EXPLORESPACE TECH

TECHNOLOGY DRIVES EXPLORATION

Cryogenic Fluid Management

National Academies: Decadal Survey on Biological and Physical Sciences 2023 - 2032

John Dankanich

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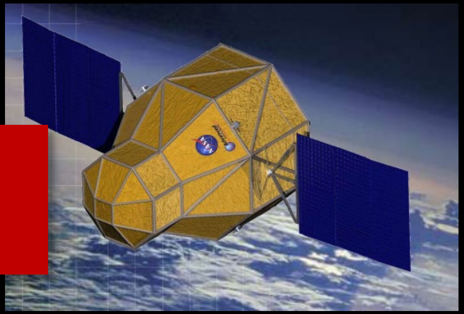
GO: Develop cryogenic storage, transport, and fluid management technologies for surface and in-space applications.

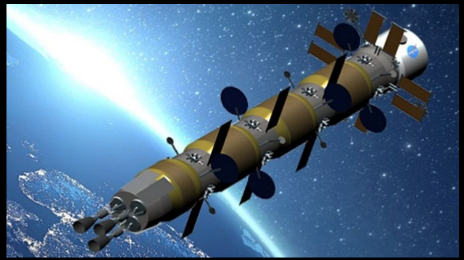
Developing technologies for near zero boil off storage, high efficiency chill-down and liquification, propellant transfer, and instrumentation to support Mars transportation and surface ISRU architectures.

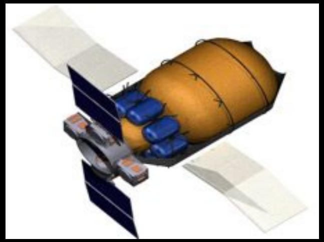


STORAGE

- LOX, LCH4, LH2
- Near Zero Boil-off – Architecture / mission dependent

- **Critical Technologies**
  - Active Thermal Control
  - High Performance Insulation
  - Structural Heat Rejection/Intercept
  - Pressure Control
  - Operations
  - Near Zero Boil-off
  - Structural Multilayer Insulation
  - Low conductance structures
  - High Efficiency High Capacity 20k and 90k Cryocoolers
  - Destratification
  - Unsettled Mass Gauging
  - Thermal Control Coatings





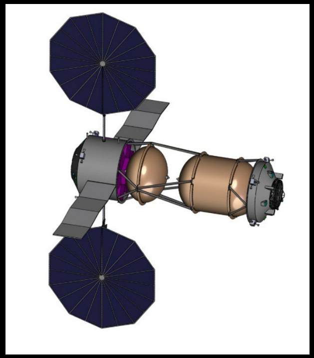
LIQUEFACTION

- H_2, O_2, CH_4
- Initial system performance:
  2 kg/hr of O_2 and .3 kg/hr of H_2
- Soft Vacuum insulation: 1.5 W/m2 at 250 K

TRANSFER

- Propellant losses ≤1% during transfer
- <1% residual in supply tank

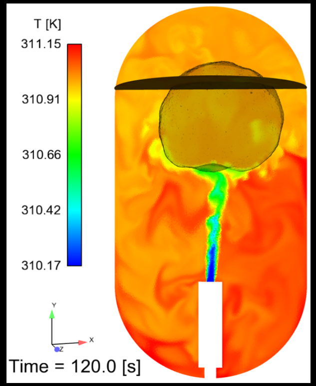
- **Critical Technologies**
  - Component Technologies
  - Operations
  - High efficiency chill down of tank and lines
  - Automated Cryo-Couplers
  - Low-leakage valves/actuators
  - Flow Meters
  - Efficient Liquid Acquisition Devices
  - Transfer pump



NON-PRIMARY PROPULSION

- Integrated RCS
- Fuel Cells
- ECLSS

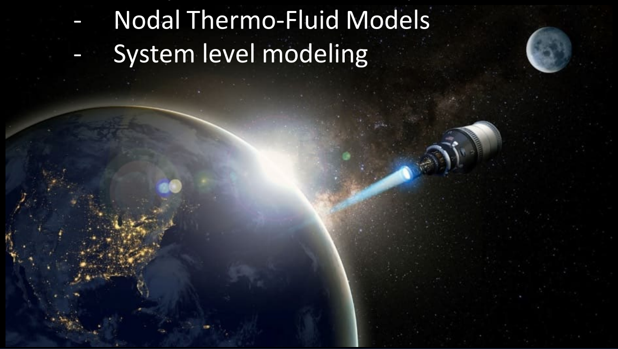
- Application Specific CFM Capabilities
- Uses components and processes from other categories



INTEGRATED OPERATIONS / PREDICTIVE PERFORMANCE

- Advanced instrumentation, data acquisition and signal processing
- Integrated Demonstration
- Accurate and robust a priori microgravity thermal-fluid predictions
  - Validated foundational physics in High Fidelity tools
  - High-to-Low Fidelity Model Integration

- Integrated System Performance Analysis
  - Low predictive uncertainty
  - Nodal Thermo-Fluid Models
  - System level modeling



CFM State of the Art

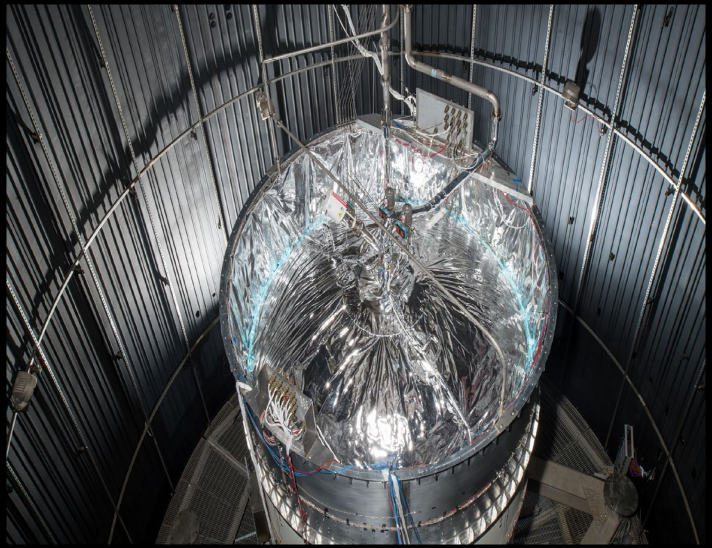
CFM capabilities must address the operational implementation and use of the technologies in a system, and the technical design of the CFM system. Many of the components required to close the gaps are the same but have diverging requirements or implementation strategies that change how the technology is used.

STORAGE

- Extensive experience in ground demonstration
- Longest H_2 cryogenic propulsion storage system has performed storage operations in space is 9 hrs
- Performed 4.5 Month CH4 subscale storage on RRM3

KEY Design Details

- Tank pressure regulation
- Methods of venting
- Structural heat load
- Total heat input over time
- Active cooling – **1W lift @ 20k; 20W lift @ 90k**



LIQUEFACTION

- **Ground based demonstration** and analytical performance model validation of **LN2**

KEY Design Details

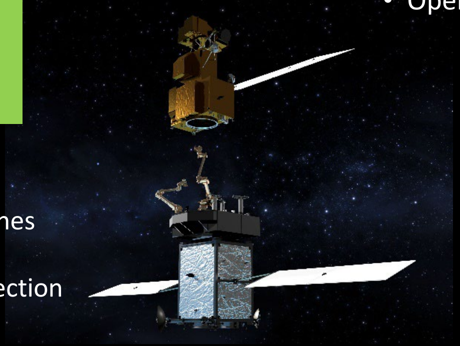
- Condensation, fluid physics, fluid purity
- Active cooling integration
- High performance insulation in appropriate environment

TRANSFER

- **Component brassboard** hardware **ground testing only**

Key Design Details

- Pump or pressure driven transfer
- High efficiency chill down of tank and lines
- Active cooling
- Low-leakage valves/actuators, leak detection
- Phase separation/Liquid acquisition



NON-PRIMARY PROPULSION

- **Ground based testing** of Integrated RCS in thermal vacuum

KEY Design Details

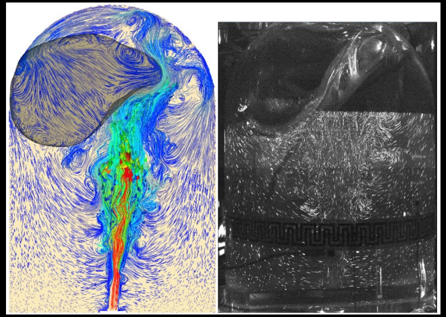
- Application specific technologies and operational processes

INTEGRATED OPERATIONS / PREDICTIVE PERFORMANCE

- Fluid property knowledge gaps
- Instrumentation
- Model development and validation for both high and low fidelity applications

KEY Design Details

- Zero-G Mass Gauging
- Operational and predictive fluid dynamics and thermodynamics



CFM Critical Technologies Current Investments

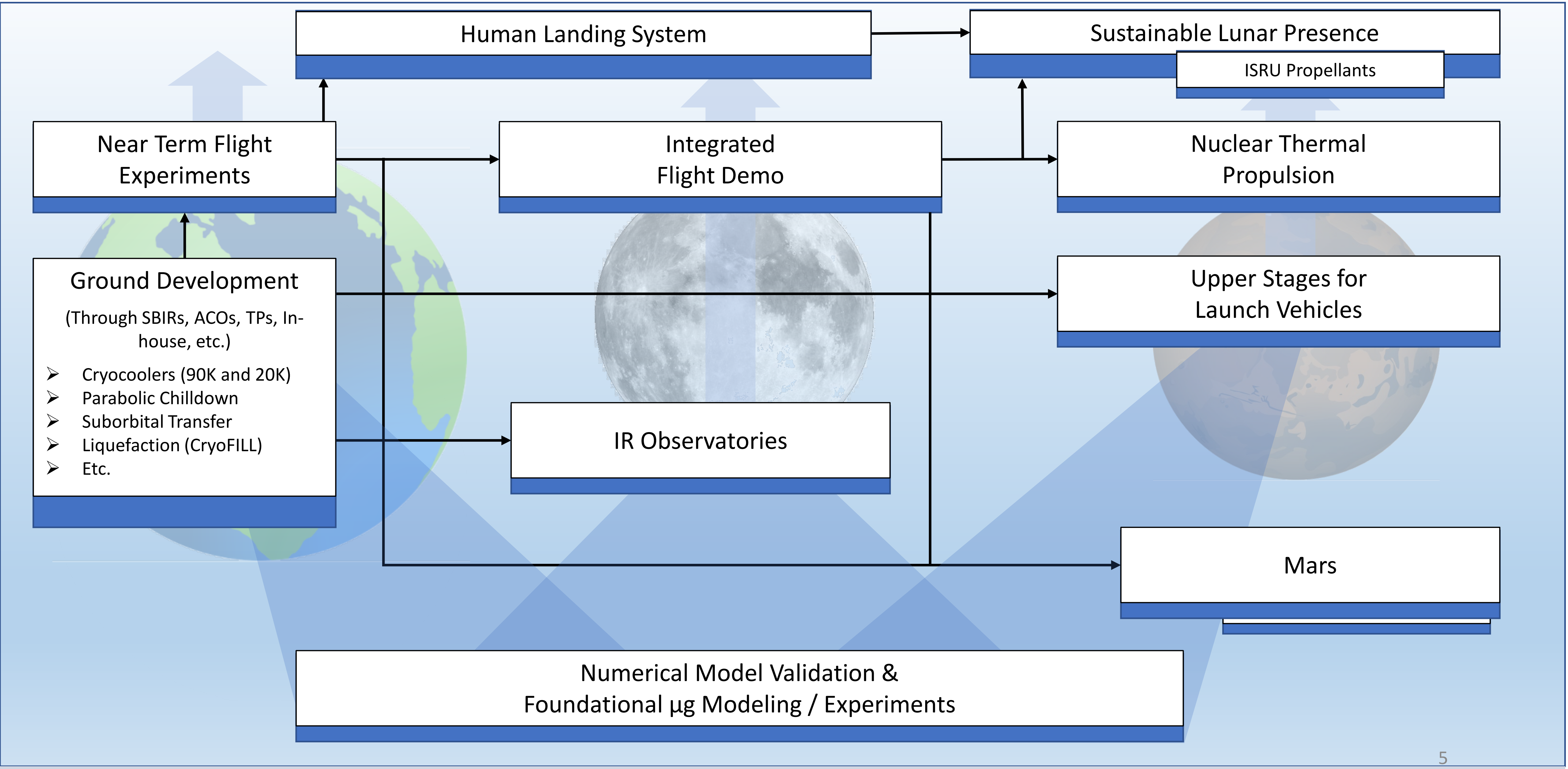
CFM Critical Technology Gaps	Cross Cutting or Fluid Specific	Current TRL	Gap Addressed**
Low Conductivity Structures	Cross Cutting	6	Tipping Point (TP)
High Vacuum Multilayer Insulation	Cross Cutting	6	FY20 TP
Sun Shields (deployment mechanism)	Cross Cutting	5	JWST / TP
Tube-On-Shield BAC	Cross Cutting	5	TP, In-house
Valves, Actuators & Components	Cross Cutting	4-5	TP, In-house
Vapor Cooling	Fluid Specific	6	TP, In-house
Propellant Densification	Fluid Specific	5	TP, In-house
Unsettled Liquid Mass Gauging, multiple methods	Cross Cutting	4-7	TP, ECI, FO, In-house
Sub-surface Helium Pressurization in Micro-g	Cross Cutting	5	ZBOT / TP
Line Chilldown (MPS, iRCS, Transfer)	Cross Cutting	5	TP
Pump Based Mixing	Cross Cutting	5	ZBOT / TP
Thermodynamic Vent System	Cross Cutting	5	TP
Tube-On-Tank BAC	Cross Cutting	5	In-house
Liquid Acquisition Devices	Fluid Specific	5	TP
Advanced External Insulation	Cross Cutting	4	Paragon / CELSIUS
Automated Cryo-Couplers	Cross Cutting	4	TPs, HLS, ECI
Cryogenic Thermal Coating	Cross Cutting	4	TP, In-house
High Capacity, High Efficiency Cryocoolers 90K	Cross Cutting	4	In-house
Soft Vacuum Insulation	Cross Cutting	3	MAV (MSR)
Structural Heat Load Reduction	Cross Cutting	3	CIF
Propellant Tank Chilldown	Cross Cutting	4	FY20 TP
Transfer Operations	Cross Cutting	4	FY20 TP
High Capacity, High Efficiency Cryocoolers 20K	Fluid Specific	4	In-house
Liquefaction Operations (MAV & ISRU)	Fluid Specific	4	TP / In-house
Para to Ortho Cooling	Fluid Specific	4	TP
Cryogenic Flow Meter	Both	4	TP w/o data rights
Autogenous Pressurization in Micro-g*	Fluid Specific	4	ZBOT / TP
CFM Modeling Capability			ZBOT, In-house, STRG, FO

- NASAs CFM Portfolio has contributed extensively to bringing CFM critical technologies to TRL 4-6
- Significant SBIR program leverage
- Nearly all are receiving active investments
- Recent focus has been on advancing the CFM component and subsystem technologies beyond the mid-range TRL level and developing integrated flight demonstrations to support NASAs future missions
- Future focus will be closing out the current lower TRL investments and development of the near-term flight demonstrations
- HLS Leverage for multiple components
- Industry leverage (e.g. Lockheed Martin, Blue Origin, SpaceX)
- SMD ZBOT demonstrations and model validation
- High to low fidelity model development and validation to predict future mission capabilities

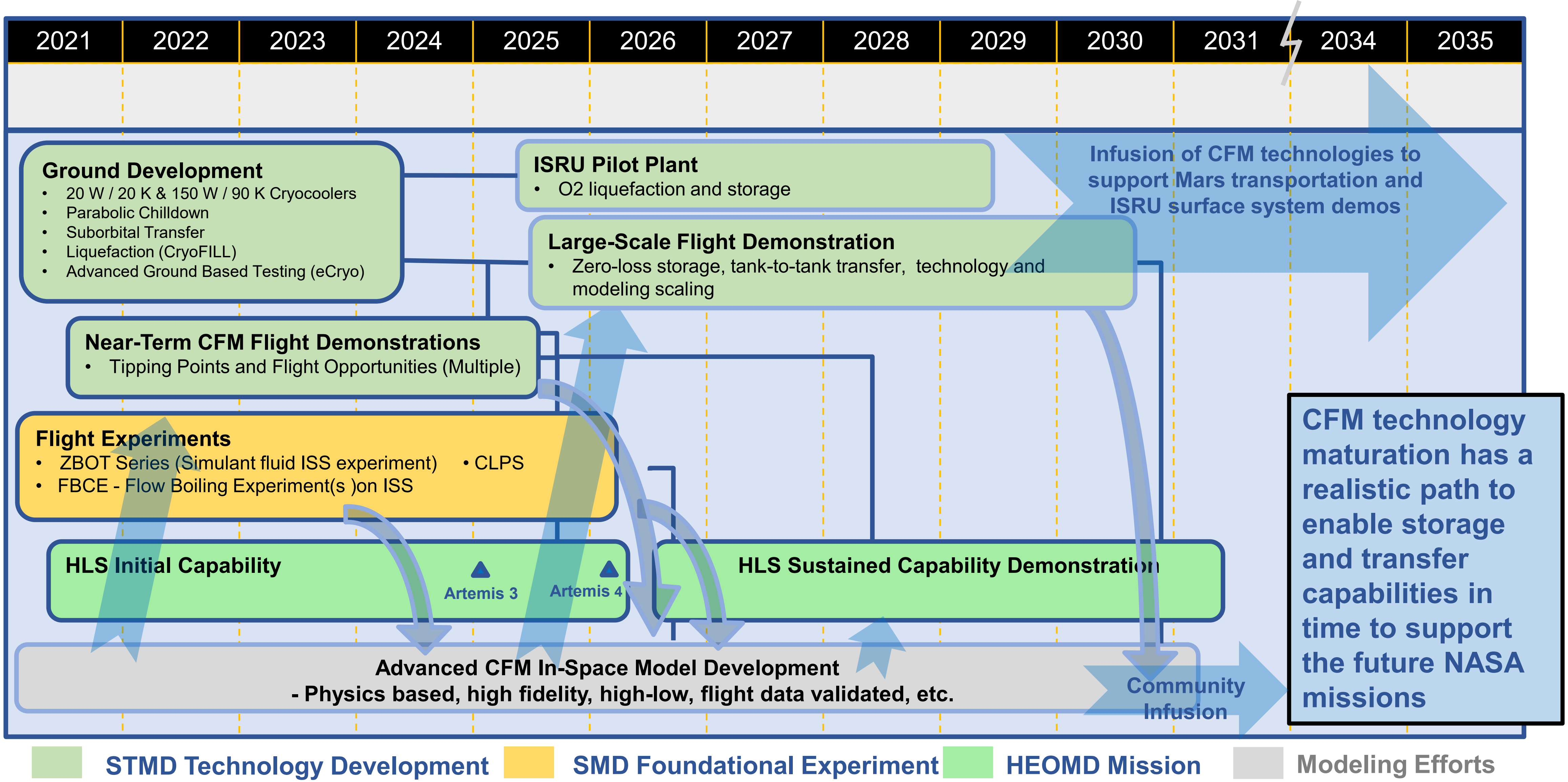
* Note:Traditional settled pressurization methods TRL 9

** Note: Addressing the gap does not in all cases equate to gap closure; some gaps are fluid or architecture specific; the goal is to develop high-fidelity models to support mission designs.

Long Term CFM Strategy and End User Applications



CFM Notional Near-Term Roadmap



Notional Timeline

Flight Demonstration are Required to Mature Tech

Capabilities Needed	Major CFM Technologies For In-Space System Concepts	*TRL6+ Reliant on Micro-Gravity Demonstration?*	*NEP / Chem, SEP / Chem, All-Chem (CH_4 Propellant)*	*NTP Vehicle, All-Chem (H_2 Propellant)*	*Artemis Sustaining Missions (H_2 or CH_4 Propellant)*
Propellant Storage throughout Mission	*TVS & Injector*	***Y***	*X*	***X***	***X***
	MLI	***N***	*X*	***X***	***X***
	150W / 90K Cryocooler	***N***	*X*	***X***	***X***
	Broad Area Cooling (Tube on Shield)	***N***	*X*	***X***	***X***
	20W / 20K Cryocooler	***N***	-	***X***	***X***
	Broad Area Cooling (Tube on Tank)	***Y***	-	***X***	***X***
	2-Stage Cooling System Design & Operations	***Y***	-	***X***	***X***
	OLAF Valves*	***N***	***X***	***X***	***X***
Propellant Transfer throughout Mission	*Unsettled Fluid Acquisition (LAD)*	***Y***	***X***	***X***	***X***
	Helium Pressurization (Unsettled)	***Y***	***X***	***X***	***X***
	OLAF Cryo-Couplers and Valves*	***N***	***X***	***X***	***X***
	Transfer System Operations; Tank and Line Chilldown (Unsettled or Settled)	***Y***	***X***	***X***	***X***
Automated Stage Operations throughout Mission	*Unsettled Mass Gauging Systems*	***Y***	***X***	***X***	***X***
	Advanced command & control avionics used for automated mission operations	***N***	***X***	***X***	***X***

LCD MISSION OBJECTIVES INCLUDE MODELING INFUSION AS PART OF TECHNOLOGY TRANSFER

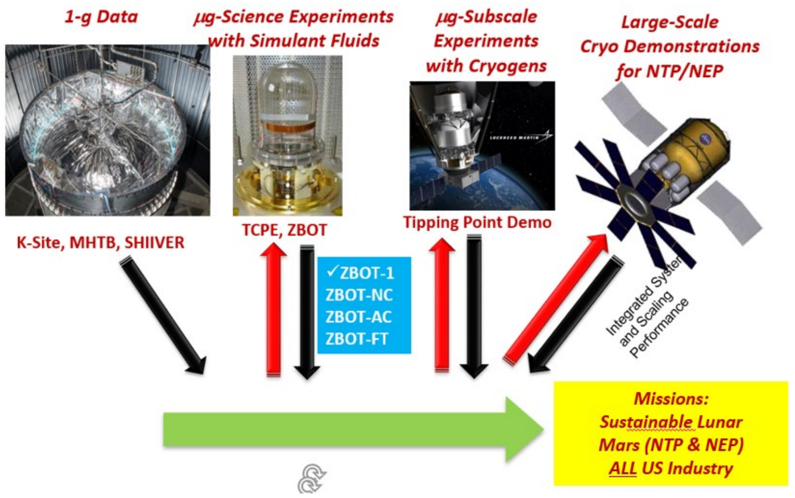
- Goal of modeling project is to close gaps in predicting the performance of cryogenic propellant in a low-gravity environment.
  - In low-g, capillary forces dominate body forces leading to non-intuitive and un-expected physics.
  - Better understanding and accurate models are critical for sizing hardware and operations for storage and transfer of cryogenic propellant in a low-gravity environment.

- Predictive Model Development work Includes:
  - First Principal Physics CFD model
  - Empirical based multi-node lumped models

- Models that are developed need to be anchored to experimental data in a relevant environment

ZBOT BPS Opportunities are Critical for Anchoring CFM Models and Closing our Technology Gaps

Infusion of Tipping Point Demonstrations to Anchor Cryogenic Models



Current CFM Model Maturity Level (CFD-Notional)

Operation	Important Process/Mechanism	Model V&V: Numerical Implementation 1g (Settled)	Model V&V: Numerical Implementation 0g (Unsettled)	Data Pedigree: 1G Sim Fluid Scaled	0G Sim Fluid Scaled	1G Cryo	0G Cryo Small –Scale	0G Cryo Large-Scale
Self-Pressurization	Evaporation/Condensation	☑	☑	ZBOT-1	ZBOT-1	K-site MHTB SHIIVER	RRM3	Future Demo
	Boiling	☑	☑		ZBOT-1		?	Future Demo
Pressure Control	Axial Jet Mixing	☑	☑	ZBOT-1	ZBOT-1 TPCE	K-Site	TP's	Future Demo
	Droplet Spray-bar	☑	Wall film formation	ZBOT-DP	ZBOT-DP	MHTB	TP's	Future Demo
	Broad Area Cooling	☑	☑	ZBOT-DP	ZBOT-DP	LOX ZBO	RRM3 TP's	Future Demo
Autogenous Pressurization	Unsubmerged	☑	☑			EDU	TP's	Future Demo
	Submerged	☑	☑			EDU	TP's	Future Demo
Tank Chill-down & Filling	Inject-Hold-Vent Cycles	☑	Droplet-liquid coalescence – wall effects	ZBOT FT Tank Filling(DLR)	ZBOT FT Tank Filling(DLR	K-site	TP's	Future Demo
Transfer line	Chill-down	☑	☑	FBCE-Line Chill-down	FBCE-Line Chill-down	UF-LN2 GRC-LH2	JAXA LN2 TP's	Future Demo
	Heating/Boiling during steady state transfer	☑	☑	FBCE	FBCE	GRC-LH2 Hendricks		Future Demo
Non-Condensable Effects	Pressurization	☑	☑	ZBOT-NC	ZBOT-NC	*Olsen*	TP's	Future Demo
	Axial Jet Condensation During Filling	☑	☑	ZBOT-NC	ZBOT-NC	Bullard LH2	TP's	Future Demo
	Droplet Phase Change	☑	☑	ZBOT-DP	ZBOT-DP	MHTB	TP's	Future Demo
Slosh	Like Pressurant	☑	☑			DLR/JAXA	TP's	Future Demo
	Unlike Pressurant	☑	☑				TP's	Future Demo
Liquefaction	Partial–g hot vapor condensation	☑	Partial - G			CryoFILL		
	Transient Behavior	☑	Partial- G			CryoFILL		

LEGEND
Understanding, Theory, & Implementation:
(NASA 7009 V&V)
- Well Understood (Level 3)
- Sufficient Eng. know how (Level 2)
- Difficulties to overcome (Level 1)
- Large knowledge gap (Level 0)

LEGEND
Benchmark Tests:
(NASA 7009 Data Pedigree)
- Level 3 Test Anchored
- Level 2 Test Anchored
- Level 1 Test Anchored
- Future V&V Target
- No V&V target

Capability Gap Performance Goals

When is the desired outcome for CFM achieved?

- When the CFM community has the technology to enable low-risk cryogenic fluid management operations with predictive performance capability across all applications, configurations, fluids and scales.

So what's the real challenge?

- There are A LOT of applications, with a range of configurations and methods of implementing the many technologies over multiple fluids over vast scales.
  - Technology performance is highly dependent on interfaces and configurations
  - Physical processes change as scales and fluids change

The envisioned future state for CFM can only be achieved through digital representations of the CFM systems anchored by BPS experiments.

**The BPS ZBOT experiment opportunities are at a premium.
Expansion to include Suborbital (minutes of μ-g) BPS opportunities enables more fluids and configurations and also maximize ISS ZBOT opportunities and add confidence for transportability of results.**