



Physical Sciences Research Program Presentation to National Academies CBPSS

Oct 19 – 21, 2022

Francis Chiaramonte
Program Scientist for Physical Sciences
Biological and Physical Sciences Division
Science Mission Directorate
NASA HQ





Contributors

- **DeVon Griffin – Physical Sciences Program Manager**
- **Hans Hansen - Physical Sciences Deputy Program Manager**
- **Kelly Bailey – GRC Portfolio Manager**
- **Shawn Reagan - MSFC Portfolio Manager**
- **Mike Sansoucie – Materials Science and Biophysics**
- **David Urban – Science Lead GRC**
- **Dan Dietrich – Combustion Science**
- **John Mcquillen – Fluid Physics**
- **Suman Sinha Ray – Complex Fluids/Soft Matter**

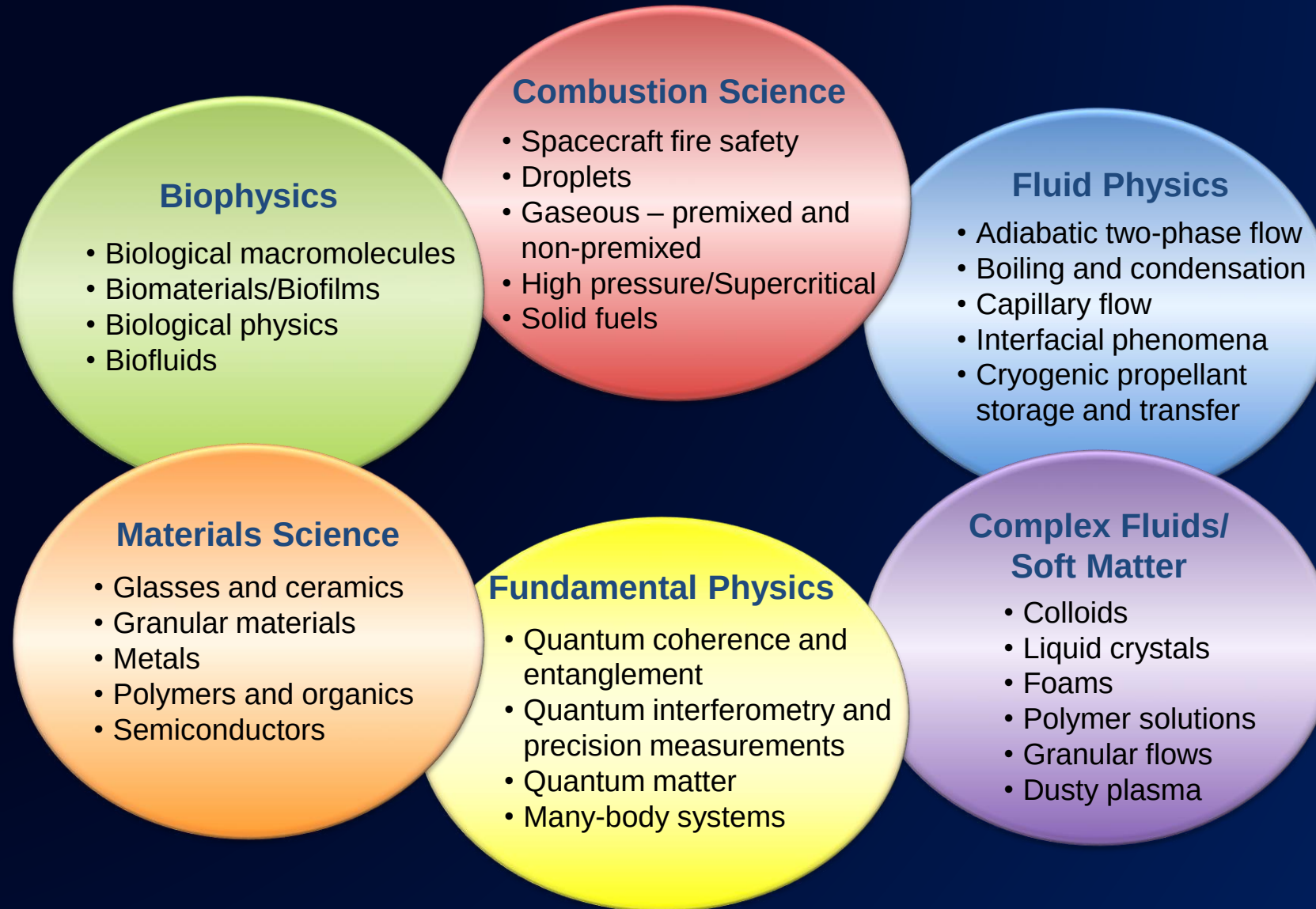


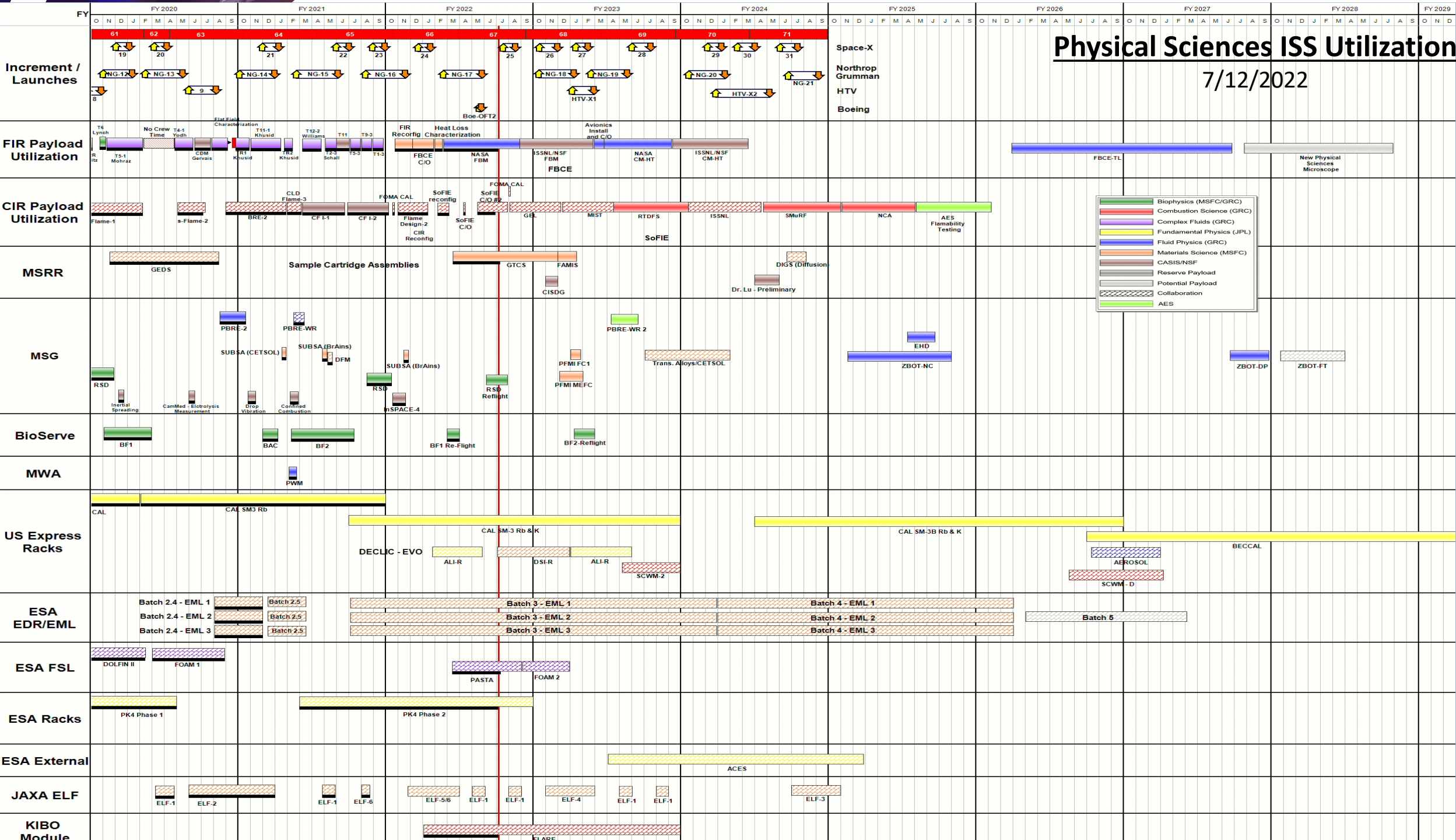
Agenda

- **Overview**
 - Physical Sciences Research Areas
 - Solicitation Plan
 - Impact of current BPS plan
- **Research activities by Discipline**
- **ISS Utilization Schedule**

Physical Science Research Areas and Solicitation Plan

BPS Physical Sciences Research Areas







Solicitation – Physical Science Informatics (PSI) 2022

ROSES - 2022 PSI Program Element

- Released: **September 15, 2022**
- Eligible flight and ground investigations: 86
- Proposals Due: January 10, 2023
- Selections: June 2023

- Solicits ground-based research proposals. (Annually)
- Solicits proposals from the following six research areas: **Biophysics, Combustion Science, Complex Fluids, Fluid Physics, Fundamental Physics, and Materials Science.**
- Ground-based research proposals that present a compelling case on how the data from the PSI system will be used to promote the advancement of further research using data analysis, or numerical and analytical models, or new ground-based experiments.
- Awards: \$100,000 in year one and \$125,000 in year two.
- Approximately 5 proposals will be selected.

- The program element will be available in NSPIRES as part of ROSES-2022.
- For additional information on the PSI database, visit: <https://nasa.gov/PSI>

Solicitations 2022 -2028

Combustion

- Supercritical Water Waiting for Decadal Survey Results, one award, 2025 – 2028
- Other topics await Decadal Survey results: [Candidates: Transcritical Combustion & Flammability of Materials](#)

Fluids Physics

- Multiphase flow with heat transfer - Three awards are planned. Will be coordinating with Decadal Survey results. Funding 2023 – 2027. [Candidate: Oscillating Heat Pipes & other Thermal Management.](#)
- AEROSOL – one award. Coordination with CNES – DECLIC. 2025 -2028

Materials Science

- Four to Five awards planned. Potential areas include, EML Batch 5, Lunar Concrete, microstructure of materials for additive manufacturing, will align with Decadal Survey. Funding 2023 – 2027. [Candidate: EML Batch -5 & Concrete on the Moon](#)

Soft Matter

- One award to support: [Liquid Crystal Film Experiment with Kasetsart University with Thailand.](#)

Impact of Current BPS Plan and past decisions

- From 2006 to 2016 PS program was rebuilt from 6 flight experiments to 70 with limited ground program.
- Since then, about 3 -5 experiments have been added and 13 -15 were cut due to budget overruns and other issues. So roughly 60 experiments will be completed.
- Current emphasis has limited Physical Sciences investigations beyond Quantum Science
- Lack of robust flight and ground programs in fluids, combustion, materials and soft matter
- Challenge: Will need to rebuild the Physical Sciences research community

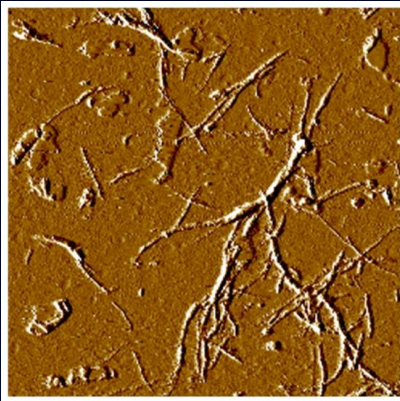
Research Activities by Discipline

Biophysics

Biomaterials – RSD: Protein Fibrillization, Bioreactor - ISS

- Amyloid fibrils are misfolded proteins that self-assemble to form β -sheet rich fibrillar structures.
- Amyloid fibrils are relevant to amyloid diseases such as Alzheimer's, Parkinson's, prion diseases, and type 2 diabetes.
- Studying how these proteins clump together could help scientists understand the processes behind the development of these neurodegenerative diseases.
- Space provides an ideal environment to examine the formation of these protein clumps without the interference of containers.
- Ring Shear Drop focused on the effects of interfacial shear on the fibrillization kinetics of human insulin.
- Preliminary findings:
 - Increasing interfacial shear rate produced a monotonic increase in intrinsic fibrillization rate and a monotonic decrease in fibrillization time.
 - Protein concentration did not significantly impact the intrinsic fibrillization rate or times; however, a minimum fibril concentration for gelation was found.
 - Protein microstructure showed increasing aggregation and plaque/cluster formation with time.

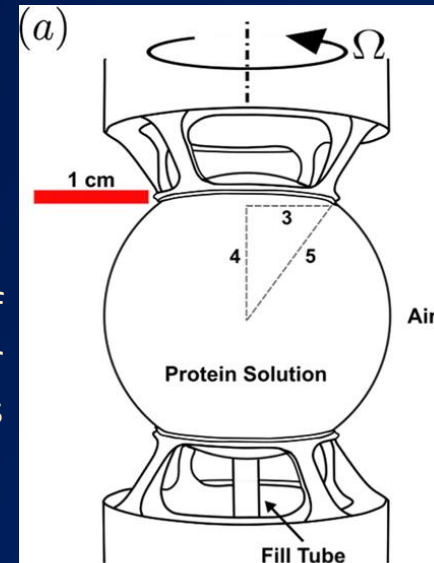
Image of fibrils taken from the bulk (Balaraj, Hirs et al. Soft Matter 2017)



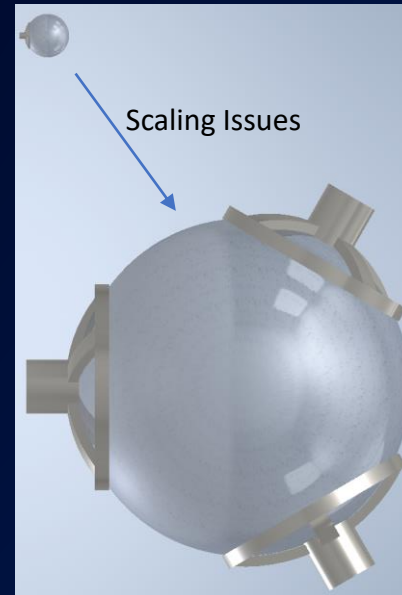
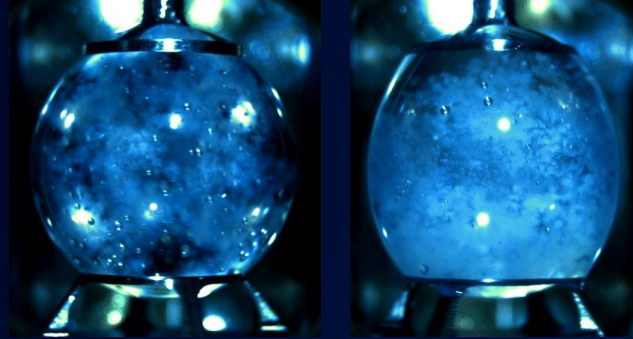
Dilute protein solution droplet in nearly containerless bioreactor on ISS.



Schematic of the ring shear drop apparatus



RSD

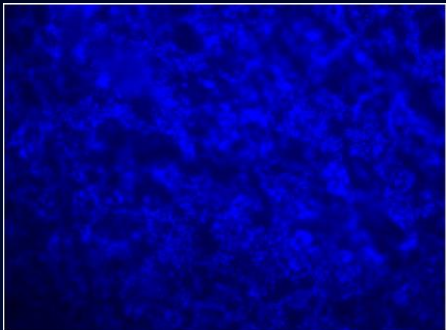


Future Opportunities – Biophysics

- Partner with Space Biology

Biofilms

- Biofilm growth has been observed in Soviet/Russian (Salyuts and Mir), American (Skylab), and International (ISS) Space Stations, sometimes jeopardizing key equipment like spacesuits, water recycling units, radiators, and navigation windows.
- Biofilm formation also increases the risk of human illnesses and therefore needs to be well understood to enable safe, long-duration, human space missions. Here, the design of a NASA-supported biofilm in space project is reported.
- The adhesion of bacteria to surfaces and therefore the initial biofilm formation is strongly governed by topographical surface features of about the bacterial scale.
- Experiments conducted aboard the ISS will provide unique insight into the mechanisms of attachment, growth and subsequent proliferation of biofilms in the absence of convection, critically important for continued presence in space- both on ISS and long duration missions.
 - To search for potential solutions, different materials and surface topologies will be used as the substrata for microbial growth.
 - A novel lubricant-impregnated surface will be assessed for potential Earth and spaceflight anti-biofilm applications.
- Studies on the effects of the space environment on bacterial or fungal biofilms will help with mitigation strategies of biodegradation or biocorrosion of materials and biofouling of fluid systems.
 - Advance fundamental knowledge for developing materials that are resistant to or inhibit biofilm formation and growth.
 - Reduce the dependency on chemical agents, which are potential health and ECLSS hazards in closed spacecraft environments.



P. aeruginosa biofilm
formed on quartz.



Biofilm sample
tray

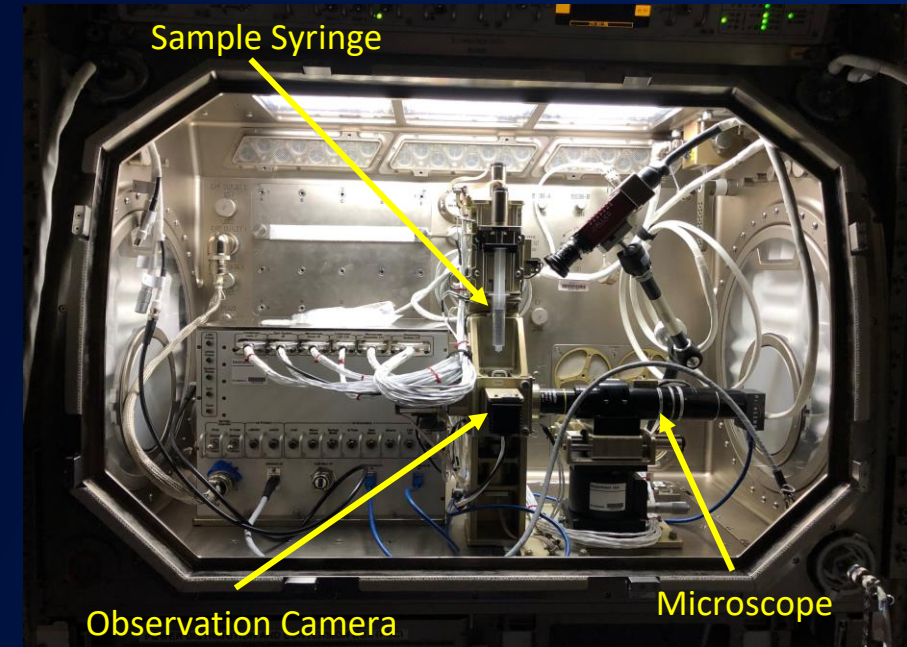
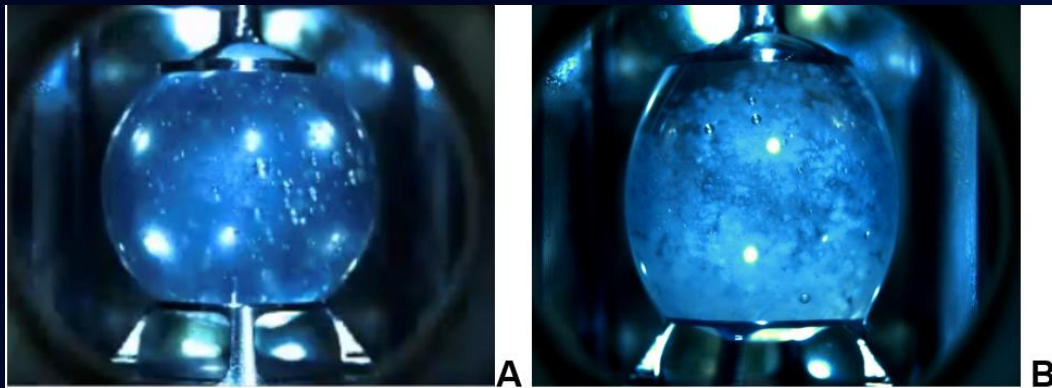


Extensive biofilm
formation in ISS
water recovery
system

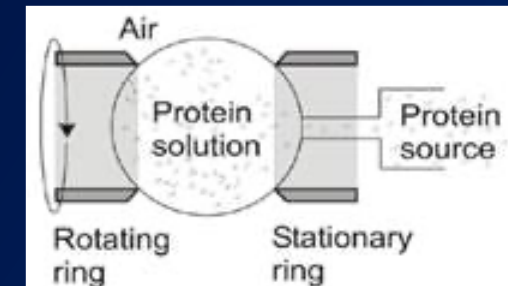
Containerless Bioreactor – from the RSD experiment

RSD was developed by BPS for the processing of biological fluids in microgravity. Using surface tension, RSD provides a containerless reactor in which the experimental fluid is held and processed in a spherical drop (corralled by surface tension). The drop is held between two small rings designed to minimize contact area. One of the rings is capable of rotation in order to induce flow inside the drop.

Biological & Physical Sciences (BPS) - RSD was developed by BPS for the Amyloid Fibril Formation (AFF) experiment PI: Amir Hirs/RPI,
ISS National Lab (ISSNL) is using the RSD hardware for biological experiments as well; the Interfacial Bioprocessing of Pharmaceuticals (IBP) experiment PI: Juan Lopez/ASU



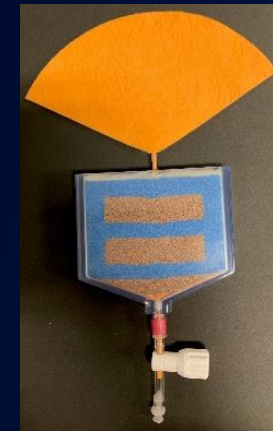
Launched on SpaceX CRS-18 – July 2019,
Installed MSG, astronaut Nick Hague



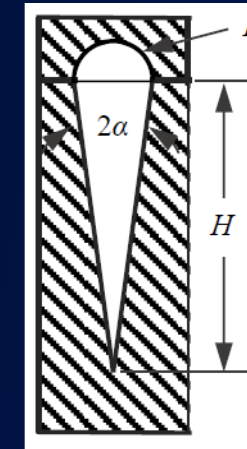
Plant Water Management – using capillary driven flow strategies

Plant Water Management (PWM), PI: Mark Weislogel, Portland State University

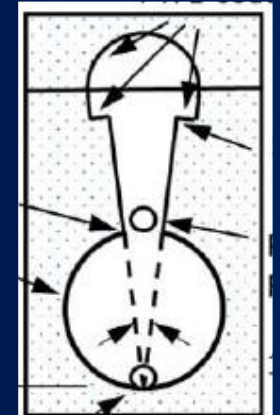
- Objective: Evaluate options for adequate hydration and aeration techniques for soil media and other farming strategies including but not limited to: Aeroponics, Hydroponics, and Soil-based media
- Soil (PWM-S): Establish a “capillary gradient” using material wettability to provide controlled to establish the ability to compare typical
- Hydroponics (PWM-H): Demonstrate the ability to utilize system geometry to provide positive water control for plant hydration.
- Root Accommodation Channel (PWM-HRAC): Provide accommodations for root growth as plant matures in a hydroponic channel.
- Parallel Channel (PWM-PHRAC): Examine system stability for growing multiple plants at different growth stages and water uptake rates.



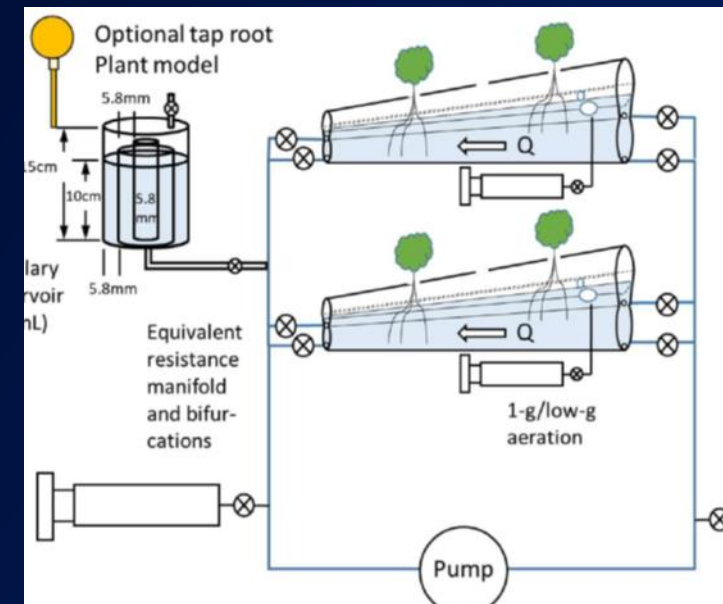
PWM –S test cell



PWM –H Cross-Section



PWM –HRAC Cross-Section



PWM –PHRAC Test Setup

Combustion

High Pressure Transcritical Combustion (HPTC)

Overview:

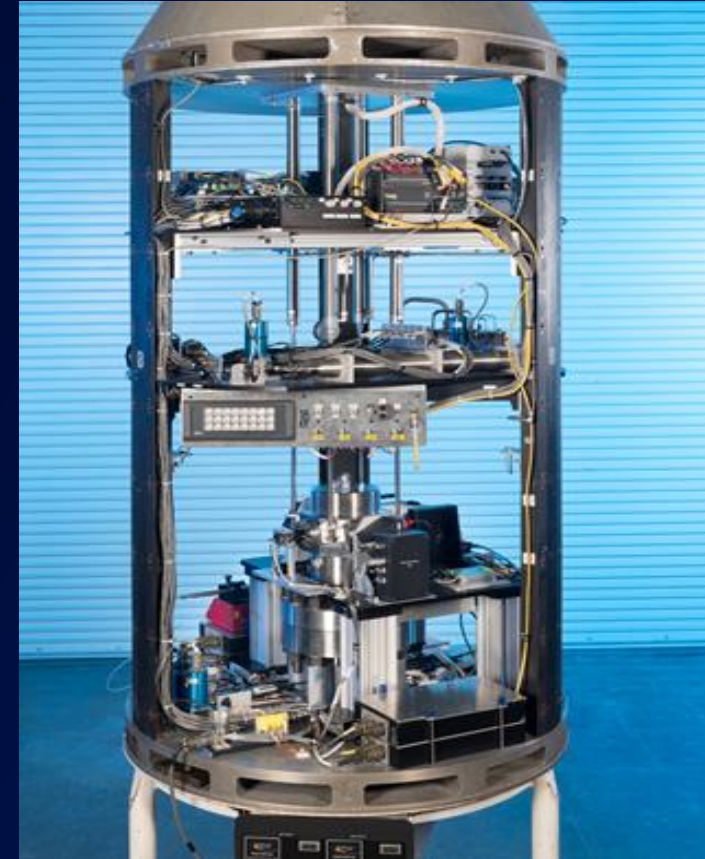
Transformative research to enable the design of **future internal combustion** engines moving to higher operating pressures to increase efficiency while simultaneously reducing pollutant emissions and novel applications such as supercritical water oxidation (SCWO) for waste incineration. Since the buoyant force scales with pressure squared, fundamental combustion studies in terrestrial laboratories are increasingly difficult because of the dominance of the buoyant force. The microgravity environment allows for extended length and/or time scales without the intrusion of a dominant buoyant flow. This in turn enables diagnostic techniques, that otherwise prove intractable in 1-g environments, to obtain transformative insights into supercritical phenomena.

Relevance/Impact:

Strong advocacy in military and industrial applications; e.g., advanced turbine combustors, advanced diesel engines, rocket engines (increased efficiency, power density and reduced emissions)

Fundamental thermophysical data and thermodynamic state data for supercritical fuel/oxidizer mixtures

Part of a larger GRC program in high pressure transcritical phenomena that has international collaborations (CNES) and interest from HEO (SCWO).



HPTC Drop Tower facility

Spacecraft Fire Safety - Solid Fuels

BPS Portfolio - Solid Fuel Ignition and Extinction (SoFIE)

Material Ignition and Suppression Test (MIST)

Fernandez-Pello: UC Berkeley

Fundamental experiments of solid material ignition from an external heat source



Spacecraft Materials Microgravity Research on Flammability (SM μ RF)

Olson: NASA GRC

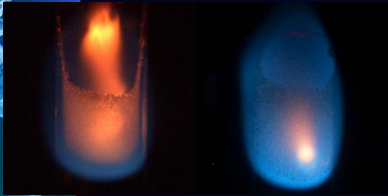
Flame spread experiments studying the flammability limits of solid fuels



Narrow Channel Apparatus (NCA)

Miller: San Diego State University

Flame spread experiments focused on thick polymeric materials



Residence Time Driven Flame Spread (RTDFS)

Bhattacharjee: San Diego State University

Opposed-flow flame spread over thin acrylic sheets to examine fuel thickness effects



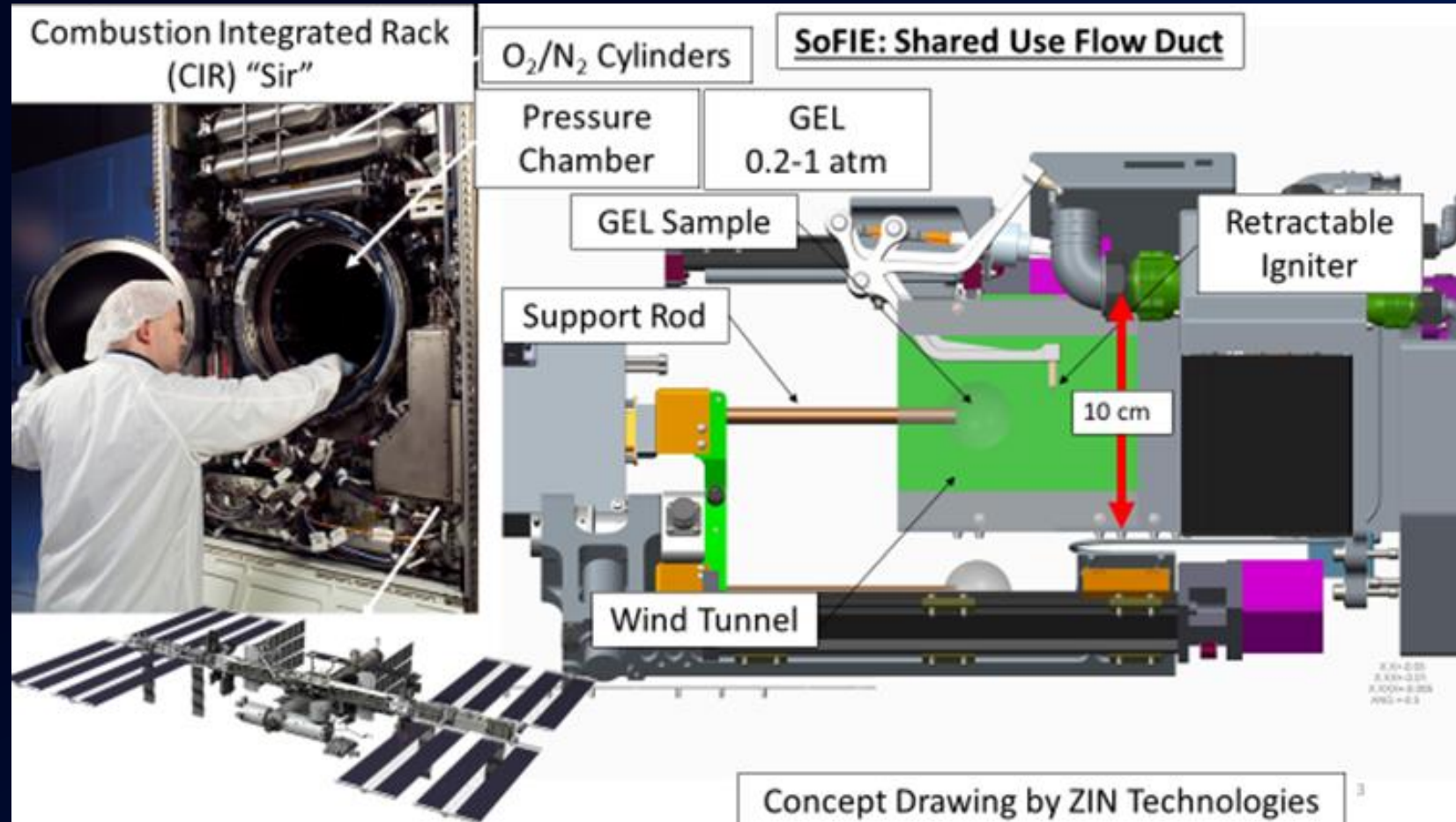
Growth and Extinction Limit (GEL)

T'ien: Case Western Reserve University

Investigating effect of gravity, flow, O₂, pressure, and fuel preheating on the combustion of polymeric spheres



Use of the Combustion Integrated Rack - Flammability of Solid Fuels for Fire Safety



Flammability Limits At Reduced-g Experiment (FLARE)

JAXA PI: Prof. Osamu Fujita, Hokkaido Univ.

US Co-Is: Dr. Sandra Olson, NASA GRC

Dr. Harold Beeson, NASA

Prof. Carlos Fernandez-Pello, U. C. Berkeley

International Co-Is: Many Japanese Co-Is, Guillaume Legros,
U. Pierre Marie Curie, Thomas Rohr, ESA, Marika Orlandi, ESA

Project Manager: Shigeki Kamigaichi, JAXA

Project Scientist: Masao Kikuchi, JAXA

Objective

To develop a methodology to correlate material flammability limits in normal gravity and microgravity, which allows quantitative estimation of material flammability limit in microgravity based on the flammability data obtained on the ground. The project involves an international team including JAXA, NASA, ESA and universities in Japan, USA and France.

Experimental Approach:

- Perform extensive research via ground-based experiments, including 1g and parabolic flight tests, and via theoretical formulations.
- Flight experiments on orbit in ISS/KIBO will be performed to verify the correlation.
- By the end of the project, a new fire safety standard test method for screening spacecraft materials will be proposed that addresses the shortcomings of existing standard test method such as NASA STD 6001B.

Relevance/Impact:

Fundamental Science – studying materials flammability in space allows us to accurately control the flow field and thus elucidate the importance of a critical Damkohler number (flow time /reaction time) on flame extinction. Efficiency - The anticipated improved methodology should reduce time and cost for the spacecraft material screening.

Safety - Terrestrial fire safety; spacecraft fire safety

Development Approach:

Experiment uses same hardware as JAXA's "Solid Combustion" International research team





Combustion Research with Roscosmos

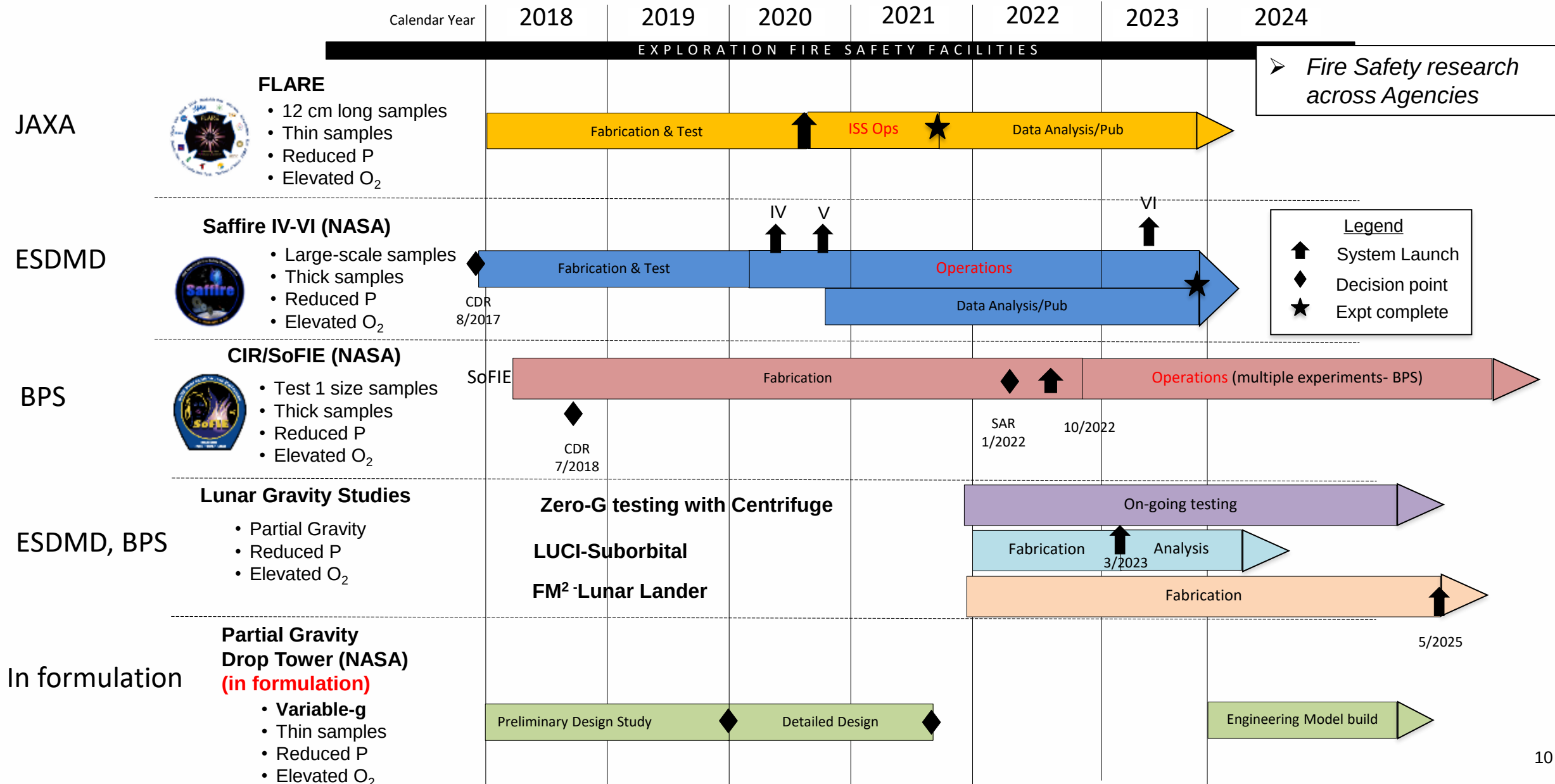
Investigations:

- SoFIE - Material Ignition and Suppression Test (MIST)
- SoFIE - Growth and Exinction Limit of Solid Fuels (GEL)
- ✓ ACME – Advanced Combustion via Microgravity Experiments - ISS ops completed

Cosmonauts Anton Shkaplerov (foreground) and Oleg Artemiev (background) performing a gaseous fuel bottle swap for the ACME experiment, “Electric-Field Effects on Laminar Diffusion Flames (E-FIELD Flames)”



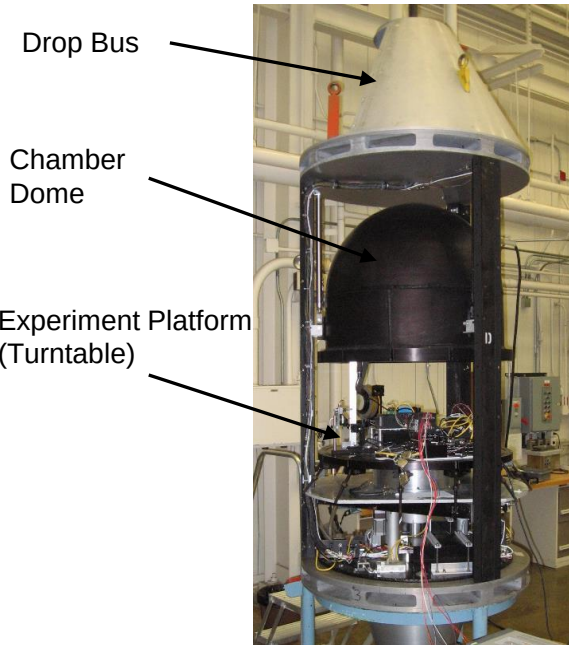
International Roadmap - Reduced Gravity Plan for Flammability Studies



Future Opportunities - Combustion

Progression of Partial-Gravity Test Methods

- ◆ Each test method builds on the methods below and to the left
- ◆ The New Shepard test method may become the “workhorse” for flammability testing if the proof-of-concept test is successful (early 2023)

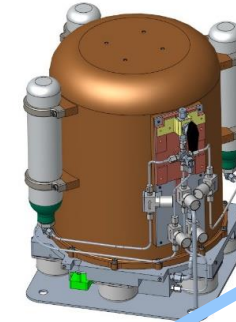


Parabolic Aircraft (10 -20 sec)

- Partner with ESA
- Short burn duration
- Few Opportunities
- G-jitter 0.01 to partial-g
- Currently to 21%O₂

Blue Origin New Shepard Experiment (2 minutes)

- Lower Coriolis force (larger radius)
- Moderate burn duration
- Fewer opportunities (TBD)



CAD model of the Engineering Development Unit for the CLPS flammability experiment

Commercial Lander Payload Services (CLPS) on the Moon

- Ground truth for Lunar-g flammability
- Small test samples
- Lunar Surface
- Very Limited opportunities



Blue Origin, used with Permission (Erika Wagner)

ZGRF Centrifuge Rig (5 sec)

- Many tests
- Large Coriolis forces
- Short burn duration



Saffire partners from ESA in the reduced gravity aircraft

- ◆ A Lunar “ground truth” is necessary to validate results from the Earth-bound test platforms
 - Flammability limits and flame spread
- ◆ All test methods support numerical modeling

High Pressure Transcritical Combustion (HPTC)

Ground Based - Drop Tower

Overview:

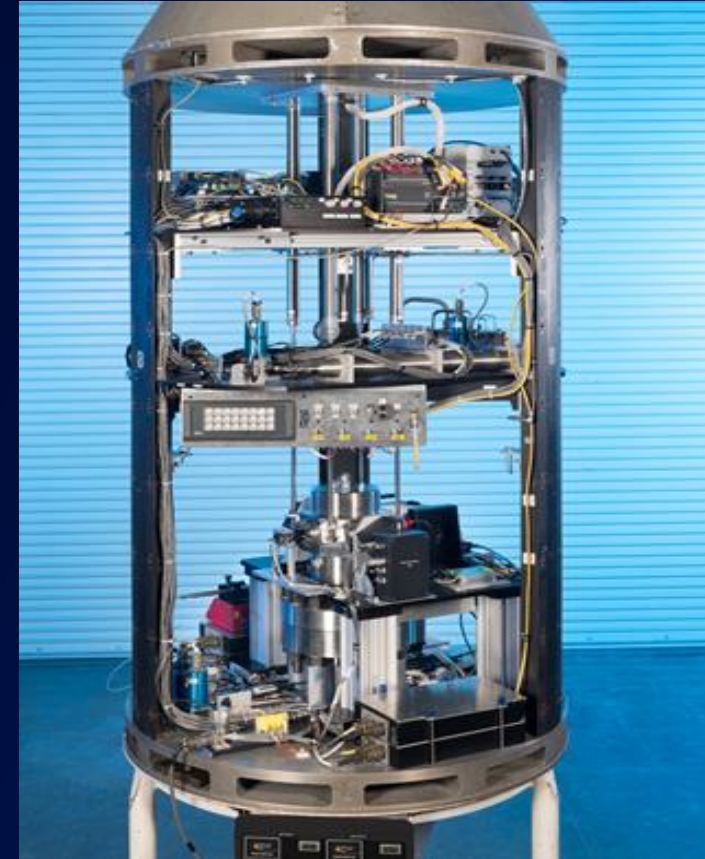
Transformative research to enable the design of **future internal combustion** engines moving to higher operating pressures to increase efficiency while simultaneously reducing pollutant emissions and novel applications such as supercritical water oxidation (SCWO) for waste incineration. Since the buoyant force scales with pressure squared, fundamental combustion studies in terrestrial laboratories are increasingly difficult because of the dominance of the buoyant force. The microgravity environment allows for extended length and/or time scales without the intrusion of a dominant buoyant flow. This in turn enables diagnostic techniques, that otherwise prove intractable in 1-g environments, to obtain transformative insights into supercritical phenomena.

Relevance/Impact:

Strong advocacy in military and industrial applications; e.g., advanced turbine combustors, advanced diesel engines, rocket engines (increased efficiency, power density and reduced emissions)

Fundamental thermophysical data and thermodynamic state data for supercritical fuel/oxidizer mixtures

Part of a larger GRC program in high pressure transcritical phenomena that has international collaborations (CNES) and interest from HEO (SCWO).



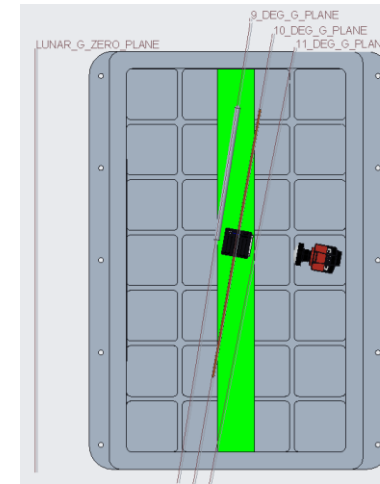
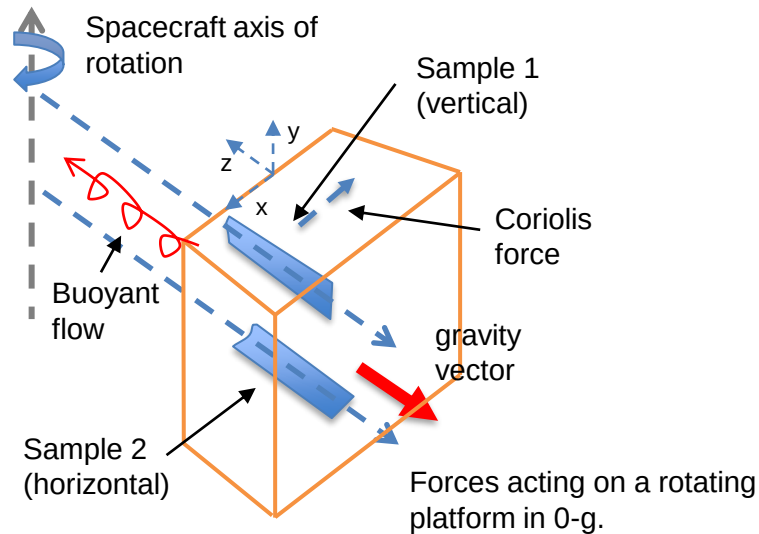
HPTC Drop Tower facility

Lunar-g Combustion Investigation (LUCI) – Sub-Orbital

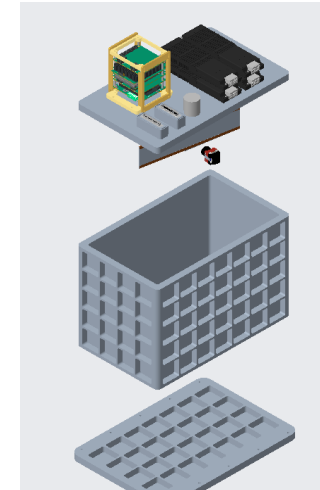
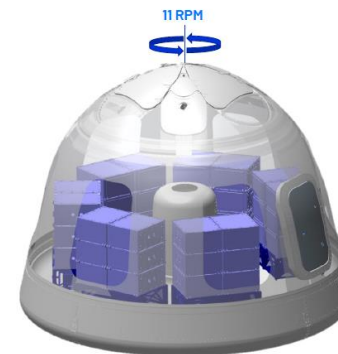


Lunar Gravity Sub-Orbital Flight (Lunar-g Combustion Investigation - LUCI)

- ◆ Objective: Investigate flame spread of SiBAL fabric and PMMA rod samples.
- ◆ Mission Concept Review - aligned the concept with Exploration Capabilities Office, HLS Materials and Process personnel
- ◆ Working with Blue Origin to develop and tailor test plans
- ◆ Flight is still planned for 1st Quarter of CY2023
- ◆ Will provide 2-minute partial-g test capability to extend drop tower testing



Above: Sample alignment and camera view inside the combustion chamber.
Below: Payload locker configuration in the Blue Origin New Shepard capsule.



Left: Concept for the experiment enclosure;
Below: Double locker for the LUCI experiment in the experiment stack.

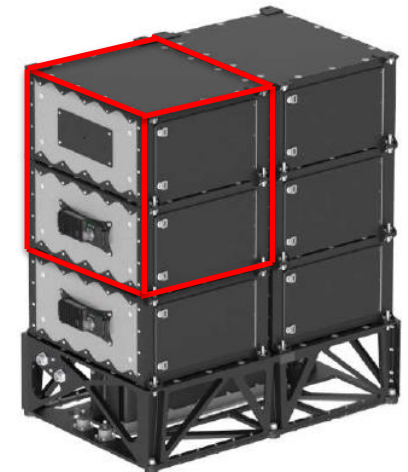
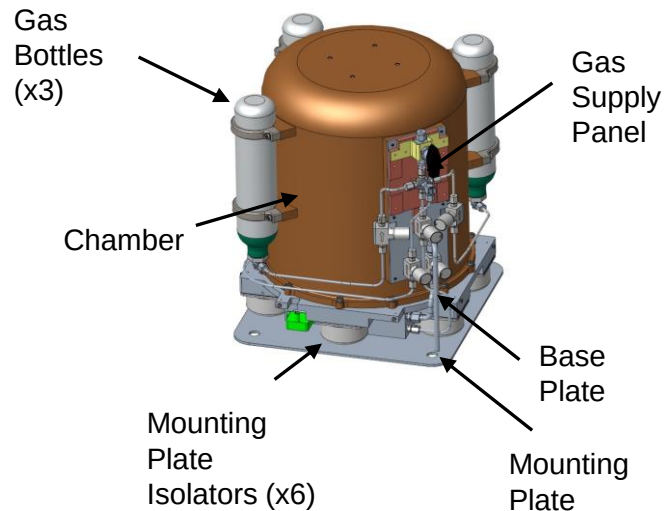


Figure 3-2
Payload Stack with six single lockers

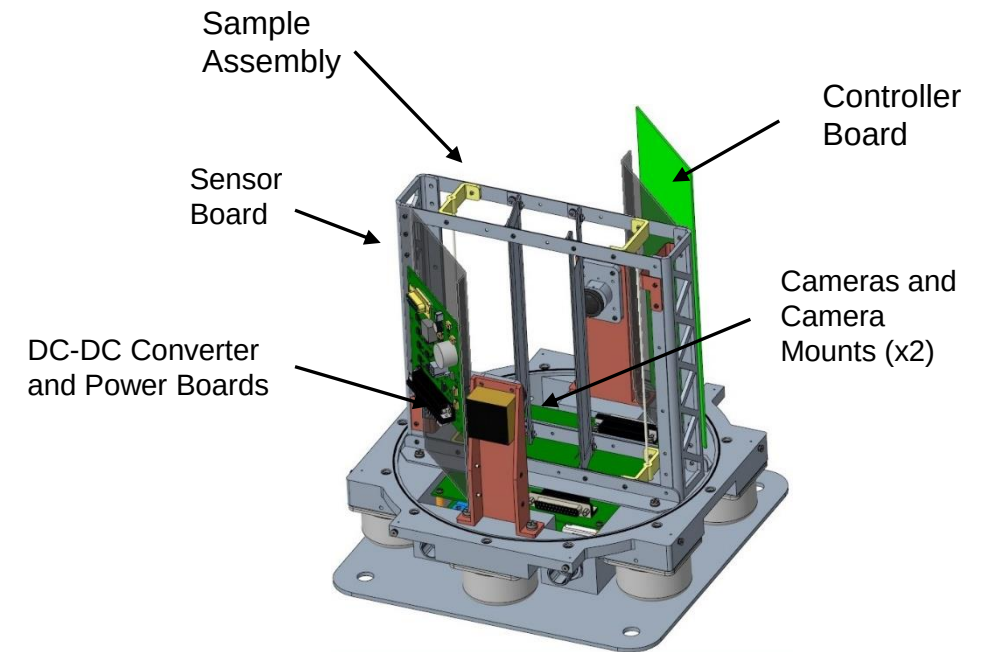
Spacecraft Fire Safety, Flammability of Materials on the Moon (FM²) – **Commercial Lunar Payload Services**



- ♦ Objective: provide extended-duration ground-truth testing for flame spread, growth, and extinguishment for 4 samples that include SiBAL fabric and PMMA rod samples.
- ♦ Working with Mars Campaign Development-Exploration Capabilities management and the HEOMD representatives to the CLPS Manifest Selection Board (CMSB) to get manifested on a CLPS mission
- ♦ CP-22 is scheduled to launch in February 2026
 - Destination is Lunar South Pole
 - Delayed from May 2025 launch
 - Flight Hardware Availability is now May 2025



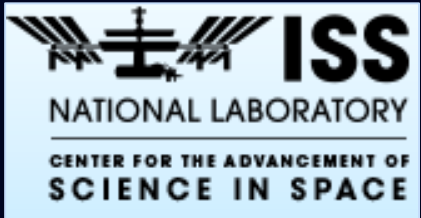
CAD model of the external FM² design (Base plate is 28.5 cm x 28.5 cm; Chamber is 38.5 cm tall. Maximum weight is 25 kg)



CAD models of the internal FM² design

Fluid Physics

OGA and NASA Collaborations/Partnerships



- **ISSNL/NSF**
 - ISSNL and NSF selected two research teams to conduct experiments on NASA BPS's **Flow Boiling and Condensation Experiment**.
 - ISSNL to use the RSD hardware developed by NASA –BPS. Data to be shared.
- **NASA STMD**
 - **Zero Boiloff Tank experiment** series (ZBOT -1, NC and DP) – Modeling support
 - Moon to Mars Planetary Automated Construction Technologies (MMPACT) – in discussion
 - Oscillating Heat Pipes – GSFC Data, numerical simulation, BPS investigation – in discussion
- **NASA – ESDMD**
 - **Packed Bed Reactor Experiment** – Water Purification/Recovery systems
 - SoFIE -Spacecraft Fire Safety/ Materials Flammability
- **NASA BPS – Space Biology**
 - **Plant Water Management** experiments
 - Biofilms experiments – two investigations
- **NASA – ISS Program**
 - KERMIT - Microscope

BPS Research: Advanced Thermal Management Technologies

applicable to THERMAL-472, THERMAL-483, THERMAL-519, THERMAL-604

Title: Flow Boiling and Condensation Experiment - ISS

PI: Prof. Issam Mudawar, Purdue University, Mojib Hasan, NASA GRC

Objective:

- Obtain flow boiling data to validate models for microgravity flow boiling critical heat flux (CHF) and dimensionless criteria to predict minimum flow velocity required to ensure gravity-independent CHF.
- Obtain condensation data to validate models for microgravity behavior.

Status: ISS Flow boiling tests successfully completed in July, 2022. Condensation tests to start in 2023.

Applications:

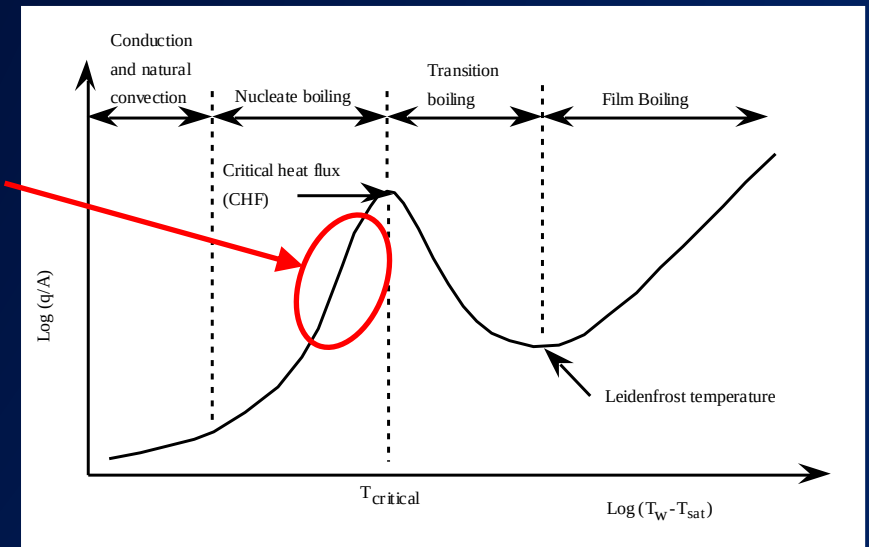
- Thermal Control for ECLSS in crewed spacecraft and lunar & Martian habitats
- Thermal management for rovers and spacecraft
- Energy conversion, Rankine power cycle, for large power demands.

Potential Technology Impacts:

More efficient heat transfer:

- Isothermal temperature control
- Reduced mass
- Wider Range of Heat loads.

Sweet Spot



Boiling Heat Transfer

Flow Boiling and Condensation Experiment (FBCE)

Flow Boiling - CHF Results for Double-sided Heating

High Velocity Flow Rate
(1.9 – 2 m/s)



Horizontal 1g



μg

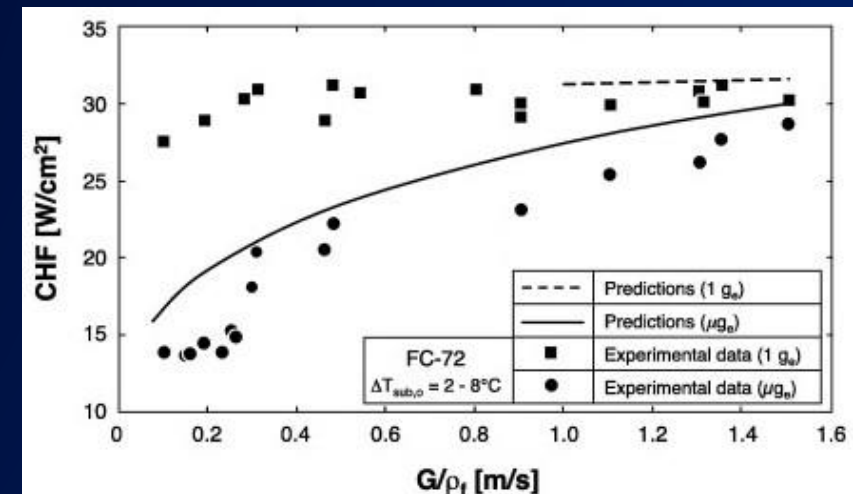


Low Velocity Flow Rate
(0.1 - 0.11 m/s)

Horizontal 1g



μg



Critical Heat Flux as a Flow Rate

FBCE Breakthrough Application to Electric Vehicle Charging

- ❑ *What is unique about our new technology is ability to charge EVs in less than 5 minutes, eliminating a major obstacle facing the EV market!*
- ❑ *And what is important to NASA is that this technology utilizes science learned from our NASA research, namely using subcooled flow boiling of dielectric fluid to greatly enhance cooling of the conductor within the charging cable, which allows delivery of unprecedented 2,400 Amps, compared to 520 Amps for today's most advanced chargers on the market.*
- ❑ *The new technology is subject of a joint patent (pending at present) between Purdue University and Ford Motor Company.*

BPS Research: Advanced Thermal Management Tech. applicable to THERMAL-604

Title: Electrohydrodynamic (EHD) Expt.

PI: Prof. Jamal Yagoobi, Worcester Polytechnic Inst.

Jeff Didion, NASA GSFC

Objective: Develop theoretical foundation and test the effects of microgravity on electrically generated two-phase flow and an electrically driven liquid film boiling using a dielectric fluid.

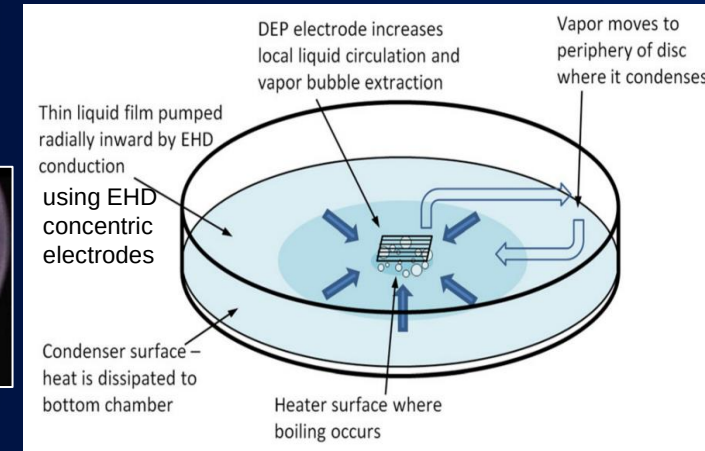
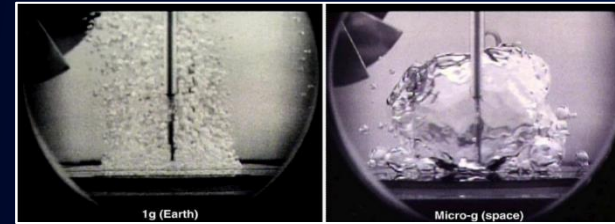
Application: Electric field based, two-phase thermal management systems

Benefits:

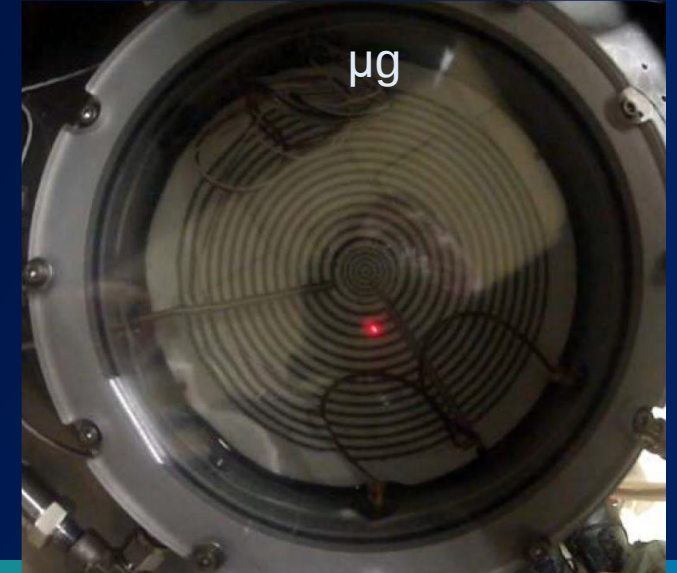
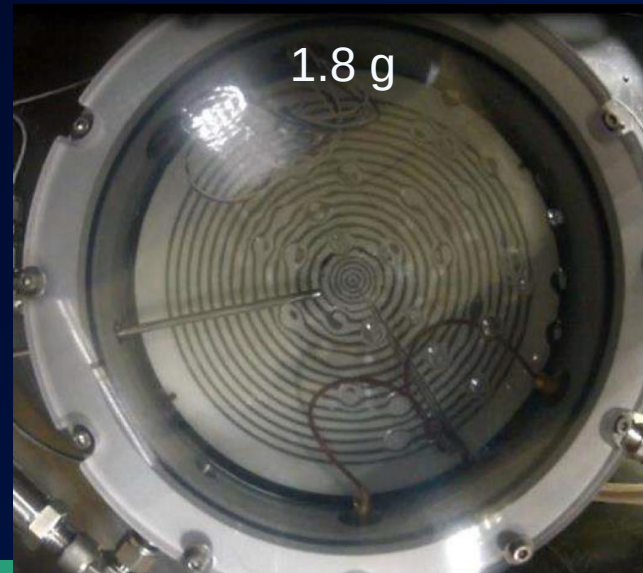
- Simple design, Light weight
- Non-mechanical, no rotating machinery
- Low power consumption
- Low acoustic noise

Potential Technology Impacts:

- Cool high powered electronic chips
- Smallsat Thermal Management



EHD experiment concept



Title: ZBOT-NC Experiment (Non-Condensable Gas Effects) - ISS

PI: Dr. Mohammad Kassemi (Case Western Reserve University)

STMD Application: CFM-462, CFM-477, CFM-492, CFM-1194

Objective: Investigate the impact of Non-Condensable Gas (NCG) pressurants on tank pressure control in microgravity

Key science questions to be investigated & knowledge gained:

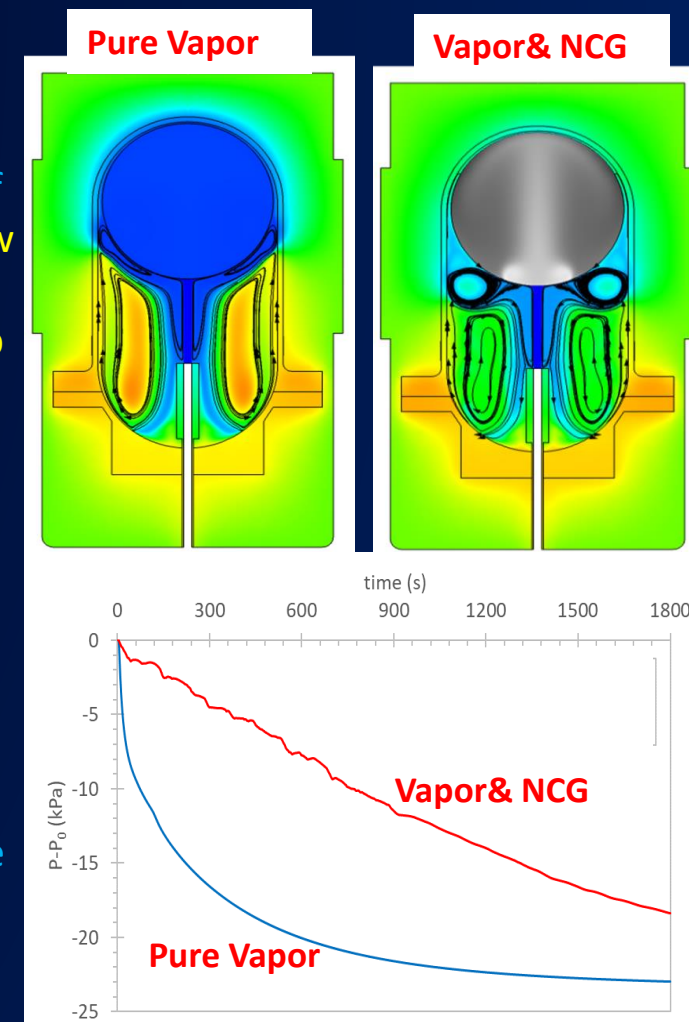
1. Can NCGs build a transport barrier in the ullage and disrupt tank pressure control in microgravity?
2. What are the kinetic effects of NCGs on interfacial condensation and tank depressurization?
3. Can a unique Marangoni convection generated by NCGs divert the subcooled jet away from the liquid/vapor interface and change the flow structures in the tank?

Anticipated Technology Impact:

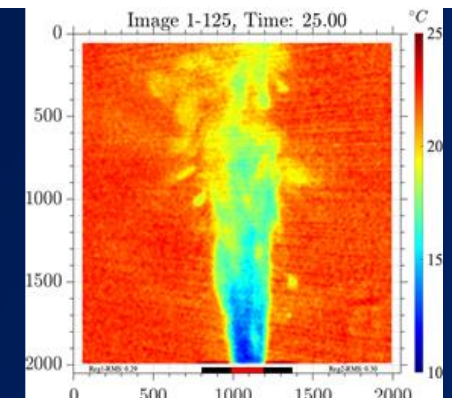
- State-of-the-Art CFD model developed and validated for NCG effects to aid the propellant tank scaleup design
- Determine whether the current axial jet mixing pressure control strategy is effective in presence of NCGs in microgravity
- Shift to autogenous pressurization or use droplet injection cooling

CFD model predictions of change in flow structure and pressure drop rate due to NCG effects during jet mixing in microgravity

↓
Need Microgravity data to validate these crucial predictions



Whole Field Quantum Dot Thermometry Diagnostics developed by ZBOT to capture signatures of Marangoni convection



ZBOT – FT: Zero Boiloff Tank - Filling & Transfer Experiment – ISS CLD



Investigator team:

DLR sponsored - Prof. Michael Dreyer – U. Bremen;
NASA sponsored - Dr. Mo Kassemi – CWRU

Objectives:

- Use a small-scale simulant fluid experiment and 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.
- Investigate the integrated system level dynamics of two-phase two-tank system in microgravity and assess if **no-vent tank-to-tank transfer** is feasible in microgravity for cryogenic refueling.

Collaboration Approach: Experiment concept driven by NASA STMD goals

- Ground based study – drop tower/aircraft testing DLR; numerical simulation NASA
- Flight hardware development – DLR
- ISS or Commercial LEO Destinations, launch, integration and ops – NASA ISS-PO and BPS

Application:

Cryogenic Fuel Depot, Lunar lander (Human Landing System)

In-Space Servicing, Assembly, and Manufacturing (ISAM), and Mars transit vehicles

- Propellant Tank Chill down and Propellant Tank Transfer Operations

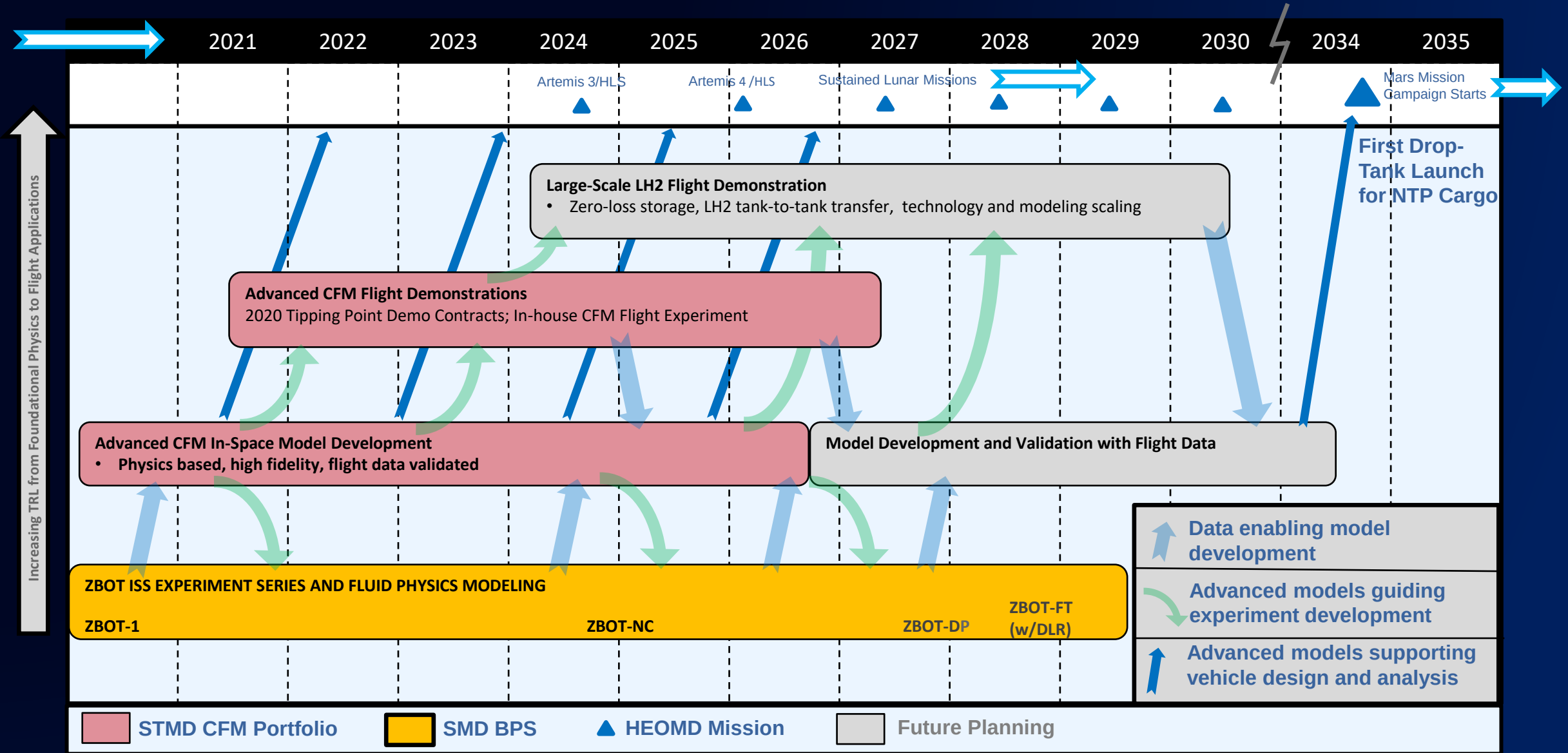
Status:

- ✓ Ground Tests: 2019 – 2025, in progress
- ✓ DLR Phase A/0 flight experiment study – 1/2023 to 1/2024
- Flight experiment – contingent upon cost estimates from Phase A/0 study
- International Agreement for space experiment – first draft has been developed
- Flight hardware development **plan**: 2024 – 2028, ISS ops: 2028-29



NASA concept for an in-space propellant depot.

STMD Path from Foundational Physics to Enabling CFM for Crewed Missions



Future Opportunities – Fluid Physics

BPS Research: Advanced Thermal Management Technologies – Ground based applicable to THERMAL-519 - STMD

Title: Pulsating/Oscillating Heat Pipes

PI teams: GSFC, JPL (numerical modeling) and Univ. Iowa grant, STMD grants.

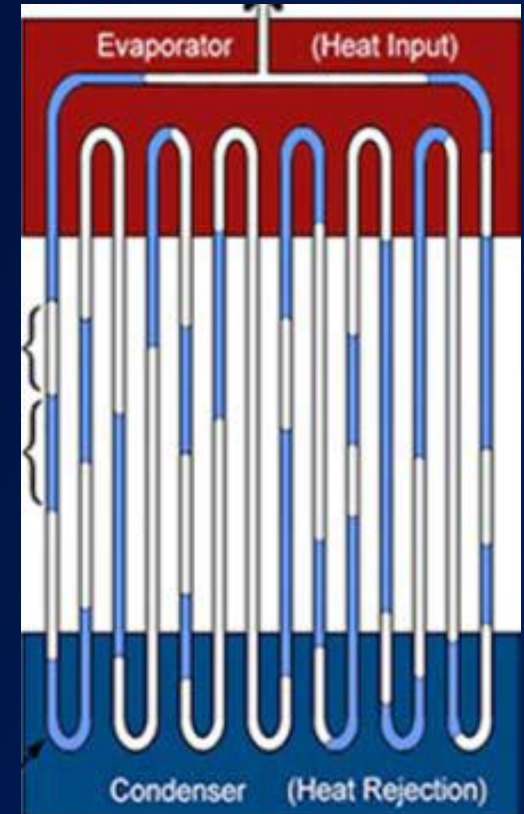
Objective: Explore Operational Envelope with extensive testing to validate models that focus on heat transfer and internal fluid dynamics to predict effective thermal conductance.

Research Focus

- Liquid film dynamics and heat transfer.
- Impact of fill level on contribution of latent vs. sensible heat transfer.
- Boiling nucleation in a fixed volume system.

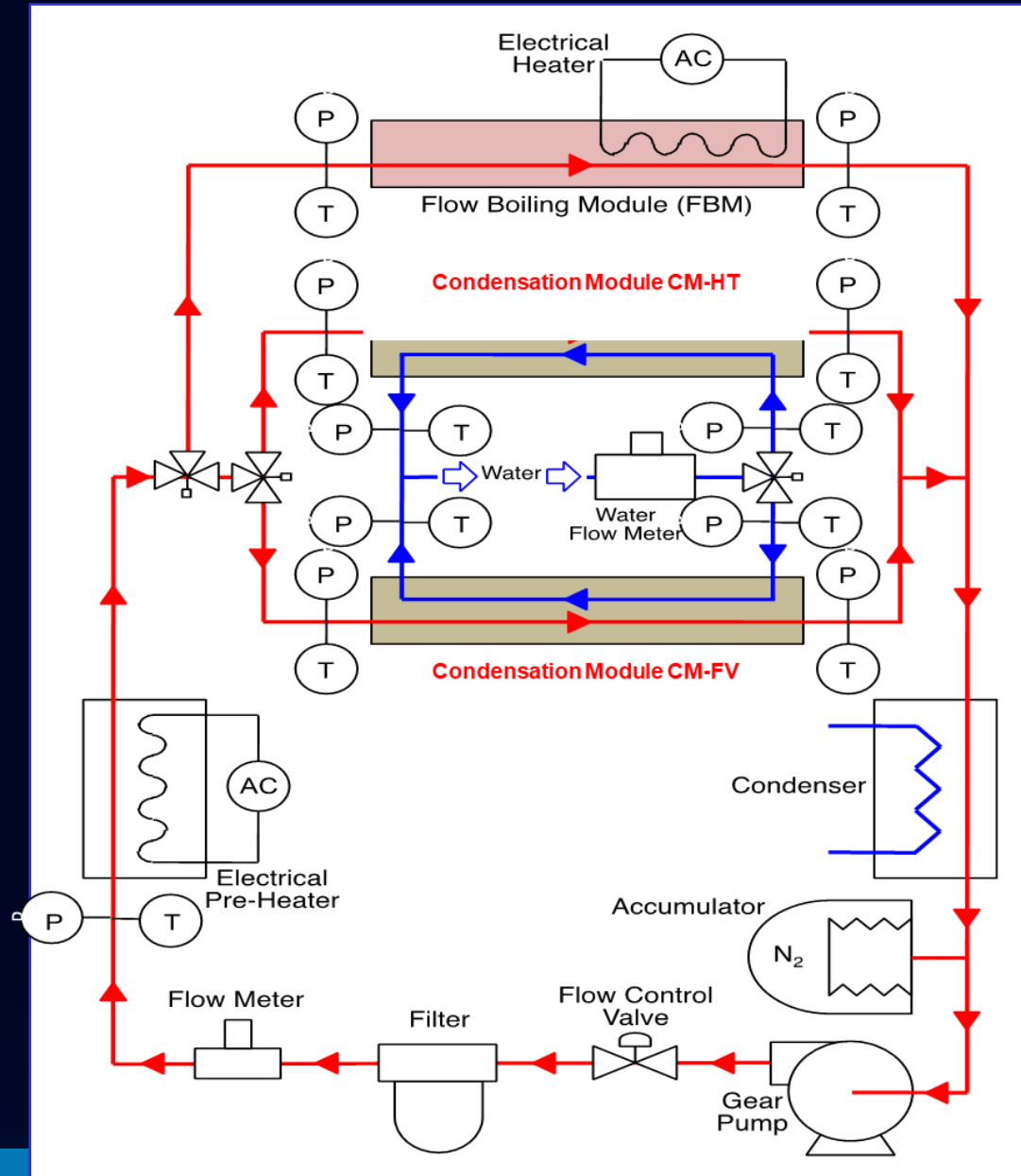
Potential Technology Impacts:

- Isothermal control for electronic cooling in satellites
- Cooling large space telescopes
- Extended heat transfer length. Smaller Radiators. Not prone to fouling.
- Lower fabrication costs.



Pulsating/Oscillating heat pipe schematic

Flow Boiling and Condensation Experiment - ISS



Contains three test modules:

- ✓ Flow Boiling Module (FBM)
- ✓ Condensation Module CM-HT for heat transfer measurements
- Condensation Module CM-FV for flow visualization (Paused)

Sub-loops

- nPFH sub-loop
- Water sub-loop

Packed Bed Reactor Experiment – ISS or CLD

- 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.*

BPS response –

PBRE- 1 & 2, PI: Brian Motil, NASA GRC

Co-I: Vemuri Balakataiah, University of Houston

Fundamental understanding of two-phase flow through wetting and non-wetting spherical beds to improve fundamental understating of packed bed reactors in reduced gravity and improve predictive numerical modeling.

PBRE-WR-1 and future series 2 -6, PI: Layne Carter, NASA MSFC

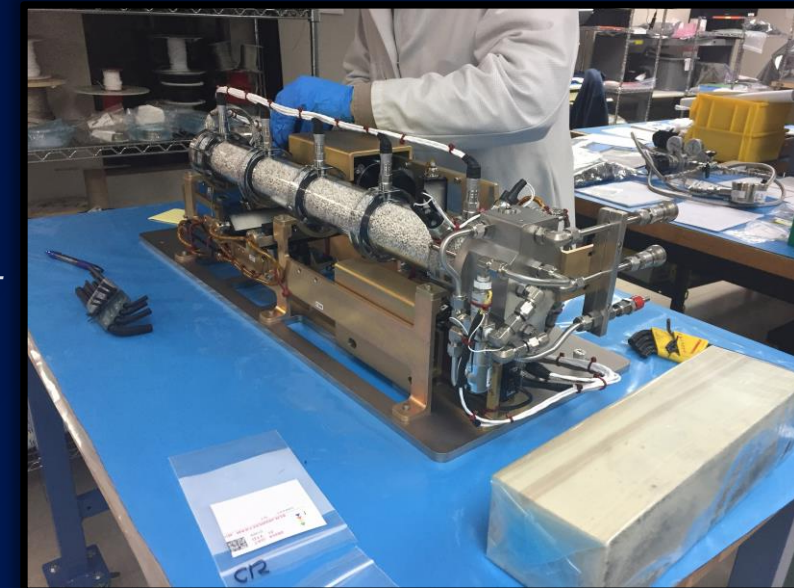
The hardware for packed bed reactor experiment (PBRE) examined the behavior of gas and water flows through a test section consisting of beads. PBRE-2 expands the parameter range of the previous set of tests to examine the effect of high gas flows through 2 mm glass beads. PBRE-Water Recovery is the first 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.

Next Steps: Utilize Tomography system with PBRE hardware to yield 3-D imaging of voids, gas bubbles and liquid - vapor interface

PBRE-2 test column with 2mm glass beads



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



Packed Bed Reactor Experiment Water Recovery 1 - 6 (PBRE -WR): BPS – AES Collaboration

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	Preflight testing, hardware	Co-I/PS	PI, urine transfer	
PBRE- WR -6 Flow Restrictor	Preflight testing, hardware prep, MI&O (via SLPS)	Co-I/PS	PI- Flow Restrictor	

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

Title: ZBOT-DP Expt. (Droplet Phase Change Effects) – ISS, CLD

PI: Dr. Mohammad Kassemi (Case Western Reserve University)

STMD Application: CFM-462, CFM-477, CFM-492, CFM-1194

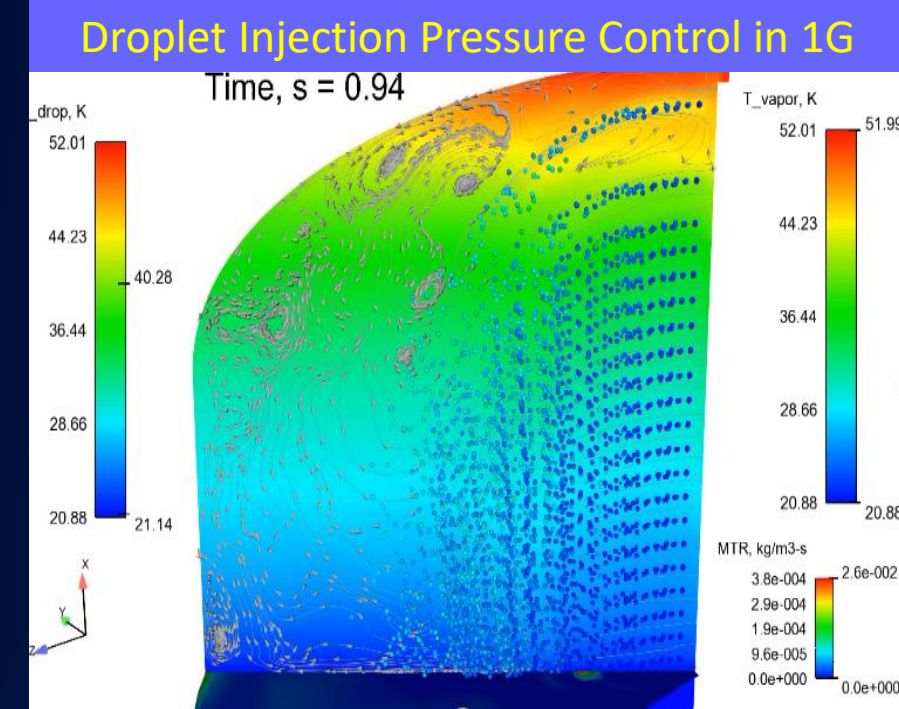
Objective: Study the effect of droplet phase change and transport on tank pressure control and tank chilldown in 0g.

Key science questions to be investigated & knowledge gained:

1. How is transport of droplet in the ullage different in 0g?
2. What is the effect of droplet evaporation on tank pressure? Is it affected by non-condensable gases?
3. How is droplet-wall and droplet-interface heat transfer modified in 0g ?
4. What is the effect of flash vaporization at the walls?
5. Is the Leidenfrost effect strong enough to propel droplets away from the wall in 0g?

Anticipated Technology Impact:

- Droplet Injection cooling is gravity-dependent but never tested in microgravity – test data to show if this strategy is feasible for pressure control & tank chilldown in microgravity?
- State-of-the-Art CFD model developed and validated for droplet phase change/transport to aid the propellant tank scaleup designs



1G behavior of droplet injected using a spray bar during tank pressure control. How will these droplets behave in 0g?!

➔ Specific Questions 1-5

Materials Science

Electromagnetic Levitator - EML

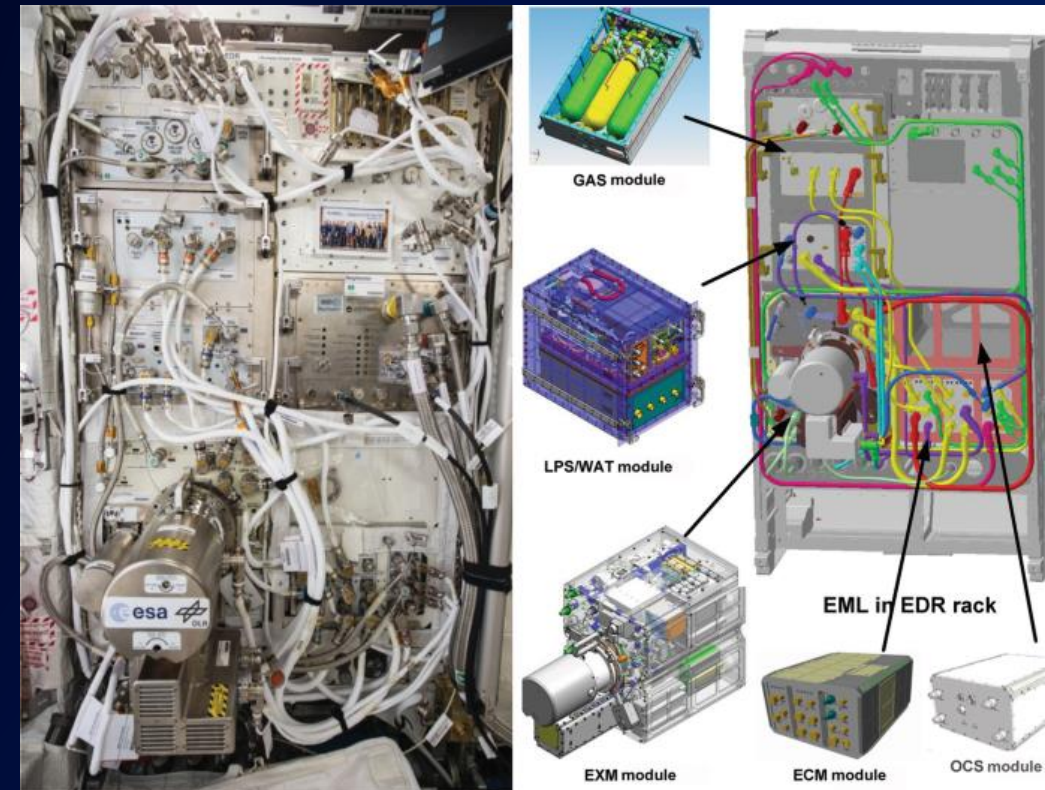


Research Areas of Interest

Thermophysical properties of metal alloys. For both fundamental and applied (in-space manufacturing) studies.

International Space Station Electromagnetic Levitator (ISS-EML)

- A multi-user facility for the melting and solidification of conductive metals, alloys, or semiconductors in ultra-high vacuum, or in high-purity gaseous atmospheres.
- The heating and positioning of the sample are accomplished using electromagnetic fields generated by a coil system.
- Installed - European space laboratory, Columbus.



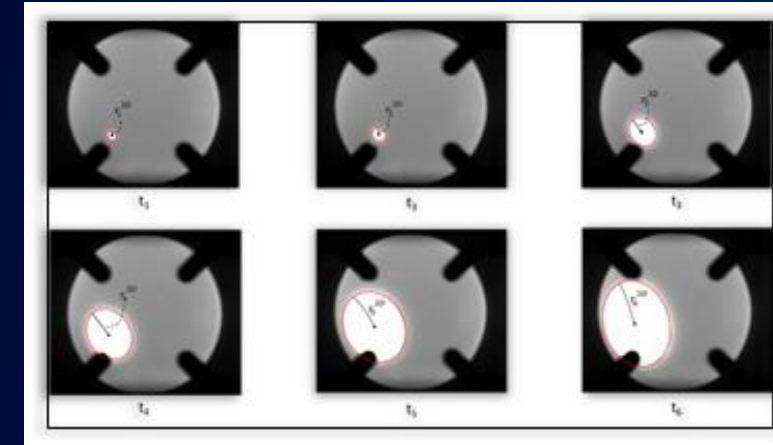
EML on board the ISS

Thermophysical Properties - EML Batches 1-4

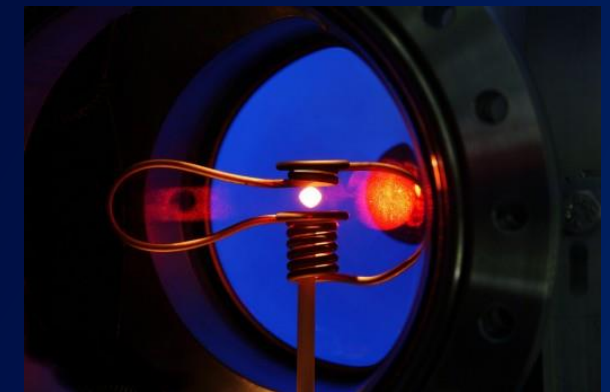


International Space Station Electromagnetic Levitator (ISS-EML) - ESA

- A multi-user facility for the melting and solidification of conductive metals, alloys, or semiconductors in ultra-high vacuum, or in high-purity gaseous atmospheres.
- The heating and positioning of the sample are accomplished using electromagnetic fields generated by a coil system.
- Installed in the European space laboratory Columbus.
- There are currently 3 US PIs with experiments on the ISS-EML
- Robert Hyers, University of Massachusetts
 - Objective: Investigate the thermophysical properties of high-temperature materials used for modeling of material production processes, e.g. additive manufacturing, welding, and casting.
- Kenneth Kelton, Washington University in St. Louis
 - Objective: Correlate the nucleation kinetics with the local structure of a liquid alloy by measuring its thermophysical properties. Applications include bulk metallic glass materials.
- Douglas Matson, Tufts University
 - Objective: Investigate the effect of fluid flow on the solidification path of aerospace alloys, and to measure the thermophysical properties of high-temperature materials. Applications include turbine blades, industrial welding, automobile components.



Growth velocity analysis of a ZrNi ISS-EML sample. Liquid is gray, solid is white.



Sample levitated in an EML at DLR.

Thermophysical Properties



Sample levitated in ELF on ISS during Dr. Matson's ops.



JAXA Electrostatic Levitation Furnace (ELF 1 -6)

- Materials science facility for thermophysical properties (e.g. density, surface tension, and viscosity) measurement of molten metals, alloys, glasses, and oxides.
- ELF is installed in the MSPR-2 (Multi-purpose Small Payload Rack #2) in Japanese Experimental Module "KIBO" in the ISS.
- Samples are levitated with an electrostatic field and heated with 4 970nm 40W lasers.

US investigators:

- Robert Hyers, University of Massachusetts
 - Objective: Advance the understanding of photo-refractivity, which has applications in holographic storage, adaptive optics, and phase-conjugate mirrors, using $\text{Bi}_{12}\text{SiO}_{20}$ and $\text{Bi}_{12}\text{GeO}_{20}$.

Douglas Matson, Tufts University

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

Ranga Narayanan, University of Florida

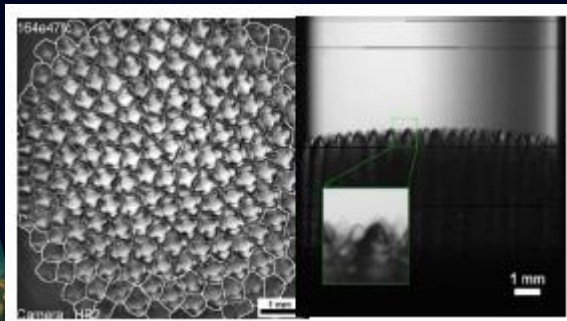
- Objective: Investigate a novel method to determine the interfacial tension, which is a property that impacts industrial processes such as semiconductor crystal growth and additive manufacturing.

Richard Weber, Materials Development, Inc

- Objective: Develop new understanding of the behavior of oxide liquid, glass and ceramic materials in extreme conditions and non-equilibrium conditions. Applications include photonics, lasers, and piezo electrics.

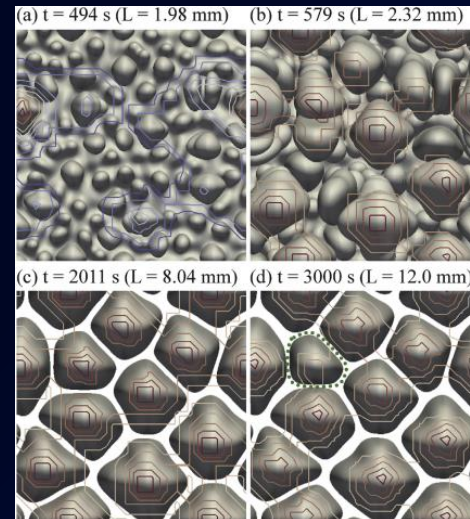
Solidification – DECLIC

- Device for the study of Critical Liquids and Crystallization – Directional Solidification Insert (DECLIC-DSI) is a facility that can be used to study directional solidification of transparent alloys, such as succinonitrile (SCN).
- These alloys solidify the same way metals do and form the same microstructures in the process.
- Dr. Rohit Trivedi, Iowa State University
 - Objective: Examine the origin and growth of dendrite side-branches during directional solidification. Improved understanding of microstructure formation provides insight into enabling the development of advanced materials of commercial importance.



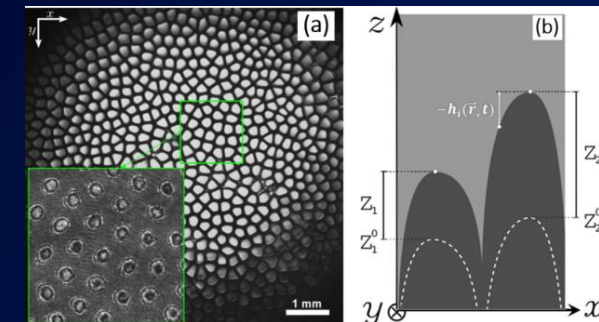
Axial and transverse views of dendritic interface in DECLIC-DSIR on ISS.

Mota, Ji, Lyons, Strutzenberg, Trivedi, Karma & Bergeon, IAC-19-A2.6.2 (October 2019).



Phase field model of interface shape and thermal field for $v=4 \mu s$ in DECLIC-DSI composition.

Song, et. Al., Acta Mat, 150 (2018)

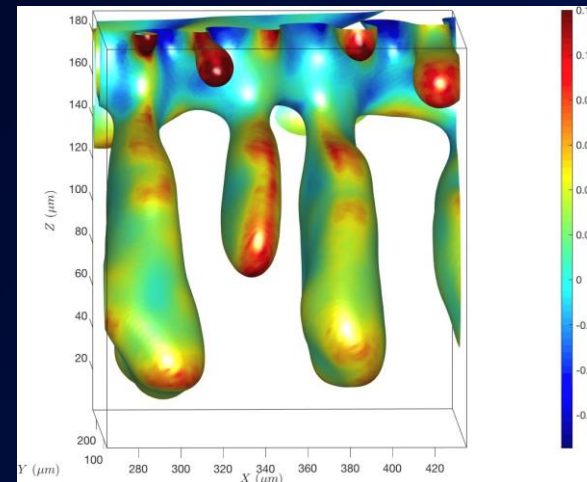
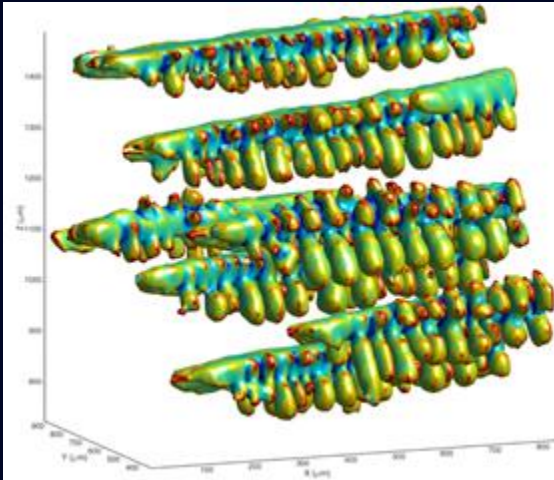


Axial view of interface with corresponding view of interferometric construction.

Pereda, et. al., Phys Rev E, 102.3, 32804.

Directional Solidification – Metal Alloy systems

- The Solidification Using a Baffle in Sealed Ampoules (SUBSA) hardware is a furnace that can heat samples up to 850°C for a variety of materials science experiments, and there are currently 3 NASA-funded Investigators with upcoming SUBSA experiments:
 - **Dusan Sekulic, University of Kentucky**
 - Objective: Better understand processing kinetics (enhanced wetting, spreading, capillarity) of brazing in low-g environments.
 - **Christoph Beckermann, University of Iowa**
 - Objective: Improve the understanding of the columnar-to-equiaxed transition (CET) during solidification of metal alloys.
 - **Peter Voorhees, Northwestern University**
 - Objective: Given the importance of dendrite fragmentation on the presence and location of a CET, examine the roles of melting and capillarity induced pinching on dendrite arm fragmentation, retraction and coalescence during cooling.



Capillary induced fragmentation

Solidification – Freeze Casting

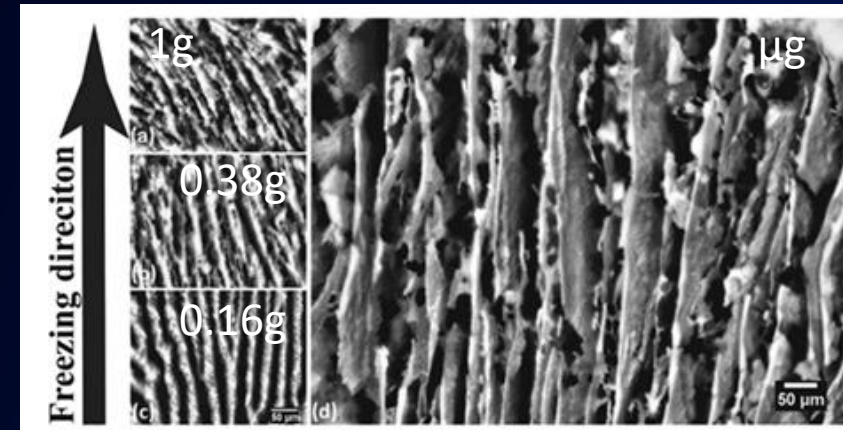
- The Pore Formation and Mobility Investigation (PFMI) hardware will melt samples of a transparent modeling material, e.g. succinonitrile and succinonitrile water mixtures. There are currently 2 Investigators with upcoming PFMI experiments:

- **David Dunand, Northwestern University**

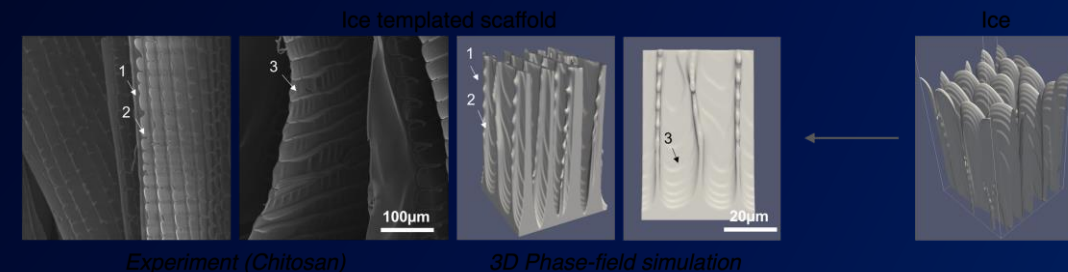
- Objective: Improve understanding of solidification behavior of freeze cast materials, which will allow for the development of improved processing techniques.
- Potential applications include high strength, low weight materials.

- **Ulrike Wegst, Northeastern University**

- Objective: Investigate the underlying physics of forming complex scaffolds using the freeze casting methodology.
- Potential applications include lightweight structural materials as well as scaffolds for peripheral nerve repair.



Dunand: Longitudinal cross-sections of sintered TiO₂ samples sintered from 20 wt% TiO₂ aqueous suspensions directionally solidified under (a) terrestrial, (b) Martian, (c) lunar, and (d) microgravity conditions.



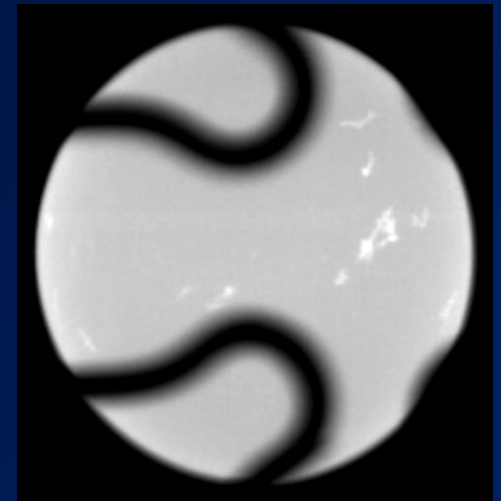
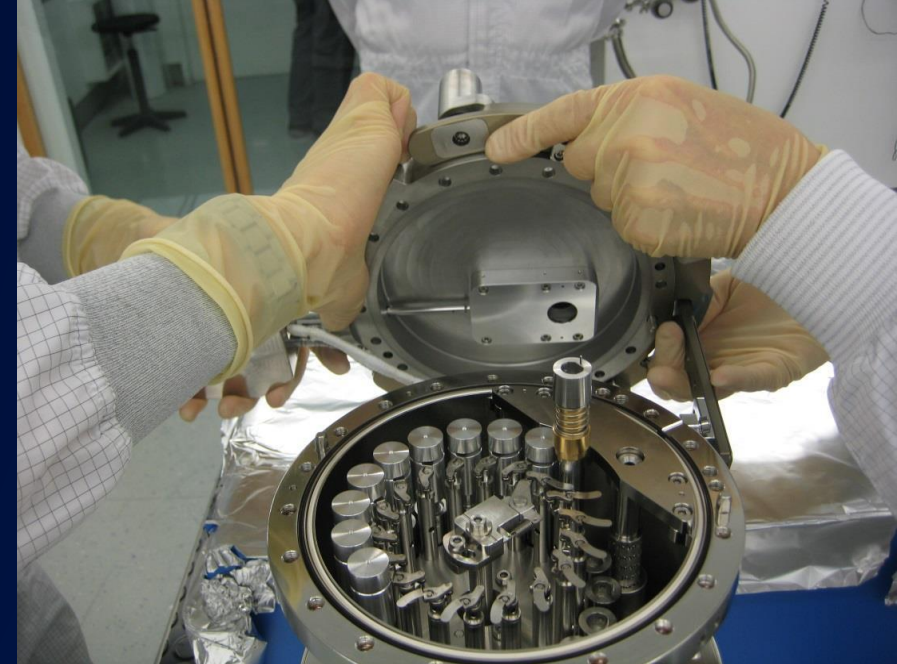
Wegst: Features of freeze-cast templated structures captured by both experiment and 3D phase-field simulation. The salient features include the formation of **lamellae** (1), **undulated ridges** (2) and **wrinkled cell walls** (3).

Ji et al. (2019) MRS Fall Meeting 2019, 1-6 December, Boston, MA, USA

Future Opportunities – Materials Science

EML Batch 5

- **Objective:** Continue US involvement in ISS-EML experiments. Research in thermophysical properties, fundamental or applicable to exploration.
- **Approach:** utilize ESA ISS-EML
- **Application:**
 - Accurate thermophysical properties are necessary for models used to speed the discovery and development of materials and processes.
 - Applications include manufacturing on the Moon, Mars, and on Earth.
- **Experimental Justification:**
 - For the continued improvement of materials processing, with increasing requirements on chemical composition, microstructure and behavior in use, the reliable and accurate knowledge of the relevant thermophysical properties of high-temperature melts is necessary.
 - Understanding of the physical phenomena involved, from alloy thermodynamics, heat and mass transfers, to solid-liquid interface dynamics, macro- and microstructure and defect formation.

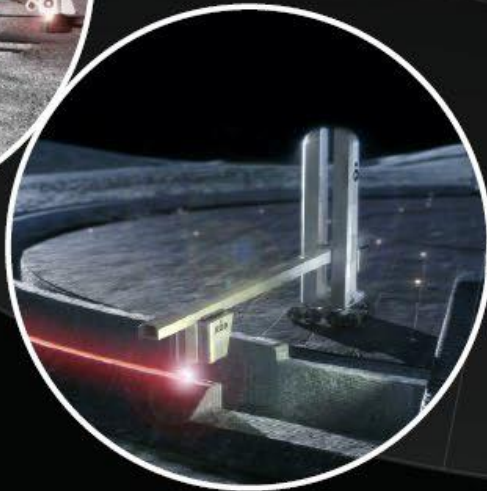


Lunar Construction Capability Development Roadmap



Phase 1:

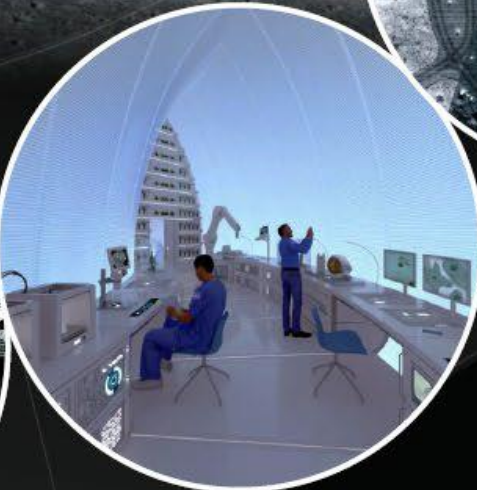
Develop & demonstrate excavation & construction capabilities for on-demand fabrication of critical lunar infrastructure such as landing pads, structures, habitats, roadways, blast walls, etc.



Phase 2: Establish lunar infrastructure construction capability with the initial base habitat design structures.



Phase 4: Complete build-out of the lunar base per the master plan and add additional structures as strategic expansion needs change over time.



Phase 3: Build the lunar base according to master plan to support the planned population size of the first permanent settlement (lunar outpost).



Concrete on the Moon – using Lunar Regolith

- Experiment under consideration as part of the **Artemis III** astronaut mission
- **Objective:** Analyze the microstructure in regolith-based materials produced in the reduced gravity of the lunar surface.
 - Hardened material would then be brought back to Earth and its mechanical properties evaluated.
- **Approach:** Conduct experiment on the Moon.
 - The astronauts will obtain a small sample of lunar regolith that will be mixed with binder. Some binders will require heat for sample curing.
 - 3 different binders are being considered.
- **Application:**
 - In-situ resources can be effectively used to develop, deliver, and demonstrate on-demand infrastructure to sustain a prolonged presence on the Moon, such as landing pads, habitats, shelters, roadways, berms, and blast shields.

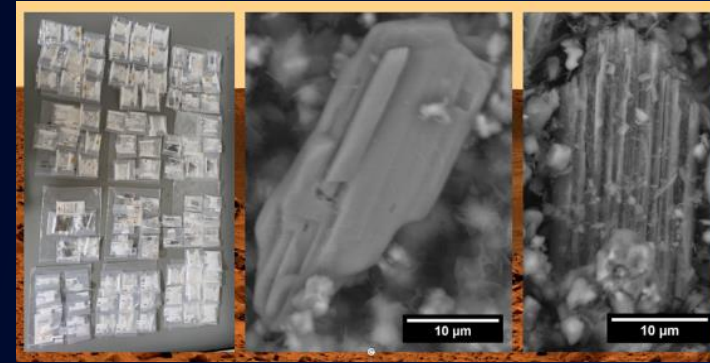


BPS Research

Related to Lunar Surface Construction

applicable to MANU-1095

- **Title:** Microgravity Investigation of Cement Solidification (MICS)
- **PI:** Dr. Aleksandra Radlinska, Penn State
- **Objective:** Investigate how microgravity influences the hydration of cementitious systems (Portland cement).
- **Results:**
 - As the gravity level decreased the amount of trapped air and porosity in the samples increased
 - Cement's solidification reaction and resultant microstructure is dependent on the level of gravity.
 - Crystals tend to grow larger in microgravity and they grow in a different orientation.
 - The results indicate that cement solidified in the reduced gravity environment will have different structural and strength properties from 1g.
- **Potential Technology Impacts:** Lunar berms, landing pads, roads

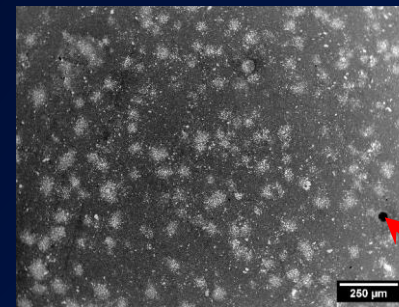


1g

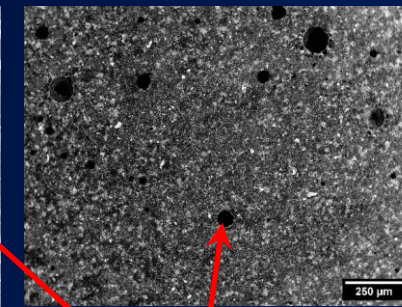
µg

The images on the right show gypsum crystal from samples in 1g and µg. The µg crystal shows how minimized fluid convection and a diffusion-controlled hydration process promote a nonuniform microstructure in microgravity.

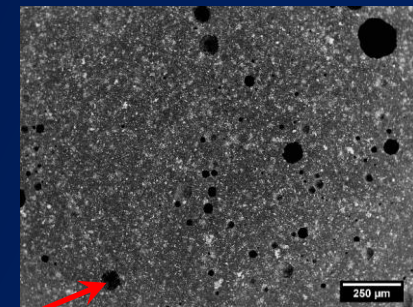
Astronaut Alexander Gerst conducting the MICS experiment on the ISS



1g



0.17g (Lunar)



µg

Trapped air

Materials Science

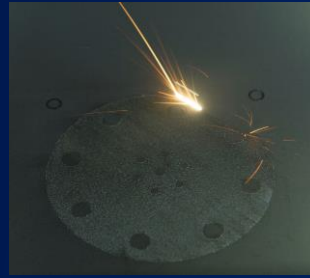
In-Space Manufacturing

- “The need for a deeper understanding of nonequilibrium phenomena is nowhere greater than in materials science” [1].
 - Materials made by either nature or manufacturing are rarely the result of equilibrium processes.
 - Advanced manufacturing processes, such as additive manufacturing (AM), present new challenges and opportunities for using and understanding nonequilibrium processes.
 - Materials out of equilibrium, such as metallic glasses and high entropy alloys, also present new challenges and opportunities
- Investigating the extreme temperature, solvent, or stress gradients imposed by AM processing provides insight into non-equilibrium reactions and the properties of the metastable materials they produce.
- Furthermore, the capability to fabricate spare parts, replacement units, specialty tools in situ does not exist beyond small demonstration components fabricated from polymers.
- In order to develop and optimize advanced manufacturing processes and enable functionalities such as autonomous self-correction during fabrication, one element that still needs to be understood is how specific materials and material systems behave under the processing and usage conditions.
 - On-orbit, this may mean adjustments due to a lack of buoyancy driven convection or other detectable differences in the thermal environment.
 - For example, in metal additive manufacturing utilizing bound metal deposition, the non-linear shrinkage of parts is affected by gravity.

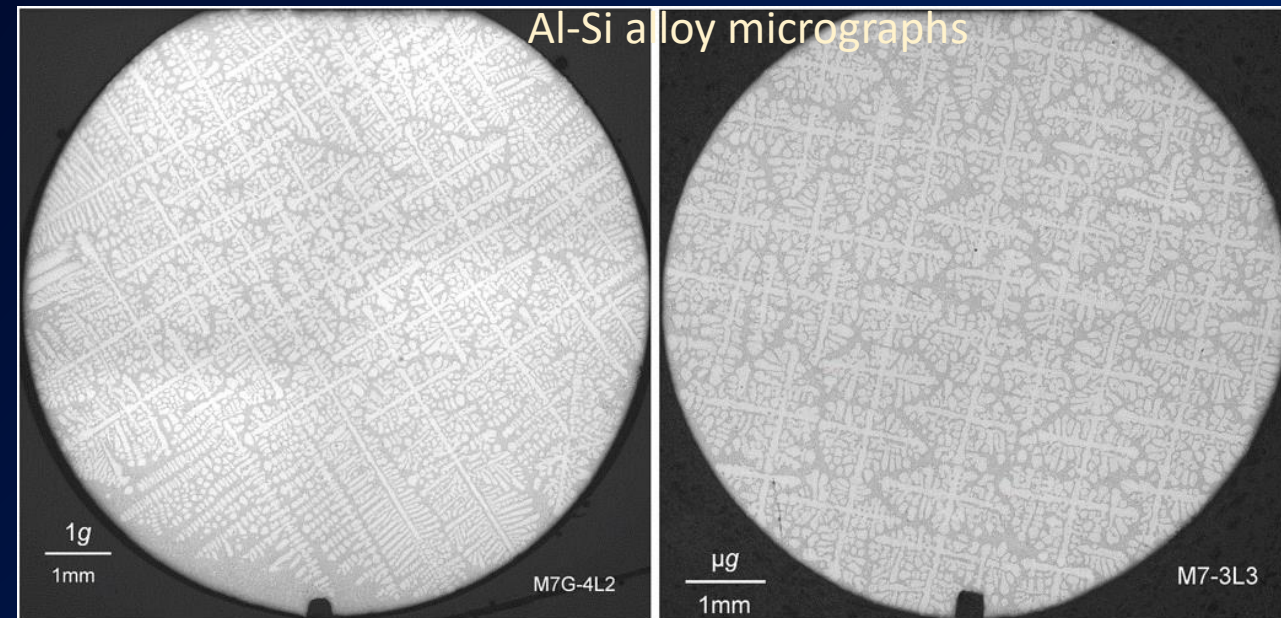
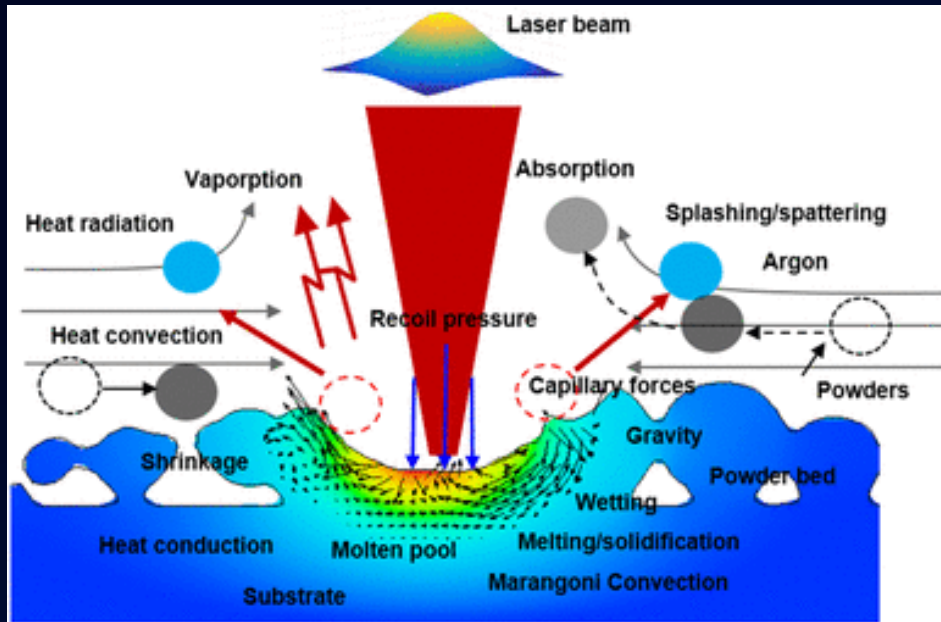
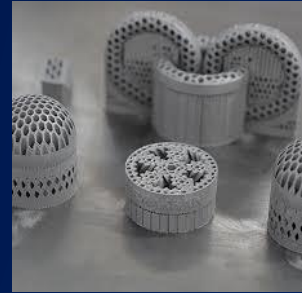


Materials Science – In-Space Manufacturing (con'd)

- A reduced gravity environment inhibits masking phenomena such as buoyancy driven convection and sedimentation to perform experiments targeted to address gaps in fundamental understanding of the underlying physics of materials science.
- Coupling key benchmark experiments with rapidly evolving multiscale modeling (micro, meso, and macro) techniques provides significant insights into underlying physics of microstructure formation and evolution during solidification processes in reduced gravity.
- Understanding the underlying physics during solidification, as the departure from equilibrium increases, is a gap in knowledge that has potential to be fundamentally transformative.
- For example, both terrestrial and in-space manufacturing techniques, such as additive manufacturing techniques such as **Selective Laser Melting (SLM)**, **Direct Energy Deposition (DED)**, **Bound Metal Deposition**, as well as high-speed processing techniques in glass forming systems.



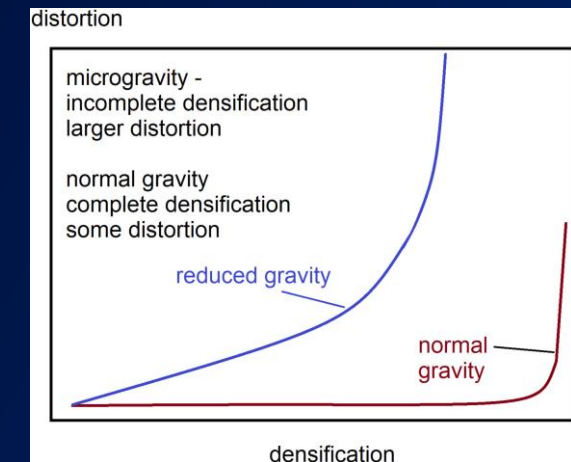
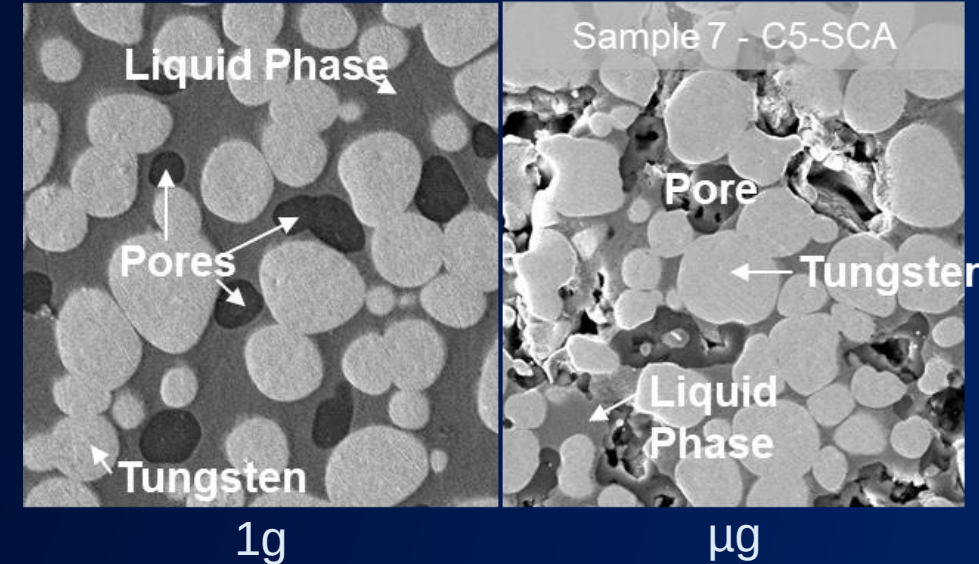
Selective laser melting of a part.



BPS Research: Lunar Surface Manufacturing and Repair

applicable to MANU-644

- **Title:** Gravitational Effects on Distortion and Sintering (GEDS)
- **PI:** Dr. Rand German, San Diego State University
- **Objective:** GEDS has three critical goals: (i) the in-depth analysis of the liquid phase sintering-induced pore-grain structure evolution, (ii) understating gravitational effects on distortion during sintering and, (iii) exploring sintering under microgravity conditions as a promising technique for in-space fabrication and repair.
- **Results:** Removal of gravity results in pore coalescence, loss of skeletal rigidity, and distortion without full densification.
- The results indicate that parts sintered in microgravity may have decreased strength due to limited pore migration/push out to the surface.
- **Potential Technology Impacts:** additive manufacturing

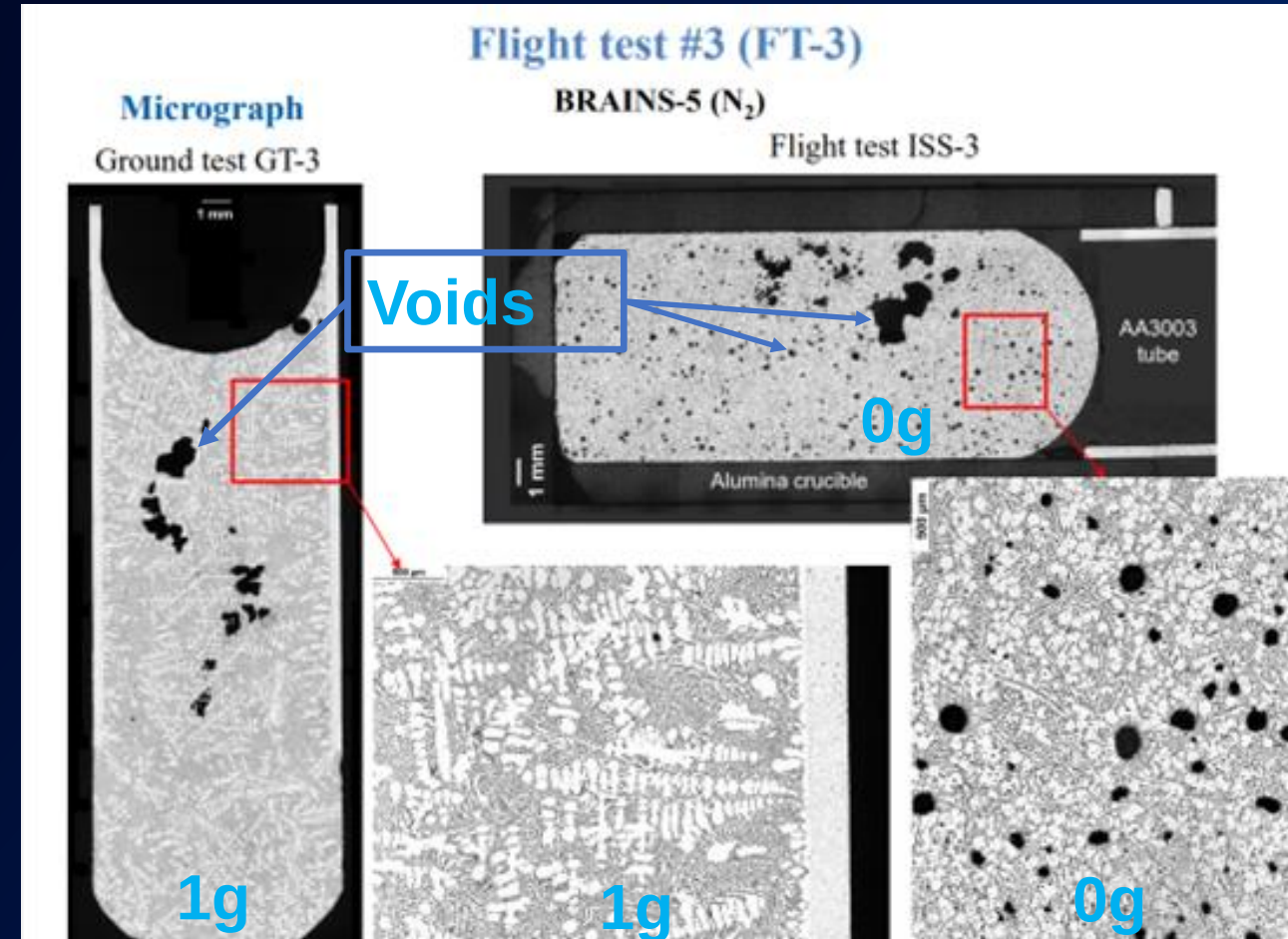


Sintering in microgravity results in more distortion and less densification.

BPS Research: Welding in Space

applicable to MANU-646

- **Title:** BRazing of Aluminum Alloys IN Space (BRAINS)
- **PI:** Dr. Dusan Sekulic, Univ. of Kentucky
- **Objective:** Increase understanding of processing kinetics during brazing in μg
- **Results:** Validated model of braze behavior. Provided results informing many aspects of practical braze joint design including flow distances, porosity/microstructure formation, surface clad behaviors, mechanisms of added and imbedded fluxes. **Larger number of voids and greater distribution in microgravity. Al-Si alloy.**
- **Potential Technology Impacts:** space welding and brazing, In-space Servicing, Assembly, and Manufacturing (ISAM)



Distributed porosity and round α phase in microgravity ISS sample vs typical dendritic formation in ground sample

New Mid- Temperature Furnace for CLD

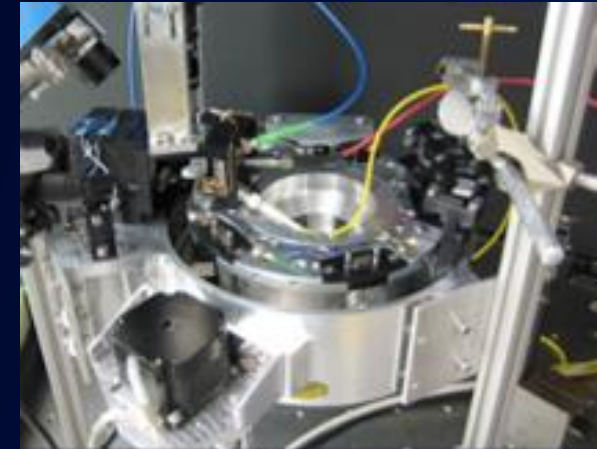
NASA ISS- PO to develop a furnace with the following capabilities.

- Tentative Capabilities:
 - Temperature: 1250 C,
 - Sample translation,
 - Heated zones
 - 16 mm sample diameter (vs 12mm on current SUBSA).
- Use on ISS and then transfer to Commercial Space Stations
- ISS PO to release a Request for Information (RFI) – receive recommendations from Science community for additional capabilities.

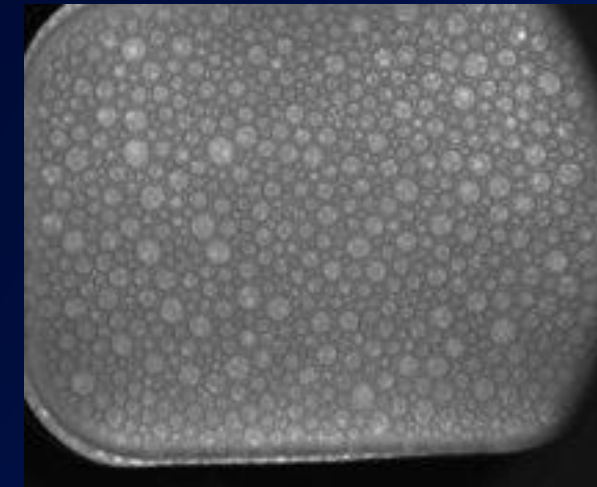
Soft Matter

Foam Optics And Mechanics (FOAM) - ISS

- ESA Team Coordinator : Professor Dominique Langevin (University of Paris, France)
- US PI: Douglas Durian, Physics Department, University of Pennsylvania
- Team: D. Weaire (Ireland); Nicolas Vandewalle, Hervé Caps, Giles Delon (Belgium); Ko Okamura (Japan); Andrei Sonin (Russia)
- Objectives:
 - To exploit microgravity conditions to quantify and elucidate the unusual elastic character of foam structure and dynamics.
 - To observe how the foam melts into a simple viscous liquid as a function of both increasing liquid content and shear strain rate.
 - The flight research generates valuable fundamental guidance for the development of foam materials with more desirable rheology and better stability.



ESA - FOAM C Hardware, ISS Image



FOAM C Image from ISS

Liquid Crystal Film Experiment - ISS

Title: STUDY OF STRUCTURES & DYNAMICS OF INCLUSIONS ON 2 DIMENSIONAL FREELY SUSPENDED SMECTIC LIQUID CRYSTAL FILMS IN MICROGRAVITY

Investigator team:

Thailand – PI Prof. Chattam and Co –I Prof. Pattanaporkratana; Kasetsart University; Co-I Natthawat Hongkarnjanakul, Engineer, Geo-Informatics and Space Technology Development Agency (Gistda)
NASA sponsored – TBD, via solicitation

Objectives:

- Using ISS **KERMIT** microscope, investigate liquid crystal film defects (island) and the effects of Lehmann rotation in microgravity. To study Lehmann effect (continuous rotation of liquid crystal droplets subjected to a temperature gradient) and Marangoni effect on smectic island of freely suspended film by heating the film or creating partial pressure across the film (i.e. to have a small confined enclosure on either side of film) and study rotation mechanism of the island.

Collaboration Approach:

- Flight hardware development – Kasetsart University, Thailand Government
- Guidance during hardware development - NASA BPS and ISS-PO
- ISS, launch, integration and ops – NASA ISS-PO and BPS

Status:

- ✓ KU proposal and draft schedule – completed,
- International Agreement – Original agreement to be revised
- Flight hardware development - 2023 – 24, ISS ops – 2025



Drawings by Lehmann of droplet textures that wind and rotate under the action of an increasing temperature gradient*

*Lehmann O. Structur, System und magnetisches Verhalten flüssiger Krystalle und deren Mischbarkeit mit festen. Ann Phys. 1900;307:649–705

Soft Matter Mini-Workshops— Science Questions

- **Colloidal Science**

- Impact of particle shape, anisotropy, functionality, external stimuli on colloidal assembly.
- Impact of gravity on 3D printing of colloidal particles

- **Non-Newtonian Fluids**

- Fundamental understanding of rheology by understanding impact of interparticle forces and gravity
- Motility of active matter
- Non-Newtonian nature of network flow

- **Granular Media**

- Generalizability of phenomenological models for granular media
- Effect of charging on granular media flow
- Fundamental understanding of flow regime change, impact of gravity and interaction force between individual particles

Mini-Workshops - High Level Summary

- The community is eager for NASA to push the envelop of fundamentals of soft matter science in reduced- and micro-gravity science.
- Participants appreciated the event and enthusiastically participated during the mini-workshops. They also send their additional feedback after the events. The event generated many “shovel ready” ideas.
- The modularity of experimental hardware and availability of modular diagnostic capabilities were identified as key asks across forums.
- AI/ML was identified as a key component via multiple avenues for application ranging from using it as a tool for improved analytics of data and images to developing theories for fundamental science (e.g.- Physically Interpretable Neural Network).
- Community wants more interaction with other domains of space science to understand the challenges with other domain of space science, biological sciences and other domains of science.

Future Opportunities – Soft Matter

Soft Matter Dynamics Unit to remain on ISS for several years



Areas of interest

- *Foams*
- *Emulsions*
- *Colloids*
- *Gels*
- *Granular Materials*

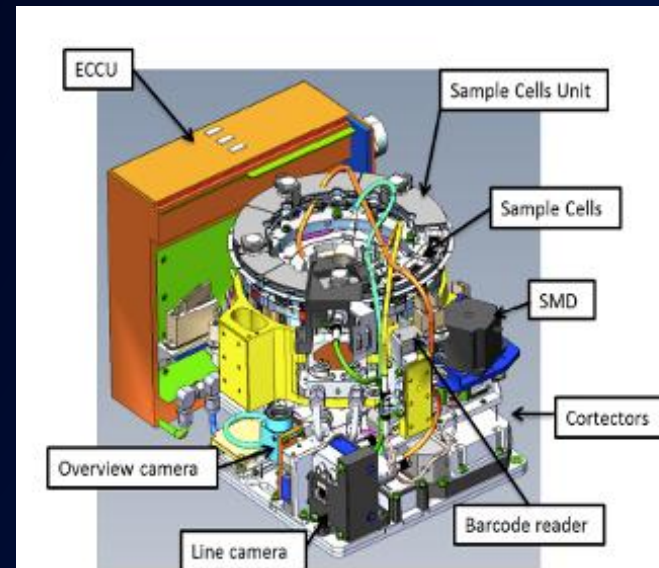


Figure 6-1: Soft Matter Dynamics Experiment Container (CAD model of the EC interior)

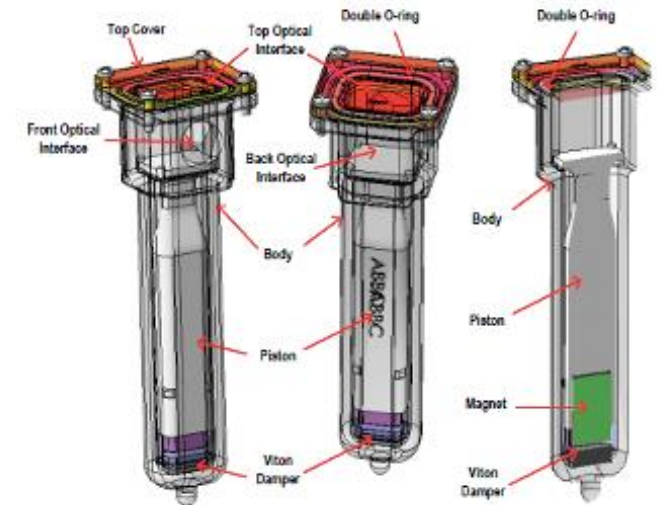


Figure 7-2: FOAM-C Design of the Sample Cell

Soft Matter Dynamics Unit

Soft Matter/Complex Fluids

Objective:

- Obtain short duration microgravity data at a ground-based research facility:
 - Identify phenomena that are obscured by buoyancy and other effects (e.g.- electrostatic charge, phase separation) that may alter anticipated behavior.
 - Explore and refine test matrices for space flight experiments.
- Demonstrate hardware and experiment feasibility.

Approach:

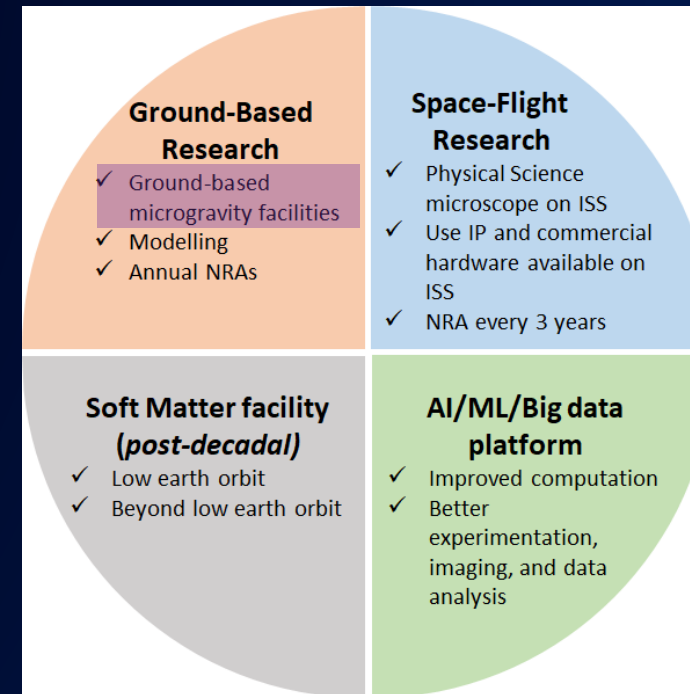
- Integrate high fidelity microscopy inline with requirements outlined in the “Grand Challenge” workshop:
 - Traditional Microscopy (transmission, reflection mode, immersion optics etc.)
 - Nipkow Disc Confocal Microscopy
 - Laser Tweezers
 - Ability to add external stimuli (e.g.- temperature gradient, magnetic field, electric field etc.)
- Utilize elongation rheometers to characterize properties and behavior of soft matter
- Develop inline high speed characterization capabilities:
 - Impedance spectroscopy
 - Voltametry

Relevance/Impact:

- Alignment with the “Grand Challenge” workshop report for soft matter.
- Provide capability to down select for flight programs.

Implementation Approach:

- Advertise ground-based low gravity capabilities to PIs in NRAs.
- Project scientists to serve as interface between PIs and facilities.
- Build microscope rigs for both 2.2 Second Drop Tower and Zero G Facility.
- Utilize 2.2 Second Drop Tower standard frame to allow integration of rheometer and other techniques between 2.2 second drop tower and Zero G Facility.
- Hardware Refresh: *Every three years*, reevaluate instrumentation specifications and capabilities and update as necessary.



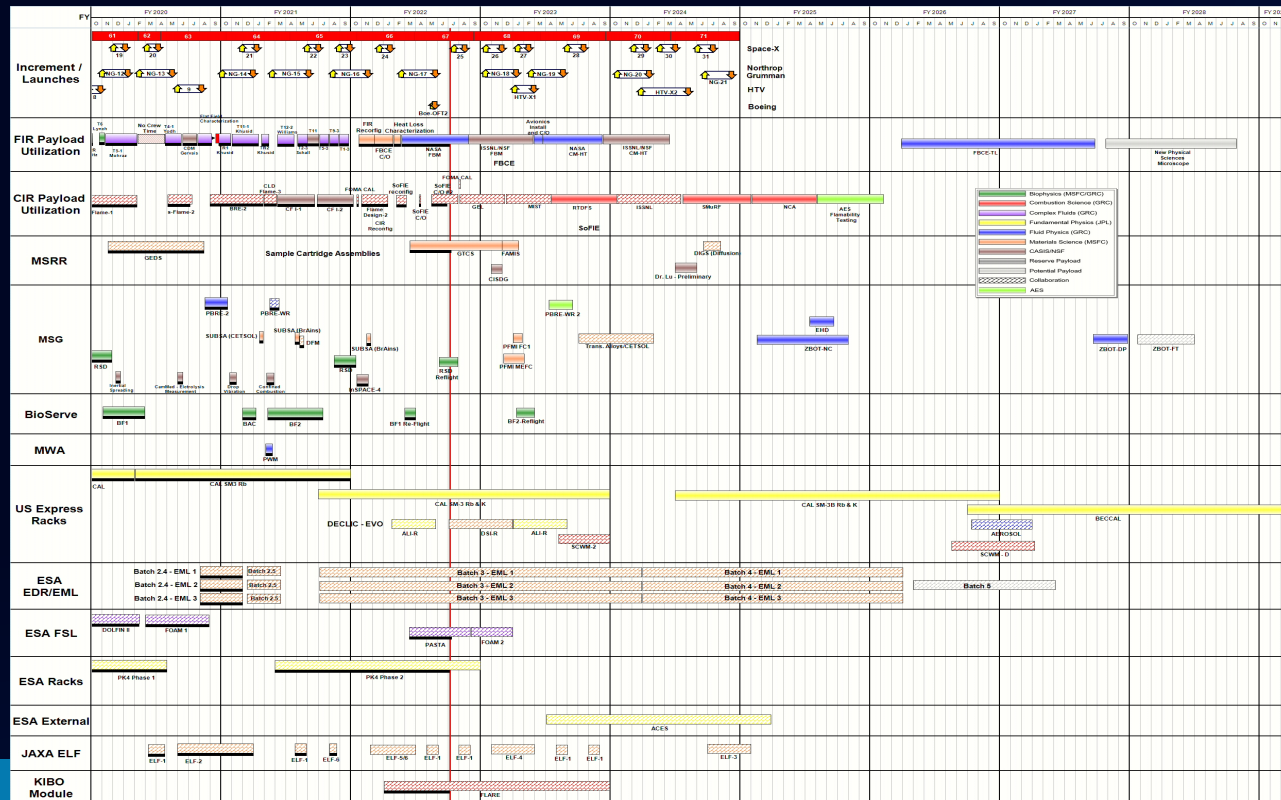
Implementation plan

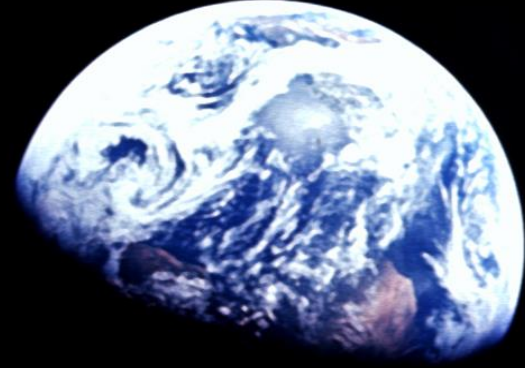


ISS or CLD Microscope Development

Conclusion

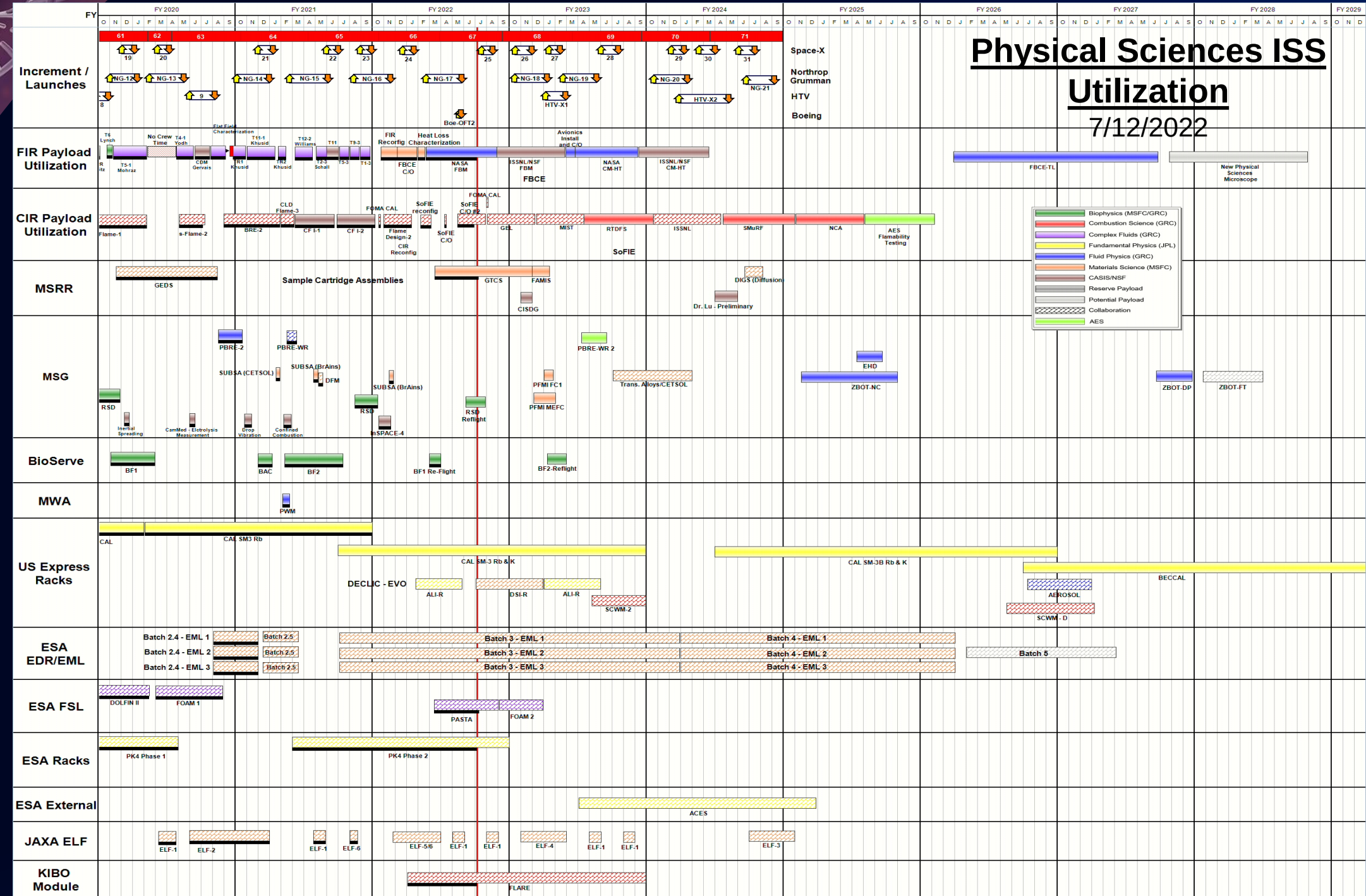
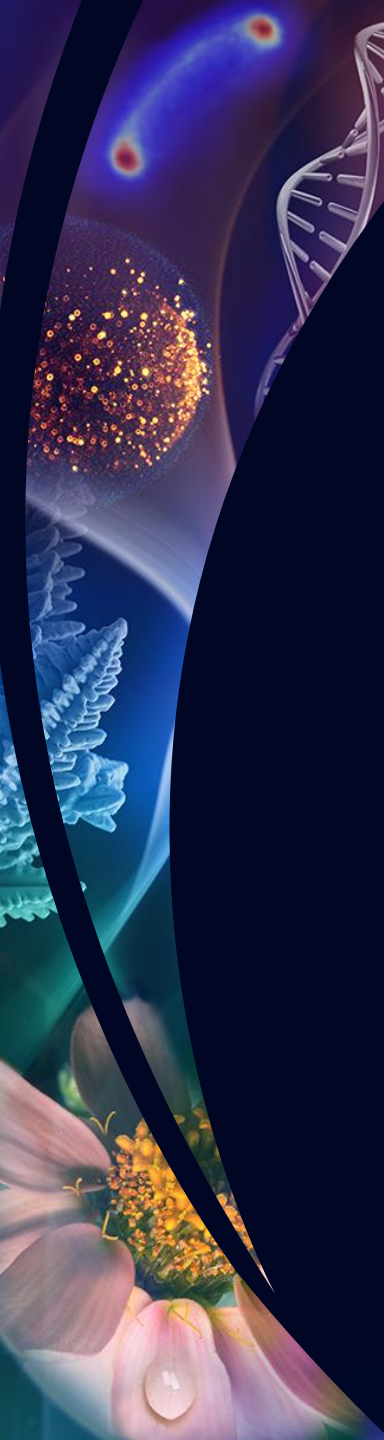
- Physical Sciences currently has a robust, diverse program rebuilt from 2006 -2016
- Future has limited investigations beyond Quantum Science
- Future plan lacks robust flight & ground programs in fluids, combustion, materials & soft matter
- Challenge: Will need to rebuild the Physical Sciences research community

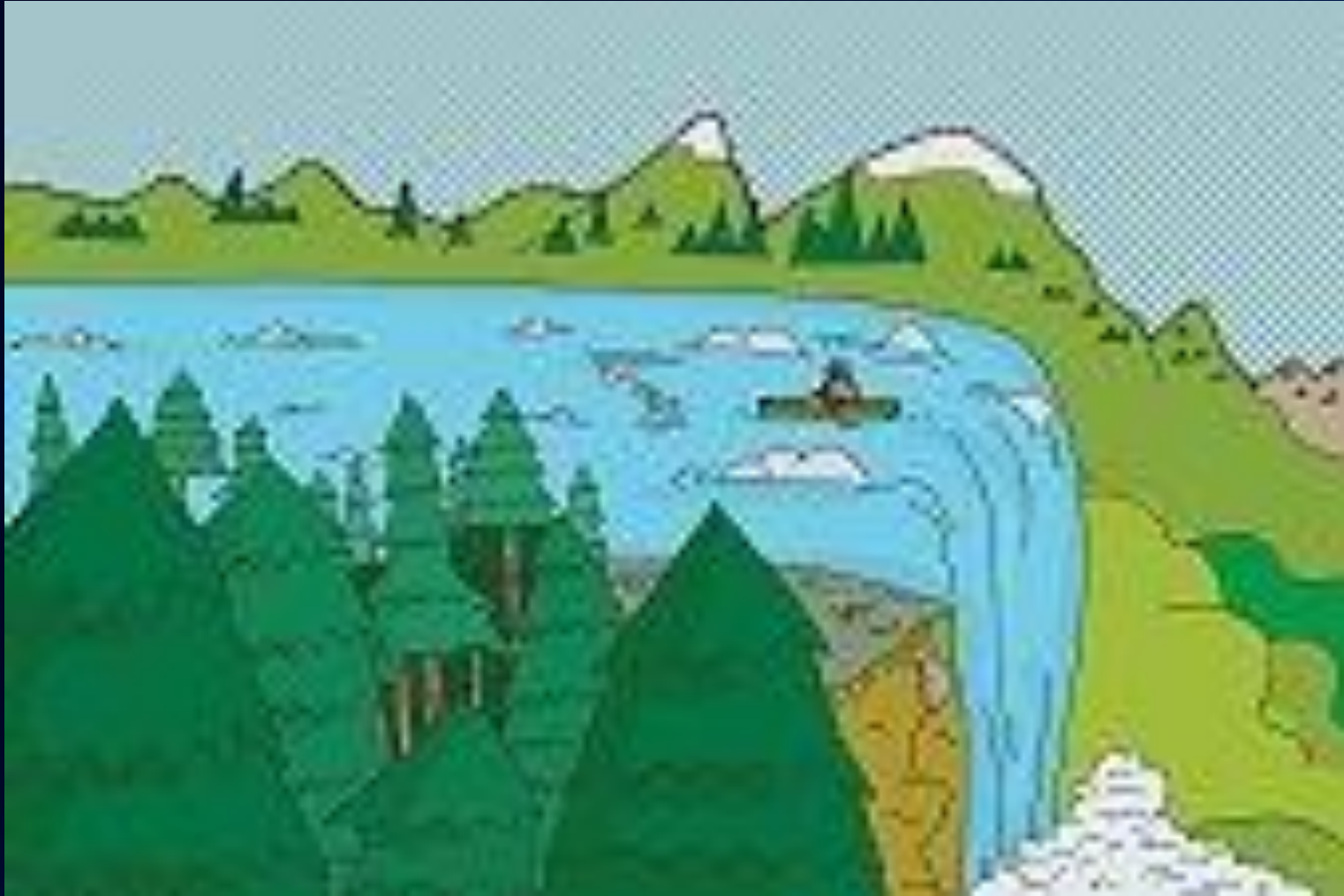




Thank you!







Colloidal Science – Community Suggestions

IMPORTANT QUESTIONS	REPRESENTATIVE EXPERIMENTAL SETUP	KEY MEASUREMENT & CONTROL VARIABLES
✓ Impact of particle shape, anisotropy, functionality, external stimuli on colloidal assembly. ✓ Impact of gravity on 3D printing of colloidal particles ✓ Competing behavior of small range molecular force in ensemble ✓ Fundamentals of colloidal robotics	✓ Modular experimental setup with multiple characterization capability as “plug-and-play” capability (e.g.- digital holographic microscope, differential dynamics microscopy) ✓ Visual characterization (e.g.- microscope) ✓ Chemical and atomic characterization ✓ External Stimuli	✓ Direct measurement of forces between particles (e.g.- optical tweezers, AFM) ✓ Mechanical force measurement ✓ Chemical signature identification (e.g.- spectroscopy) ✓ Impact of confinement ✓ In-situ chemical characterization and physical measurement ✓ 3D visualization
ABILITY TO MINIATURIZE EXPERIMENTAL SETUP	AI/ML TO AID IN RESEARCH	INTERDISCIPLINARITY
✓ Can be done (e.g.- micro-/nano-fluidics) ✓ Power requirement is a key concern ✓ Micro-spectroscopy capability will be needed	✓ Using advanced routine in image analysis is important (e.g.- computer vision) ✓ Key component in developing fundamental models (e.g.- Physics Informed Neural Network) ✓ Inner coworking/ relative dependence on variables in “black box” model needs to be understood for the growth	✓ Chemistry, physics and biology needs to work together ✓ Colloidal science needs to work with biology more for the growth

FEW SUGGESTIONS ARE HIGHLIGHTED HERE

Non-Newtonian Fluids– Community Suggestions

IMPORTANT QUESTIONS ✓ Fundamental understanding of rheology by understanding impact of interparticle forces and gravity ✓ Motility of active matter ✓ Non-Newtonian nature of network flow ✓ Failure mechanism in non-Newtonian fluids ✓ Understanding of weak interaction forces	REPRESENTATIVE EXPERIMENTAL SETUP ✓ Modular experimental setup with multiple characterization capability as “plug-and-play” capability ✓ Visual characterization (e.g.- differential dynamics microscopy) ✓ Chemical and atomic characterization ✓ Using living organism as a model system ✓ Rheological characterization (e.g.- elongation rheometry) ✓ Particle image velocimetry	KEY MEASUREMENT & CONTROL VARIABLES ✓ Variations in electric field (individual particle response to electric field) ✓ Quality of microgravity produced on earth ✓ High speed camera, Digital camera ✓ Photoelastic measurements ✓ Changing softness, shape, polydispersity, surface cohesivity, electrostatics of the particles
ABILITY TO MINIATURIZE EXPERIMENTAL SETUP ✓ Can be done (e.g.- micro-/nano-fluidics) ✓ Modular microscopy/visual experimental capability is a concern ✓ Micro-spectroscopy capability will be needed	AI/ML TO AID IN RESEARCH ✓ Using advanced routine in image/data analysis is important (e.g.- computer vision) ✓ Doesn’t see AI/ML a key component in fundamental model development ✓ AI/ML is a tool ✓ Worried that too much focus on AI/ML can take away focus from fundamental science	INTERDISCIPLINARITY ✓ Chemistry, physics and biology needs to work together ✓ Impact of biological organism and large-scale structure is main focus instead of cellular structure

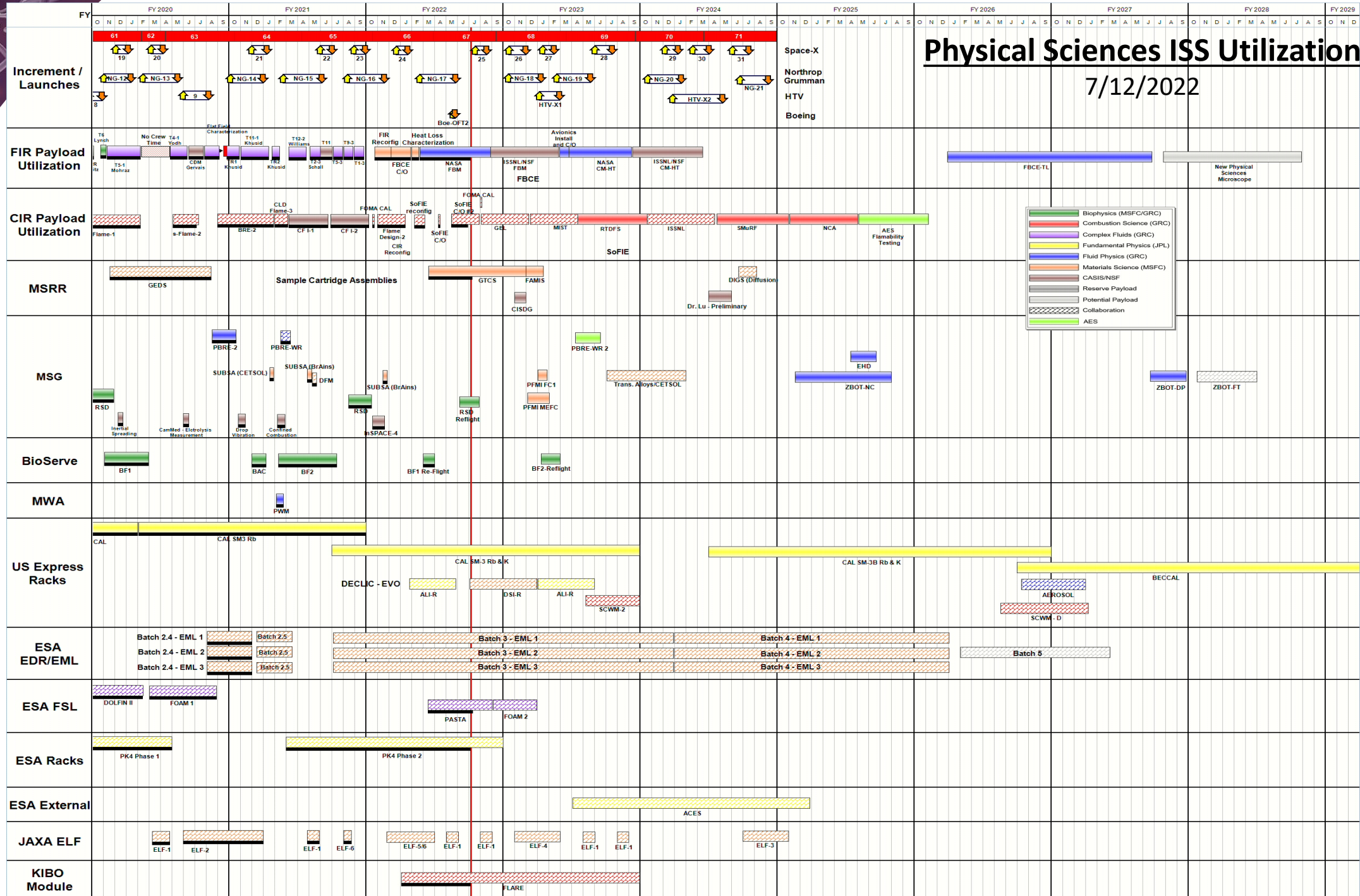
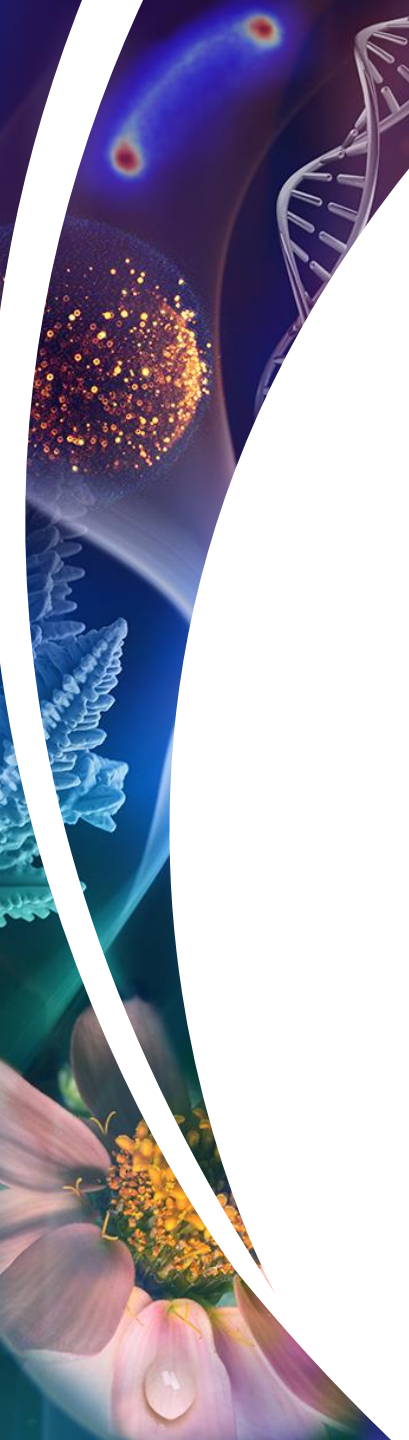
FEW SUGGESTIONS ARE HIGHLIGHTED HERE

Granular Media– Community Suggestions

IMPORTANT QUESTIONS ✓ Generalizability of phenomenological models for granular media ✓ Effect of charging on granular media flow ✓ Fundamental understanding of flow regime change and impact of gravity ✓ Interaction force between individual particles	REPRESENTATIVE EXPERIMENTAL SETUP ✓ Hopper system with capability of charging particles Dynamic shear stress tester ✓ Rotating tumbler flow, flow down chute, particle falling on a plate forming heap. ✓ Penetrometer ✓ Capability of adding fluid ✓ Individual grain behavior (e.g.- AFM)	KEY MEASUREMENT & CONTROL VARIABLES ✓ Flow rate, stresses under different perturbation ✓ Force Sensor (loadcell, strain gauge) ✓ Time scale resolution (e.g.- vibrational technique- oscillatory shear test) ✓ Ability to standardize and prepare materials in space
ABILITY TO MINIATURIZE EXPERIMENTAL SETUP ✓ System size is very important. Granular media doesn't scale well because of polydispersity, size etc ✓ Some systems can be scaled down but they are limited ✓ Small systems can help in studying individual particle behavior	AI/ML TO AID IN RESEARCH ✓ Using advanced routine in image/data analysis is important (e.g.- computer vision) ✓ AI/ML is still a new area. While some were excited , others were cautious that too much focus can divert research dollar from fundamental science	INTERDISCIPLINARITY ✓ Chemistry, physics and biology needs to work together ✓ Main focus is physics of the fluid ✓ Needs to work and interact closely with other domains of space science (e.g.- astrophysics). Ask for NASA was to help facilitate that.

FEW SUGGESTIONS ARE HIGHLIGHTED HERE

ISS Utilization Schedule



Commercial Space Stations

The Commercial Landscape

LEO Orbital

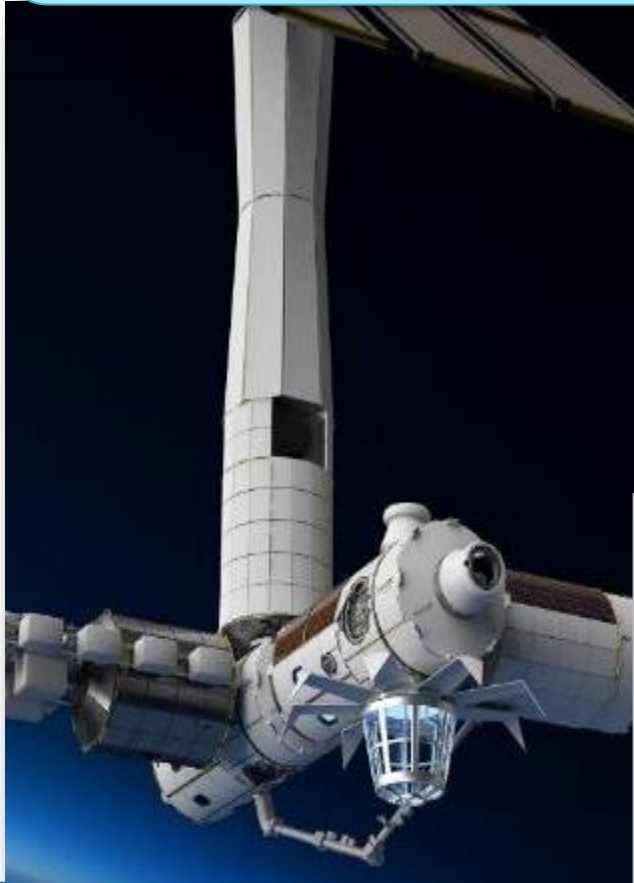
- ISS – NASA Commercial Crew Astronauts
- ISS – Private Astronaut Missions
- Commercial LEO Destinations (CLD)
- Short-Term Non-Governmental Missions

Suborbital

- Rocket-Powered Vehicles
- High-Altitude Balloons
- Parabolic Flights*



NASA's Commercial LEO Destinations Portfolio



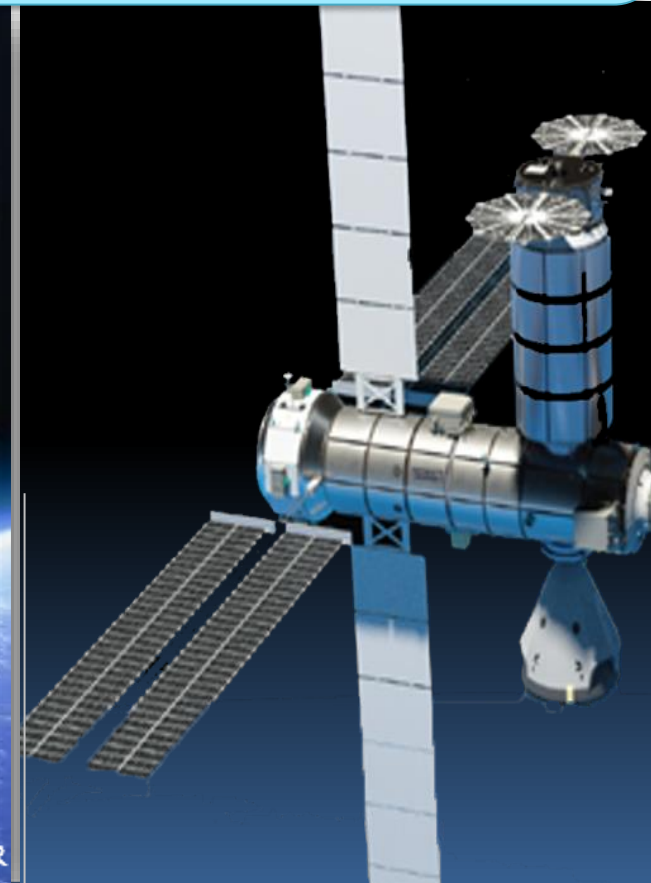
AXIOM
SPACE



BLUE ORIGIN
SIERRA
SPACE



 **NANORACKS**
 **LOCKHEED MARTIN**



NORTHROP
GRUMMAN

COMMERCIAL LOW-EARTH ORBIT DESTINATIONS



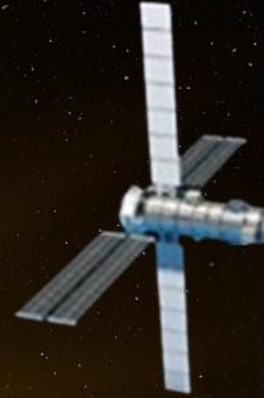
Axiom Port Module

- Axiom Port Contract was awarded in February 2020 to allow attachment of Commercial Elements or Commercial Segments to the ISS
- It will be used for commercial space activities



Nanoracks

- Starlab: Large inflatable habitat and a metallic docking node, power and propulsion element, and external robotic arm
- Four main operational departments: a biology lab, plant habitation lab, physical science and materials research lab, and an open workbench area
- External Payloads: 6



Northrop Grumman

- Provides for a permanent presence of 4 crew members
- Contains Habitat Modules (HM) equipped as permanent crew habitat and cargo modules.
- Contains Service Module (SM) evolved from Cygnus resupply vehicle
- Provides for multiple internal and external payloads



Blue Origin

- Capacity for 10 astronauts, and multiple internal and external payloads
- 15-year lifespan and consists of six destination elements, bringing a futuristic space architecture
- Orbital Reef ecosystem provides turnkey services for global markets, providing all essentials to make this a truly commercial platform that attracts a broad range of customers