

Physical Sciences Program



Presented to
Committee on Biological and Physical Sciences in Space
Irvine, CA
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EXPLORE

Francis Chiaramonte
Program Scientist for Physical Sciences
SLPSRA



Management Team

- DeVon Griffin, PM
- Francis Chiaramonte, PS
- Kelly Bailey, GRC PM
- David Urban, GRC Science lead
- Dan Dietrich, Combustion lead
- John McQuillen, Fluids lead
- Shawn Reagan, MSFC PM
- Mike Sansoucie, MSFC, Science co-lead
- Louise Strutzenberg, MSFC, Science co-lead
- Karen Stephens, PSI Project Mgr.
- Harri Vanhala, NRESS, NRA Manager
- Preethi Manoharan, NRESS, NRA Manager

1. **Space Policy Directive and Lunar Explorations**
2. **SLPSRA Vision**

Status, Planning, and Research Accomplishments

3. **Physical Sciences Program, Overview and Collaboration Summary** - *Longstanding partnerships with other organizations and, if appropriate, our leadership role in that partnership, Include partnerships with CASIS ISSNL; emphasize where we provided scientific expertise*
4. **Research Accomplishments, Highlights and Platforms**
5. **SLPSRA Spinoffs** - *The benefits for exploration and/or life on Earth*

Trends, Forecasting Science Directions in the Community

7. **Workshops and NRA Plans** - *Interactions with the broad community through things like SDTs, workshops, PSI*
8. **Collaboration Experiments for Exploration**
9. **Potential new concepts and Collaboration**

Challenges of Interest for the Decadal Survey

10. **Challenges**

Backup

11. Candidate Partial Gravity Experiments
12. Flight Project Mapping to Decadal Survey Identifiers & PSI Investigations - *The linkage to the high priority research areas in the Decadal Survey*
13. Collaborations Partnerships and agreements
 - Russia
 - ESA
 - JAXA
 - DLR
 - CNES
 - S. Korea
 - ISSNL
 - NIST
 - NSF
 - STMD
 - AES

1. Space Policy Directive and Lunar Explorations

SPACE POLICY DIRECTIVE-1



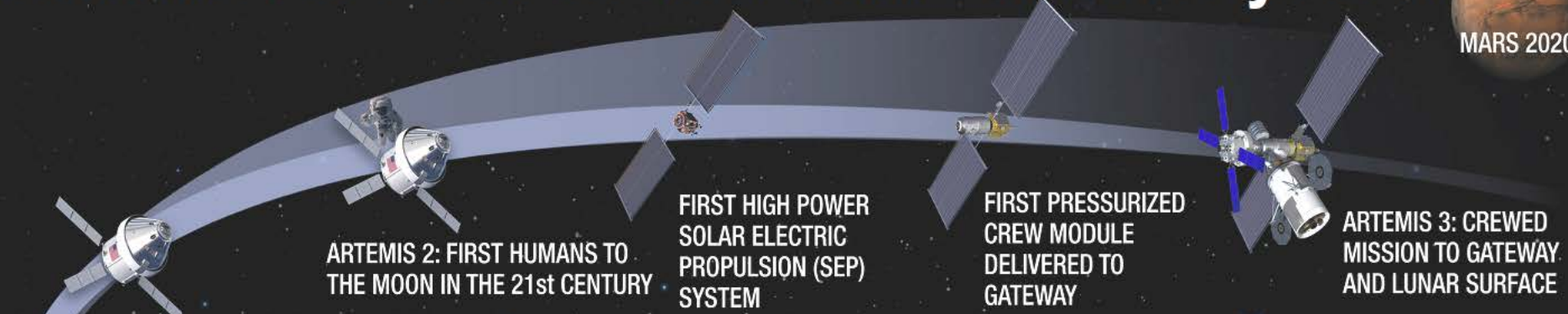
“Lead an innovative and sustainable program of exploration with commercial and international partners to enable human expansion across the solar system and to bring back to Earth new knowledge and opportunities.

Beginning with missions beyond low-Earth orbit, the United States will lead the return of humans to the Moon for long-term exploration and utilization, followed by human missions to Mars and other destinations.”

Artemis Phase 1: To the Lunar Surface by 2024



MARS 2020



Commercial Lunar Payload Services
 - CLPS delivered science and technology payloads

Early South Pole Crater Rim Mission(s)
 - First robotic landing on eventual human lunar return and ISRU site
 - First ground truth of polar crater volatiles

Large-Scale Cargo Lander
 - Increased capabilities for science and technology payloads

Humans on the Moon - 21st Century
 First crew leverages infrastructure left behind by previous missions

LUNAR SOUTH POLE CRATER TARGET SITE

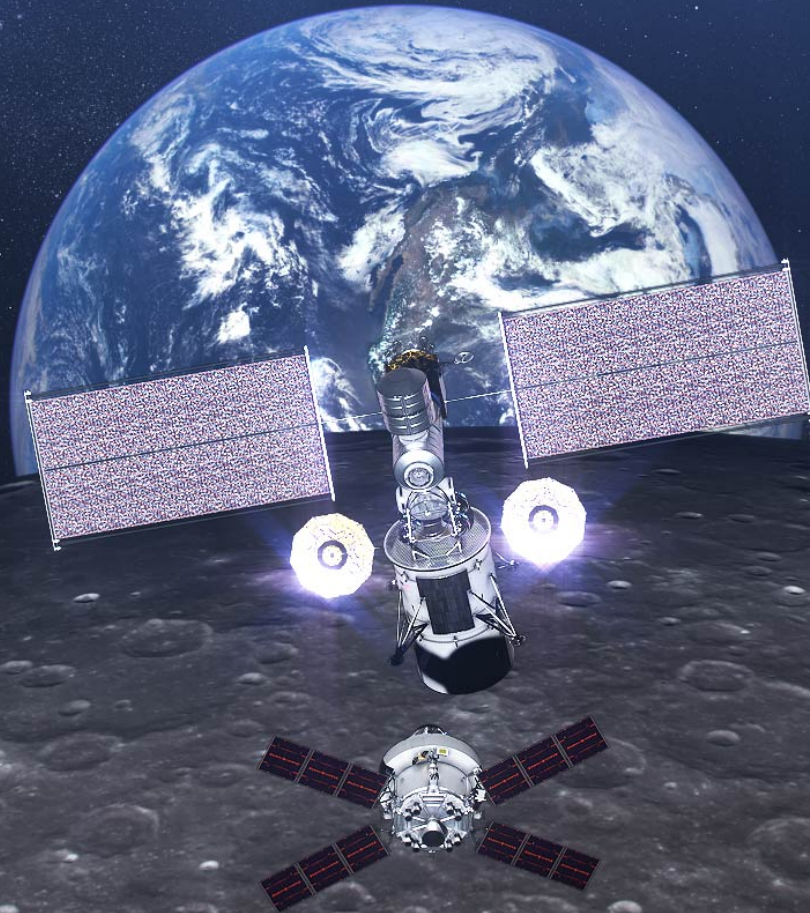
Phase 1 & Phase 2 Definitions

Phase 1: Today – 2024 Human surface landing

Missions and systems required to achieve landing humans on the surface of the Moon in 2024

Phase 2: 2024

Establish a sustainable long-term presence on and around the Moon



Phase 1 Gateway configuration focuses on the minimum systems required to enable a 2024 human lunar landing

- Provides aggregation point for 2024 human expedition to the South Pole
- Establishes strategic presence around the Moon
- Adds resilience and robustness in the lunar architecture
- Provides building block for potential future, expanded capabilities on and around the Moon



DEVELOPMENT IS UNDERWAY

2024

Develop essential hardware and systems required for a 2024 landing

CREW

At least 2 on the South Pole

SUITS

Initial capability suit

EXPEDITION DURATION

Hours-Days (open trade)

ROCKETS



PARTNERS



Significant collaboration with U.S. industry



Potential opportunities for international partners

ACCESS



REUSABILITY

not required



2028

Establish a sustainable human lunar presence with robust, reusable systems

CREW

Up to 4 on the Moon

SUITS

Sustained capability suit

EXPEDITION DURATION

Days-Weeks (open trade)

ROCKETS



PARTNERS



U.S. industry and international collaboration

ACCESS



REUSABILITY

mostly reusable system



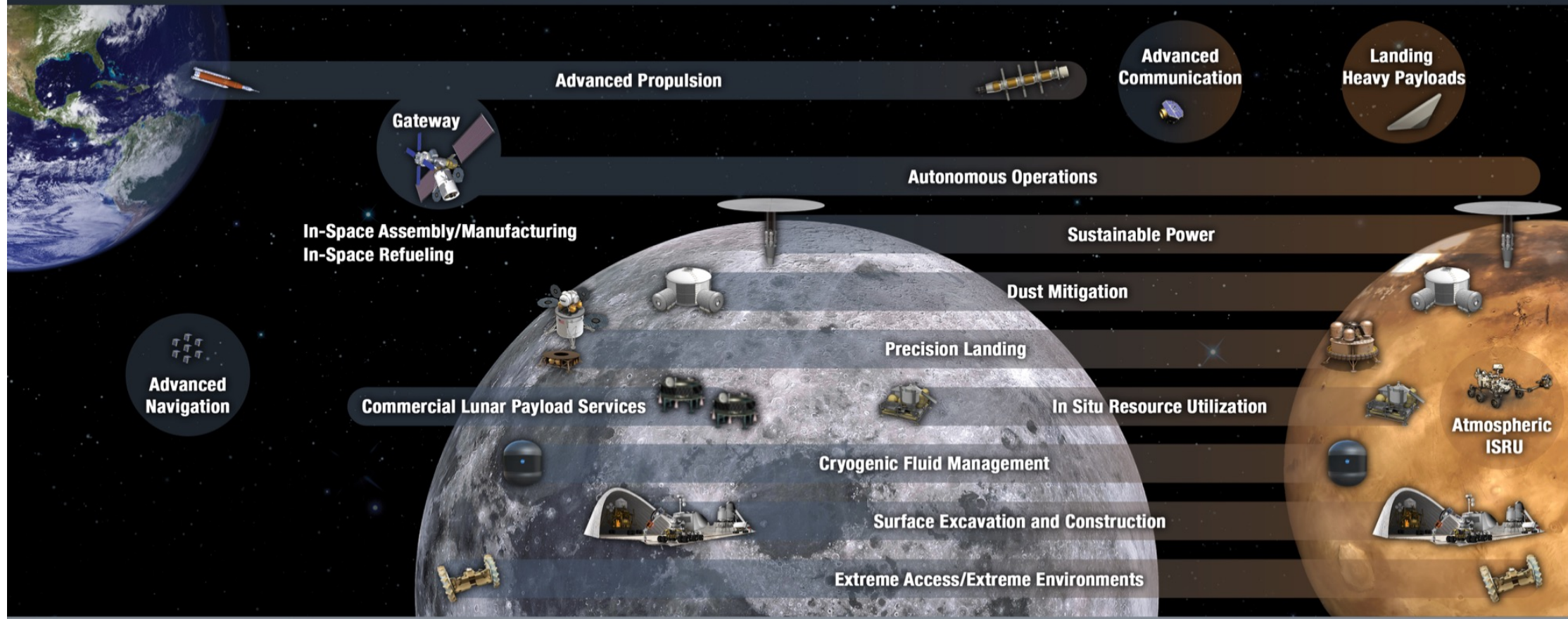
Reaching The Moon And Mars Faster With NASA Technology

Rapid, Safe, and Efficient
Space Transportation

Expanded Access to Diverse
Surface Destinations

Sustainable Living and Working
Farther from Earth

Transformative Missions
and Discoveries

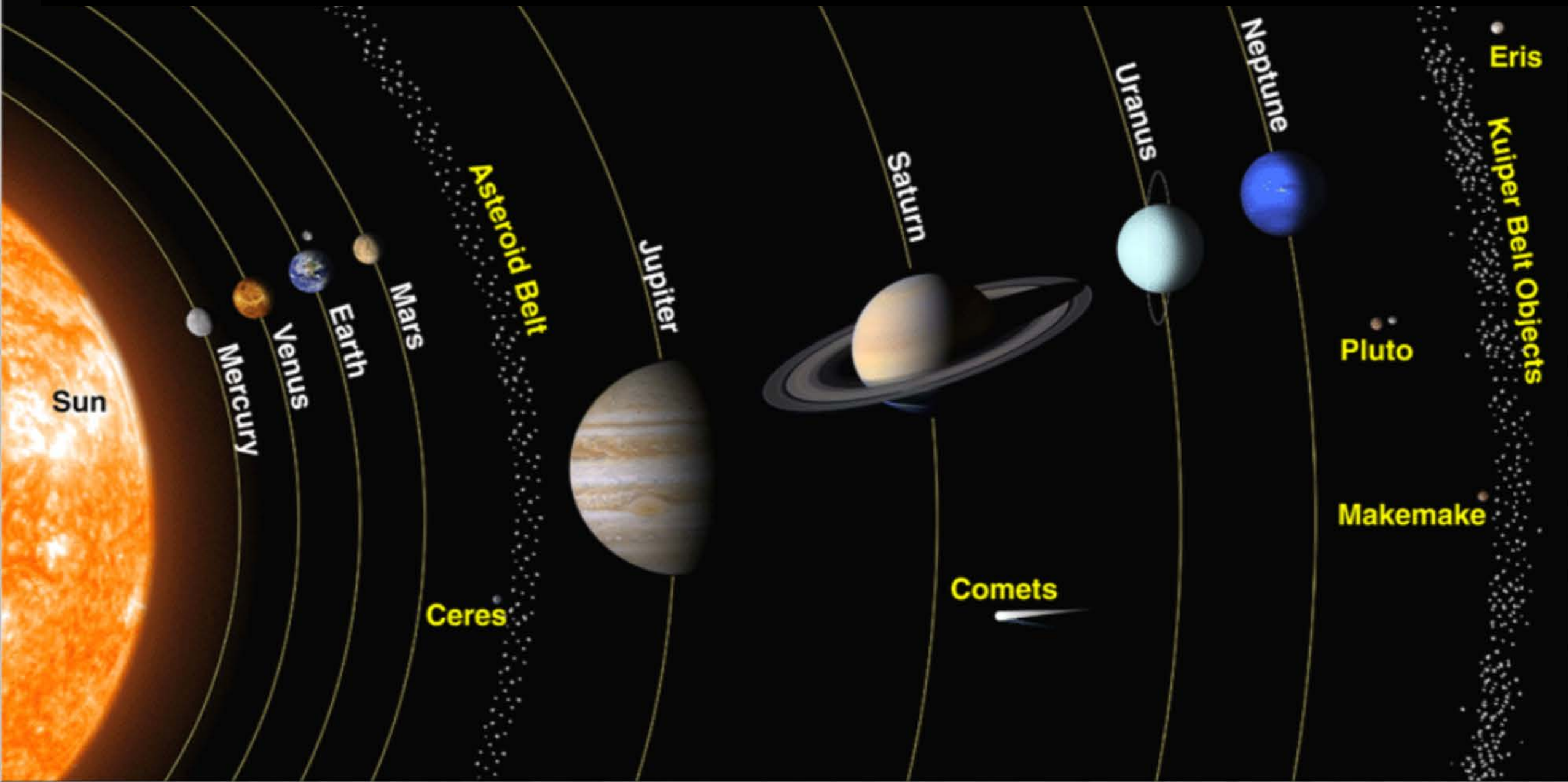


2020

GO | LAND | LIVE | EXPLORE

203X

OUR SOLAR SYSTEM

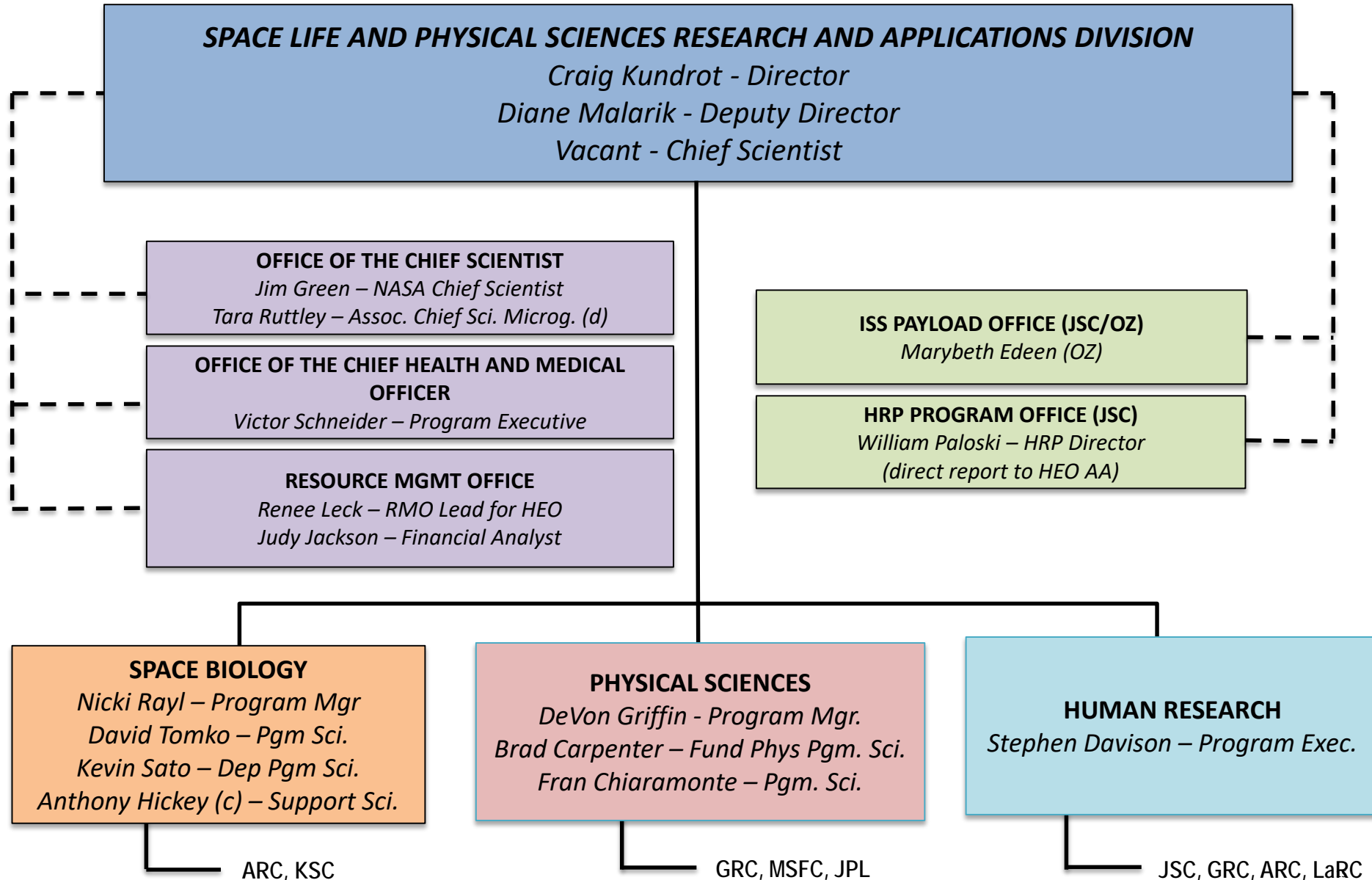


CONCEPT MARS HABITAT



2. SLPSRA Vision

Space Life and Physical Sciences Research and Applications Division (SLPSRA) Organizational Structure

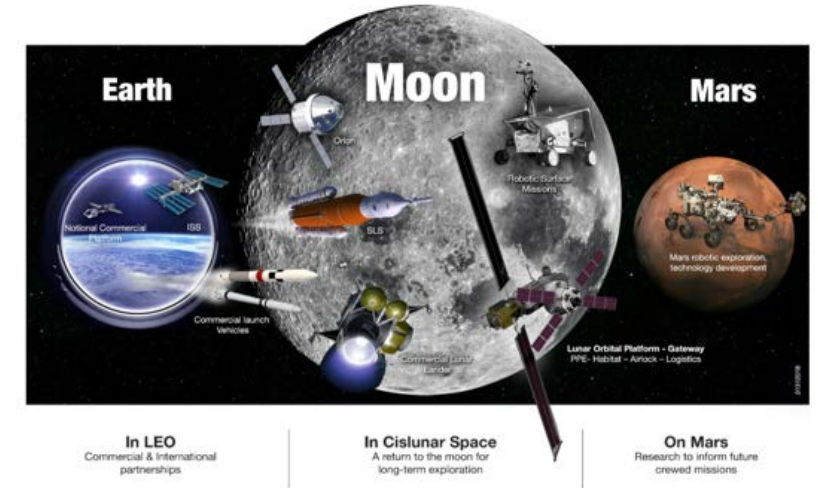


Vision

We lead the space life and physical sciences research community to enable space exploration and benefit life on Earth

Mission

1. Enable exploration (EE)
2. Pioneer scientific discovery (PSD)

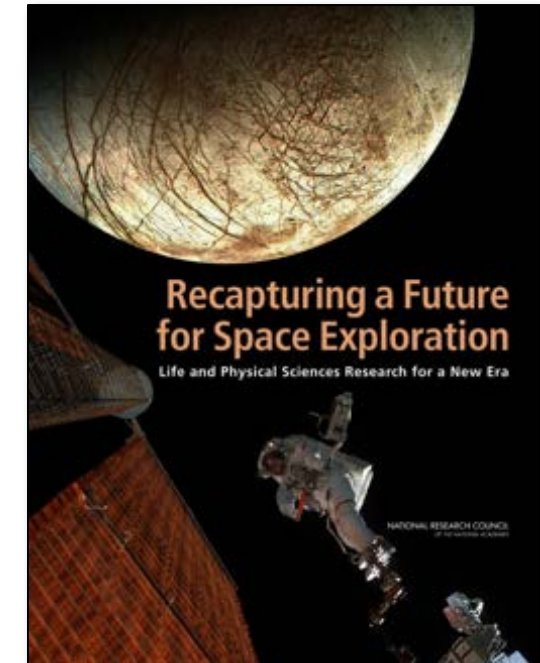


Goals

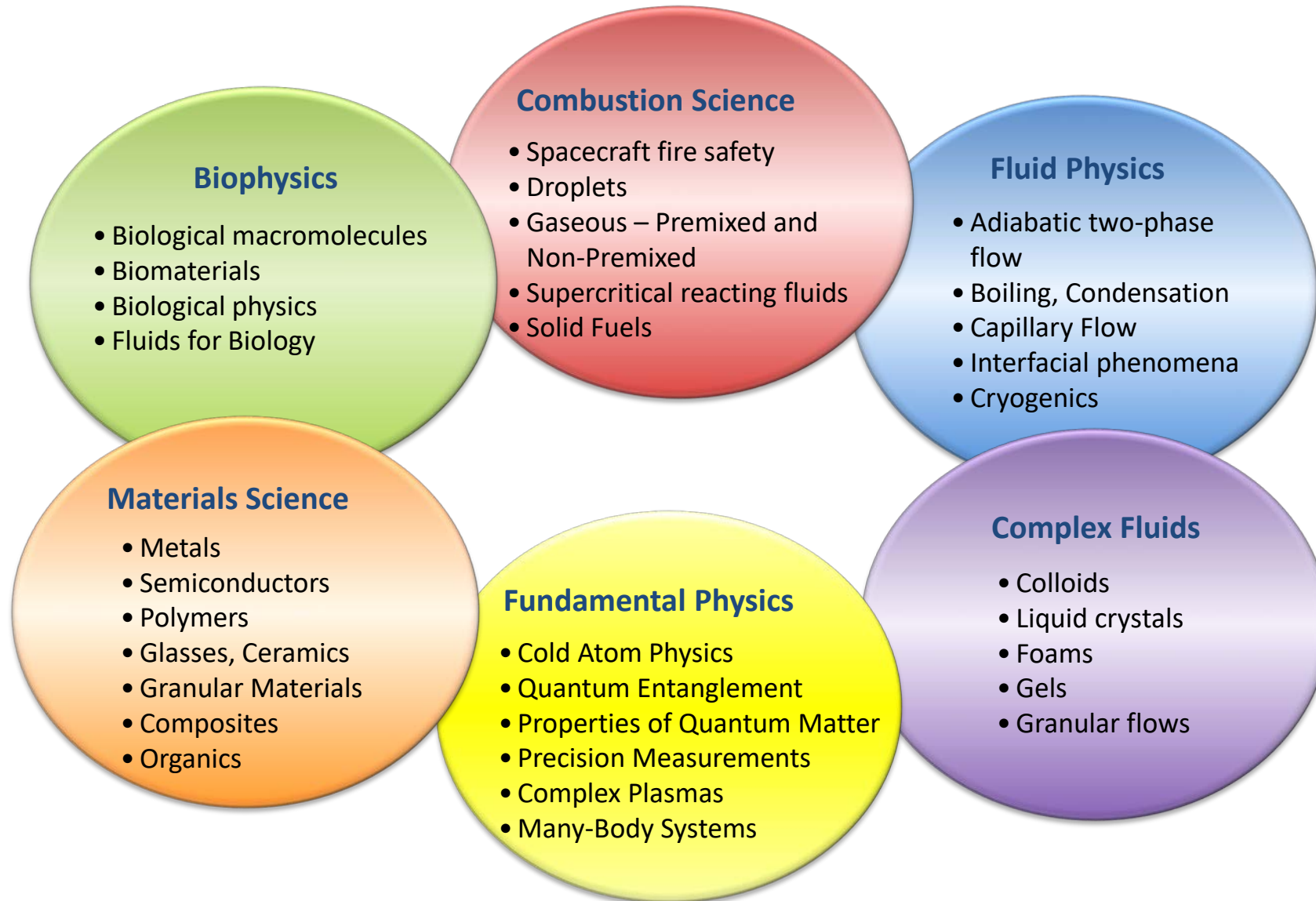
1. EE in response to pull
2. EE by providing push
3. PSD by refining use of all platforms
4. PSD by helping others utilize space
5. Inspire and train next generation
6. Maintain key capabilities

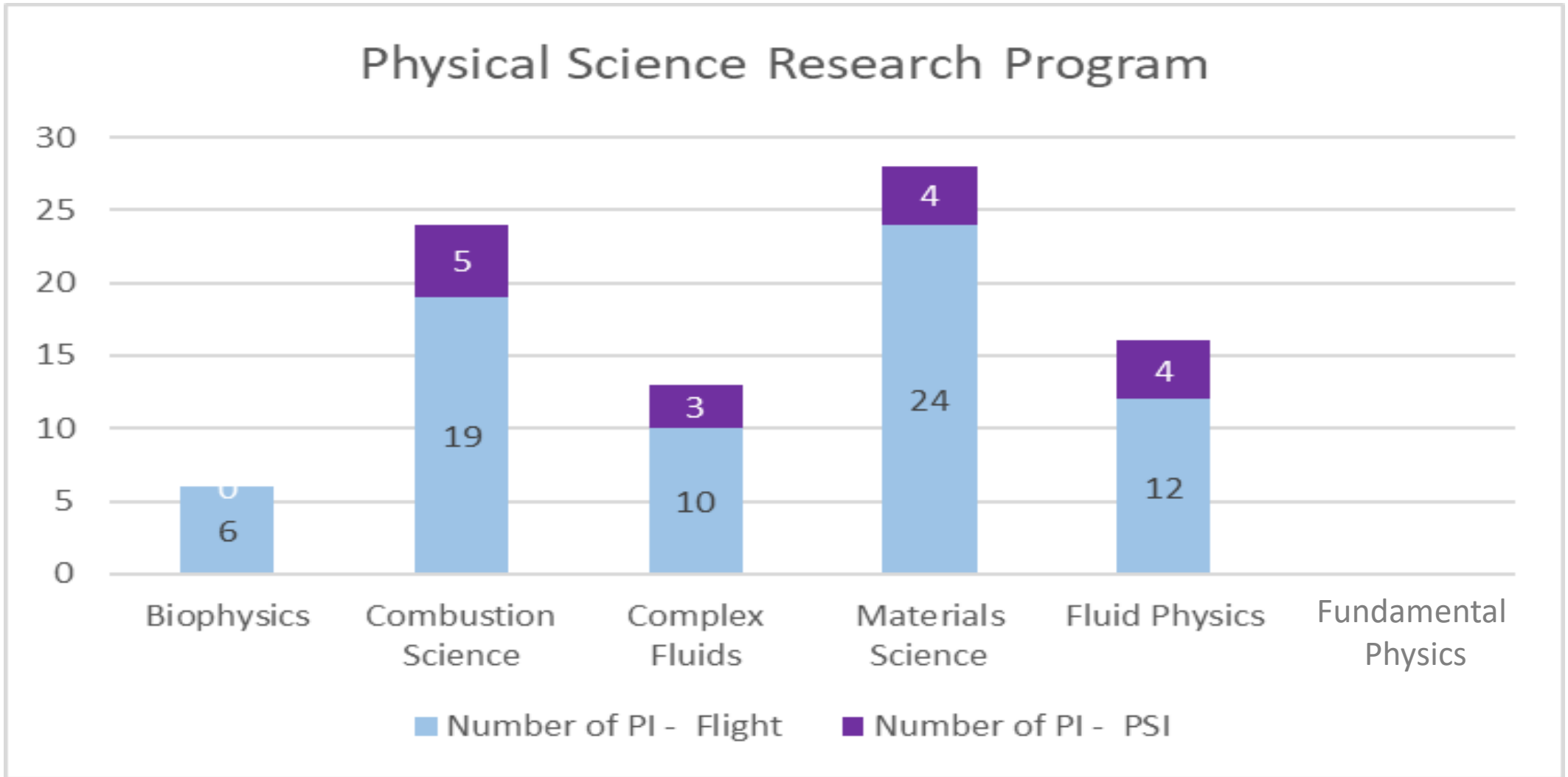
Implementation Principles

1. Ensure Scientific Integrity
2. Maximize Open Science
3. Cultivate Partnerships
4. Use Stepping Stones
5. Be an Early Adopter
6. Share Methods and Results



3. Physical Sciences Program Overview and Collaboration Summary

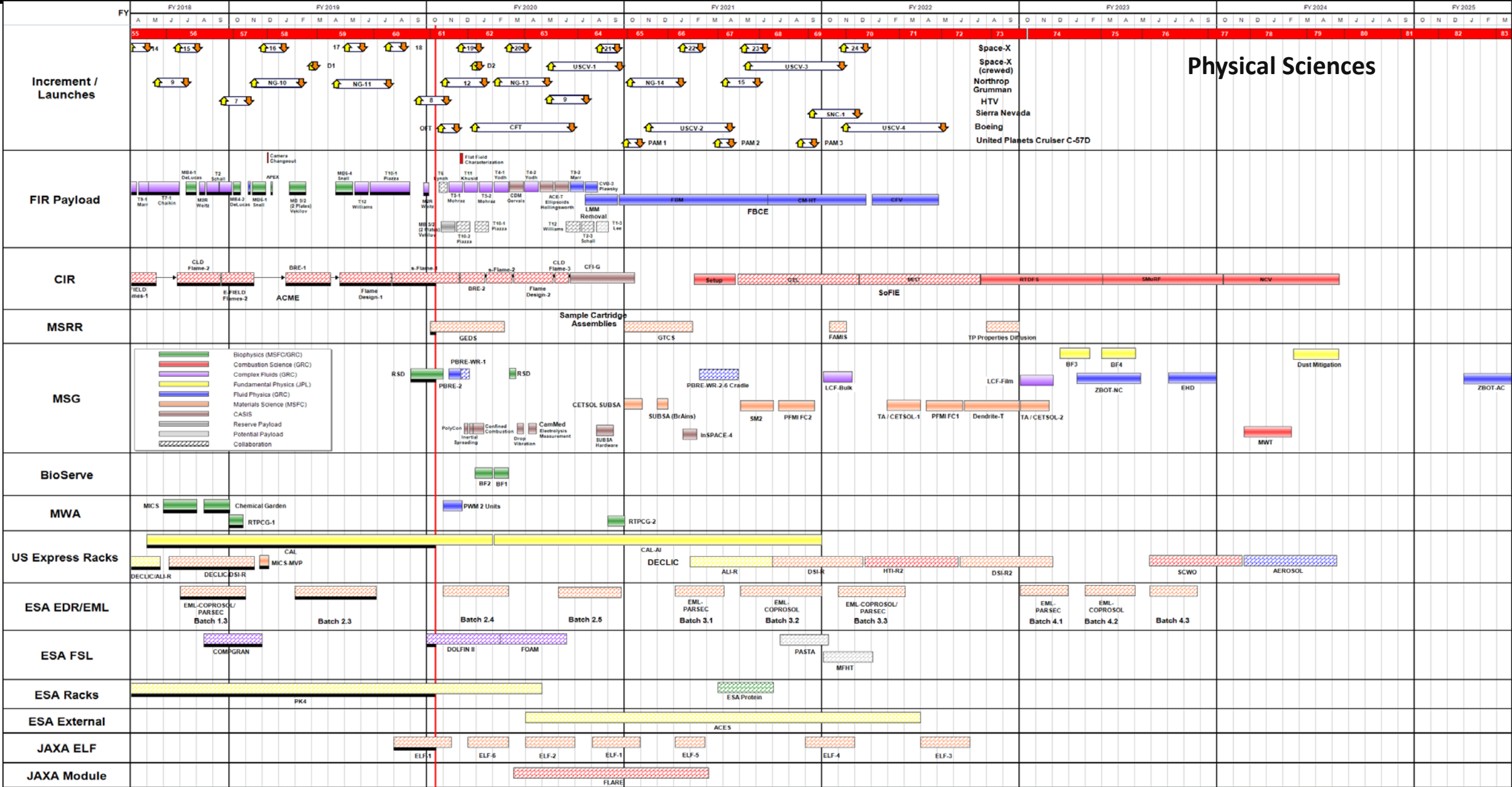




* Fundamental Physics presented separately



Physical Sciences ISS Utilization Schedule





Collaboration Summary for Physical Sciences



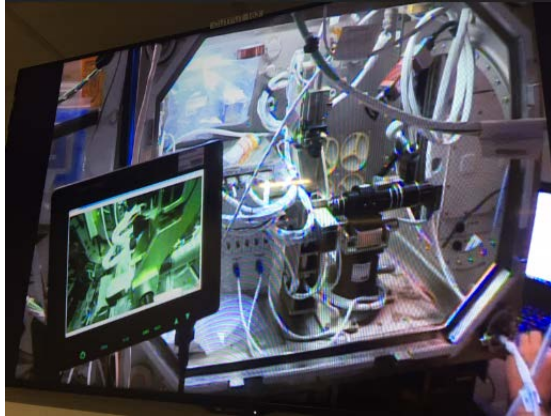
Agency	Expts	Disciplines	Experiment Acronyms	Notes
Roscosmos	15	Complex Fluids, Combustion, Materials Science	OASIS* CFI, ACME-E-Field, BRE, S-Flame, Flame Design, CLD Flames, SoFIE-Gel, SoFIE-MIST, Brazing, Diffusion, LCF-Bulk 1,2, LCF-Film 1,2,3	Russian Crew time for Russian investigator access to NASA SLPS experiment
ESA	25	Complex Fluids, Fluid Physics, Fundamental Physics, Materials	EML: Batch 1-M,K,H , Batch 2-M,K,H, Batch 3-M,K,H, Batch 4-M,K,H, MSRR/MSL: Cetsol, Micast, MFHT, FOAM, Dolfin, Pasta, Compgran , PK-4, ACE T2, ACE T10, Protein, Transparent Alloys, ACES, PK4	Access to ESA hardware in exchange for NASA Crew time and upmass
JAXA	5	Materials Science, Combustion	ELF-US- 1, 2, 3, 4, 5, 6; Flare, FLEX-2J , GCE-US	Access to JAXA furnace for various NASA resources and experiments
CNES	7	Combustion, Fluids, Fundamental Physics	HTI-R , ALI-R, DSI-R, HTI-R2, DSI-R2, SCWO and AEROSOL	CNES hardware NASA upmass crew time
DLR	3	Fundamental Physics, Fluid Physics	CCF , BECCAL, ZBOT-FT (ground program)	DLR hardware, NASA upmass and crew time
South Korea	2	Complex Fluids	ACE - T1 , ACE-T1R	NASA resources, S. Korea share science
ISS National Lab (CASIS)	11	Biophysics, Complex Fluids, Materials Science	LMM Bio-1 , LMM Bio-3 , MICS , RTPCG-1 , RTPCG-2 , ACE-T6 , ACE-H2 , ACE-T1 , ACE-2R , ACE-T7 , ACE-T9, MICS	NASA hardware & PIs, ISSNL crew time MICS - ISSNL investigators
NIST	4	Fundamental Physics, Materials	ACES, MICS , MICS-MVP , ELF-US-1	NIST Co-I on proposals
NSF	1	Fundamental Physics	PK-4	NSF funded, select own PIs
Multi Agencies	1	Combustion	Transcritical Combustion (ground program)	SLPS drop tower rig, guest PIs, discussion
NASA - STMD	3	Fluid Physics	ZBOT , ZBOT-NC, ZBOT-AC, ZBOT-FT	SLPS Hardware, STMD sim. Code
NASA - AES	6	Fluid Physics, Combustion	PBRE-WR 1 - 6, SCWO	SLPS core hardware, AES PI, test articles

* Blue wording- Completed Experiments

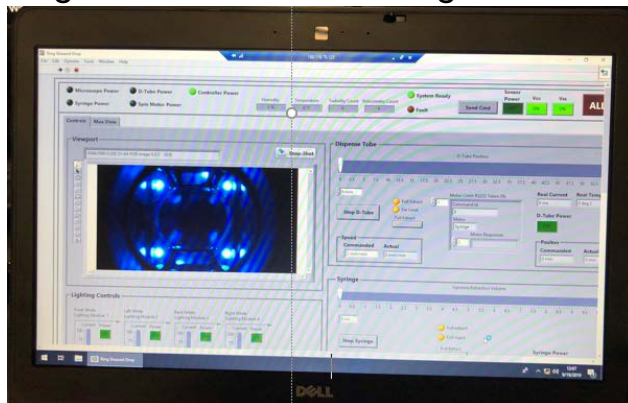
4. Research Accomplishments and Highlights

On-Orbit Operations

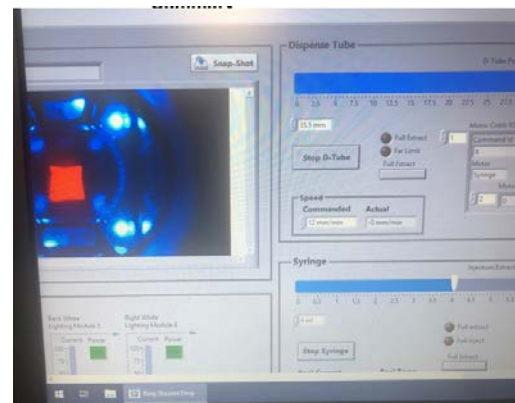
- **RSD was installed** in the MSG 9/19/2019 by Astronaut Nick Hague. The installation went very smoothly and took ~1.5 hours



- **Within 90 minutes** the Windows 10 computer inside the RSD was Communicating with the remote Operator in the HOSC; the lights were working and the motors turning...



LED Lights in the RSD – as viewed through the Observation Camera



Red LED: Turbidity Light as viewed through the Observation Camera

A Science@NASA YouTube that featured MICS launched in July, (<https://www.youtube.com/watch?v=JC-OA-EkmOY>), and has had over 22,200 views. This past week, the internet began churning with new articles highlighting the experiment – 19+ and 2 short informal YouTubes last week alone.

CNN World online published “**Astronauts make concrete in space for the first time**” at <https://www.cnn.com/2019/09/10/world/astronaut-cement-space-station-scj-trnd/index.html> and another substantial article, “**Astronauts mix cement on ISS, pave way for future space colonies**” at Astronomy.com <https://astronomy.com/news/2019/09/first-cement-mixed-in-space-paves-the-way-for-otherworldly-buildings> likely called attention to the experiment and which led to the many additional articles this week.

2 YouTubes including a “**Slap You With Science: Astronauts Make Cement In Space**” at <https://www.youtube.com/watch?v=JC-OA-EkmOY> and “Astronauts make cement in space for the first time” at <https://www.youtube.com/watch?v=XAmUYEpMUTO> .

Additional Web articles:
The article was picked up by at least 17 more websites.

Microgravity Investigation of Cement Solidification using the Multi-use Variable-gravity Platform (MICS-MVP)

This project examined cement solidification in microgravity to help better understand the chemistry and microscopic structures involved and how changes in gravity may affect the process. This investigation is foundational for understanding **cement hydration** on extraterrestrial bodies, and it sheds considerable light on crystal hydration kinetics, phase formations, pore distribution, and material properties. Understanding and controlling the crystal growth kinetics and morphology could significantly increase cement strength. The Multi-use Variable-gravity Platform (MVP) allowed the investigation of how cement may hydrate in Lunar or Martian gravity.

CNN covers MICS work

9/10/2019

0 Comments

<https://www.cnn.com/2019/09/10/world/astronaut-cement-space-station-scj-trnd/index.html>



Astronauts make concrete in space for the first time

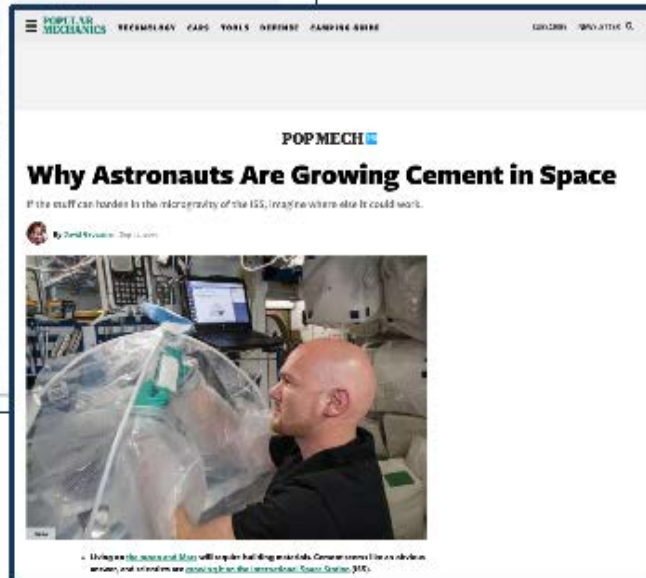


By Ashley Strickland, CNN

Updated 11:27 AM ET, Tue September 10, 2019



CNN World online



Popular Mechanics online

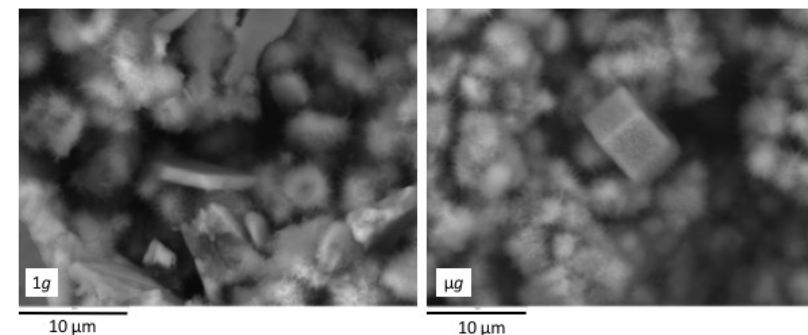


μg observations:

- Better distribution of hydration products (minimal sedimentation)
- Prismatic (uniform) growth of CH
- Increased porosity within the matrix

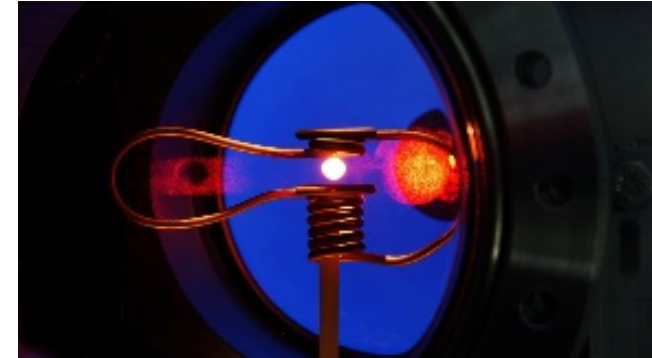
Inferences:

- Change in microstructure will change material properties
- Results provide benchmark data toward understanding cement hydration on extraterrestrial bodies such as the moon and Mars.



Calcium hydroxide (CH, portlandite) crystals seen in the fractured cross section of C_3S pastes solidified in 1g and μg . The hexagonal CH crystal morphology is plate-like in 1g, while prismatic in μg .

- **Batch 2 is currently on ISS**
 - Batch 2.3 ran February through June, 2019
 - Batch 2.4 will begin in October, 2019
- **Batch 3 is tentatively scheduled to launch in late 2020**
- **Batch 4**
 - Proposals were due July 15, 2019
 - Dr. Hyers submitted 2 and collaborated on 9 others
 - Dr. Matson submitted 2 and collaborated on 7 others
 - Dr. Kelton submitted 1 and collaborated on 1 other
 - Selection & Flight TBD



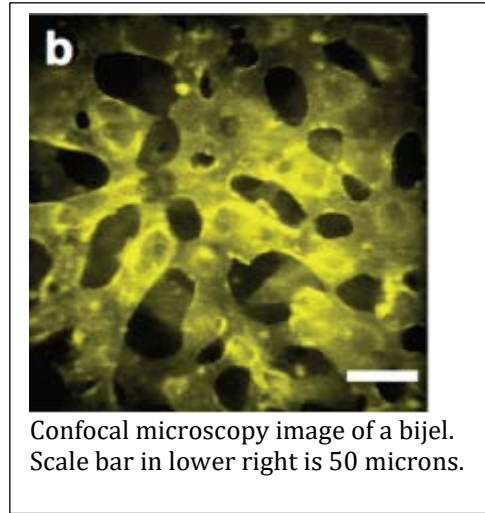
Electromagnetic Levitation

Performing electromagnetic levitation in the microgravity environment of the ISS provides an opportunity for a better understanding of **the physical properties of metals** and bulk metallic glasses. Levitation provides the opportunity to perform “containerless” experiments that eliminate the interactions between a sample and the container wall. The microgravity environment removes the effects of gravity as the samples are melted and solidified. Levitation experiments in FY19 provided data for several PIs. Objectives of these PIs included: 1) better manufacturing of cast superalloy components to improve efficiency, safety, and reliability of rocket and jet engines; 2) understanding the ability of metallic liquids to form Bulk Metallic Glasses, which are an emerging class of materials with several applications, including cryogenic gears for planetary exploration; 3) investigating thermophysical properties of high-temperature materials to allow more efficient and reliable production of metallic parts using these alloys.

Three Advanced Colloids Experiments (ACE) operated in the Fluids Integrated Rack and Light Microscopy Module to study colloids:

- ACE-M2R (Weitz, Harvard) samples were observed again after first imaged 5 years ago and being exposed to the microgravity environment. The prolonged absence of sedimentation led to particles aligning themselves into rows that formed microcrystals. These crystals did not propagate from the container wall (as in 1-g), but which were initiated within the colloidal solution. Initial analysis suggests that gels will eventually “freeze”
- ACE-T-10 (Piazza, Italy) studies colloids in which the attraction between nanoparticles gets stronger with increased temperature. While at room temperature, the colloid behaves as a liquid. When the suspension is heated to above 40°C, the particles rapidly stick to each other, forming a rigid network that can sustain its own weight – a process called gelation. By placing the system under controlled stress without the directional masking effects of gravity, the ability to understand some forms of material aging and collapse (including some types of earthquakes) become possible.
- ACE-T-12 (Williams, University of Louisville) examined particle “haloing”, where smaller particles halo (shroud) larger particles thus controlling attractions between particles. The goal of this experiment is to increase the number of charge carriers in a gel colloidal system and holds open the possibility for a significant increase in solar panel efficiency.

- Operations Completed for ACE-T10 June 18 – August 30
- PI Visits and ground testing: ACE-T4 (July 23-25), ACE-T11 (August 5-6), ACE-T5 (August 13-14)
- Samples filled ACE-T11 (September 4-6) and T5-1 & 2 (September 10-12)
- ACE-T10 featured by ISS Chief Scientist at NG-11 FRR (April)



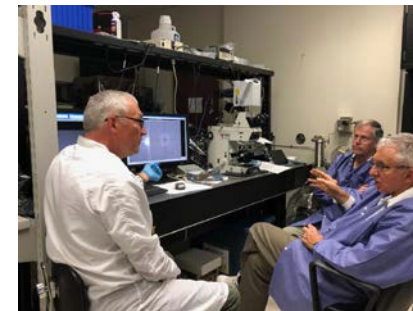
ACE-T10 site visit: Buzzaccaro University of Milan, Italy



ACE-T4 Experiment Site visit and ground simulation with Chandan Kundan from the University of Pennsylvania



Two of the publication covers by Professor Mohraz



Grounding testing of ACE-T-11 flight samples, August 5-6, 2019



ACE-T5 Experiment Site visit and ground simulation with Science Team from the University of California-Irvine,

PI: Mark Weislogel, Portland State University

- **Units 1 & 2**

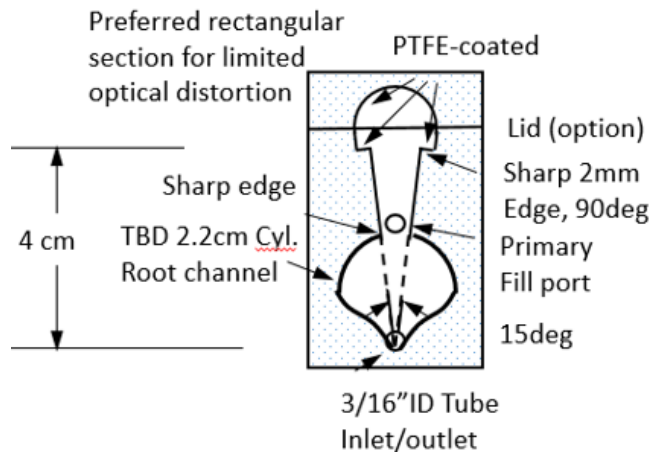
- Soil (PWM-S) and Hydroponics (PWM-H) experiments launched in July on SpaceX CRS-18

- **Units 3 & 4 (REMIS)**

- Awarded to CSS
- Root Accommodation Channel (PWM-HRAC) and Parallel Hydroponics Channels (PWM-PHRAC)
- Kickoff meeting in August
- CDR scheduled in October 2019



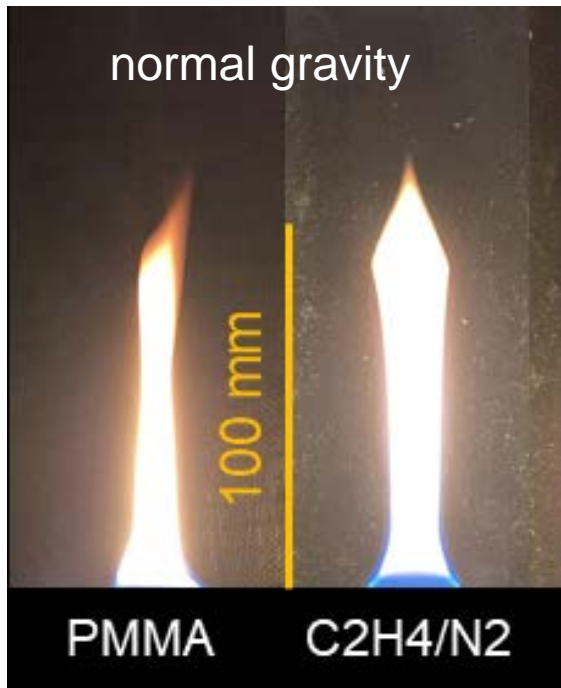
PWM-S (left) & PWM-H (right) installed in Maintenance Work Area Engineering Unit at NASA JSC



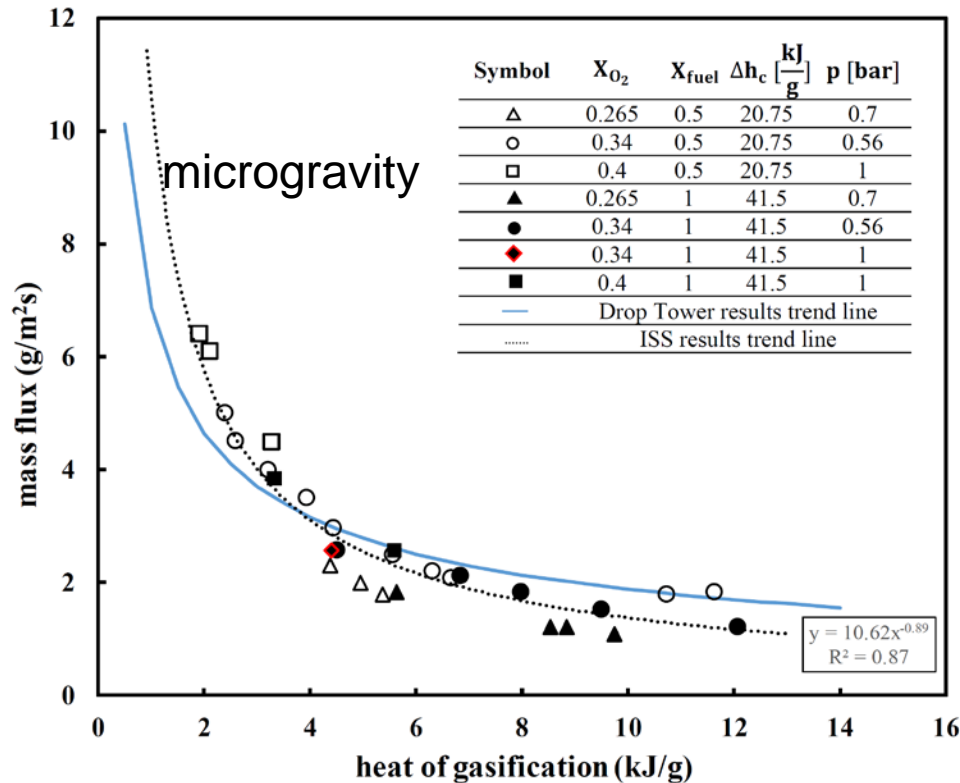
Cross-sectional schematic of Hydroponics Root Accommodation Channel

In a collaborative effort with SLPSRA Plant Biology program and NASA KSC, the plant water management experiment was launched to the ISS to identify issues with the use of soil substrates and satisfactory plant hydration and nutrition, and root aeration. A hydroponics test cell concept is being evaluated as hydration concept for a food production capability in space.

- **High Pressure Transcritical Combustion facility operational in drop tower (experiments this year - 1 MS thesis, 1 publication)**
- **ACME Coflow Laminar Diffusion Flame experiments on ISS leading to improved simulation capabilities and new design tools**
- **ACME Burning Rate Emulator experiments on ISS providing insights into polymer burning in microgravity**
- **ACME Flame design experiments on ISS providing valuable data on soot formation processes in idealized flames**
- **ACME Electric-Field Effects on Laminar Diffusion Flames on ISS showing the degree to which an electric field can control and stabilize flames**
- **Flammability Limits At Reduced-g Experiment workshop with participants from ESA, JAXA and NASA highlighted status of flammability research and roadmap for future work**



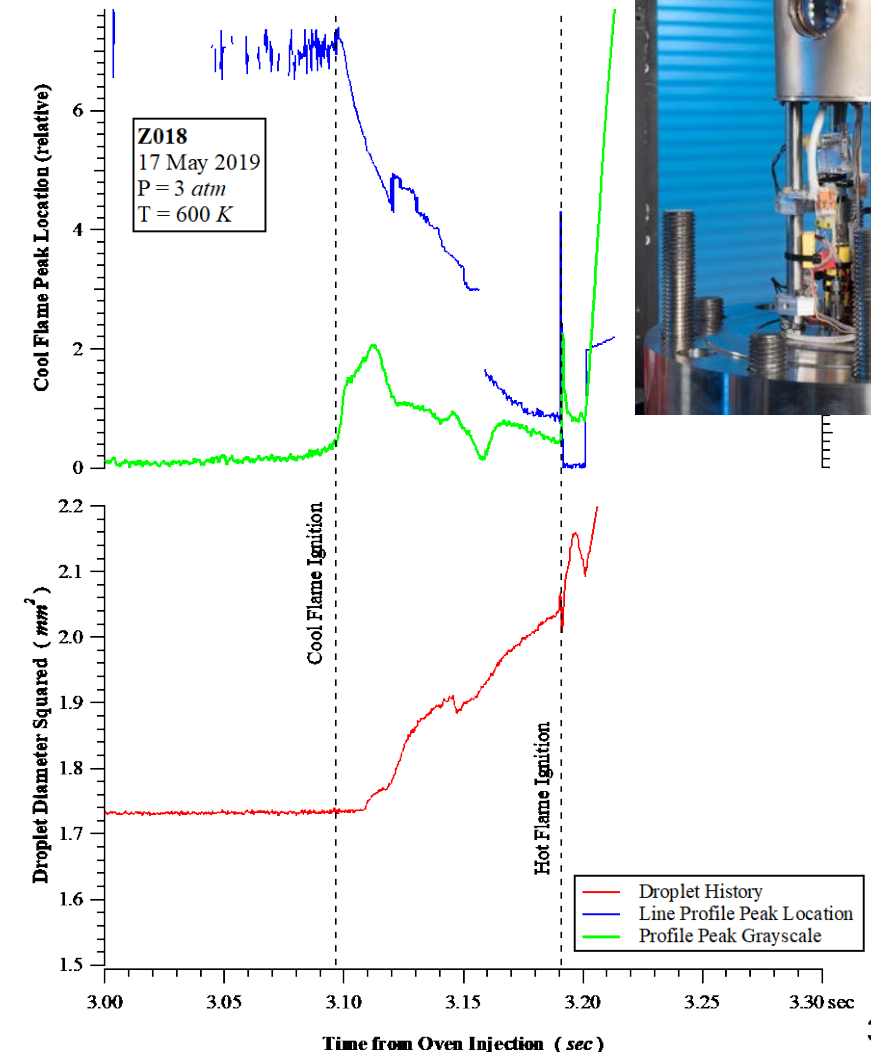
Demonstration of a BRE emulation



- On ISS, BRE matched the heats of combustion and gasification for dozens of condensed fuels.
- Future spacecraft will have $0.27 < X_{O_2} < 0.4$.
- In these environments, BRE finds that typical polymers will burn steadily in μg .
- The good news is that polymers cannot burn steadily when $X_{O_2} < 0.27$.

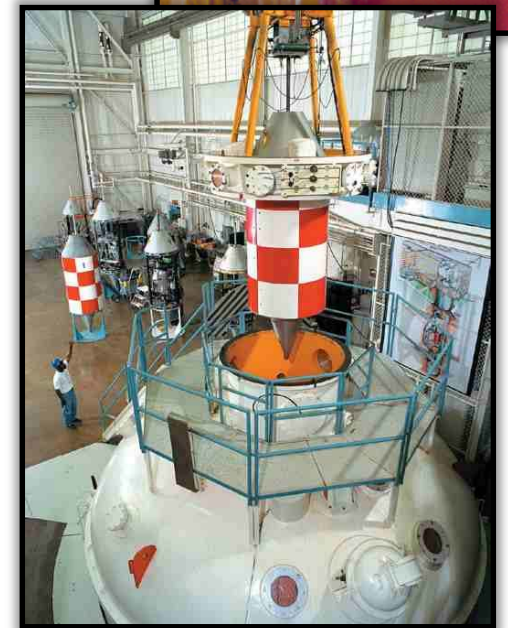
BRE (Burning Rate Emulator) (Quintiere, U. Maryland) is focused on **gaseous flames to simulate the characteristics of a flame spreading over a condensed (solid) surface**. Using a gaseous flame greatly provides the capability to study in more detail the interaction between the flame and the surface, providing results that can be generalized across different materials. The results showed the significance of radiative heat loss from the flame and the reduction of soot during the test. Using this technique a limiting oxygen concentration for combustion of solid polymers in quiescent microgravity was identified.

- **Highest priority research area from 2014 combustion workshop**
 - Significant collaboration opportunities with outside research groups (NSF, AFOSR, ARO)
- **High pressure facility built and operational in GRC Zero-Gravity facility**
- **On-going experiments involving droplet ignition**
 - Unique observations of two-stage ignition behavior and cool flame propagation
- **Access to high quality microgravity environment offers significant potential to improve understanding of high pressure combustion**



Zero-G Facility

- 11 drops completed in August-September
- 89 Drops FY19 to date
- **High Pressure Trans-Critical Combustion**
 - 37 drops completed to date, n-Dodecane fuel, up to 25 atm, 750° K
 - Moving to 50 atm
 - Preparing SCWO insert for Q1 FY 20
- **Began Plant Bio tests with Univ. of Florida Sept 23.**
- **Working on design for Nano-Rack Hitchhiker accommodation**



RSD Hardware – ISSNL, *Accelerated Reactions of Microdroplet*

- **New Venture with ISSNL**

- REMIS/RSD – contract for RSD Operations is in place, signed 2/15/2019 (updated 5/15/2019 with new schedule to reflect flight aboard SpX-18).
- REMIS/RSD – Kickoff Meeting held Thursday, 5/15/2019.
- ISSNL is Proposing to use the RSD Flight Hardware for An Experiment to Study Chemical Reaction Dynamics with Purdue University. Meetings to Date show Promise.
- SLPSRA guided development of Science Requirements Document with ISSNL for *Accelerated Reactions of a Microdroplet* experiment.
- NASA oversight transferred to ISS-PO with MSFC support

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Materials

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Biophysics

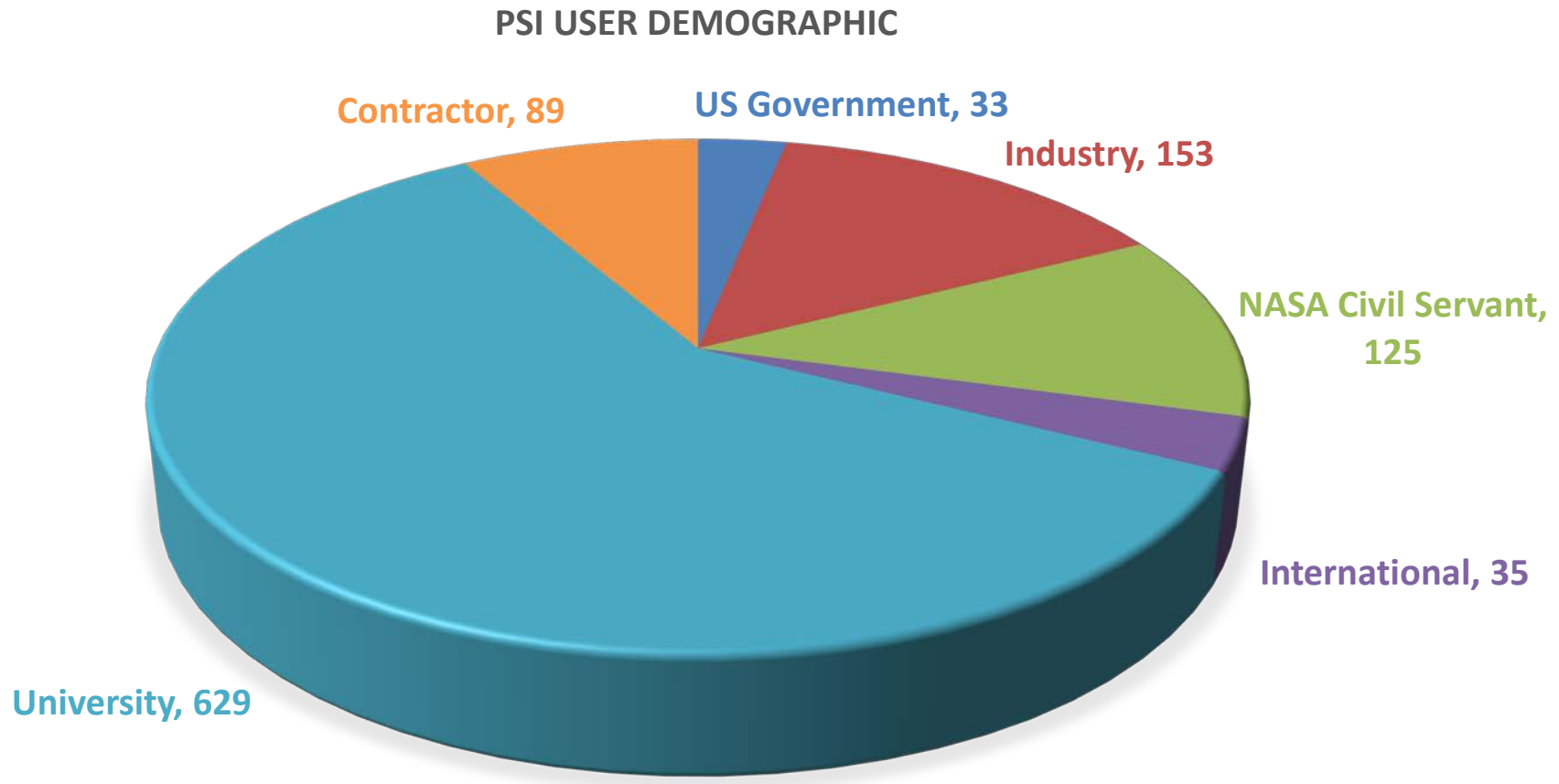
- Wenchuan Ma, James F. Lutsko, Jeffrey D. Rimer, Peter G. Vekilov, “Antagonistic cooperativity between crystal growth modifiers,” *Nature*, 2019 or 2020.

‘I want to thank you for the continued support from NASA, without which this work would not have been possible. Both of my NASA grants, NNX14AD68G and NNX14AE79G, are duly acknowledged in the paper. Please note that the second author, Jim Lutsko, who carried out crucial molecular modeling of the observed phenomena, is a member of the ESA team supported by the PRODEX Programme (Contract No. ESA17 AO-2004-070). My participation in this team was generously supported by the second of the listed NASA grants.

Once again, thank you very much for your dedicated support of outstanding science in my group and in the entire NASA program.”

With best regards,

Peter Vekilov



1,064 current users accessing 8.2 TB of scientific data

Data Repository

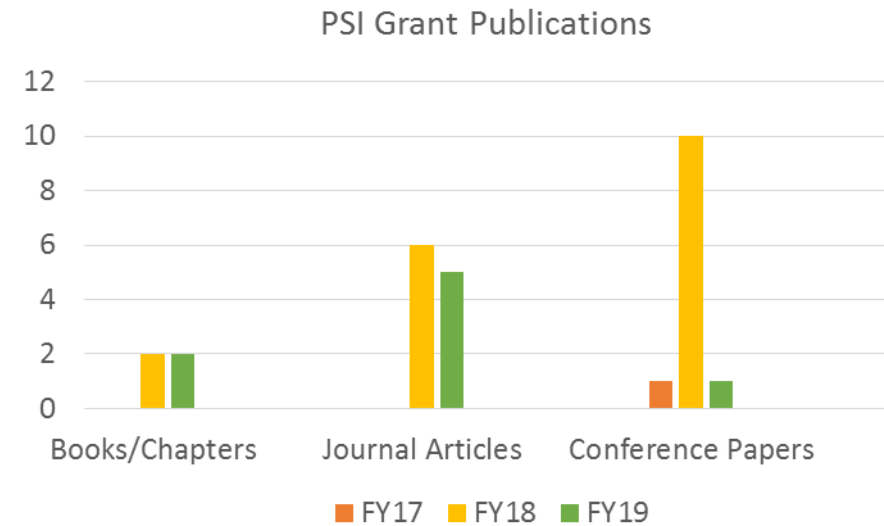
PSI study archive:

	Cum	FY19
- Biophysics	0	0
- Combustion Science	15	2
- Complex Fluids	16	1
- Fluid Physics	14	4
- Fundamental Physics	3	0
- Materials Science	15	1
- Total	63	8



PSI NRA Awarded Grants by Discipline

	Cum	FY19
- Biophysics	0	0
- Combustion Science	7	1
- Complex Fluids	4	1
- Fluid Physics	8	1
- Fundamental Physics	0	0
- Materials Science	7	2
- Total	26	5



PSI NRA Grant Publications*

	W/Abstracts	W/O Abstracts
- FY17	9	3
- FY 18	31	11
- FY 19**	22	22
- Total	62	36

* Does not include Abstracts

**FY19 numbers cover Oct 2018 – July 2019

4. SLPSRA Spinoffs

- **CO2 Removal**
- **Contingency Urinal**
- **P&G's Colloidal suspension experiment & patents**

Why is advanced CO₂ Removal important?

Carbon Dioxide Removal Assembly (CDRA)

- Scrubs CO₂ at 3 mmHg
- Crew headaches
- Dust and debris



NASA Exploration Challenges

- Scrub CO₂ at 2 mmHg for 4 crew
- Improve reliability & efficiency
- Reduce maintenance requirements

Why is the Liquid Amine CO₂ Removal (LACR) System important?

Solid Sorbent Beds

Liquid Sorbent Loop

System	TRL*
CDRA (Current)	9
4BMS-X (NASA)	5-6
Thermal Amine (United Technologies)	6-7
ACLS (European Space Agency)	6-7
Liquid Amine Carbon Dioxide Removal System - LACRS (NASA)	2-3

Liquid Amine is a fundamentally different approach to CO₂ Removal

*TRLs estimated by AES LSS CO₂ Removal Co-Task Lead – Darrell Jan, PhD

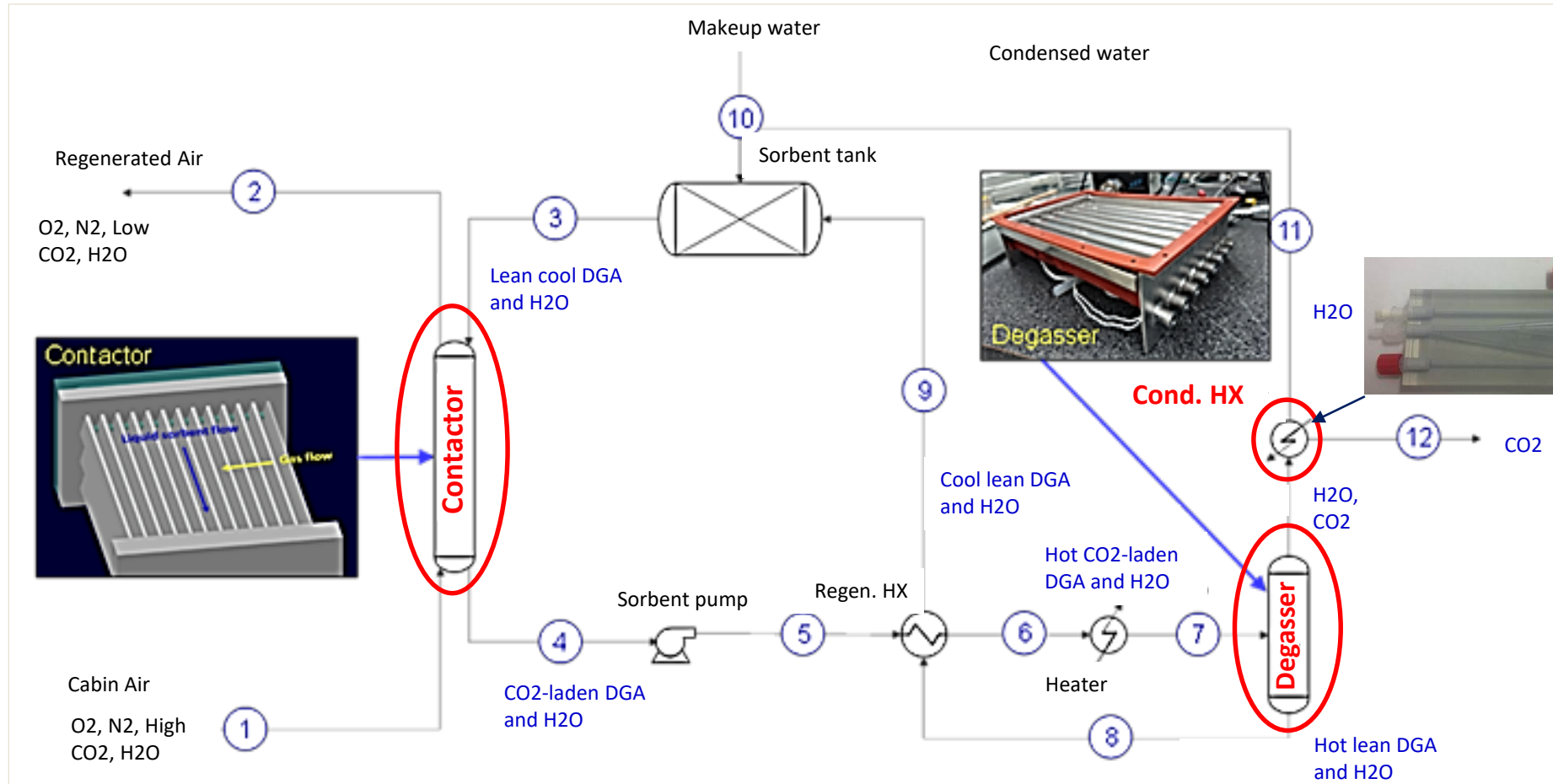
Regenerable CO₂ liquid sorbent (Front-Runner: 65 vol.% Diglycolamine/35 vol.% Water)

- High capacity
- Rapid kinetics
- Low vapor pressure
- Chemically Stable

(1) Microgravity fluid management system

- Capillary structures
- Flow balance
- Thermal balance

(3) Optimization of Integrated System for CO₂ Removal



Liquid Amine CO2 Removal System - Reference Schematic

Not complete
 Complete or near complete

Up on ISS
Flight Demos

Initial Experiments

CSELS

CapiSorb

LACR Validation System



Fundamental capillary behavior

Demo contactor-degasser liquid loop with fluid simulant

- No CO2 scrubbing
- Ambient temperature
- Tox. 0, constant volume, and constant viscosity fluid

Demo high fidelity contactor-degasser-condenser liquid loop with fluid simulant

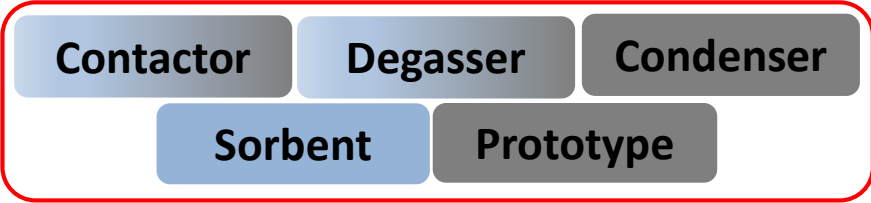
- No CO2 scrubbing
- 23 C to 115 C
- Tox. 0, hygroscopic, varying viscosity fluid
- Some instrumentation & controls

Demo fundamental LACR system

- Demo and optimization of CO2 scrubbing
- Nearly all components, instruments, & controls
Liquid Amine - Tox. 2

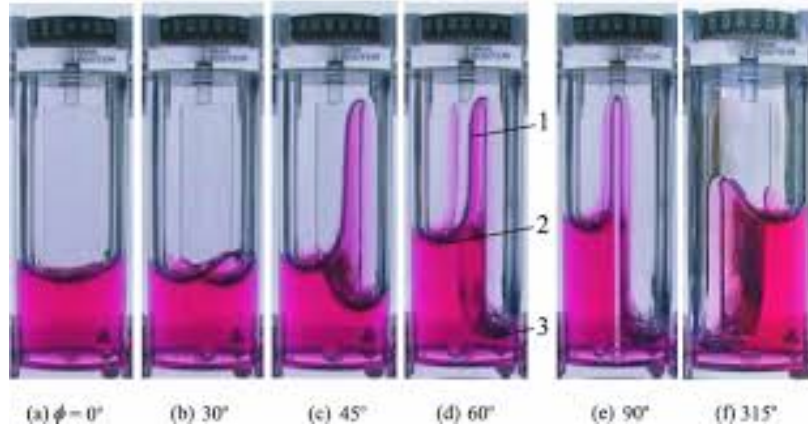


Formulation



Down on Ground
Lab Testing

Contingency Urinal: Progression from Fundamental Science to Flight Hardware for Human Spaceflight



Capillary Flow Experiment

Fundamental Research

Rigid surface
Simple geometry

Perfectly wetting fluid
No contamination

Fluid velocity is tightly controlled and well measured

Goal:
Fundamental measurements



Space Cup

Applied Science

Rigid surface
Complex geometry

Partially wetting fluid
Solids contamination

Testing a wide range of partially controlled fluid velocities

Goal:
Demonstrate that complex capillary systems can work



Collapsible Contingency Urinal

Flight System

Collapsible surface
Complex/variable geometry

Partially wetting fluid
Variable and contaminated

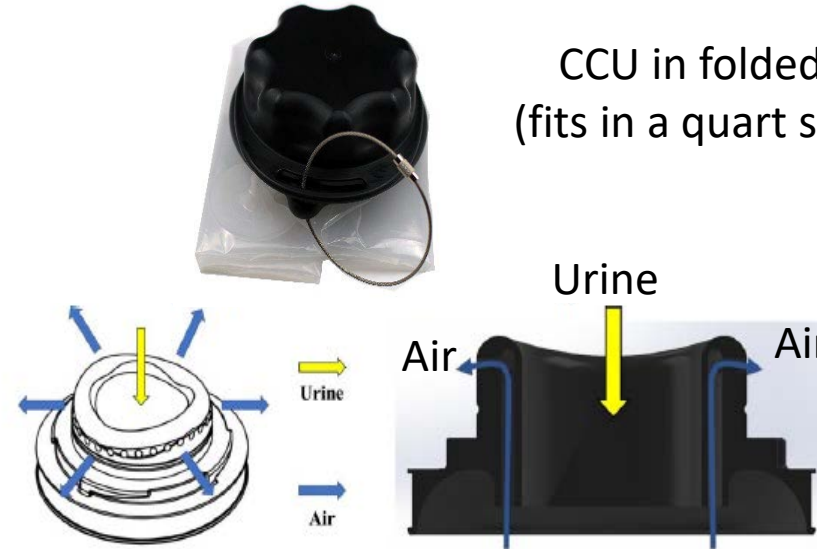
Must operate across a wide range of uncontrolled fluid velocities, with foam/bubbles

Goal:
Meet life support system functional requirements

Collapsible Contingency Urinal (CCU) Design Details

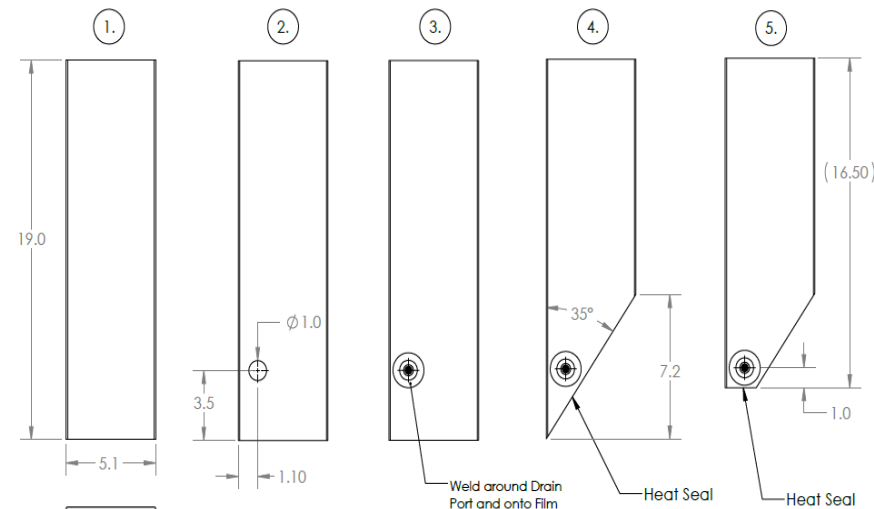
Exploded Assembly	Part Name	Material	Forming
	① Umbrella Valve	EPDM	COTS
	② Hard Lid	Ultem®	CNC
	③ Hard Lid Gasket	Silicone	Laser Cutting
	④ Rubber Cap	9474LE	Molding
	⑤ Human Interface	Silicone	CNC
	⑥ Retaining Wire	18-8 SS	COTS
	⑦ Adhesive Strip	9474LE	Cutting
	⑧ Button Head Bolt	18-8 SS	COTS
	⑨ Clamp Ring	Ultem®	CNC
	⑩ Heat-Staked Insert	Brass	COTS & Heat Staking
	⑪ Flexible Bag	LDPE	Cutting & Heat Sealing
	⑫ Drain Port	LDPE	COTS & Heat Welding

Exploded assembly of CCU components



CCU in folded configuration (fits in a quart size Zip-Lock bag)

Human Interface: wide entry for easy voiding, air vent that doesn't interfere with urine capture or containment



Assembly sequence for flexible bag: crease facilitates capillary pumping

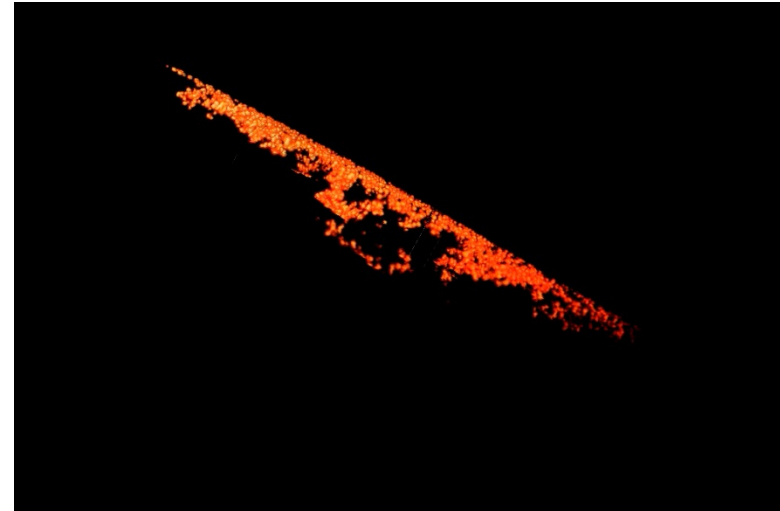
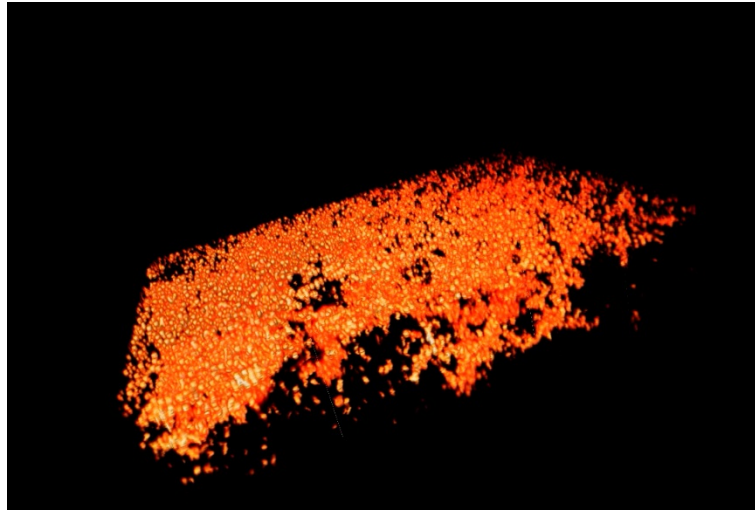
- Approved as a backup system for Orion Spacecraft
 - Even though an ISS test has not been conducted, an ISS test is a possibility
- Five collapsible urine bags will replace 42lbs of diapers
- NASA patent is under internal review and has been given priority one ranking
- Developed by Mark Weisogel and NASA JSC (John Graf)

Dr. Matt Lynch, Procter & Gamble (P&G), continues to learn from and innovate with Advanced Colloids Experiments flying on the International Space Station (ISS).

Benefits, spin-offs, and applications from this work include:

- an extended product shelf-life,
- enhanced product quality,
- lowered production cost (stabilizers are expensive),
- reduced transportation cost (by concentrating essence),
- four patent applications have been filed, inspired by the (ACE-M1 and BCAT) experiments.
- This work leads to new applications with the development of new products. P&G is estimated to launch related products in the next year or so.

Completion of ACE-T6, April 12, 2018



Composite 3D image of NASA Advanced Colloids Experiment (ACE-T6) courtesy of P&G

On April 12, NASA Glenn Research Center’s space operations team remotely completed the first 3D imaging experiment for the Advanced Colloids Experiment with Temperature control (ACE-T6) on the International Space Station (ISS).

ACE-T6, which was conducted for Procter & Gamble Co. (P&G), was in development for more than eight years using a variety of imaging techniques with hardware developed by Glenn and their ISS integration contractor, ZIN Technologies, Inc., Middleburg Heights, Ohio. The Science Investigator is Dr. Matthew Lynch, Principal Scientist at P & G.

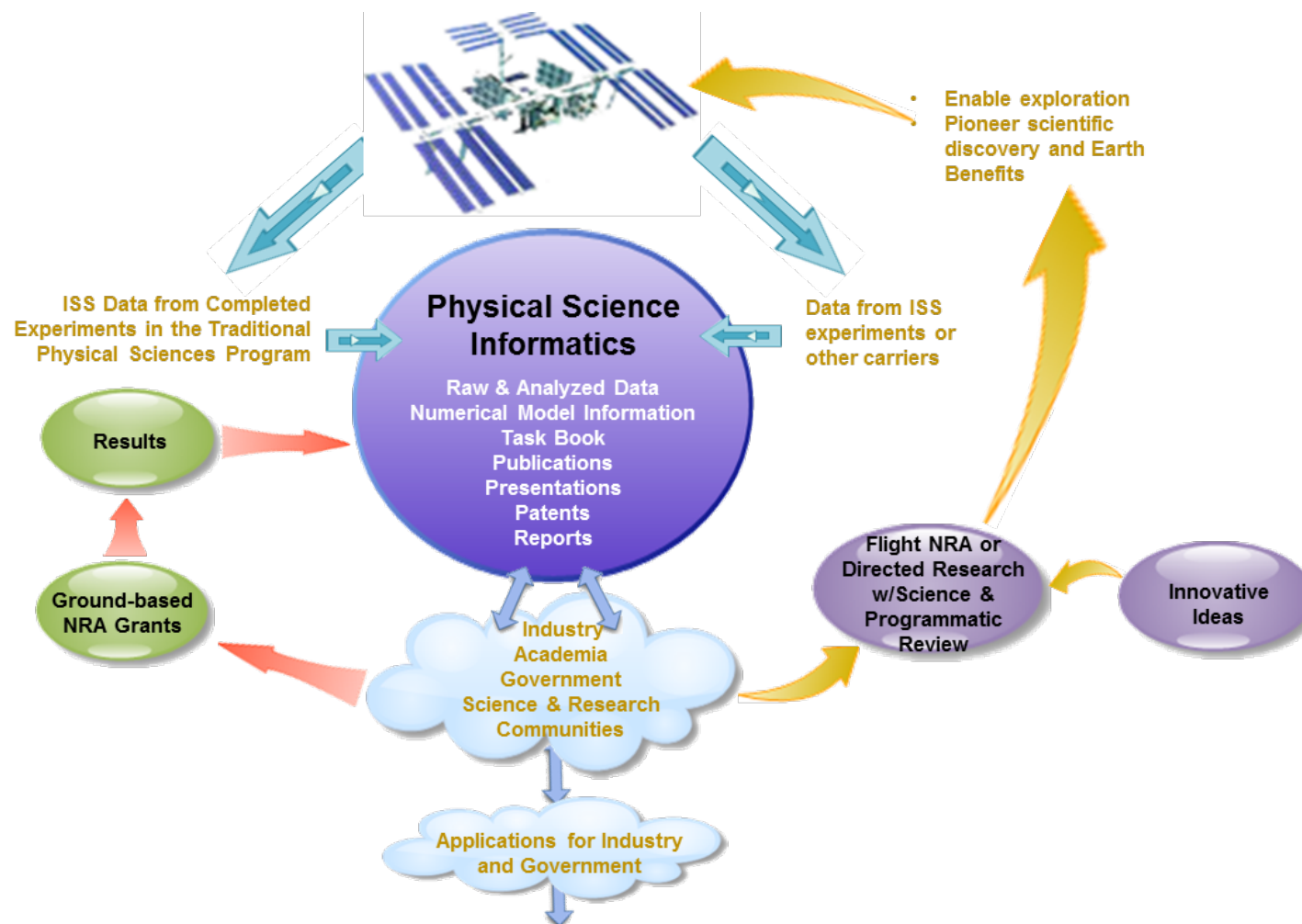
The experiment studies the behavior of colloids, or microscopic particles, in gels and creams, by using the space station’s newly upgraded microscope, the Light Microscopy Module. Because of last year’s multi-million dollar confocal upgrade to the LMM, researchers are now able to view micron-sized particles in consecutive 2D layers, or slices, and combine them into 3D models that can be viewed from any angle. These models greatly increase the ability for scientific observations of how colloidal systems evolve. In a microgravity environment, these systems can be observed on a timescale where particles settle 100,000 times slower than on Earth, revealing previously hidden thermo-dynamic interactions.

ACE will continue using this imaging technology through 2019 and will include colloidal research of now visible insights into particle shapes, coatings, chemistry and manipulation with magnetic fields. This work is anticipated to lead to functional materials, commercial enhancements of battery performance, improved solar cells, the use of magnetic lassos for targeted drug delivery and the deep delivery of “cosmetics” that make repairs.

Industries effected by the understanding of colloids range from petro-chemicals and consumer products to food and pharmaceuticals. ACE-T6 was developed and operated by P&G, Space Life and Physical Sciences Research and Applications (SLPSRA), NASA Headquarters, NASA’s Glenn Research Center, the Center for the Advancement of Science in Space (CASIS) and NASA Johnson Space Center’s Space Operations.

- P & G Corporate site:
- <https://news.pg.com/blog/company-strategy/taking-innovation-out-world>
- **Three patents motivated/inspired by NASA Experiments on ISS**
 1. US 10,080,814: **Sprayable freshening product** comprising suspended particles and methods of freshening the air or a surface with the same
 2. US 10,076,583: Phase-stable, **sprayable freshening compositions** comprising suspended particles and methods of freshening the air or a surface with the same
 3. US 10,143,764: Phase-stable, **sprayable freshening compositions** comprising suspended particles
- **Most Compelling Science on ISS 2013**
- https://www.nasa.gov/mission_pages/station/research/news/2013_most_compelling_awards/

7. Workshops and NRA Plans



- Outcomes:**
- ❖ Global access to cutting-edge research data
 - ❖ Fuel innovation & discovery leading to increased economic growth
 - ❖ Acceleration from ideas to research to products
 - ❖ Enhancement and verification of numerical and analytical models
 - ❖ Increased products, patents, and publications
 - ❖ Advancement of fundamental research

PSI website:
<http://psi.nasa.gov/index.html>

Plenary Session Presentations

Functional Materials

Corning Functional Materials Overview - *Jay Sutherland*, Corning

Lunar Infrastructure and Surface Operations

Lunar Infrastructure and Surface Operations - *John Vickers*, NASA

Materials Characterization, Microstructure and Process Modeling

Tiny-but-tough: Emerging Nanomaterials for Space Exploration- *Debbie Senesky*, Stanford

Computational Materials Science

Machine Learning and Artificial Intelligence applications to Materials Science for customized solutions - *Teodoro Laino*, IBM

In-Space Manufacturing

Overview of the In-Space Manufacturing Technology Portfolio - *Tracie Prater*, NASA

Additive Manufacturing

Key Trends in Additive Manufacturing - *Michael Holman*, Lux Research

ISS Materials Facilities and Research

MIS Current and Future Advanced Manufacturing Programs on the ISS - *Justin Kugler*, Made In Space

MISSE Flight Facility on the ISS and Future ISS Programs - *Mark Gittleman*, Alpha Space

The ISS Microgravity Science Glovebox: Experiments in Solidification, Payloads for Material Science Aboard the ISS, Pore Formation and Lyophilization - *Chris Butler*, TecMasters & *George Tipker*, Techshot & *Ken Savin*, ISSNL

Experiments using the ISS Electrostatic Levitation Furnace (ELF) and the Solution Crystallization Observation Facility (SCOF) - *Hirohisa Oda*, JAXA

Experiments using the ISS Electromagnetic Levitator (EML) – *Mike SanSoucie*, NASA

NASEM Roundtable on LEO Materials Research

Proposed NASEM Roundtable on Advanced Materials and Manufacturing in LEO - *Mike Roberts*, ISSNL

Breakout Sessions:

- Functional Materials
- Lunar Infrastructure and Surface Operations
- Materials Characterization, Microstructure and Process Modeling

- **Materials Science in Space Workshop**

- July 29, 2019 in Atlanta, GA
- Joint Workshop with ISS National Lab (ISSNL) and NASA
- Over 100 people attended the Workshop
- After the talks in the morning, the participants split into 3 breakout sessions
 - Functional Materials
 - Materials Characterization, Microstructure and Process Modeling
 - Lunar Infrastructure and Surface Operations
- Co-Chairs have assembled the Workshop results into a **final report** for each breakout session
- Final report to be released soon
- The final integrated report to be published as a NASA Technical Memorandum (TM) by MSFC
- NASA SPSRA and the ISSNL are looking for **collaborative research** areas based on the recommendations from the Materials Workshop report.

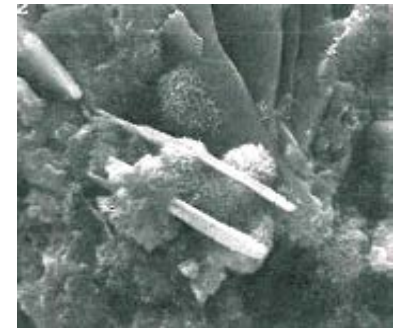
- **NASA Research Announcement (NRA)**
 - solicit reduced-gravity research to be conducted on the ISS.
 - Use Workshop report to develop solicitation
 - planned release - September or October, 2020.
 - Funding planned to start in Oct. – Nov. 2021

Materials Science theme areas most likely include:

- Advanced/Additive manufacturing
- Joining, welding, and brazing
- Thermo-physical property measurements on novel alloys
- Lunar infrastructure and surface operations
- Materials characterization, solidification microstructure, and process modeling (cement, metals, etc.)



Levitated sample
JAXA's ELF ground unit



Terrestrial sample evaluation
Portland Cement paste



Exploration Concept 56

Agenda

Plenary

Welcome and Opening Remarks

NASA's Exploration Vision and Reduced Gravity Challenges - *Joel Kearns*, NASA GRC

Space Life and Physical Sciences Fluid Physics Focused Research Plan - *Fran Chiaramonte*, NASA HQ

Water Recovery Presentations

Overall Challenges: ISS Water Recovery System, Vapor Compression Distillation Process in Microgravity - *Layne Carter*, NASA MSFC and *Greg Schunk*, NASA MSFC

Water Handling Issues in Life Support - *Mark Weislogel*, Portland State University

Packed Bed Reactor Experiment - *Brian Motil*, NASA GRC

Boiling and Condensation Presentations

Spacecraft Power Systems - *Raymond Beach*, NASA GRC

Challenges in Cryogenic Systems - *Michael Meyer*, NASA GRC

JAXA's Two Phase Flow Experiment - *Hitoshi Asano*, Kobe University

Flow Boiling and Condensation Experiment – *Issam Mudawar*, Purdue University

Zero Boil-Off Tank - *Mohammad Kassemi*, Case Western Reserve University

Thermal Management Systems Reduced Gravity Issues - *Eugene Ungar*, NASA JSC

Heat Pipes Presentations

Overall Challenges - *Eric Sunada*, JPL

Oscillating Heat Pipes - *Daniel Pounds*, ThemAvantTechnologies

ESA's Enhanced Evaporators - *Carlo Iorio*, UniversitéLibrede Bruxelles

ESA's Pulsating Heat Pipes Experiment - *Luca Pietrasanta*, University of Brighton

Hardware Presentations

ESA –Heat Transfer HOST 1 - *Daniele Mangini*, ESA

Flow Boiling and Condensation Experiment (FBCE) - *Monica Guzik*, NASA GRC

ElectroHydroDynamics(EHD) - *Jeffrey Didion*, NASA GSFC

Packed Bed Reactor Experiment (PBRE) - *Brian Motil*, NASA GRC

Breakout Sessions:

- Flow Boiling and Condensation
- Heat Pipes
- Water Recovery

- **SLPSRA Fluid Physics Workshop**

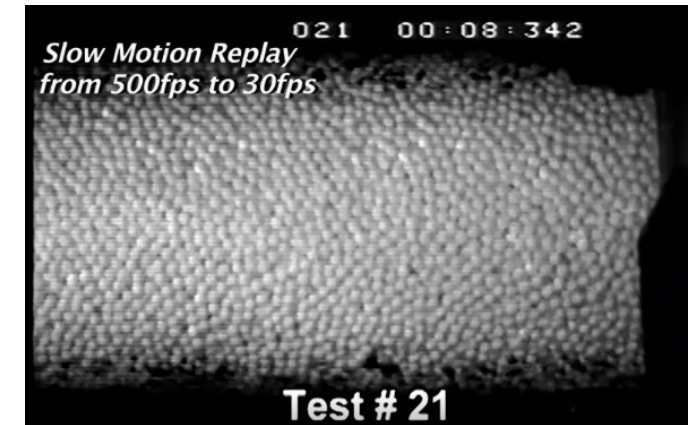
- Oct 16-17, 2019
- NASA SLPSRA Workshop, hosted at GRC
- Over 125 people attended the Workshop
- After the talks in the morning, the participants split into 3 breakout sessions
 - Heat Pipes
 - Water Recovery
 - Boiling and Condensation
- Co-Chairs have assembled the Workshop results into a **final report** for each breakout session
- Draft report due Dec. 20, 2019
- Final Report Feb. 28, 2020

- **NASA Research Announcement (NRA)**

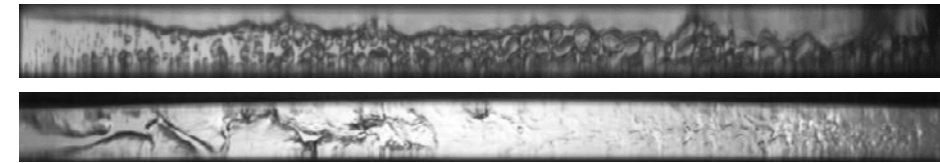
- solicit reduced-gravity research to be conducted on the ISS.
- Use Workshop report as basis for solicitation.
- planned release - September or October, 2020
- Funding planned to start in Oct. - Nov. 2021

- **Fluid Physics** theme areas will most likely include:

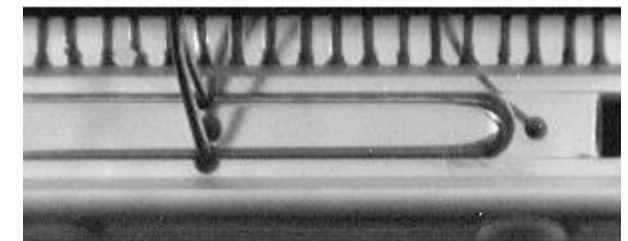
- Water Recovery
- Heat Pipes
- Flow Boiling and Condensation



Packed Bed Reactor Experiment



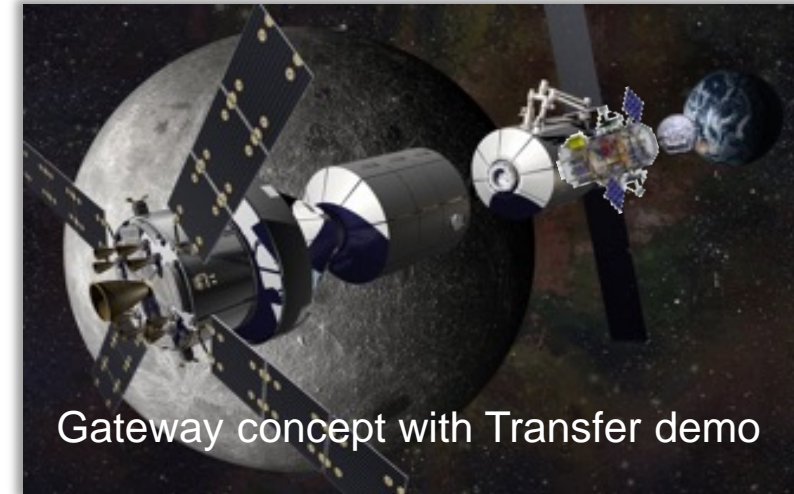
FBCE, Flow Boiling: 1-g (top), reduced-g (bottom)



Constrained Vapor Bubble Experiment

Boiling and Condensation –

- “Demonstrate a system capable of autonomous transfer and storage of tens of tons of cryogenic hydrogen with negligible losses for up to a year at Gateway and on the lunar surface.” (STMD to release solicitation next year).
- It is anticipated that **boiling** will occur during 1) tank to tank transfer and 2) initially in the receiver tank.



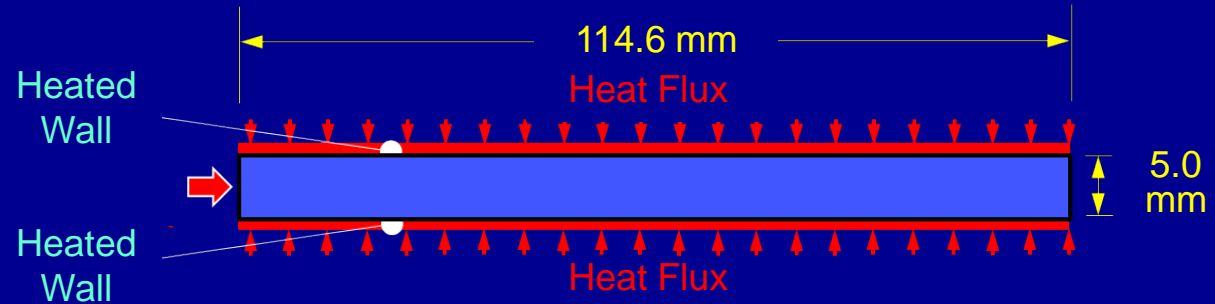
Water Recovery –

- Anomalies on the ISS Water Recovery System (WRS) indicate **the pressure drop** across restrictions is higher in μ -G than 1-G. Also, unexpected **accumulation of gas** has occurred on the WRS filters during ISS operations.
- Use space based water recovery systems are be ubiquitous – ISS, Gateway, Lunar surface habitats and Mars transit.

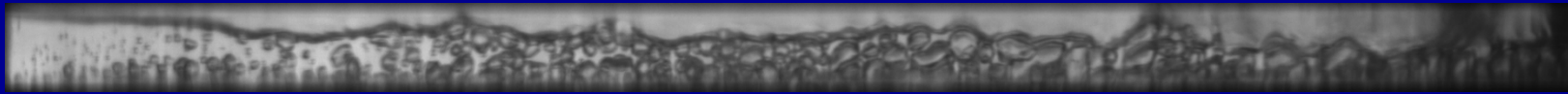


ISS WRS

**CHF Results for
Double-sided Heating:
Low U
(0.1 - 0.11 m/s)**



Horizontal one g_e



Source: Kharangate, C.R., O'Neill, L.E., Mudawar, I., Hasan, M.M., Nahra, H.K., Ramaswamy, B., Hall, N.R., Macner, A.M., and Mackey, J.R., 2015, "Flow Boiling and Critical Heat Flux in Horizontal Channel with One-sided and Double-sided Heating," *International Journal of Heat and Mass Transfer*, Vol. 90, pp. 323-338.

Microgravity



Source: Konishi, C., Lee, H., Mudawar, I., Hasan, M.M., Nahra, H.K., Hall, N.R., Wagner, J.D., May, R.L., and Mackaey, J.R., 2015, "Flow Boiling in Microgravity: Part 2 – Critical Heat Flux Interfacial Behavior, Experimental Data, and Model," *International Journal of Heat and Mass Transfer*, Vol. 81, pp. 721-736.

Observations:

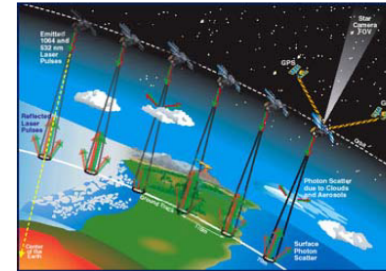
1. CHF in horizontal one g_e flow at low U is associated with appreciable stratification resulting from strong buoyancy and weak inertia
2. CHF in microgravity at low U drastically different in interfacial structure compared to one g_e

Heat Pipes

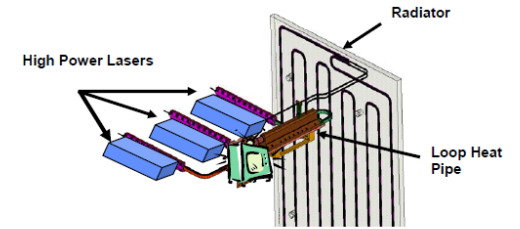
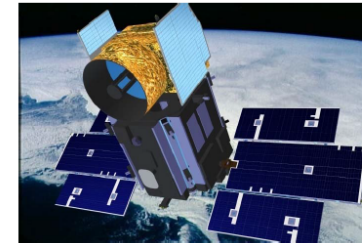
- For heat pipes in general - since the pressure difference between the vapor and liquid phases is sustained by the surface tension force, it is important to understand the change in **capillary driven flows** in reduced or microgravity as compared to various 1-G orientations to prevent dry out (**capillary limit**).
- Examples - some satellites use **loop heat pipe** (LHP) systems. Future space telescopes and space-based Earth resource imaging satellites will require passive cryogenic heat transport devices that can thermally couple remote cryo-coolers to sensor or instrument of interest. A **cryogenic loop heat pipe** (CLHP) provides a highly efficient thermal-conductive link between a cryogenic heat source such as an infrared detector and a cryogenic heat sink like a cryocooler in a spacecraft.



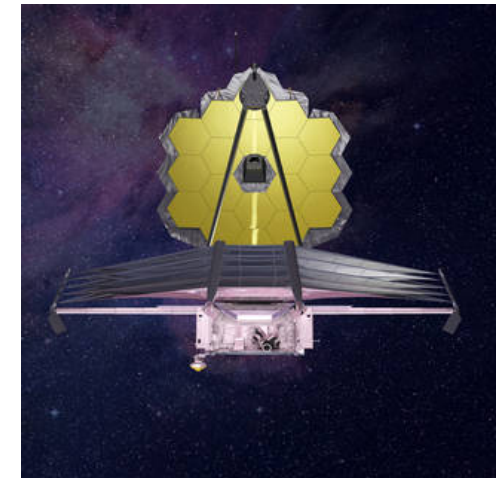
HPs/LHPs on ICESat GLAS



- GLAS has high powered lasers to measure polar ice thickness
- First known application of a two-phase loop to a laser
- 2 LHPs; Laser altimeter and power electronics – Propylene LHPs
- Launched January, 2003
- Both LHPs successfully turned on
- Very tight temperature control ~ 0.2 °C



Capillary Two-Phase Systems: 2015 TFAWS



James Webb Telescope

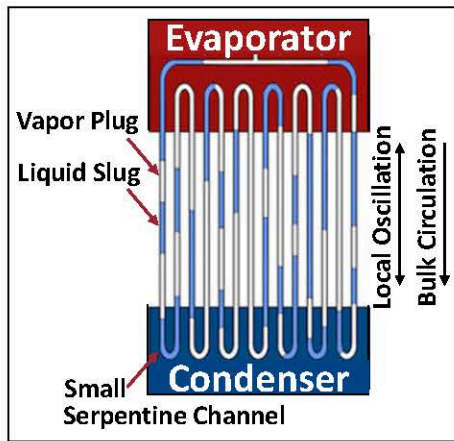
Oscillating Heat Pipes

A New Thermal Management Technology

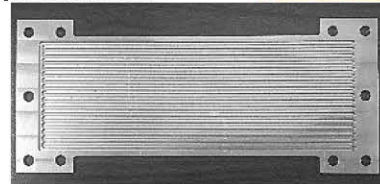
- Passive, wickless, and generally gravity-independent—functions as a heat spreader or heat pipe

Design

- Serpentine collection of microchannels
- Evacuated and partially filled with a fluid
- Surface tension effects create a natural separation of liquid slugs and vapor bubbles



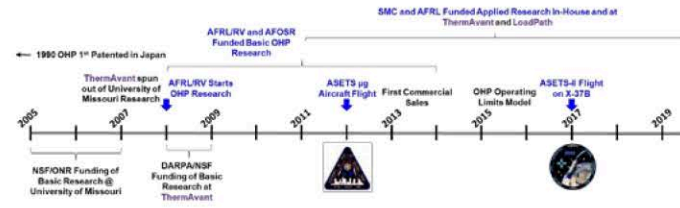
OHP Schematic
THE AIR FORCE RESEARCH LABORATORY



ASETS-II Flight Hardware (Top) and ASETS-II OHP w/o Lid (Left)



Video of OHP Operation



Thermal Management Tech Comparison

	Heat Pipe	Loop Heat Pipe	OHPs
Heat Flux	6.2 W/cm ²	67 W/cm ²	>300 W/cm ²
Temperature	<80 °C	< 80 °C	> 150 °C
Max Length	<3 m	<30 m	>2 m?

Operation

- Differential heating of the OHP creates a pressure imbalance/instability
- Heat transferred through two-phase flow without the need for an expensive wick
- Majority of heat transfer is forced convection

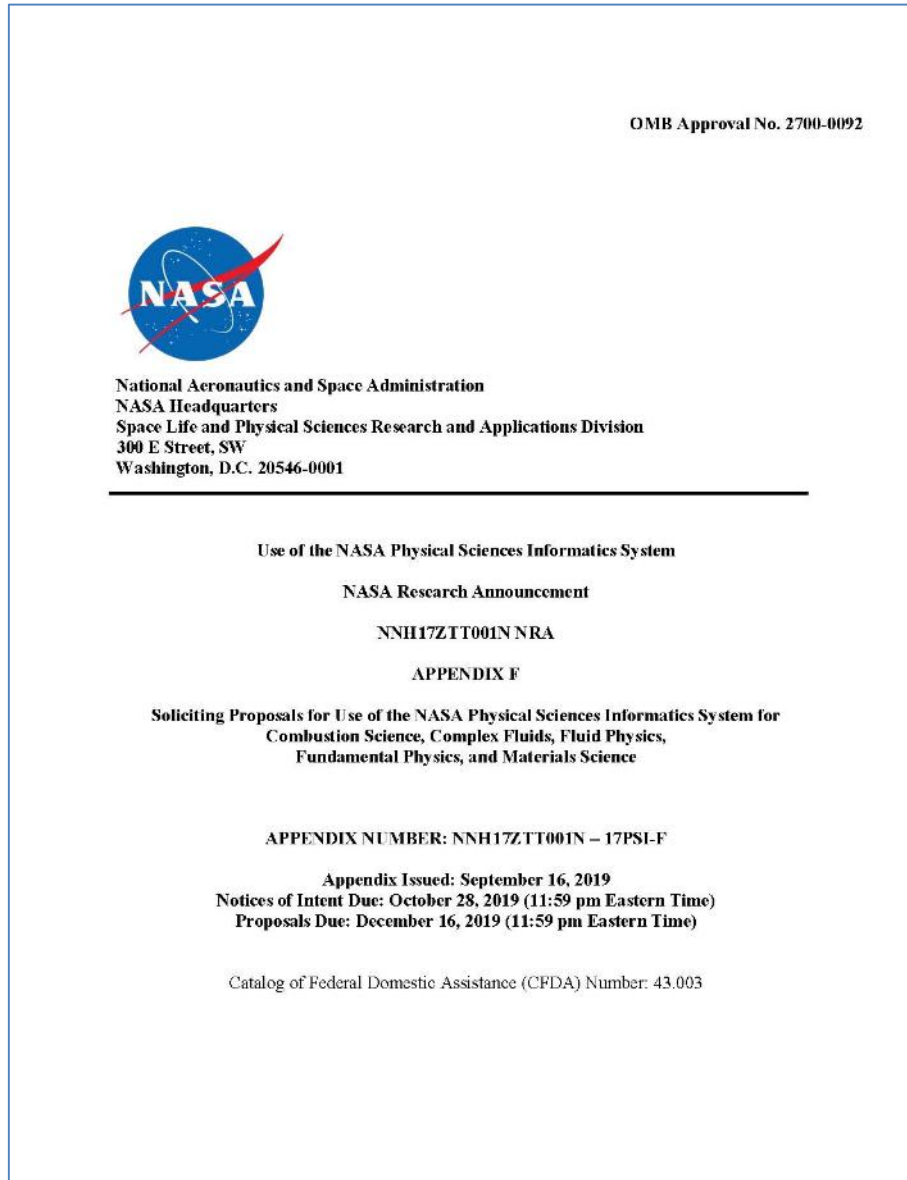


X-37B Orbital Test Vehicle



- **Tentative Workshop plan - October 2020 or 2021**
 - Candidate Topics
 - Solid fuels
 - Spacecraft materials flammability
 - Fire safety roadmap - optimize flight and ground resource utilization
 - Fire safety plans from other space agencies
- **NRA - Fire Safety using SoFIE and possibly MWT:**
 - to be released in Oct - Nov 2021 or 2022
 - funding to start in Oct – Dec. 2022 or 2023





PSI Appendix F

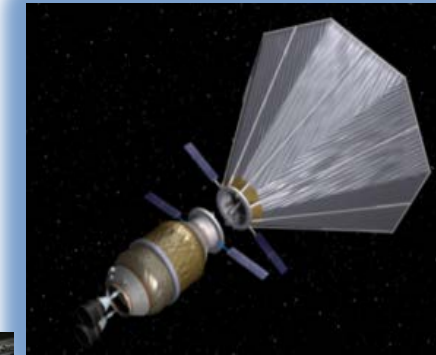
- Released: September 16, 2019
- Eligible experiments: 63
- **Proposals Due: December 16, 2019**
- Awards (target): June 2020
- Solicits ground-based research proposals from established researchers and graduate students. (Annually)
- Solicits proposals from the following five research areas: Combustion Science, Complex Fluids, Fluid Physics, Fundamental Physics, and Materials Science.
- **Awards: \$100,000/year for two years.**
- **Approximately 5 proposals will be selected.**
- The NRA is available at:
<https://tinyurl.com/NASA-PSI-F>
- For additional information on the PSI database, visit: <http://psi.nasa.gov>

PSI NRA	Release Date	Proposals Due	Selection Announcement
Appendix D	Sept. 15, 2017	Dec. 15, 2017	May, 2018
Appendix E	Sept. 14, 2018	Dec. 14, 2018	June, 2019
 Appendix F	Sept. 16, 2019	Dec. 16, 2019	June, 2020
Appendix G	Sept. 15, 2020	Dec. 15, 2020	June, 2021
Appendix H	Sept. 15, 2021	Dec. 15, 2021	June, 2022
Appendix I	Sept. 14, 2022	Dec. 15, 2022	June, 2023

*Five selections planned per year

8. Collaboration Experiments for Exploration

- Feasibility of imminent Lunar & future Mars Missions depend largely on successful implementation of ZBO Cryogenic Tank Pressure Control for propellant storage & transfer. Estimates for LH2 are 2% loss per day.
- ZBO brings significant cost saving through payload mass reduction but is complicated to design due to complex two phase fluid/heat transfer.
- The Zero Boil Off Tank (ZBOT) Experiments use small-scale *simulant*-fluid tests aboard the ISS to study the underlying fluid physics of tank pressurization & pressure control in order to optimize in-orbit propellant storage & transfer processes.

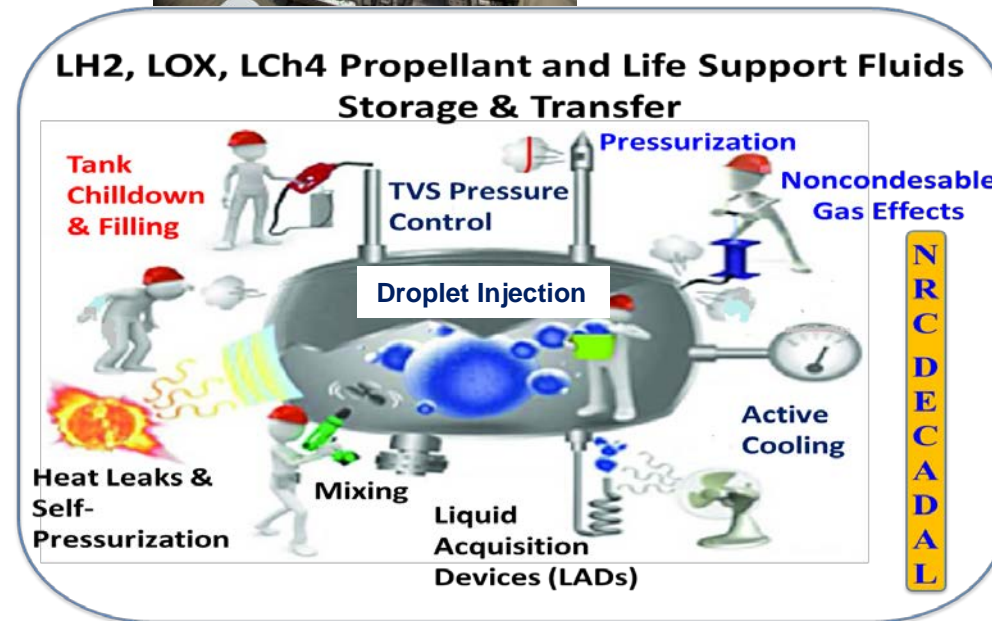


Cryogenic Fuel Depot concept (above)



ZBOT-1 on ISS (left)

- **ZBOT-1: Self-Pressurization & Jet Mixing (2017)**
 - Self-Pressurization, Thermal stratification, 0G boiling
 - Jet Mixing/Cooling, Thermal destratification, Ullage-Jet dynamics
- **ZBOT-NC: Effect of Non-Condensable Gases (2023)**
 - NC effect on self-pressurization / stratification
 - NC effect on pressure control / destratification
 - Condensation suppression, Marangoni convection
- **ZBOT-AC: Active Cooling Pressure Control (2025)**
 - Droplet Spray Bar (TVS) Cooling
 - Broad Area Cooling (BAC)
- **ZBOT-FT: Filling & Transfer (est. 2026-27)**
 - Joint effort with DLR
 - Tank Chilldown and Tank-to-Tank Transfer
- **ZBOT-TT: Tank Transfer (launch date-TBD)**
 - NASA effort with US industry.
 - Tank Chilldown and Tank-to-Tank Transfer



Investigator team:

Michael Dreyer - DLR

Mo Kassemi - NASA

TBD - Additional Investigators

Objectives:

Use a **small scale simulant fluid experiment** and hand-in-hand CFD model development to investigate and understand the effect of microgravity on evaporation, condensation and boiling phenomena and the associated two-phase flow transport regimes that **impact tank and line chill-down and tank to tank transfer operations** during refueling of spacecraft propellant tanks from orbiting fuel depots.

Approach:

1. Experiment concept driven by STMD goals
2. International Collaboration between NASA SPLS, ISS-PO and DLR
 - **Ground based study – DLR led (NASA and DLR approved)**
 - Flight hardware development – DLR (In discussion)
 - ISS launch, integration and ops – NASA

Application:

Cryogenic Fuel Depot, Lunar lander and Mars transit vehicles

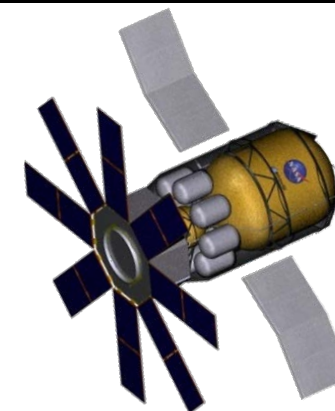
- Propellant Tank Chill down
- Propellant Tank Transfer Operations

Tentative Schedule:

Ground Tests: 2019 - 2022

Flight hardware development: 2022 - 2026

ISS operations: 2026-27



Cryogenic Fuel Depot concept

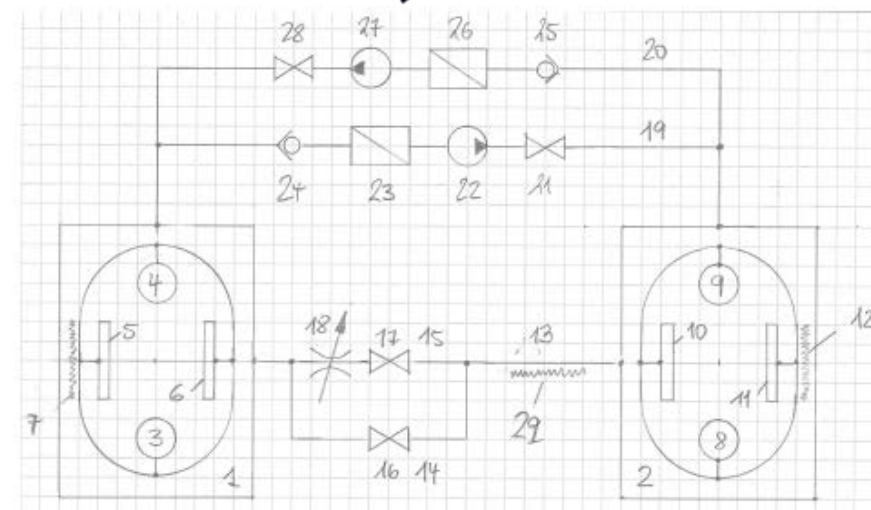


Figure 3.1: Generic drawing of the experiment setup, not to scale. The setup consists of two fluid containers, a donator tank 1 and a receiver tank 2, which are connected by several lines. The optical setup to enable observation is not shown. The setup aims at simulating the situation of a cargo spacecraft with a full propellant tank 1 docked to another spacecraft with an empty propellant tank 2. The components are explained in the text. The components are necessary to perform a repeatable model experiment on the International Space Station. They are not necessarily parts of the original hardware.

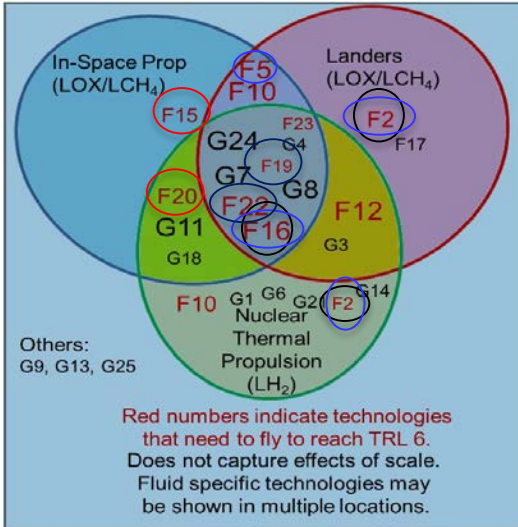
Concept from Professor Dreyer's draft ZBOT- FT ground-based proposal submitted to DLR, Jan. 2019

1. Ground Program (DLR - ready to proceed, NASA SLPSRA - under review)
 1. Mature U. Bremen proposal submitted to DLR
 2. Duration: September 2019 – September 2022
 3. Investigators:
 1. DLR PI – Michael Dreyer
 2. NASA PI – Mo Kassemi
 4. Activities:
 1. DLR - Laboratory studies and Bremen Drop Tower testing
 2. NASA - numerical modeling, host U. Bremen student
 5. Document development: draft SRD for flight experiment

2. Proposed Flight Program (NASA in discussion with DLR)
 1. Timeline 2022 – 2027
 2. International Agreement
 1. DLR – Develop Flight Hardware
 2. NASA – Provide Integration, Launch Services and ISS crew time
 3. Joint Proposal submitted to DLR and NASA for peer review
 1. DLR PI - Michael Dreyer, Co-Is - TBD
 2. NASA PI – Mo Kassemi, NASA Co-Is - TBD
 4. Flight Experiment Reviews
 1. NASA SCR/RDR with mature SRD – NASA and DLR selected panel members
 2. DLR – conduct engineering reviews with NASA involvement

- **Tank Filling and Chardown:** Cooling a tank before filling through multiple: Inject Liquid – Hold – Vent cycles in microgravity.
 - liquid injection, dispersion and transport in the tank, chill-down through inject-hold-vent cycle, film formation, condensation, and heat transfer on the tank wall and transient configuration of the two phases are all strongly gravity dependent.
- **Tank-to-Tank Transfer:** Complicated process involving pressurization of supply tank – transport through transfer lines – cooling/filling the receiver tank.
 - Pressurization of the supply tank, two phase fluid flow regimes/boiling in the transfer lines, filling of the receiver tank through inject-hold-vent cycle and configuration of the two phases in both receiver and supply tanks are all gravity-dependent and drastically different than in 1g.

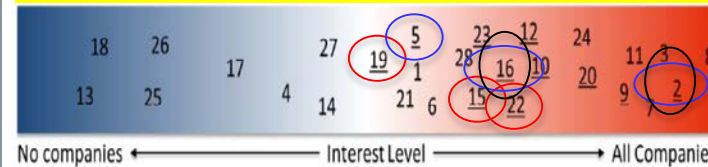
CFM Tech across Multiple Architecture



Mission Architecture



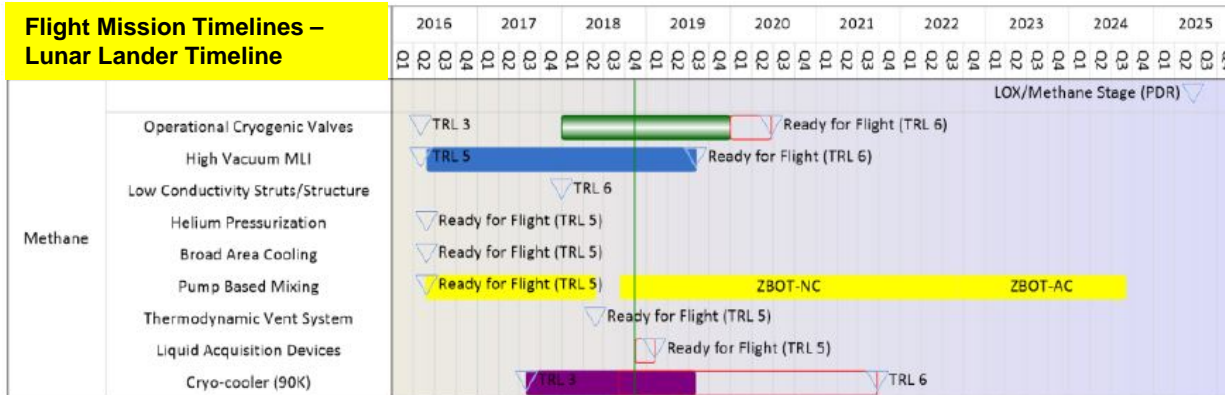
Heat Map of Industry Interest



Required CFM Technology Elements

Technology	No
Advanced External Insulation	1
Autogenous Pressurization	2
Automated Cryo-Couplers	3
Cryogenic Thermal Coating	4
Helium Pressurization	5
High Capacity, High Efficiency Cryocoolers 20K	6
High Capacity, High Efficiency Cryocoolers 90K	7
High Vacuum Multilayer Insulation	8
Liquefaction Operations (MAV & ISRU)	9
Liquid Acquisition Devices	10
Low Conductivity Structures	11
MPS Line Chillydown	12
Para to Ortho Cooling	13
Propellant Densification	14
Propellant Tank Chillydown	15
Pump Based Mixing	16
Soft Vacuum Insulation	17
Structural Heat Load Reduction	18
Thermodynamic Vent System	19
Transfer Operations	20
Tube-On-Shield BAC	21
Tube-On-Tank BAC	22
Unsettled Liquid Mass Gauging	23
Valves, Actuators & Components	24
Vapor Cooling	25

Flight Mission Timelines – Lunar Lander Timeline



ZBOT-1
ZBOT-NC

ZBOT-NC

ZBOT-FT
ZBOT-TT

ZBOT-1
ZBOT-NC

ZBOT-AC

ZBOT-FT
ZBOT-TT

ZBOT-AC

PBRE-2

PI: Brian Motil, NASA GRC

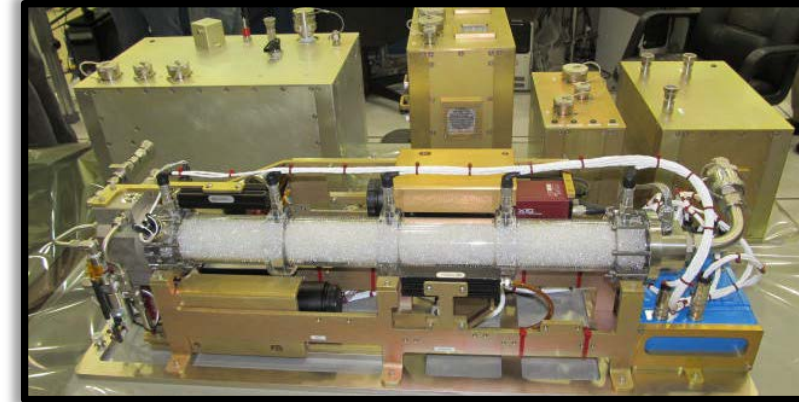
Co-I: Vemuri Balakataiah, University of Houston

PBRE-WR-1 (Reactor)

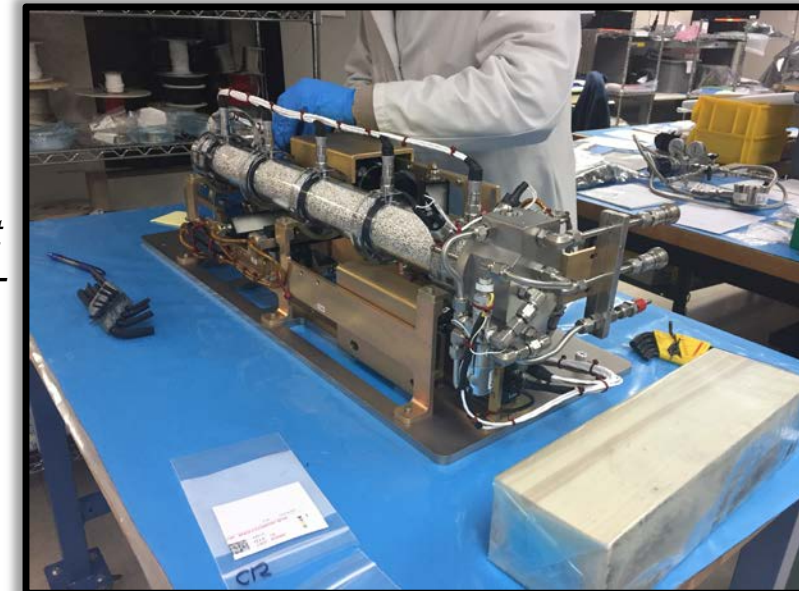
PI: Layne Carter, NASA MSFC

- Goal: The hardware for packed bed reactor experiment (PBRE) will be relaunched to examine the behavior of gas and water flows through a test section consisting of beads. PBRE-2 will expand the parameter range of the previous set of tests to examine the effect of high gas flows through 2 mm glass beads. PBRE-Water Recovery is the first of a series of experiments in support of the Advanced Environmental Systems (AES) and will examine the flows through a catalyst particles used in the water processing assembly (WPA) aboard the ISS.
 - The PBRE-2/WR Flight Hardware successfully passed the Engineering Review Board/System Acceptance Review on August 19, 2019.
 - Scheduled to launch on NG-12 in Oct 2019.
-
- *Anomalies on the ISS Water Recovery System (WRS) indicate **the pressure drop** across restrictions is higher in m-G than 1-G. Also, unexpected **accumulation of gas** has occurred on the WRS filters during ISS operations.*







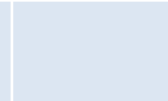
PBRE-2 test column with 2mm glass beads



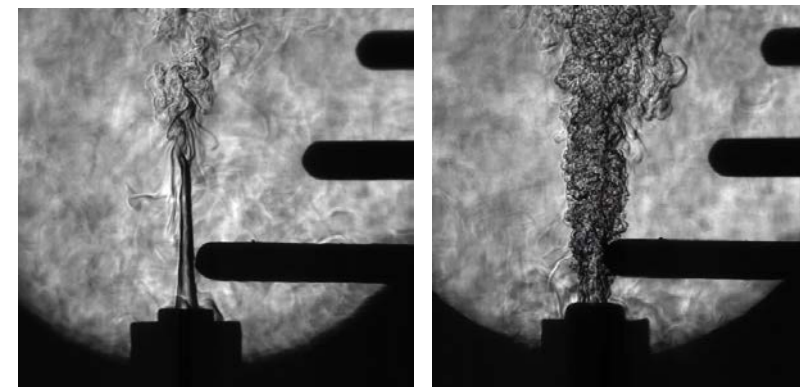
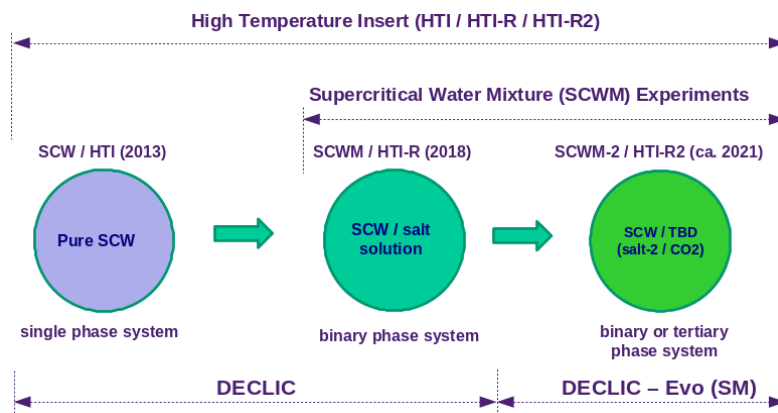
PBRE-Water Recovery test column with 3-mm alumina beads



Direct application to ISS Water Recovery System and precursor for future ECLSS systems

Experiment name/test sect	Tasks	SLPSRA costs	AES costs	Test section
PBRE-2 (SLPSRA) (SpX 16)	Camera repair, test material, Preflight testing, MI&O, hardware prep	PI and Co-I, PS, Grant, Cradle/test section	N/A	
PBRE-WR-1, Applied packing material (SpX 16)	Preflight testing, MI&O, hardware prep	Cradle/test section, Co-I/PS	PI, ISS WR packing material	
PBRE-WR-4 Purge Filter	Preflight testing, hardware prep, MI&O (coordinated through SLPS)	Co-I/PS	PI, new cradle with replaceable test sections.	
PBRE-WR-5 Lee Orifice #1 & #2 Check Valve	Preflight testing, hardware prep, MI&O (via SLPS)	Co-I/PS	PI, orifice and valves	
PBRE-WR-2 Brine filter	Preflight testing, hardware prep, MI&O (via SLPS)	Co-I/PS	PI, brine filter	
PBRE-WR-3 Urine Transfer Filter	Preflight testing, hardware prep, MI&O (via SLPS)	Co-I/PS	PI, urine transfer hose	
PBRE- WR -6 Flow Restrictor	Preflight testing, hardware prep, MI&O (via SLPS)	Co-I/PS	PI- Flow Restrictor	

SCWM, SCWM-2 ... focused on near-critical phenomena with multi-phase systems (salt/water mixtures)



Re = 448, Pr/F² = 1.4

Re = 2680, Pr/F² = 0.5

Supercritical jet injected into supercritical water; turbulent transition highly dependent on buoyancy

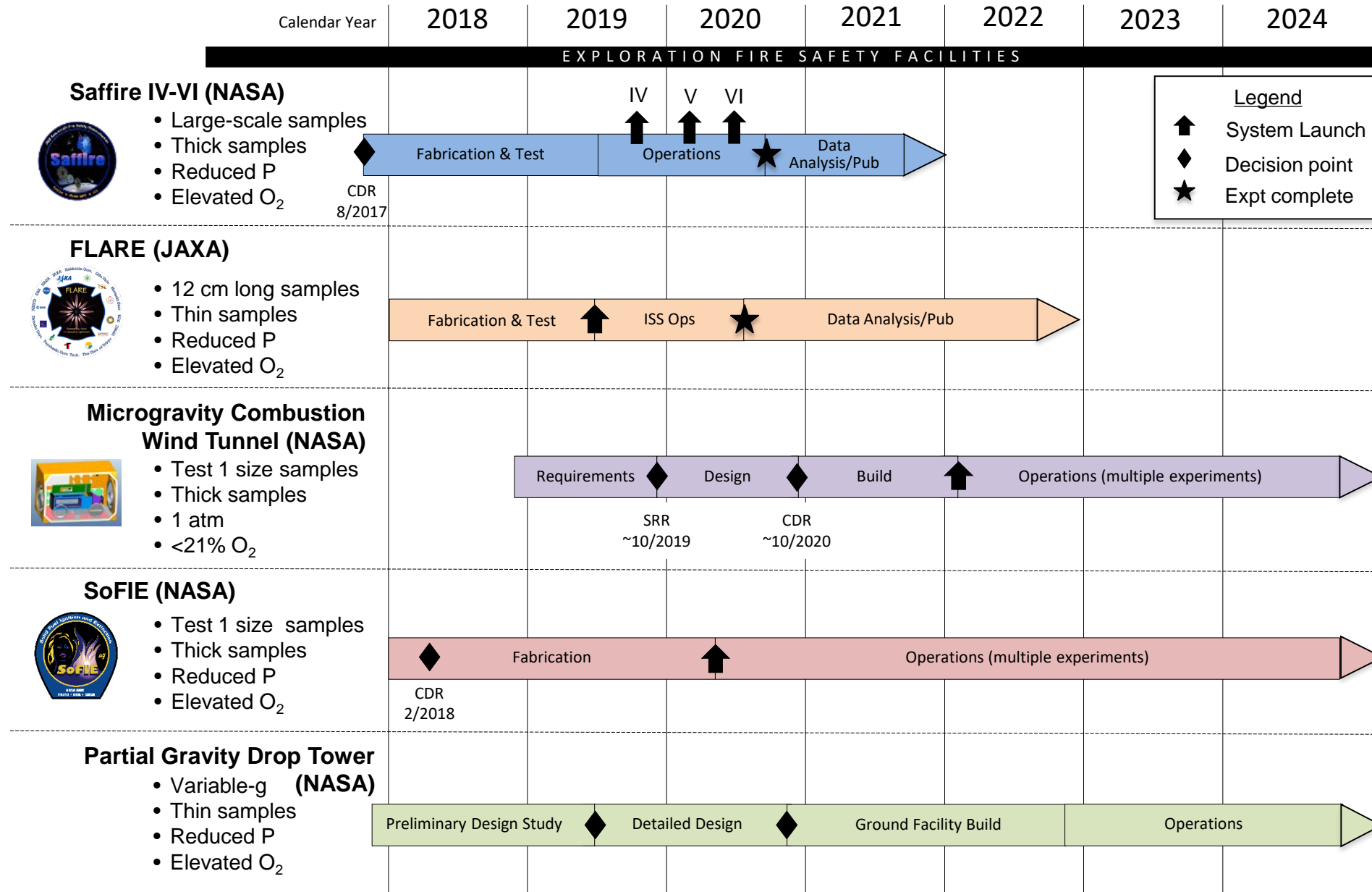
SCWO (for EXPL-1) ... ca. 2022-23, new science aligned with NASA's Advanced Exploration Systems (AES) with a focus on oxidative reactions on waste water (using Urine Simulant).

Science Objectives:

- phase partition and salt (e.g., metabolic Ca⁺²) precipitant transport in supercritical water
- influence of near-critical and supercritical behavior on turbulent transitions and bulk mixing
- spontaneous combustion, stability and structure of hydrothermal flames using ersatz aqueous waste concentrates (e.g., urine brine)



Co-flow fuel jet, 30% C₂H₆O (aq) in core and air in annular region injected into bulk SCW reactor



9. Potential new concepts and collaboration

STMD has a commitment to develop CFM technologies in support of the agency's missions

- There are current activities and future planning that support lunar exploration, Martian exploration, and long term sustainability on the moon and Mars
- These technology developments are following a roadmap of discrete tasks that will contribute to an overall portfolio to support agency goals

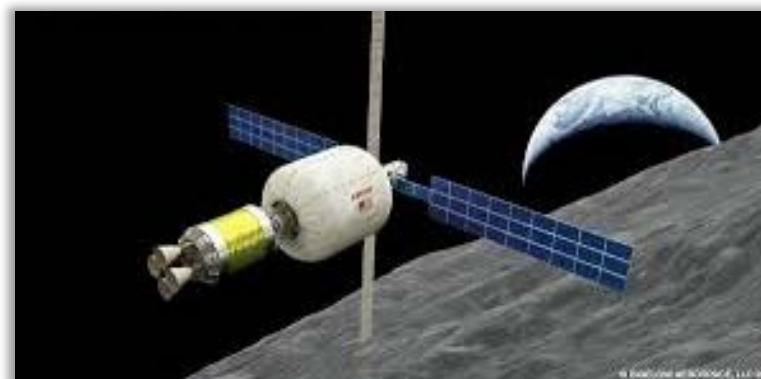
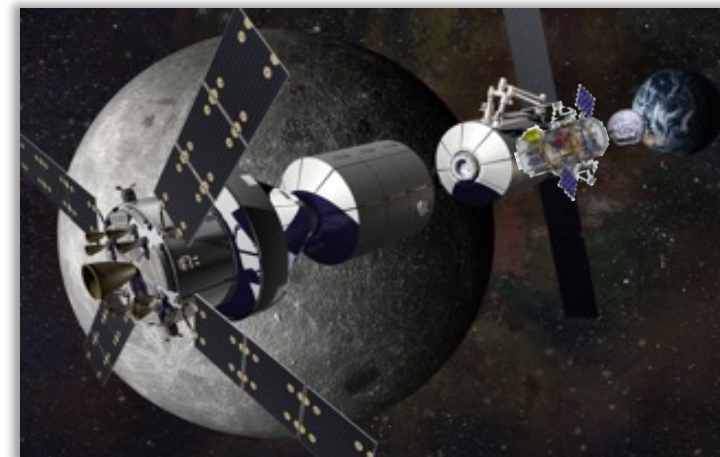


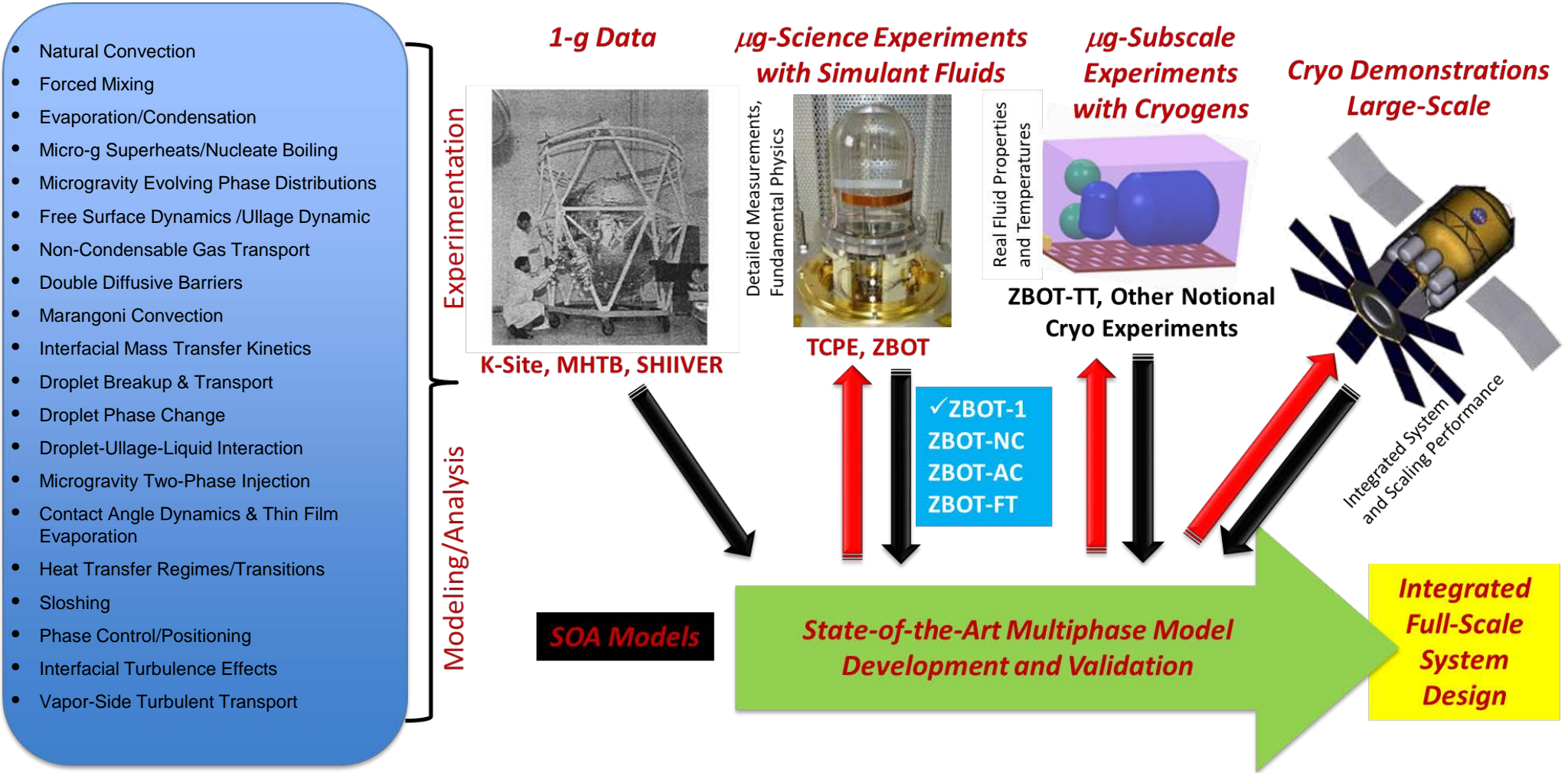
STMD had identified a Key Technology Challenge that supports the agency's vision and guidance.

- Demonstrate a system capable of autonomous transfer and storage of tens of tons of cryogenic hydrogen with negligible losses for up to a year in space and on the lunar surface.

STMD Anticipates a mid FY20 NRA to be released for a transfer demo at Gateway

- Demonstrate enabling technology for a propellant depot at Gateway needed for both lunar sustainability and Mars Transit
- Integrated demo, including, but not limited to the following technologies:
 - Autogenous pressurization
 - Multilayer Insulation
 - 90 K Cryocoolers
 - Tube-on-tank
 - Unsettled Mass Gauge
 - Thermodynamic Vent
 - Transfer Operations
 - Line-chilldown 2 phase flow meter
 - Automated Cryo-coupler

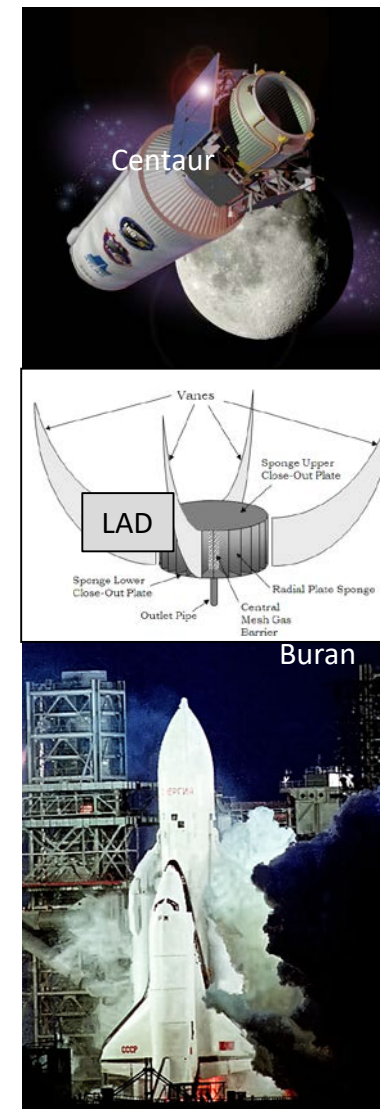




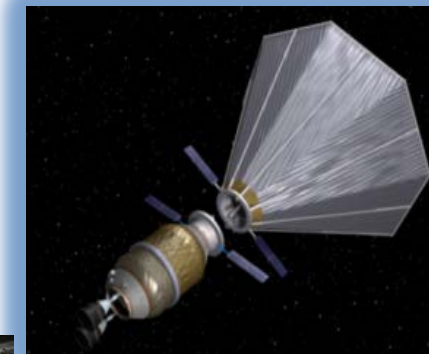
- We have limited demonstration of the capability to store cryogenic propellants in space for more than a few hours in microgravity
 - SOA is Centaur's 9 hours with boil-off rates on the order of 4-5% per day of LH2 and 1-2% per day of LO2
- We have limited demonstration of a flight-proven method to gauge cryogenic propellant quantities accurately in microgravity
 - Need to prove methods for use with both settled and unsettled propellants over the full range of fill levels
- We have not yet demonstrated that we can get gas-free liquid cryogens out of a tank in microgravity
 - Gas-free liquid is required for safe operation of a cryogenic propulsion system
 - Need robust surface-tension **liquid acquisition device (LAD)** analogous to SOA storables
 - Only known experience in the world is the Russian Buran's single flight (liquid oxygen reaction control system)
- We have not yet demonstrated the ability to move cryogenic liquids from one tank (or vehicle) to another in microgravity

Note

A flight demonstration with cryogenic propellant storage, expulsion, and transfer can remedy these problems (*and other more subtle ones*) and further mature these technologies!



- Feasibility of imminent Lunar & future Mars Missions depend largely on successful implementation of ZBO Cryogenic Tank Pressure Control for propellant storage & transfer. Estimates for LH2 are 2% loss per day.
- ZBO brings significant cost saving through payload mass reduction but is complicated to design due to complex two phase fluid/heat transfer.
- The Zero Boil Off Tank (ZBOT) Experiments use small-scale *simulant*-fluid tests aboard the ISS to study the underlying fluid physics of tank pressurization & pressure control in order to optimize in-orbit propellant storage & transfer processes.

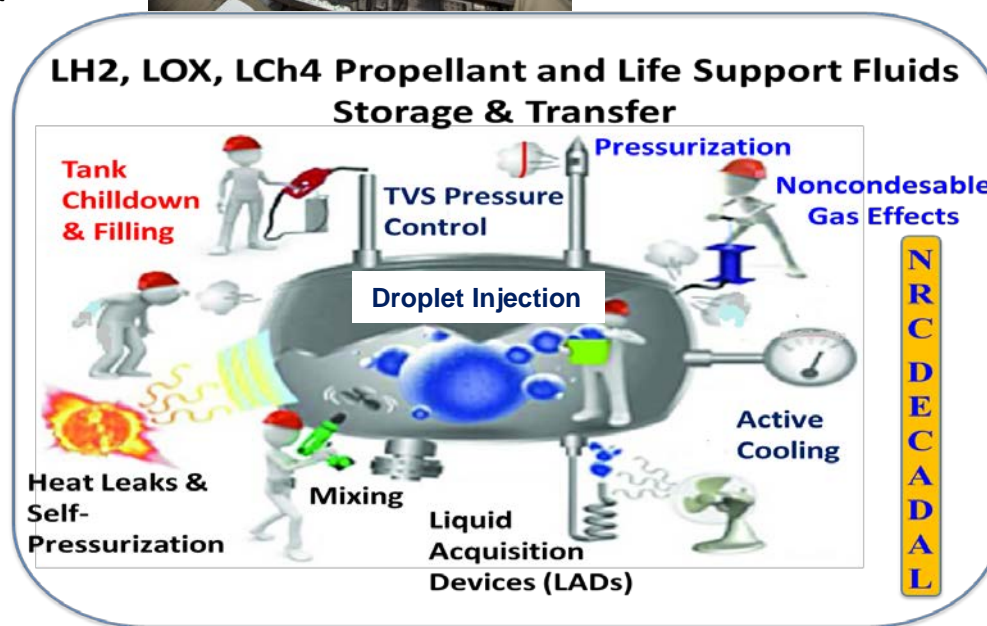
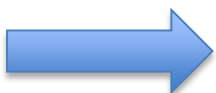


Cryogenic Fuel Depot concept (above)



ZBOT-1 on ISS (left)

- **ZBOT-1: Self-Pressurization & Jet Mixing (2017)**
 - Self-Pressurization, Thermal stratification, 0G boiling
 - Jet Mixing/Cooling, Thermal destratification, Ullage-Jet dynamics
- **ZBOT-NC: Effect of Non-Condensable Gases (2023)**
 - NC effect on self-pressurization / stratification
 - NC effect on pressure control / destratification
 - Condensation suppression, Marangoni convection
- **ZBOT-AC: Active Cooling Pressure Control (2025)**
 - Droplet Spray Bar (TVS) Cooling
 - Broad Area Cooling (BAC)
- **ZBOT-FT: Filling & Transfer (est. 2026-27)**
 - Joint effort with DLR
 - Tank Chilldown and Tank-to-Tank Transfer
- **ZBOT-TT: Tank Transfer (launch date-TBD)**
 - NASA effort with US industry.
 - Tank Chilldown and Tank-to-Tank Transfer



Investigator team: Partnership

NASA SLPSRA, STMD, ISSPO, US Liquid Propellant Industry and possibly Universities

Objectives:

Conduct a **small to medium scale, long duration cryogenic fluid experiment on the ISS**. Investigate and understand the effect of microgravity on evaporation, condensation, boiling phenomena and the associated two-phase flow transport regimes that **impact tank and line chill-down and tank to tank transfer operations** during refueling of spacecraft propellant tanks from orbiting fuel depots.

Initial Concept:

- **External ISS payload**, small to medium scale
- **Cryogenic Working fluid**: Liquid Nitrogen
- Instrumentation: flow meters, thermocouples, pressure gages.
- Optional instrumentation: External viewing ports for cameras, full field temperature and flow visualization
- **Driven by NASA STMD and industry goals**

Goal: To produce high fidelity validation data to improve numerical models

Approach: Partnership - Roles and Responsibilities

- NASA, Industry, Universities – Ground studies
- US Industry - Flight hardware development
- NASA - Launch, mission integration & ops, crew time & numerical analysis of flight data

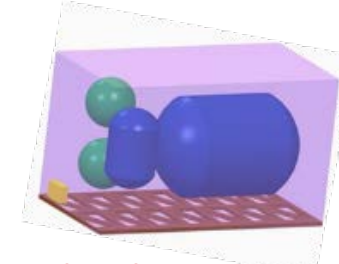
Application:

Cryogenic fuel resupply or depot, Lunar lander, Mars transit vehicles

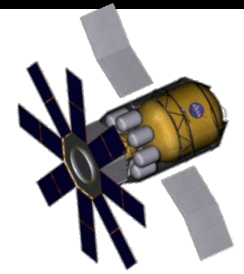
- Propellant Tank Chill down
- Propellant Tank Transfer Operations

Next Steps:

- RFI and Workshop with MOU or Agreement to be developed.



μg-Subscale Experiment with Cryogenics (proposed project)



Cryogenic Fuel Depot concept (notional, future large scale flight demo)

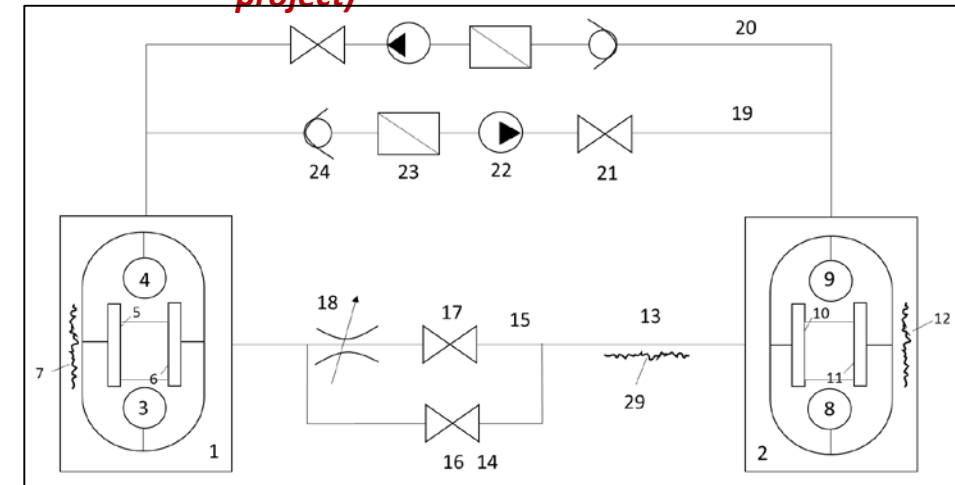


Figure: Generic drawing of the experiment setup, not to scale. The setup consists of two fluid containers, a donator tank 1 and a receiver tank 2, which are connected by several lines. The optical setup to enable observation is not shown. The setup aims at stimulating the situation of a cargo spacecraft with a full propellant tank 1 docked to another spacecraft with an empty propellant tank 2. The components are explained in the text. The components are necessary to perform a repeatable model experiment on the International Space Station. They are not necessarily parts of the original hardware.

Tentative Schedule:

Ground Tests: 2021- 2022, Flight hardware development: 2022 – 2025, ISS operations: 2026

ZBOT-TT : NASA Will Provide these Services to the Payload Developer

The ISS Program Office will provide:*

1. Launch to the space station Installation on station at identified site
2. The FRAM (attachment interface) and robotics interface to external station payload locations. (as well as the robotics operations)
3. In-orbit utilities and operations support including crew or robotics time (if needed)
4. Data handling and delivery (to the TREK workstation)
5. End-of-life removal and disposal
6. Some limited interface-to-ISS testing (for power and data type interfaces) are provided.
7. Crew time
8. Data services and ISS support personnel

NASA SLPSRA will provide:

1. Guidance through NASA review process and development of the Science/Technical Requirements Document
2. Numerical modeling of ground and flight results, and analysis of flight data
3. Full field temperature and flow visualization techniques

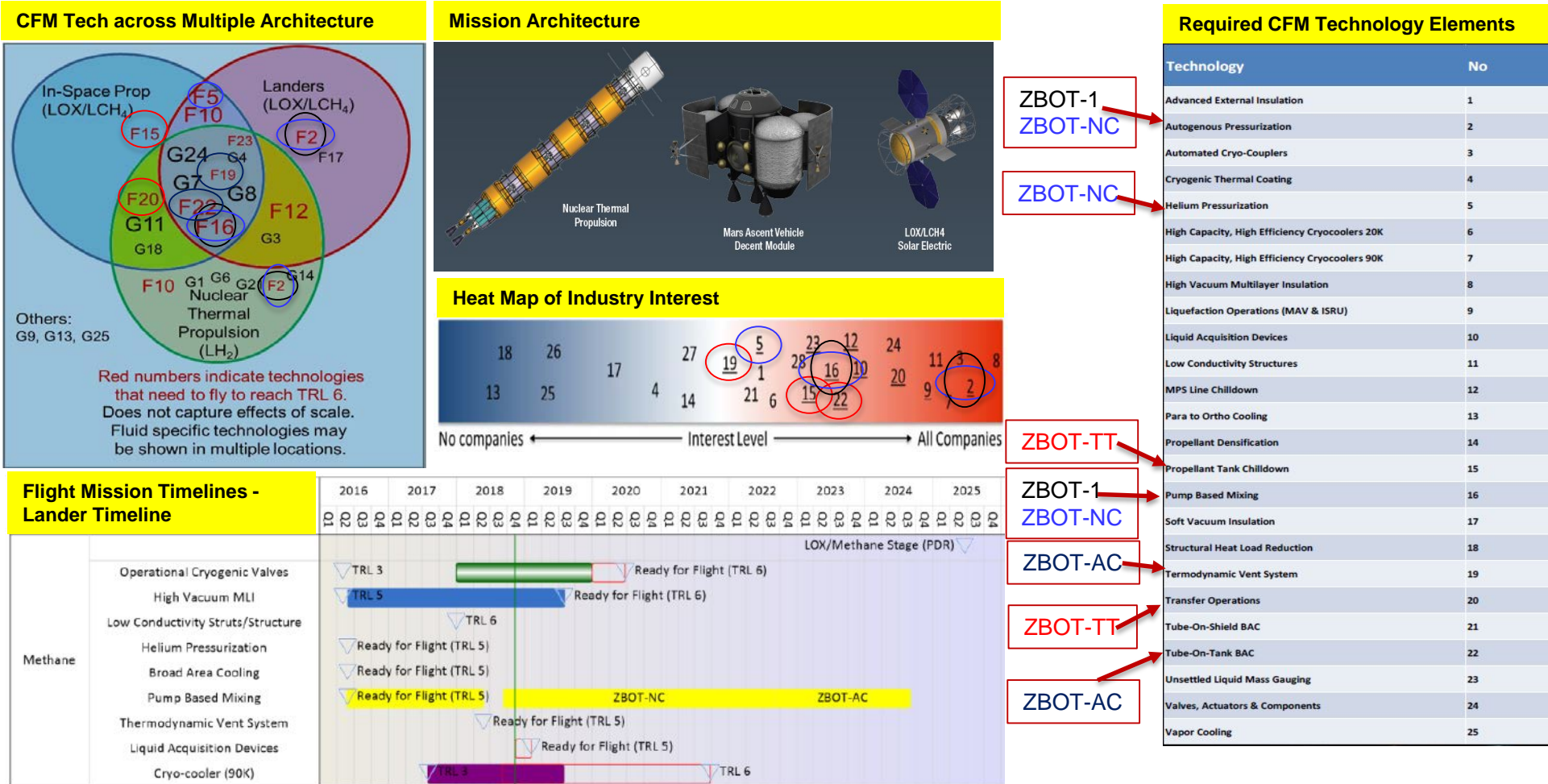
*Supplemental source: "A Researcher's Guide to the ISS Technology Demonstration" Website:

https://www.nasa.gov/sites/default/files/files/2013_ISS_Tech-Demo-mini-book-web_LATEST%282%29.pdf

ZBOT – TT : NASA is looking for Industry Partners to Provide

1. Hardware ground testing.
2. Flight hardware development with the necessary NASA technical, engineering and safety reviews (SRR, PDR, CDR, etc.) –
 - Documents: Technical/science requirements, engineering and safety
 - System design
 - Hardware build
 - Testing
 - Verification
 - Payload delivery to NASA for integration and launch
3. Benefit to Payload Developers -
 - Significant influence on the experiment design
 - Exclusive data rights for 12 months. (Note - Data will eventually be uploaded to the NASA Physical Sciences Informatics System (PSI) and available to the public).
 - Stepping stone to more advanced cryogenic propellant tank projects

Roadmap for CFM Tech Needs Across Mission Architectures and the ZBOT Series. SLPSRA – STMD Collaboration



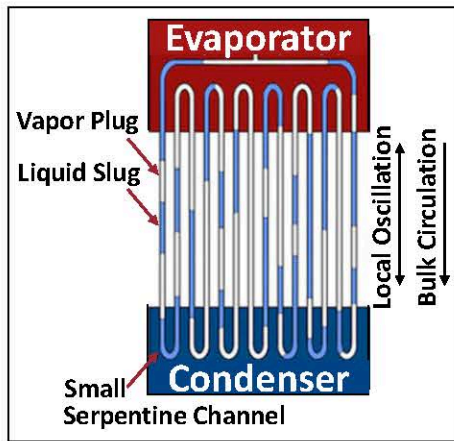
Oscillating Heat Pipes

A New Thermal Management Technology

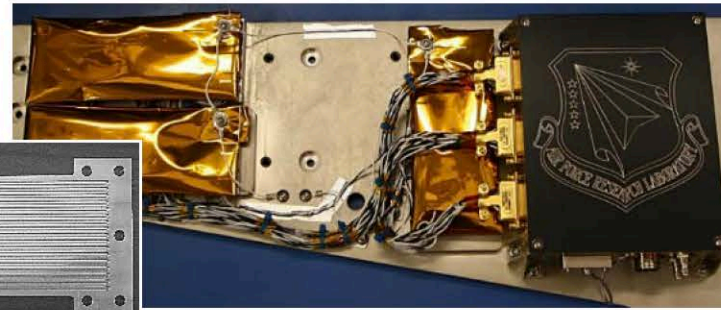
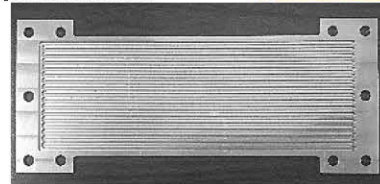
- Passive, wickless, and generally gravity-independent—functions as a heat spreader or heat pipe

Design

- Serpentine collection of microchannels
- Evacuated and partially filled with a fluid
- Surface tension effects create a natural separation of liquid slugs and vapor bubbles



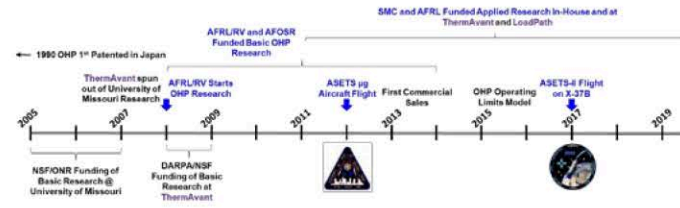
OHP Schematic
THE AIR FORCE RESEARCH LABORATORY



ASETS-II Flight Hardware (Top) and ASETS-II OHP w/o Lid (Left)



Video of OHP Operation



Thermal Management Tech Comparison

	Heat Pipe	Loop Heat Pipe	OHPs
Heat Flux	6.2 W/cm ²	67 W/cm ²	>300 W/cm ²
Temperature	<80 °C	< 80 °C	> 150 °C
Max Length	<3 m	<30 m	>2 m?

Operation

- Differential heating of the OHP creates a pressure imbalance/instability
- Heat transferred through two-phase flow without the need for an expensive wick
- Majority of heat transfer is forced convection



X-37B Orbital Test Vehicle



ASETS Flight Experiment: The First Step Towards Flight Qualification

OHP on NASA's Zero-G Aircraft

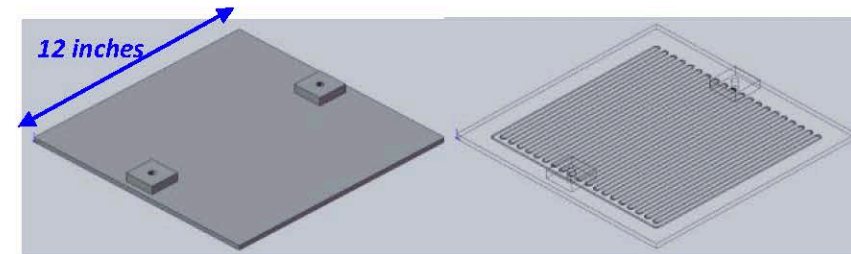
- 10 seconds of microgravity per parabola and over 80 parabolas flown on microgravity aircraft—Summer 2012

Accomplishments and Impact

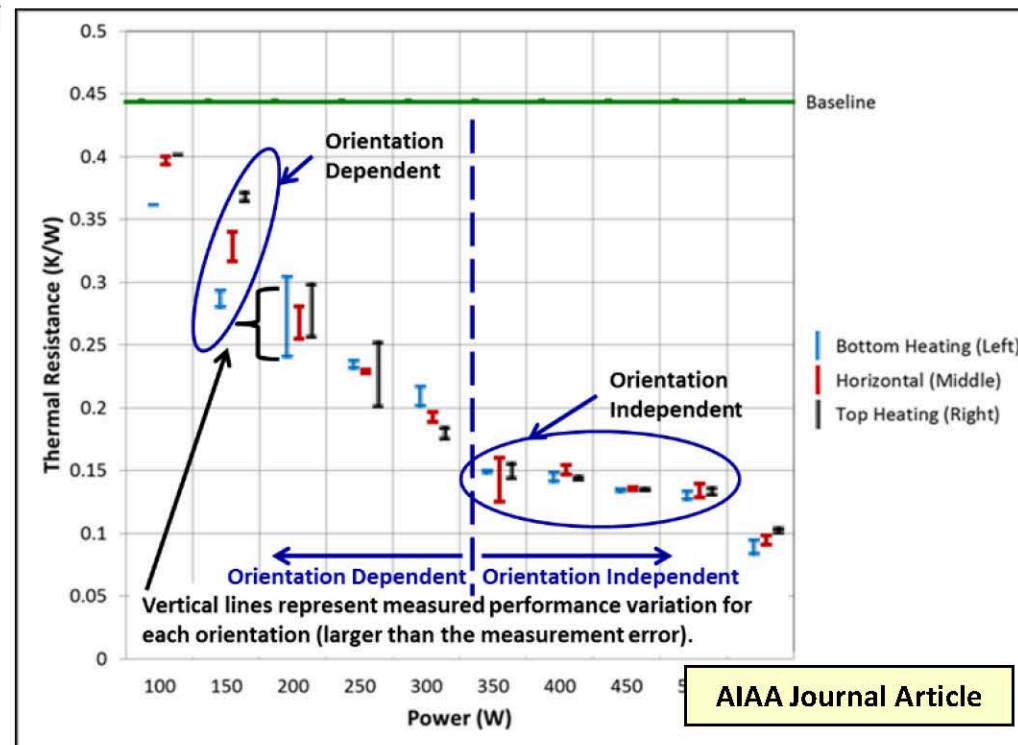
- OHP operated in steady state despite fluctuating gravity
- Flight data matches ground testing, indicating true gravitational independence above a minimum heat load
- Improved terrestrial prediction of microgravity performance



Mr. Brent Taft (upside down, PI) and Dr. Derek Hengeveld operating the OHP flight experiment on NASA's Zero-G Aircraft

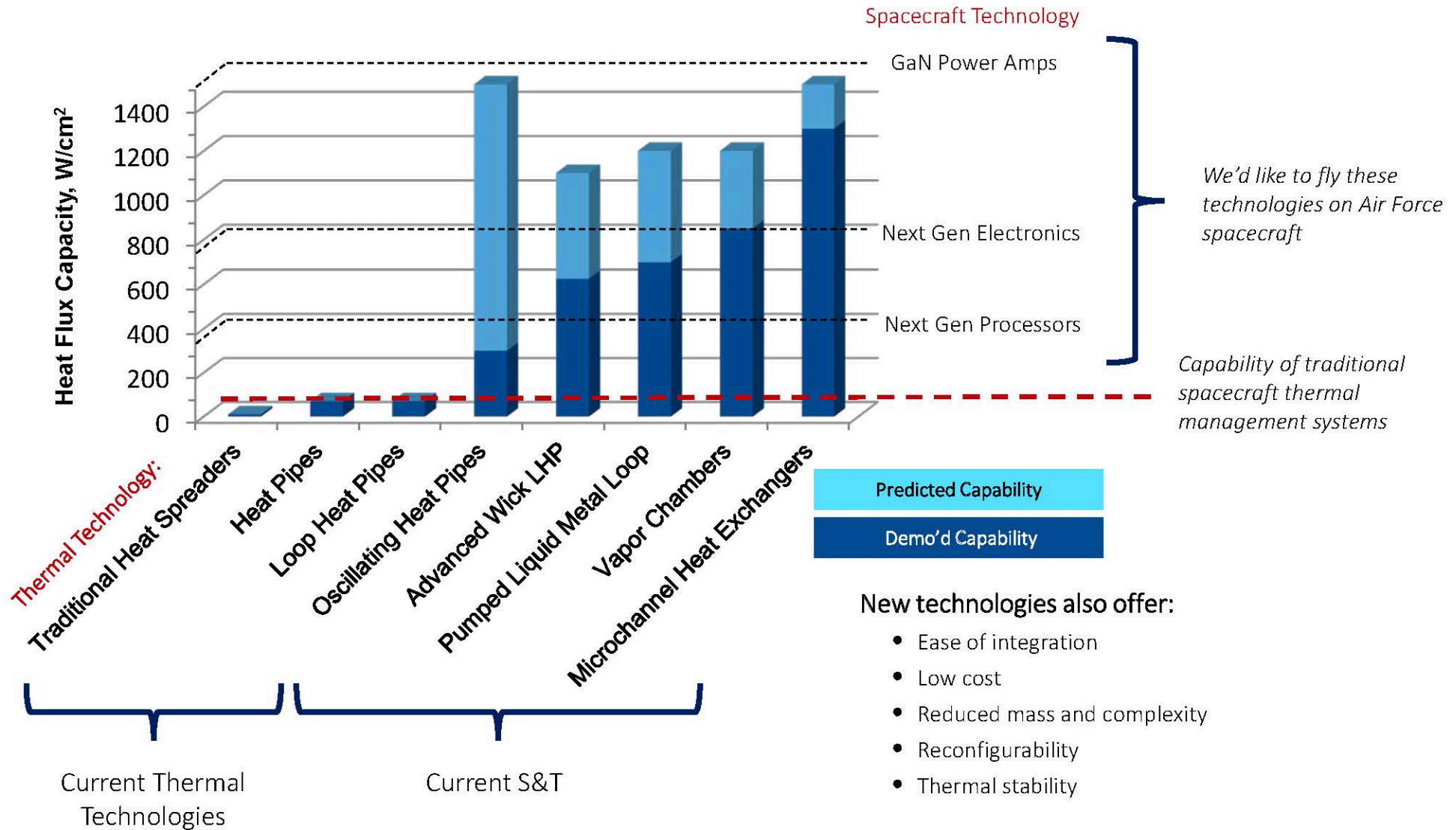


ASETS OHP Schematic: Solid View (Left) and Transparent View (Right)



ASETS Microgravity Flight Experiment Results Showing Gravity Independence of OHPs

High Flux Electronics Cooling



A Brief History of Spacecraft Thermal Control

1959

1979

1999

2019

Conduction Era

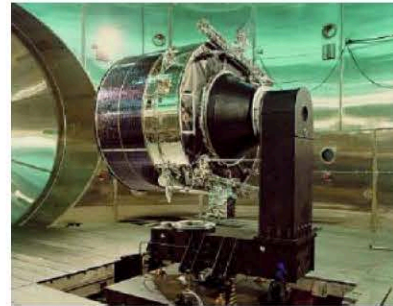
CCHP Era

LHP Era

OHP Era



Sputnik 1
1959
1st satellite



GEOS 2
1978
1st U.S. satellite to use heat pipes in TCS



Galaxy XI
1999
1st U.S. satellite to use LHPs in TCS



??
Soon?
1st satellite to use OHPs in TCS

Spacecraft thermal control paradigm changes every generation.
The time for OHPs is upon us.

NSF has expressed interest in collaborating with NASA SLPSRA in Fluid Physics and Combustion Science

Candidate areas include:

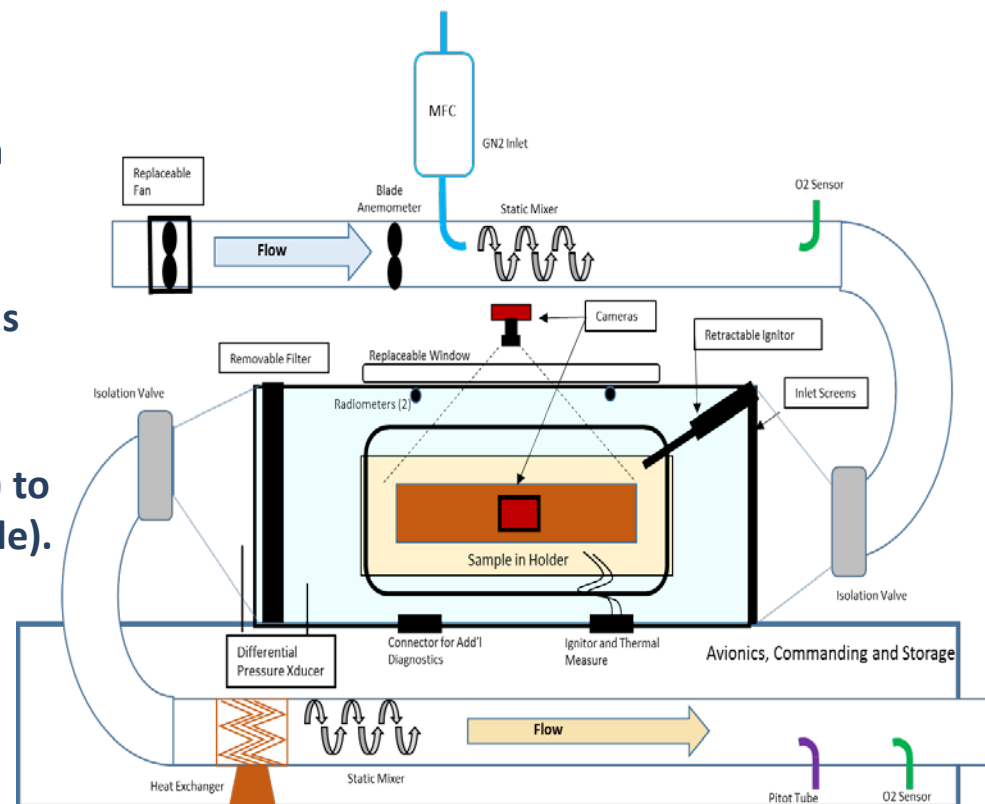
- Flow Boiling ISS experiments
- Adiabatic two phase flow – ISS experiments
- Transcritical Combustion - drop tower studies

JAXA's Two Phase Flow experiment status

- 1) Two Phase Flow unit is a JAXA, microgravity flow boiling experiment operating in the low to moderate flow regimes
- 2) The initially planned ISS testing has been completed. The PI is Prof. Ansano.
- 3) JAXA will reuse the experiment with new investigators
- 4) JAXA welcomes international Co-Is
- 5) Initial NASA – JAXA discussions have started

Proposed NASA Combustion Science collaboration with CNES, DLR and JAXA using MWT

- A large flow duct to operate in the ISS: 20 cm tall, 20 cm wide, 40 cm long)
- Can conduct flammability tests that are the identical size as ground based samples used in the NASA STD-6001 Test 1. (30 cm long x 5 cm wide x variable thickness)
- Only constant atmospheric pressure conditions achieved in MWT
- Use ISS N₂ to blend down the MSG working volume to vary O₂ concentration (~10-21% O₂) to measure flammability map. (2nd critical variable).
- Provides a flow system to vary velocity (0-50 cm/s) (critical variable)
- Can conduct flame spread/growth with larger surface area samples.
- Utilize MSG cameras and basic sensors (O₂, CO₂, thermocouples, radiometers). Fly additional diagnostics as warranted by specific investigations.
- Scar in additional capabilities to expand research opportunities to other combustion, fluid physics, and biological experiments.

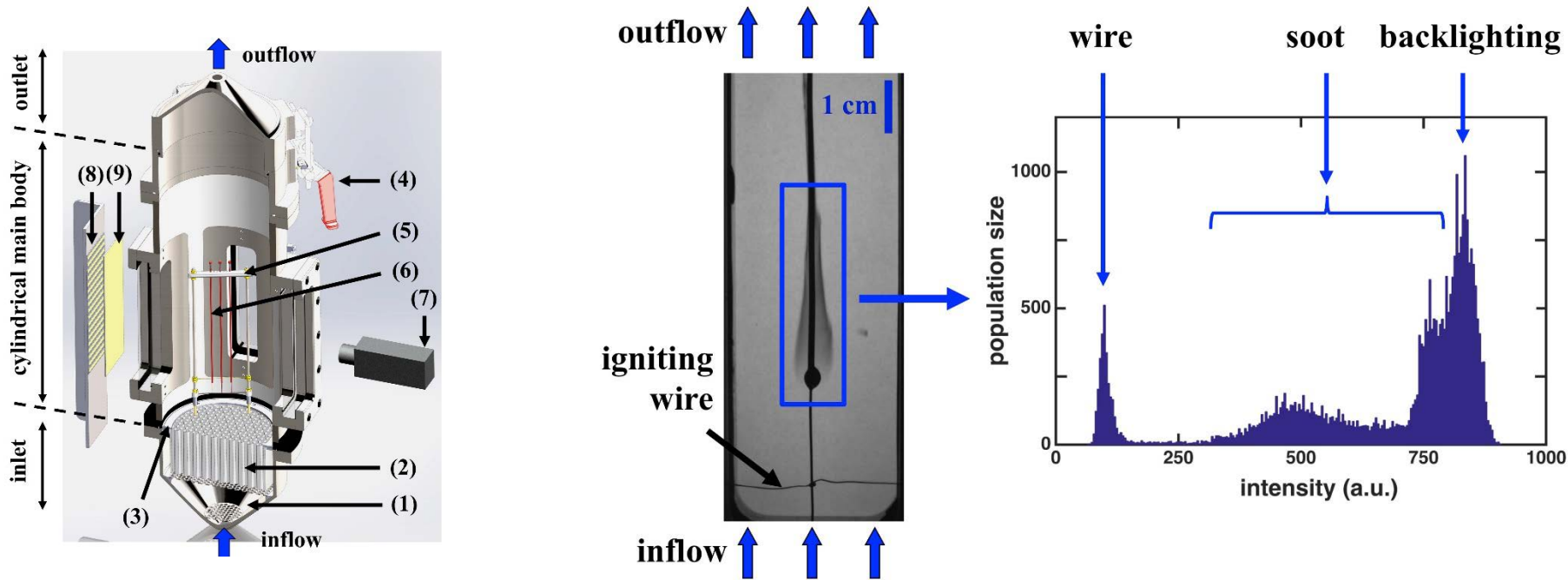


ISS MWT - MSG detailed concept

Diagnostic packages:

(PI: Guillaume Legros/Sorbonne Universités, UPMC Univ,, CNRS) – **Verbal agreement reached for investigator collaboration**

- Light Extinction Package (laser diode backlight and associated camera)



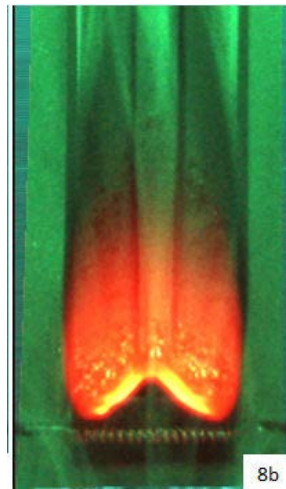
Schematic of the combustion chamber designed for the parabolic flights.

On the left, backlighting technique capturing the flame spread along the polyethylene coating of a wire in microgravity for $VOX=5$ cm/s. On the right, distribution of the intensities delivered by the pixels encompassed within the region delineated by the blue rectangle drawn on the frame.

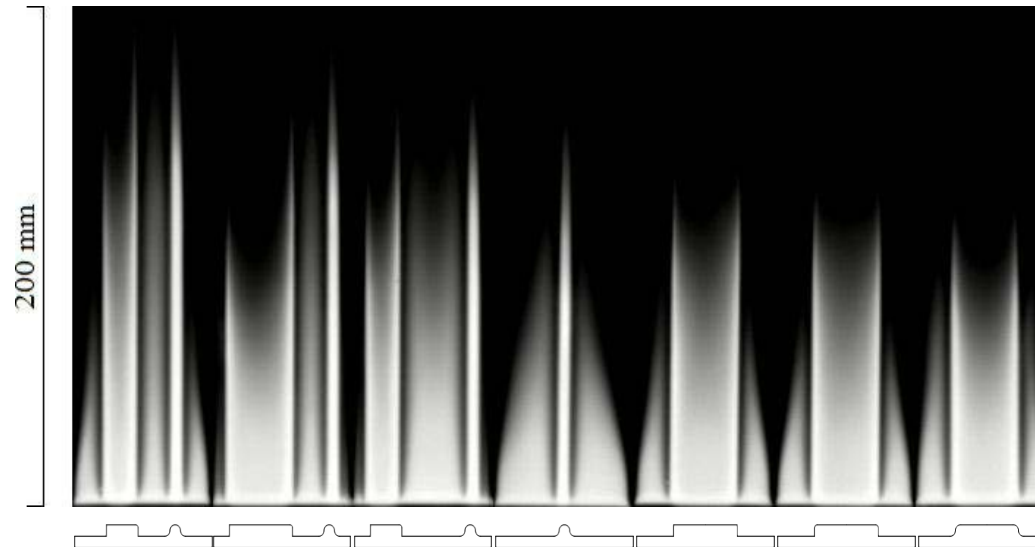
Diagnostic packages:

(PI: Christian Eigenbrod/ZARM) – **Verbal agreement reached for investigator collaboration**

- IR camera to facilitate seeing the sample through the flame



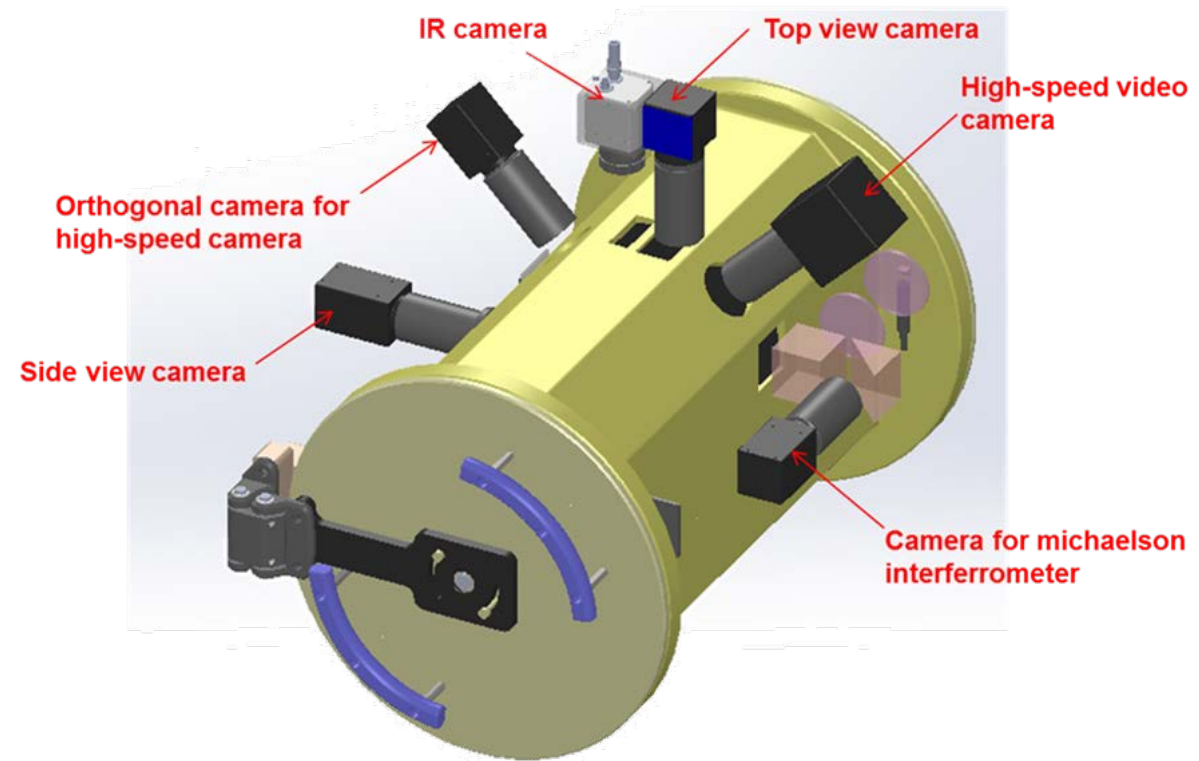
Effect of different surface structures on flame propagation (PMMA, 0g) imaged with a conventional camera



Effect of different surface structures on flame propagation (PMMA, 1g) imaged with an IR camera

Diagnostic packages derived from FLARE hardware (PI: Osamu Fujita, JAXA: Masao Kikuchi)

- IR camera
- High speed video camera
- Michaelson interferometer



FLARE Hardware Concept

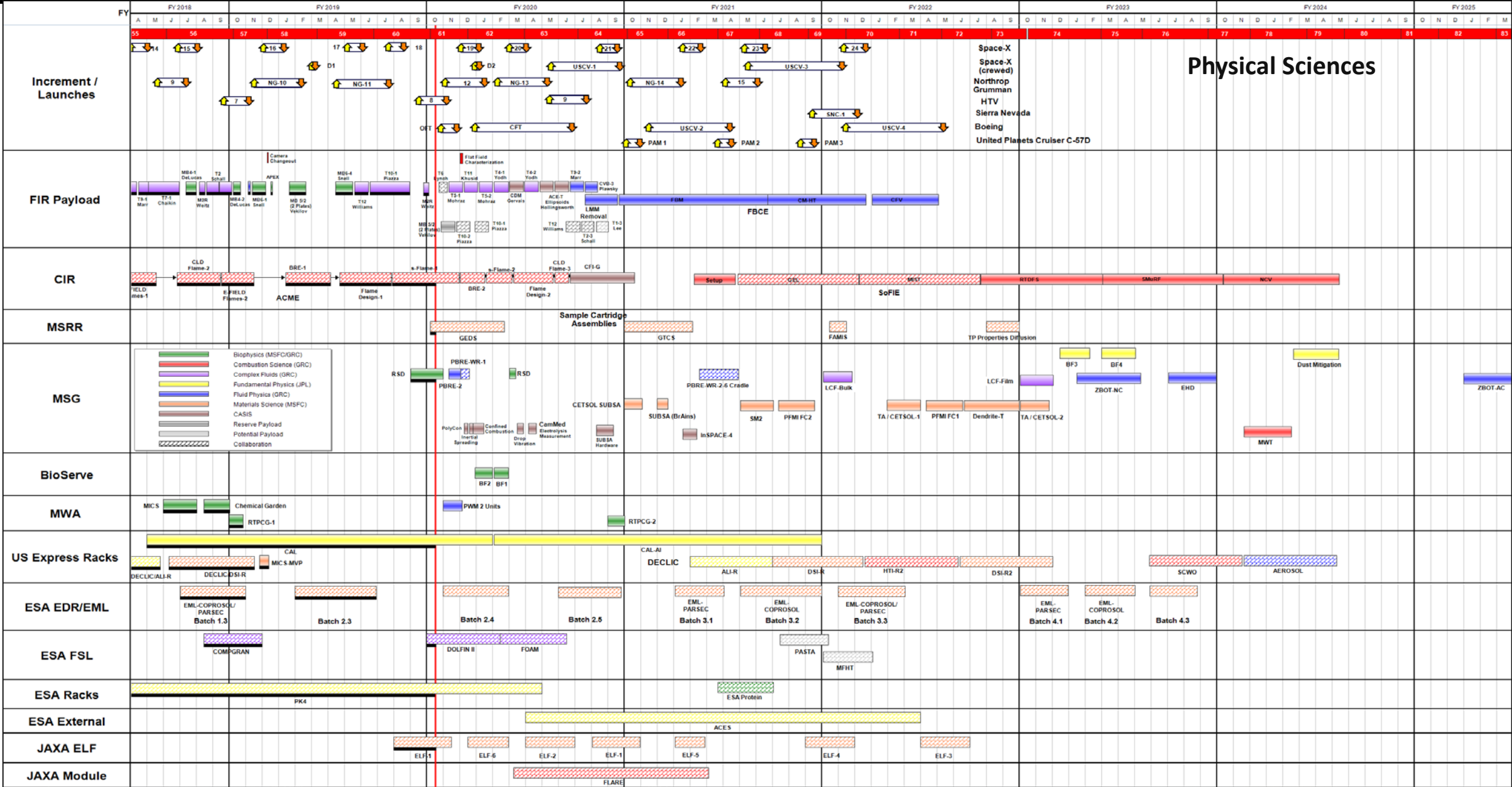
10. Challenges

• Challenges moving forward

1. Limited or no funding for ground program.
 - ground-based work serves as foundation for future flight experiments
 - ground program, at the present, primarily consists of investigators currently in flight program.
2. Cost overruns on existing flight projects due to:
 - Change in science requirements
 - Unexpected engineering challenges during Phase C/D
3. Resource limited on the ISS
 - SLPSRA crew time: 9.5 hours for current increment and zero hours the next.
4. Limited of partial gravity research facilities to support lunar exploration
 - Suborbital - 3 minutes (new)
 - Aircraft - 22 sec (existing)
 - Drop Tower - 10 sec (proposed at GRC)



Physical Sciences ISS Utilization Schedule





Thank you

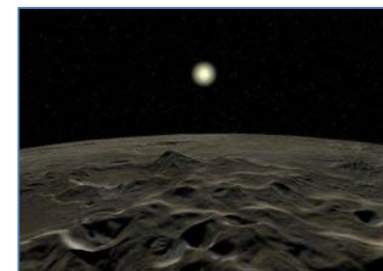
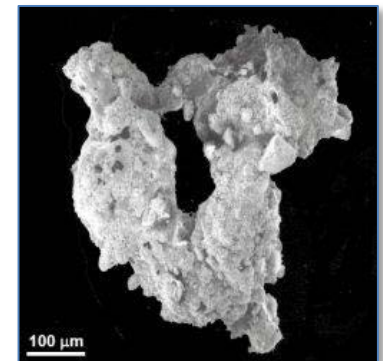
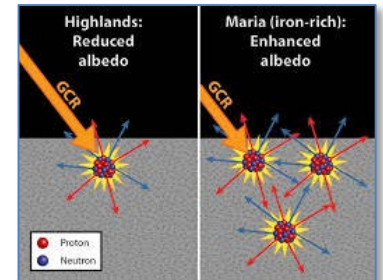




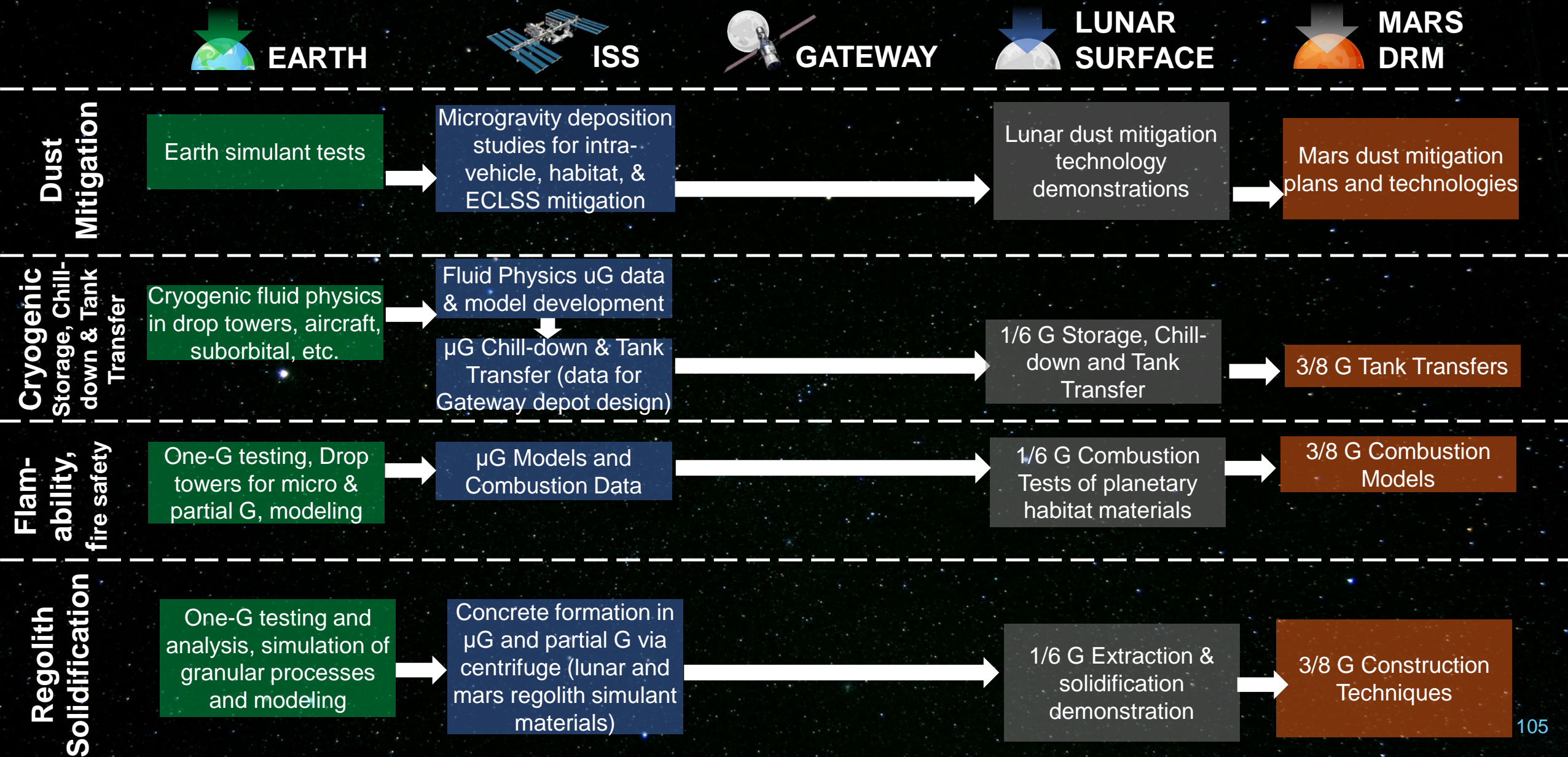
Back - Up

11. Candidate Partial Gravity Experiments

- **Reduced gravity (1/6-g)**
 - Flammability, fire safety
 - Two phase flow (pool and flow boiling, packed bed reactors, cryogenic fuel storage and transfer)
 - In Space Manufacturing (Additive/Advanced Manufacturing)
 - Soldering, brazing, welding
 - Food crop production
 - Bone loss, muscle loss, cardiovascular deconditioning
- **Deep space radiation & albedo radiation**
 - Radiation effects on microbes, plants, crew
- **Lunar regolith and dust**
 - Granular materials processing
 - In-situ surface construction, cement/concrete production
 - Metal and/or O₂ extraction from regolith
 - Dust mitigation
- **Unattenuated solar spectrum and plant growth**
- **Closed habitat (pCO₂, pH₂O, T, infrequent influx of crew and materials)**
 - Microbiome of humans, plants, vehicle
 - Biofilm production, biocorrosion

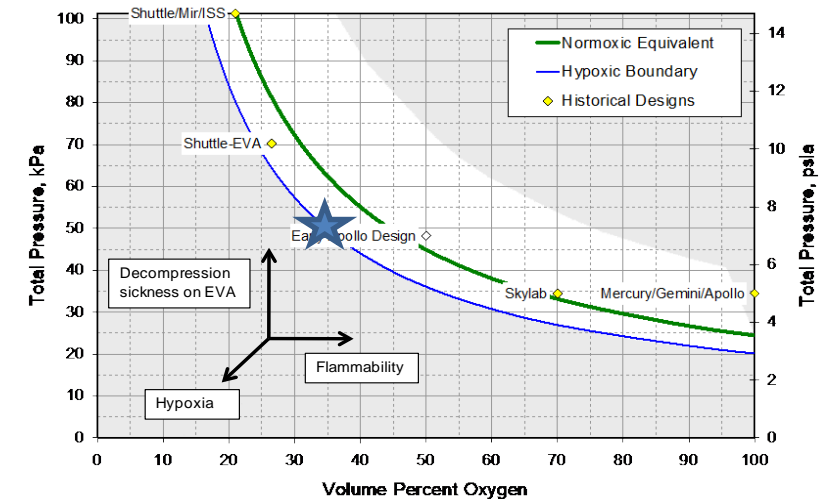


Cross-platform Strategy for Exploration-related Physical Sciences

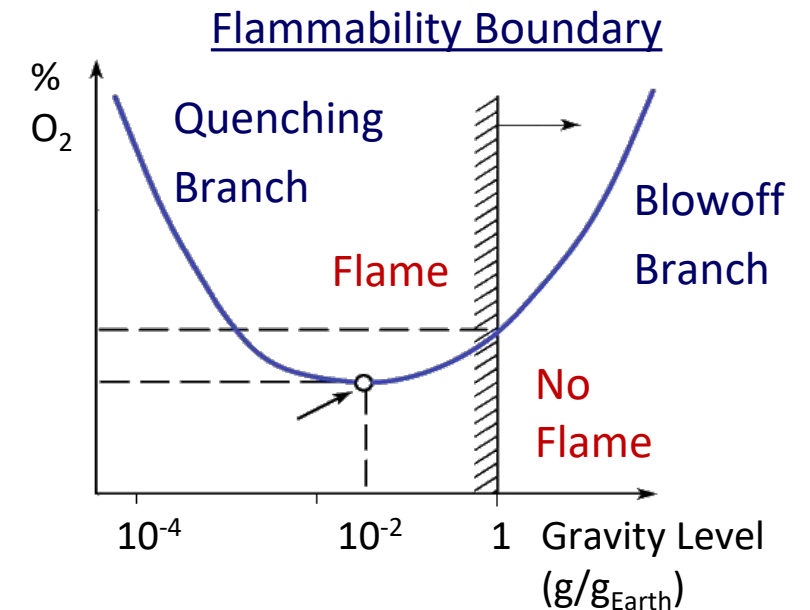


- Future exploration activities will occur in a 0.34 O₂ mole fraction, 8 psia, partial gravity (e.g., lunar) environment
- Fire is VERY sensitive to oxygen mole fraction
 - Increased heat release rate
 - Some materials that are not flammable at 0.21 O₂ will be flammable at 0.34 O₂
- The flame generates a buoyant flow so forced flow is not necessary to support a flame
- Existing data show that lunar gravity represents the most flammable condition

A spacecraft/habitat at 0.34 O₂, 8 psia in a lunar gravitational field has increased material flammability, higher heat release because of increased O₂ mole fraction and peak heat release caused by the buoyant flow



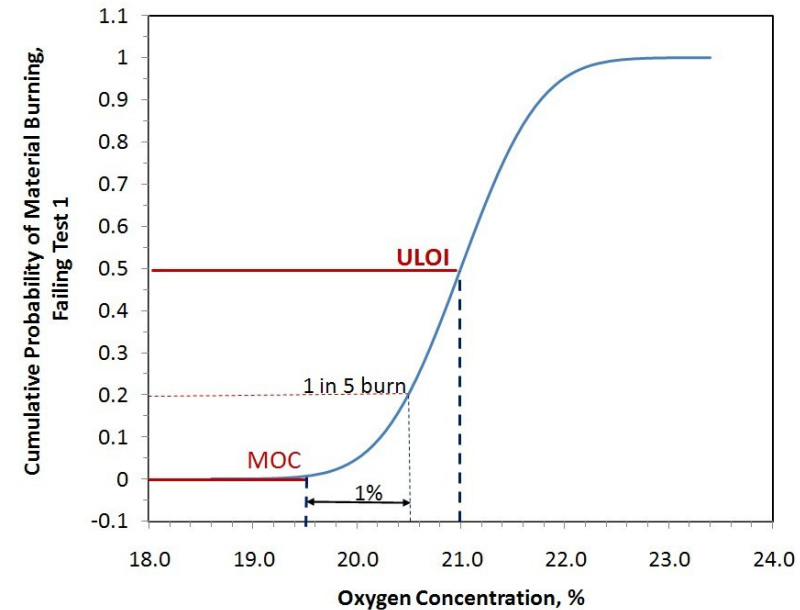
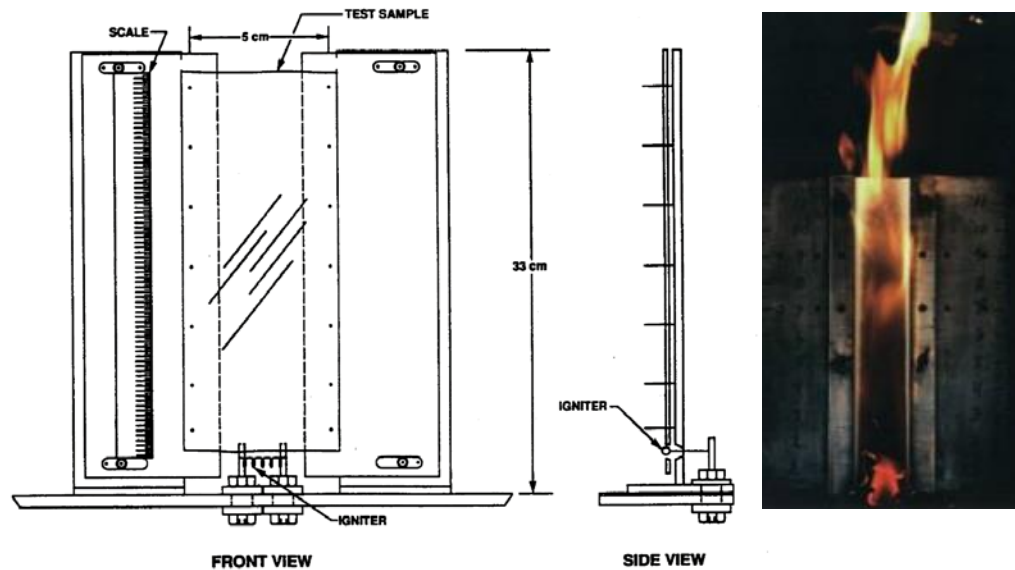
★ Proposed exploration atmosphere



Fire Safety Capability Gaps

Function	Capability Gaps	Gap criticality as applicable to mg transit Hab	Orion Need
Fire Suppression	ECLSS-compatible and rechargeable fire suppression; compatible with small cabin volumes.	5	X
Emergency Crew Mask	Single filtering cartridge mask (fire, ammonia, toxic spill), compatible with small cabin volumes (no O2 enrichment)	5	X
Combustion Product Monitoring	Contingency air monitor for relevant chemical markers of post-fire cleanup; CO, CO2, HF, HCl, HCN; battery-operated; hand-held calibration duration 1-5 years; survives vacuum exposure.	5	X
Low- and partial-gravity material flammability	Identify material flammability limits in low-g environment	4	X
Post-fire cleanup/smoke eater	Contingency air purifier for post-fire and leak cleanup; Reduce incident response time by 75% compared to getting in suits and purging atm	4	X
Fire Scenario Modeling and Analysis	Definition of a realistic spacecraft fire to size	3	X
Fire Detection	Early fire detection; particle size discrimination (false alarms)	2	X

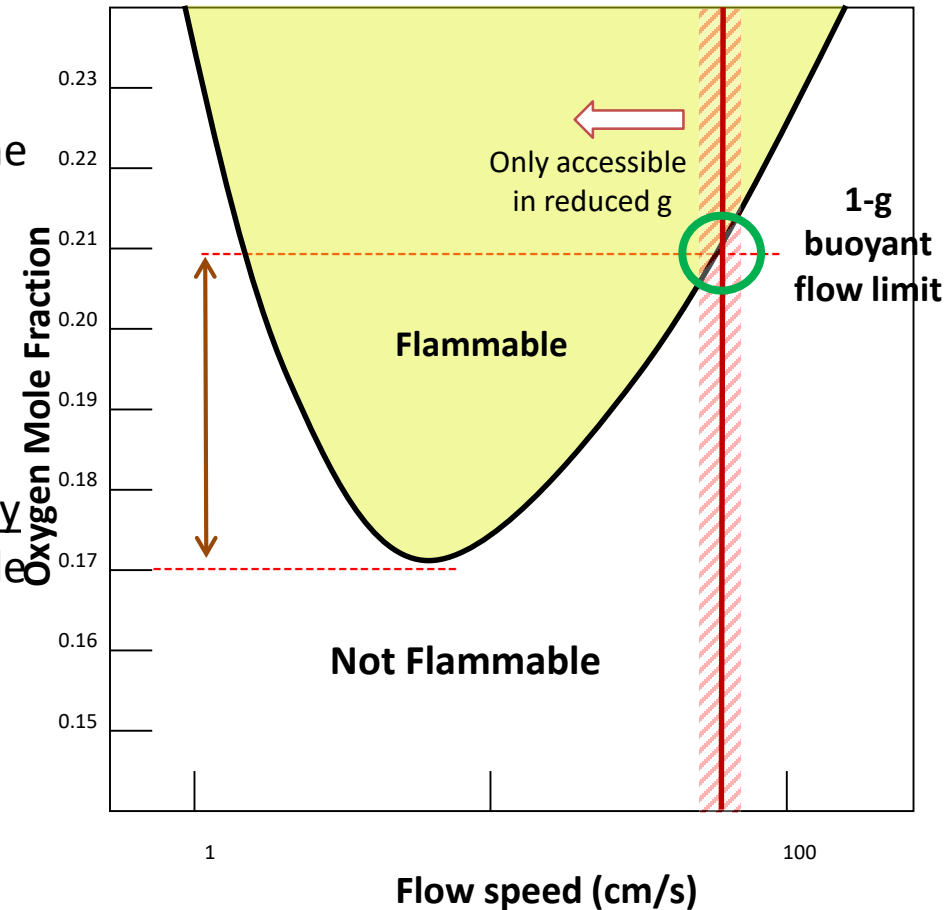
Material Flammability: NASA STD-6001 Test 1 - Upward Flame Spread Test



- ◆ Fails test if sample material is consumed past 15 cm
- ◆ Assumed to be worst case scenario for flammability
- ◆ Some materials have shown the opposite results
- ◆ Other figures of merit
 - Maximum Oxygen Concentration (MOC): all tests will pass the test
 - Upward Limiting Oxygen Index (ULOI): half of the tests will pass; half will fail

- ◆ Material flammability depends on the ambient flow
- ◆ In 1-g, the flame generates the flow by buoyancy (natural convection)
- ◆ In reduced – g the material can burn just fine with a lower flow and at a lower oxygen concentration; see region between two horizontal red lines
- ◆ Drop tower tests for various materials have shown that the oxygen mole fraction decrease could be between 0.02 and 0.06 by volume depending on the material. See mole fraction between vertical black arrow.
- ◆ Historically NASA STD-6001 Test 1 has been assumed to be the worst case condition for flammability. But this graph shows that in reduced –g, this is not the case. See region between the two horizontal red lines.

Typical Flammability Boundary for a Solid Fuel



This could impact Fire Safety for planetary habitats.

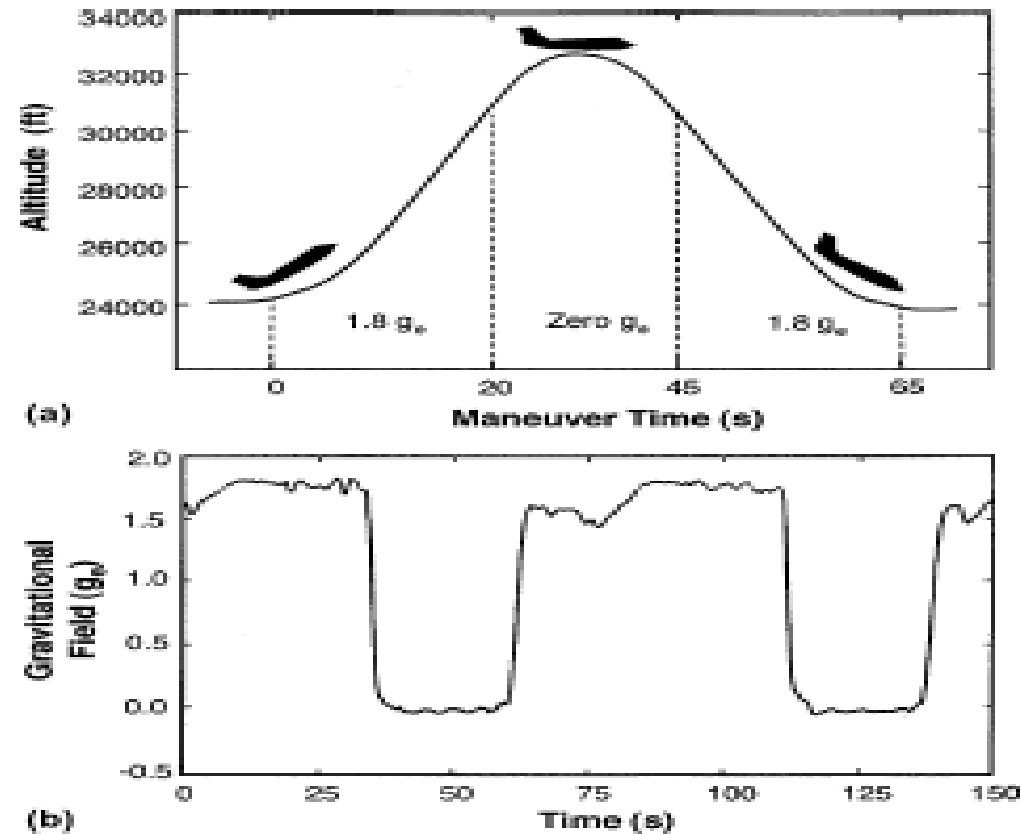
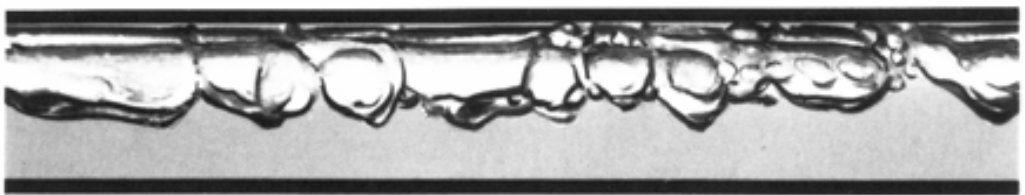


Fig. 4. (a) Trajectory and (b) gravity change of parabolic flight.

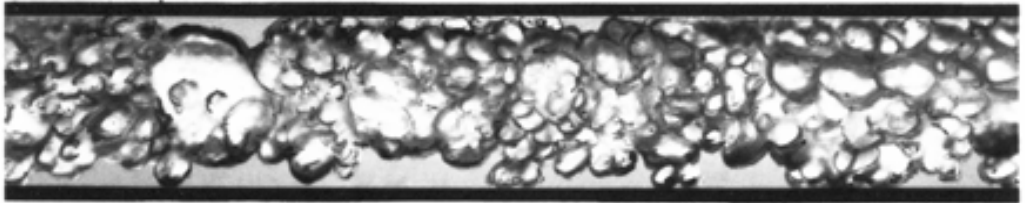
Adiabatic Two Phase Flow from Parabolic Aircraft Tests

EFFECT OF G-LEVEL ON MULTIPHASE FLOW

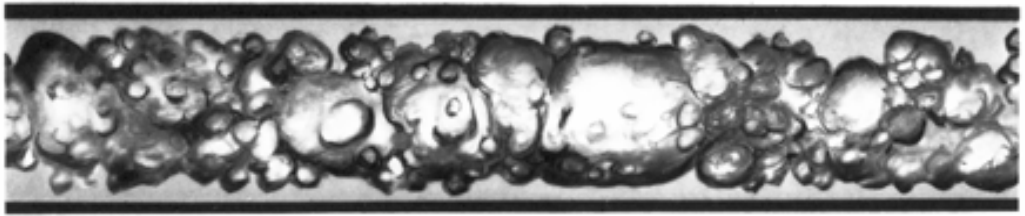
BUBBLY FLOW
NORMAL GRAVITY
~ 1.0 G'S



BUBBLY FLOW
LUNAR GRAVITY
~ 0.17 G'S



BUBBLY-SLUG FLOW
ZERO GRAVITY
< 0.01 G'S



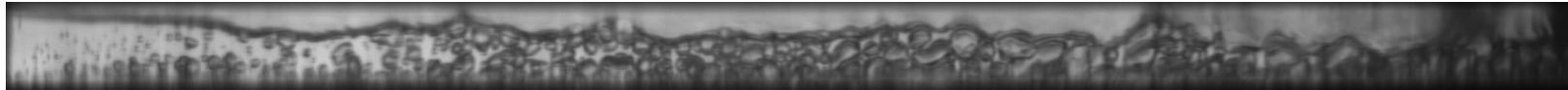
FLOW →

AIR-WATER IN 1.27 CM ID TUBE
SUPERFICIAL GAS VELOCITY ~ 0.55 M/S
SUPERFICIAL LIQUID VELOCITY ~ 0.55 M/S

This could impact ECLSS Systems, e.g. water recovery, on the Martian and Lunar surface and ISRU, e.g. cryogenic storage of oxygen and methane rocket propellant using carbon dioxide from the Mars atmosphere and water from Mars soil.

CHF Results for Double-sided Heating: Low U (0.1 - 0.11 m/s)

Horizontal one g_e

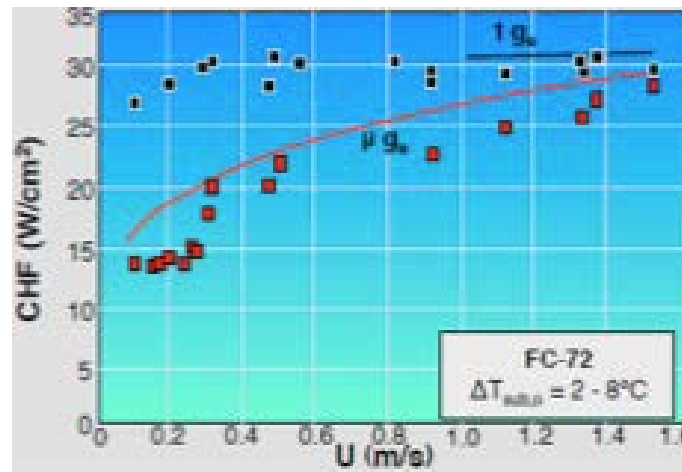


Source: Kharangate, C.R., O'Neill, L.E., Mudawar, I., Hasan, M.M., Nahra, H.K., Ramaswamy, B., Hall, N.R., Macner, A.M., and Mackey, J.R., 2015, "Flow Boiling and Critical Heat Flux in Horizontal Channel with One-sided and Double-sided Heating," *International Journal of Heat and Mass Transfer*, Vol. 90, pp. 323-338.

Microgravity μg



Source: Konishi, C., Lee, H., Mudawar, I., Hasan, M.M., Nahra, H.K., Hall, N.R., Wagner, J.D., May, R.L., and Mackaey, J.R., 2015, "Flow Boiling in Microgravity: Part 1 – Interfacial behavior and experimental heat transfer results," *International Journal of Heat and Mass Transfer*, Vol. 81, pp. 705-720.



Critical Heat Flux (CHF) data and model predictions for microgravity and Earth gravity for flow boiling

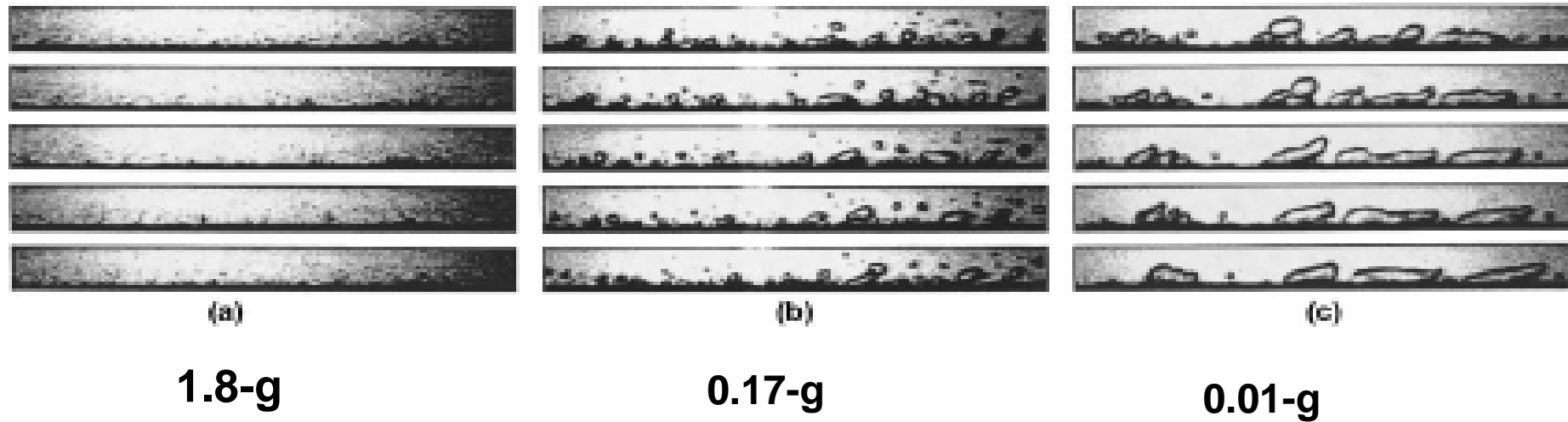
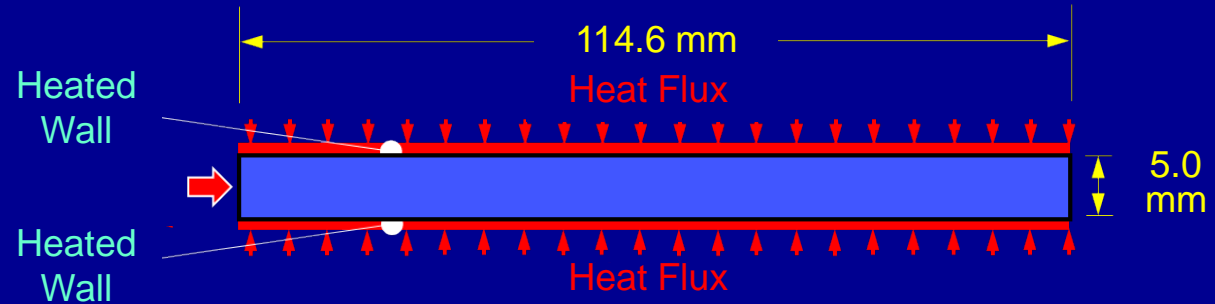


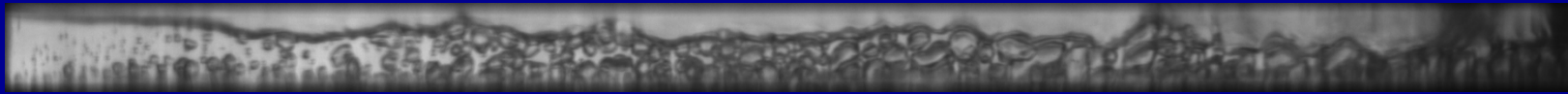
Fig. 6. Sequential images for $U = 0.14$ m/s, $\Delta T_{\text{sub}} = 22.8$ deg C and $q = 17.1$ W/cm². Corresponding to CHF in: (a) 1.8-g, (b) Lunar-g (0.17g) and (c) near zero-g.

This could impact Martian or Lunar surface power systems if a Rankine power system is utilized

**CHF Results for
Double-sided Heating:
Low U
(0.1 - 0.11 m/s)**



Horizontal one g_e



Source: Kharangate, C.R., O'Neill, L.E., Mudawar, I., Hasan, M.M., Nahra, H.K., Ramaswamy, B., Hall, N.R., Macner, A.M., and Mackey, J.R., 2015, "Flow Boiling and Critical Heat Flux in Horizontal Channel with One-sided and Double-sided Heating," *International Journal of Heat and Mass Transfer*, Vol. 90, pp. 323-338.

Microgravity



Source: Konishi, C., Lee, H., Mudawar, I., Hasan, M.M., Nahra, H.K., Hall, N.R., Wagner, J.D., May, R.L., and Mackaey, J.R., 2015, "Flow Boiling in Microgravity: Part 2 – Critical Heat Flux Interfacial Behavior, Experimental Data, and Model," *International Journal of Heat and Mass Transfer*, Vol. 81, pp. 721-736.

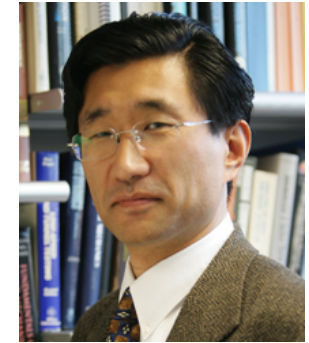
Observations:

1. CHF in horizontal one g_e flow at low U is associated with appreciable stratification resulting from strong buoyancy and weak inertia
2. CHF in microgravity at low U drastically different in interfacial structure compared to one g_e

Boiling – Horizontal, 1-g at low velocity

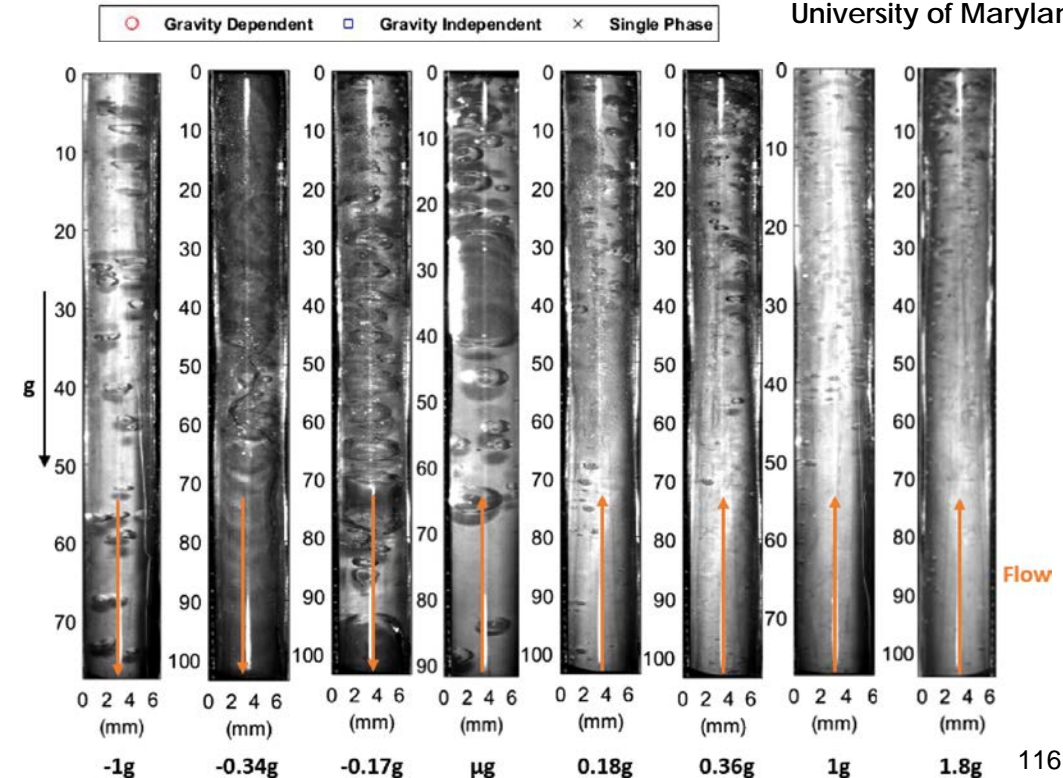
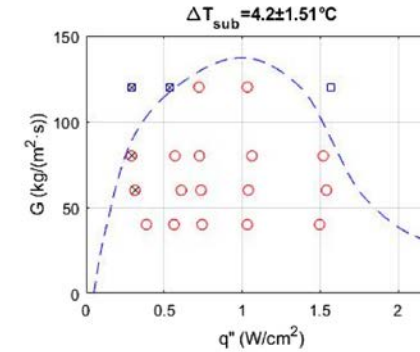


Lebon MT, Hammer CF, **Kim J.** "Gravity effects on subcooled flow boiling heat transfer." *International Journal of Heat and Mass Transfer*. 2019 Jan;128: 700-14. <https://doi.org/10.1016/j.ijheatmasstransfer.2018.09.011> , Jan-2019



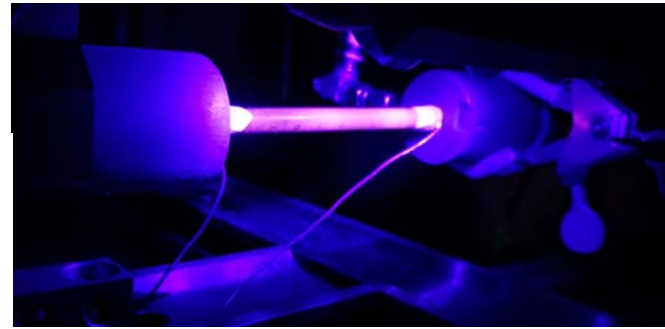
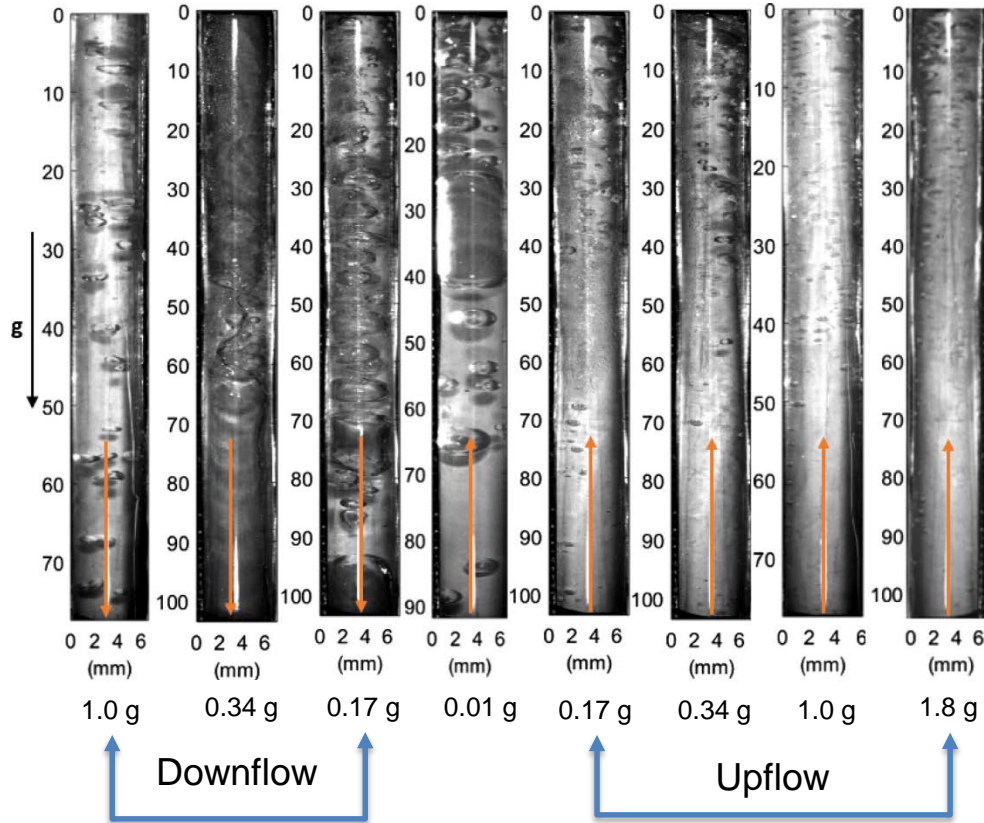
Jungho Kim, Ph.D.
University of Maryland

- Parabolic flights and testing occurred aboard Zero-G's B727.
- In microgravity, bubbly flow heat transfer is less in microgravity compared to normal gravity due to the decrease in slip velocity, bubble detachment frequency, and turbulent mixing.
- The reduction in heat transfer was continuous across all gravity levels only if the flow regime was consistently bubbly flow.
- Sometimes single phase flow was observed in normal gravity while two phase flow was observed in microgravity. The rapid growth of the thermal boundary layer in microgravity for these cases promoted nucleation, resulting in higher heat transfer coefficients compared to normal gravity.
- The effect of gravity on heat transfer decreased as both mass flux and heat flux increased.
- At high mass flux, the forced convection dominated the gravity effect.
- At high heat flux, the annular flow liquid film evaporation dominated the gravity effect

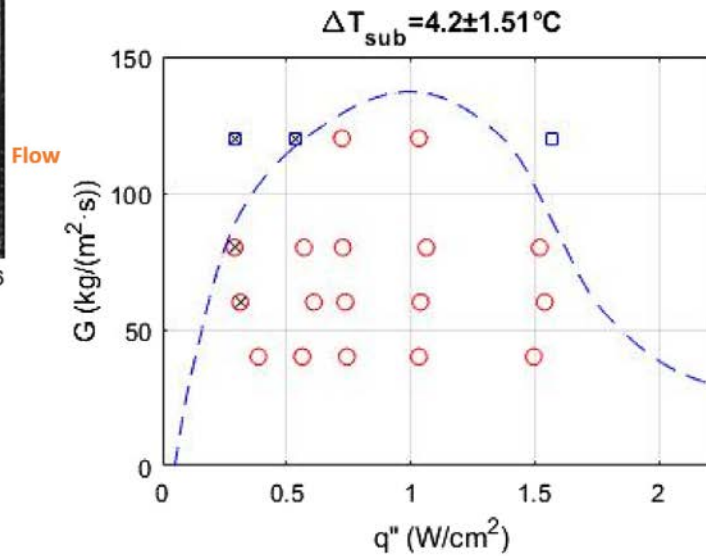


Multiphase Flow & Heat Transfer Experiment

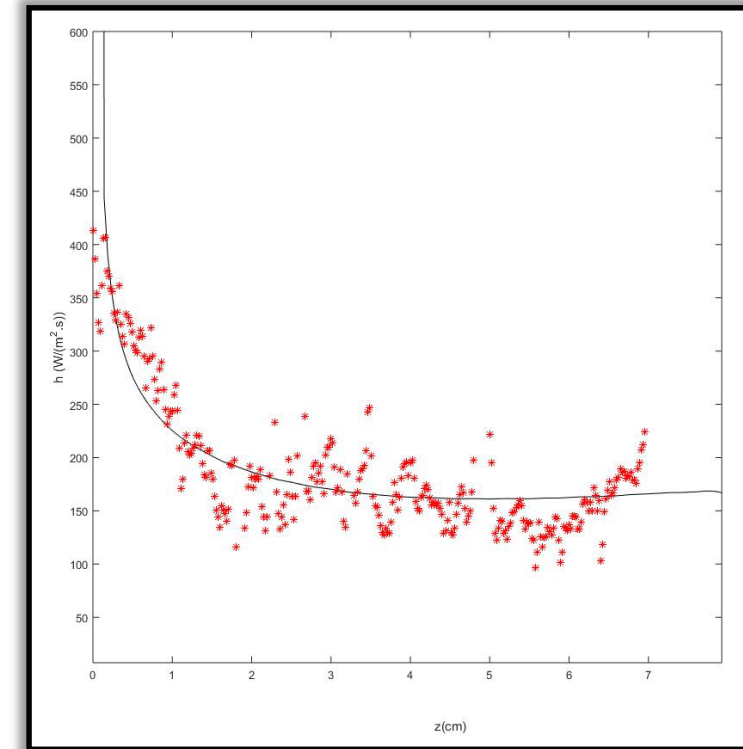
Comparison of magnitude and direction of gravity and velocity vector.



Test Section Coated with Temperature Sensitive Paints



○ Gravity Dependent □ Gravity Independent × Single Phase



Comparison of single phase heat transfer coefficients corrected for local velocities with measured two-phase heat coefficients for bubble flows.



12. Flight Project Mapping to Decadal Survey Identifiers and PSI Investigations

- Ring Sheared Drop for the study of amyloid formation (AP5)
- Characterization of Biofilm Formation, Growth, and Gene Expression on Different Materials and Environmental Conditions in Microgravity (P1, P2)
- Polymicrobial Biofilm Growth (on Stainless Steel) and Control during Spaceflight (P1, P2)
- Microstructure Evolution in Freeze-Cast Materials (AP5, AP9)
- Structure-Property-Processing Correlations in Freeze-Cast Biomimetic Materials (AP5, AP9)
- Protein Crystal Growth (AP9)
 - LMM Bio 1 and 4
 - LMM Bio 2 and 5
 - LMM Bio 3 and 6
 - RTPCG - 1
 - RTPCG - 2

Non-premixed Gaseous Flames

- ACME – BRE (Burning Rate Emulator) ([AP7](#), [AP8](#), [TSES 8](#))
- ACME – CLD Flame (Coflow Laminar Diffusion Flame); ([AP7](#), [AP8](#))
- ACME – E-FIELD Flames (Electric-Field Effects on Laminar Diffusion Flames) ([AP7](#), [AP8](#))
- ACME – Flame Design (*soot inception and transport*) ([AP7](#), [AP8](#))
- ACME – s-Flame (Structure and Response of Spherical Diffusion Flames) ([AP7](#), [AP8](#))

Solid Fuel, Flammability (AP7, AP8, TSES 8)

- SoFIE - Residence Time Driven Flame Spread (RTDFS)
- SoFIE - Narrow Channel Validation (NCV)
- SoFIE - Spacecraft Materials Microgravity Research on Flammability (SMuRF)
- SoFIE - Growth and Extinction Limit of Solid Fuels (GEL)
- SoFIE - Material Ignition and Suppression Test (MIST)
- FLARE (JAXA) – Flammability Limits At Reduced-g Experiment
- Saffire 1- 6 (Spacecraft Fire Safety Demonstration Project), AES Led

Supercritical Reacting Fluids (AP5, TSES6)

- Super Critical Water Mixture, DECLIC (HTI-R/SCWM), with CNES
- Super Critical Water Oxidation, DECLIC-EVO, (SCWO) with CNES and NASA's AES

- **Advanced Colloids Experiments (FP1, AP5)**
 - ACE T2, ACE T4, ACE T5
 - ACE T7, ACE T9, ACE T10
- **Liquid Crystal Experiments (FP1, AP5)**
 - LCF – Bulk, Liquid Crystal Nanoplates
 - LCF – Bulk, Ferromagnetic Liquid Crystal Colloids in Microgravity
 - LCF – Film, Nanoparticles and Topological Defects in Thin Films,
 - LCF – Film, Monodisperse Liquid Crystal Domains,
 - LCF – Film, Ferromagnetic Liquid Crystal Colloids in Microgravity,
- FOAM, ESA led, (AP5)
- PASTA, ESA led, (AP5)
- Compgran, ESA led, (AP3)

- Packed Bed Reactor Experiment (PBRE) (AP1, TSES6 – T6)
 - PBRE-2
 - Packed Bed Reactor Experiment Water Recovery, (PBRE-WR 1 – 6), with NASA's AES
- Flow Boiling and Condensation Experiment (FBCE) (AP1, TSES1 – T1)
- Multiphase Flow and Heat Transfer Experiment (MFHT), ESA led experiment, “Flow Boiling,” (AP1, TSES1 – T1, TSES6 – T21 & 22),
- ElectroHydro Dynamic Experiment (EHD) (AP1, TSES1 – T1)
- Zero Boil Off Tank (ZBOT) Experiments (AP1, TSES2 – T3)
 - ZBOT experiment (data used by NASA's STMD)
 - ZBOT- NC experiment (data to be used by NASA's STMD)
 - ZBOT- AC experiment (data to be used by NASA's STMD)

- **Thermophysical Properties**

- EML Batches - 1, 2, 3, 4 – PARSEC: Peritectic Alloy Rapid Solidification with Electromagnetic Convection, (AP9)
- EML Batches – 1, 2, 3, 4, - ICOPROSOL: Thermophysical Properties and Solidification Behavior of Undercooled Ti-Zr-Ni Liquids Showing an Icosahedral Short-Range Order, (AP9)
- EML Batches 1, 2, 3, 4 - THERMOLAB: Thermophysical Properties of Liquid Metallic Alloys - Modelling of Industrial Solidification Processes and Development of Advanced Product, (AP9)
- ELF 1 - A Novel Way To Measure Interfacial Tension Using The Electrostatic Levitation Furnace (AP9)
- ELF 2 - Microgravity Investigation of Thermophysical Properties of Supercooled Molten Metal Oxides (AP9)
- ELF 3 - Thermophysical Properties and Transport Phenomena Models and Experiments in Reduced Gravity (AP9)
- ELF 4 - Round Robin - Thermophysical Property Measurement (AP9)
- ELF 5 – Supercooled Molten Oxides (AP9, AP10)
- ELF 6 – Fluidity of High Temperature Oxide Melts for Creating Novel Functional , non-equilibrium Materials, (AP9, AP10)

- **Microstructure and Morphology of Materials**

- Liquid Phase Sintering (AP9)
- Crystal Growth of Ternary Compound Semiconductors by Vapor Transport (FP1, AP9)
- Fabrication of Amorphous Metals in Space (Bulk Metallic Glasses) (AP9, AP10)
- Diffusion Coefficients of Dopants in Si and Ge Melts (AP9)
- Columnar to Equiaxed Formation (AP9)
- Coarsening of Dendritic Solid Liquid Mixture: The Low Volume Limit (AP9)
- Brazing of Aluminum Alloys (AP9, AP10)
- Cement Solidification (AP9, AP10, TSES16)
- Spatiotemporal Evolution of Three-Dimensional DENDRITIC Array Structures, DECLIC-DSI-R with CNES (AP9)
- Thermosolutal Convection during Cellular/Dendritic Pattern Formation of Single Crystal Metallic Alloys, (AP9)
- SiGe experiments in the GHF, (AP9)

PSI NRA Selected Proposals by Research Area

Appendix	Awarded proposals by research area				
	Combustion Science	Complex Fluids	Fluid Physics	Fundamental Physics	Materials Science
Appendix A	1	-	1	-	-
Appendix B	2	1	2	-	3
Appendix C	2	1	2	-	1
Appendix D	1	1	2	-	1
Appendix E	1	1	1	-	2
Total	7	4	8	-	7

Of the awarded proposals, 4 were submitted by graduate students and 22 were submitted by established researchers.

26 Awarded PSI Grants

	PI Name	PI Organization	Proposal Title	Research Area	Investigation(s) Used	Appendix Selected
1	Yiguang Ju	Princeton University	Quantitative Studies of Cool Flame Transitions at Radiation/Stretch Extinction Using Counterflow Flames	Combustion Science	FLEX-1	PSI A (2016)
2	Tanvir Farouk	University of South Carolina	Effect of external thermo-convective perturbation on cool flame dynamics: A multidimensional multi-physics CFD analysis	Combustion Science	FLEX-1	PSI B (2016)
3	Sean Garrick	University of Minnesota	Utilization of the smoke aerosol measurement experiment data for advanced modeling and simulation of smoke generation in micro-gravity	Combustion Science	SAME	PSI B (2016)
4	Fumiaki Takahashi	Case Western Reserve University	Structure and stabilization of laminar jet diffusion flames	Combustion Science	SLICE	PSI C (2017)
5	Thomas Avedisian	Cornell University	Use of FLEX data to enhance video image processing for studying combustion of soot-producing jet fuel droplets and their blends with bio-derived fuels	Combustion Science	FLEX-1	PSI C (2017)
6	Mitchell Smooke	Yale University	Computational and Experimental Analysis of SPICE Data Sets	Combustion Science	SPICE	PSI D (2018)
7	Paul DesJardin	State University of New York	Concurrent Flame Spread Modeling using Flamelet Generated Manifolds in Microgravity with Comparison to BASS Experiments using Two-Color Tomography	Combustion Science	BASS	PSI E (2019)

	PI Name	PI Organization	Proposal Title	Research Area	Investigation(s) Used	Appendix Selected
8	Lou Kondic	New Jersey Institute of Technology	Structure evolution during phase separation in colloids under microgravity	Complex Fluids	ACE-M1, BCAT-3, BCAT-4, BCAT-5, BCAT-6, PHaSE	PSI B (2016)
9	James Swan	Massachusetts Institute of Technology	Dynamic self-assembly driven by time with varying fields	Complex Fluids	InSPACE-3, InSPACE-3+	PSI C (2017)
10	Michael Cromer	Rochester Institute of Technology	Investigating the Role of pre-Shear and Pre-Stretching in the Transient Extensional Flow of Dilute Polymer Solutions: Modeling Benchmarking and Numerical Simulations	Complex Fluids	SHERE, SHERE-II, SHERE-R	PSI D (2018)
11	Anand Oza	New Jersey Institute of Technology	Phase Transitions in Colloid-Polymer Mixtures in Microgravity	Complex Fluids	BCAT 3 - 6	PSI E (2019)
12	Sinisa Mesarovic	Washington State University	Computational Framework for Capillary Flows	Fluid Physics	CCF, CFE	PSI A (2016)
13	Amir Riaz	University of Maryland, College Park	Gravity Scaling of Pool Boiling Heat Transfer: Numerical Simulations and Validation with MABE and NPBX	Fluid Physics	MABE, NPBX	PSI B (2016)

	PI Name	PI Organization	Proposal Title	Research Area	Investigation(s) Used	Appendix Selected
14	Yongsheng Lian	University of Louisville	Development and Verification of a 3D Nucleate Pool Boiling Simulation Model Using PSI Data	Fluid Physics	NPBX	PSI B (2016)
15	Vladimir Ajaev	Southern Methodist University	Modeling phase change and thermocapillary flow in the Constrained Vapor Bubble experiment	Fluid Physics	CVB, CVB-2	PSI C (2017)
16	Mark Weislogel	Portland State University	NASA CCF PSI data reduction and benchmark	Fluid Physics	CCF	PSI C (2017)
17	Jeffrey Allen	Michigan Technological University	Testing the Equivalence of Evaporation and Condensation Coefficients using the Constrained Vapor Bubble (CVB) Data from ISS Experiments	Fluid Physics	CVB, CVB-2	PSI D (2018)
18	Paul Steen	Cornell University	Capillary Flows and Draining in Microgravity	Fluid Physics	CFE	PSI D (2018)
19	Joel Plawsky	Rensselaer Polytechnic Institute	Loop-Based Constrained Vapor Bubbles	Fluid Physics	CVB	PSI E (2019)
20	Ebrahim Asadi	University of Memphis	Enhancement and Verification of Quantitative Phase-Field Crystal Modeling using NASA-PSI Coarsening in Solid-Liquid Mixtures Experiments Data	Materials Science	CSLM, CSLM-2, CSLM-2R, CSLM-3	PSI B (2016)

	PI Name	PI Organization	Proposal Title	Research Area	Investigation(s) Used	Appendix Selected
21	Kegang Wang	Florida Institute of Technology	Testing Analytical and Numerical Models in Phase Coarsening using NASA Physical Sciences Informatics System	Materials Science	CSLM, CSLM-2, CSLM-2R, CSLM-3	PSI B (2016)
22	Mohsen Eshraghi	California State University, Los Angeles	Pore-Mushy Zone Interaction during Directional Solidification of Alloys: Three Dimensional Simulation and Comparison with Experiments	Materials Science	PFMI	PSI B (2016)
23	Mohsen Asle Zaeem	Missouri University of Science and Technology	New Insights on Solid-Liquid Interface Anisotropy Effects on Solidification Patterns of Pure and Alloy Systems in Microgravity	Materials Science	IDGE, MICAST/CSS 6 & 7	PSI C (2017)
24	Kumar Ankit	Arizona State University	Advanced Modeling and Simulation of Crystal Growth Dynamics	Materials Science	IDGE	PSI D (2018)
25	Siddhartha Pathak	University of Nevada	Understanding the Local Structure-Property Relationships of Solders in Terrestrial vs. Microgravity Environments	Materials Science	ISSI	PSI E (2019)
26	Surrendra Tewari	Cleveland State University	Spurious Grain Formation in Alloys Directionally Solidified on the Space Station due to Marangoni Convection	Materials Science	MICAST/CSS, PFMI	PSI E (2019)

13. Collaboration Summary by Organization – International, ISS National Lab Interagency and NASA



International Collaborations



(March 26, 2018) - Expedition 55 Commander Anton Shkaplerov (foreground) and Flight Engineer Oleg Artemyev, both cosmonauts representing Roscosmos, replace a gas bottle inside the Destiny lab module's Combustion Integrated Rack (CIR). The bottle exchange was in support of the Electric-Field Effects on Laminar Diffusion Flames (E-FIELD Flames) experiment of the Advanced Combustion via Microgravity Experiments (ACME) project. A bottle of 40% methane (diluted with nitrogen) was replaced with a bottle of 100% ethylene, enabling a shift in testing from non-sooty to very sooty flames.



	Experiment	Principal Investigator	Russian Investigators	Collaboration Status	ISS Ops
1	Observation and Analysis of Smectic Islands (OASIS)	Professor Noel Clark, University of Colorado	Professor Pavel Dolganov & Professor Vladimir Dolganov, Institute of Solid State Physics Professor Efim Kats, Landau Institute Theoretical Physics	Science Protocol & ISS PSF Protocol - signed. Experiment Ops COMPLETED	July 2015-Jan. 2016, Mar 2016
2	Cool Flames Investigation - Open Science, (CFI-OS)	Lead: Professor F. Williams, Univ. of California, San Diego Also: Prof. Dryer, Princeton, Prof. Farouk, Univ. S. Carolina Dr. Nayagam, Case Western Dr Dietrich, NASA GRC	Dr. Sergey Frolov, N.N. Semenov Inst. Chemical Physics <i>Open Science Users – not funded</i> , Prof. Valentin Basevich, Dr. Andrei A. Belyaev, Dr. Sergey N. Medvedev, Dr. Igor Assovskii, Prof. Nickolay Smirnov, Moscow Lomonosov St Dr. V. Tyurenkova, Scientific Research Inst. System Analy. Inst. of Chemical Kinetics-Combustion, RAS Siberian Div. Dr. O. Korobeinichev, Dr. T. Bolshova, Dr. D.Knyazkov,	Science Protocol – signed ISS PSF Protocol - signed. Experiment Ops COMPLETED	March - Sept 2017
3	Coflow Laminar Diffusion Flame (CLD Flame) – ACME	Professor Marshall Long, Yale University	Prof. Sergey Minaev, Far Eastern Federal University Dr. Valerii Babushok, Far Eastern Federal University Dr. Fedir Sirotkin, Far Eastern Federal University Dr. Evgenii Sereschenko, Russian Academy of Sciences	Science Protocol – signed ISS PSF Protocol - signed	2017-18
4	Electric-Field Effects on Laminar Diffusion Flames (E-FIELD Flames) -ACME	Professor Derek Dunn-Rankin, University of California - Irvine	Prof. Sergey Minaev, Far Eastern Federal University Dr. Fedir Sirotkin, Far Eastern Federal University Dr. Valerii Babushok, Far Eastern Federal University Dr. Roman Fursenko, Far Eastern Federal University	Science Protocol – signed ISS PSF Protocol - signed	2017-18
5	Burning Rate Emulator (BRE) -ACME	Prof. J Quintiere, University of Maryland	Dr. Alexander Snegirev, Peter the Great Saint-Petersburg State Polytechnic University (modeling)	Science Protocol – signed ISS PSF Protocol signed	2018-19
6	Structure and Response of Spherical Diffusion Flames (s-Flame) - ACME	Professor C. K. (Ed) Law, Princeton University	Drs. Vladimir Gubernov & Andrei V. Kolobov P.N. Lebedev Physical Institute, Russian Academy of Sciences (modeling)	Science Protocol - signed ISS PSF Protocol signed	2019-20
7	Flame Design - ACME	Professor Richard Axelbaum, Washington University, St. Louis	Prof. Dr Sergei Frolov, Dr. Valentin Basevich, Dr. Mikhail Sinev, and Dr. Pavel Vlasov, N.N. Semenov Institute of Chemical Physics RAS (modeling)	Science Protocol – signed , ISS PSF Protocol – signed	2019 -20



NASA - Roscosmos Bilateral Collaboration in SLPSRA

Physical Sciences, (continued)




#	Experiment	Principal Investigator	Russian Investigators	Collaboration Status	ISS Ops
8*	BRAzing of Aluminum Alloys IN Space	Professor Dusan Sekulic, University of Kentucky	Professor Mikhail Krivilev, Udmurt State University of Russia (modeling and theory)	Science Protocol – signed	2021
9	<u>M</u> aterial <u>I</u> gnition and <u>S</u> uppression <u>T</u> est (MIST) - SOFIE	Professor Carlos Fernandez-Pello, University of California Berkeley	Professor Nickolay Smirnov, M.V. Lomonosov State University (2D & 3D modeling, 1 g tests & flight data analysis)	Science Collaboration established, in discussion	2020-22
10	<u>G</u> rowth and <u>E</u> xinction <u>L</u> imit of Solid Fuels (GEL) - SOFIE	Professor James S. T'ien, Case Western Reserve University	Professor Oleg Korobeinichev, Institute Chemical Kinetics & Combustion, Siberian Br RAS (1g temp, species; flight data analysis)	Science Protocol - draft	2020-22
11*	Diffusion Coefficients of Dopants in Si and Ge Melts	Professor Ostrogorsky, Illinois Tech	Professor G.N. Kozhemyakin and Dr. A.E. Voloshin A.A. Shubnikov Institute of Crystallography, RAS, (prep of flight samples)	Science Collaboration established, In discussion	2021
12	Liquid Crystal Nanoplates, LCN, (LCF - Bulk)	Professor Cheng, Texas A&M	Prof. Vladimir Dolganov, Inst. of Solid State Physics, Prof. Efim Kats, Landau Inst. Theoretical Phy (analysis, benchmark tests)	Science Protocol - draft	2022
13*	Ferromagnetic Liquid Crystal Colloids in Microgravity, (LCF – Bulk and Film)	Professor Clark, University of Colorado – Boulder	Professor A.A. Levchenko, Professor Pavel Dolganov, Institute of Solid State Physics, Prof. Efim Kats, Landau Institute of Theoretical Physics, Russian Academy of Sciences, (analysis, benchmark test-surf ten)	Science Collaboration established, in discussion	2022-23
14*	Nanoparticles and Topological Defects in Thin Films, (LCF – Film)	Professor Rosenblatt, Case Western Reserve	Prof. Leonid V. Mirantsev, Institute of the Problems of Mechanical Engineering, RAS, St. Petersburg; Dr. Elena Pikina, Oil and Gas Research Institute, RAS, (theory)	Science Collaboration established, in discussion	2022-23
15*	Monodisperse Liquid Crystal Domains, (LCF – Film)	Professor Yokoyama, Kent State University	Professor Alexander Emelyanenko, Head of Liquid Crystal Laboratory, Lomonosov Moscow State (modeling, benchmark tests)	Science Protocol-draft	* MaterialsLab NRA 2022-23

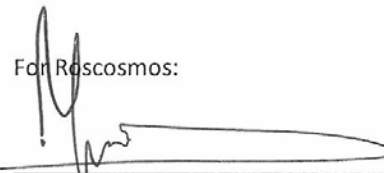
NASA-Roscosmos Protocol
Utilization Sharing Plan on-board ISS
July 18, 2013

1. Roscosmos and NASA agree to work together to increase ISS utilization on-board ISS
2. Starting fall 2013, Roscosmos agrees to perform up to 5 hours per week average of USOS Utilization activities as agreed by NASA and TsNIIMASH for cooperative research approved by the Program Science Forum. The amount of hours can be increased with Program Manager concurrence.
3. Any video on NASA utilization activities being performed by Russian crew members will be sent to MCC-M at the same time the video is received by NASA.
4. Any data downlinked on NASA utilization activities being performed by Russian crew members will be sent to MCC-M within 24 hours of the data being received by NASA.
5. Any downlink video or data files from USOS science hardware under this agreement can be provided to Russian investigators with no constraints.
6. No compensation for crew time or utilization video/data files will result from this agreement. --

For NASA:


Michael T. Sutfredini 7/18/13

For Roscosmos:


Alexey B. Krasnov
18.07.13

Facility	Collaboration Status
Electromagnetic Levitator (EML)	Trilateral Agreement signed Feb. 17, 2017
Plasma Kristall - 4 (PK-4)	ESA-Roscosmos Agreement. No Trilateral agreement required. NASA investigators are members of ESA's topical team and will share results.

ESA-NASA-Roscosmos Protocol
Collaborative Research using the EML Facility
17 February 2017

1. The ElectroMagnetic Laboratory (EML) science team includes scientists supported by ESA, NASA and Roscosmos who are jointly defining research activities using the ElectroMagnetic Laboratory (EML) on the ISS.
2. Roscosmos, ESA and NASA will engage in collaborative research using the EML facility to optimize and increase ISS utilization on-board ISS.
3. Concerning their collaborative research using the EML facility, ESA, NASA and Roscosmos concur on the following:
 - a. EML facility contributions: (1) built and operated by ESA, (2) launched by NASA and (3) accommodated in an ESA rack location.
 - b. This Protocol applies to the remainder of EML batch 1 through EML batch 4.
 - c. The "NASA-ESA Technical Understanding on Operation of Facilities" signed 17 July, 2013 by the NASA and ESA ISS Program Managers identifies responsibilities for operations and maintenance to support collaborative use of the EML facility.
 - d. Beginning in Increment 51/52, Roscosmos will provide crew time for EML experiment operation, up to 10 hours/year. This crew time provided by Roscosmos is considered joint NASA-Roscosmos research time, under the NASA-Roscosmos "Utilization Sharing Plan Onboard ISS" protocol signed 28 January, 2016.
 - e. ESA will provide ground and onboard training to the cosmonauts via videos and other supporting documentation.
 - f. ESA will perform EML operations from MUSC (Cologne).
4. All collected science data will be shared between ESA, NASA, and Roscosmos.
5. No compensation for crew time or other resources will result from this Protocol.

For ESA:


Bernardo Patti (date) 16/2/17

For NASA:


Kirk Shireman (date) 16/2/17

For Roscosmos:


Alexey Strelnikov (date) 16.02.17.

- **NASA- ESA Technical Understanding Document Operation of Facilities.**
- **ESA uses International Topic teams. NASA funded scientists were competitively selected through NRA or ESA AO to participate in:**
 - MSRR/MSL, LGF and SQF, SCA - Sample Cartridge Assembly, Materials Science experiments
 - Transparent Alloys experiments - MSG
 - Electromagnetic Levitator Series(EML): Materials Science experiments*
 - Atomic Clock Ensemble in Space experiment (ACES)

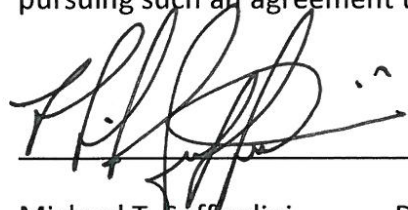
*EML Trilateral formed with ESA -Roscosmos-NASA, 2017

NASA-ESA Technical Understanding on Operation of Facilities
July 2013

NASA and ESA consider that the objectives in Annex 1 will be accomplished for the purpose of jointly implementing coordinated maintenance and operation of utilization facilities on ISS. These objectives will enable on-orbit collaborative use of the MSG, MSL, MSRR, EML, and ACES facilities. MSG, MSL, and MSRR have been used for ongoing science cooperation under the Early Utilization MOU. Annex 1 defines the technical responsibilities of NASA and ESA for each facility. Results from this coordination will be shared between the scientific teams under the experiment specific implementation processes.

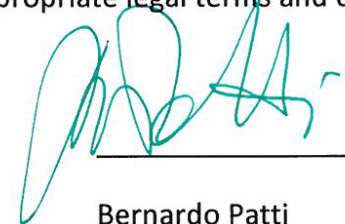
This Technical Understanding (TU) documents NASA's and ESA's common position that their respective roles and responsibilities are equitably distributed for a common goal of enabling maximum utilization research. In the event that activities under this TU vary or do not proceed as expected, then NASA and ESA will consult with each other.

If expansion of these activities requires additional resources or the activities are beyond the scope of this TU which would require a legally binding agreement, NASA and ESA will consider pursuing such an agreement to include all of the appropriate legal terms and conditions.



7/17/13

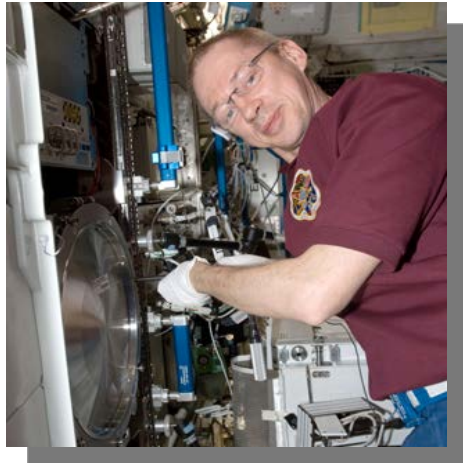
Michael T. Suffredini Date
NASA



17/07/2013

Bernardo Patti Date
ESA

In exchange for crew time and sustaining engineering for MSRR, NASA funded scientists participate in ESA experiments on the MSL/SCA, EML and ACES. ESA investment is shown below. (Note ACES developed by ESA and CNES. EML developed by ESA and DLR). Each facility required more than ten years to develop.



*MSRR/MSL, LGF/SQF, SCA MATERIALS: Investigate microstructure of materials using directional solidification. Astronaut Frank DeWinne completing installation in the **MSRR/MSL** prior to on-orbit commissioning October 2009. MSL developed by ESA.*



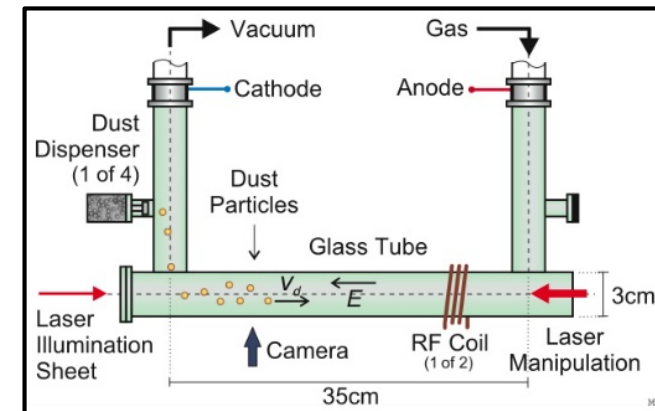
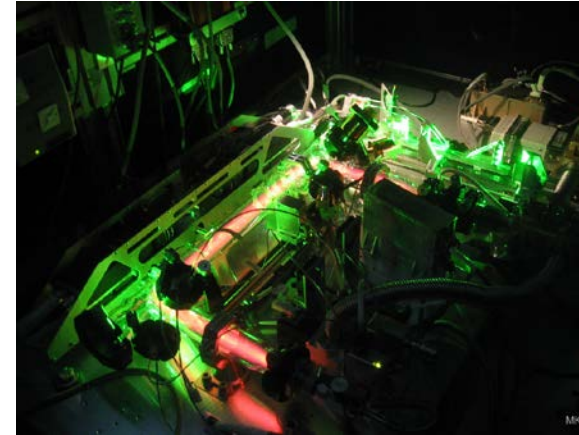
*Electromagnetic Levitator Furnace MATERIALS: Investigate thermophysical properties of metal alloys. Astronaut Alexander Gerst completing installation of the **ESA (with DLR) EML**, October 2014 on ISS*



Atomic Clock Ensemble in Space. Time measurements made at various locations around the world with atomic clock on the ISS. ESA to provide two microwave link ground stations for NIST and JPL.

Plasma Krystall Experiment – 4 (PK-4) is a collaboration between ESA and Roscosmos, and is installed in the Russian segment of the ISS.

NASA and NSF Dusty Plasma scientists, selected through a joint NASA/NSF solicitation in 2017, are collaborating with ESA and Roscosmos investigator science teams.



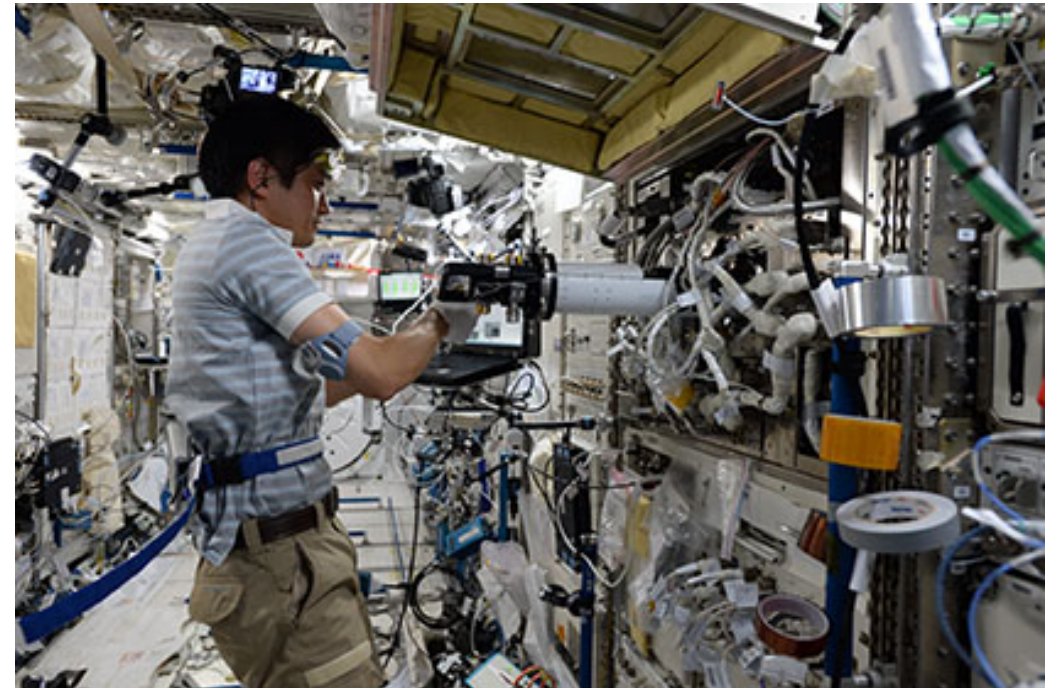
Plasma Krystall-4 (PK-4): Investigate wave synchronization using dusty plasma: Transport Properties, Thermodynamics, Kinetics and Statistical Physics, and Non-linear waves and Instabilities in the plasmas.

NASA and JAXA have a mutual interest to share ISS flight hardware for life and physical science research to leverage their programs and to maximize the efficient utilization of facilities.

ELF

**Under JP-US OP3,
Amendment 1 - Technical Understanding
Document (TU) – various Enclosures.**

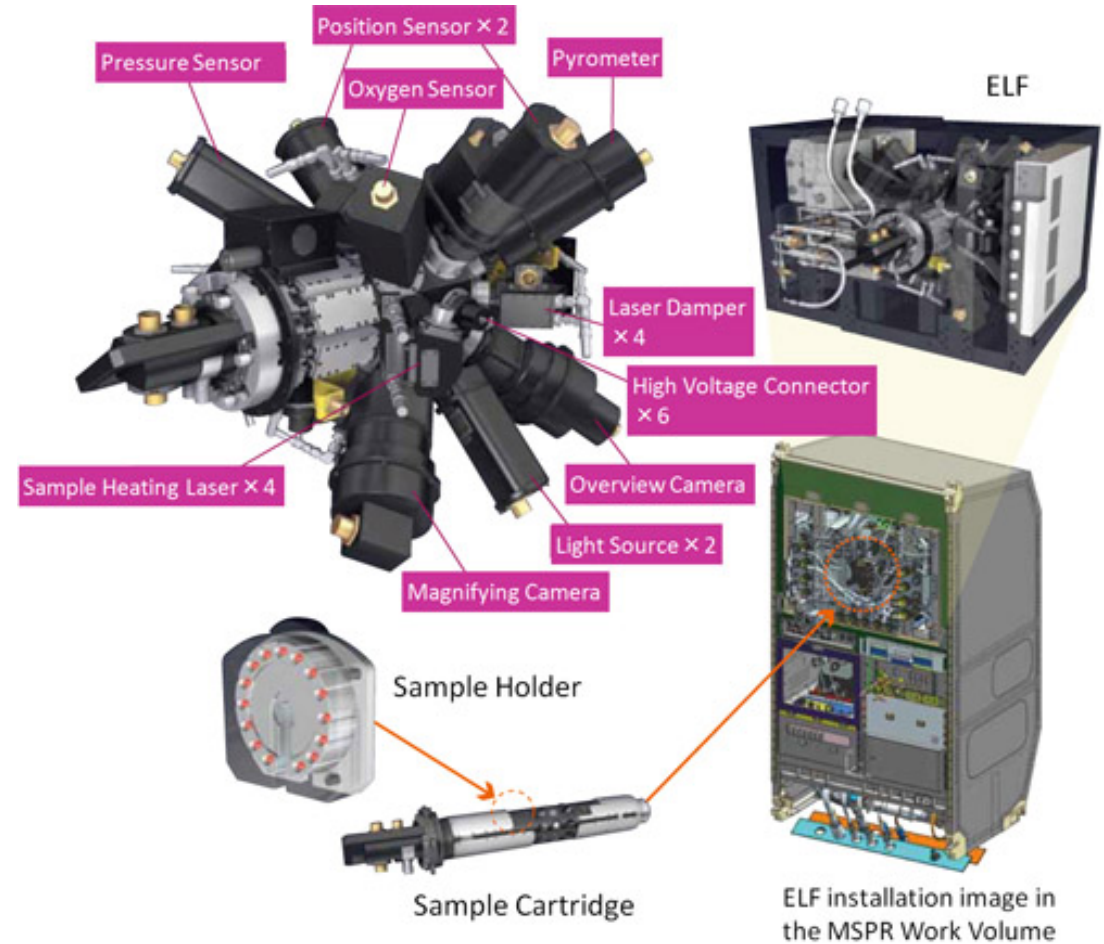
Four NASA funded ELF investigators will use JAXA's Electrostatic Levitation Facility (ELF) furnace. In return JAXA will participate in NASA's Human Research Studies on the ISS.



ELF on ISS



ELF on orbit



JAXA's Electrostatic Levitation Furnace (ELF)

Bose Einstein Condensate, Cold Atom Lab (BECCAL)

- DLR - NASA International Agreement
- DLR to build an EXPRESS rack payload that builds upon DLR's sounding rocket program and offer enhancements over CAL
- To be installed on ISS at conclusion of CAL operations, about 2020.



Investigator team:

Michael Dreyer - DLR
Mo Kassemi - NASA
TBD - Additional Investigators

Objectives:

Use a small scale simulant fluid experiment and hand-in-hand CFD model development to investigate and understand the effect of microgravity on evaporation, condensation and boiling phenomena and the associated two-phase flow transport regimes that **impact tank and line chill-down and tank to tank transfer operations** during refueling of spacecraft propellant tanks from orbiting fuel depots.

Approach:

1. Experiment concept driven by STMD goals
2. International Collaboration between NASA SPLS, ISS-PO and DLR
 - Ground based study – DLR led (DLR approved)
 - Flight hardware development – DLR (In discussion)
 - ISS launch, integration and ops – NASA

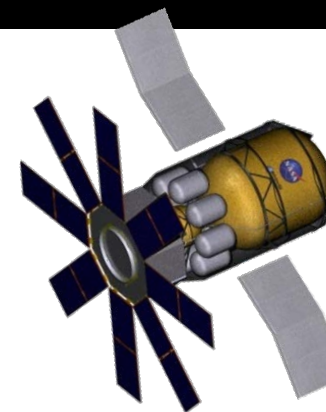
Application:

Cryogenic Fuel Depot, Lunar lander and Mars transit vehicles

- Propellant Tank Chill down
- Propellant Tank Transfer Operations

Tentative Schedule:

Ground Tests: 2019 - 2022
Flight hardware development: 2022 - 2026
ISS operations: 2026-27



Cryogenic Fuel Depot concept

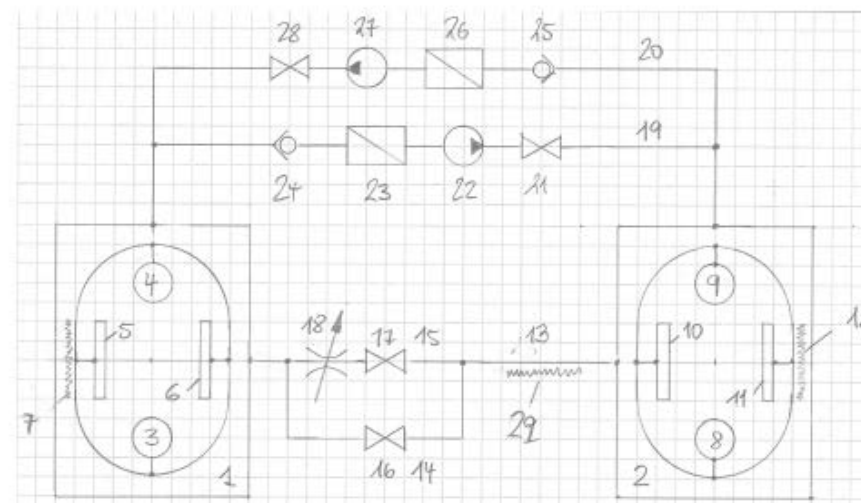


Figure 3.1: Generic drawing of the experiment setup, not to scale. The setup consists of two fluid containers, a donator tank 1 and a receiver tank 2, which are connected by several lines. The optical setup to enable observation is not shown. The setup aims at simulating the situation of a cargo spacecraft with a full propellant tank 1 docked to another spacecraft with an empty propellant tank 2. The components are explained in the text. The components are necessary to perform a repeatable model experiment on the International Space Station. They are not necessarily parts of the original hardware.

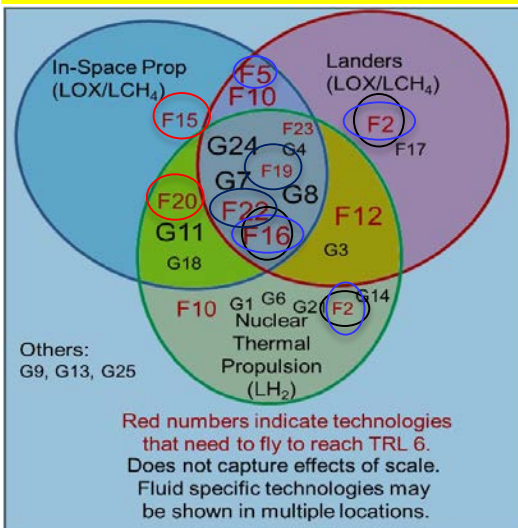
Concept from Professor Dreyer's draft ZBOT- FT ground-based proposal submitted to DLR, Jan. 2019

1. Ground Program (DLR - ready to proceed, NASA SLPSRA - under review)
 1. Mature U. Bremen proposal submitted to DLR
 2. Duration: September 2019 – September 2022
 3. Investigators:
 1. DLR PI – Michael Dreyer
 2. NASA PI – Mo Kassemi
 4. Activities:
 1. DLR - Laboratory studies and Bremen Drop Tower testing
 2. NASA - numerical modeling, host U. Bremen student
 5. Document development: draft SRD for flight experiment

2. Proposed Flight Program (NASA in discussion with DLR)
 1. Timeline 2022 – 2027
 2. International Agreement
 1. DLR – Develop Flight Hardware
 2. NASA – Provide Integration, Launch Services and ISS crew time
 3. Joint Proposal submitted to DLR and NASA for peer review
 1. DLR PI - Michael Dreyer, Co-Is - TBD
 2. NASA PI – Mo Kassemi, NASA Co-Is - TBD
 4. Flight Experiment Reviews
 1. NASA SCR/RDR with mature SRD – NASA and DLR selected panel members
 2. DLR – conduct engineering reviews with NASA involvement

- **Broad Area Cooling (BAC)** : Cooling tank wall using gaseous tube on wall heat exchange strategy.
 - Implementation/Performance of BAC is greatly affected by the configuration of Ullage and extent and nature of fluid flow and convection in the tank that are all strong functions of gravity.
- **Tank Filling and Chillover:** Cooling a tank before filling through multiple: Inject Liquid – Hold – Vent cycles in microgravity.
 - liquid injection, dispersion and transport in the tank, chill-down through inject-hold-vent cycle, film formation, condensation, and heat transfer on the tank wall and transient configuration of the two phases are all strongly gravity dependent.
- **Tank-to-Tank Transfer:** Complicated process involving pressurization of supply tank – transport through transfer lines – cooling/filling the receiver tank.
 - Pressurization of the supply tank, two phase fluid flow regimes/boiling in the transfer lines, filling of the receiver tank through inject-hold-vent cycle and configuration of the two phases in both receiver and supply tanks are all gravity-dependent and drastically different than in 1g.

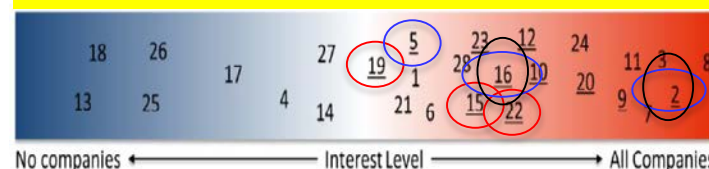
CFM Tech across Multiple Architecture



Mission Architecture



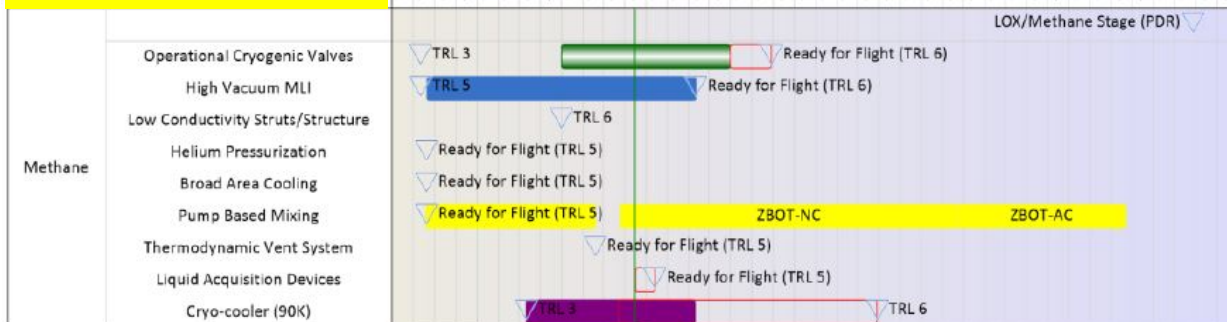
Heat Map of Industry Interest



Required CFM Technology Elements

Technology	No
Advanced External Insulation	1
Autogenous Pressurization	2
Automated Cryo-Couplers	3
Cryogenic Thermal Coating	4
Helium Pressurization	5
High Capacity, High Efficiency Cryocoolers 20K	6
High Capacity, High Efficiency Cryocoolers 90K	7
High Vacuum Multilayer Insulation	8
Liquefaction Operations (MAV & ISRU)	9
Liquid Acquisition Devices	10
Low Conductivity Structures	11
MPS Line Chillydown	12
Para to Ortho Cooling	13
Propellant Densification	14
Propellant Tank Chillydown	15
Pump Based Mixing	16
Soft Vacuum Insulation	17
Structural Heat Load Reduction	18
Thermodynamic Vent System	19
Transfer Operations	20
Tube-On-Shield BAC	21
Tube-On-Tank BAC	22
Unsettled Liquid Mass Gauging	23
Valves, Actuators & Components	24
Vapor Cooling	25

Flight Mission Timelines – Lunar Lander Timeline



ZBOT-1
ZBOT-NC

ZBOT-NC

ZBOT-FT
ZBOT-TT

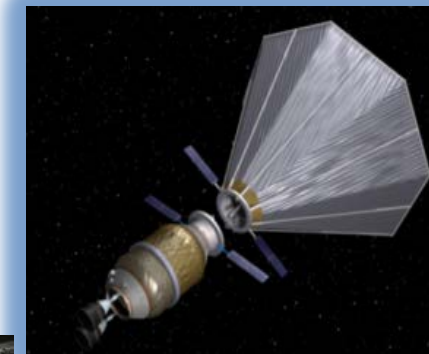
ZBOT-1
ZBOT-NC

ZBOT-AC

ZBOT-FT
ZBOT-TT

ZBOT-AC

- Feasibility of imminent Lunar & future Mars Missions depend largely on successful implementation of ZBO Cryogenic Tank Pressure Control for propellant storage & transfer. Estimates for LH2 are 2% loss per day.
- ZBO brings significant cost saving through payload mass reduction but is complicated to design due to complex two phase fluid/heat transfer.
- The Zero Boil Off Tank (ZBOT) Experiments use small-scale *simulant*-fluid tests aboard the ISS to study the underlying fluid physics of tank pressurization & pressure control in order to optimize in-orbit propellant storage & transfer processes.



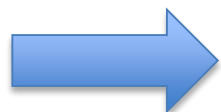
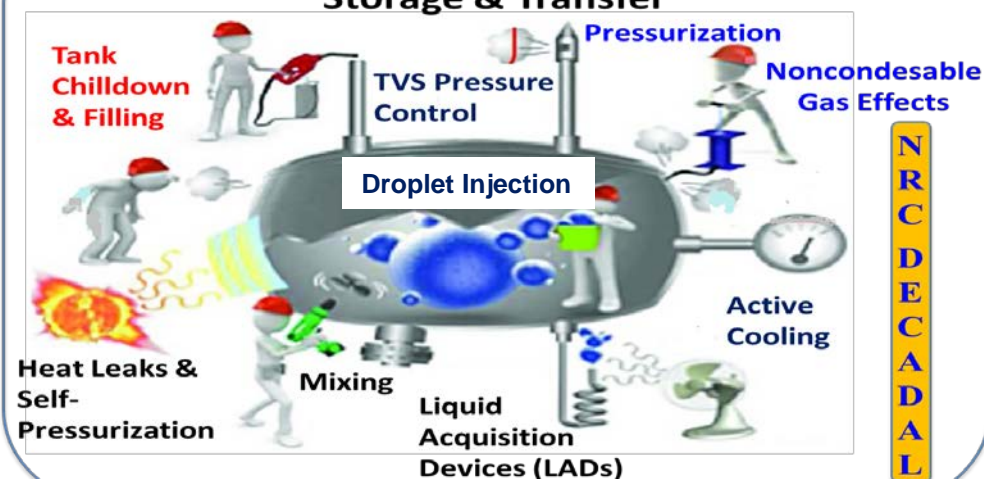
Cryogenic Fuel Depot concept (above)



ZBOT-1 on ISS (left)

- **ZBOT-1: Self-Pressurization & Jet Mixing (2017)**
 - Self-Pressurization, Thermal stratification, 0G boiling
 - Jet Mixing/Cooling, Thermal destratification, Ullage-Jet dynamics
- **ZBOT-NC: Effect of Non-Condensable Gases (2023)**
 - NC effect on self-pressurization / stratification
 - NC effect on pressure control / destratification
 - Condensation suppression, Marangoni convection
- **ZBOT-AC: Active Cooling Pressure Control (2025)**
 - Droplet Spray Bar (TVS) Cooling
 - Broad Area Cooling (BAC)
- **ZBOT-FT: Filling & Transfer (est. 2026-27)**
 - Joint effort with DLR
 - Tank Chilldown and Tank-to-Tank Transfer
- **ZBOT-TT: Tank Transfer (launch date-TBD)**
 - NASA effort with US industry.
 - Tank Chilldown and Tank-to-Tank Transfer

LH2, LOX, LCh4 Propellant and Life Support Fluids Storage & Transfer

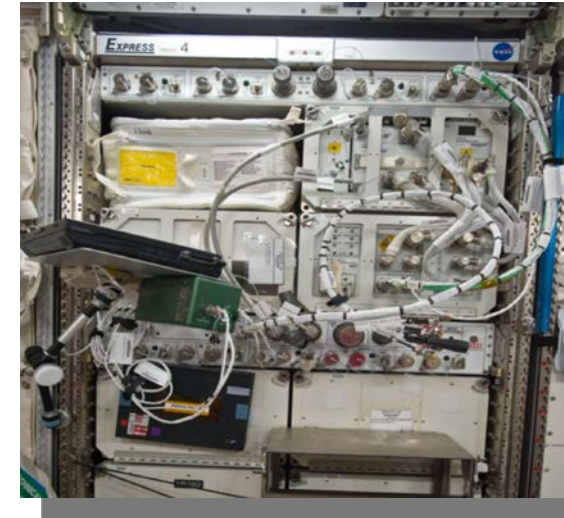


1. **DECLIC Letter of Agreement and Addendum** – Bilateral collaboration for the use of **DECLIC** and **DECLIC Reflight** experiments. Experiments include critical point phenomena, transparent metal model solidification and super critical water mixture. CNES built the hardware, requiring nine years to develop, and also provides ground operations support. The CNES investment is shown below. NASA provided the launch and crew time. NASA funded scientists participate in the experiments:

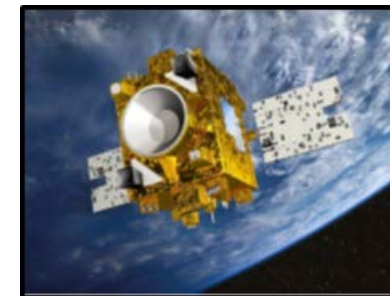
- **High Temperature Insert, HTI & HTI-R** (ISS ops complete)
- **Directional Solidification Insert, DSI & DSI-R**
- **Alice Like Insert, ALI & ALI-R**

2. Microscope

- **A team** of scientists will enhance the test precisions by determining the orbit of the satellite using the state-of-the art laser ranging technique.



CNES-DECLIC in an ISS EXPRESS Rack: Conducts Materials, Fluids and Fundamental Physics experiments:

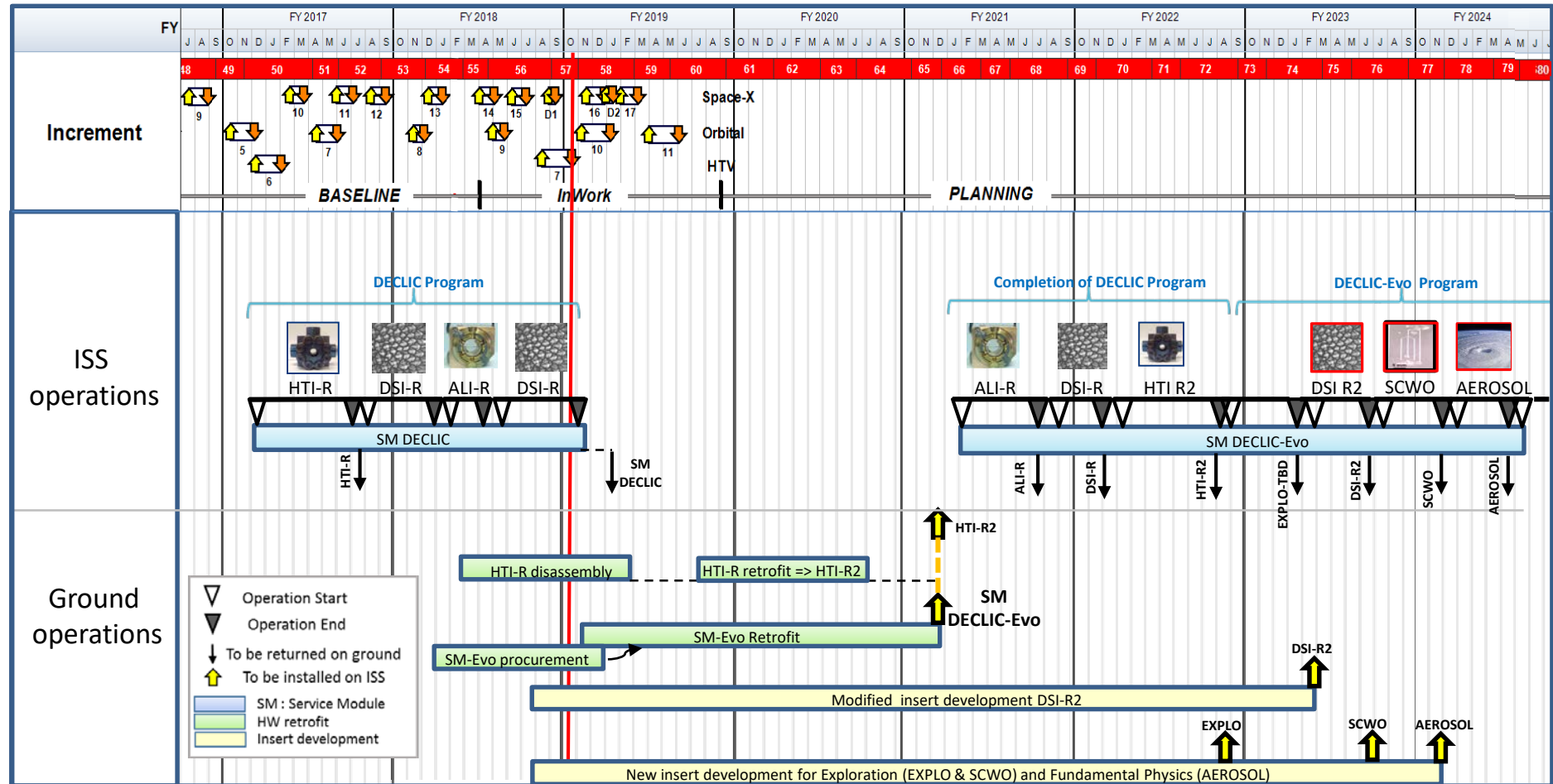


Microscope: Precise position location

The next amendment will include the following:

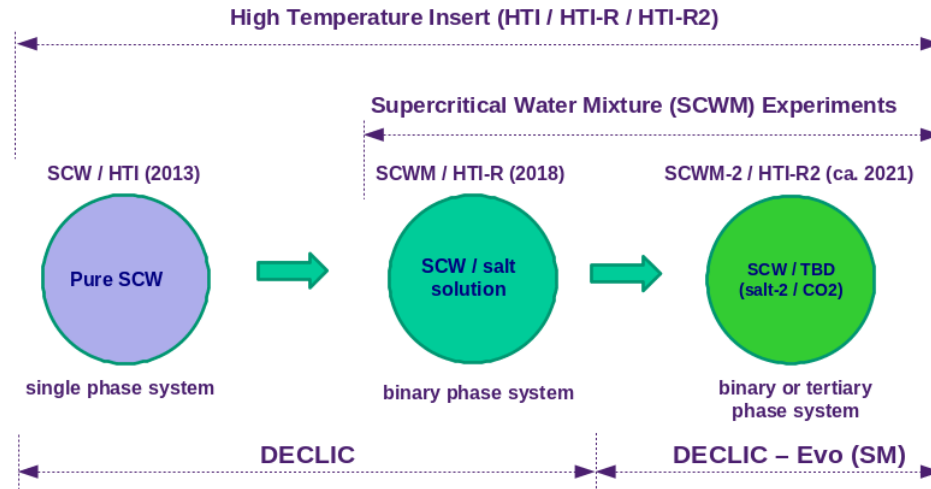
- 1) NASA to launch the DECLIC Service Module and conduct the ALI-R, DSI-R, and HTI-R2 experiments.
- 2) CNES to develop three new experiment inserts for DECLIC-Evo. One insert will be relevant to NASA's exploration program SCWO, also the DSI-R2 insert, and one fundamental insert , AEROSOL, for Water Condensation.
- 3) NASA to provide launch services and ISS operations for the three DECLIC- Evo inserts. NASA to provide at least one reflight of the Service Module in the event that repairs are necessary.

CNES DECLIC/DECLIC-Evo Program



Version of Oct. 9, 2018

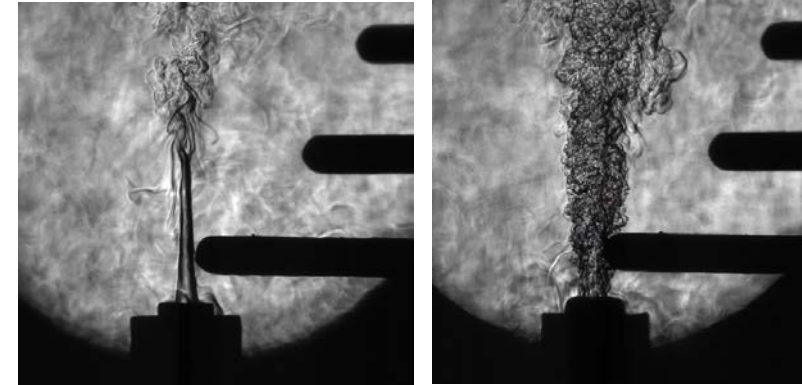
SCWM, SCWM-2 ... focused on near-critical phenomena with multi-phase systems (salt/water mixtures)



SCWO (for EXPL-1) ... ca. 2022-23, new science aligned with NASA's Advanced Exploration Systems (AES) with a focus on oxidative reactions on waste water (simulated urine).

Science Objectives:

- phase partition and salt (e.g., metabolic Ca^{+2}) precipitant transport in supercritical water
- influence of near-critical and supercritical behavior on turbulent transitions and bulk mixing
- spontaneous combustion, stability and structure of hydrothermal flames using ersatz aqueous waste concentrates (e.g., urine brine)



$\text{Re} = 448, \text{Pr}/F^2 = 1.4$

$\text{Re} = 2680, \text{Pr}/F^2 = 0.5$

Supercritical jet injected into supercritical water; turbulent transition highly dependent on buoyancy



Co-flow fuel jet, 30% $\text{C}_2\text{H}_6\text{O}$ (aq) in core and air in annular region injected into bulk SCW reactor

Advanced Colloids Experiment – ACE T1

PI: Chang-Soo Lee, Chungnam University, S. Korea

Approach: FIR/LMM, Launch: SPX-9 and HTV-6, modules 1 and 2

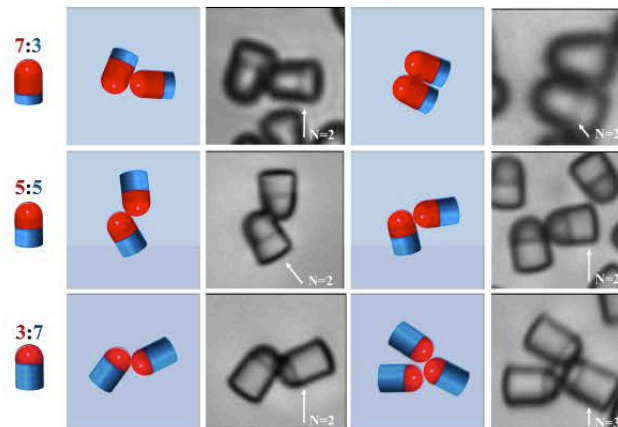
ACE-T1 studies 3D self-assembly of complex (Janus, multi-sided) particles that are hydrophobic and hydrophilic (repel and attract water). Microgravity allows for the observation of 3D assembly of submicron particles that would sediment on Earth. The project studies colloidal engineering with an emphasis on self-assembly, which spontaneously forms precisely organized structures by thermodynamic equilibrium. This work has the promise of ultimately providing efficient and affordable manufacturing processes for functional devices and materials with novel or enhanced properties. The complex structures that result from self-assembly at the particle level are regulated by directional interactions. When assembling particles into larger 3D colloidal building blocks on Earth, gravity dominates, masking the electrostatic and van der Waals interactions that we need to better understand to control the creation of 3D structures. The microgravity environment can explore the effects of colloidal particle shape anisotropy. This has the promise of using particle shape-selective interactions with directional interactions.

Letter of Agreement

The National Aeronautics and Space Administration (NASA) and Chungnam National University (CNU) (hereinafter jointly referred to as the “Parties”) have expressed a mutual interest in collaborating on the Advanced Colloids Experiment (ACE) to observe the behavior of colloidal systems using a microscope in the microgravity environment of the International Space Station (ISS).

Ground-Testing

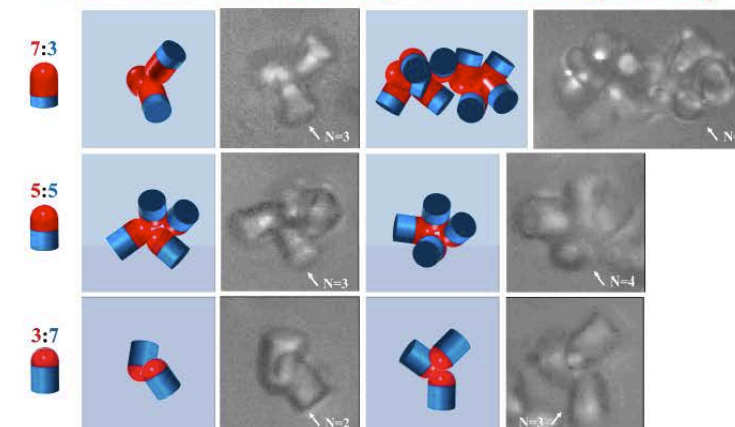
“ 2D Self-Assembly on Earth ”



We see 2D self-assembly on Earth (1g).

International Space Station

“ 3D Self-Assembly in microgravity ”



We are now seeing 3D self-assembly for the first time. This is made possible using the microgravity (μg) environment aboard the ISS.



ISS National Lab (CASIS) Collaboration



Established ISS National Lab (CASIS) – SLPSRA PS Collaboration



Number	Experiment or hardware developed by SLPSRA	CASIS crew time (originally covered by SLPSRA), hours
1	Light Microscopy Module: Biological Samples (LMMBIO – 1)	10
2	Light Microscopy Module: Biological Samples (LMMBIO – 3)	10
3	Advanced Colloids Experiment (ACE – T6)	6
4	Cement Reference Experiment	5
5	Light Microscopy Module LMM upgrade – confocal and LMM camera	14
6	Advanced Colloids Experiment ACE – H2, installation only* (completed)	2
7	Advanced Colloids Experiment ACE – T1, installation only	2
8	Advanced Colloids Experiment ACE – 2R, installation only	2
9	Advanced Colloids Experiment ACE – T7, installation only	2
10	Advanced Colloids Experiment ACE – T9, installation only	2
11	Real Time Protein Crystal Growth RTPCG 1 and 2	-
	Approximate crew time provided by ISS National Lab (CASIS)	55



Interagency Collaborations

NASA – NIST MOU: to support NASA’s MaterialsLab Microgravity Materials Science Program.

Goals of partnership:

- 1) support NASA’s MaterialsLab microgravity materials science program and materials research conducted on the International Space Station (ISS);
- 2) facilitate collaboration between the NASA microgravity materials science program and the NIST Material Measurement Laboratory (MML) materials measurement science programs;
- 3) accelerate the development of U.S. industry innovative materials and processes through critical experiments that evaluate predictive models;
- 4) provide essential data needed for modeling of materials behavior that supports the NIST mission and NIST in its leadership role in MGI.

Signature page from NASA - NIST MOU

V. POINTS OF CONTACT

The following personnel are designated as the points of contact between the Parties in the performance of this MOU.

NASA

Name Francis P. Chiaramonte
Title Program Executive
Life and Physical Sciences
Division
Email francis.p.chiaramonte@nasa.gov
Telephone (202) 358-0693
Address 300 E Street, SW, HQ:CR000
Washington, DC 20546

NIST

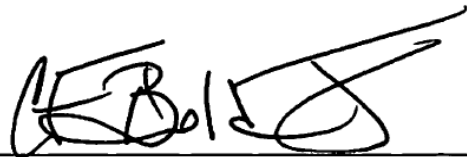
Name Richard E. Ricker
Title Technical Program Director for
Manufacturing
Materials Measurement
Laboratory
Email richard.ricker@nist.gov
Telephone (301) 975-6023
Address 100 Bureau Drive, Stop 8300
Gaithersburg, MD 20899

VI. SIGNATORY AUTHORITY

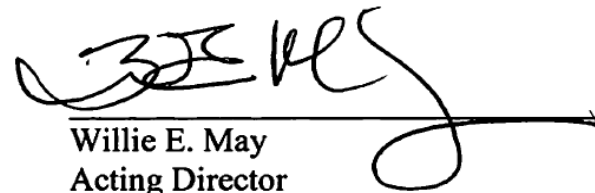
Approved and authorized on behalf of each Party by:

National Aeronautics and Space
Administration

National Institute of Standards and
Technology



Charles F. Bolden, Jr.
Administrator
[Date] 3/2/2015



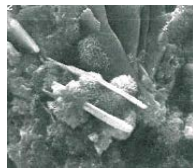
Willie E. May
Acting Director
[Date]

Microgravity Investigation of Cement Solidification (MICS)

PI: Prof. Aleksandra Radlińska (Penn State),
 Co-Investigators: Dr. Richard Grugel (NASA MSFC), Prof. Barry Scheetz (Penn State), Dr. James Pawelczyk (Penn State), Ms. Annmarie Ward (Penn State), **Dr. Jeffery Bullard (NIST), Mr. Dale Benz (NIST)**. Also Sauereisen Corporation, BASF Corporation, and IPA Systems via CASIS collaboration



ISS tests -2018



Terrestrial sample evaluation. Portland Cement paste



Concrete -most widely used, greatest volume, man-made material. Hoover Dam

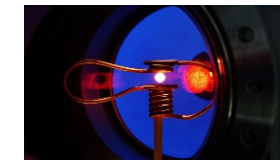
Research at NIST includes efforts to develop Sustainable Engineered Materials (SEM), including concrete made from Portland Cement. Input from NIST concrete stakeholders has shown that a focus on hydration models, concrete placement, and repair technologies are needed to continue to make concrete a sustainable infrastructure material.* MICS data from ISS allows modelers access to data without the effects of settling/buoyancy in order to more fully understand the governing equations and develop advanced models.

Round Robin - Thermophysical Property Measurement Experiments

Investigator Team: PI, Douglas Matson (Tufts University), Mikhail Krivilev (Udmurt State University), Vijay Kumar (Tufts University), Masahito Watanabe (Gakushuin University), Takehiko Ishikawa (JAXA), Hiroyuki Fukuyama (Tohoku University), Shumpei Ozawa (Chiba Institute of Technology), Geun Woo Lee (KRISS), Andreas Meyer (DLR), Hans Fecht (University of Ulm), Rainer Wunderlich (University of Ulm), G. Pottlacher (TU-Graz), **Kenneth Kroenlein (NIST)**, Mike Sansoucie



Levitated sample in JAXA's ELF ground unit



Levitated sample test in ESA's EML furnace test on ISS

Objectives:

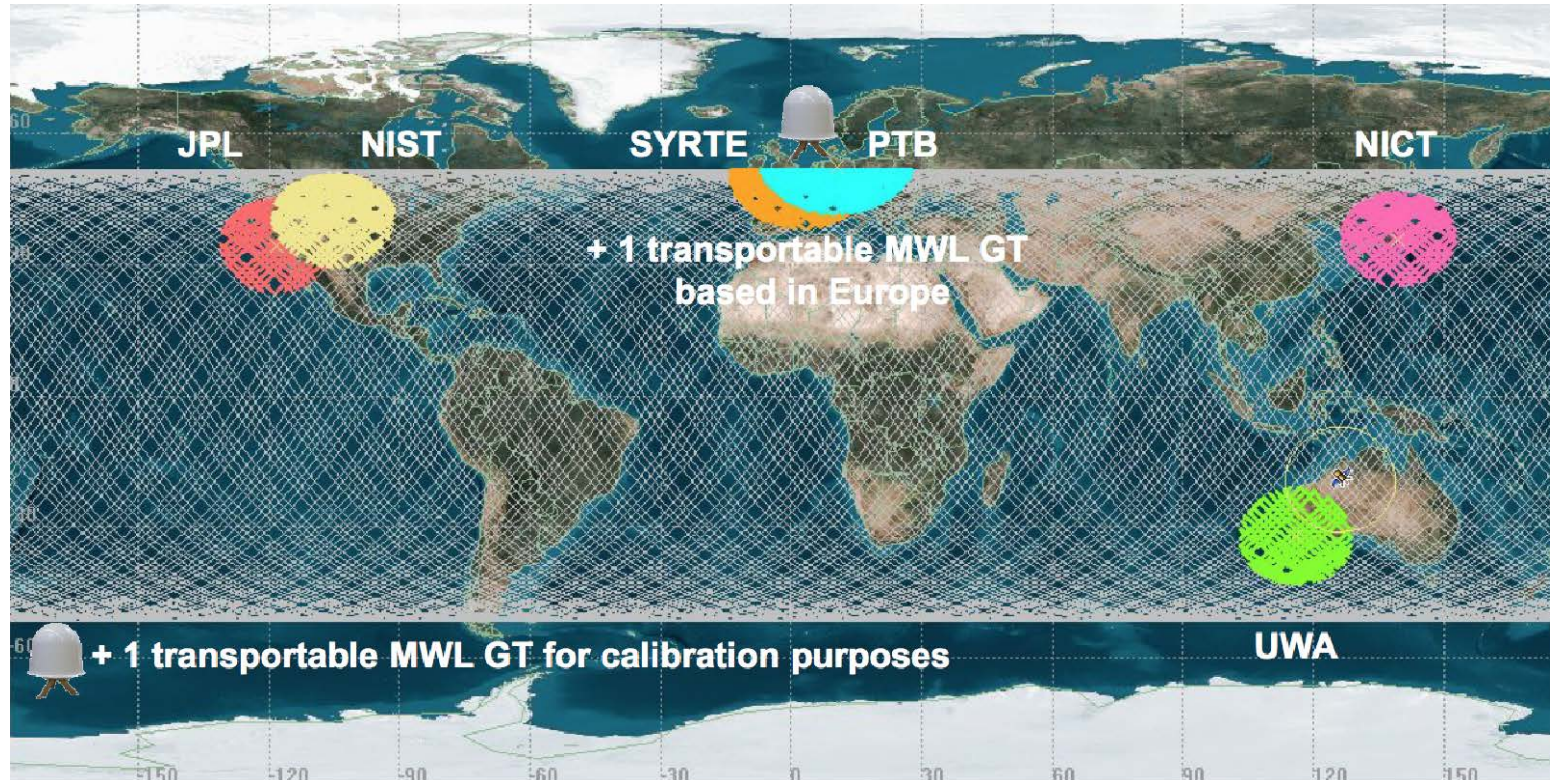
Understand and control the sources of measurement error and to provide a baseline dataset for quantifying uncertainty in measurements (both space- and ground-based)

Relevance/Impact:

Baseline dataset (ensures the highest quality data). Proposed materials have industrial applications (casting, nuclear fuel rods, metallic glass)

NIST - NASA Collaboration in Time Transfer Technology – Fundamental Physics Experiment - ACES

Ground link stations at leading US time and frequency metrology institutions for the critical global coverage



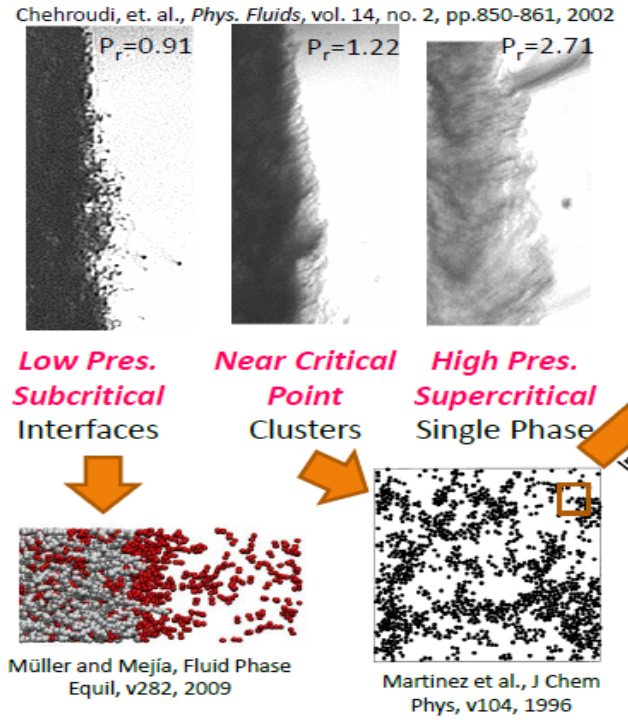
NASA supports NIST participation in the ESA Atomic Clock in Space (ACES) mission, providing a demonstration of US time-keeping and time-transfer technologies

Plasma Krystall Experiment – 4 (PK-4) is a collaboration between ESA and Roscosmos, and is installed in the Russian segment of the ISS.

NASA and NSF Dusty Plasma scientists, selected through a joint NASA/NSF solicitation in 2017, are collaborating with ESA and Roscosmos investigator science teams.

Combustion Research - High-Pressure Nonequilibrium Energy Conversion expt.

NASA - Multiple Government Agency collaboration – in discussion



Multiagency Initiative??

USNA UNITED STATES NAVAL ACADEMY

ARL

ARL-RP-0551, 2015

NIST National Institute of Standards and Technology U.S. Department of Commerce

Sandia National Laboratories

COMBUSTION RESEARCH FACILITY

AFRL ROCKET LIFE

- Need: Improving propulsion efficiencies from the current level requires engine combustors to operate at pressures beyond our existing knowledge and understanding (Rockets > 100bar; Gas Turbines > 60bar; Diesel IC > 40bar)
- Scientific Challenges & Engineering Opportunities: Understand, quantify and model high-pressure, transcritical, thermodynamic and chemical nonequilibrium phenomena, including stateless regimes, to control and enhance combustion processes at conditions relevant to current and future propulsion systems.
- Why can we do this now: Recent improvements in molecular dynamics and high-resolution experimental diagnostics allow the establishment of a scientific foundation for nonequilibrium phenomena at high pressures.



NASA Collaborations

STMD and SLPSRA



STMD Endorsement Letter for ZBOT – Senior Technical Officer, Jeff Sheehy



Email to: Angel Otero (angel.m.oter@nasa.gov), SLPS Deputy Director

Copy to: Marshall Porterfield (d.marshall.porterfield@nasa.gov)

April 23, 2014

Bradley Carpenter, (bcarpenter@nasa.gov)

Mohammad Kassemi (mohammad.kassemi@nasa.gov)

Francis Chiaramonte (francis.p.chiaramonte@nasa.gov)

Tom St.Onge (thomas.h.stonge@nasa.gov)

George Nelson (george.nelson-1@nasa.gov)

Michael Meyer (michael.l.meyer@nasa.gov)

Dear Mr. Otero,

The purpose of this email is to emphasize the importance of the **full series of Zero Boil-Off Tank** (ZBOT) Experiments.

Missions that utilize cryogenic life support supplies, cryogenic propellants, or very low temperature cryogens for scientific instrumentation all require strategies to actively control pressure buildup and minimize or eliminate the venting of fluids that boil off. Due to the recent cancellation of the Cryogenic Propellant Storage and Transfer (CPST) flight demonstration, the ZBOT series will be the only comprehensive set of experiments conducted in the microgravity environment, which substantially increases their importance to the agency.

The **ZBOT series of three experiments** incrementally build upon each other in complexity to provide a comprehensive theoretical and experimental microgravity foundation for future cryogenic storage tank design. Specifically, the **ZBOT-2** experiment will focus on the impact of non-condensable pressurant gas, which can change evaporation and condensation rates by creating a transport barrier in the vapor phase that directly impacts the ability to control tank pressure. The ZBOT-3 experiment will then compare the transport and phase change phenomena that govern two of the most common strategies to mix and cool the fluids. **ZBOT-3** data will also elucidate the droplet-ullage interacting transport and phase change behavior in microgravity.

The data obtained from these highly controlled and instrumented experiments in the microgravity environment will be critical for validating models that will be used to design integrated low- and zero-boil-off cryogenic fluid storage and utilization concepts for a wide range of missions.

Consequently, I strongly endorse the full series of ZBOT experiments, including ZBOT-2 and ZBOT-3. Please contact me if you wish to discuss this topic further.

Warm regards,

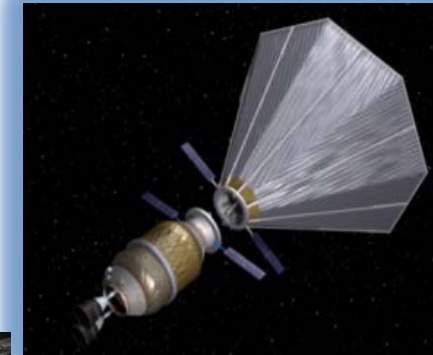
Jeffrey Sheehy, PhD

Senior Technical Officer

Space Technology Mission Directorate

256-698-8635

- Feasibility of imminent Lunar & future Mars Missions depend largely on successful implementation of ZBO Cryogenic Tank Pressure Control for propellant storage & transfer. Estimates for LH2 are 2% loss per day.
- ZBO brings significant cost saving through payload mass reduction but is complicated to design due to complex two phase fluid/heat transfer.
- The Zero Boil Off Tank (ZBOT) Experiments use small-scale *simulant*-fluid tests aboard the ISS to study the underlying fluid physics of tank pressurization & pressure control in order to optimize in-orbit propellant storage & transfer processes.

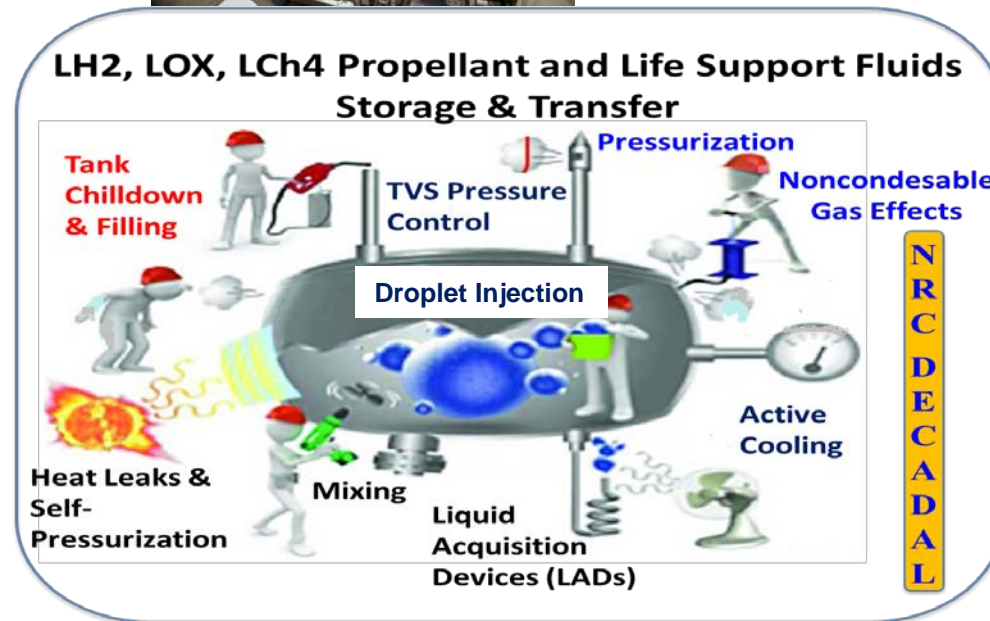
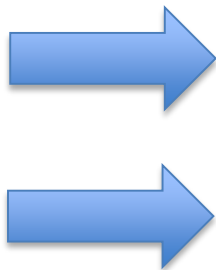


Cryogenic Fuel Depot concept (above)



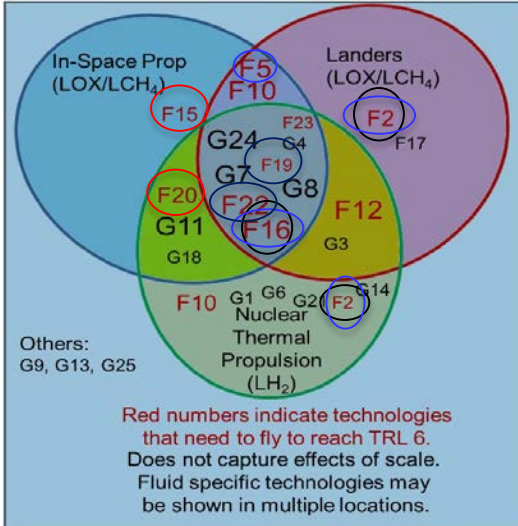
ZBOT-1 on ISS (left)

- **ZBOT-1: Self-Pressurization & Jet Mixing (2017)**
 - Self-Pressurization, Thermal stratification, 0G boiling
 - Jet Mixing/Cooling, Thermal destratification, Ullage-Jet dynamics
- **ZBOT-NC: Effect of Non-Condensable Gases (2023)**
 - NC effect on self-pressurization / stratification
 - NC effect on pressure control / destratification
 - Condensation suppression, Marangoni convection
- **ZBOT-AC: Active Cooling Pressure Control (2025)**
 - Droplet Spray Bar (TVS) Cooling
 - Broad Area Cooling (BAC)
- **ZBOT-FT: Filling & Transfer (est. 2026-27)**
 - Joint effort with DLR
 - Tank Chilldown and Tank-to-Tank Transfer
- **ZBOT-TT: Tank Transfer (launch date-TBD)**
 - NASA effort with US industry.
 - Tank Chilldown and Tank-to-Tank Transfer



Roadmap for CFM Tech Needs Across Mission Architectures

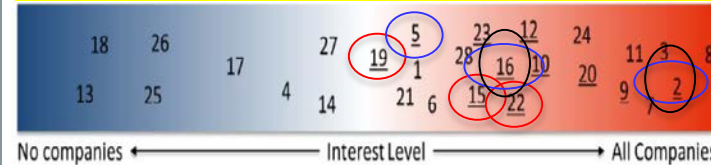
CFM Tech across Multiple Architecture



Mission Architecture



Heat Map of Industry Interest



Required CFM Technology Elements

Technology	No
Advanced External Insulation	1
Autogenous Pressurization	2
Automated Cryo-Couplers	3
Cryogenic Thermal Coating	4
Helium Pressurization	5
High Capacity, High Efficiency Cryocoolers 20K	6
High Capacity, High Efficiency Cryocoolers 90K	7
High Vacuum Multilayer Insulation	8
Liquefaction Operations (MAV & ISRU)	9
Liquid Acquisition Devices	10
Low Conductivity Structures	11
MPS Line Chilldown	12
Para to Ortho Cooling	13
Propellant Densification	14
Propellant Tank Chilldown	15
Pump Based Mixing	16
Soft Vacuum Insulation	17
Structural Heat Load Reduction	18
Thermodynamic Vent System	19
Transfer Operations	20
Tube-On-Shield BAC	21
Tube-On-Tank BAC	22
Unsettled Liquid Mass Gauging	23
Valves, Actuators & Components	24
Vapor Cooling	25

Flight Mission Timelines - Lander Timeline



ZBOT-1
ZBOT-NC

ZBOT-NC

ZBOT-TT

ZBOT-1
ZBOT-NC

ZBOT-AC

ZBOT-TT

ZBOT-AC

ZBOT – TT : Zero Boiloff Tank – Tank Filling and Transfer Experiment – (cryogenic resupply for space exploration vehicle)

Investigator team: Partnership

NASA SLPSRA, STMD, ISSPO, US Liquid Propellant Industry and possibly Universities

Objectives:

Conduct a **small to medium scale, long duration cryogenic fluid experiment on the ISS**. Investigate and understand the effect of microgravity on evaporation, condensation, boiling phenomena and the associated two-phase flow transport regimes that **impact tank and line chill-down and tank to tank transfer operations** during refueling of spacecraft propellant tanks from orbiting fuel depots.

Initial Concept:

- **External ISS payload**, small to medium scale
- **Cryogenic Working fluid:** Liquid Nitrogen
- Instrumentation: flow meters, thermocouples, pressure gages.
- Optional instrumentation: External viewing ports for cameras, full field temperature and flow visualization
- **Driven by NASA STMD and industry goals**

Goal: To produce high fidelity validation data to improve numerical models

Approach: Partnership - Roles and Responsibilities

- NASA, Industry, Universities – Ground studies
- US Industry - Flight hardware development
- NASA - Launch, mission integration & ops, crew time, numerical analysis of flight data

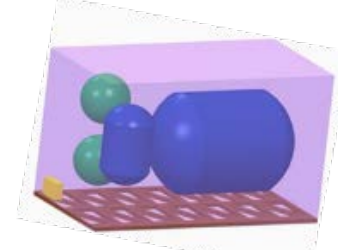
Application:

Cryogenic fuel resupply or depot, Lunar lander, Mars transit vehicles

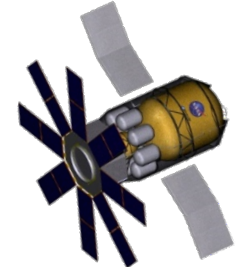
- Propellant Tank Chill down
- Propellant Tank Transfer Operations

Next Steps:

- RFI and Workshop with MOU or Agreement to be developed.



µg-Subscale Experiment with Cryogenics (proposed project)



Cryogenic Fuel Depot concept (notional, future large scale flight demo)

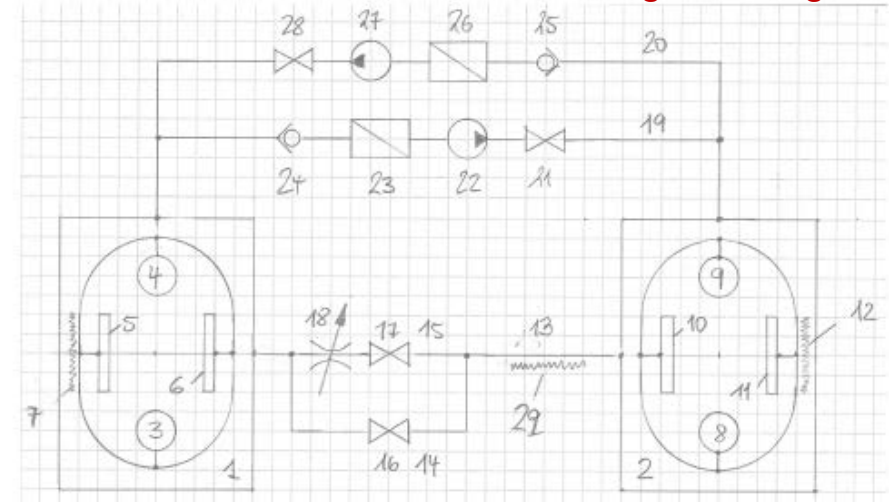


Figure 3.1: Generic drawing of the experiment setup, not to scale. The setup consists of two fluid containers, a donor tank 1 and a receiver tank 2, which are connected by several lines. The optical setup to enable observation is not shown. The setup aims at simulating the situation of a cargo spacecraft with a full propellant tank 1 docked to another spacecraft with an empty propellant tank 2. The components are explained in the text. The components are necessary to perform a repeatable model experiment on the International Space Station. They are not necessarily parts of the original hardware.

Tentative Schedule:

Ground Tests: 2021- 2022,

Flight hardware development: 2022 – 2025,

ISS operations: 2026

AES and SLPSRA

PBRE-2

PI: Brian Motil, NASA GRC

Co-I: Vemuri Balakataiah, University of Houston

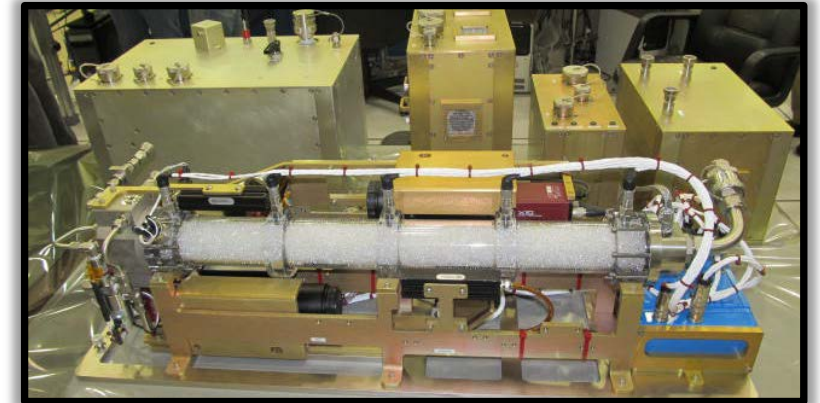
PBRE-WR-1 (Reactor)

PI: Layne Carter, NASA MSFC

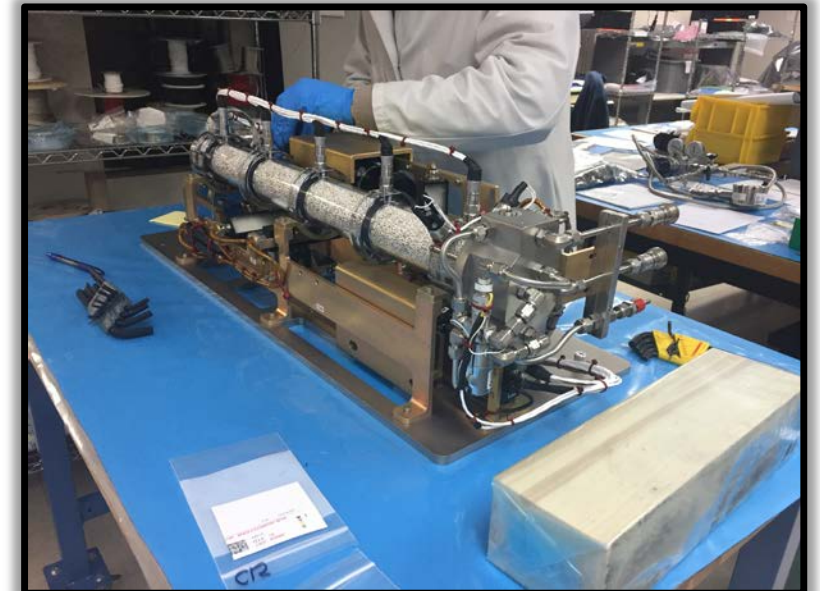
- The PBRE-2/WR Flight Hardware successfully passed the Engineering Review Board/System Acceptance Review on August 19, 2019.
- Scheduled to launch on NG-12 in Oct 2019.

-
- *Anomalies on the ISS Water Recovery System (WRS) indicate **the pressure drop** across restrictions is higher in m-G than 1-G. Also, unexpected **accumulation of gas** has occurred on the WRS filters during ISS operations.*






PBRE-2 test column with 2mm glass beads



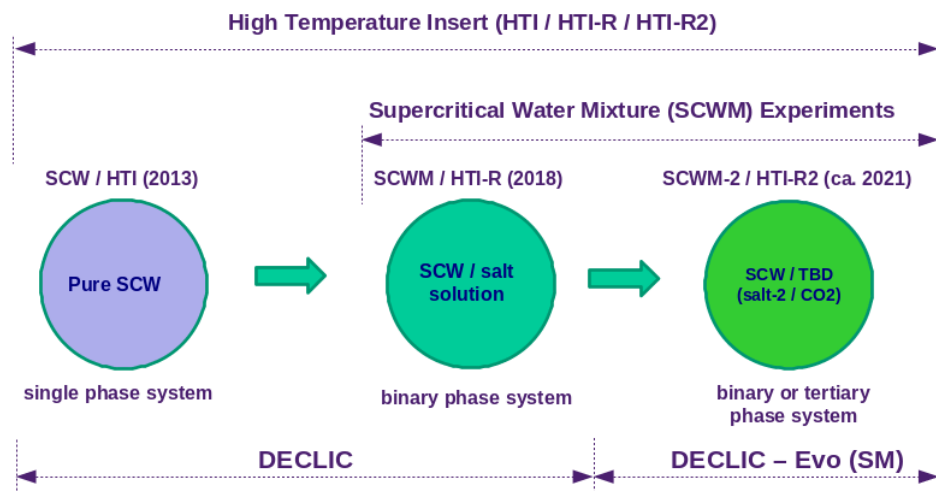
PBRE-Water Recovery test column with 3-mm alumina beads



Direct application to ISS Water Recovery System and precursor for future ECLSS systems

Experiment name/test sect	Tasks	SLPSRA costs	AES costs	Test section
PBRE-2 (SLPSRA) (SpX 16)	Camera repair, test material, Preflight testing, MI&O, hardware prep	PI and Co-I, PS, Grant, Cradle/test section	N/A	
PBRE-WR-1, Applied packing material (SpX 16)	Preflight testing, MI&O, hardware prep	Cradle/test section, Co-I/PS	PI, ISS WR packing material	
PBRE-WR-4 Purge Filter	Preflight testing, hardware prep, MI&O (coordinated through SLPS)	Co-I/PS	PI, new cradle with replaceable test sections.	
PBRE-WR-5 Lee Orifice #1 & #2 Check Valve	Preflight testing, hardware prep, MI&O (via SLPS)	Co-I/PS	PI, orifice and valves	
PBRE-WR-2 Brine filter	Preflight testing, hardware prep, MI&O (via SLPS)	Co-I/PS	PI, brine filter	
PBRE-WR-3 Urine Transfer Filter	Preflight testing, hardware prep, MI&O (via SLPS)	Co-I/PS	PI, urine transfer hose	
PBRE- WR -6 Flow Restrictor	Preflight testing, hardware prep, MI&O (via SLPS)	Co-I/PS	PI- Flow Restrictor	

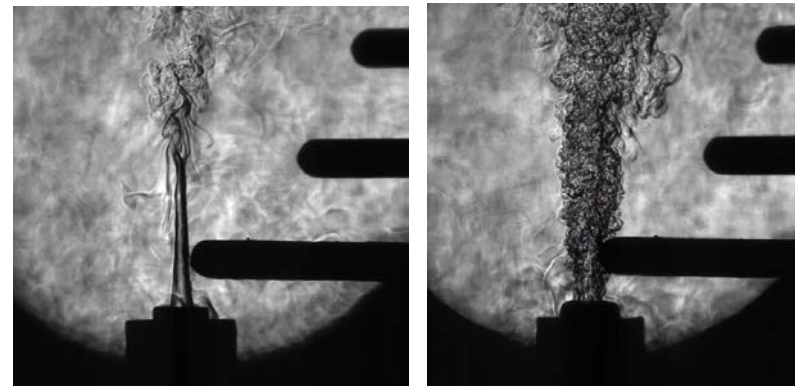
SCWM, SCWM-2 ... focused on near-critical phenomena with multi-phase systems (salt/water mixtures)



SCWO (for EXPL-1) ... ca. 2022-23, new science aligned with NASA's Advanced Exploration Systems (AES) with a focus on oxidative reactions on waste water (simulated urine).

Science Objectives:

- phase partition and salt (e.g., metabolic Ca^{+2}) precipitant transport in supercritical water
- influence of near-critical and supercritical behavior on turbulent transitions and bulk mixing
- spontaneous combustion, stability and structure of hydrothermal flames using ersatz aqueous waste concentrates (e.g., urine brine)



$Re = 448, Pr/F^2 = 1.4$

$Re = 2680, Pr/F^2 = 0.5$

Supercritical jet injected into supercritical water; turbulent transition highly dependent on buoyancy



Co-flow fuel jet, 30% $\text{C}_2\text{H}_6\text{O}$ (aq) in core and air in annular region injected into bulk SCW reactor



www.nasa.gov/spacetech

