Physical Sciences Overview
-
Deep Dive

National Academies, Decadal Survey on Biological and Physical Sciences Research in Space 2023-2032: Physical Sciences Panel
Jan 24, 2022

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Agenda

- Program Overview
- Deep Dive
  - Materials, Biophysics, Fluid Physics, Combustion & PSI
- Back-Up
  - Collaborations
  - Mapping to 2011 Decadal Survey
  - Ground-Based and ISS Facilities, Inserts and Hardware

Physical Sciences Program Overview

Combustion Science

- Spacecraft fire safety
- Droplets
- Gaseous – premixed and non-premixed
- High pressure/Supercritical
- Solid fuels

Biophysics

- Biological macromolecules
- Biomaterials/Biofilms
- Biological physics
- Biofluids

Fluid Physics

- Adiabatic two-phase flow
- Boiling and condensation
- Capillary flow
- Interfacial phenomena
- Cryogenic propellant storage and transfer

Materials Science

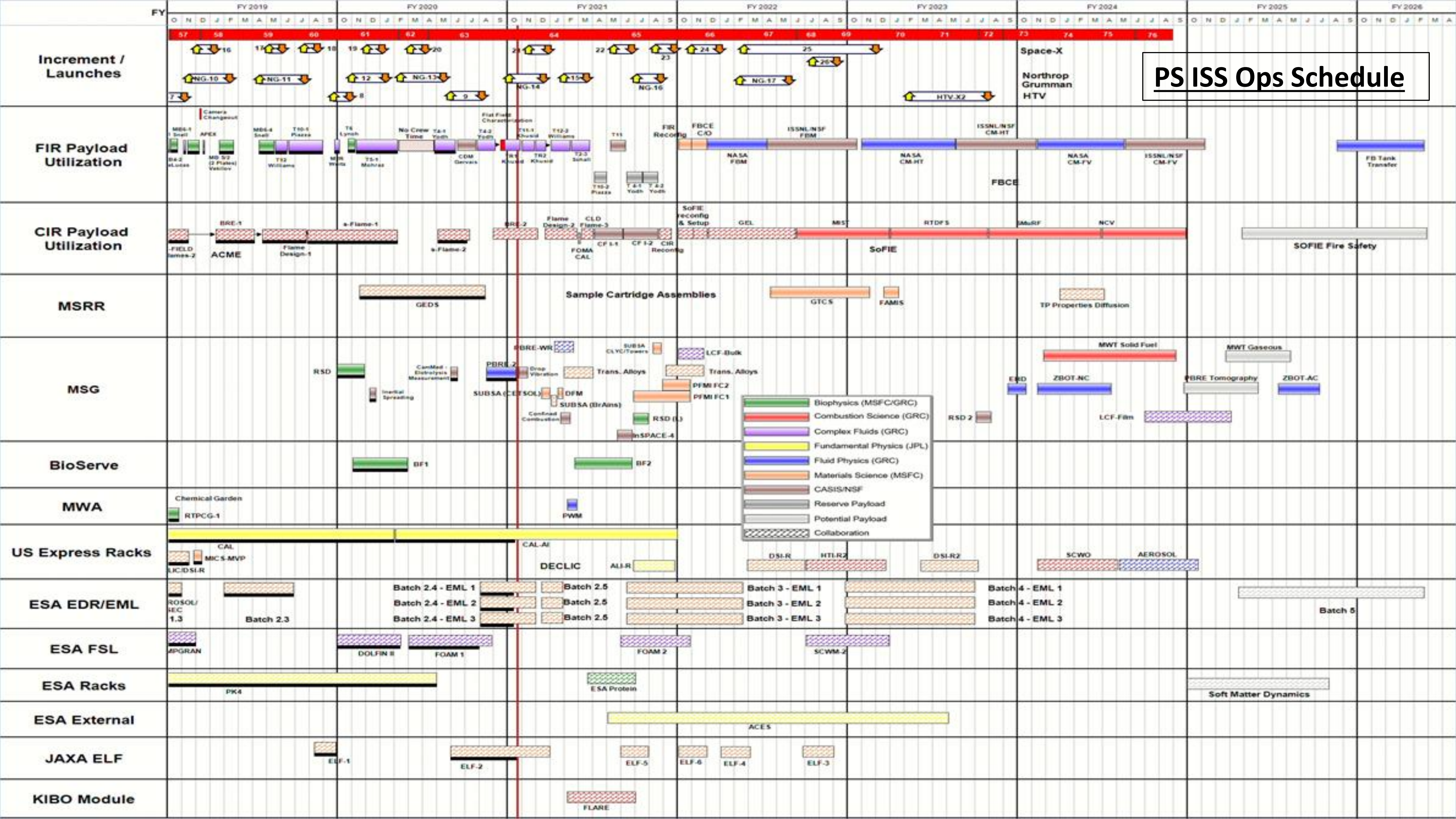
- Glasses and ceramics
- Granular materials
- Metals
- Polymers and organics
- Semiconductors

Fundamental Physics

- Quantum coherence and entanglement
- Quantum interferometry and precision measurements
- Quantum matter
- Many-body systems

Complex Fluids/ Soft Matter

- Colloids
- Liquid crystals
- Foams
- Polymer solutions
- Granular flows
- Dusty Plasma

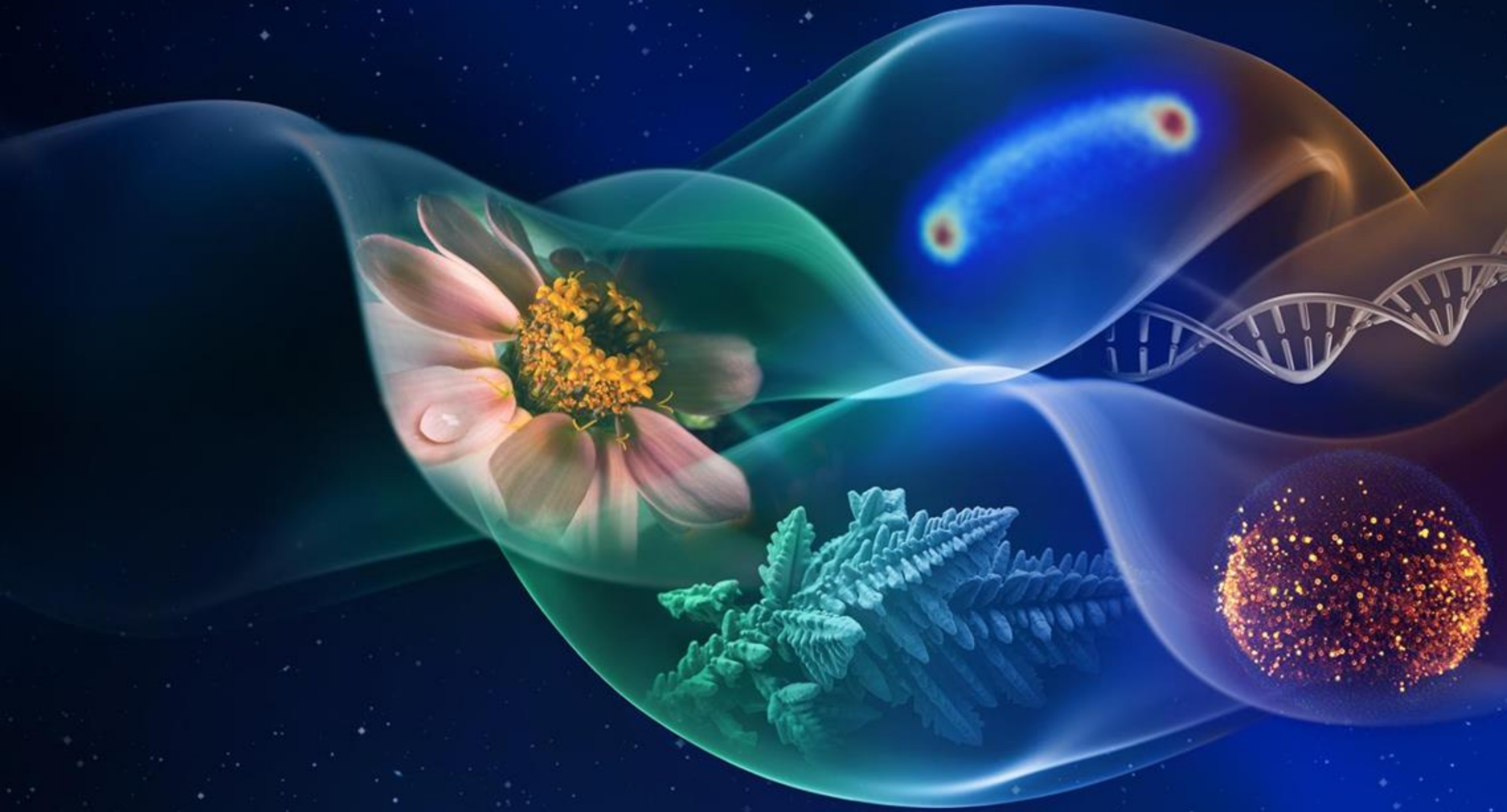


PS ISS Ops Schedule
FY
FY 2019
FY 2020
FY 2021
FY 2022
FY 2023
FY 2024
FY 2025
FY 2026
Increment / Launches
Space-X
Northrop Grumman
HTV
NG-10
NG-11
NG-13
NG-14
NG-16
NG-17
HTV-X2
FIR Payload Utilization
FIR Reconfig
FBCE C/O
ISSNL/NSF FBM
NASA FBM
NASA CM-HT
ISSNL/NSF CM-HT
NASA CM-FV
ISSNL/NSF CM-FV
FB Tank Transfer
FBCE
No Crew Time
CIR Payload Utilization
BRE-1
ACME
s-Flame-1
s-Flame-2
Flame Design-1
Flame Design-2
CLD Flame-3
BRE-2
FOMA CAL
CIR Reconfig
SoFIE reconfig & Setup
GEL
MIST
RTDFS
SoFIE
NCV
SOFIE Fire Safety
MSRR
GEDS
Sample Cartridge Assemblies
GTCS
FAMIS
TP Properties Diffusion
MSG
RSD
PBRE-WR
PBRE 2
LCF-Bulk
Trans. Alloys
Drop Vibration
SUBSA CLYC/Towers
PFMI FC2
PFMI FC1
DFM
SUBSA (BrAins)
Confined Combustion
RSD (L)
InSPACE-4
Inertial Spreading
RSD 2
MWT Solid Fuel
MWT Gaseous
EBD
ZBOT-NC
PBRE Tomography
ZBOT-AC
LCF-Film
Biophysics (MSFC/GRC)
Combustion Science (GRC)
Complex Fluids (GRC)
Fundamental Physics (JPL)
Fluid Physics (GRC)
Materials Science (MSFC)
CASIS/NSF
Reserve Payload
Potential Payload
Collaboration
BioServe
BF1
BF2
MWA
Chemical Garden
RTPCG-1
PWM
US Express Racks
CAL
CAL-AI
MICS-MVP
DECLIC
ALI-R
DSI-R
HTI-R2
DSI-R2
SCWO
AEROSOL
ESA EDR/EML
Batch 2.3
Batch 2.4 - EML 1
Batch 2.4 - EML 2
Batch 2.4 - EML 3
Batch 2.5
Batch 3 - EML 1
Batch 3 - EML 2
Batch 3 - EML 3
Batch 4 - EML 1
Batch 4 - EML 2
Batch 4 - EML 3
Batch 5
ESA FSL
DOLFIN II
FOAM 1
FOAM 2
SCWM-2
ESA Racks
PK4
ESA Protein
Soft Matter Dynamics
ESA External
ACES
JAXA ELF
ELF-1
ELF-2
ELF-5
ELF-6
ELF-4
ELF-3
KIBO Module
FLARE

Physical Sciences Path to Future Program

- Future priorities to be determined by the work of the Decadal Committee and Panels
- Subsequent input, based Decal Survey
  - Input from peer community via workshops with key stakeholders – academia, industry, other government agencies
    - Solicited topical areas of interest before (mini-whitepapers)
    - Discussion/prioritization during workshop meetings
    - Summary recommendations in key topical areas
  - Consultation with key NASA stakeholders (e.g., AES)
  - Use Science Definition Teams (SDT) to further refine and define future program directions
    - SDT panel members experts from the peer community – ideally with minimal ties to the program

DEEP DIVE



Materials Science

Physical Sciences - Lunar Surface Science Workshop

The NASA Biological and Physical Sciences Division completed a workshop on fundamental and applied research on the Moon in physical sciences on **August 18–19, 2021**. This workshop brought together the scientific community, commercial companies, and NASA Divisions and Programs with the goals of discussing investigations on reduced gravity and lunar environmental effects in physical sciences research for sustained lunar human habitation and in preparation for human exploration to Mars and to inform and inspire the science community to contribute white papers for the Biological and Physical Sciences Decadal Survey. Lunar Surface Science Workshop (usra.edu)

This workshopl focused on:

- Lunar dust and its properties, behavior, and mitigation
- Life support and thermal management
- Materials flammability and habitat fire safety
- Extraction of water-ice from regolith research, including separation, purification, electrolysis, and liquefaction
- Lunar environment and its effects on materials
- Lunar research in extraction, processing, and handling
- Lunar research for advanced manufacturing
- Fundamental physics research on the lunar surface

Products from the Workshop:

- Workshop Report from the community input and findings from the breakout sessions
- Inspiring the community to produce and submit whitepapers for the Decadal Survey

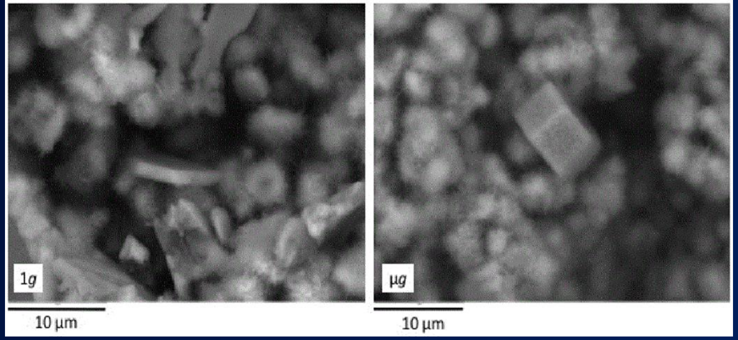
STMD - one of the top 10 Recommendations from the Chief Architect

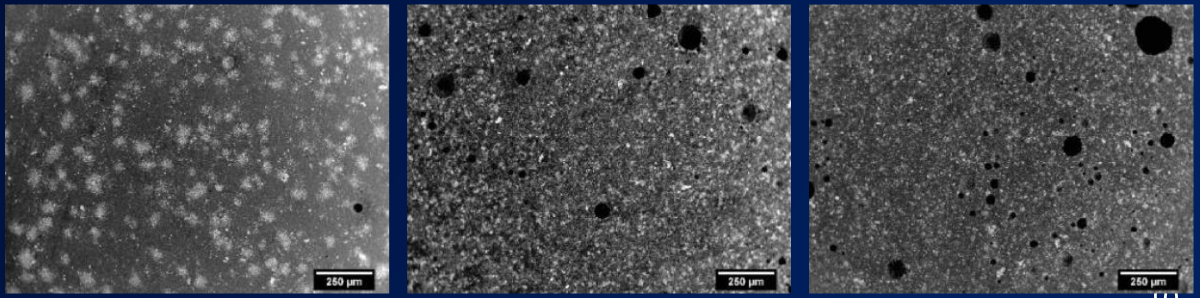
ISRU technologies for the collection of Al and Si

While metal extraction from regolith has been considered after oxygen has been removed, limited work has been performed to date. New work is required to advance technologies/processes/systems focused on metal/silicon extraction from either post oxygen extraction or specifically focused on metal extraction from the start. In particular, aluminum production can be enabling for manufacturing products such as power transmission lines, power infrastructure, shelter structures, habitat parts and repair of these systems as well as to emerging space industries interested in lunar operations. Metal/aluminum production quality must be tied and coordinated with manufacturing and construction processes, techniques and product properties to balance the complexity and cost of regolith-to-part implementation.

Materials Science

- BPS is working with STMD to explore materials science aspects of lunar construction.
- There is a lack of materials science understanding of regolith-based materials produced in the combined lunar environment consisting of reduced gravity, vacuum, and thermal extremes. This may affect porosity, microstructure, and materials properties in reduced gravity.
- Microstructure, solidification, and thermophysical properties experiments could help optimize materials and processes required to create infrastructure on demand on the Moon.
  - The fundamental physics of relevant materials and processes in reduced gravity will enable successful construction of Lunar infrastructure such as habits, landing pads, roads, and structural ceramic materials.
- Experiments with Portland cement in reduced gravity were completed, which will help with NASA's exploration missions.
  - The Microgravity Investigation of Cement Solidification (MICS) experiment showed that as the gravity level decreased the amount of trapped air and porosity in the samples increased.
    - This implies less strength when compared with Earth cements.





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The Lunar Resources company "extractor" could appear on the lunar surface in a few years

https://arstechnica.com/ 1/21/2022

In addition to the private capital raised to date, the National Science Foundation and NASA have provided the company with about $3 million in funding to develop a prototype reactor that could be sent to the Moon for a

The technology to extract metals has its roots at NASA. It is called Molten Regolith Electrolysis, by which lunar regolith is heated to a temperature of 1,600 degrees Centigrade, melted, and then electrolyzed to produce oxygen and metals, such as iron and silicon. Although the composition varies by location, lunar soil is composed of about 40 to 45 percent oxygen, 20 percent silicon, and 10 percent aluminum, with smaller amounts of iron

Materials Science

Lunar Construction

- There is a lack of materials science understanding of regolith-based materials produced in the combined lunar environment consisting of reduced gravity, vacuum, and thermal extremes.
- The fundamental physics of relevant materials and processes in reduced gravity will enable successful construction of Lunar infrastructure such as habits, landing pads, roads, and structural ceramic materials.
- Ground based testing and analysis, and the ISS flight experiments provides a supporting data set to help drive future decisions on materials and processing techniques.

Materials Science

In-Space Manufacturing

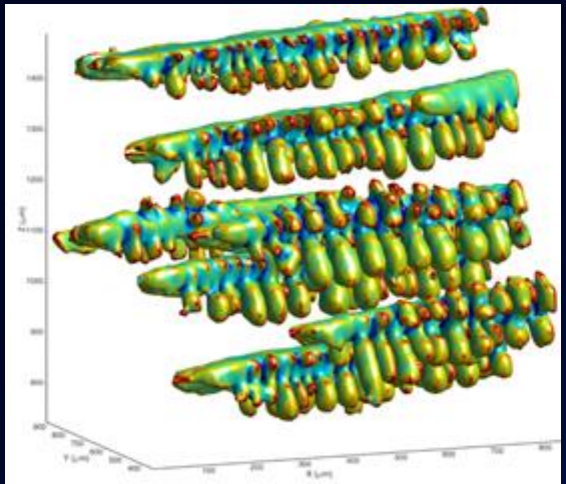
- "The need for a deeper understanding of nonequilibrium phenomena is nowhere greater than in materials science" [1].
  - Materials made by either nature or manufacturing are rarely the result of equilibrium processes.
  - Advanced manufacturing processes, such as additive manufacturing (AM), present 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.

1. National Academies of Sciences, Engineering, and Medicine 2019. Frontiers of Materials Research: A Decadal Survey. Washington, DC: The National Academies Press. https://doi.org/10.17226/25244

Materials Science

Solidification and Microstructure

- Experiments in solidification are being done multiple pieces of hardware, including:
  - Solidification Using a Baffle in Sealed Ampoules (SUBSA)
  - Pore Formation and Mobility Investigation (PFMI)
  - Critical Liquids and Crystallization – Directional Solidification Insert (DECLIC-DSI)
- Our PIs are studying a variety of phenomena including
  - The roles of melting and capillarity induced pinching on dendrite arm fragmentation, retraction and coalescence during cooling.



Materials Science

Solidification and Microstructure

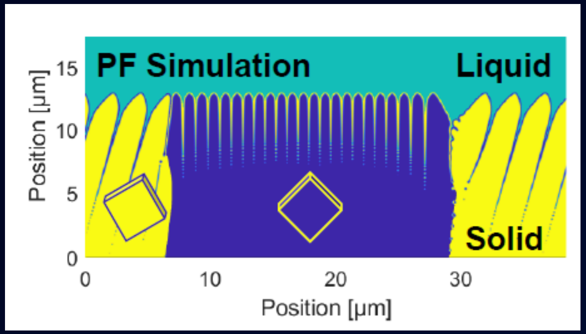
- A reduced gravity environment inhibits masking phenomena such as buoyancy driven convection and sedimentation to perform experiments targeted to address gaps in fundamental understanding of the underlying physics of materials science.
- Several of the solidification experiments in microgravity are being used to anchor multi-scale models of microstructure evolution relevant to AM processes.
  - For example, columnar and equiaxed grain structures are widely observed solidification microstructures in additively manufactured components [1].
    - BPS-funded research on columnar to equiaxad transition (Beckermann, Voorhees, Karma) could provide knowledge useful for improvement of additively manufactured parts.
- The rapid cooling rates associated with AM have been shown to lead to the formation of potentially deleterious phases not observed with standard castings.
- Predicting microstructure formation under far from equilibrium conditions presents a new set of challenges.

1. DebRoy, et. al., “Additive manufacturing of metallic components – Process, structure and properties,” Progress in Materials Science, Volume 92, 2018, Pages 112-224, https://doi.org/10.1016/j.pmatsci.2017.10.001.

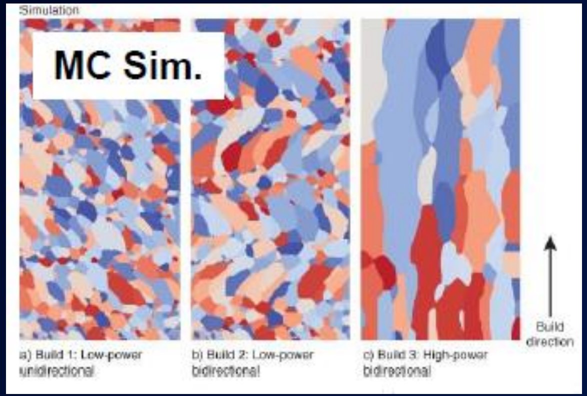
Materials Science

Solidification and Microstructure

- Modeling
  - Various modeling and simulation methods, including first-principles calculation, molecular dynamics simulation, phase field method, finite element method, Monte Carlo, cellular automata, calculation of phase diagrams (CALPHAD), and machine learning, have been applied to accelerate the development of novel materials out of equilibrium.
  - Modeling and simulation methods mentioned above span large length scales from macroscale, mesoscale and microscale.
    - Modeling provides a critical linkage between experimental observations and underlying physics across these length scales



Phase field model of an additive manufacturing process



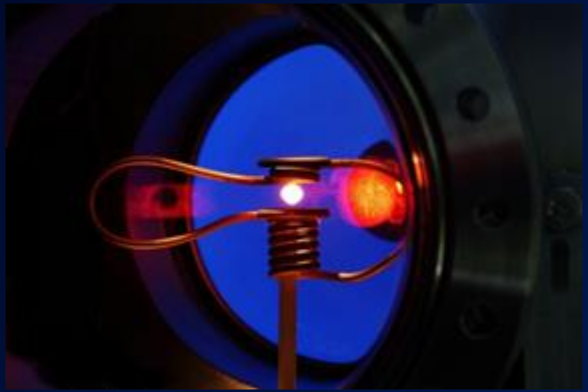
Monte Carlo simulation of an additive manufacturing process [2].

1. B. Richter, J. Pauza, A. Rollett, E. Glaessgen, "Phase Field Informed Monte Carlo Texture Evolution Models for Additive Manufacturing," MS&T 2021 conference, Columbus, OH.
2. T.M. Rodgers, J.D. Madison, and V. Tikare, "Simulation of metal additive manufacturing microstructures using kinetic Monte Carlo," Comp. Mater. Sci., 2017.

Materials Science

Thermophysical Properties

- Experiments are being conducted on the European Space Agency (ESA) Electromagnetic Levitator (ISS-EML)
- Experiments include the following:
  - Investigate the thermophysical properties of high-temperature materials used for modeling of material production processes, e.g. additive manufacturing, welding, and casting.
  - Correlate the nucleation kinetics with the local structure of a liquid alloy by measuring its thermophysical properties. Applications include bulk metallic glass materials.
  - 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
- ISS-EML could be crucial for the measurement of thermophysical properties relevant to in-space manufacturing



Materials Science

Thermophysical Properties

- Experiments are being conducted on the Japanese Aerospace eXploration Agency (JAXA)

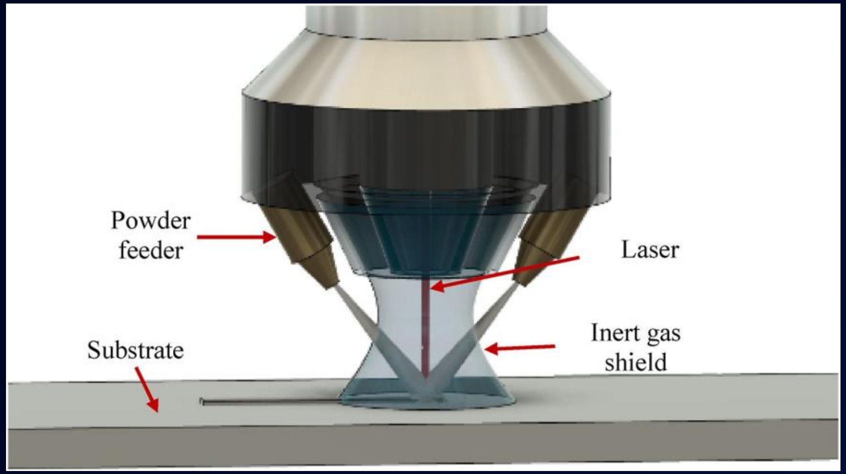
Electrostatic Levitation Furnace (ELF)

- The experiments include such things as
  - How to understand and control the sources of measurement error and to provide a baseline dataset for quantifying uncertainty in measurements (both space- and ground-based)
  - Develop new understanding of the behavior of oxide liquid, glass and ceramic materials in extreme conditions and non-equilibrium conditions.
  - 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.
  - Advance the understanding of photorefractivity, which has applications in holographic storage, adaptive optics, and phase-conjugate mirrors
- Supercooled liquids and glasses are cases of non-equilibrium materials that are essential for production of photonics and laser products. Understanding how different liquids “evolve” towards glass underpins development of new and higher performance materials. Improvements in quantum efficiency, transmission and optical properties are an essential underpinning for transformational products.
- ELF has the potential to study metal oxides from regolith to exotic glass materials for advanced fiber optics and lasers

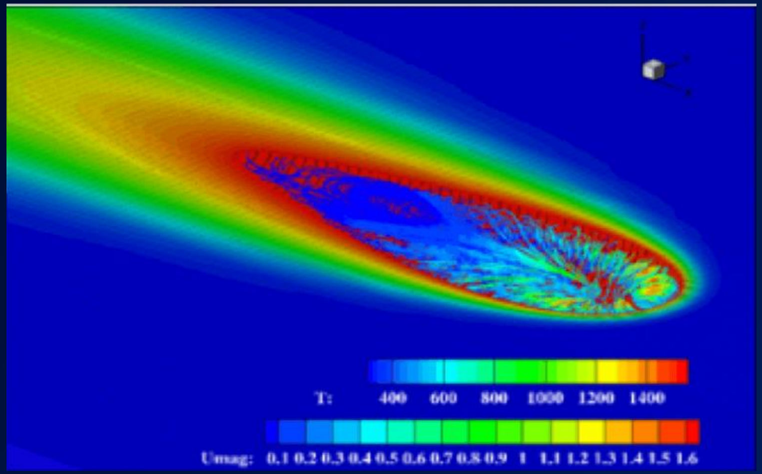
Materials Science

Thermophysical Properties

- Advancements of metallic and non-metallic materials additive manufacturing (AM) processing depends heavily on high resolution numerical simulations.
  - It is important to understand processes on the small time (µs) and length (µm) scales that are relevant in AM.
  - The role of these simulations become more important for in-space manufacturing where process optimization by trial and error is costly, time consuming, and may not be practical in some cases.
  - However, measurements of these properties are extremely scarce and practically non-existent for low gravity cases.



Schematic of a direct energy deposition process



Thermo-fluid model of an additive manufacturing process.

Biophysics

NASA Biological Materials, Biomaterials and Biomimetics Workshops in April 2014 & at the MRS Fall Meeting & Exhibit Boston, MA, December 3, 2014

Three Thematic Areas: Biological Materials, Biomaterials and Biomimetics for μ-g research.

Panel Participants: Prof. Ulrike Wegst, Chair (Dartmouth), Prof. Jacinta Conrad, Co-Chair (Univ. of Houston), Dr. Dongbo Wang, Co-Chair (NIST)

Intra-Agency Cooperation: Dr. Richard Ricker (NIST), Dr. Joseph A. Akkara (NSF), Dr. Jim Drummond, Dr. Rosemarie Hunziker, Dr. Nadya Lumelsky & Dr. Fei Wang (NIH).

Keynote Speaker: Prof. Jennifer Lewis (Harvard) addressed key detrimental effects of gravity on 3D tissue/Organ development.

Outcome from April 2014 MaterialsLab Workshop: Defined the Scope of the Biomaterials Program

Biological Materials: materials of biological origin, e g., proteins, biopolymers. Investigate fundamental phenomena in solidification and/or other processes of organization (nucleation, growth, self-organization, etc.)

Biomaterials: materials substituting tissues or organs, aiding their regeneration, or interfacing with these, e.g., tissue scaffolds, implant materials. Primarily elucidate cell-material interactions affecting cellular functions, organization, differentiation, etc.

Biomimetics: bio-inspired materials that emulate function and/or principles of optimization such as hierarchical structures, multi-functionality, e.g., synthetic nacre (bulk materials), omniphobic surfaces, including materials synthesized in aqueous environments.

Outcome from April & December 2014 Workshops: Top Ranked RFI Responses for Each Focus Area

Biological Materials:

1)Role of appendage-driven motility and adhesion on biofilm formation
2)Colloidal model systems for solution crystallization
3)Microgravity and the mechanism of biofilm formation

Biomaterials:

1) Human stem cell growth proliferation and differentiation, and tissue regeneration
   under extended zero gravity
2) Three-dimensional complex tissue engineering in microgravity {RSD}
3) Pigment-based melanins as a technology for water purification for manned missions

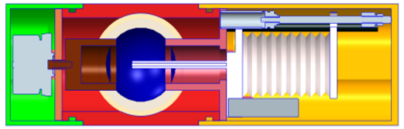
Biomimetics:

1)Micro-gravity freeze casting
2)Micro/nanofabrication using liquid-based template in low-gravity environment
3)Biomimetic sensing films for water monitoring on the International Space Station

Biophysics Program: MaterialsLab Reference Experiments

Macromolecules

Decadal Themes: FP1, AP9



Amyloid Fibril Formation

A. Hirsa, Rensselaer Polytechnic Institute

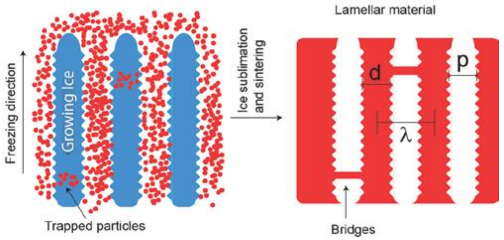
Quantify the effects of flow on fibrillization in the bulk and at interfaces (air/water), which can only be performed in the microgravity environment where deleterious effects from sample dimensions are mitigated.

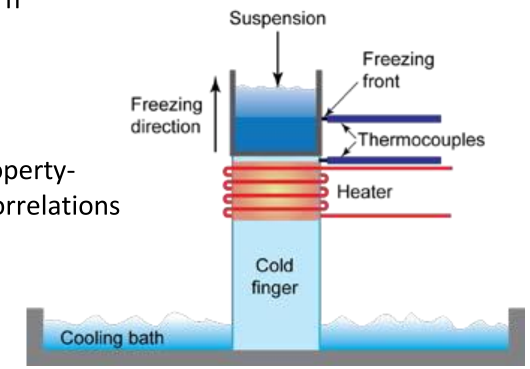
Freeze Casting

Decadal Themes: AP5, AP9

Microstructure Evolution in Freeze-Cast Materials

D. Dunand, Northwestern





Structure-Property-Processing Correlations

U. Wegst, Dartmouth

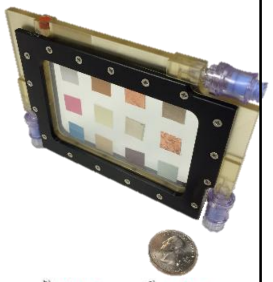
Conduct microgravity experiments on the formation of substrates, scaffolds, and surfaces relevant to biomaterials research, e.g. freeze casting.

Biofilms

Decadal Themes: P1, P2

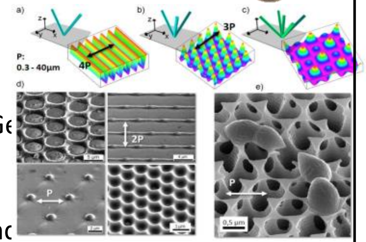
Polymicrobial biofilm growth and control during spaceflight

McLean, Texas State, San Marcos



Biofilm Formation, Growth, & Ge Expression on Different Materials anc Environmental Conditions.

Zea, Colorado



Elucidate material/cell interactions in biofilm formations. Determine physical mechanisms of gravity-sensing in bacteria/fungi that leads to different formations of biofilms in microgravity

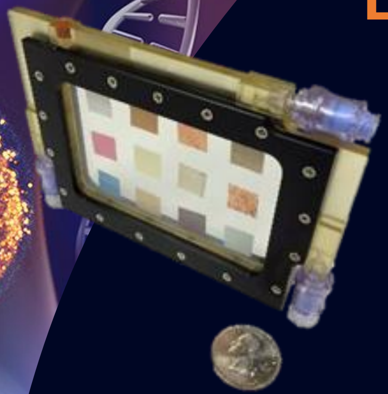
CASIS partnership

CASIS and NASA have collaborated on potential ways to utilize MaterialsLab to benefit both organizations through ongoing discussions

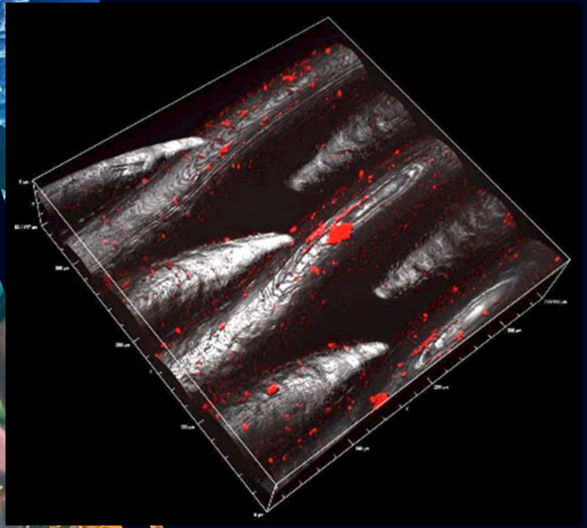
- Shared hardware and science teams
- Overlapping research goals
- Commercial usage of resources

CASIS endorses the development of all six theme areas in the MaterialsLab program: Biomaterials, Glasses and Ceramics, Granular Materials, Polymers and Organics, Metals, and Semiconductors, and will support its growth where possible

Biological Materials - Biofilms



BioCell used in biofilm experiments on the ISS

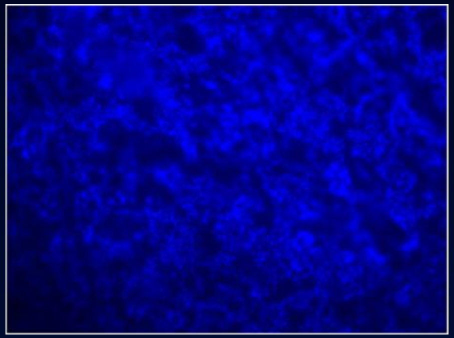


Bacterial contamination of a steel wire mesh.

- **The goal of these experiments is to support space exploration by developing knowledge of biofilm formation and inhibition mechanisms.**
- **The experiments use BioCells, which are placed in a Plate Habitat (PHAB) for incubation.**
- **Sample analysis will be completed on ground using confocal microscopy, RNA-sequencing, and/or scanning electron microscopy.**
- **There are currently 2 PIs with Biofilms experiments on the ISS:**
- **Luis Zea, University of Colorado, Boulder**
    - Objective: Characterize biofilm mass, thickness, morphology and the associated gene expression using different spaceflight-relevant microbial species and substrata materials, to help determine the physical mechanisms of material/micro-organisms interaction in biofilms.
- **Robert McLean, Texas State University**
    - Objective: Develop knowledge of biofilm formation and inhibition mechanisms with respect to varying material/microorganism interactions

Biological Materials - 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

Biomaterials – RSD: Protein Fibrilization, Bioreactor

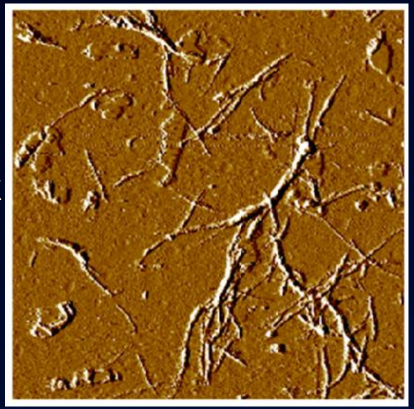
- **In the ring-sheared drop (RSD) hardware on ISS, a liquid drop is constrained by two contact rings, where the rings differentially rotate. This differential rotation generates a flow in the bulk primarily through surface shear viscosity.**
- **PI: Amir Hirsa, Rensselaer Polytechnic Institute; Co-I: Juan Lopez, Arizona State University**
  - Objective: Examine the formation and flow of amyloids in the absence of surface tension and other complications created by the solid walls of a container. Results could contribute to better understanding of Alzheimer’s disease as well as to development of advanced materials.
- **PI: Juan Lopez; Co-I: Amir Hirsa**
  - Dr. Lopez is working with the ISSNL on a follow-on RSD experiment.
  - The goal of the project is to understand and control protein aggregation at free surfaces, especially when the concentration of protein is high. Protein aggregation at free surfaces is an Achilles' heel in pharmaceutical manufacturing that degrades product quality and process yield.
  - The new droplet deployment system develop and launched. Protein solution samples to be tested.

Left: Christina Koch Operating RSD Flight Hardware on ISS
Upper Right: RSD Test Cell   Lower Right: Pinned Drop on ISS

Biomaterials – RSD: Protein Fibrillization, Bioreactor

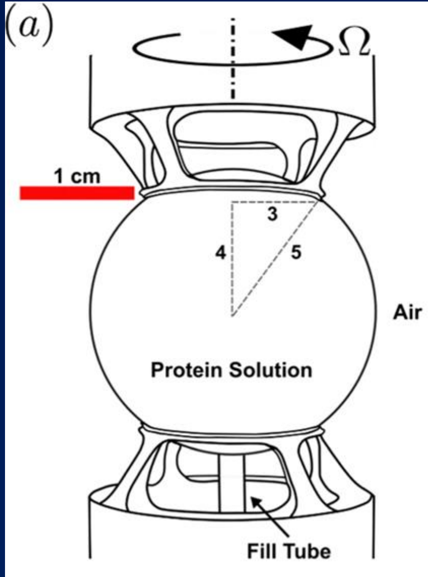
- Amyloid fibrils are misfolded proteins that self-assemble to form β-sheet rich fibrillar structures.
- Amyloid fibrils are relevant to amyloid diseases such as Alzheimer's, Parkinson's, prion diseases, and type 2 diabetes.
- Studying how these proteins clump together could help scientists understand 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, Hirsa et al. Soft Matter 2017)



Dilute protein solution droplet in nearly containerless bioreactor on ISS.

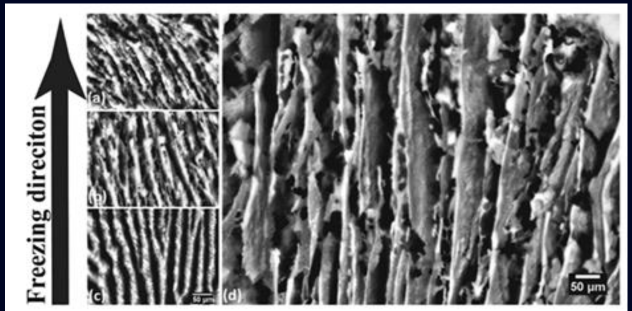
Schematic of the ring shear drop apparatus



Biomimetics – Freeze Casting

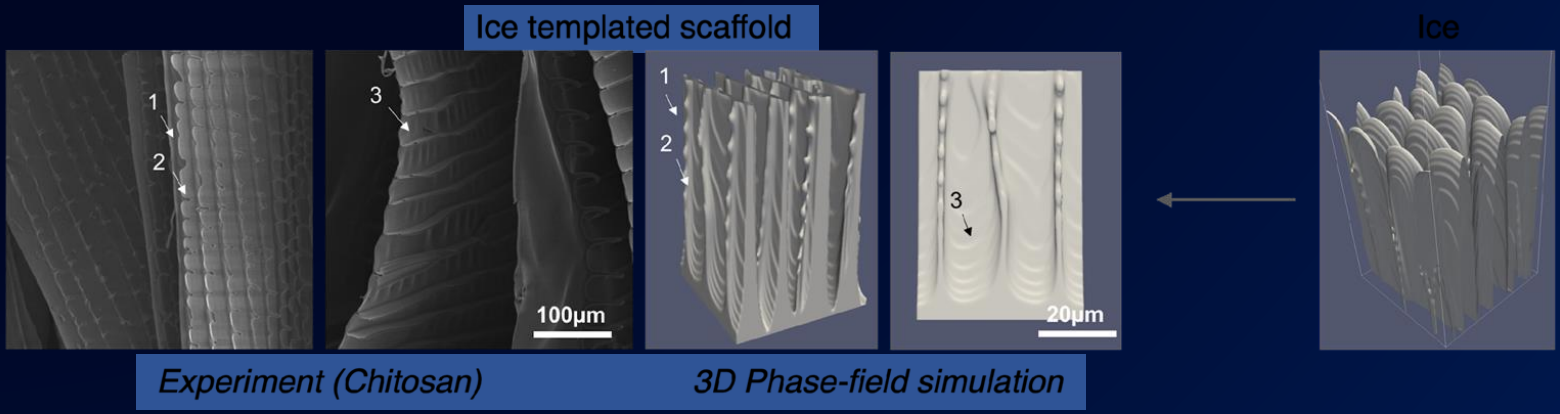
The **Pore Formation and Mobility Investigation (PFMI) hardware** will melt samples of a transparent modeling material, e.g. succinonitrile and succinonitrile water mixtures. There are currently 2 Investigators with upcoming PFMI experiments:

- David Dunand, Northwestern University
  - Objective: Improve understanding of solidification behavior of freeze cast materials, which will allow for the development of improved processing techniques



Longitudinal cross-sections of sintered TiO_2 samples sintered from 20 wt% TiO_2 aqueous suspensions directionally solidified under (a) terrestrial, (b) Martian, (c) lunar, and (d) microgravity conditions.

- Ulrike Wegst, Northeastern University
  - Objective: Investigate the underlying physics of forming complex scaffolds using the freeze casting methodology.



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

Long-Term Vision

- Key themes emerging from the panel recommendations:
  - Biological materials: controlling cell-material interactions
  - Biomaterials: controlling cell-cell interactions
  - Biomimetics: controlling 3-D material structure
- Long-term vision: unite these themes towards technology development of tissue engineering and 3-d bioprinting for long-duration spaceflight
- MaterialsLab and the proposed Biomaterials program will develop the fundamental insights needed to implement technological advancements in space
- Role of microgravity: understand effects of convection, gravity, and surface tension on biological systems and on materials with which they interact

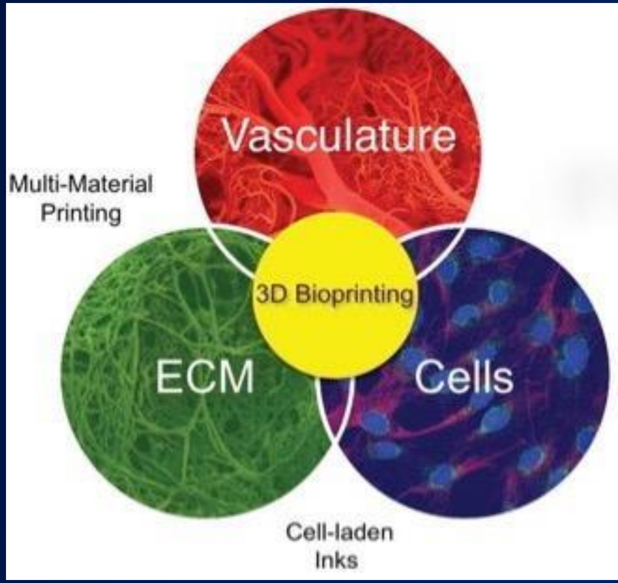


Image credit: D. B. Kolesky , R. L. Truby , A. S. Gladman , T. A. Busbee , K. A. Homan , and J. A. Lewis, *3D Bioprinting of Vascularized, Heterogeneous Cell-Laden Tissue Constructs*, Adv. Mater. 2013, 25, 3124–3130

Note: ECM - Extracellular Matrix (provides instructive clues for cell attachment, proliferation, differentiation, and ultimately tissue regeneration)

Fluid Physics

2019 NASA Fluid Physics Workshop - Recommendations

Heat Pipes:

Oscillating heat pipes, Advanced loop heat pipes, Vapor chambers, Evaporators, and Condensing radiators.

Flow Boiling and Condensation:

Application of liquid-vapor phase change as it applies to: Cryogenic fluid management for zero boiloff and propellant tank transfer, space power utilizing two phase flow and heat transfer, and two-phase thermal control for human exploration.

Water Recovery:

Processing of wastewater to potable water. Sources include - grey water, crew urine, humidity condensate, CO2 Reduction (e.g., Sabatier) product water *Goal:* extend the recovery for exploration missions to virtually 100%

Packed Bed Reactor Experiment

- *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.*

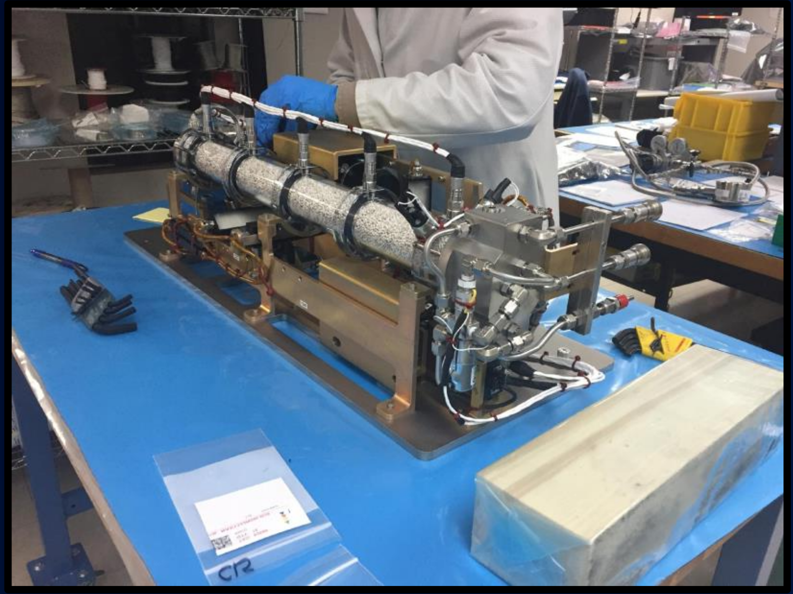
BPS response –
PBRE- 1 & 2, PI: Brian Motil, NASA GRC
Co-I: Vemuri Balakataioh, University of Houston
Fundamental understanding of two-phase flow through wetting and non-wetting spherical beds to improve fundamental understating of packed bed reactors in reduced gravity and improve predictive numerical modeling.

PBRE-2 test column with 2mm glass beads

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.

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



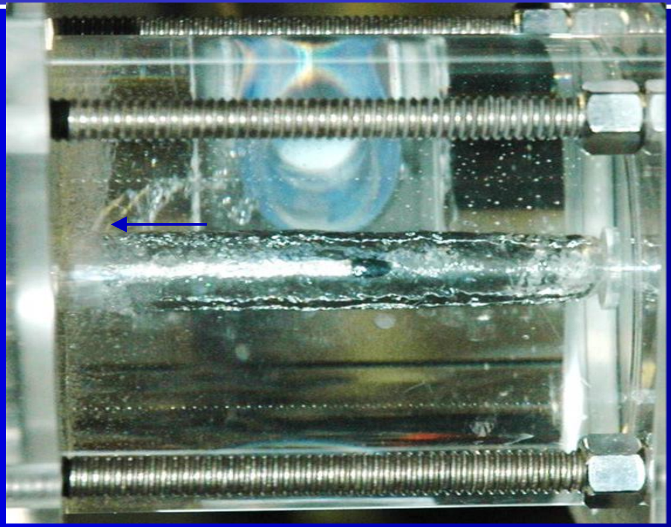
Next Steps: Utilize Tomography system with PBRE hardware to yield 3-D imaging of voids, gas bubbles and liquid - vapor interface

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

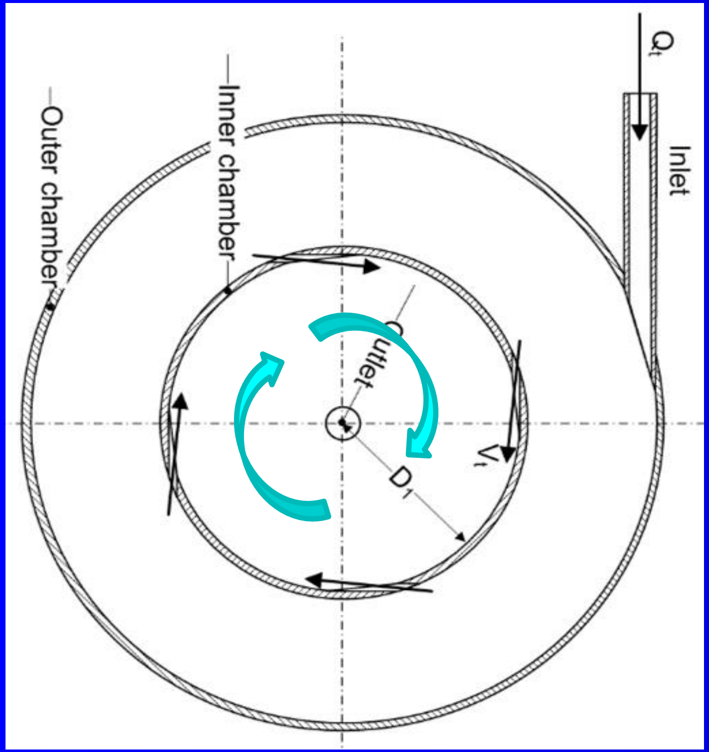
Experiment name/test sect	Tasks	SLPSRA costs	AES costs	Test section
PBRE-2 (SLPSRA) (SpX 16)	Camera repair, test material, Preflight testing, MI&O, hardware prep	PI and Co-I, PS, Grant, Cradle/test section	N/A	
PBRE-WR-1, Applied packing material (SpX 16)	Preflight testing, MI&O, hardware prep	Cradle/test 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 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	

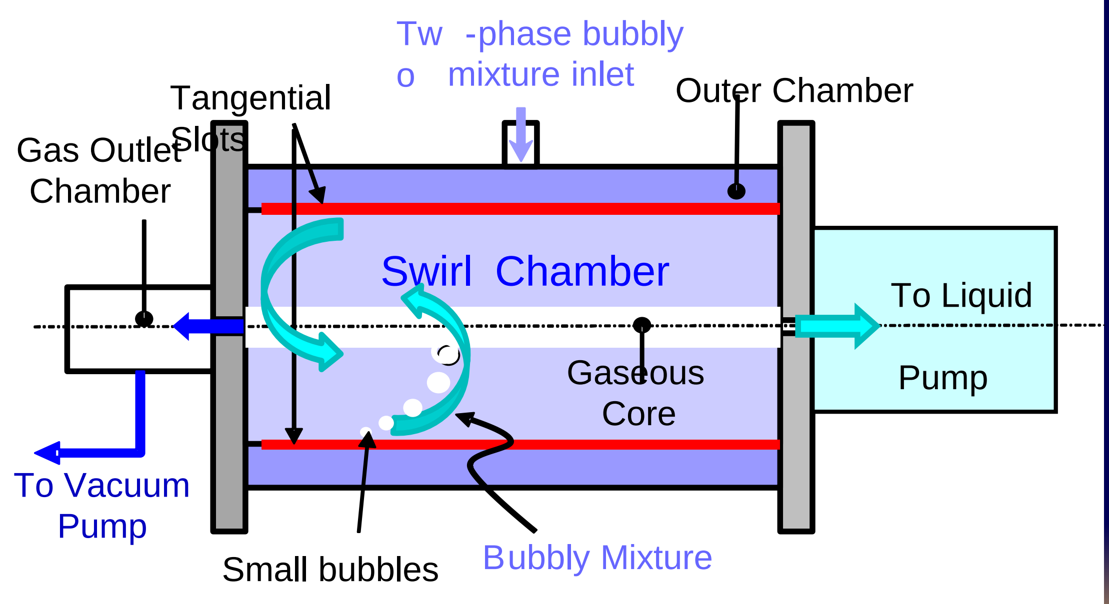
Direct application to ISS Water Recovery System and precursor for future ECLSS systems

DYNASWIRL® Separator



Side view of
Swirl chamber



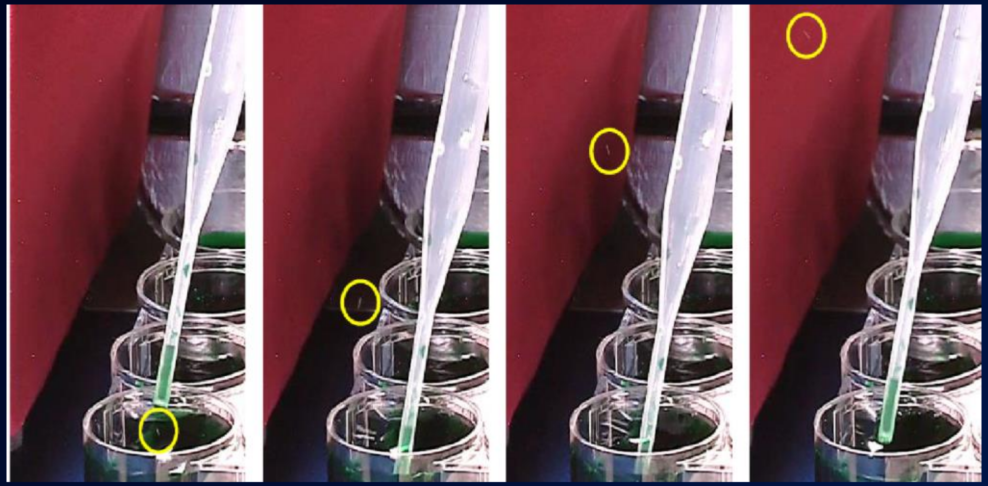


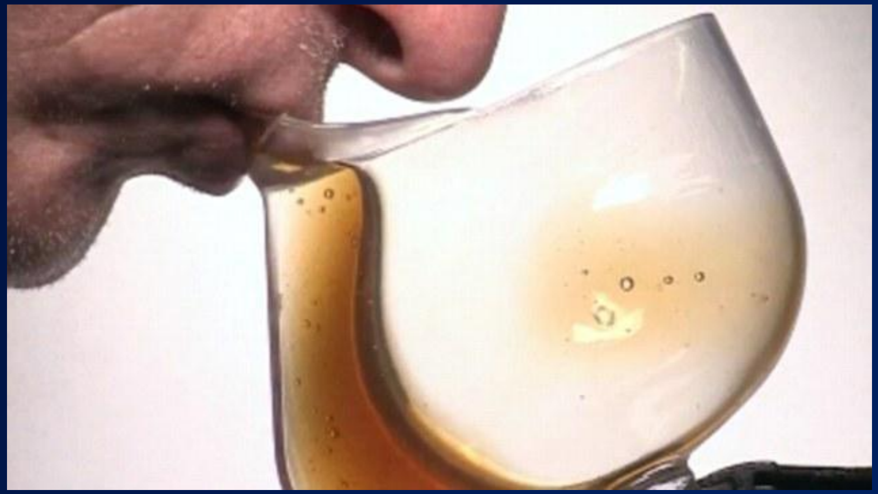
Fluid Physics

The ability to reliably and safely handle fluid systems is problematical due to the complex wetting behavior that is easily affected by contact angle, surface geometry, contaminants both in the fluid and on the surface, and flow.

Management of multiphase fluids will require advances on our understanding of fluid behavior and fluid system design this includes:

- Packed Bed Reactors
- Liquid / vapor separators
- Plant hydration and aeration – effects on the root zone
- Pipetting



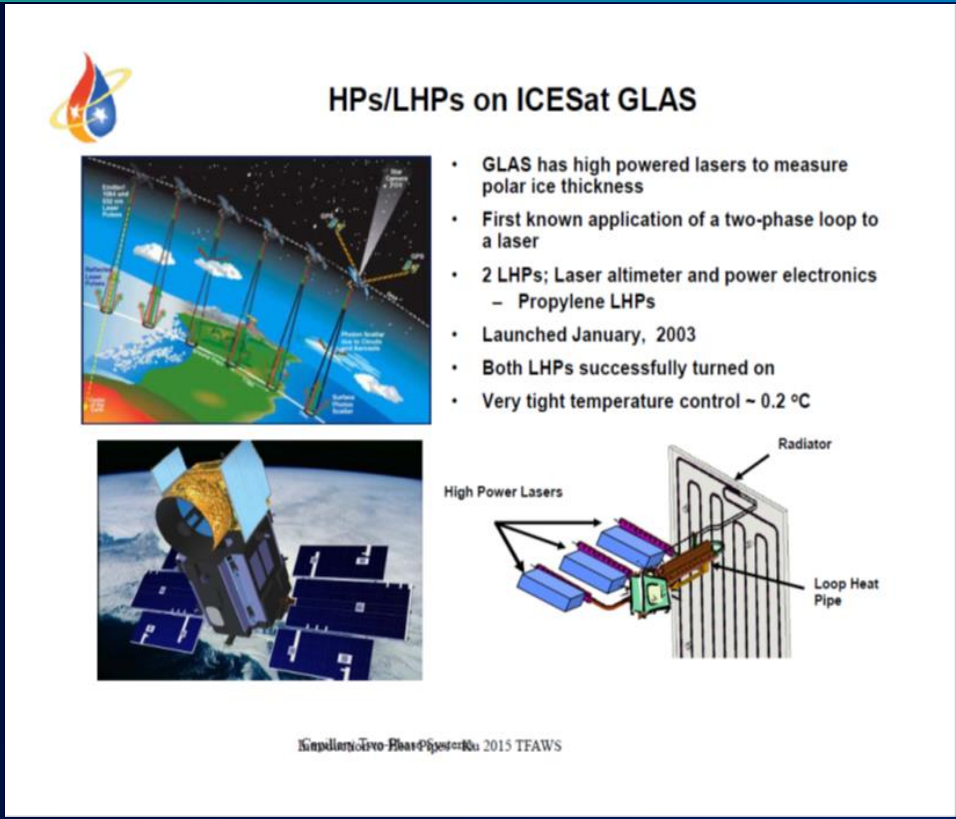


Fluid Physics

Heat Pipes – cooling electronic scientific instruments and sensors, energy conversion systems, etc.

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 cryo-cooler in a spacecraft.



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

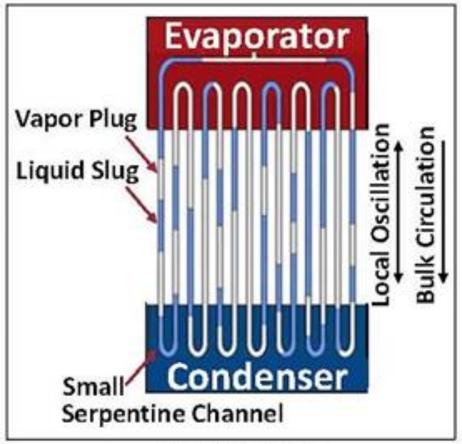
- Serpentine collection of microchannels
- Evacuated and partially filled with a fluid
- Surface tension effects create a natural separation of liquid slugs and vapor bubbles

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?

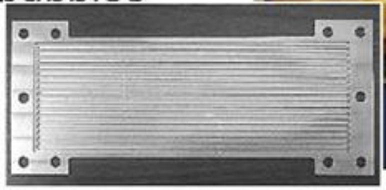
Operation

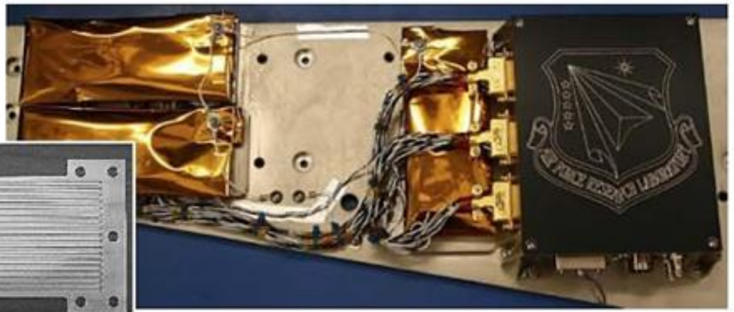
- Differential heating of the OHP creates a pressure imbalance/instability
- Heat transferred through two-phase flow without the need for an expensive wick
- Majority of heat transfer is forced convection



OHP Schematic

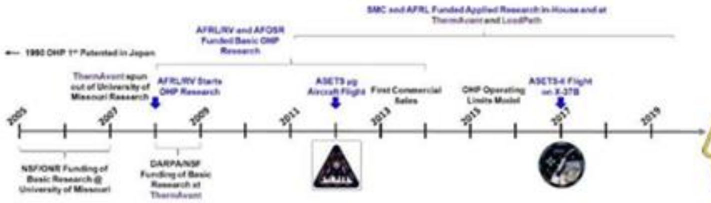
Video of OHP Operation



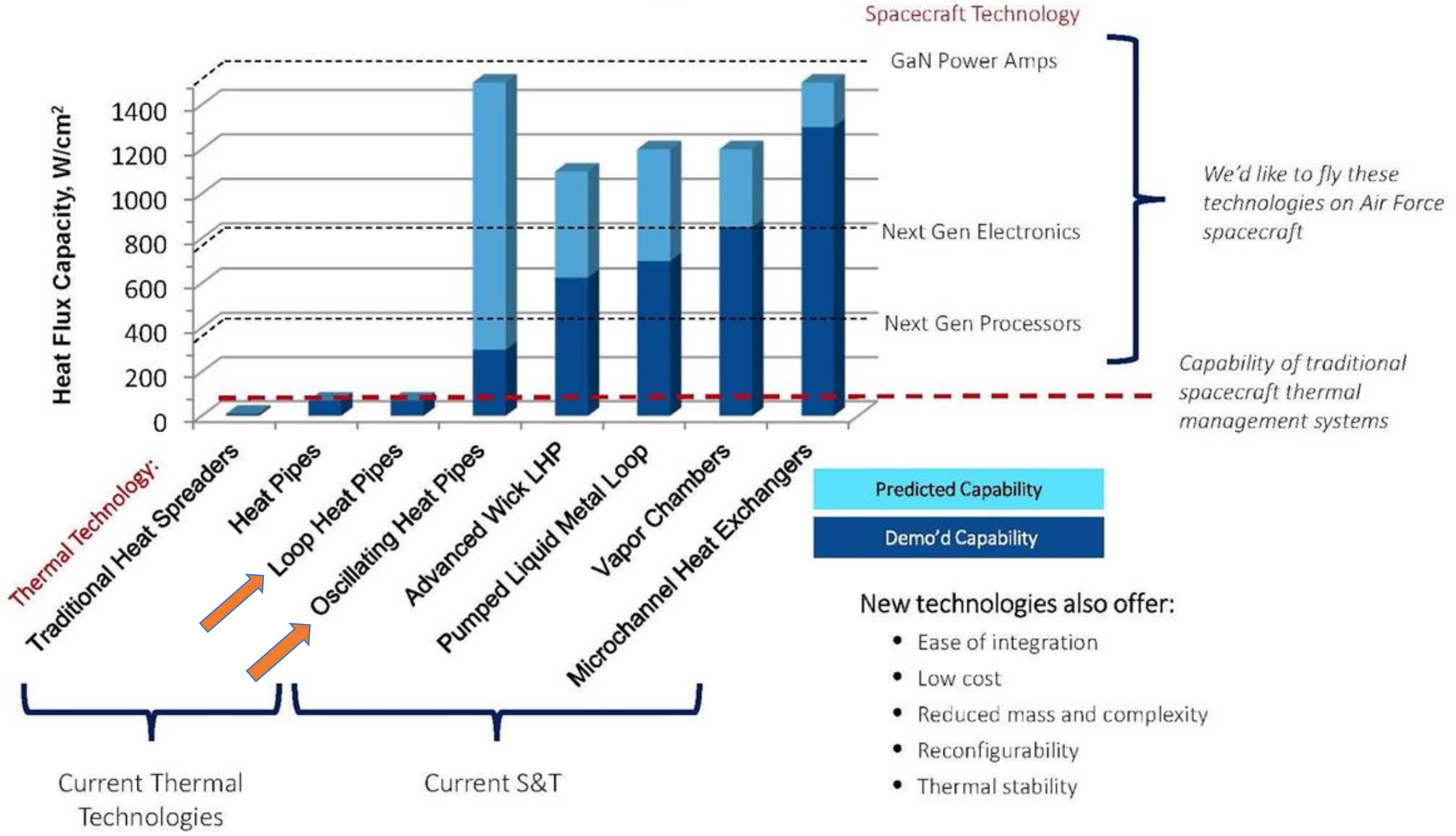


ASETS-II Flight Hardware (Top) and ASETS-II OHP w/o Lid (Left)

X-37B Orbital Test Vehicle



High Flux Electronics Cooling

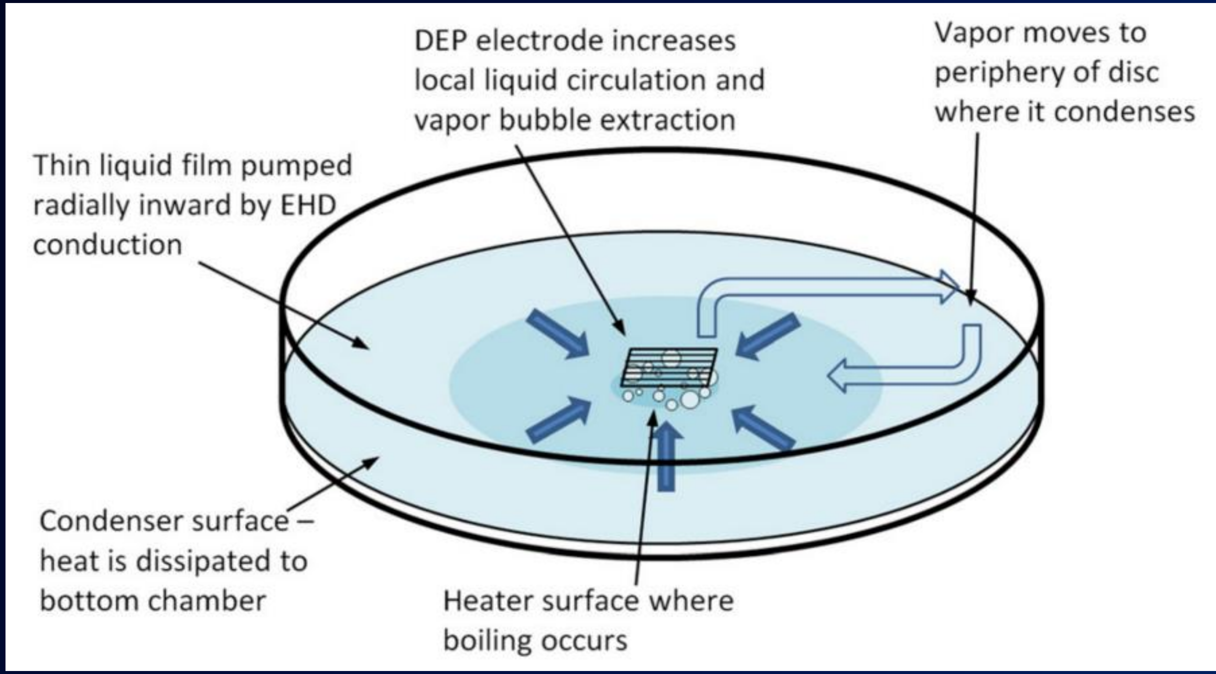


New technologies also offer:

- Ease of integration
- Low cost
- Reduced mass and complexity
- Reconfigurability
- Thermal stability

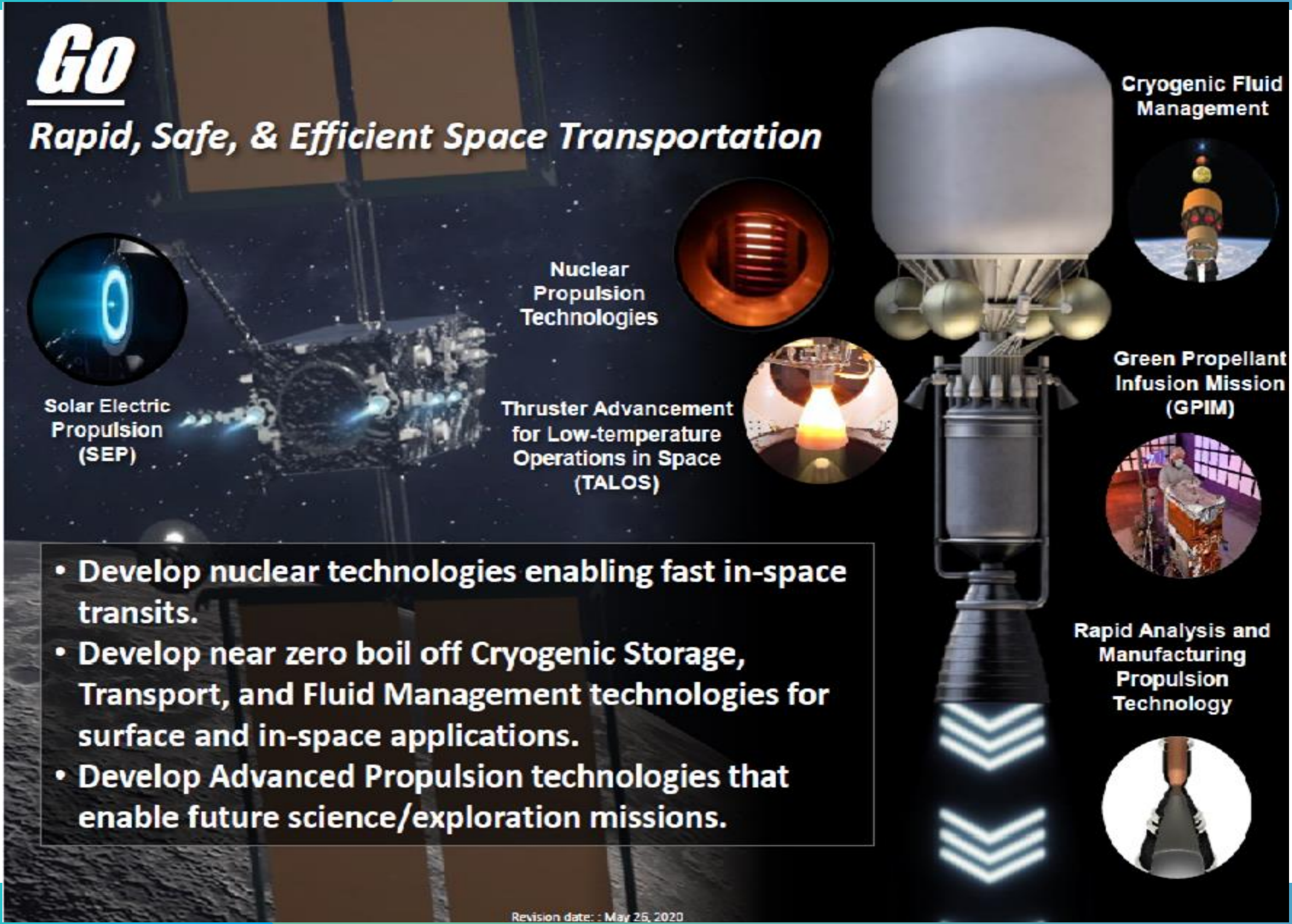
Thermal Management - Electronic Cooling for Spacecraft

- **Electrohydrodynamics Experiment (EHD)**
  - PI: Jamal Yagoobi, Worcester Polytechnic Institute
    - Objective: Characterize the effects of gravity on the interaction of electric and flow fields in the presence of phase change specifically pertaining to EHD generated two-phase flow and liquid film boiling and di-electro-phoretically (DEP) extracting bubbles from heating surface.



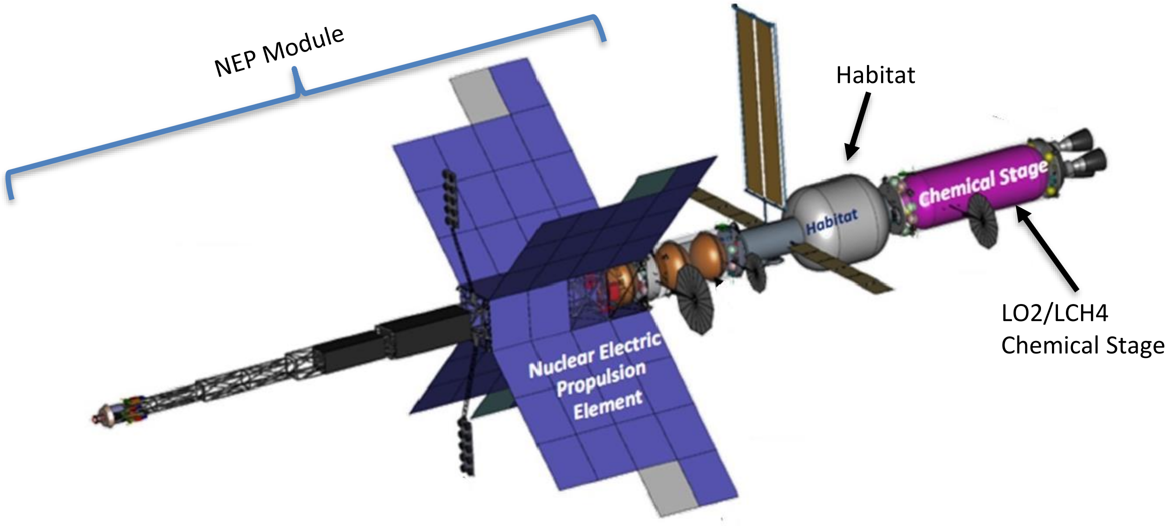
EHD experiment Concept

STMD Strategic Framework Overview



Mars Transfer Vehicle Concepts Overview

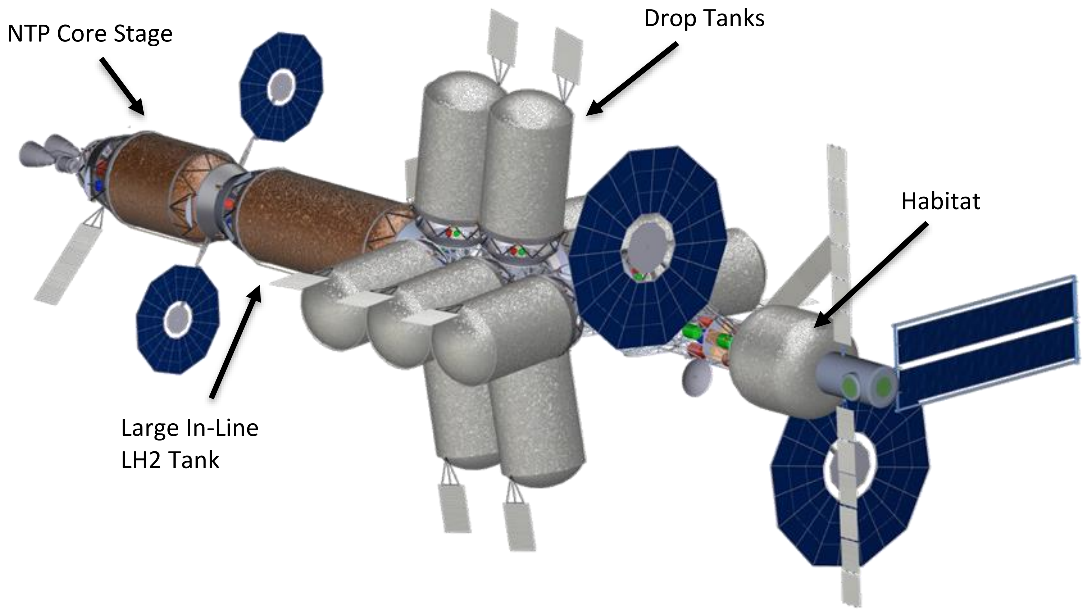
NEP/Chem Hybrid Vehicle Concept



- 1.9 MWe Nuclear Reactor and power Conversion
- Large Radiators for waste heat rejection
- Hall effect ion thruster clusters
- Large habitat for crew
- Liquid oxygen/liquid methane (LO2/LCH4) chemical propulsion stage
- “Storable” propellant reaction control propulsion
- In-space assembly, fueling

NTP Vehicle Concept

- Multiple Nuclear Thermal Rocket Engines
  - Reactor, LH2 pump, hydrogen heat exchange, and a converging expanding nozzle to generate thrust
- Large habitat for crew
- Liquid hydrogen storage in multiple large tanks
- “Storable” propellant reaction control propulsion
- In-space assembly



Zero Boil-Off Tank (ZBOT) Experiments & Collaborations

ZBOT's transformative science reveals fundamental microgravity physical phenomena that enables development of Zero-Boil-Off technology for Propellant Tank CFM

ZBOT Series - ISS Experiment Objectives:

- **ZBOT-1: Pressurization & Pressure Control (2017)**
  - Pressurization, pressure reduction by Jet Mixing & destratification
  - PIV Diagnostics for full field velocimetry
- **ZBOT-NC: Effect of NonCondesable Gases (2024)**
  - Noncondensable gas effects on evaporating and condensing mass transfer during pressurization and pressure control
  - QDT Diagnostics for full field thermometry
- **ZBOT-DP: Droplet Phase Change (TBD)**
  - Spraybar droplet injection pressure control
  - Tank chilldown & ventless filling
- **ZBOT-FT: Tank Filling & Transfer (TBD) - DLR Collaboration**
  - *Donor tank* - autogeneous pressurization and liquid extraction
  - *Line Chilldown*
  - *Receiver tank* - no-vent filling transfer
- **ICEE – (TBD) small –mid scale tech demo with cryogenic fluid**

ZBOT Collaboration Approach:

- **STMD:** (2008-Present)
  - Consensus on experiments' goals & objectives
  - ZBOT Model development & validation with ZBOT microgravity data
  - ZBOT Model development & validation against NASA 1g large tank cryogenic experiments
  - Funding for Highly Parallel Computational Infrastructure and model development
  - ZBOT aligned with NASA Technology Taxonomy 14.1
- **DLR:** (2018-Present)
  - Ground-based Research
    - DLR: Drop tower & aircraft testing
    - NASA BPS : Numerical modelling
  - ISS Flight Experiment (TBD)
    - DLR: Flight Hardware development
    - NASA ISS Program Office: ISS integration & launch
    - NASA BPS: Science Requirements Definition (SRD), Numerical modelling & validation, & crew operations

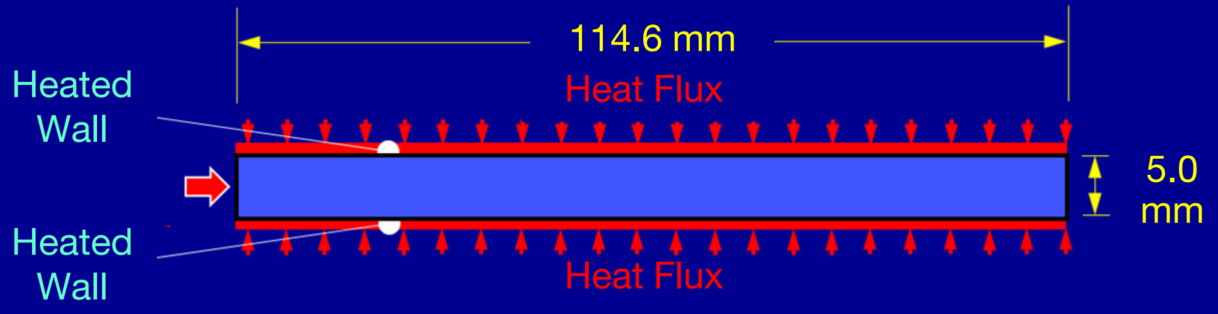
Space Nuclear Propulsion for Human Mars Exploration

Operating temperatures for the power conversion subsystems tested to date are at the minimum acceptable level to meet nuclear electric propulsion (NEP) needs. Brayton energy conversion technologies are more advanced than other types, but they introduce new types of risks, and demonstrated power levels for space-qualified systems are orders of magnitude below that required for a <u>1 to 2 MWe system</u>. A Rankine power conversion system, although used extensively in terrestrial systems, would pose additional risks associated with handling a two-phase flow in zero gravity. Liquid metal working fluids adopted for some power conversion options would also likely introduce the need for refractory metals in the power conversion sections. Advanced NEP systems will likely be able to convert perhaps 20 to 35 percent of the thermal energy from the reactor coolant into electrical power.

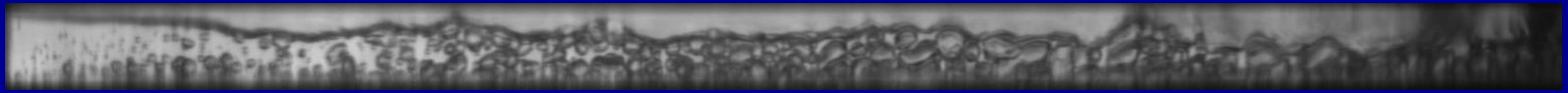
National Academies of Sciences, Engineering, and Medicine. 2021. Space Nuclear Propulsion for Human Mars Exploration.

FBCE - Flow Boilin

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.

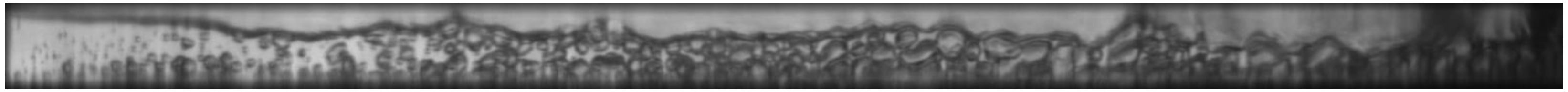
Observations:

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**

Flow Boiling: 0-g to 1-g comparison, low velocity

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

Horizontal one g_e



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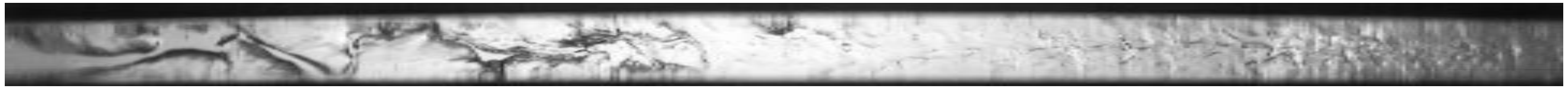
Microgravity µg



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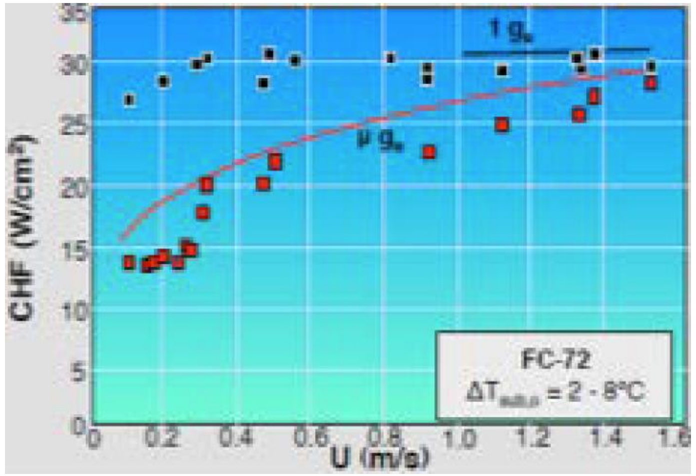


Critical Heat Flux (CHF) data and model predictions for microgravity and Earth gravity for flow boiling

Flow Boiling and Condensation Experiment (FBCE)

FBCE Modules

- **Flow Boiling Module**—Steady-state boiling
  - Saturated and sub cooled flow boiling
  - CHF
  - Effect of residual gravity vector
  - Understand system stability
- **Condensation Module**—Steady-state condensation
  - Saturated vapor and two-phase inlet
  - Heat transfer coefficients
  - Pressure drop data
- Flow observation – TBD future module

Flow Boiling Module in Assembly

Condensation/Heat Transfer Insert

FBCE Exploration Applications

- Nuclear electric propulsion (NEP) using nuclear fission/Rankine power cycle for future space missions to Mars (Moon, Mars and beyond) and deep space missions
- Nuclear fission/Rankine power cycle for planetary habitat power generation
- Vapor compression heat pump for planetary bases (Moon, Mars)
- Thermal control systems and advanced life support systems for spacecraft
- Cryogenic systems: nuclear thermal propulsion (NTP), fuel depots, tank chilldown

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

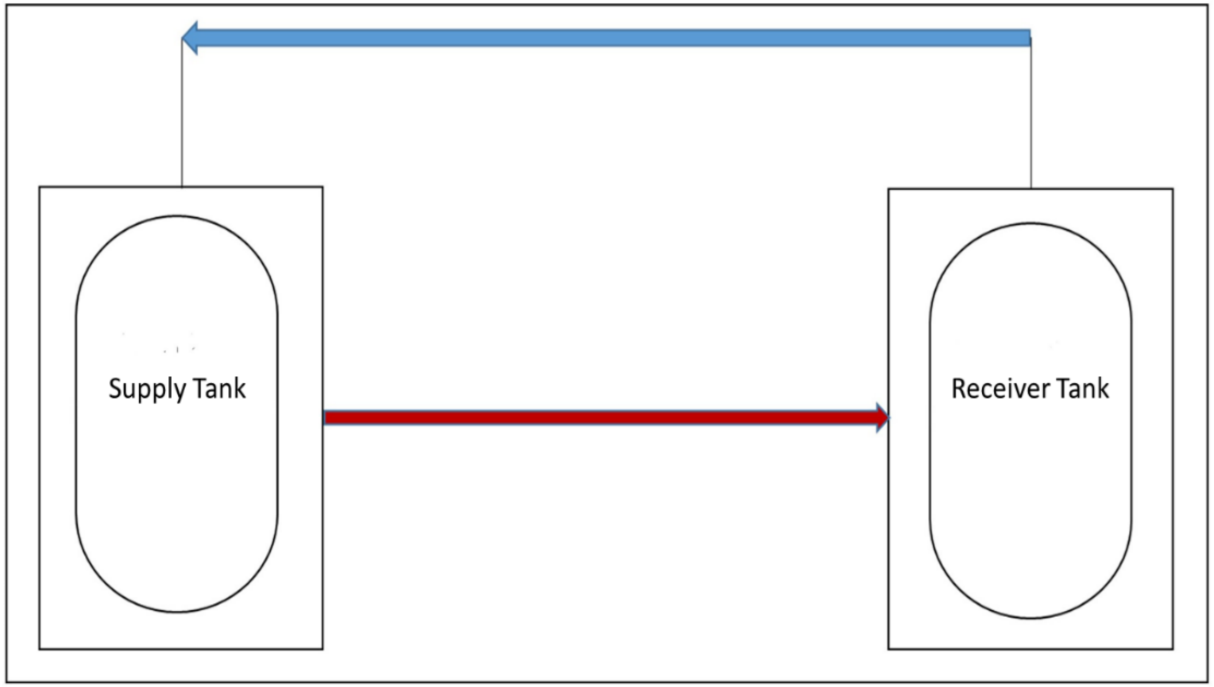
Horizontal one g_e

Microgravity

APPENDIX A : *Soliciting Proposals for Fluid Physics Experiments on the International Space Station in Flow Boiling to Support Cryogenic Propellant Tank Transfer Research*

Research Emphases

- NASA plans to conduct boiling and condensation experiments aboard the ISS using the Flow Boiling and Condensation Experiment (FBCE), in the Fluids Integrated Rack. The FBCE is an integrated two-phase flow boiling and condensation facility intended to serve as a primary platform for obtaining two-phase flow and heat transfer data in microgravity using the research fluid, normal perfluorohexane.
- Once currently planned test runs for FBCE are completed, NASA intends to replace the original flow boiling module with a new boiling module that has a geometry that more resembles the propellant tank transfer process.
- Through this Appendix, NASA is seeking proposals to determine the best use of the new flow boiling module for the FBCE using simulant fluid, in support of in-space cryogenic propellant tank transfer research.



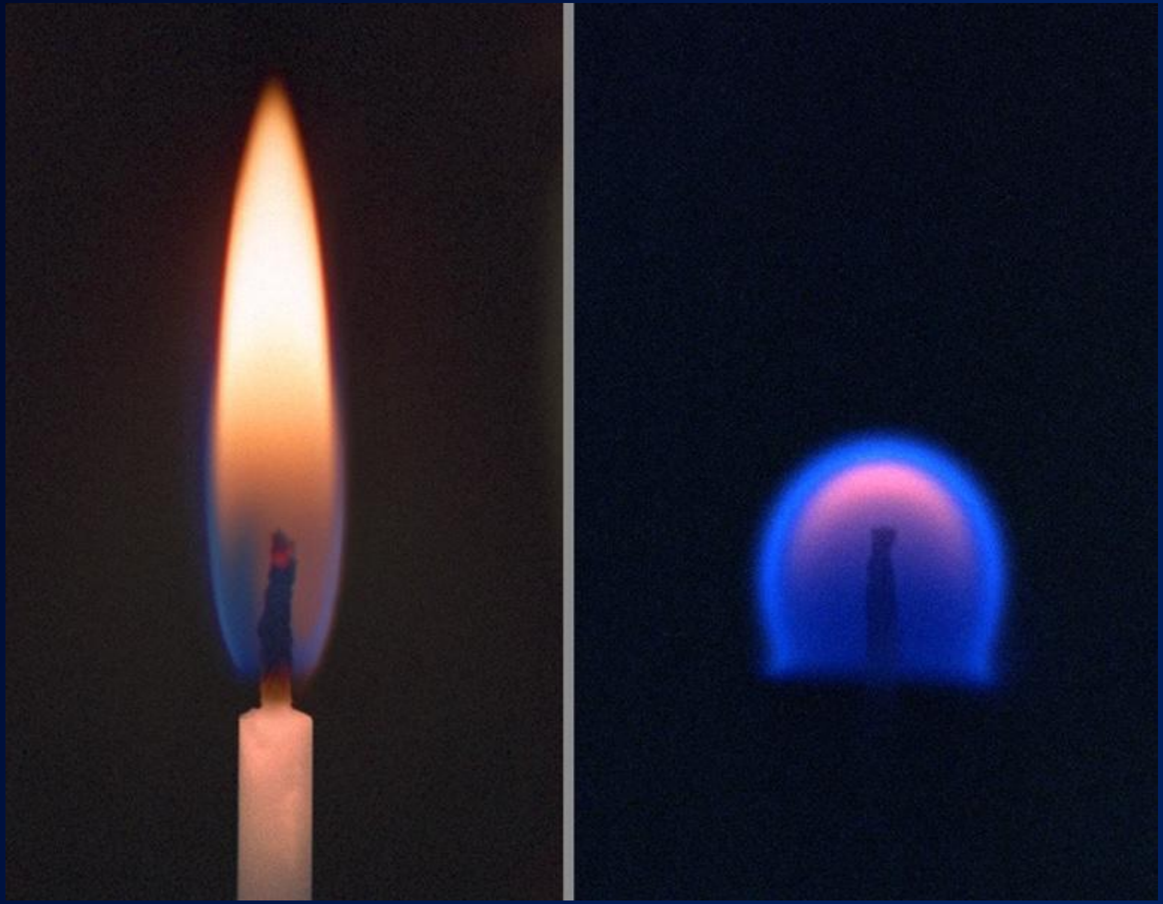
Simplified in-space cryogenic propellant refueling concept and experiment

- Specifically, the new boiling module will investigate the flow boiling (film, nucleate, etc.) occurring in the transfer line using the research fluid, normal perfluorohexane. All proposal concepts must fit within FBCE hardware capabilities that are currently designed.

Combustion

Approach

- Two parts to the microgravity combustion science program
  - Fundamental combustion science – use the microgravity environment to improve our fundamental understanding of combustion processes
    - Combustion is a complex phenomena with enormous practical applications
    - “The effects of buoyancy are so ubiquitous that their enormous negative impact on the rational development of combustion science is generally not recognized,” M. King (1997)
  - Enabling NASA’s exploration missions (e.g., spacecraft fire safety)
    - Artemis atmospheres will be at higher O2 percentage and lower pressure (normoxic conditions)
    - Negatively effects material flammability, flame spread, fire detection and suppression



2014/2015 Combustion Workshop Recommendations

- Overwhelmingly endorsed high pressure transcritical combustion as highest priority
  - Significant practical interest as engines move to higher operating pressures
  - Significant buoyant forces (scaling with P^2) for terrestrial studies
  - Likelihood of transformative discoveries
  - Significant interest from industry and other government agencies
- Strong endorsement for low temperature cool flames research
  - Leverage discovery of quasi-steady cool flames in FLEX that highlighted potential of microgravity research
- Emphasis for fire safety on fundamental material flammability

2014 Combustion Workshop findings

High Pressure Transcritical Combustion (HPTC) - Highest priority of workshop recommendations. 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.

Spacecraft Fire Safety/Materials Flammability - Future missions to the Moon will present an abundance of technical challenges and ensuring crew safety from accidental or unplanned fires is one of them. These technical challenges go far beyond those present on the International Space Station (ISS) for several noteworthy reasons:

1. The ability of the crew to egress the vehicle and return to safety (e.g., Earth) is much more limited.
2. The Artemis program currently calls for the exploration cabin atmospheres to be significantly higher (0.34 volume fraction) at lower pressure. The means materials will ignite easier, burn faster and require more suppressant and more materials will be flammable.
3. Lunar habitats will not be buoyancy-free and the resulting flow will be strong enough to enhance material flammability and fire spread/growth.

High Pressure Transcritical (HPTC)

Highly inter-disciplinary topic

- Thermophysical properties
- Phase change
- Chemical kinetics

SDT recommended broad range of topics for study in final report to NASA

NASA built hardware and began preliminary experiments

Collaborations initiated with AFOSR

Interest from JAXA and ESA

High Pressure – Transcritical Combustion (HPTC)

Science Team: V. Nayagam, M.C. Hicks, U. Hegde, D.L. Dietrich (in-house effort)
Project Manager: D.L. Dietrich
Engineering Team: E. Neumann, V. Valetta, A. Ogorzally, D. Gotti, J. Owens (in-house effort)
GRC Project Scientist: M.C. Hicks

Objective:

- Leverage the microgravity environment to obtain transformative benchmark data on high pressure, transcritical phenomena
    - Terrestrial laboratory studies compromised by strong buoyant flow (~ P^2)

Approach:

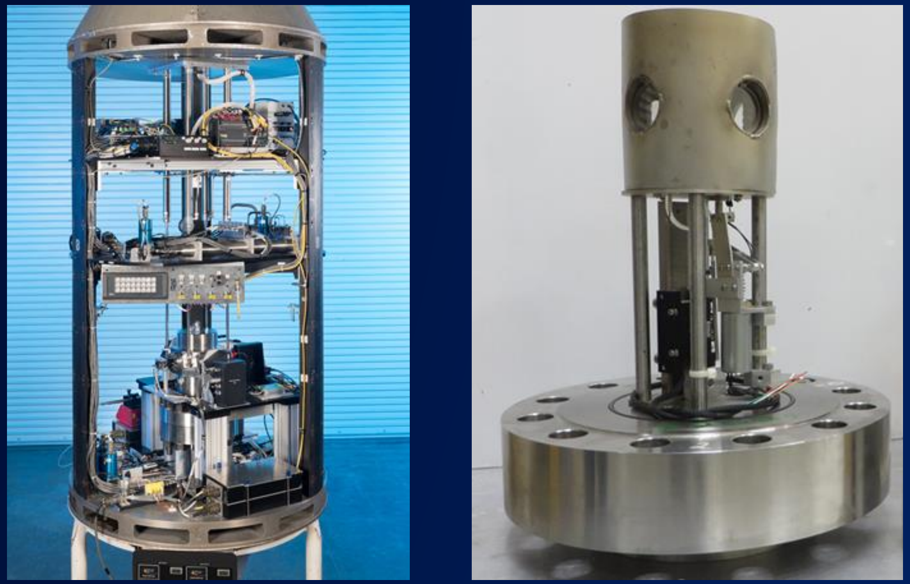
- Design and build HPTC apparatus (chamber, control system, diagnostics) for 0-g facility
    - Demonstrate facility with two studies determined relevant in 2014 combustion workshop
        - Single fuel droplet ignition(idealization of process that occurs in diesel engine for example)
        - Phase interface experiments to study liquid break-up and atomization models
- NRA solicitation to engage peer community based on 2021 SDT report
    - HPTC facility can then support new investigators/investigations (modeling and experiments)

Relevance/Impact:

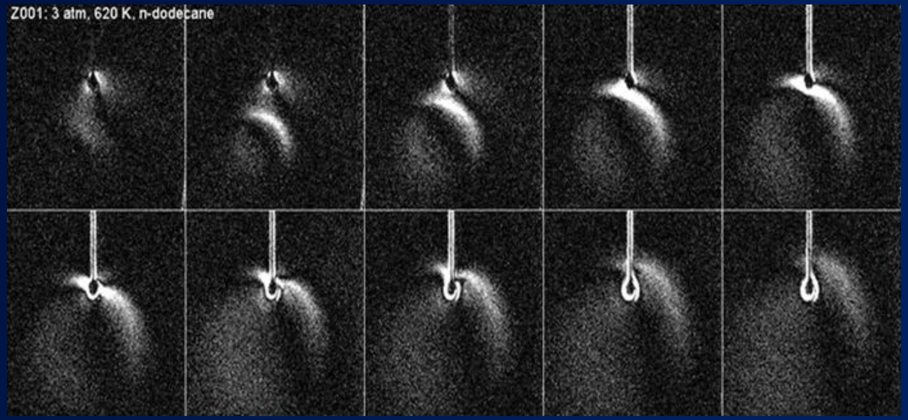
- Strong advocacy in military and industrial applications; e.g., advanced turbine combustors, advanced diesel engines, rocket engines (increased efficiency, power density and reduced emissions)
- Fundamental thermophysical data and thermodynamic state data for supercritical fuel/oxidizer mixtures
- Part of a larger GRC program in high pressure transcritical phenomena that has international collaborations (CNES) and interest from HEO (SCWO).

Research Partners:

- **Collaboration with MUERP** consortium investigating HPTC phenomena led by Prairie View A&M Univ.



High Pressure Transcritical Combustion Facility: shown in drop "vehicle" in drop configuration (L) and close-up of Droplet Module Insert used for high pressure droplet combustion experiments.

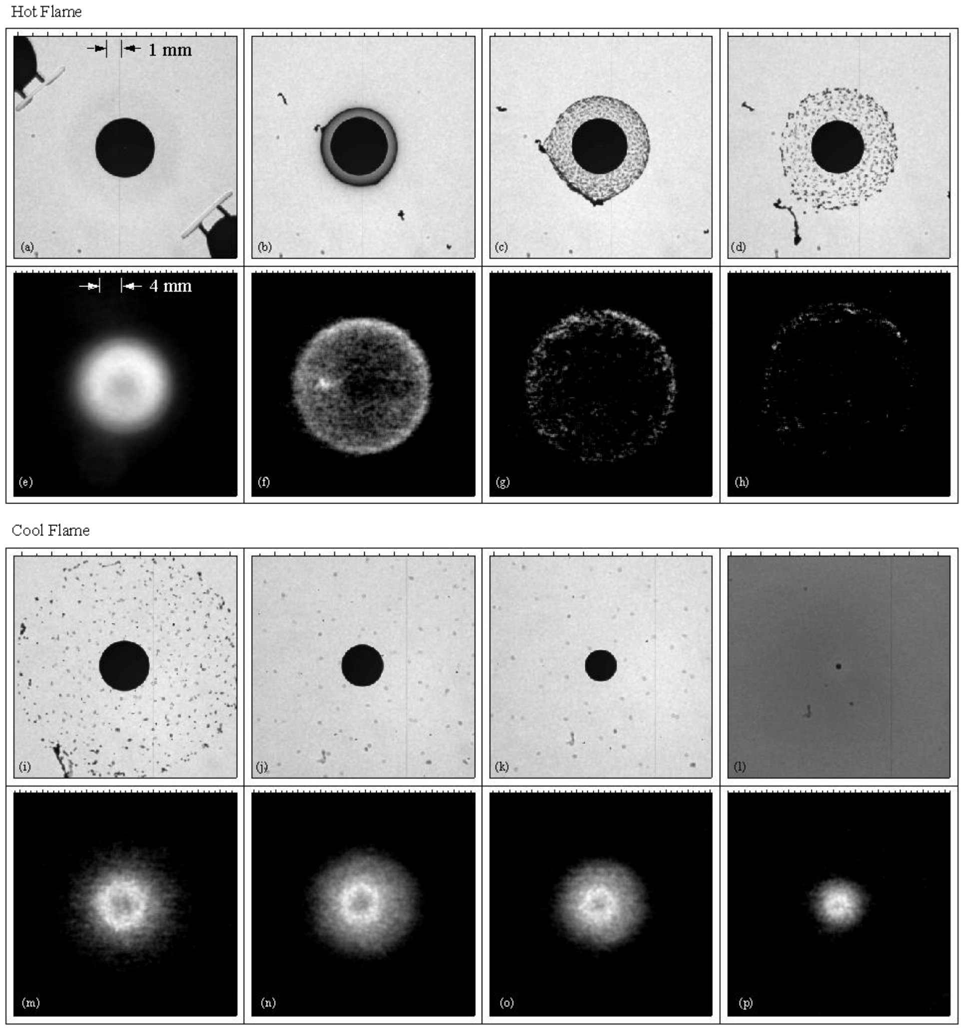


0-g "Cool Flame" showing spherical ignition kernel *diffusively* propagating upward in a dual stage ignition with full ignition occurring shortly after last image frame shown (n-decane 620 K, 2 atm)

Discovery of Quasi-Steady Cool Flames

ISS droplet experiments showed unexpected (and thought to be impossible) cool-flame supported droplet combustion
Relevance: Improved understanding of low temperature chemical kinetics important in future internal combustion engines

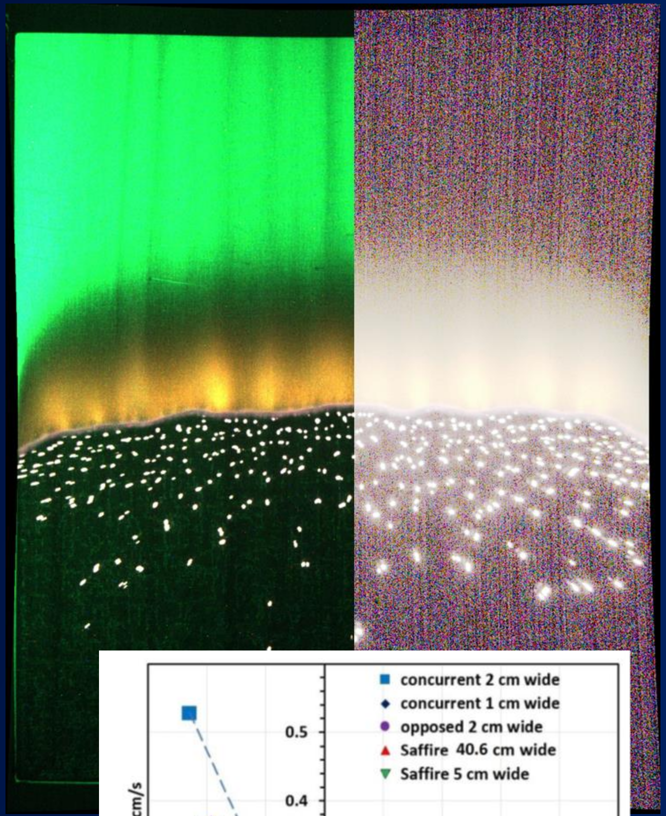
- Over 200 citations between the first two (below) and approximately 500 citations of PI/Co-I publications of ISS cool flame results
- Discovery led to further discoveries of academic and practical importance
  - Spontaneous hot-flame re-ignition
  - Dual flame
  - Warm flames (intermediate temperature chemical kinetics)

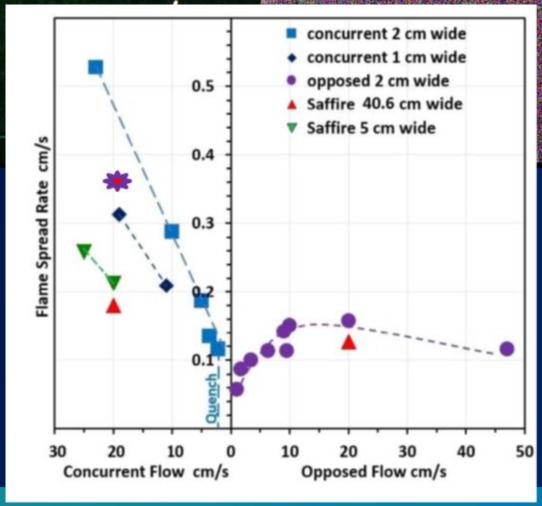


- Nayagam, V., Dietrich, D. L., Ferkul, P. V., Hicks, M. C., and Williams, F. A. (2012). *"Can cool flames support quasi-steady droplet burning"*, **Combustion and Flame**, 159: 3583 – 3588.
- Farouk, T. I. and Dryer, F. L. (2013). *"Isolated n-heptane droplet combustion in*

Spacecraft Fire Safety

- Collaboration with AES
  - BPS focusses on fundamental aspects of material flammability and flame spread
  - AES supports technology development, risk assessment, development of fire standards
- SoFIE next set of experiments in the CIR
- Collaboration with AES on Saffire
  - Large scale fire in an Cygnus re-supply vehicle (performed after undocking from ISS, but before re-entry to atmosphere)
  - International participation from ESA, JAXA, Roscosmos
- Collaboration on JAXA FLARE experiments
- Future experiments focused on hazards of the proposed Artemis atmospheres
  - 34% oxygen, reduced pressure (facilitates EVA)
  - Increased material flammability and fire risk



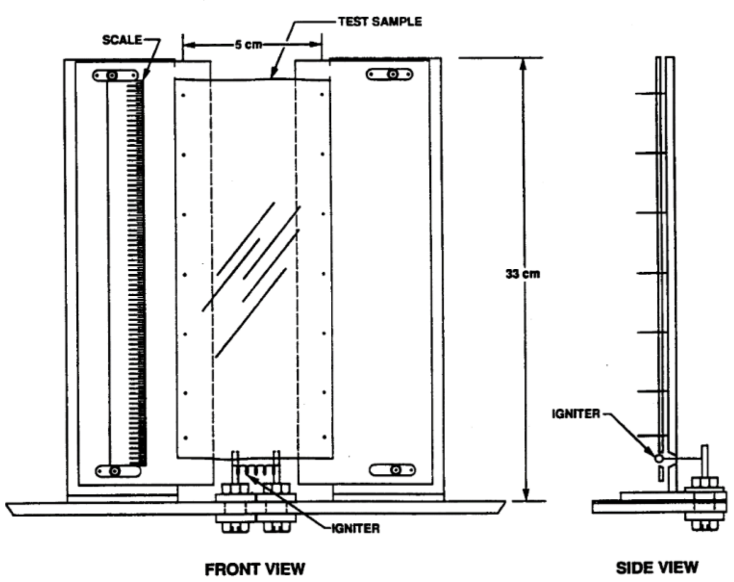


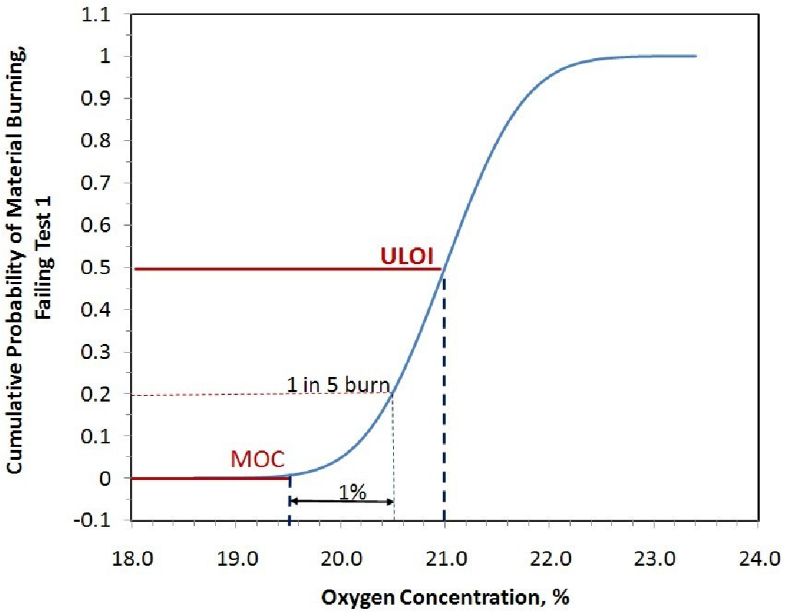
Spacecraft Fire Safety Development

BPS Element →

Function	Capability Gaps	AES Gap Criticality (5 highest)
Fire Detection	Early fire detection; particle size discrimination	2
Fire scenario modeling and analysis	Determination of a realistic spacecraft fire	3
Post-fire clean-up/smoke eater	Contingency air purifier for post-fire and leak cleanup; Reduce incident response time for suit DON and purging atm	4
Elucidate fundamental physical/chemical aspects of material flammability	**Identify material flammability limits in reduced gravity**	**4**
Combustion product monitoring	Contingency air monitor for relevant chemical markers of post-fire clean-up (CO, CO_2, HF, HCl, HCN); battery operated; hand-held; 1 – 5 year calibration; vacuum compatibility	5
Emergency crew mask	Single filtering cartridge mask (fire, ammonia, toxic spill), compatible with small cabin volumes (no O_2 enrichment)	5
Fire suppression	ECLSS-compatible and rechargeable fire suppression; compatible with small cabin volumes	5

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



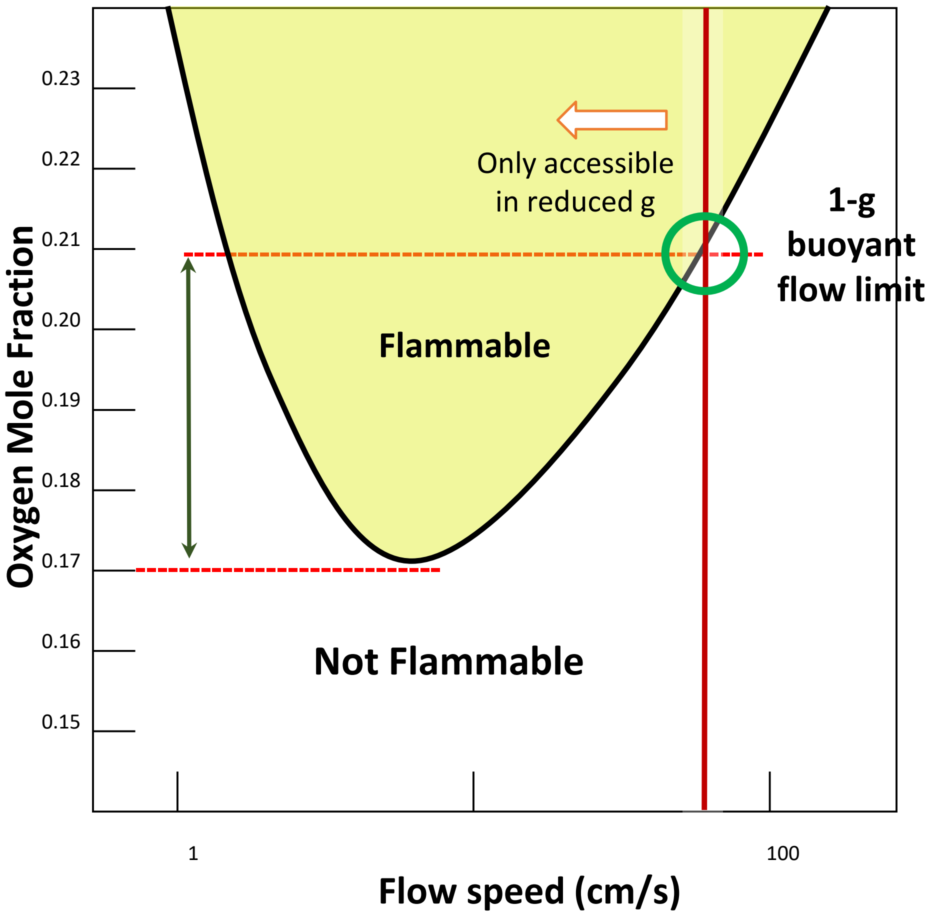


- Fails test if sample material is consumed past 15 cm
- Assumed to be worst case scenario for flammability
- Some materials have shown the opposite results
- Other figures of merit
  - Maximum Oxygen Concentration (MOC): all tests will pass the test
  - Upward Limiting Oxygen Index (ULOI): half of the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

Material Flammability Maps

- 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 <u>0.02 and 0.06 by volume</u> 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



Spacecraft Fire Safety Program

Transforming NASA's spacecraft fire safety practices to performance-based certifications and risk-based analyses requires a knowledge of fire behavior in spacecraft environments that is currently severly lacking

Technology Needs Drive Science

BPS

- Fundamental science building blocks of fire safety
- Flame extinction
- Chemical kinetics
- Property evaluation
- Radiative transport
- Fundamental models of ignition/flame spread

- Hardware (CIR, Subobital Lunar –g , (MWT on hold)
- PI community
- GRC in-house team

AES

- Technology development
  - Fire detector
  - Fire extinguisher
- Large scale testing
  - Vehicle-scale experiments (e.g.Saffire)
  - Vehicle specific considerations (e.g. Orion hatch design)
- Engineering level test campaigns
  - Battery safety
  - Testing of real spacecraft materials
  - Technology evaluation
- Model development
  - Vehicle scale modeling
  - Risk assessment
  - Design tools

Science Feeds Technology Development

Physical Sciences Informatics System - PSI

Solicitation - Physical Science Informatics (PSI) 2021

- **ROSES - 2021 PSI Program Element**

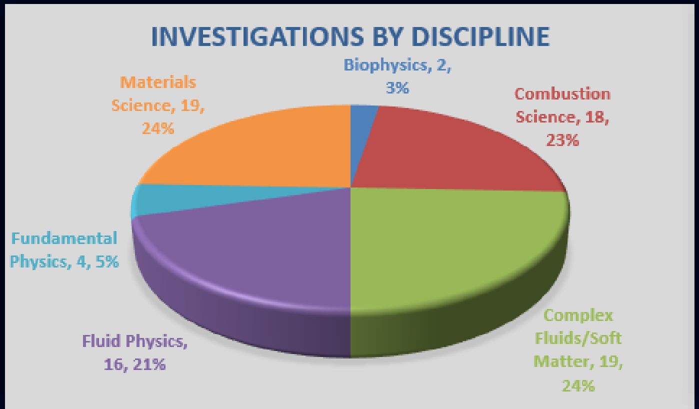
- Released: September 15, 2021
- Eligible flight and ground investigations: 78
- Proposals Due: January 10, 2022
- Selections (target): June 2022

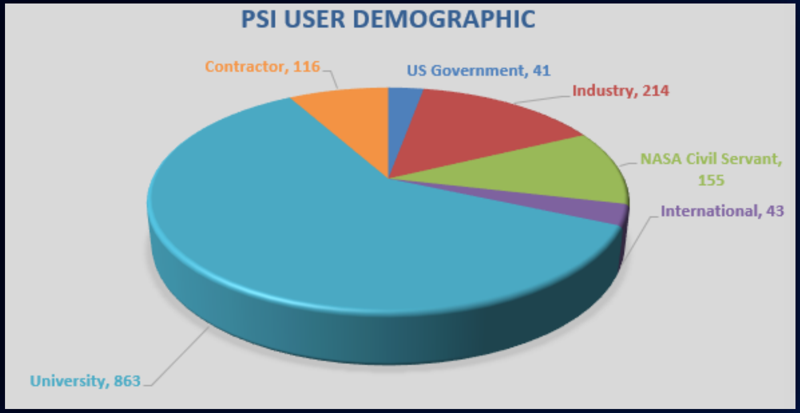
- Solicits ground-based research proposals. (Annually)
- Solicits proposals from the following six research areas: Biophysics, Combustion Science, Complex Fluids, Fluid Physics, Fundamental Physics, and Materials Science.
- Ground-based research proposals that present a compelling case on how the data 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/year for two years.
- Approximately 5 proposals will be selected.

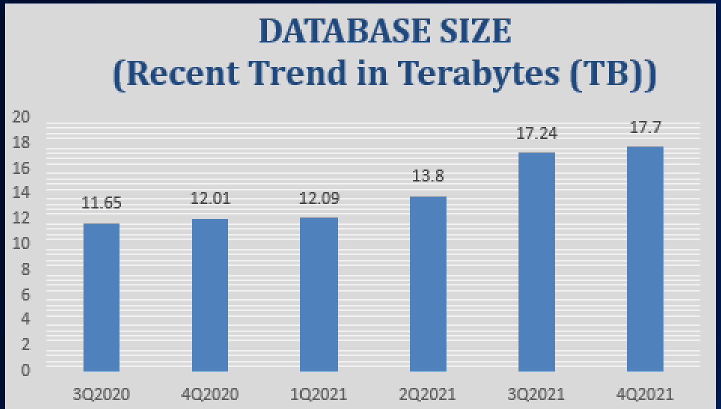
- The program element will be available in NSPIRES as part of ROSES-2021.
- For additional information on the PSI database, visit: https://nasa.gov/PSI

PSI Statistics (Oct 2021)

78 Investigations | 1,432 Users (+32) | 174 Proposals | 36 Awarded PIs

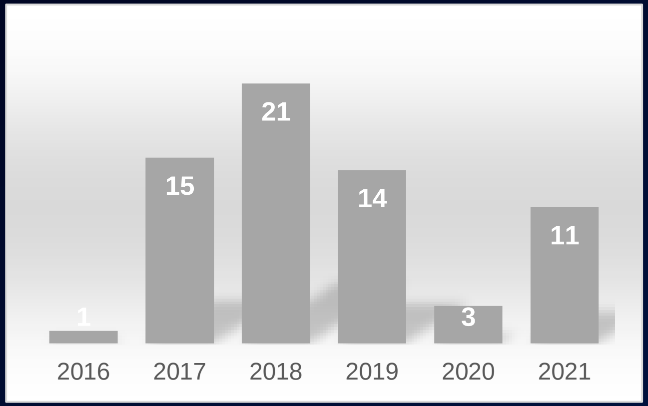


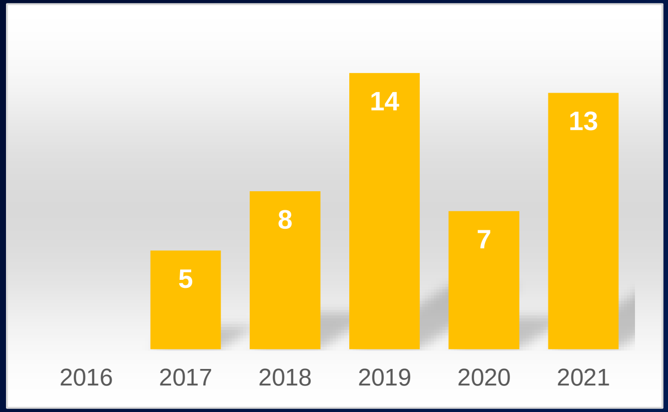


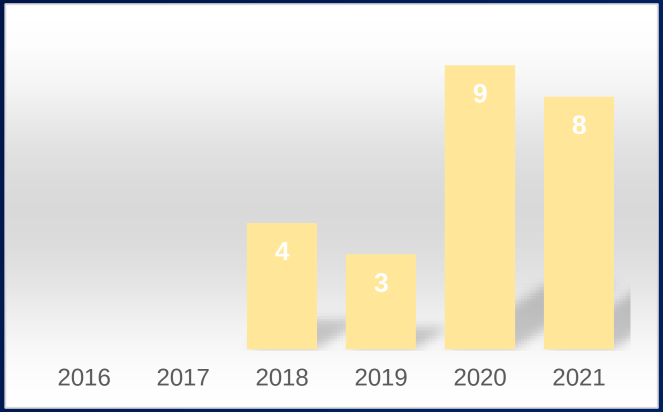


PSI Metrics

65 Presentations/Abstracts (+2) | 47 Journal Articles | 24 Other Pubs








Thank you