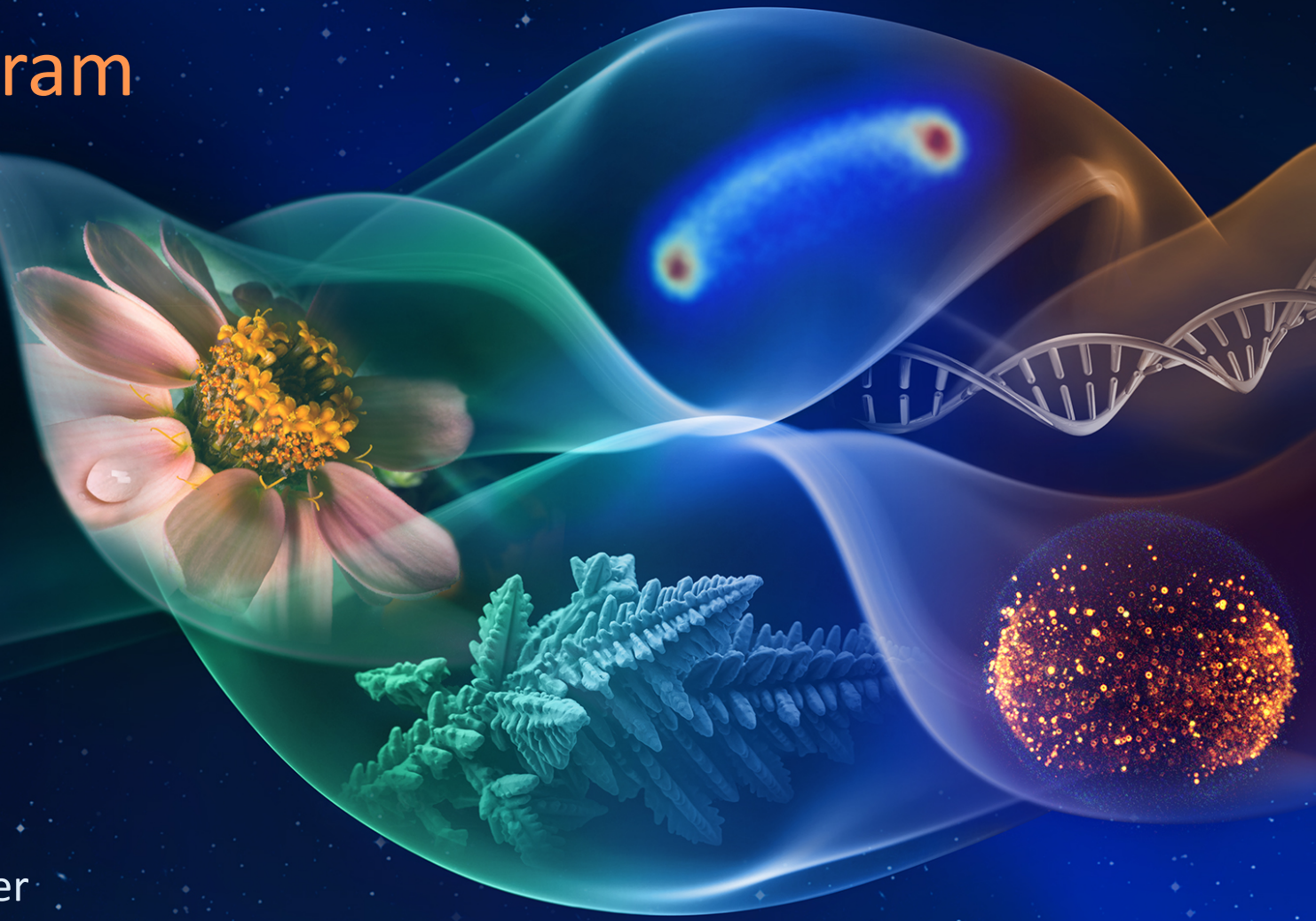
Overview of NASA's Reduced-Gravity Research Program



JASMAC 33
October 2021

David L. Urban
NASA John H. Glenn Research Center

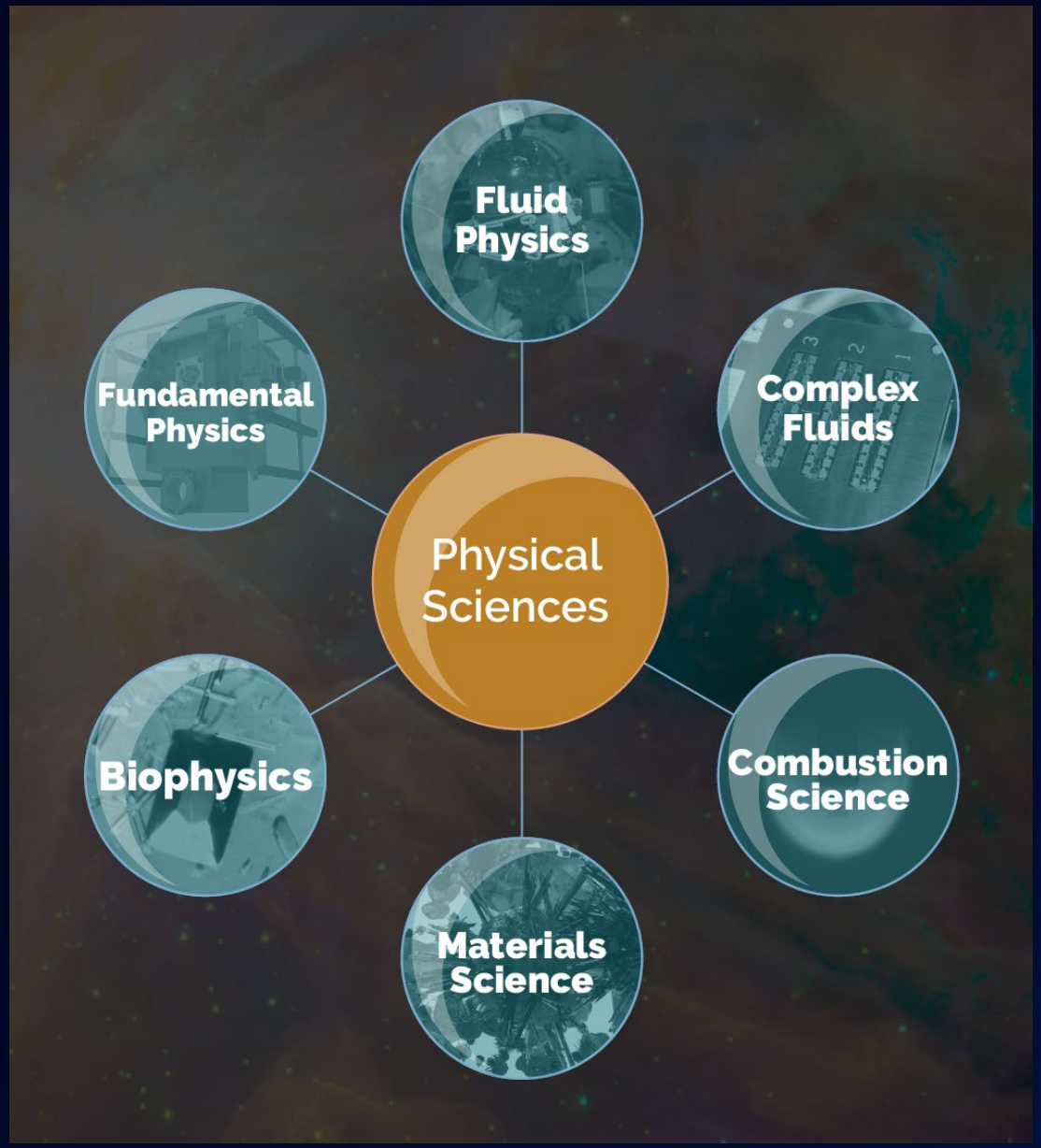


Agenda

- **Physical Science**
- **Life Science**

Contributors

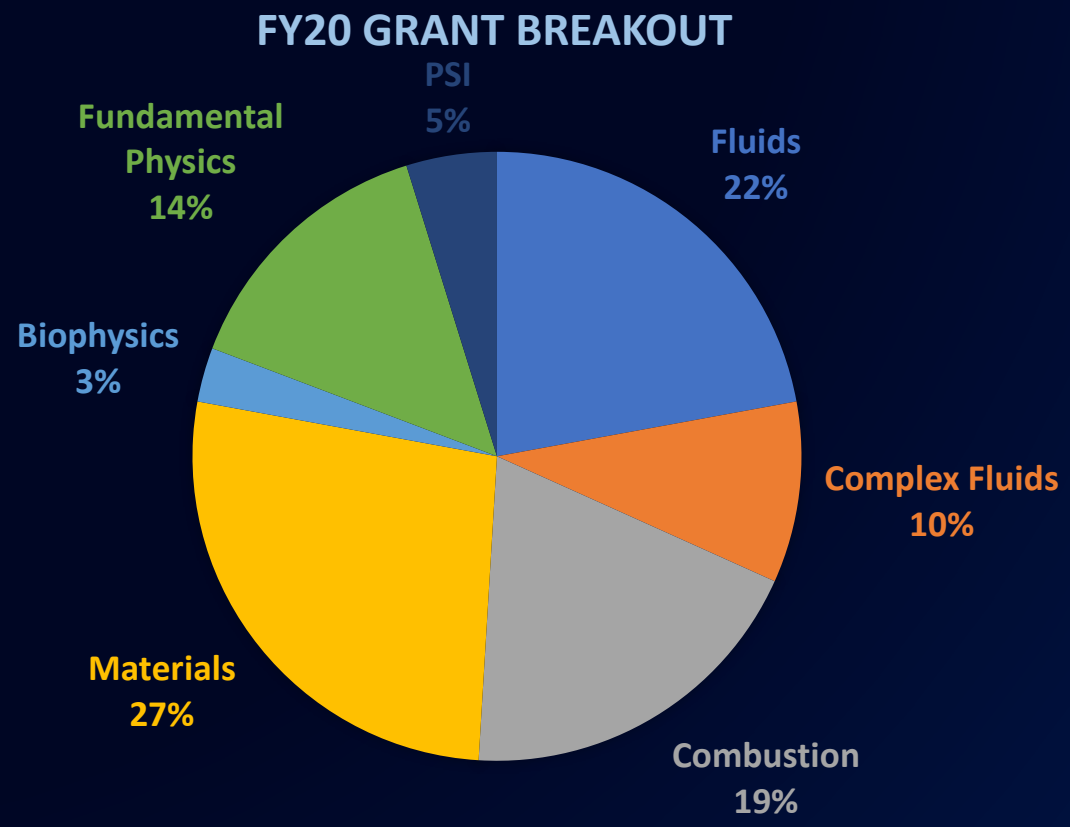
- **Fran Chiaramonte, Program Scientist for Physical Sciences**
- **Brad Carpenter, Fundamental Physics Program Scientist**
- **Sharmila Bhattacharya, Space Biology Program Scientist**



Physical Sciences Objectives

- Investigate **fundamental laws** of physics and **physical processes** using the space environment
- Identify the underlying **processes** and develop models for physical systems in space
- Develop **technologies** to enable spaceflight research
- Promote **open science** through Physical Science Informatics
- Transfer the knowledge and technology of space-based research to **benefit life on Earth**

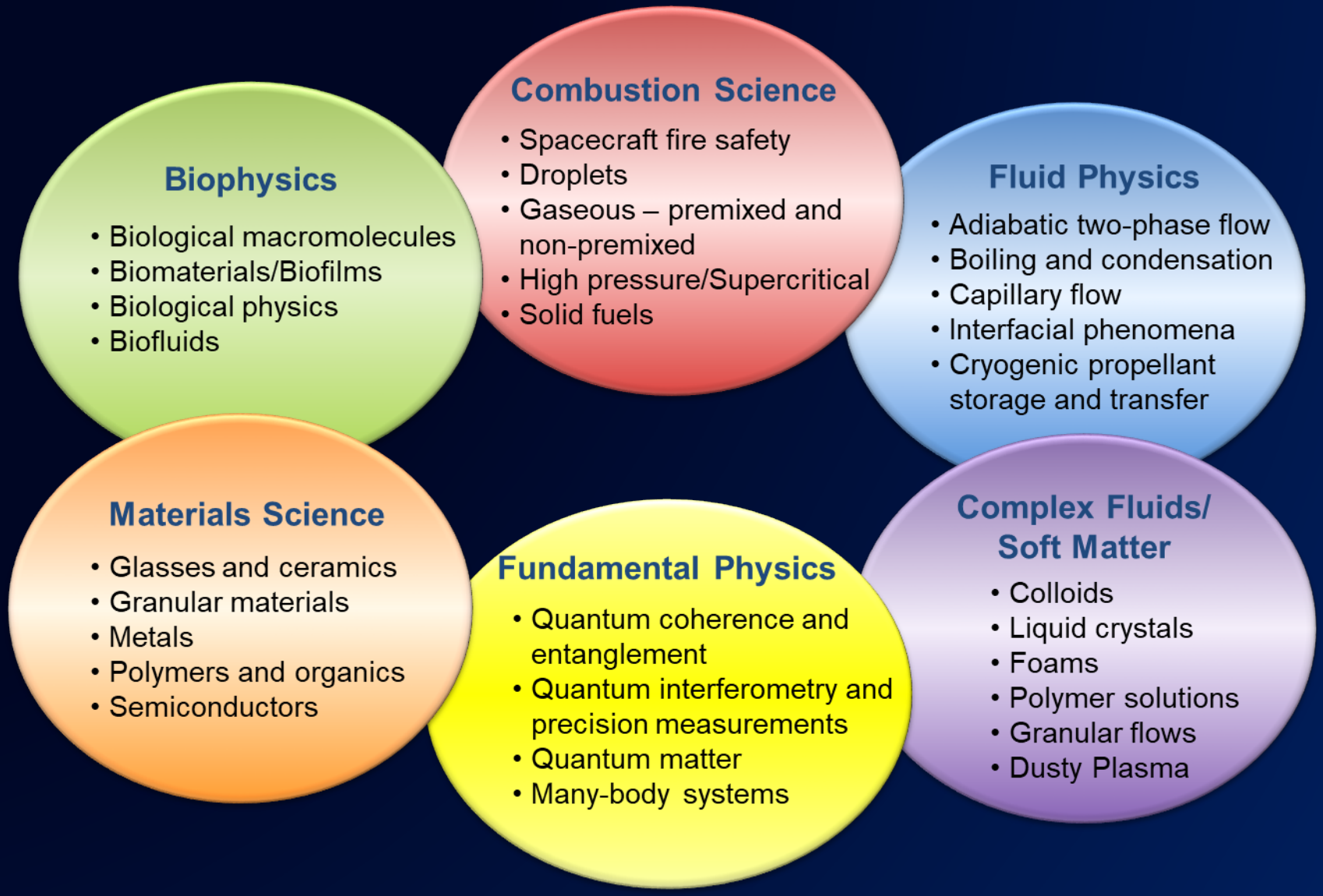
Physical Sciences Content



Total PS FY20 Grants	104
Flight	64
Ground	40

Number Directed vs Competed	
Directed	10
Competed	94

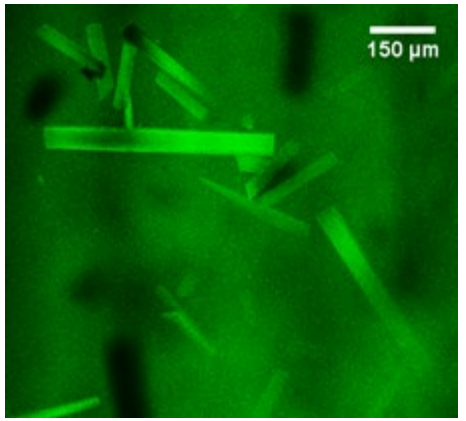
Physical Sciences Program Overview



Biophysics

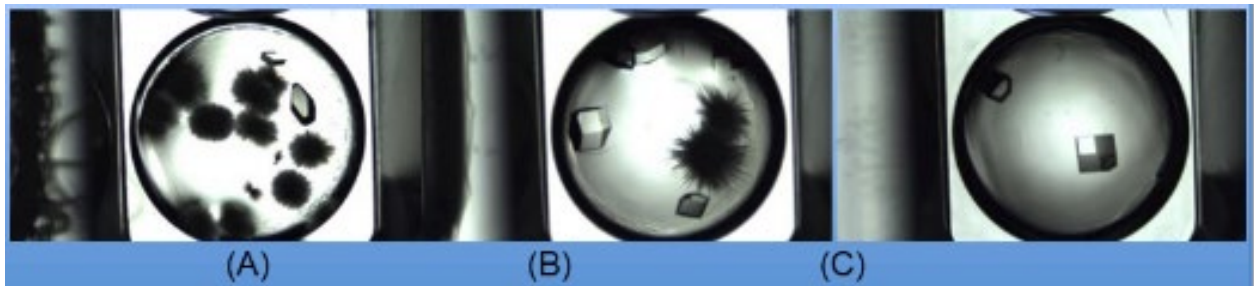
Protein Crystal Growth

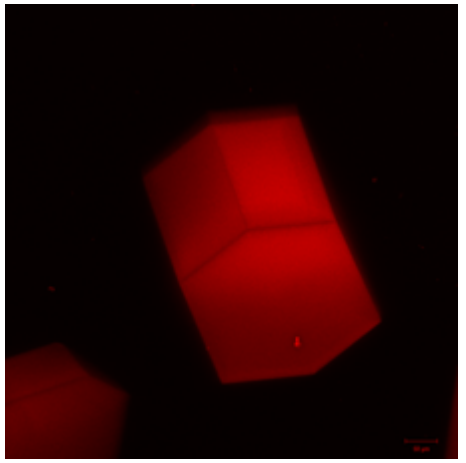
The Light Microscopy Module (LMM) is a modified commercial, highly flexible, state-of-the-art light imaging microscope facility that provides researchers with powerful diagnostic hardware and software onboard the International Space Station (ISS).



ISS-grown crystals of fluorescently-labeled pfGST (DeLucas).

The Real-Time Protein Crystal Growth - 2 (RTPCG-2) project is designed to allow protein crystallization experiments on the International Space Station (ISS) that more closely mimic terrestrial methods, with on-orbit screening and optimization of crystallization conditions in an iterative process.



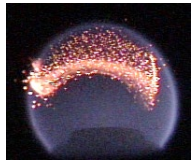


ISS-grown crystals of fluorescently-labeled lysozyme (DeLucas).

Combustion Science

Fundamental Combustion - Gaseous Fuels

Advanced Combustion via Microgravity Experiments (ACME)



Burning Rate Emulator (BRE)
Quintiere & Sunderland: UMd
A fire safety experiment using gaseous fuels to study solid fuel flammability



Electric-Field Effects on Laminar Diffusion Flames(E-FIELD Flames)
Dunn-Rankin: UCI
An experiment using electric fields to control flames



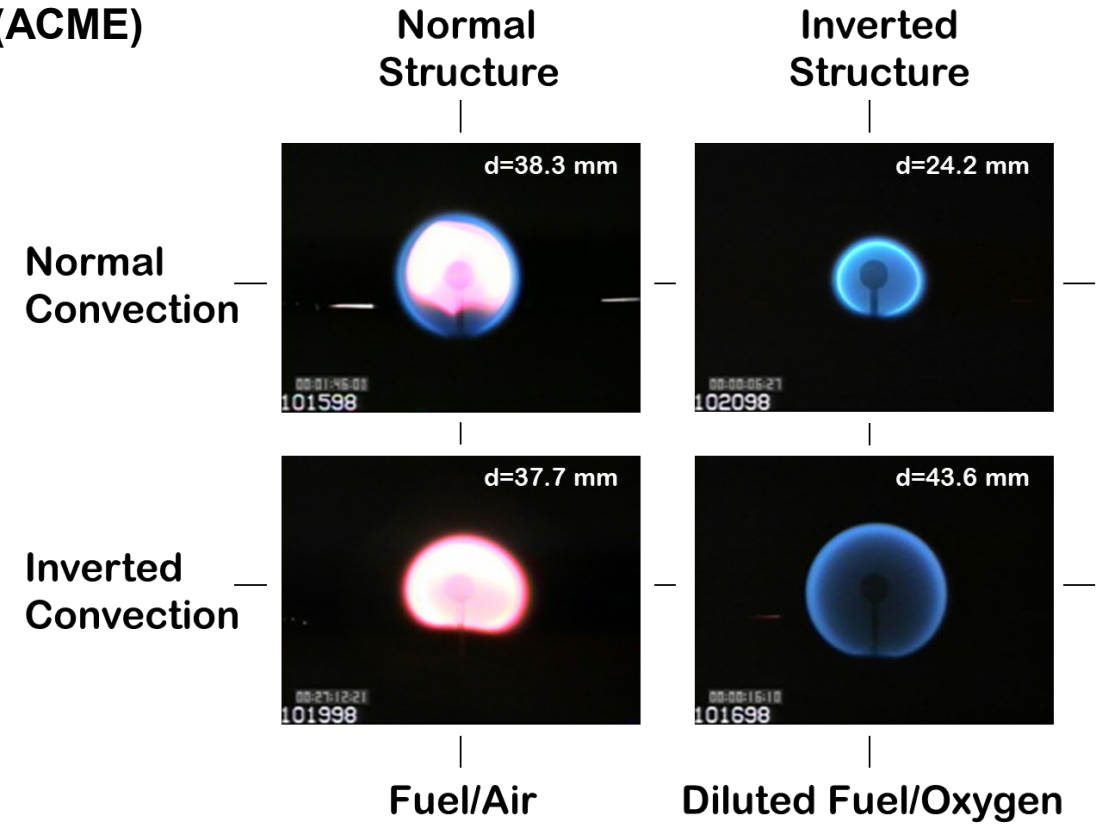
Flame Design
Axelbaum: WUStL et al.
Experiments examining soot inception and transport and flame structure



Structure and Response of Spherical Diffusion Flames (s-Flame)
Law: Princeton
An investigation studying soot formation/destruction mechanisms and combustion chemistry



Coflow Laminar Diffusion Flame (CLD Flame)
Smooke and Long: Yale
Detailed experiments on the structure and stability of gas-jet diffusion flames

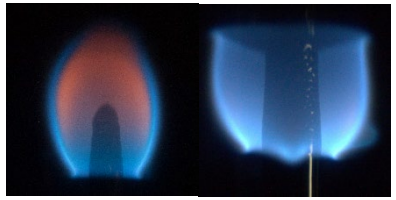


$\dot{m}_{C_2H_4} = 1.51 mg/s$

Flame Design: Axelbaum WUStL et al.
Soot inception and transport through control of the flame structure
To guide lower polluting combustors and to facilitate carbon sequestration

Spacecraft Fire Safety - Solid Fuels

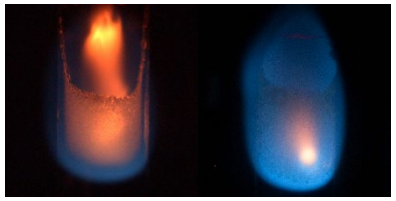
Solid Fuel Ignition and Extinction (SoFIE)



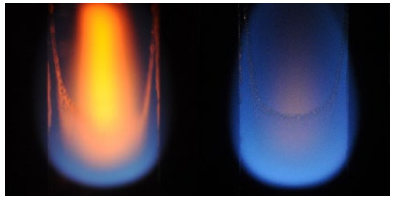
Material Ignition and Suppression Test (MIST)
Fernandez-Pello: UC Berkeley
Fundamental experiments of solid material ignition from an external heat source



Spacecraft Materials Microgravity Research on Flammability (SMµRF)
Olson: NASA GRC
Flame spread experiments studying the flammability limits of solid fuels



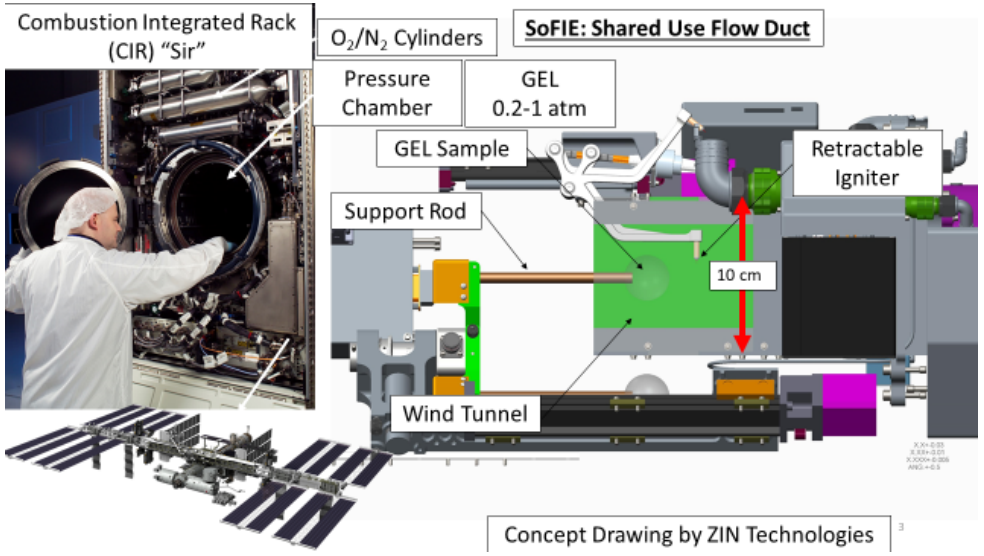
Narrow Channel Apparatus (NCA)
Miller: San Diego State University
Flame spread experiments focused on thick polymeric materials



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, O_2, pressure, and fuel preheating on the combustion of polymeric spheres



Supercritical Water Mixture and Oxidation (SCWM and SCWO)

High Temperature Insert HTI/HTI-R1/ HTI-R2

Pure SCW — 2011

DECLIC

SCW / salt solution — 2017

SCW / TBD (salt-2 / CO2) — 2021

DECLIC-Evo

SCWO — ca 2024

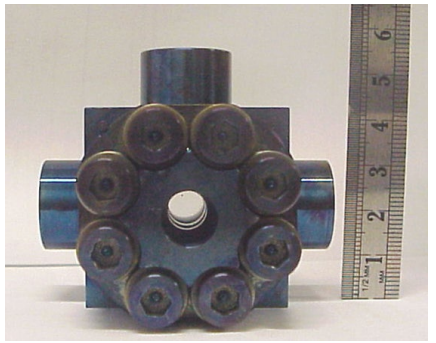
SCWO-D Insert

Behavior of Pure Water Near the Critical Point
Yves Garrabos, ICMCB, Bordeaux, PI
Carole Lecoutre, ICMCB
Michael Hicks, GRC
Uday Hegde, CWRU

Behavior of a Salt-Water Mixture Near the Critical Point-1 (SCWM-1)
Michael Hicks, GRC, PI
Uday Hegde, CWRU
Yves Garrabos, Carole Lecoutre, Sam Marre, ICMCB, Bordeaux

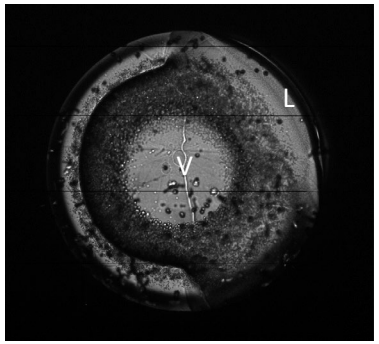
Behavior of a Salt-Water Mixture Near the Critical Point-2 (SCWM-2)
Michael Hicks, GRC, PI
Uday Hegde, CWRU
Yves Garrabos, Carole Lecoutre, Sam Marre, ICMCB, Bordeaux

Supercritical Water Oxidation (SCWO) Processes Including Phase Transitions, Transcritical Fluid Dynamics and Hydrothermal Flames

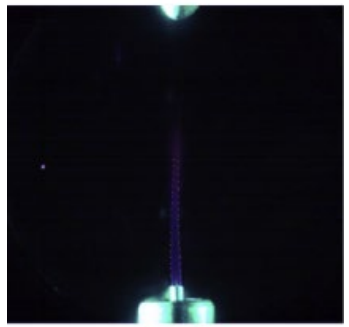


HTI/HTI-R insert (DECLIC)

DECLIC Hardware developed by:
CNES, Toulouse
Cecile Fiachetti, PM
Christophe Delaroche, PM



Dissolution of the Liquid (L)-Vapor (V) interface near the critical point (SCWM-1)



10 mm

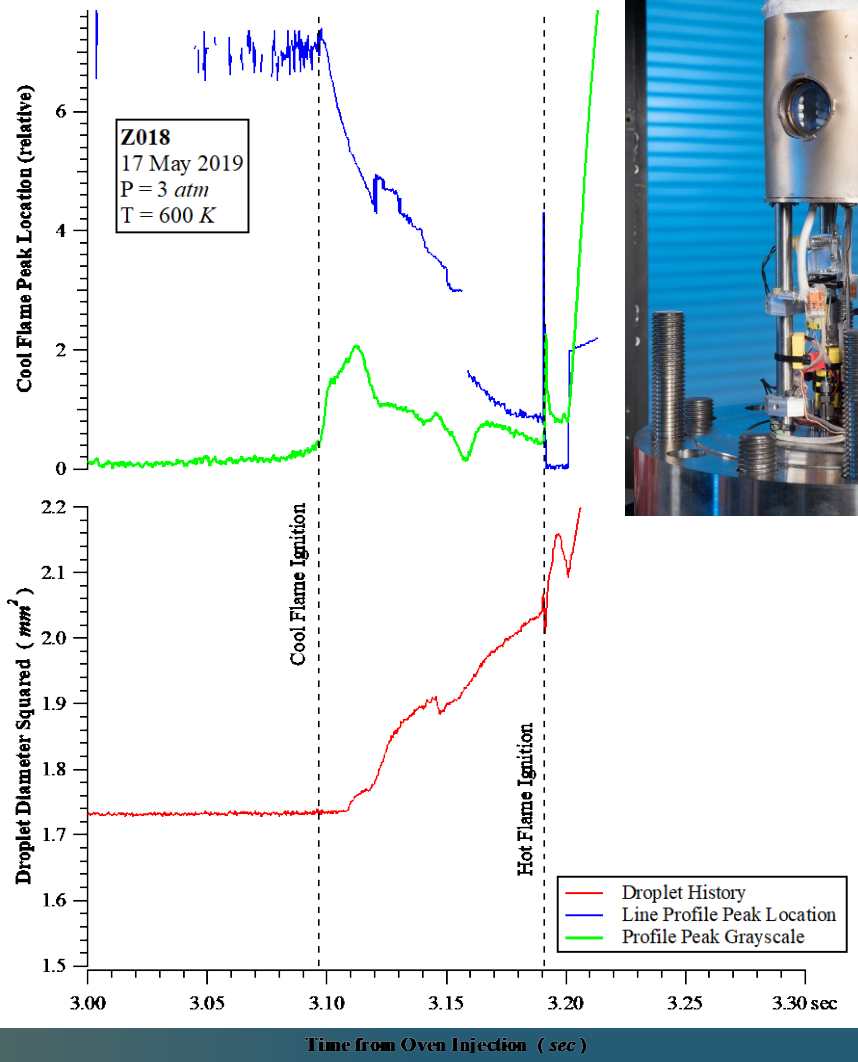


Ethanol-Water Hydrothermal Flames-GRC SCWO Lab

Future Combustion Research

High Pressure Transcritical Combustion (HPTC)

- Highest priority research area from 2014 peer-review of combustion program
- Leverage the discovery of cool-flame supported droplet combustion
- High pressure facility built and operational in GRC Zero-Gravity facility
- On-going experiments involving droplet ignition
- Access to high quality microgravity environment offers significant potential to improve understanding of high pressure combustion
- Science Definition Team to provide peer input for future activities in process



Reduced Gravity Flammability Threshold Tests

Objective

- **Quantify the low-g oxygen upward flammability thresholds for typical spacecraft materials and compare results with thresholds determined in normal gravity**

gravity

Ultem 1000



Nomex



Mylar



Right: Centrifuge test rig for the Zero Gravity Facility



- **Tests were conducted in Zero Gravity Facility at NASA-GRC for Ultem 1000, Nomex, and Mylar**
  - 5.2-sec limits samples to thin materials
- **Modified test technique to determine the extinguishment limit (Maximum Oxygen Concentration)**

Ferkul, P. V. and Olson, S.L., Zero-Gravity Centrifuge Used for the Evaluation of Material Flammability in Lunar-Gravity, AIAA 2010-6260, 40th Int. Conf. Env. Syst, (2010).

Blue Origin New Shepard Partial-g Concept

- Blue Origin's New Shepard vehicle is being upgraded to enable rotation about it's vertical axis during the low gravity portion of the flight
- Flight Opportunities Program purchased payload space on New Shepard for the initial flight
- Concept of Operations
  - Capsule is spin-stabilized at apogee using its reaction control system
  - Up to 2 minutes of lunar-g at steady state
  - Lunar-g ~11 rpm at 1.25 m
- Capabilities
  - Individual payloads up to 150 lbm
  - Single, double, and full stack lockers
    - 20.6' x 16.3" x 9.5"; 20.6" x 16.3" x 18"; 28" x 32" x19", respectively
  - Greater that 800 W available
  - Total payload capacity up to 900 lbm
- Proof-of-Concept Flight planned for early 2023



Saffire-IV, V, and VI Summary

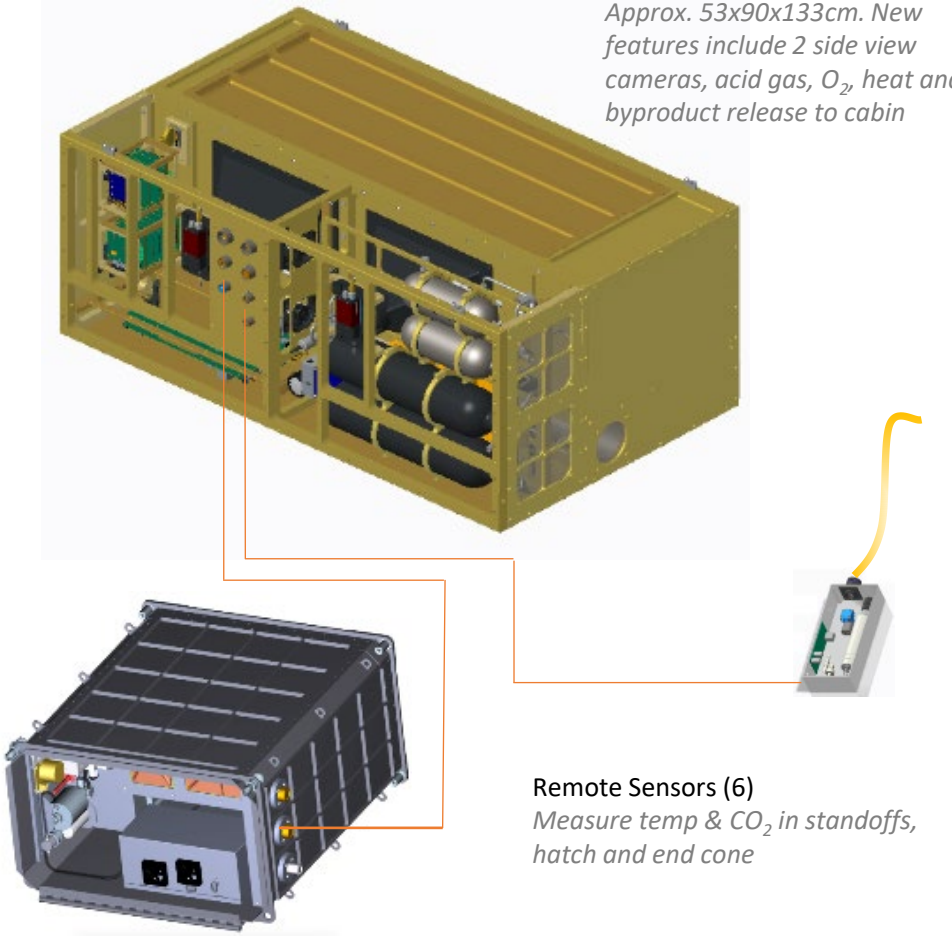
Needs:

- Demonstrate spacecraft fire monitoring and cleanup technologies in a realistic spacecraft fire scenario
- Characterize fire growth in high O_2, low pressure atmospheres in microgravity
- Obtain data to validate models of realistic spacecraft fire scenarios

Objectives:

Assess flame growth and spread of large-scale microgravity fire (spread rate, mass consumption, heat release) in exploration atmospheres

- Evaluate fire behavior for a range of materials and configurations
- Demonstrate fire monitoring and response technology on all three flights



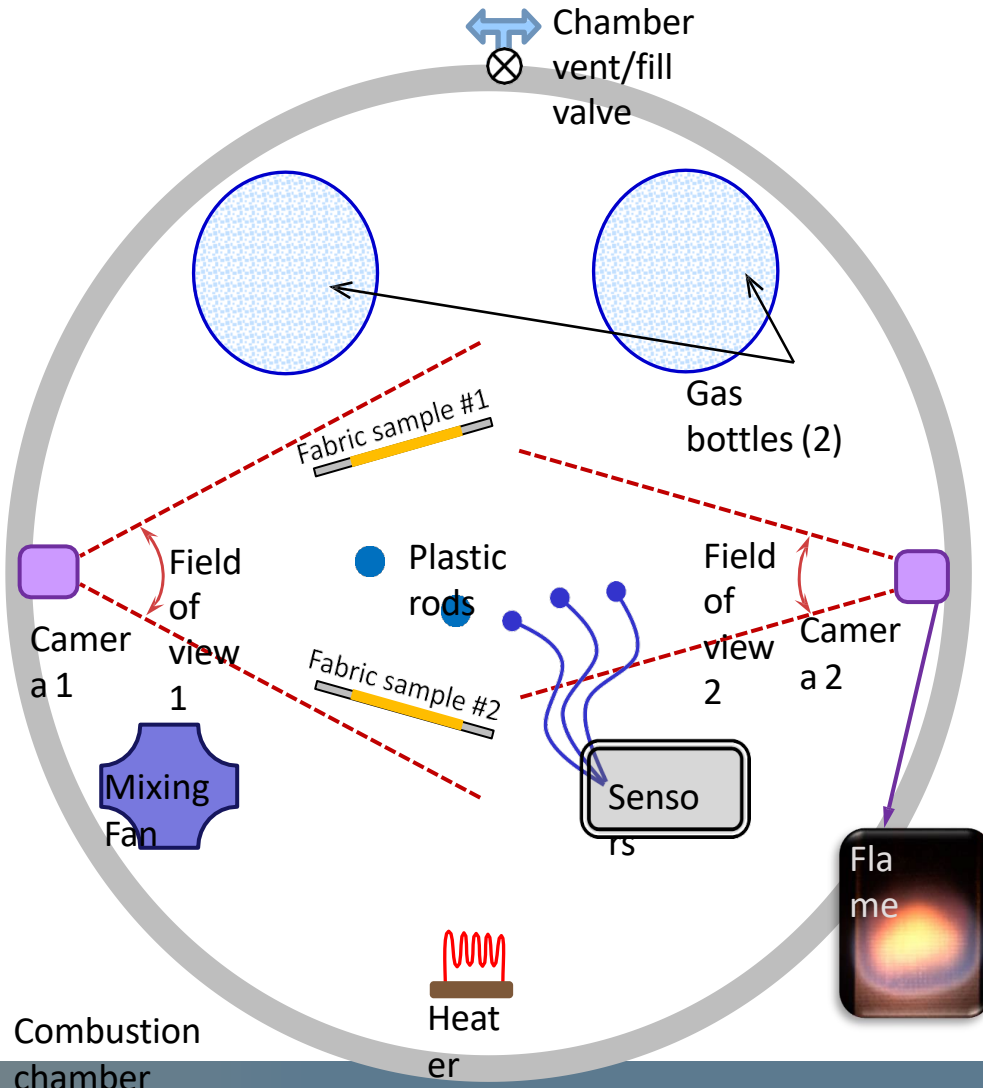
Saffire Flow Unit
Approx. 53x90x133cm. New features include 2 side view cameras, acid gas, O_2, heat and byproduct release to cabin

Remote Sensors (6)
Measure temp & CO_2 in standoffs, hatch and end cone

Far Field Diagnostics (in Mid Deck Locker)
Avionics, CO_2 scrubber, Smoke Eater, Combustion Products Monitor, particulate monitors (DustTrack & Ion Chamber)

Commercial Lunar Payload Services (CLPS) experiment

- Hypothesis: some materials burning in Lunar-g are more flammable than on Earth. This has important implications for the current 1-g material screening method used by NASA
- Four fuel samples individually burned in Lunar gravity; Cameras and other sensors record flame characteristics.
- Oxygen limits for upward and downward spread on the Moon will be compared to 1-g values.
- Measured flame characteristics in 1-g and Lunar-g will be compared to detailed model predictions. These comparisons will refine pressure-gravity scaling relations and will be applied to other g-levels.

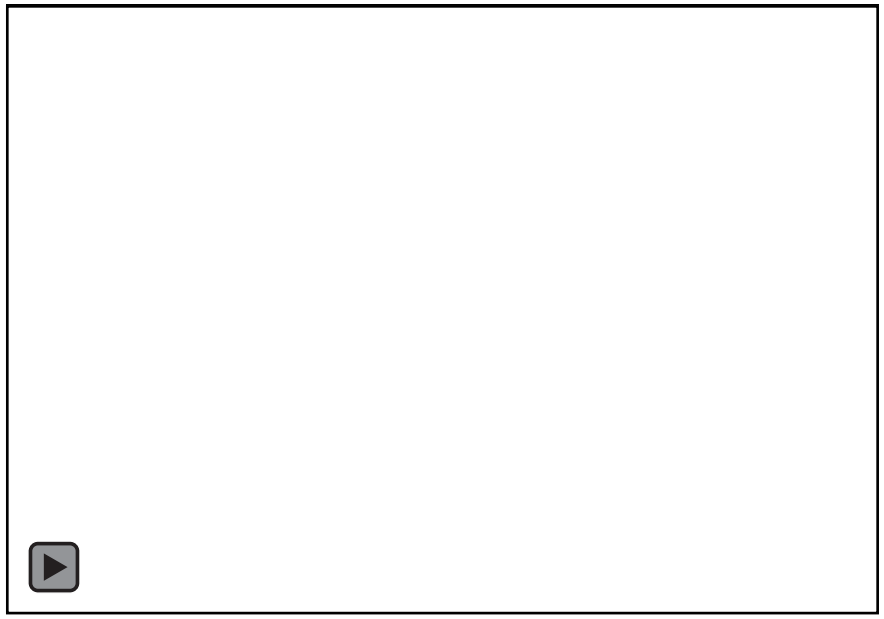


Complex Fluids

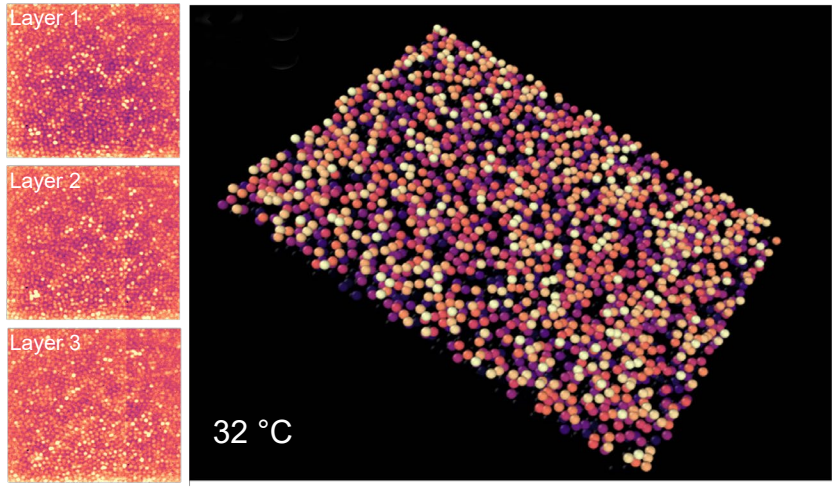
Complex Fluids: Colloids

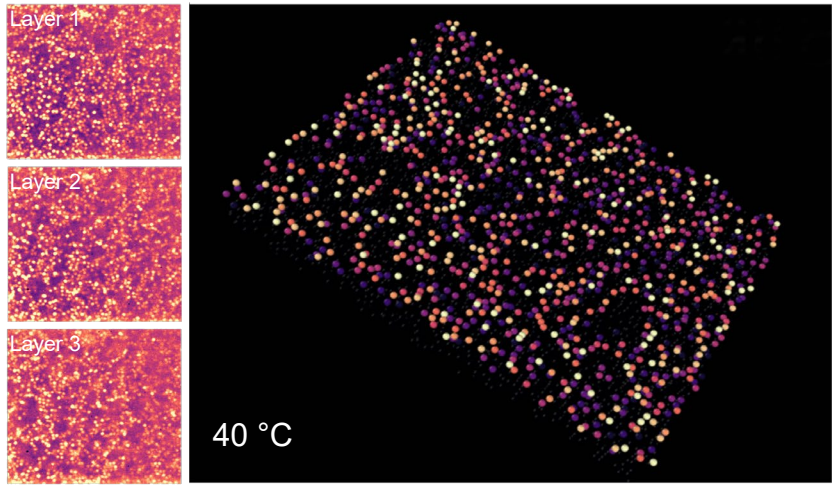
Advanced Colloids Experiments – Temperature Controlled (ACE-T)

Objectives: Obtain phase diagrams as a function of temperature, particle concentration and geometry.



ACE-T6





ACE-T4 Examine the evolution of microstructure of gels and in response to internal stresses as a function of temperature. These insights, enabled by microgravity, could be useful for the design of tougher and more durable gels.

Fluid Physics

Boiling and Condensation

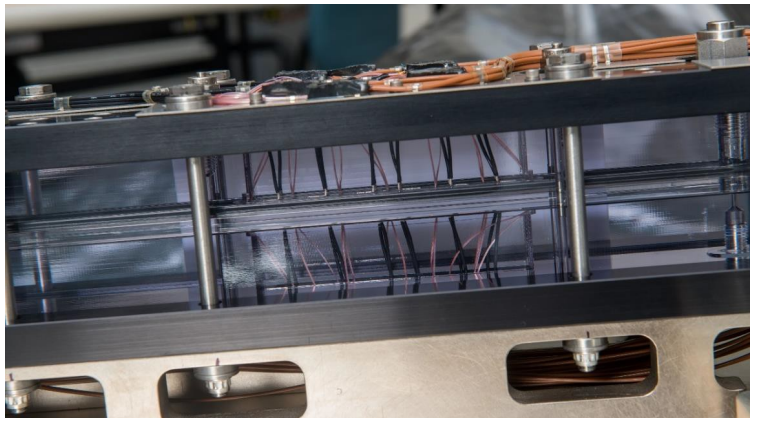
Objectives:

- Obtain flow boiling database in long-duration microgravity environment
- Obtain flow condensation database in long-duration microgravity environment
- Develop experimentally validated, mechanistic model for microgravity flow boiling critical heat flux (CHF) and dimensionless criteria to predict minimum flow velocity required to ensure gravity-independent CHF
- Develop experimentally validated, mechanistic model for microgravity annular condensation and dimensionless criteria to predict minimum flow velocity required to ensure gravity-independent annular condensation; also develop correlations for other condensation regimes in micro

Applications:

- Rankine Power Cycle
- Two-Phase Thermal Management Systems
- Cryogenic Line Chill-down

Heated Section of Flow Boiling Test module



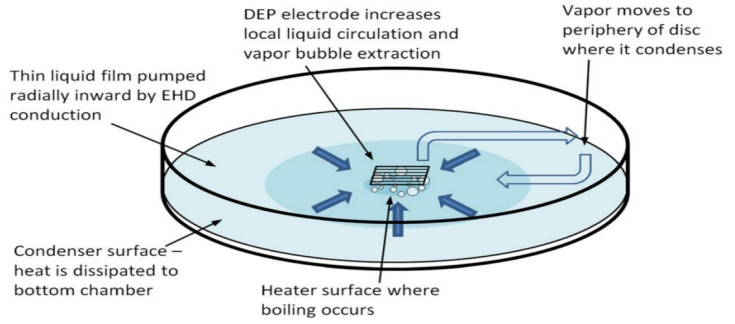
μG Flow Boiling Test on aircraft



μG Condensation Test on aircraft



EHD experiment Concept

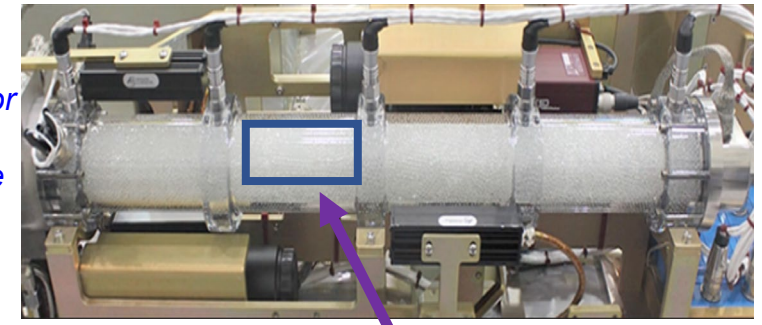


Adiabatic Two-Phase Flow

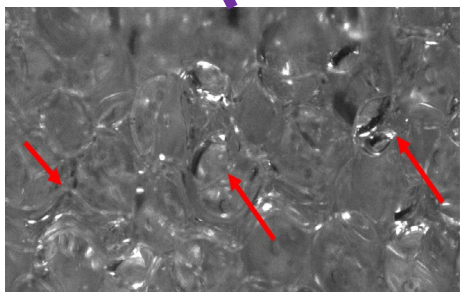
Objectives:

- Investigate the impact of packing diameter on the role and effects of gravity on hydrodynamics of gas-liquid flow through porous media. Packed Bed Reactor Experiment (PBRE-1)
- Extended investigation on the impact of packing diameter on the role on hydrodynamics of gas-liquid flow through porous media in microgravity. Packed Bed Reactor Experiment (PBRE-2**)**,
- Develop/validate scaling laws and design tools for future water recovery system components such as filtration beds, filters and fittings in μ-g and partial-g environments, including start up and transient operations. Packed Bed Reactor Experiment-Water Recovery (PBRE-WR)

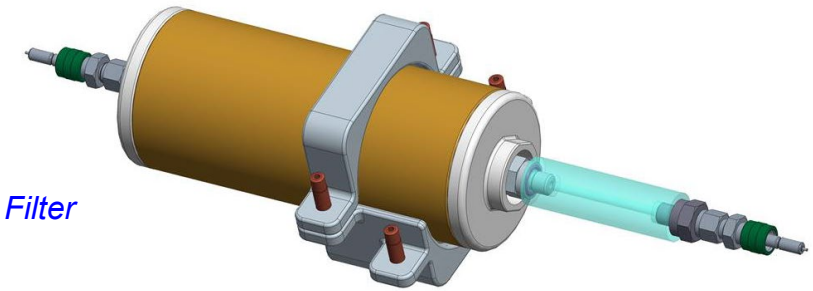
Packed Bed Reactor Experiment Test Section and Cradle



Trapped bubbles inside the packed bed affect the pressure drop and distribution and flushing the column before each run with gas or liquid seems to impact the effective porosity in the bed



CAD Model of Urine Transfer Filter Test Article



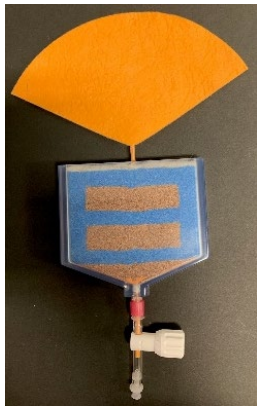
Capillary Flow

Plant Water Management (PWM) Objectives:

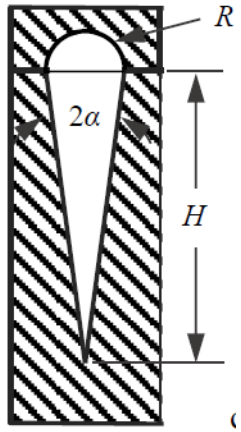
- Evaluate options for adequate hydration and aeration techniques for soil media and other farming strategies including but not limited to: Aeroponics, Hydroponics, and Soil-based media

Test Modules:

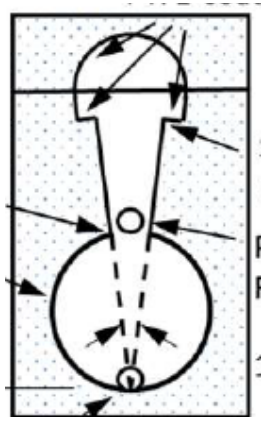
- Soil (PWM-S): Establish a “capillary gradient” using material wettability to provide controlled to establish the ability to compare typical
- Hydroponics (PWM-H): Demonstrate the ability to utilize system geometry to provide positive water control for plant hydration.
- Root Accommodation Channel (PWM-HRAC): 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.



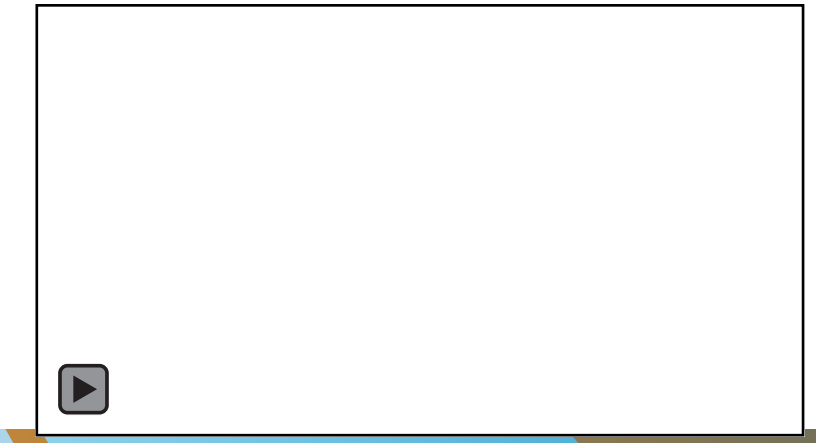
PWM –S test cell



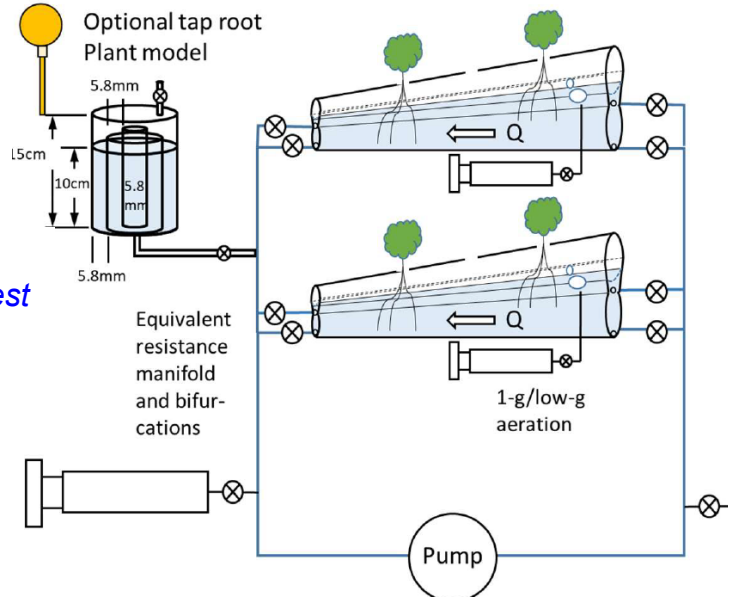
PWM –H Cross-Section



PWM –HRAC Cross-Section



Portland State Drop Test of PWM-H with plant simulate

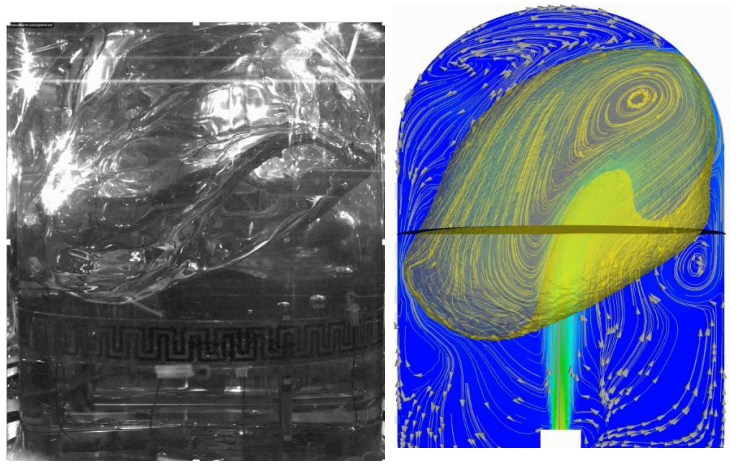


PWM – PHRAC Test Setup

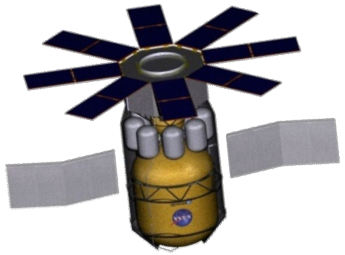
Fluid Physics: Cryogenic Fluid Management

Zero Boil Off Tank Experiment –Series
Objectives:

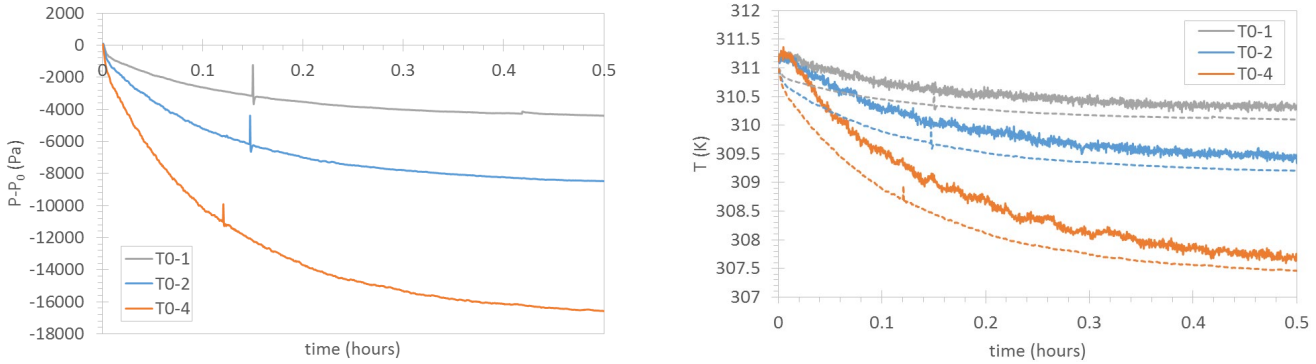
- Establish a microgravity foundation for comparison and optimization future propellant transfer, storage and pressure control design.
- Investigate the effect of heat transfer on tank pressurization in microgravity and observe impact of mixing on destratification.
- Investigate the effect of noncondensable gasses on microgravity vapor transport in the ullage during pressurization.
- Examine an array of spray cooling strategies on tank cooling and pressure control.
- Understand the effect of microgravity on two-phase phase change and flow on tank filling of a volatile fluid.



Ullage Shape during jet mixing
(left –experiment, Right model)



Cryogenic Fuel Depot Concept



Impact of jet mixing on
(left -saturation pressure, right- temperature)

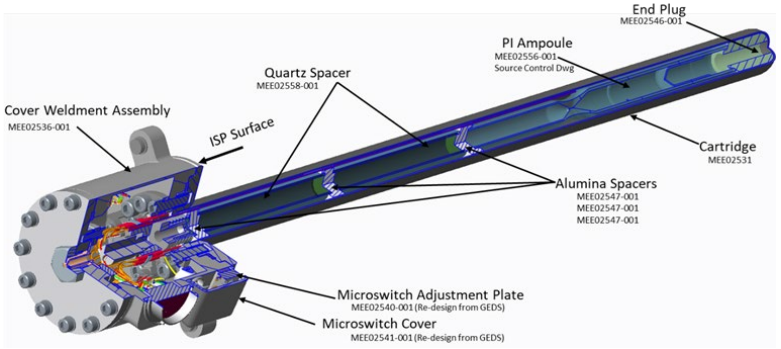
Materials Science

Solidification – High Temperature

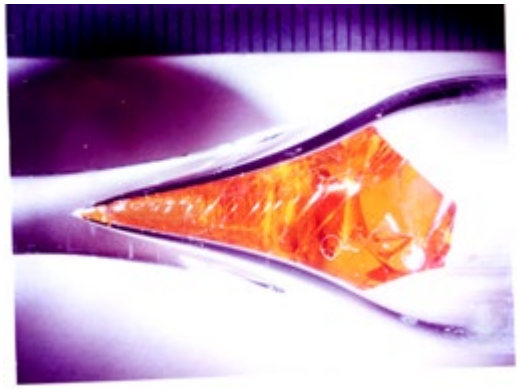
Materials Science Research Rack (MSRR) Materials Science Laboratory (MSL) Low Gradient Furnace (LGF)

Sample Cartridge Assemblies (SCA) for the PIs to perform their science

- Rand German, San Diego State
  - Objective: Understand the underlying scientific principles to predict density, size, shape, and properties for liquid phase sintered bodies over a broad range of compositions.
- Ching-Hua Su, NASA MSFC
  - Objective: Evaluate the effects of gravity on Physical Vapor Transport (PVT) container-less growth processes of semiconductors. Microgravity PVT-grown semiconductors could provide improved crystalline quality and electro-optical properties.
- Doug Hofmann, NASA JPL
  - Objective: Develop tungsten-reinforced bulk metallic glass (BMG) matrix composites and demonstrate wear resistance as compared to samples made on the ground.
- Alexsander Ostrogorsky, Illinois Institute of Technology
  - Objective: Measure diffusion coefficients of dopants in germanium. An accurate understanding of the diffusivities of impurities in Si and Ge is of high technical value for industry.

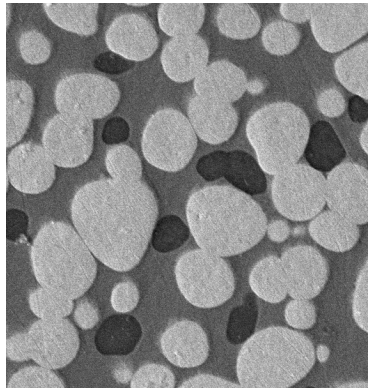


Design of SCA for Dr. Su.

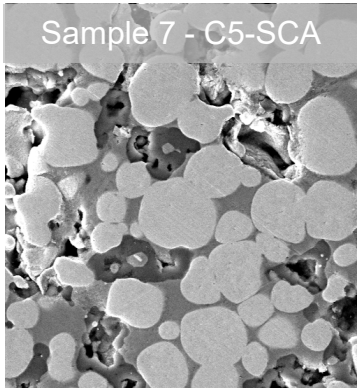


Horizontally grown ZnSe crystal grown horizontally on ground in support of Dr. Su's experiment. The (110) facets aligned parallel to the gravitational direction.

GEDS



Ground experiment:
Pores and grains are round

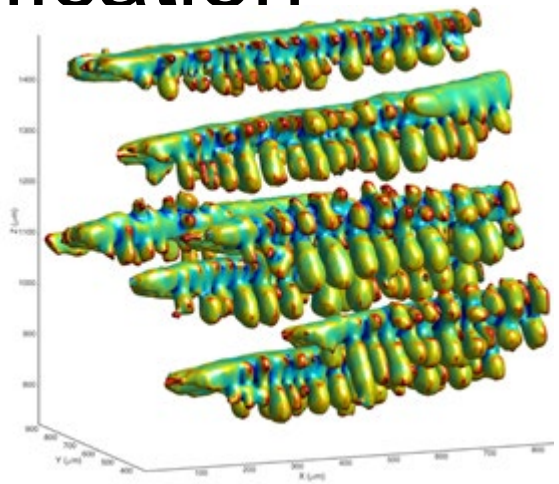


Microgravity Experiment:
Less densification and different pore/grain distribution

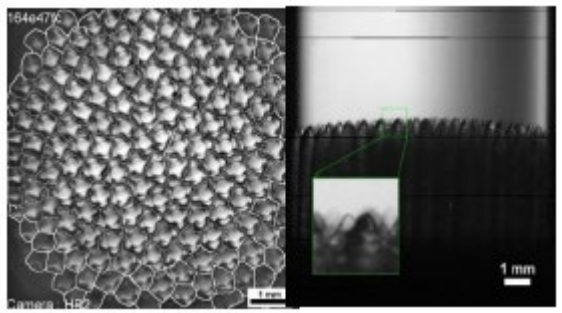
- The Gravitational Effects on Distortion in Sintering (GEDS) experiment focuses on understanding the underlying scientific principles to predict density, size, shape, and properties for liquid phase sintered bodies over a broad range of compositions.
- The GEDS experiment completed heat cycles at over 1200°C to induce liquid phase sintering densification of high-density tungsten alloys
  - Early results indicate less densification in microgravity, even with liquid formation to assist sintering.
- The pathway for microstructure-density-distortion is clearly different in microgravity from that on Earth.

Solidification

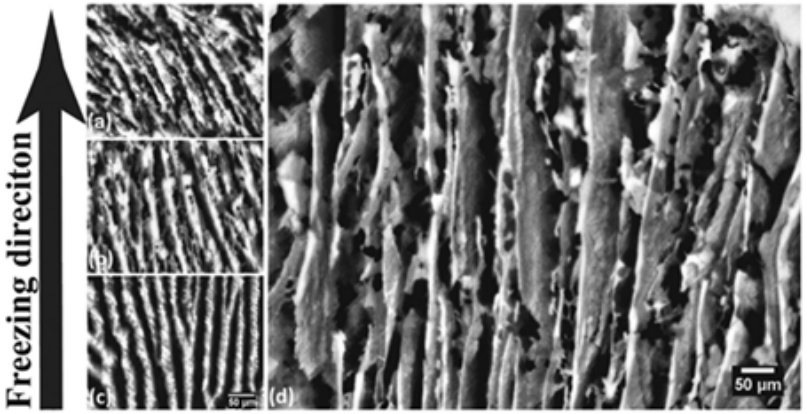
- Mid Temperature
- Low Temperature
- Transparent Alloys



Pb-Sn alloys pr



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).



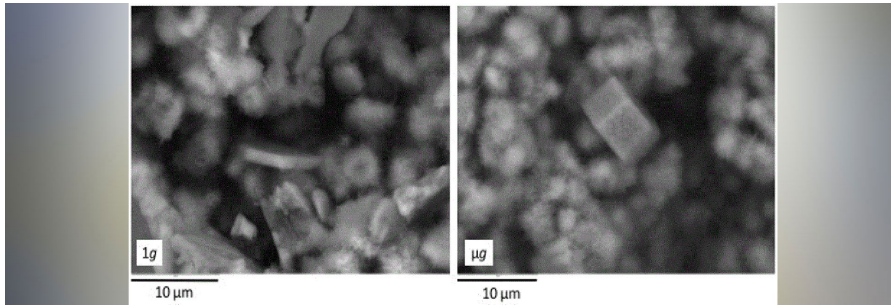
Dunand: Longitudinal cross-sections of sintered TiO_2 samples sintered from 20 wt% TiO_2 aqueous suspensions directionally solidified under (a) terrestrial, (b) Martian, (c) lunar, and (d) microgravity conditions.

Microgravity Investigation of Cement Solidification (MICS)

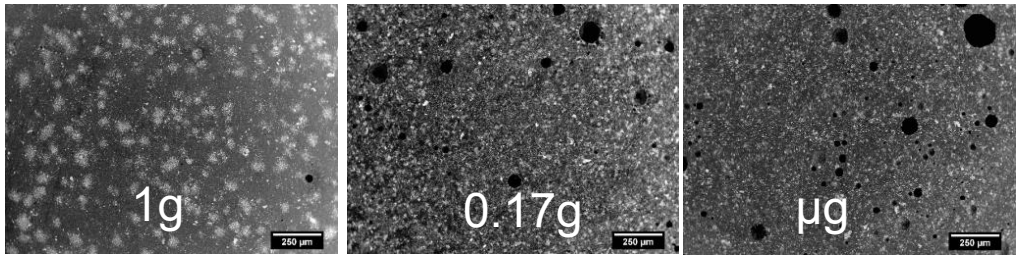
- The MICS experiment used burst pouch samples (shown below).
- Astronauts mixed the Portland cement and water while on orbit by bursting the seal between pouches.
- The TechShot Multi-use Variable-gravity Platform (MVP) was also used to simulate Lunar and Martian gravity.
- Aleksandra Radlińska, Penn State University
  - Objective: Investigate and understand the complex hydration reactions, solidification, and microstructure formation in cement paste subjected to a reduced environment.



MICS burst pouch



Microstructure of solidified cement on Earth and in microgravity (ISS). Crystals tend to grow larger and more uniform in reduced gravity.



As the gravity level decreases, the amount of trapped air and porosity in the samples increases. Microgravity conducted on ISS. Lunar gravity on ISS using centrifuge, MVP..

Fundamental Physics Research 2021

Atomic Clock Ensemble in Space – ESA project, NASA providing technical support and ground links. 1E-16 clock measures gravitational red shift – 3 PIs

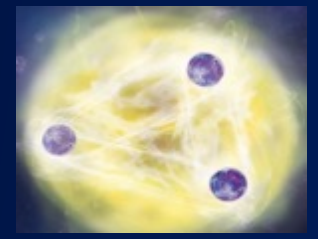
Plasma Kristall 4 – ESA-DLR/Russian project, NASA funding PIs. Continuing a series of experiments on dusty plasmas – 5 PIs

Direct Detection of Dark Energy – Einstein Elevator Experiment – NASA/DLR collaboration, using new DLR drop facility. Search for departures from Newtonian gravitational attraction at small length scales as predicted by modified gravity theories of Dark Energy – 1 PI, directed study

Cold Atom Laboratory – NASA project, first cold atom research facility in orbit. Launched 2018, still working toward full capabilities. Results so far include Bose-Einstein condensates in bubble geometries and picokelvin temperatures in Ru. K capabilities coming with installation of new electronics – 5 PI teams

CAL Flight Investigations

- Zero-G Studies of Few and Many Body Physics (**PI E. Cornell**)
- Atom interferometry Will Pave the Way for Definitive Space-based Tests of Einstein's Theory of General Relativity (**PI N. Bigelow, Co-PI W. Ketterle, Co-PI W. Phillips**)
- Microgravity dynamics of bubble-geometry Bose-Einstein condensates (**PI Nathan Lundblad**)
- Fundamental Interactions of Atom Interferometry with Ultracold Quantum Gases in a Microgravity Environment (**PI Jason Williams**)
- Development of Atom Interferometry Experiments for the International Space Station's Cold Atom Laboratory (**PI Cass Sackett**)



Efimov states – three-body self-similar molecules



An astronaut tries Galileo's test of the universality of free-fall

Physical Sciences Conclusion

- **As NASA plans to…**
  - return to the lunar surface,
  - develop sustainable lunar habitation, and
  - prepare to explore Mars

- **Physical Sciences intends to…**
  - Utilize multiple research facilities and
  - spaceflight platforms

- **To understand the physics underlying numerous systems and disciplines to,**
- **Enable exploration,**
- **Benefit Earth: new materials, energy efficiency, pollutant reduction, and to**
- **Increase scientific understanding.**

Overview of the Space Biology Program

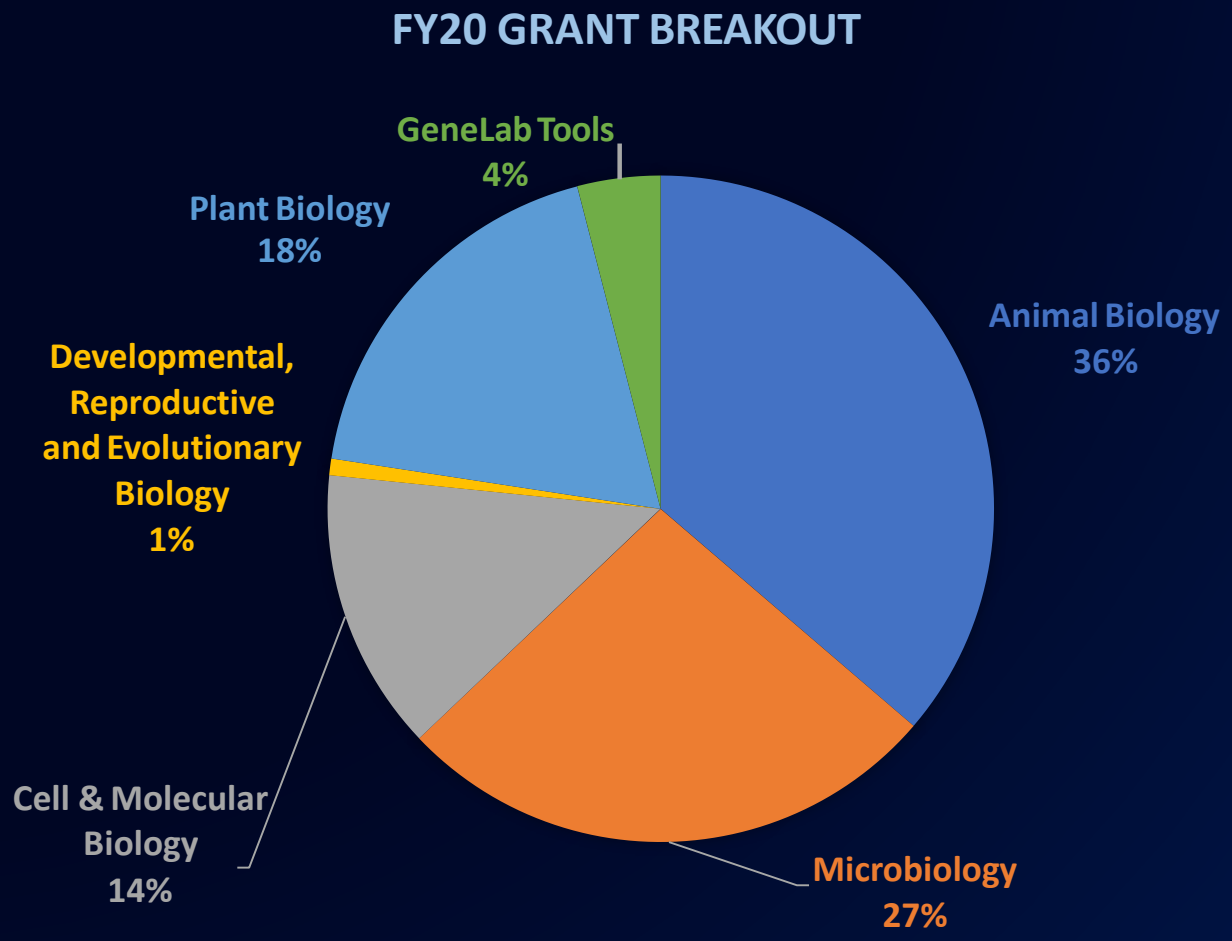




Objectives

- Discover how biological systems **respond** to the space environment
- Identify the underlying **mechanisms** and develop models for biological systems in space
- Provide mechanistic understanding to support human **health in space**
- Promote **open science** through the GeneLab Data System and Life Sciences Data Archive
- Develop **technologies** to enable spaceflight research
- Transfer the knowledge and technology of space-based research to **benefit life on Earth**

Space Biology Content



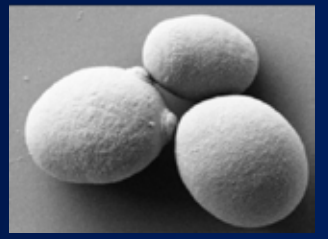
Total SB FY20 Grants	124
Flight	67
Ground	57

Number Directed vs Competed	
Directed	3
Competed	121

Lunar Explorer Instrument for Space Biology Applications (LEIA)

- LEIA is based on the 6U BioSentinel Small Sat
- Modified 4U Biosensor with a 2U “Pseudo Bus” to provide thermal control for the lunar surface and data conditioning

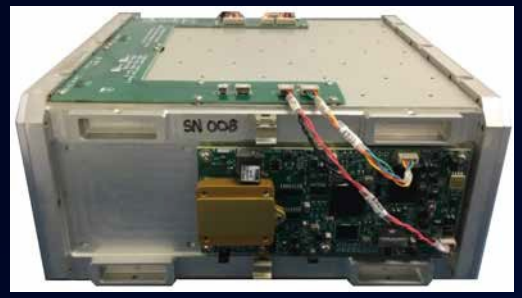




Accommodates yeast and related cellular systems

4U BioSensor Payload

(2U Pseudo Bus not shown in diagrams below)



LET spectrometer attached at one end of payload



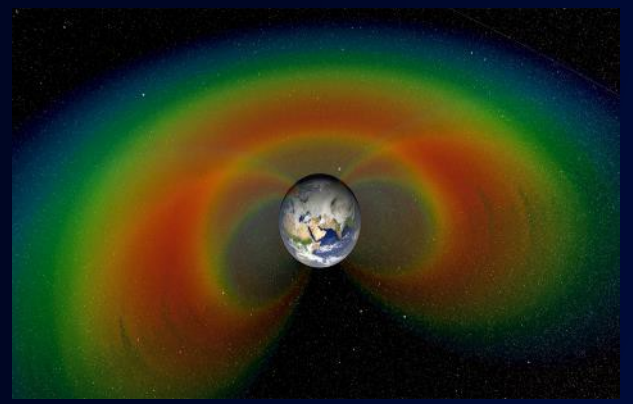


Biosensor payload with fluidic cards and optical sensors

Biologically Relevant Environmental Factors Encountered in Spaceflight

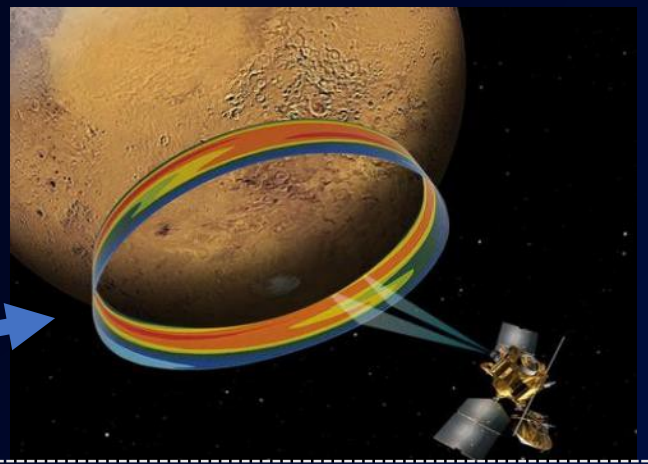
Micr







- Elevated CO2
- Reduced atmosphe pressure and eleva volumetric fracti n oxygen





COMBINATION OF MULTIPLE STRESSORS

Thriving in Deep Space (TIDES)

Biological effects of multiple **deep-space stressors**

1. Radiation
2. Gravity
3. Temperature & Atmosphere
4. Day & Night Light Cycles
5. Isolation

Cannot accurately replicate on the ground

Heavy ions can impact biological systems

Transformative biological science and exploration applications

1. Animal biology	Vertebrate and invertebrate models to probe analogous changes in humans
2. Plant Biology	From plant models to crops to sustain life for long-term human habitation
3. Microbiology	How it influences animals and plants in space







Thriving in Deep Space (TIDES)

Ground studies
Space studies
Ground & space studies

DEEP SPACE STRESSORS

Gravity | Radiation | Temperature/Atmosphere | Day/Night/Circadian Cycle | Isolation

PLATFORM PROGRESSION

Ground → Sub-Orbital → LEO/ISS → Gateway → Lunar Surface → Mars Transit → Martian Surface

Understand Fundamental Mechanisms

Use model organisms to determine fundamental biology of the human in the deep space environment

- Utilize "omics", systems biology, etc.
- Test small- & large-scale molecules, organisms, ecosystems
- Combined effects of radiation, gravity, & other stressors

Build the Blocks to Support Human Life

Study the environmental stressors in spaceflight on plants: crops and seeds

- Combined effects of radiation, gravity, & other stressors

Build a Foundation for Sustained Life on Mars

Engineer habitats and ecosystems to enable astronauts' independence from Earth

- Stabilize human/animal-plant-microbial ecosystems in the context of multiple deep space stressors

MODEL ORGANISM PROGRESSION

Unicellular (e.g., yeast, fungi)

Invertebrates (e.g., flies, worms, tardigrades) → Vertebrates (e.g., mice & rats; fish) → Humans

Simple model plants (e.g., *Arabidopsis*) → Crops & edible plants

1. Biggest Changes in Past 5 Years – "Omics" and Systems Biology

- **Changes in NASA-funded research**
  - Development of the GeneLab database (https://genelab.nasa.gov/)
    - Archive space-relevant omics data and metadata and provides collaborative space to share, analyze, visualize data
  - Update of the Ames Life Sciences Data Archive – archive of spaceflight-relevant vertebrate and invertebrate animal tissues, cells, data, etc. (https://www.nasa.gov/ames/research/space-biosciences/alsda)

2. Biggest Changes in the Past 5 Years – Genetic Engineering in Plants

- Can now evaluate all genes in combination with phenomics, proteomics, metabolomics and use as inputs to computational modeling.
- Deep insight and understanding of the gene networks and metabolic pathways allows the plant breeder to put together the best collection of 20,000+ genes using available genomic tool sets.
- This has enabled **Predictive Breeding** that shortens the time to a new crop by understanding what all the genes are doing so they can be combined into the best plant for the conditions.

3. Biggest Changes– Plant Responses to Lunar Regolith

NASA-Funded Research:

- Biological and Physical Sciences (BPS) has funded ISS research efforts assessing microbial associations with plants grown on the ISS, and studies of biofilm formation on surfaces within the ISS as a segue to geomicrobiology.
- The NASA Astrobiology Program has provided prior funding to geomicrobiology.
- The bulk of research funding for growing plants in lunar regolith, however, ended after the Apollo era.

4. Biggest Changes in the Past 5 Years 3D Tissues and Organ-on-Chip Models

- ***Program advances***: NCATS Tissue-Chips-in-Space Program initiated in 2017; Tissue Chip Testing Centers for validating MPS began in 2016; Clinical Trials-on-Chip Program launched in 2020; FDA Advancing New Alternative Methods awards for countermeasure development and toxicology; EPA SBIR awards using organ-on-chip for predictive toxicology

Space Biology Conclusion

- **As NASA plans to…**
  - return to the lunar surface,
  - develop sustainable lunar habitation, and
  - prepare to explore Mars

- **Space Biology intends to…**
  - utilize multiple biological model systems and
  - spaceflight platforms

- **To understand the mechanisms of change in biological systems in response to long duration exposure to deep space,**
- **Enable exploration,**
- **Benefit Earth: human health & controlled environment agriculture.**