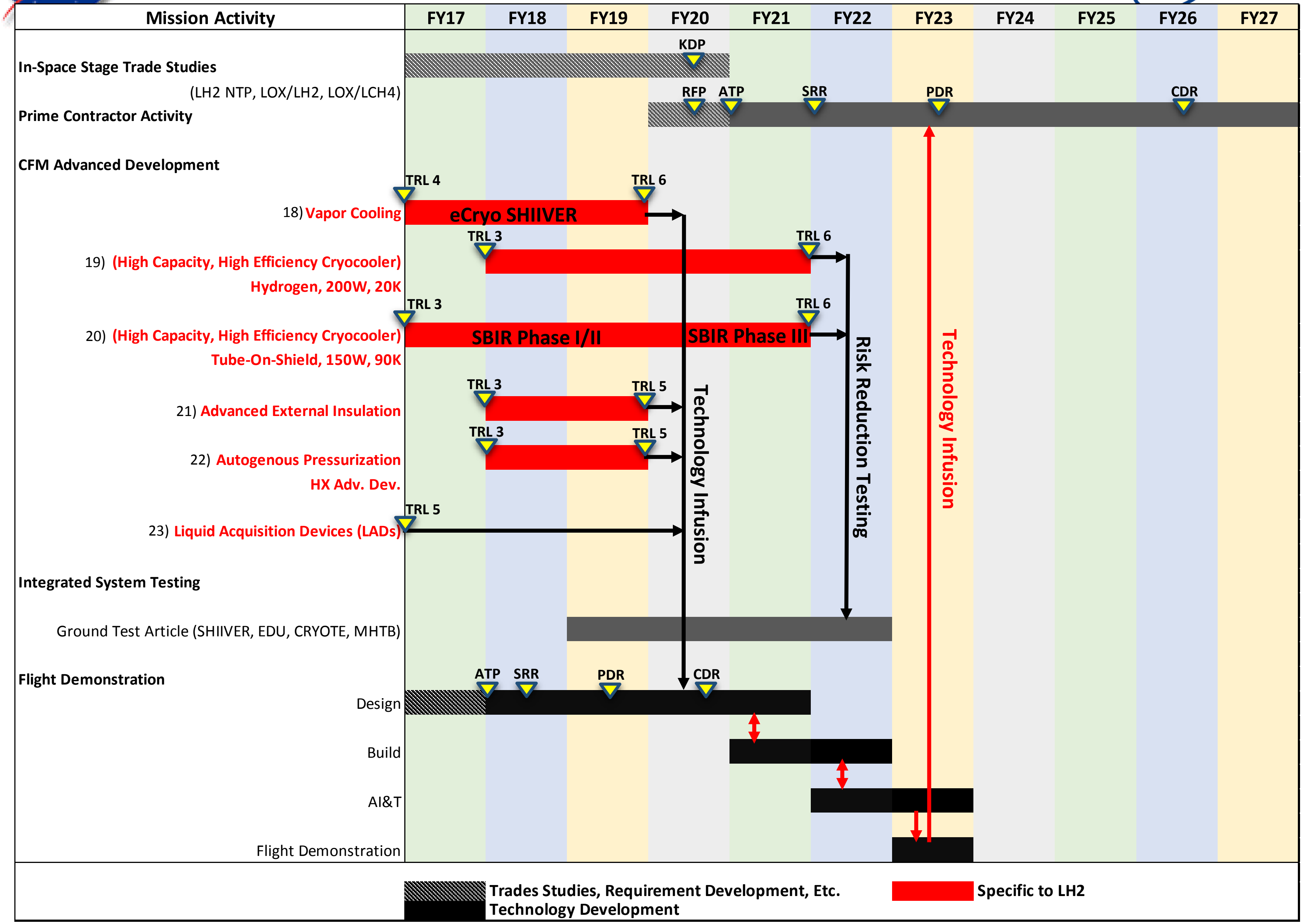
CFM Development Roadmap – Fluid Specific – LH2



Mission Activity

FY17 FY18 FY19 FY20 FY21 FY22 FY23 FY24 FY25 FY26 FY27

In-Space Stage Trade Studies
(LH2 NTP, LOX/LH2, LOX/LCH4)

Prime Contractor Activity

CFM Advanced Development

18) Vapor Cooling
19) (High Capacity, High Efficiency Cryocooler) Hydrogen, 200W, 20K
20) (High Capacity, High Efficiency Cryocooler) Tube-On-Shield, 150W, 90K
21) Advanced External Insulation
22) Autogenous Pressurization HX Adv. Dev.
23) Liquid Acquisition Devices (LADs)

Integrated System Testing

Ground Test Article (SHIIVER, EDU, CRYOTE, MHTB)

Flight Demonstration

Design
Build
AI&T
Flight Demonstration

▨ Trades Studies, Requirement Development, Etc.
■ Technology Development
🟥 Specific to LH2

Demonstrations Summary and Differences

	In-Space Stage (LH2/LO2)	In-space Stage (LCH4/LO2)	Nuclear (LH2)	Ascent Stage (LCH4/LO2)	ISRU based System (production)(LO2)	Descent Stage (LCH4/LO2)	Lunar Aggregation (no production)
Demonstration Tank Diameter (m)	3	2	3	1	TBD	1	2
Test Fluid	Hydrogen	Methane	Hydrogen	Methane	Oxygen	Methane	Hydrogen?
Duration	Several months (2-6)	Several months (2-6)	6 – 12 mo	Up to a year (reliability)	Months to a year	Up to a year (reliability)	6 mo
Location	LEO	LEO	Cis-Lunar	Cis-Lunar	Ground	Cis-Lunar	LEO/Cis-Lunar
Cryocooler	No	Yes – 90 K	Yes – 20 K Maybe – 90 K	Yes – 90 K	Yes – 90 K	Yes – 90 K	Maybe
Storage	Yes; TVS pressure control + low heat load tank	Yes; Cryocooler vs. TVS	Yes; Cryocooler + Min Heat Load Tank (External MLI?)	Yes; Cryocooler + Min Heat Load Tank	Yes; Cryocooler + Min Heat Load Tank	Yes; Cryocooler + Min Heat Load Tank	Yes; Cryocooler vs. TVS + Min Heat Load Tank
Transfer	No; (currently no reqmts)	No; (currently no reqmts)	Yes	End of Life RCS?	In gravity field	RCS?; Initial Expulsion?	Yes – partially full vs. empty?
Unsettled Gauging	No; (currently no reqmts)	No; planned settling manuevers	Yes	Yes	No	Yes	Yes
Special Conditions/ questions	In-line LH2 barrel?; minimize heat load into tank	Helium vs. autogenous pressurization	Heaters to simulate engine heat dumps?; Automated couplings	Risk of added TVS with cryocooler; MMOD?; soft vacuum insulation	Soft vacuum insulation	Risk of added TVS with cryocooler; MMOD?; soft vacuum insulation	Automated couplings; autogenous pressurization;

Conclusions

- All CFM technologies must be matured to TRL 6 to be infused in the In-Space Stage Design for PDR which is scheduled for 2023.
- Gravity independent technologies can be matured to TRL 6 via ground testing, but gravity dependent technologies must <u>successfully be demonstated in flight.</u>
- Some elements still require technology development (TRL 4 or less) and unless funding is infused to accelerate the development process, there is significant risk that the technologies will not be available in time.
- Need to understand the In-Space Architecture to design the appropriate flight demonstration
  - Some technologies are “cross cutting” and others are “fluid specific”.
  - Appropriate scaling needs to be taken in account when sizing the flight demonstration.
  - The flight demonstration preliminary design must be flexible enough at PDR to accommodate the requirements once a 2020 decision is made.
    - To meet schedule, the flight demonstration PDR will likely have to be before the 2020 KDP.
- If LOX/LH2 or NTP is selected for the In-Space Architecture, then a second flight demonstration may be needed to support LOX/LCH4 MAV/Lander.
- Based on CPST, a flight demonstration will take six years and ~$200M.
- Need to get started NOW!!!

Backup Charts

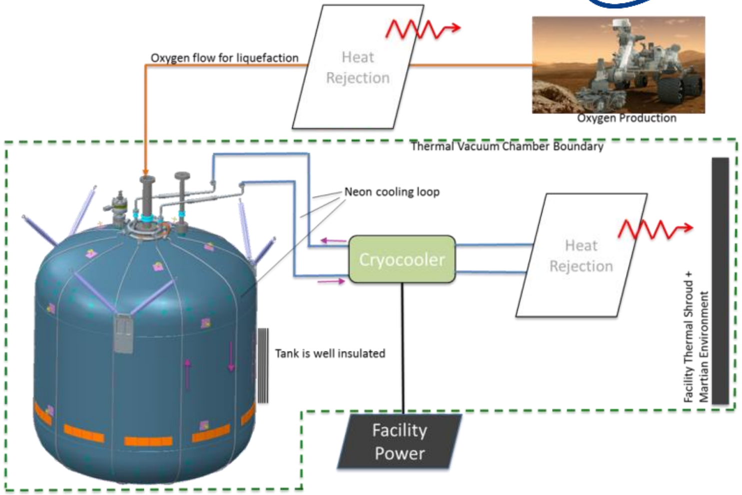
List of Acronyms

AES	Advanced Exploration Systems
AFRC	Armstrong Flight Research Center
ATP	Athority to Proceed
BAC	Broad Area Cooling
CCSC	Collaborations of Commercial Space Capabilities
CDR	Critical Design Review
CFM	Cryogenic Fluid Management
CO2	Carbon Dioxide
COPV	Composite Overwrap Pressure Vessel
CPST	Cryogenic Propellant Storage and Transfer
CryoFOSS	Cryogenic Fiber Optic Sensing System
CRYOTE	CRYogenic Orbital TEstbed
DVAT	Development & Validation of Analysis Tools
eCryo	Evolvable Cryogenics
EDU	Engineering Development Unit
ESTF	Exploration Systems Test Facility
EUS	Exploration Upper Stage
FOSS	Fiber Optic Sensing System
FY	Fiscal Year
GFRC	Goddard Flight Research Center
GRC	Glenn Research Center
HTX	Heat Exchanger
IFUSI	Improved Fundamental Understanding of Super Insulation
ISRU	In-Situ Resource Utilization
IVF	Integrated Vehicle Fluids
JSC	Johnson Space Center
JT	Joule Thomson
K	Kelvin
KDP	Key Decision Point
KSC	Kennedy Space Center
LADs	Liquid Acquisition Devices
LH2	Liquid Hydrogen
LN2	Liquid Nitrogen
LNG	Liquid Natural Gas
LOX	Liquid Oxygen
LSP	Launch Services Program
MAV	Mars Ascent Vehicle
MCU	Motor Compressor Unit
MHTB	Multi Purpose Hydrogen Test Bed
MLI	Multi Layer Insulation
MMOD	Micro Meteoroid Orbital Debris
MPS	Main Propulsion System
MSFC	Marshall Space Flight Center
NTP	Nuclear Thermal Propulsion
PDR	Preliminary Design Review
PMD	Propellant Management Devices
RCS	Reaction Control System
RFMG	Radio Frequency Mass Gauging
RFP	Request for Proposal
RRM3	Robotic Refueling Mission 3
SBIR	Small Business Innovation Research
SHIIVER	Structural Heat Intercept Insulation Vibration Evaluation Rig
SLS	Space Launch System
SOA	State Of the Art
SOFI	Spray On Foam Insulation
SRR	System Requirements Review
STMD	Space Technology Mission Directorate
TE	Tech Excellence
TIP	Technology Investment Program
TRL	Technology Readiness Level
TVS	Thermodynamic Vent System
ULA	United Launch Alliance
VATA	Vibro Acoustic Test Article
VCMLI	Vacuum Cell Multi Layer Insulation
VJ	Vacuum Jacket
W	Watts
ZBO	Zero Boil-Off

Current Technology Development Efforts

AES – Lander Tech

- ISRU Liquefaction Risk Reduction Testing
  - Demonstrate liquefaction of "ISRU Like" propellants using active cooling and tube-on-tank HTX configuration.
  - Testing conducted at MSFC (LN2), then GRC (LOX) – FY17 thru FY19
  - Fully integrated system demo at JSC – FY22 to FY23



Liquefaction Test Diagram

KSC LSP CCSC

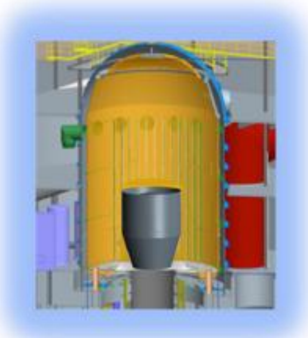
- CRYogenic Orbital TEstbed (CRYOTE 3)
  - "Flight Like" Propellant tank
  - Measurements of Heat Load, Apparent Density, and Thermal Stratification
  - Includes AFRC's Fiber Optic Sensing System (FOSS) for measurements of both temperature and strain
  - Includes AFRC's mass gauging technology CryoFOSS
  - Phase I – Funded by KSC LSP & CCSC
    - Completed in Spring FY15
    - Insulated to match targeted heat loads
    - LN2 and LH2
  - Phase II – Funded by KSC LSP, CCSC, and MSFC Scheduled for Spring of FY17
    - LN2 and LNG

CRYOTE 3 Test Article

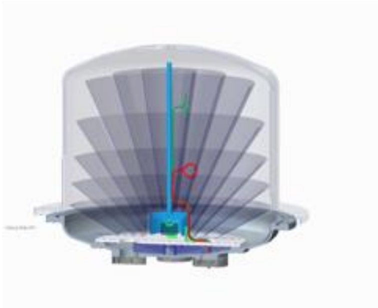
Current Technology Development Efforts

Evolvable Cryogenics (eCryo)

- Structural Heat Intercept Insulation Vibration Evaluation Rig (SHIIVER)
  - Representative of a large-scale cryogenic tank
  - Implement vapor cooling and multi-layer insulation (MLI)
- Radio Frequency Mass Gauging (RFMG)
  - Unsettled propellant mass gauging
  - Developed at GRC, tested at MSFC
  - Scheduled to fly on RRM3
- Improved Fundamental Understanding of Super Insulation (IFUSI)
  - Improving the design capabilities of MLI blankets to large-scale, cryogenic tanks
- Development & Validation of Analysis Tools (DVAT)
  - Advancement of numerical tools to cover cryogenics in both settled and unsettled conditions.
- Integrated Vehicle Fluids (IVF)
  - Evaluate the extensibility of the IVF concept for use on Exploration Upper Stage (EUS)



SHIIVER Test Article



RFMG for RRM3 Mission

Current Technology Development Efforts

SBIR Funded Activities

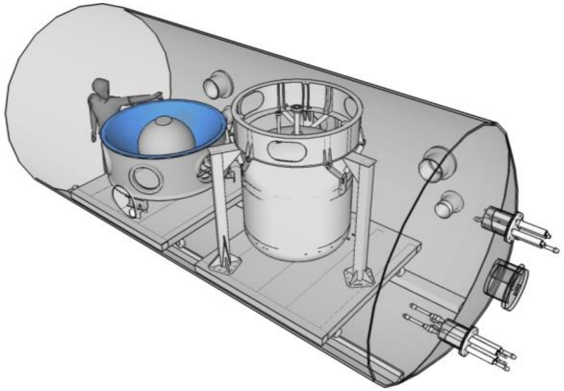
- Advanced Insulation Development – Two Phase II
- High Efficiency, High Capacity "Flight Like" 150W/90K Cryocooler – Two Phase I

SBIR/GCD Funded

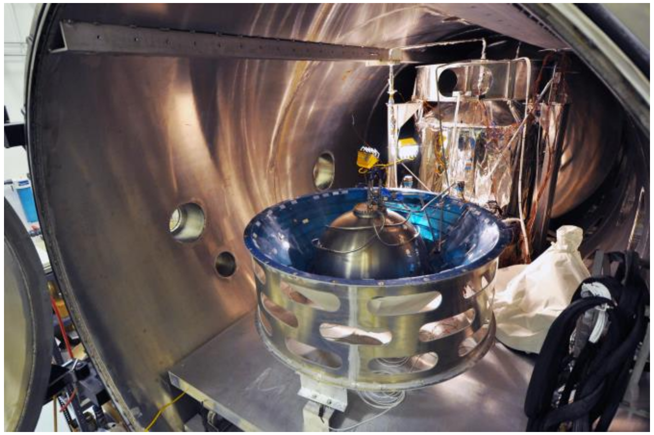
- "Flight Like" 20W/20K Cryocooler – Phase III

Other Funding Sources

- Vented Chill / No-Vent Fill
  - VATA to CRYOTE 1 Propellant Transfer
  - Minimize propellant loss during an on-orbit transfer (Propellant Depot)
  - Chill Transfer line only once
  - Does not require mass gauging or flow measurement



Exploration Systems Test Facility (ESTF)



VATA and CRYOTE 1 in ESTF