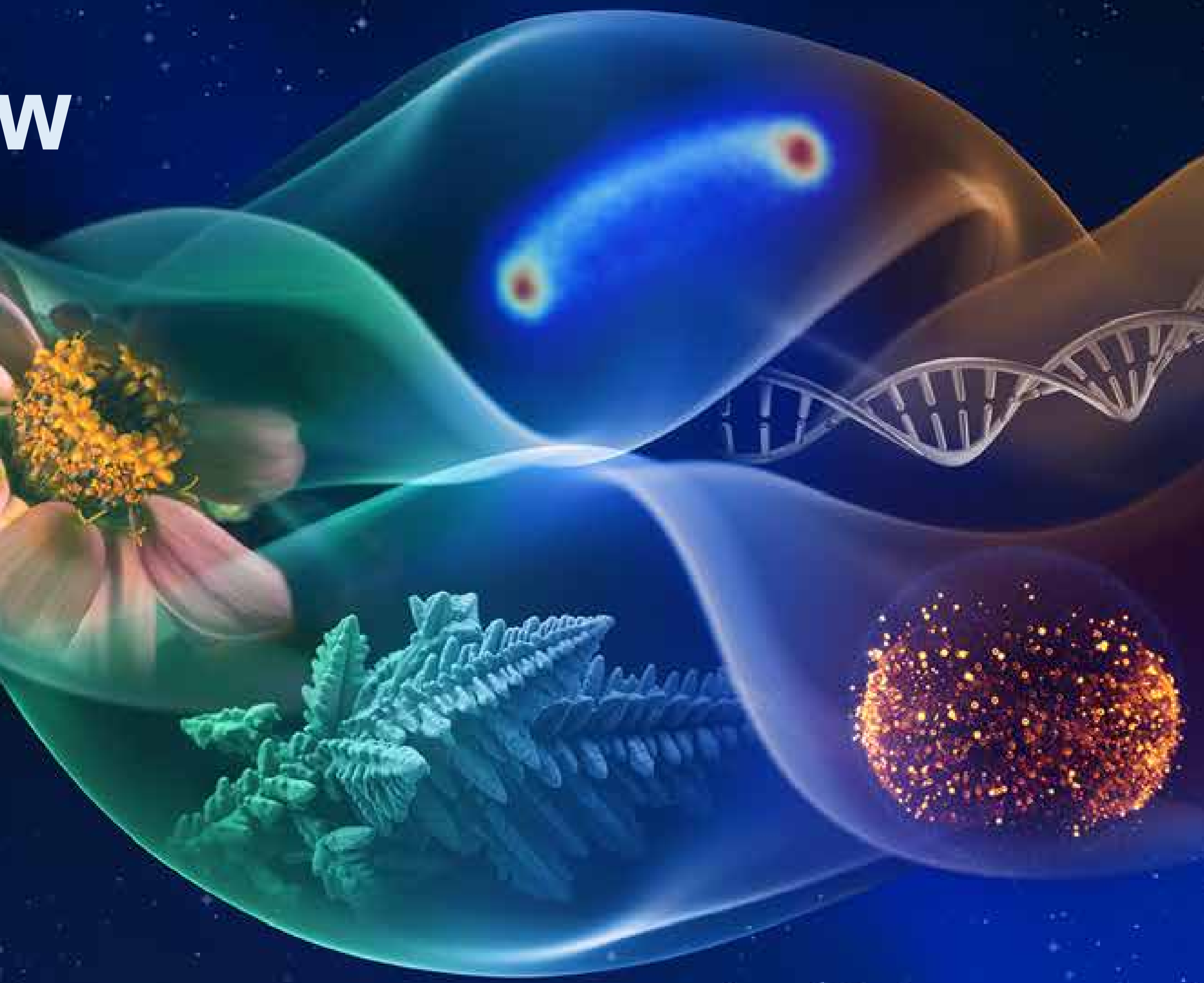
National Aeronautics and Space Administration

Physical Sciences Overview

National Academies, Decadal Survey on Biological and Physical Sciences Research in Space 2023-2032: Physical Sciences Panel
Jan 12-13, 2022



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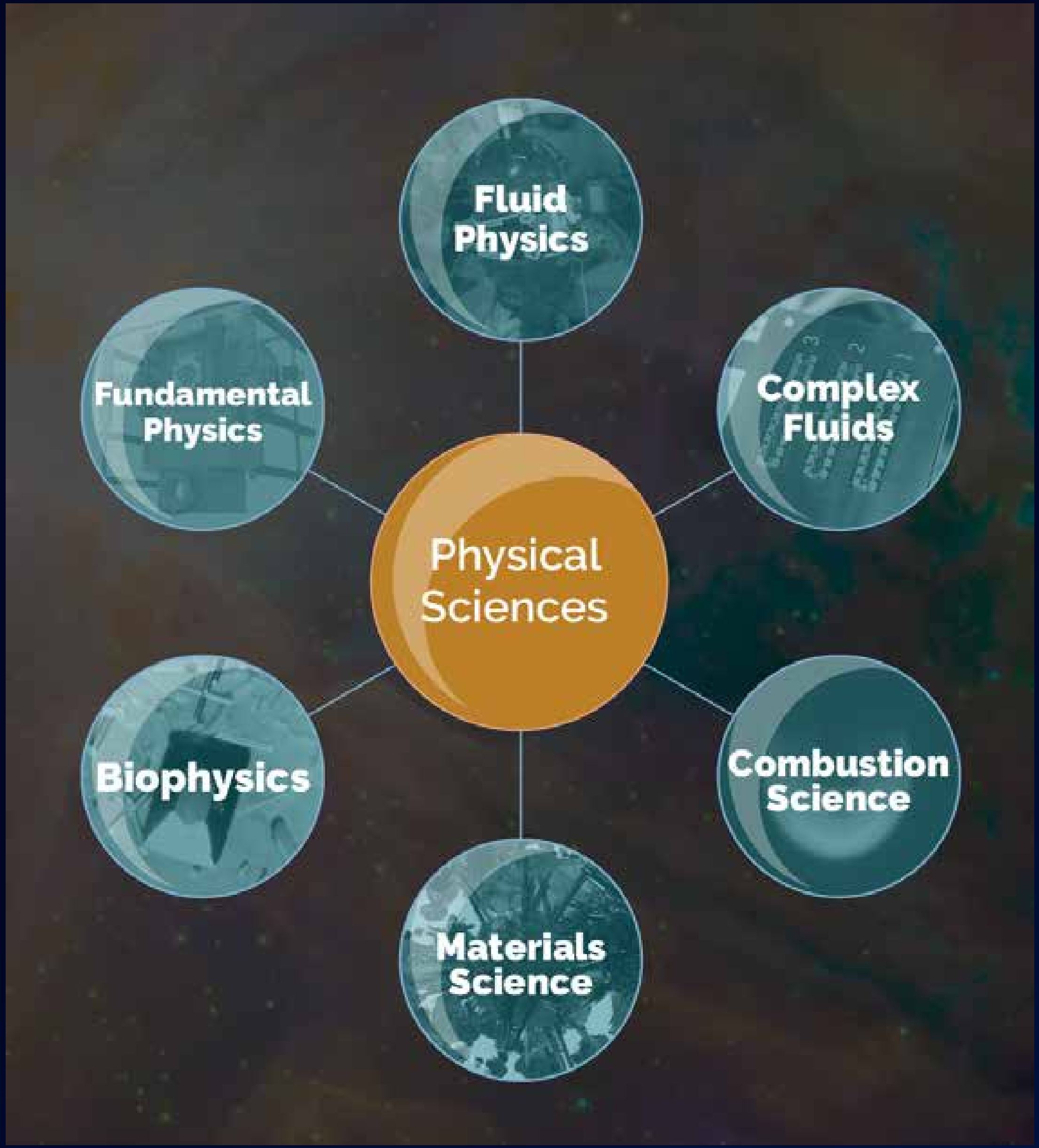
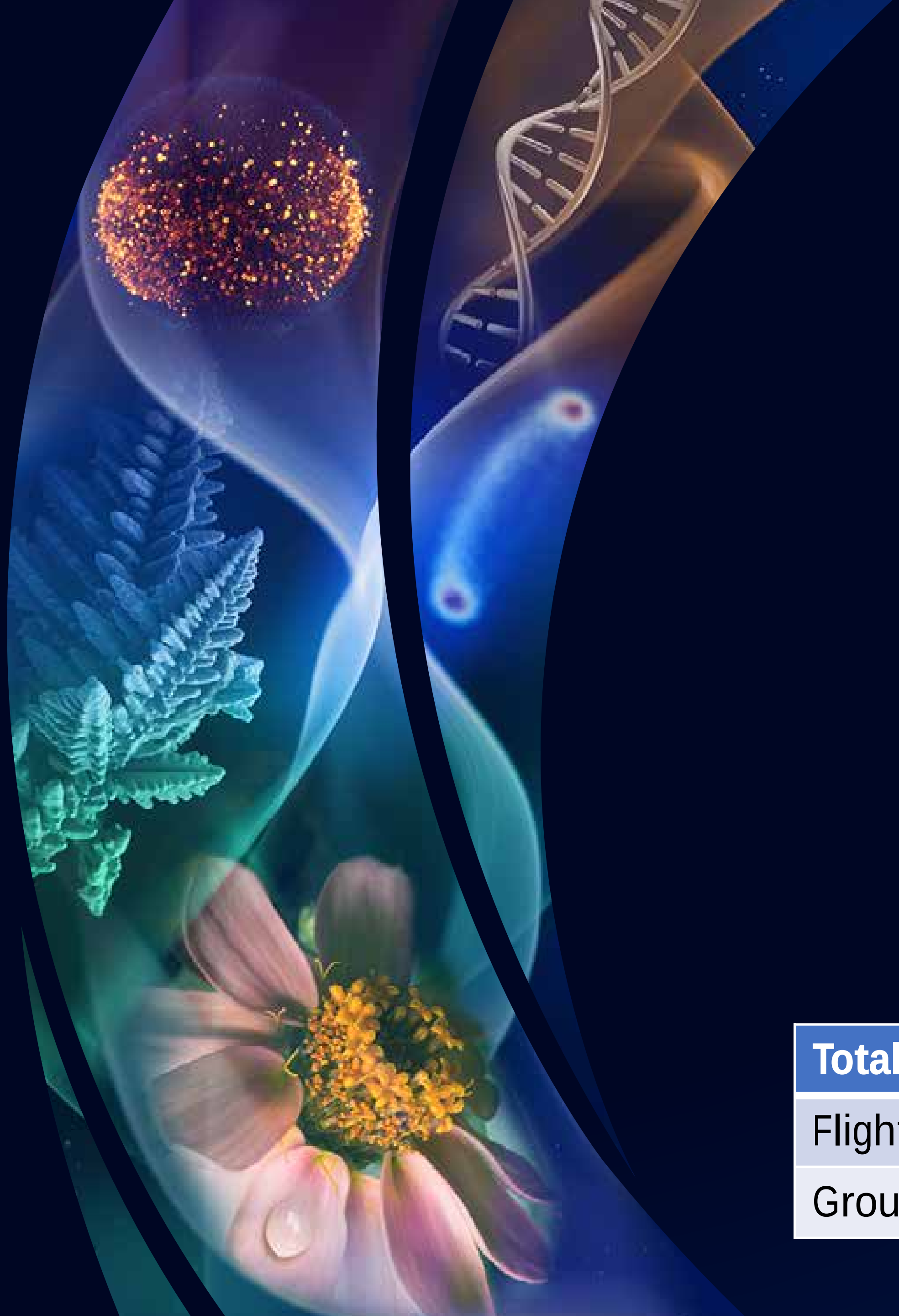


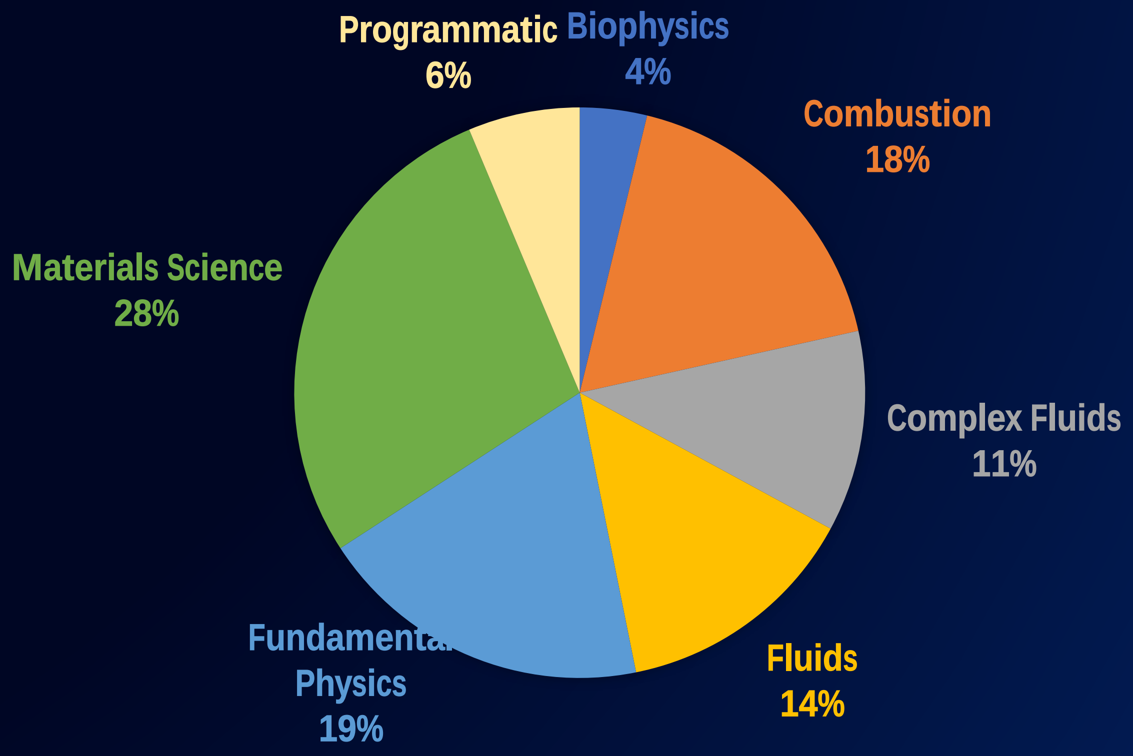
Objectives

- 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

FY21 GRANT BREAKOUT



Total PS FY21 Grants	99
Flight	66
Ground	33

Number Directed vs Competed	
Directed	2
Competed	97

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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

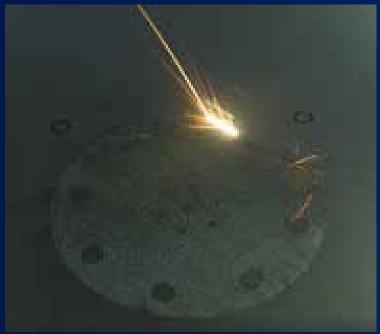
Materials Science
- Glasses and ceramics
- Granular materials
- Metals
- Polymers and organics
- Semiconductors

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

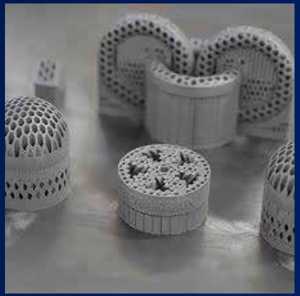
Complex Fluids/ Soft Matter
- Colloids
- Liquid crystals
- Foams
- Polymer solutions
- Granular flows
- Dusty Plasma

Materials Science

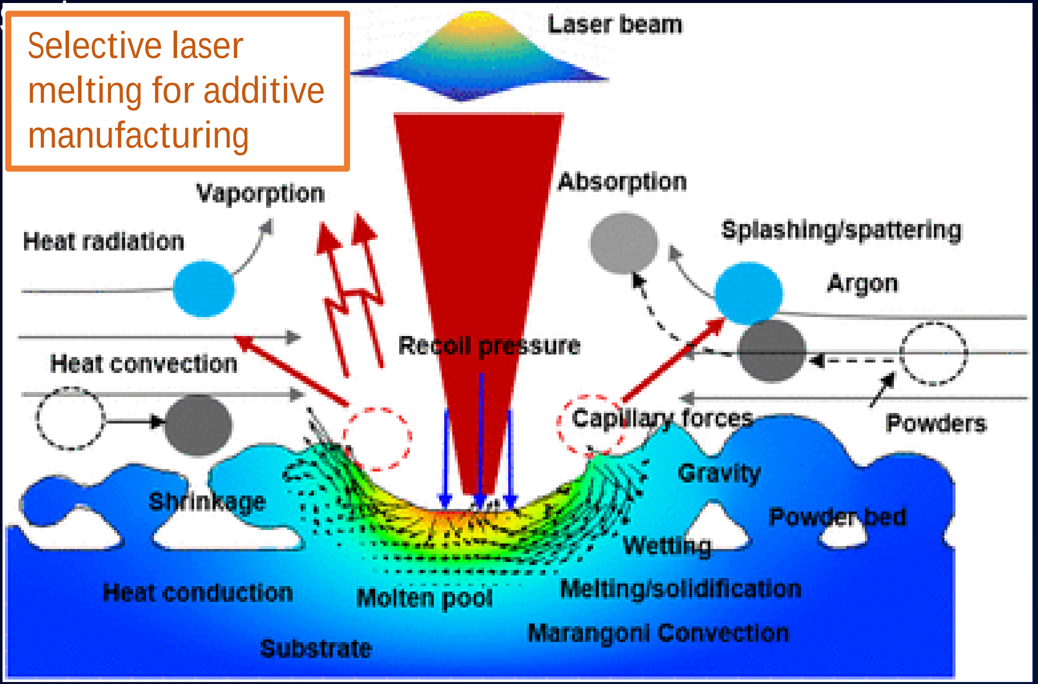
- A reduced gravity environment inhibits masking phenomena such as buoyancy driven convection and sedimentation to perform experiments targeted to address gaps in fundamental understanding of the underlying physics of materials science.
- Coupling key benchmark experiments with rapidly evolving multiscale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



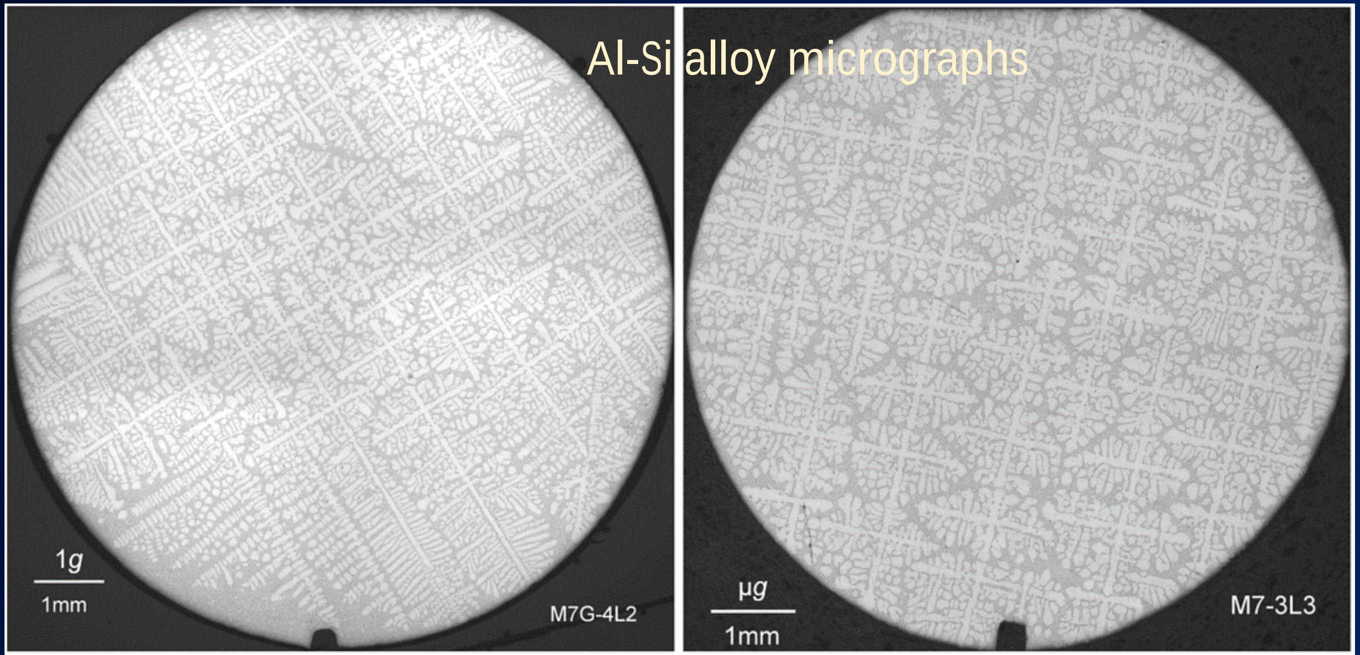
Selective laser melting of a part.



Selective laser melting for additive manufacturing

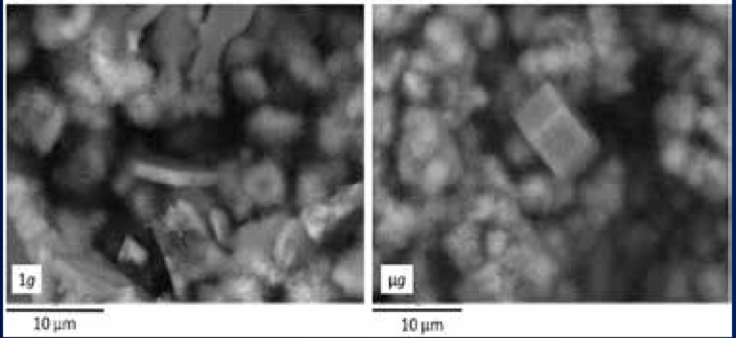


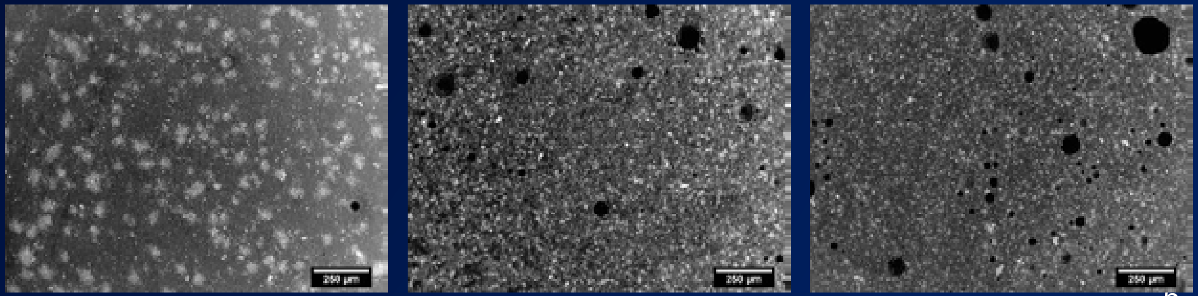
Al-Si alloy micrographs



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.

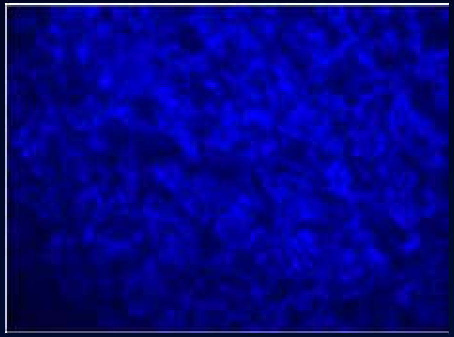




1g (1/6)g μg

Biophysics

- 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

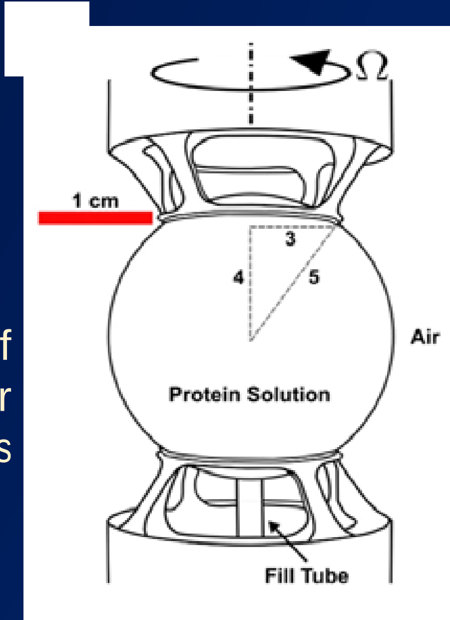
Biophysics

- 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)

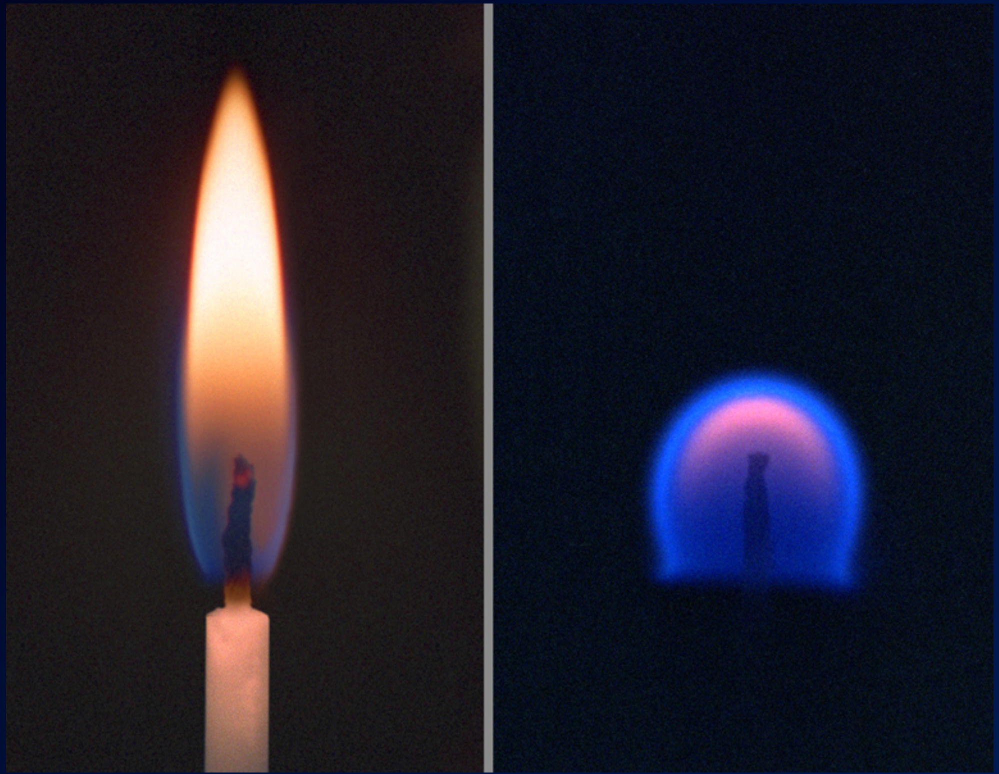
Dilute protein solution droplet in nearly containerless bioreactor on ISS.

Schematic of the ring shear drop apparatus



Combustion

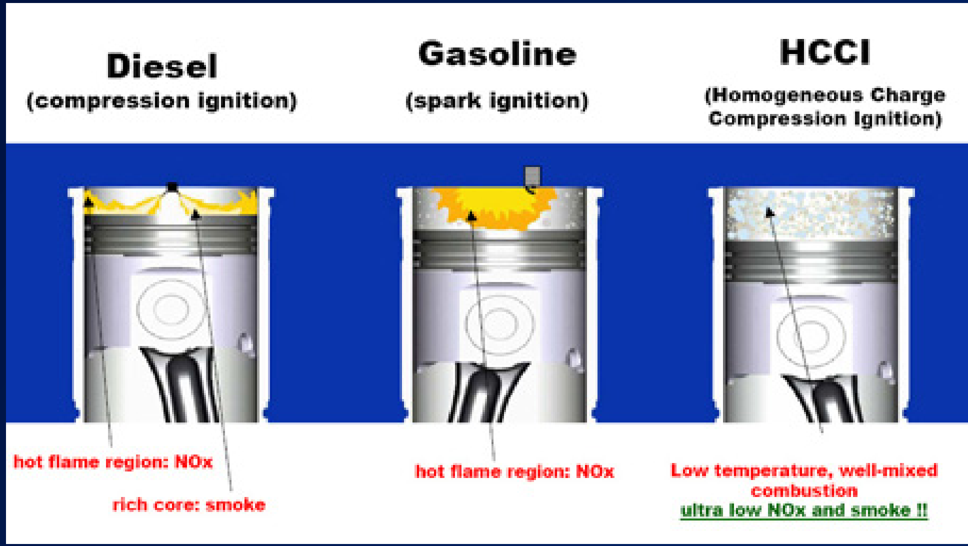
- Climate change forces us to seek carbon neutral (bio-fuel) options. This requires rethinking our engine designs for transportation. Hydrocarbon fuels provide energy storage capabilities that cannot be achieved by battery systems. Combustion will dominate civil and military air transport, rail and marine applications.
- Microgravity provides the opportunity to study combustion phenomena that cannot be studied in 1-g due to the complex buoyant flows, instabilities, and very short residence times.
- “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)



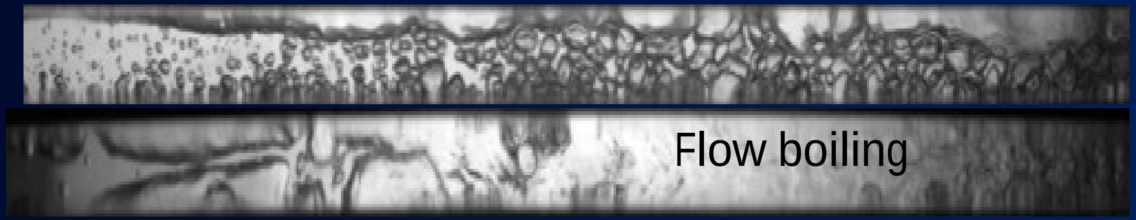
Combustion

- The existence of **cool flames** had been known for 200 years yet they had never been stabilized in a quasi-steady system, the discovery that it could be done in the CIR has had enormous impact on combustion science and future engine design.
- The design of the next generation of engines, such as (homogeneous charge compression ignition, **HCCI)** however, are limited by a lack of fundamental understanding of the thermo-physical properties, fluid behavior and chemical kinetics at these high pressures. Terrestrial laboratory studies are hampered by the ubiquitous buoyant flow that renders fundamental experiments difficult and/or impossible to interpret. Studying **high pressure transcritical phenomena** in microgravity allows researchers to investigate the fundamental aspects of phase change, chemical kinetics and property evaluation in a simplified geometry without the complicating influence of a buoyancy-induced flow.
- **Enabling space exploration - Spacecraft Fire Safety (SFS)** – Fire remains a catastrophic hazard for space travel. Planned conditions for lunar and Martian environments are even more hazardous. Fire behavior and material flammability are sufficiently different that the fire hazard is very different from 1-g

Flame Design testing in CIR/ACME

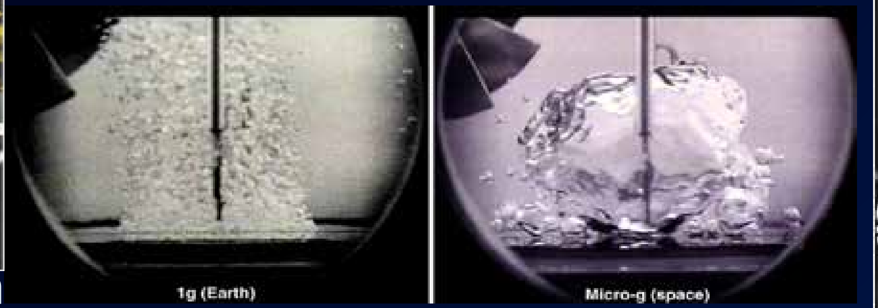


Fluid Physics

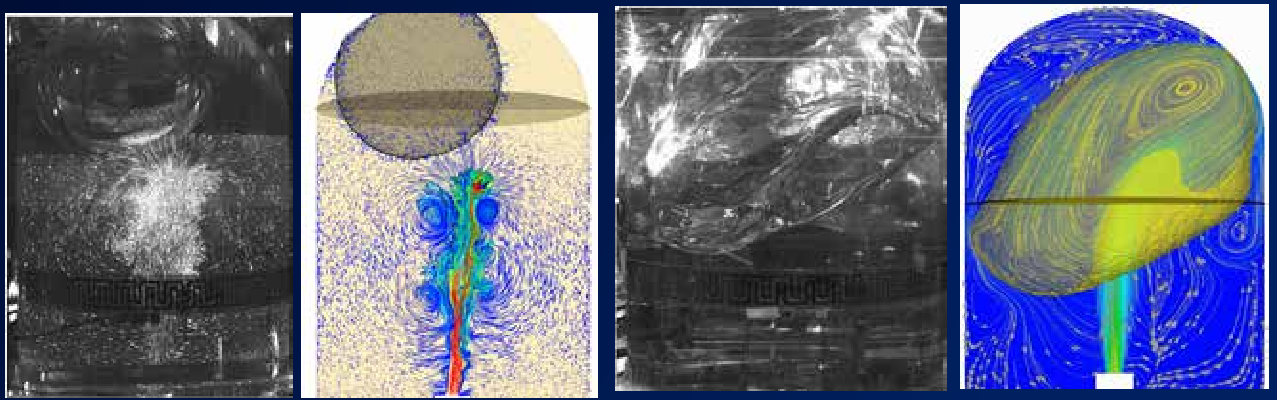
1-g
μg


- Long-duration human planetary exploration missions to Moon, Mars and beyond required understanding the phase change and transport of volatile fluids in microgravity
  - To preserve Cryogenic propellants on orbit (zero boiloff) and allow tank to tank refueling operations in space applicable to both NEP and NTP.
  - Nuclear fission Rankine power cycle for future space missions e.g. NEP (Moon, Mars) and deep space missions.
  - Vapor Compression heat pump for planetary bases (Moon, Mars)
  - Thermal Control Systems and advanced Life Support Systems for spacecraft
- Phase change issues are important at the macro scale (e.g fuel tanks but also at the micro scale e.g. **cooling of electronics,** computers, etc. in satellites and NASA's near and long term missions which will require novel technologies.

μg capillary flow in model propellant tank vane gap



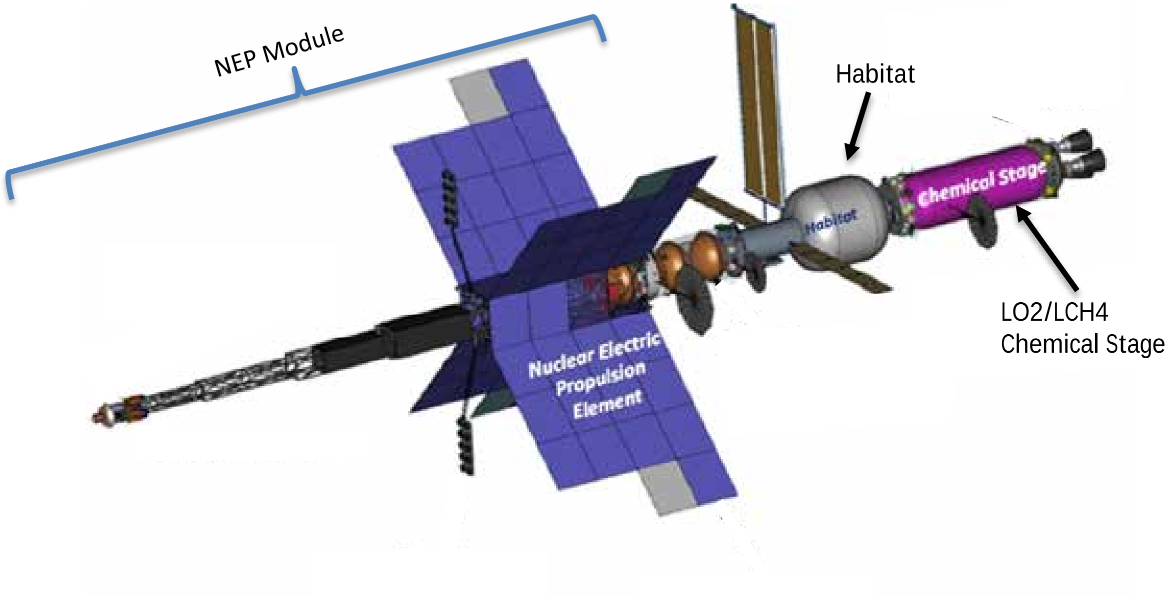
Pool Boiling



Zero Boil off Tank Experiment – ISS visual data and predictive model of fluid behavior including ullage position

Mars Transfer Vehicle Concepts Overview

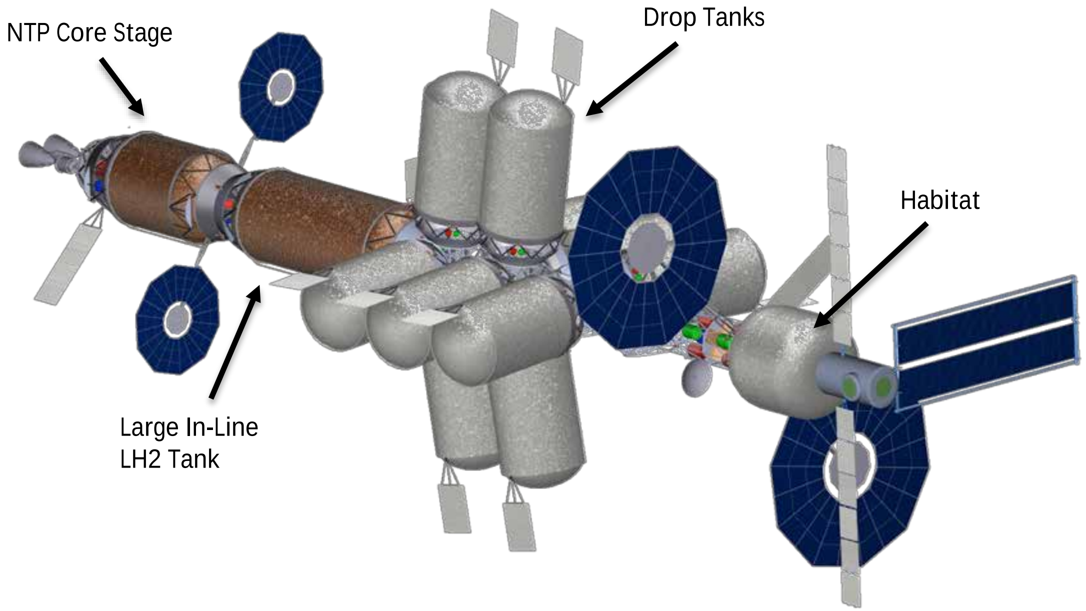
NEP/Chem Hybrid Vehicle Concept



- 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

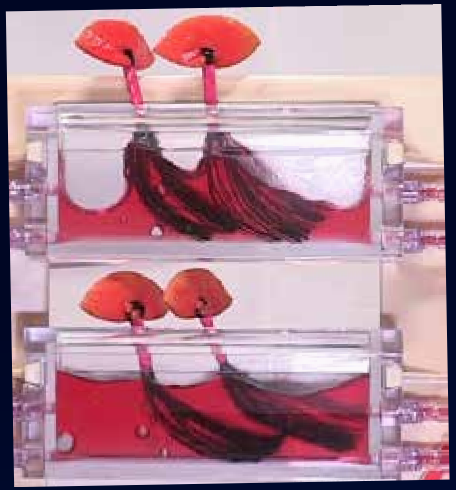


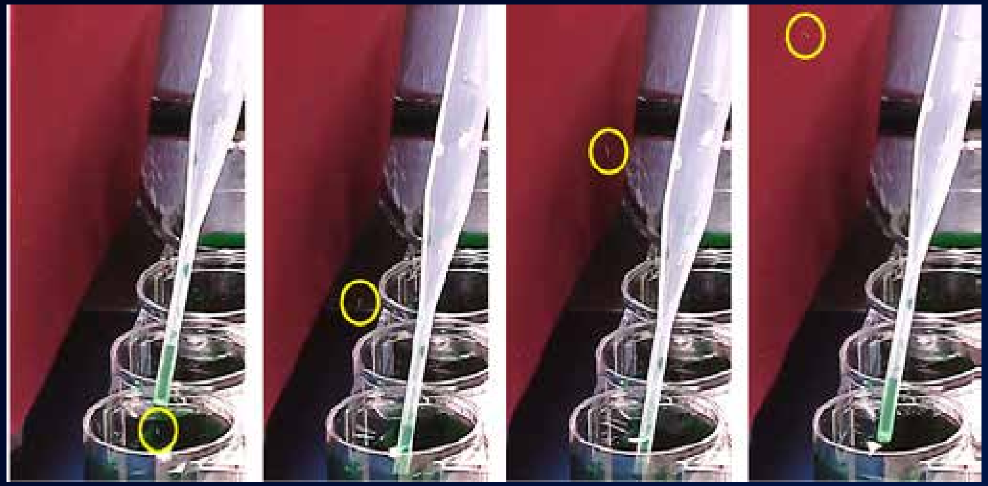
Fluid Physics

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





Thank You!