Thoughts on Cryogenic Fluid Management (CFM) Technology for Exploration Missions

Comments at the 2017 Meeting of the Committee on Biological and Physical Sciences in Space

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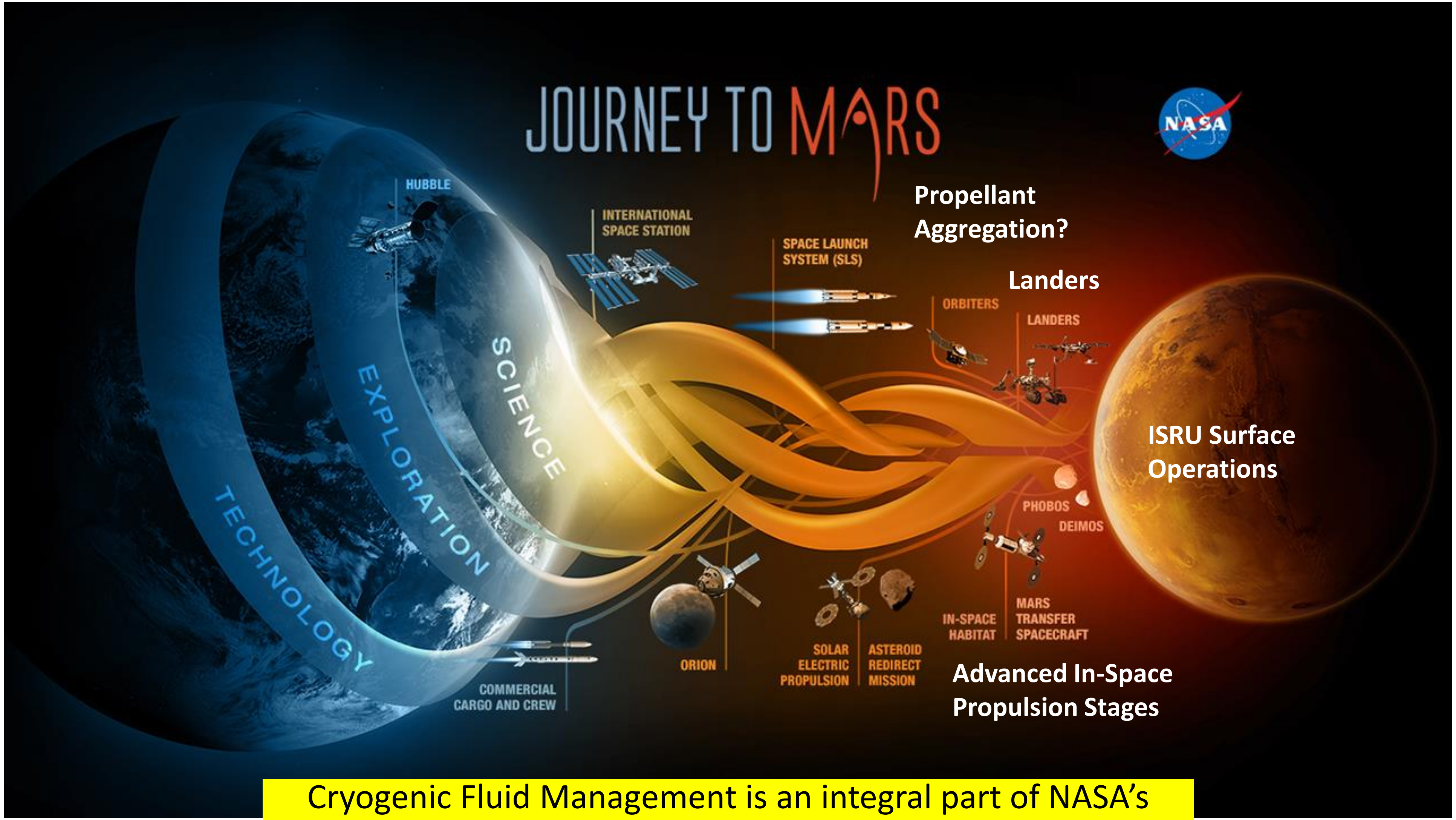
Cryogenics and NASA's "Journey to Mars"



Cryogenic Fluid Management is an integral part of NASA's Exploration plans

Approved for Public Release

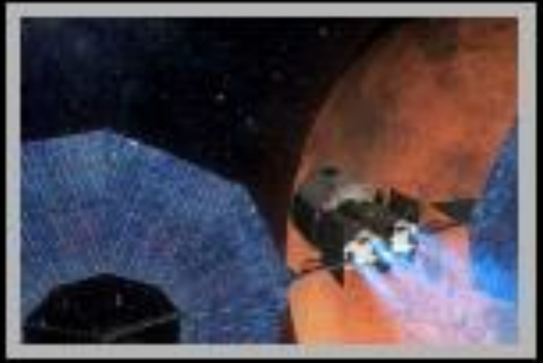
Example Candidate Propulsion Options for Crewed Mars Exploration

Split Architecture

Solar Electric Propulsion
- 440 kW Solar Arrays; 300 kW EP (2 x 150 kW)

Storable chemical propulsion
- Space storable hypergolic biprop

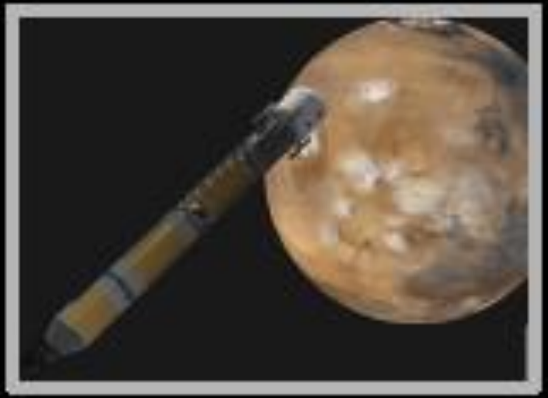
Hybrid Architecture



Solar Electric Propulsion
- 190 kW Solar Arrays; 150 kW EP

LOX / methane
- 25,000 lbf main engine; 100-1000 lbf integrated RCS
- Soft cryofluid mgt (90K)

NTP Architecture



NTP (fast transit option)
- LEU fuels & reactor dev.
- Ground test & qualification
- 25,000 lbf main engine
- Hard cryofluid mgt (20K)

Potential Enabling/Enhancing CFM Related Capabilities
- In Situ Resource Utilization (ISRU)
- Propellant transfer => tankers, propellant aggregation
- LOX/LH2 Chemical Propulsion Stages

Launch Vehicle Upper Stages Have Used Cryogens in Space for Decades. Why is the CFM State-of-the-Art Not Adequate?

=> Mission Duration

SOA launch vehicle cryogenic upper stages are typically used in space for a few hours:

- Due to the short duration, consumable losses are acceptable to mission performance
  - Propellant boil-off due to large heat loads
  - Propellant leakage overboard
  - Propellants/separate propulsion systems used to accelerate the stage and settle propellants for cryogenic propellant management, acquisition, and gauging

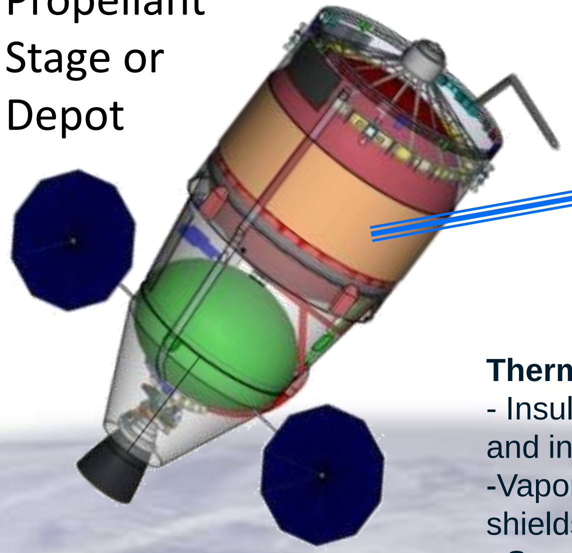
In-space transportation stages for future crewed missions to Mars will manage cryogens for many months to more than a year

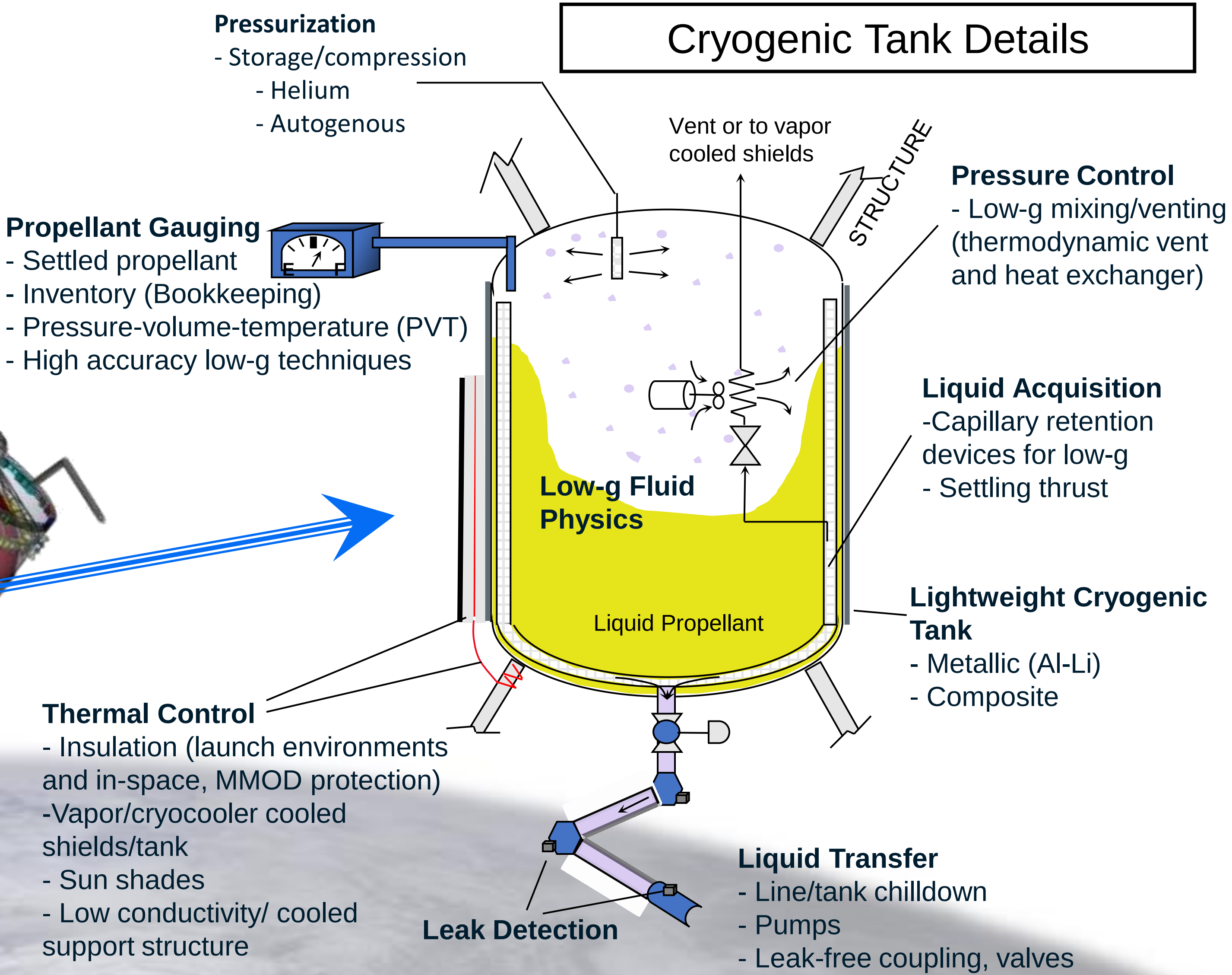
- Consumable losses accumulated over this time significantly degrade mission performance
  - Requires more launches from Earth to get sufficient initial mass in low Earth orbit (IMLEO) to complete a mission

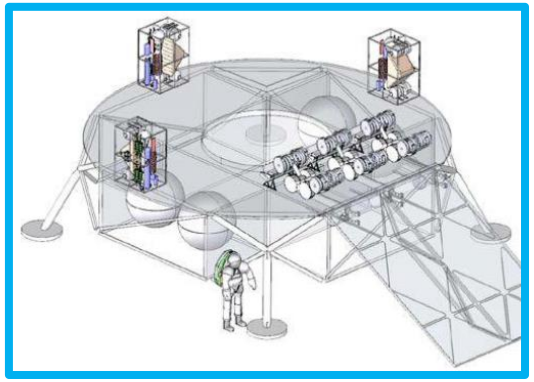
Advanced CFM Technology Can Result in a Much More Efficient Mission

Cryogenic Fluid Management (CFM) Technologies

In-Space Propellant Stage or Depot







ISRU System Needs

- Liquefaction, Storage, and Transfer
- Operation in a reduced gravity/low pressure environment

Barriers to Implementation of Advanced CFM Technology

The primary barrier is the perceived risk of the advanced technology failing to operate as expected in micro-g due to:

- *Lack of experience operating the technology in the space environment.*
- *Uncertainty associated with design/analysis tools due to limited relevant micro-g fluids data for validation (either to address specific phenomena, with cryogens, or at appropriate scale).*

Advanced CFM Technology Can Result in a Much More Efficient Mission

Relationship of Fundamental Fluid Physics Areas to Future Missions

- Natural Convection
- Forced Mixing
- Evaporation/Condensation
- Microgravity Superheat and Nucleate Boiling
- Droplet Breakup & Transport
- Droplet Phase Change
- Microgravity Two-Phase Flow & Heat Transfer Regimes/Transitions
- Interfacial Turbulence Effects
- Vapor-Side Turbulent Transport
- Non-Condensable Gas Transport
- Double Diffusive Barriers
- Marangoni Convection
- Interfacial Mass Transfer Kinetics
- Capillary Flow & Free Surface Dynamics
- Contact Angle Dynamics & Thin Film Evaporation
- Sloshing
- Phase Control/Positioning

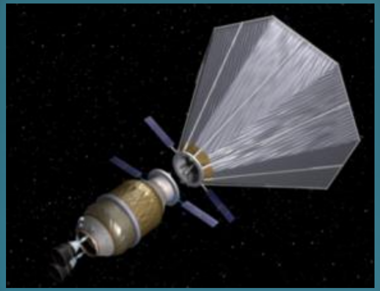
Cryogenic Fluid Management Processes

Propellant Management Systems
- Active Long Duration Cryo Storage →
- Passive Long Duration Cryo Storage →
- Quantity Gauging →
- Leak Minimization →
- Thermal Isolation of Structures →

Cryogenic Propellant Transfer
- Microgravity Fluid Transfer →
- Propellant System Chill for Transfer →
- Automated Fluid Coupling →

Cryogenic Thruster Systems
- Zero-G Cryogenic Fluid Acquisition →
- Propellant Line Conditioning →

In Situ Resource Utilization
- Liquefaction →
- Low-g Cryogen Transfer →



Cryogenic Propellant Depots (credit: ULA concept)

Large Propulsion Stages

In Situ Resource Utilization (ISRU) Lox/CH4 Spacecraft Propulsion

- → Large Science and Robotic Exploration Missions
- → Human Exploration Beyond Low-Earth-Orbit
- → Oxygen and Water Resources Platform
- → Propellant Aggregation
- → Industrial / Manufacturing Platform
- → Lunar Orbit / L2 / Mars Orbit Depots (from in-situ resources)
- → Reusable / Refuelable Upper Stages
- → Satellite Refueling and Servicing
- → Orbital Transfer Vehicle Platform
- → Large and Maneuverable Defense Systems
- → Asteroid Exploration Mining and Defense
- → Space Resources Utilization

Fundamental Fluid Physics Phenomena/Processes → **Discipline Technologies** → **Capability Technologies** → Mission Systems → Missions (Commercial & Government)

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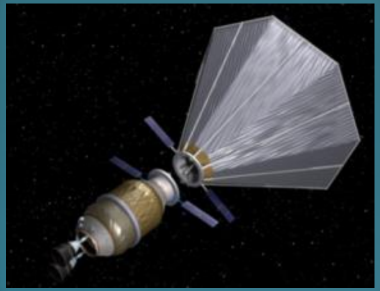
Leak Minimization
Thermal Isolation of Structures
→ **Propellant Management Systems**

Microgravity Fluid Transfer
Propellant System Chill for Transfer
Automated Fluid Coupling
→ **Cryogenic Propellant Transfer**

Zero-G Cryogenic Fluid Acquisition
Propellant Line Conditioning
→ **Cryogenic Thruster Systems**

Liquefaction
Low-g Cryogen Transfer
→ **In Situ Resource Utilization**



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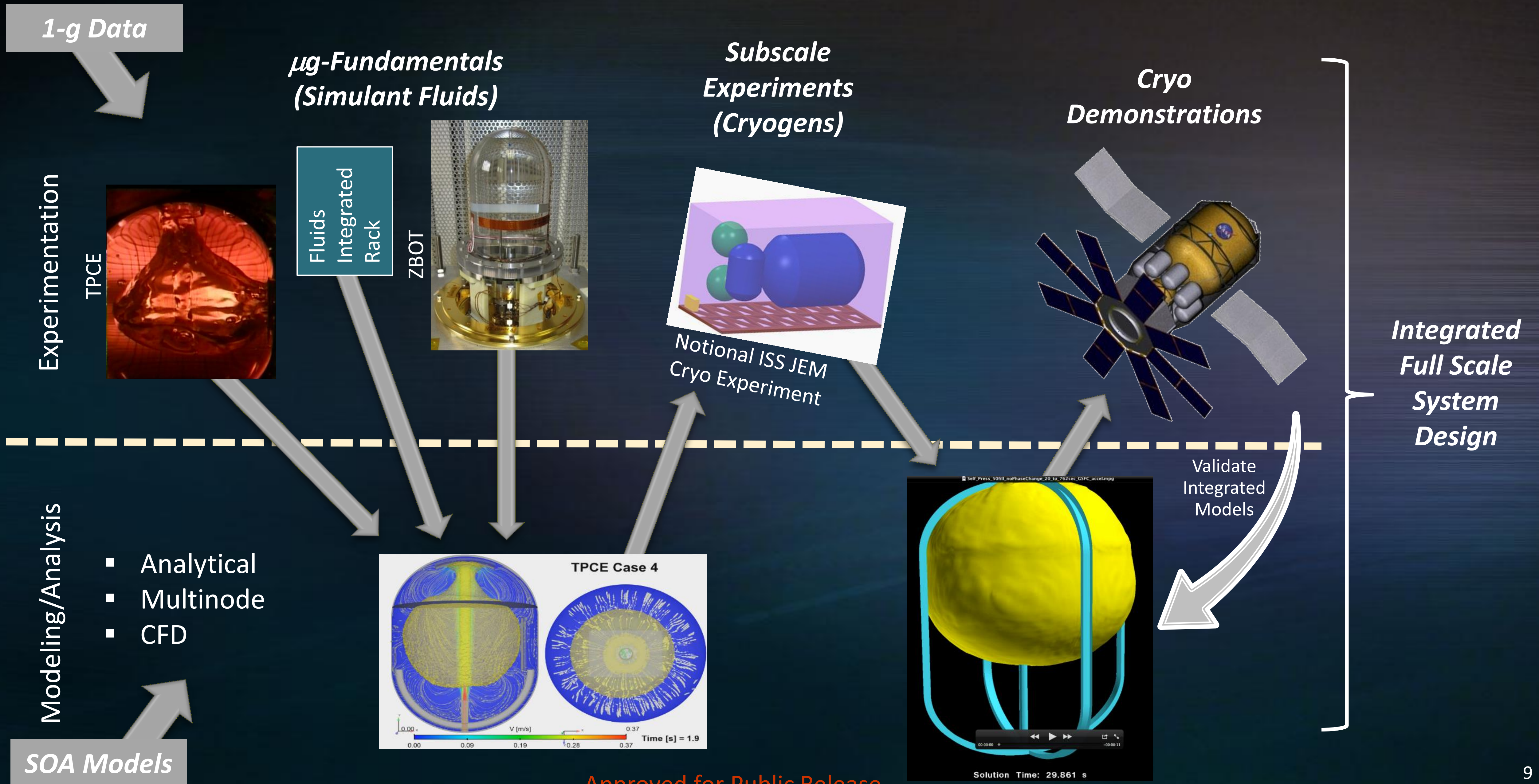
Notional Pathway to Mature Understanding of CFM Fluid Physics



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