



Microgravity Fluid Science to Enable Long-Duration Cryogenic Propulsion Missions

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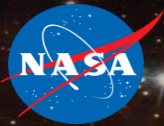


EXPLORE MOON_{to}MARS

MOON LIGHTS THE WAY

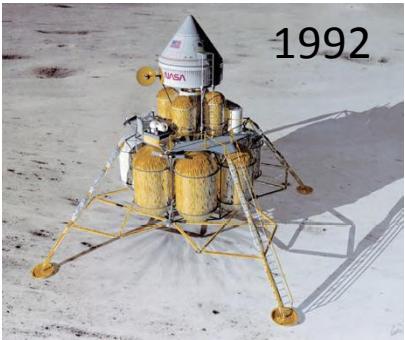


Advanced Cryogenic
Cryogenic Fluid
Management Will Be
a Critical Part of the
Crewed Missions to the
Moon and Mars ...

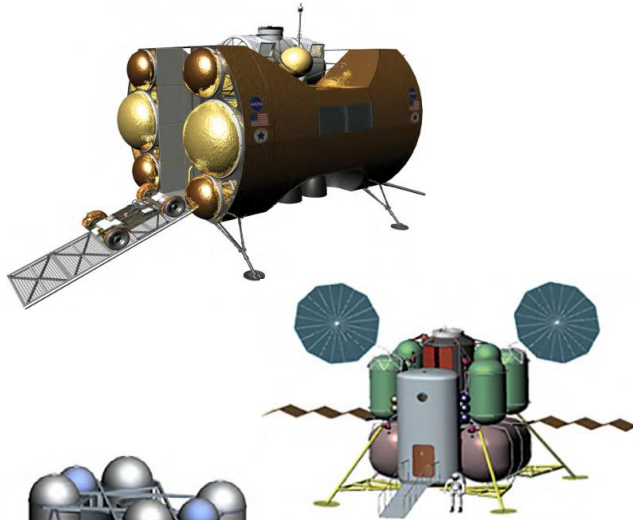


Lunar Missions

NASA and its industry and academic partners have conducted numerous studies of lunar lander options. Many of those have included high-performance cryogenic propellants (liquid oxygen with either liquid methane or liquid hydrogen fuel). In a 2019 report, Connolly* summarized roughly a hundred lunar lander concepts and variants.



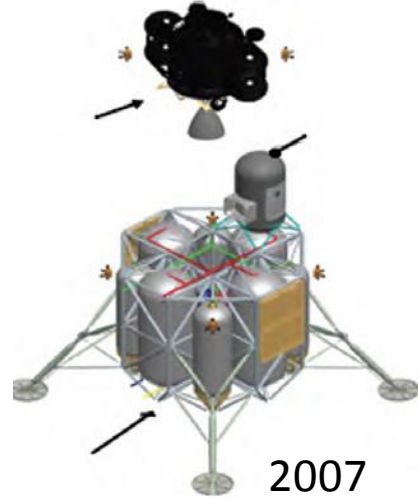
1992



2005



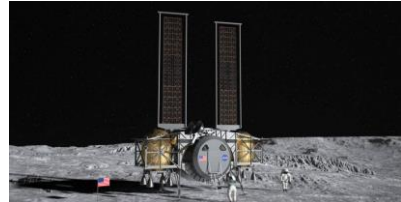
2006



2007



Credit: Blue Origin



Credit: Dynetics



Credit: SpaceX

2006 Lunar Lander Preparatory Study



Lunar Architecture Team



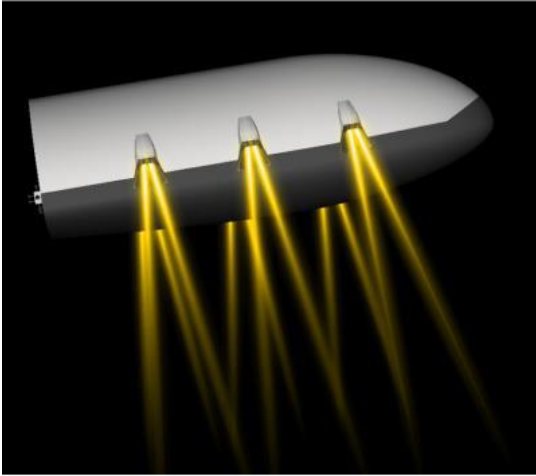
Altair



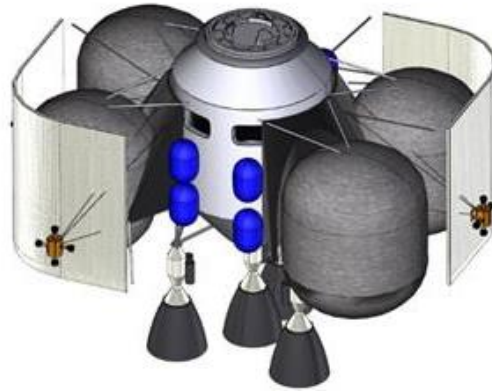
Artemis Human Landing Systems

*John F Connolly, Editor, "After LM, NASA Lunar Lander Concepts Beyond Apollo," NASA/SP-2020-220338, 2019

Mars Mission Vehicles

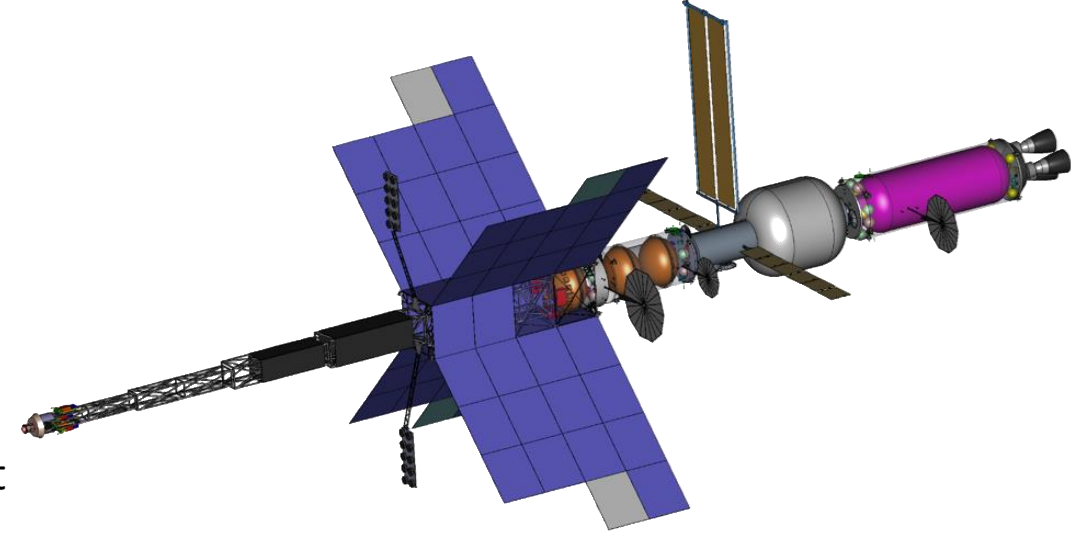


Mars Descent in Rigid Aeroshell
Vehicle Concept

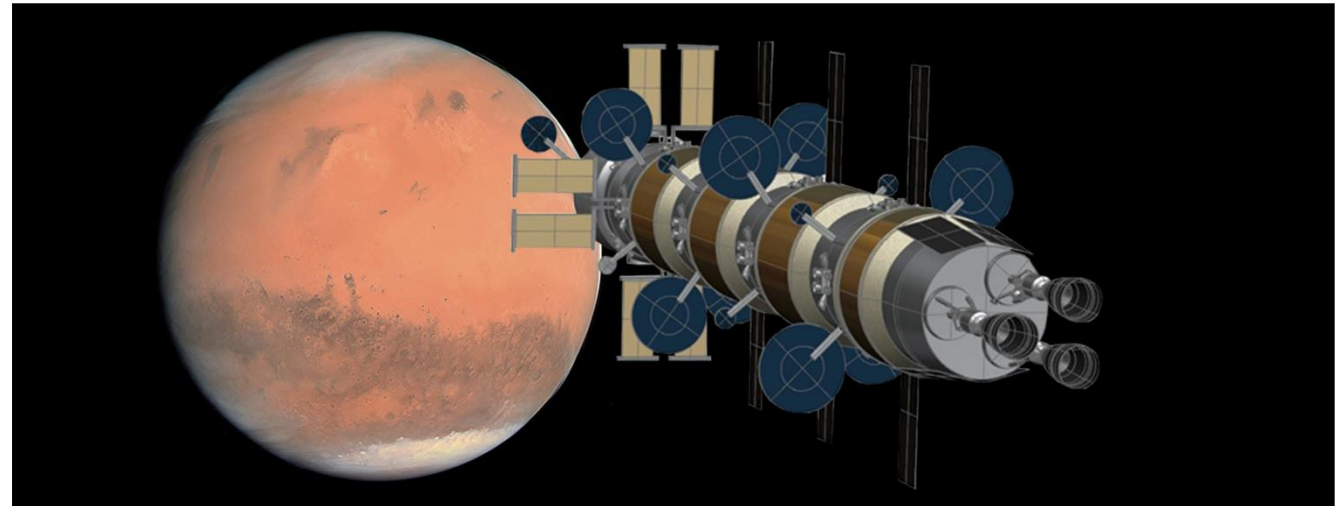


Mars Ascent Vehicle Concept

Concepts for Transportation to Mars



In Situ Propellant Production



Current state-of-the-art launch vehicle upper stages operate reliably in space with cryogenic propellants:

Why are these new missions different?

1. Storage Duration

- a) Launch vehicle upper stages operate in space for several hours before their mission is complete. They can accommodate a relatively high propellant loss rate for this short time.
- b) The crewed lunar and Mars missions require cryogenic propulsion vehicles to operate much longer in space—months to years—which in turn requires little to zero propellant loss.
 - i. The Human Lander System requires 60 to 90+ days of propellant storage and operations in space.
 - ii. Mars vehicle assembly and mission operations may require 5 years of propellant storage and operations in space.

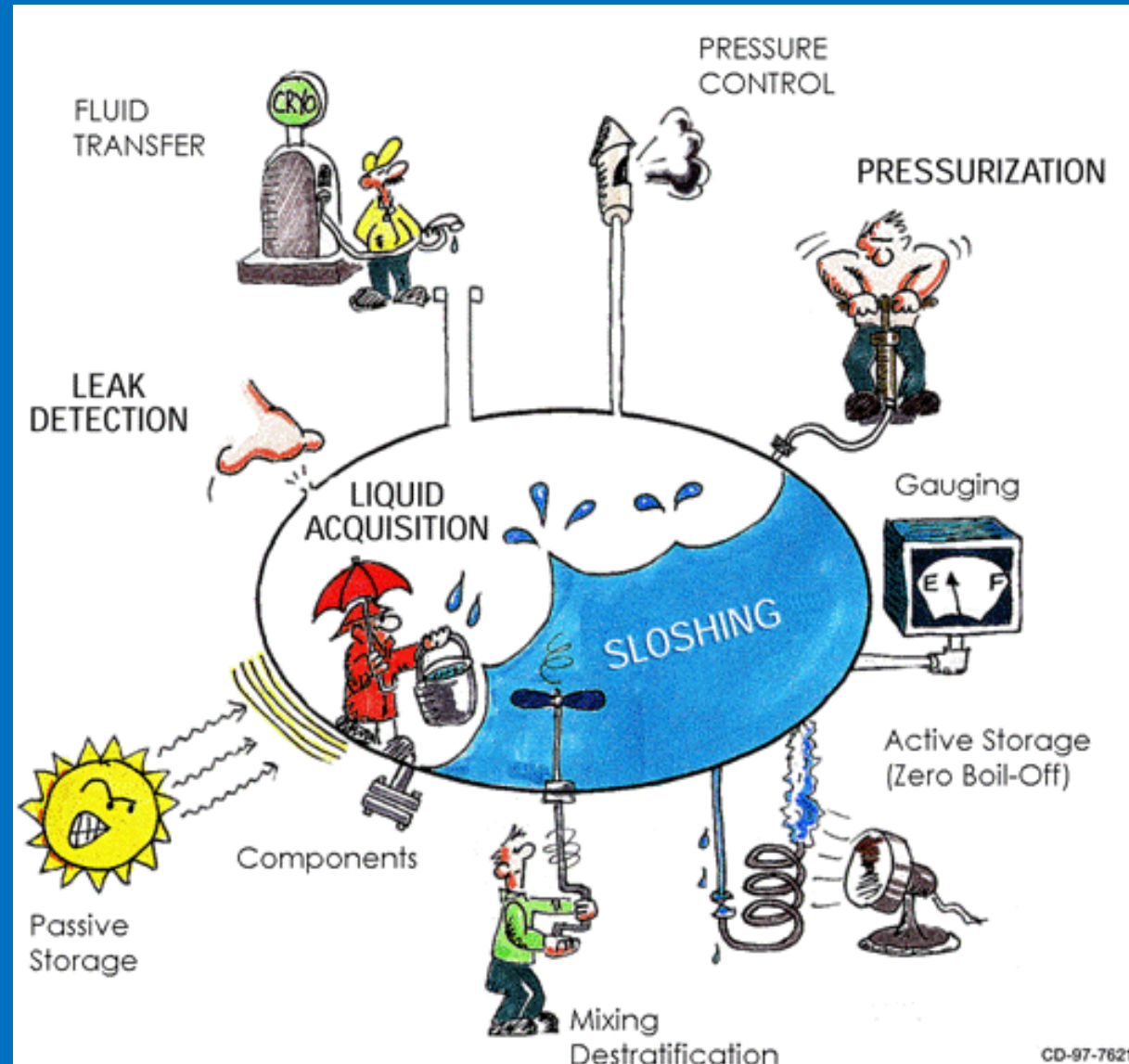
2. Propellant Management in Microgravity

- a) Upper stages rely on acceleration created by thrusters for propellant settling to manage propellant position in microgravity.
- b) For long-duration missions, the propellant consumed for settling can be inefficient and surface-tension-based propellant positioning and management may be used. This would be similar to satellite and deep space robotic probe propulsion with hypergolic propellants, but must be adapted for cryogen properties.

3. In-Space Propellant Transfer

- a) In-space transfer of cryogenic propellants has never been demonstrated.
- b) Sustainable lunar mission vehicles and crewed Mars vehicles are likely to rely on in-space fueling/refueling.

Key Processes for Cryogenic Systems



Fundamental Physical Processes in Microgravity Affecting CFM Functions



- Natural Convection
- Forced Mixing
- Evaporation/Condensation
- Microgravity Superheats/Nucleate Boiling

Phase Control/Positioning

- Interfacial Turbulence Effects
- Interfacial Mass Transfer Kinetics
- Vapor-Side Turbulent Transport



Credit: NASA

Credit: Lapilli, et al.

Credit: NASA

Credit: NASA

Credit: Mudawar

- Droplet Breakup & Transport
- Droplet Phase Change
- Droplet-Ullage-Liquid Interaction
- Microgravity Two-Phase Flow and Injection
- Contact Angle Dynamics & Thin Film Evaporation
- Heat Transfer Regimes/Transitions

- Microgravity Evolving Phase Distributions
- Free Surface Dynamics/Ullage Dynamic
- Sloshing
- Non-Condensable Gas Transport
- Double Diffusive Barriers
- Marangoni Convection

Notional Pathway to Large-Scale Cryogenic Technology Demonstration & Vehicle Design Capability



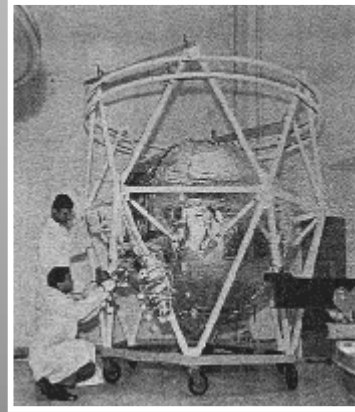
Fundamental Physical Processes Affecting CFM Functions

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Experimentation

Modeling/Analysis

1-g Data



K-Site, MHTB, SHIVER
EDU, JAXA, CNES

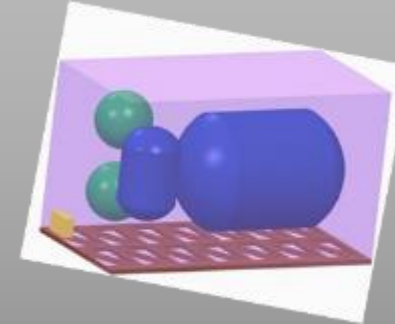
Detailed
Measurements,
Fundamental Physics

μ g-Science Experiments with Simulant Fluids



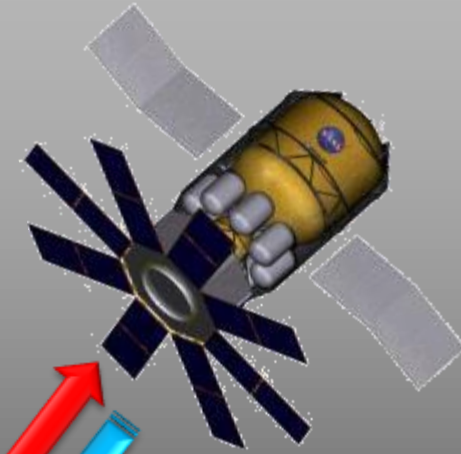
TPCE, ZBOT

μ g-Subscale Experiments with Cryogenics



Notional Cryo Experiments

Cryo Demonstrations Large-Scale



Integrated System
and Scaling Performance

SOA Models

**New State-of-the-Art Multiphase
Model Development and Validation**

**Integrated
Full-Scale
System
Design**

Foundational Understanding to Support Advanced CFM Capability Is Not a New Imperative



Scientific Direction Has Been Provided by National Academies of Science (NAS) Decadal Surveys

2000 Decadal Survey: *Microgravity Research in Support of Technologies for the Human Exploration and Development of Space and Planetary Bodies*

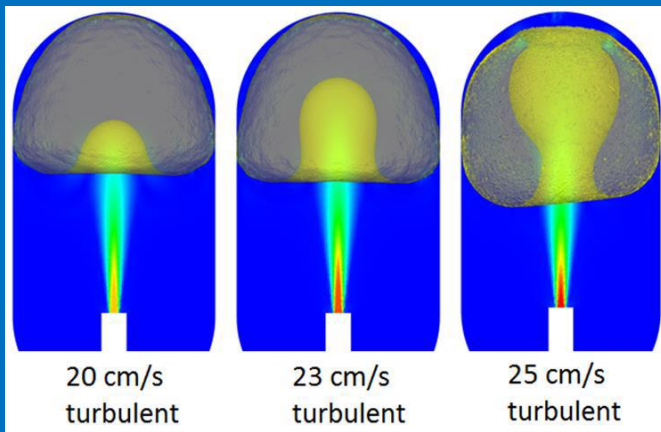
- Careful attention must be paid to understanding and modeling such important phenomena as phase distribution, phase separation, multiphase turbulence, Marangoni forces, boiling/condensing heat transfer, multiphase pressure drop, static and dynamic instabilities, and condensation-induced loads in reduced-gravity environments.
- Perform a directed program of experimental and analytical research to develop a reliable multidimensional, multi-field, two-fluid CFD model.

2011 Decadal Survey: *Recapturing a Future for Space Exploration: Life and Physical Sciences Research for a New Era*

- TSES1-T1: Research should be conducted to address active two-phase flow questions relevant to thermal management.
- TSES2-T2: Research should be conducted in support of zero-boil-off (ZBO) propellant storage and cryogenic fluid management. Physical sciences research includes active cooling, multi-phase flows, and capillary effectiveness.
- TSES2-T3: Research should be conducted in support of passive storage, fluid transfer, gauging, pressurization, pressure control, leak detection, and mixing destratification.

Key Findings & Science Deliverables of ZBOT-1 Experiment

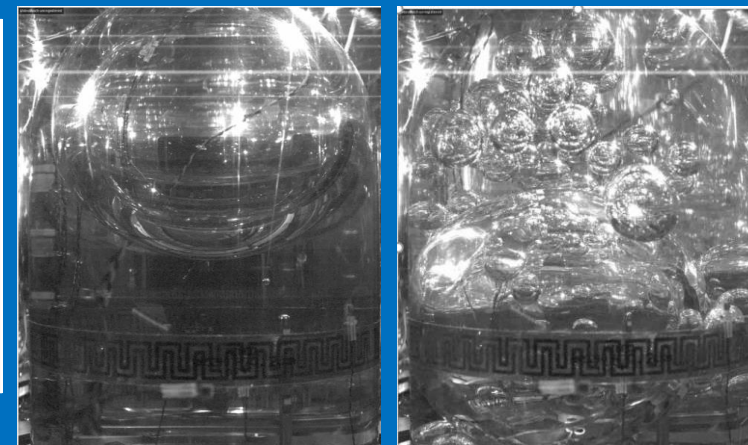
1. Provided first data on microgravity self-pressurization rate that was used to validate CFD models.
2. Showed that classic self-pressurization can be easily disrupted by nucleate boiling in microgravity as compared to 1g, due to thermal stratification in the absence of natural convection, changing heat transfer at the tank wall.
3. Revealed a non-intuitive and unexpected jet-ullage interaction and ullage deformation & movement in microgravity defying previous CFD prediction that form the basis of current tank design.
4. Established that tank fluid flow, heat transfer, ullage movement & self-pressurization rate are all insensitive to high-frequency vibrational accelerations but hugely impacted by low-frequency engine thrust acceleration.
5. Demonstrated for the first time an unexpected and inadequately understood intense microgravity cavitation during subcooled jet mixing with significant implications for tank pressure control design for microgravity operations.



**Previous CFD Model Predictions
of Microgravity Jet Ullage Interaction**



**Non-intuitive Microgravity Jet Ullage Interaction
& Current Validated CFD Model Predictions**



**Microgravity Cavitation
during Subcooled Jet Mixing**

Some Implications of ZBOT-1 findings for Propellant Tank Design



1. Thermodynamic model predictions and ground-based data can be used as conservative estimates of the stationary (long-term, undisturbed) tank self-pressurization rate needed for sizing tank insulation system.
2. Transient self-pressurization rates and pressure levels under different mission scenarios can be provided only with high fidelity by validated zero-boil-off tank (ZBOT)-CFD models to the designers.
3. Boiling will be prevalent in storage tanks in microgravity under heat fluxes that don't lead to boiling in 1g .
 - a. Use of tanks with prevalent nucleation sites on the inner surfaces is advantageous where boiling will occur sooner and with minimal intensity and is predictable by boiling incipience models.
 - b. Tanks with smooth inner surfaces can result in delayed, explosive boiling that is hard to predict and potential pressure spikes that may be detrimental to the tank structural integrity.
4. Envisioned use of thruster accelerations to position the ullage for liquid-free venting or vapor-free liquid extraction is effective, but during self-pressurization can lead to undesirably large pressure spikes.
5. Ullage–jet interaction is non-intuitive, and the envisioned use of a liquid jet to split the ullage and cool the tank wall may not be possible as envisioned by designers, especially at higher fill levels.
6. Mixing without cooling causes destratification but cannot be effective for reducing the tank pressure.
7. ZBOT experiment demonstrated that ZBO pressure control is feasible and effective in microgravity using subcooled jet mixing.
8. Unexpected ZBOT results also demonstrated intense microgravity cavitation during subcooled jet mixing that must be considered in tank pressure control design for space applications.

Concluding Thoughts

1. NASA is planning bold new missions to return humans to the Moon and ultimately to visit Mars. These missions are extremely challenging, and mission studies consistently demonstrate the benefits of leveraging propulsion with cryogenic propellants.
2. These future mission architectures impose new and challenging requirements for cryogenic propulsion:
 - a) Much longer cryogen storage durations requiring ultra-low heat loads.
 - b) Propellant management without acceleration-based settling.
 - c) In-space cryogenic propellant transfer.
3. Accurate design for high performance and safety of these systems will require high-fidelity predictive capabilities, anchored and validated with high-quality data.
4. The in-space (microgravity) environment affects many of the fundamental physical processes we need to include in physics-based modeling tools.
 - a) Microgravity phenomena, which may be third-order effects for state-of-the-art cryogenic propulsion systems, can be more critical in these new systems.

Thermal and fluid processes in microgravity will affect advance CFM system performance, yet our understanding in some areas remains incomplete. Unexpected behavior observed during the recent ZBOT-1 experiment illustrated this clearly.

⇒ The research called for by past NAS Decadal Surveys is still necessary to enable NASA's future crewed Exploration missions.