



COMBUSTION, COMPLEX FLUIDS, AND FLUID PHYSICS EXPERIMENTS ON THE ISS

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Soft Condensed Materials (Colloids)



The Physics of Colloids in Space (PCS) - 2001

- The experiment enabled scientists to monitor colloidal suspensions using:
 - Dynamic and Static Light Scattering.
 - Bragg and Low Angle Scattering.
 - Imaging over longer time periods.
- Designed to study the phase behavior, growth dynamics, morphology, and mechanical properties of different types of colloidal suspensions.
- Many basic questions about phase diagrams, thermodynamic stability, and phase transformation kinetics were answered.
- Detailed information about the structure and properties of fractal aggregates was obtained over a much wider range of measurement with more relevant conditions than possible on earth.



PCS Samples

The Binary Colloidal Alloy Tests (BCAT-3/4/5/6) - 2003 to 2012

- Each is a set of notebook sized investigations – 10 samples each.
- -3/4 significantly advanced understanding in critical point behavior of fluids, binary alloys, and surface crystallization.
- -5 studied phase separation kinetics, phase separation competing with crystallization, how seed particle size and concentration effect crystal growth in microgravity, and seeing temperature controlled melting and crystallization.



Astronaut Bill McArthur photographing BCAT samples



BCAT-5 Slow Growth Sample Module

Soft Condensed Materials (Colloids) (continued)



The Binary Colloidal Alloy Tests (continued)

- -6 continues with studies on aging of gels and late collapse, wall seed initiated crystals in the absence of gravitational jamming, non-biological self-assembly with DNA, and 3D crystallization of disks, growth and melting.

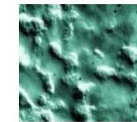
The Advanced Colloids Experiments (ACE)- 2012 and on

- Just launched this year to continue advancing our understanding in extending product shelf life, colloidal engineering, self assembly, non-biological self-replication, etc.
- Will make use of confocal microscopy in the Light Microscopy Module (LMM) on the ISS.
- Microscope features lighting from above and below as well as back lighting with 100x magnification capability.
- In 2016 a confocal head and camera will be added to enable 3-D imaging.

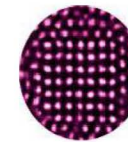
In Summary:

The series of Soft Condensed Materials has already led to many scientific breakthroughs and discoveries.

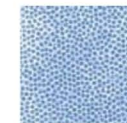
- The ISS provides the unique opportunity to study the long duration dynamics of colloidal systems free from the effects of gravity – which causes sedimentation, etc.



Weitz:
Colloidal
engineering



Chaikin: Order and patterns



Yodh:
Melting and
crystallization



BCAT experiment using the seat track setup in the Japanese Experiment Module



BCAT-6 Slow Growth
Sample Module

Rheology & Morphology of Complex Fluids

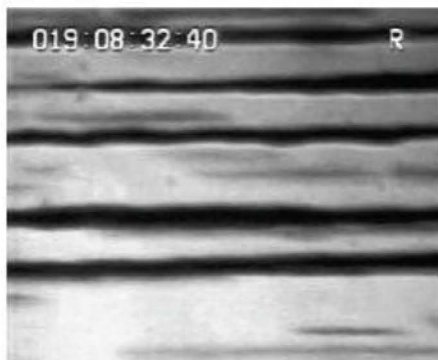


Investigating the Structures of Paramagnetic Aggregates from Colloidal Emulsions-3 (InSPACE-2/3) – 2002 to 2012

- The majority of InSPACE hardware launched in 2002 with the goal of determining the true 3-D low-energy (equilibrium) structure of an Magneto-rheological (MR) fluid while under DC and pulsed magnetic fields.
- -2 observed a regime of buckling instability in the 3-D structures under a particular magnetic field strength and pulse frequency.
- -3 is currently installed in the MSG on the ISS and will investigate the effect of non-spherical super-paramagnetic particles on the kinetics and formation of these aggregate structures that affect the visco-elastic properties of MR fluids. Operations are scheduled to start in Nov. 2012.

The **Shear history Extensional Rheology Experiment (SHERE [II])** - 2007 to 2011

- The SHERE hardware was designed to study the effects of pre-shearing by rotation on a polymer fluid while it is being stretched (elongated). In many industrial polymer processing operations the material experiences a complex flow history with both shear and extensional characteristics.
- SHERE II extended the studies by adding a rigid inert filler to change the fluid properties.



InSPACE-2 MR fluid microstructure chain in a 2 Hz pulsed magnetic field



Astronaut Mike Fincke in front of SHERE hardware in MSG



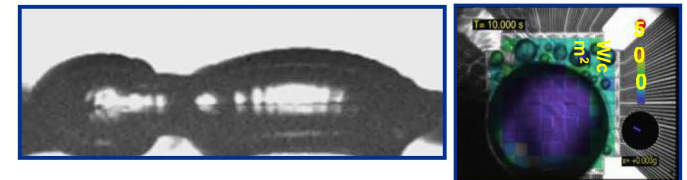
InSPACE in MSG with Vial Assembly containing MR fluid on right

Multiphase Flows



Boiling eXperiment Facility (BXF) – 2011

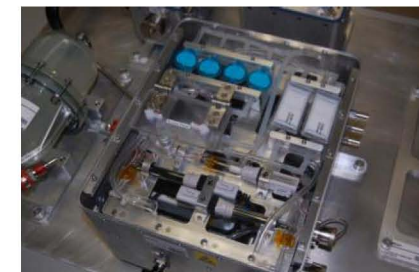
- BXF included two separate pool boiling investigations:
 - **Microheater Array Boiling Experiment (MABE)**
 - **Nucleate Pool Boiling Experiment (NPBX)**
- Advanced understanding of local boiling heat transfer mechanisms & critical heat flux in microgravity for nucleate and transition pool boiling.
- Detailed measurements of bubble growth, detachment and subsequent motion of single and merged (larger) bubbles.
- Enhanced the development of two-phase thermal management systems, which provide isothermal control with reduced radiator area and mass.
 - Pool boiling studies are the first critical step to understanding flow boiling in 0-g.
- A combined condensation and flow boiling experiment is scheduled for 2018.



(Top) Paulo Nespoli installing BXF in MSG. (Above left) Coalescence of vapor bubbles on NPBX wafer. (Above right) Subcooled nucleate boiling in μg . The MABE microheater array is colorized with actual heat flux data.

IntraVenous fluid GENERation (IVGEN) – 2010

- IVGEN successfully demonstrated the ability to generate United States Pharmacopeia (USP) grade IV fluid from *in situ* resources on the ISS.
- Incorporated two-phase technologies:
 - membrane-based air-water separators;
 - conductivity probes;
 - porous media bed.



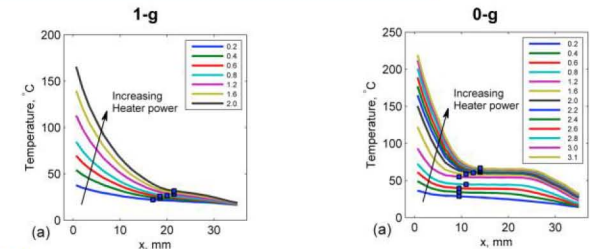
IVGEN Purifier Assembly

Dynamics, Instabilities and Interfacial Phenomena

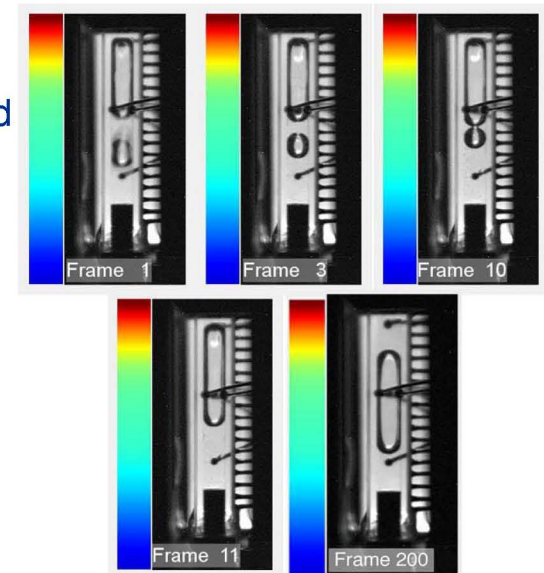


Constrained Vapor Bubble (CVB) Experiment – 2009 & 2013

- Prototype for a wickless heat pipe in microgravity – based on corner flows.
- Used pure Pentane as operating fluid for first set of experiments.
- Provided fundamental transport data including the overall stability, flow characteristics, average heat transfer coefficient in the evaporator, and heat conductance as a function of heat flow rate and vapor volume.
- Interferometry technique obtained direct measurements of fluid curvature and thickness.
- Bank of thermocouples measured the temperature gradients.
- Visualized film stability and shape of dry out regions with a microscope in detail never obtained before in microgravity.
- CVB-2 (2013) will extend data to a *binary mixture* rather than a pure fluid (Pentane – Isohexane).
- Results from CVB-1:
- Microgravity operation is significantly different from ground-based operation.
 - There is more internal fluid flow in microgravity.
 - Dryout could not be observed in microgravity.
- Heat pipes run “hotter” and at higher pressure in microgravity, while the surface intended to be cooled, runs cooler.
 - The shorter the pipe, the higher its operating pressure and temperature.
- Unexpected phenomena were observed and enhanced in microgravity including meniscus oscillations and single bubble nucleation phenomena.



Comparison of heating power (1-g vs 0-g).



Unexpected Explosive Nucleation in 0-g.

Dynamics, Instabilities and Interfacial Phenomena (continued)

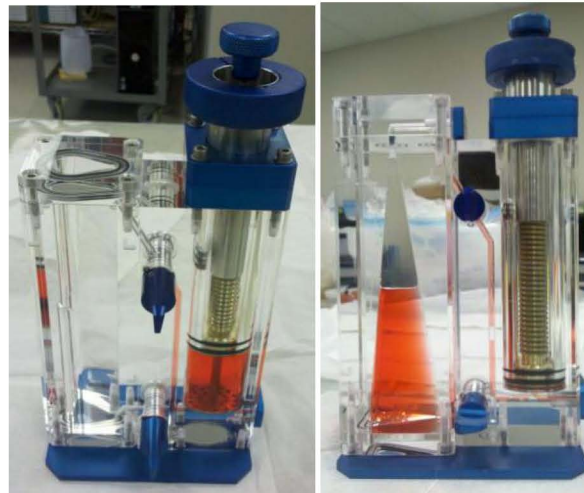


The Capillary Flow Experiment (CFE 1&2) -2004 through 2013

- Series of handheld test vessels with various test geometries to investigate the behavior of capillary flow phenomena in geometries found in capillary vanes, screens, and wicking structures.
- The working fluid is silicone oil of various viscosities, depending on the individual unit geometry.
- The results of CFE have applications in propellant management for fluid storage tanks, thermal control systems, and advanced life support systems for spacecraft.
- Critical wetting vane angles have been determined to within 0.5 degrees for Vane Gap 1 and 2 experiments.
- Bulk shift phenomena has been characterized that has implications for tank designs.



Astronaut Joe Acaba adjusting the vane angle during a recent CFE-2 Vane Gap 2 (VG2) experiment run on ISS (August 10, 2012)



Interior Corner Flow Modules (ICF4 and ICF9).



45° vane angle in microgravity.



45° vane angle in earth gravity.

Dynamics, Instabilities and Interfacial Phenomena (continued)

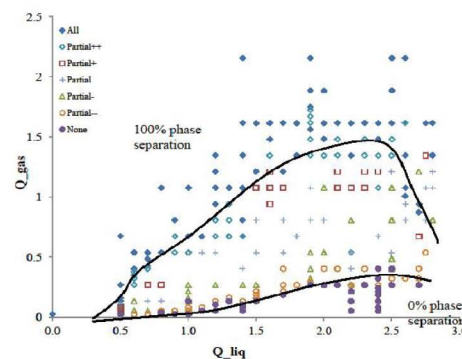


The Capillary Channel Flow (CCF) Experiment - 2011

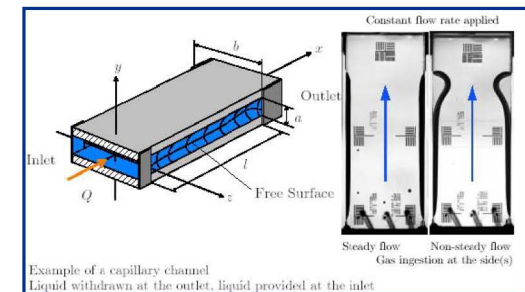
- Led by the German Space Agency (DLR) with a US/NASA Co-Investigator.
- Study of open channel capillary flow.
 - The cross section of the flow path is partly confined by free surfaces.
- Experiment has led to high fidelity models that accurately predict maximum flow rates for an open capillary channel
- Research is critical to on-orbit fuel transfers and in space propulsion systems that utilize capillary vanes.
 - Current design of spacecraft fuel tanks rely on additional reservoirs (higher mass) to prevent the ingestion of gas into the engines during firing.



Astronaut Scott Kelly installing CCF in MSG in Dec 2010.



Gas-Liquid Phase Separation Flow Regime Map



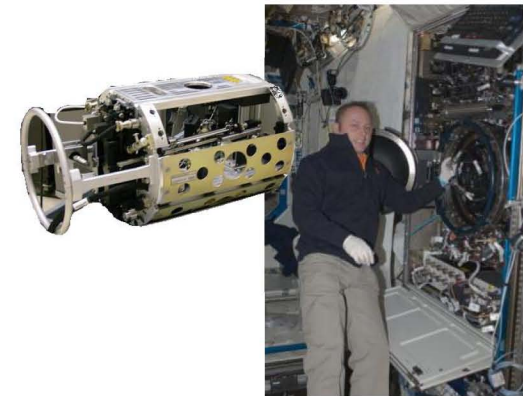
Capillary Channel Flow Test Unit (flat plate and groove geometries)

Droplet Combustion

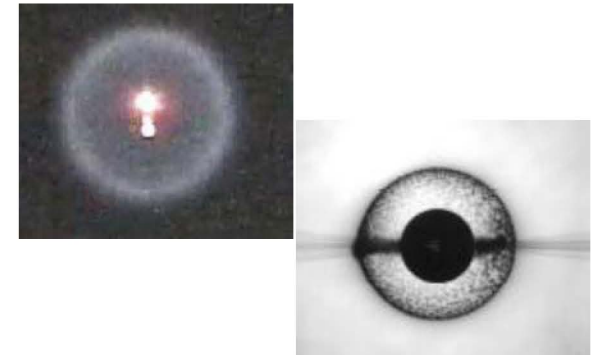


Flame Extinction Experiment (FLEX) – 2009 through 2012 FLEX-2, FLEX-2J, FLEX-ICE-GA – 2012 through 2015

- FLEX is the initial CIR payload and began operations in 2009
- Textbook problem in combustion
 - Spherically-symmetric geometry only achievable in microgravity.
 - Enables the study of chemical kinetic and transport phenomena in a simplified one-dimensional geometry.
- Over 400 droplets burned to date.
 - Heptane and methanol pure fuels
- The primary focus of the FLEX investigations is the study to flame extinction as a function of droplet diameters, ambient environment and fuel chemistry.
- FLEX-2 extends the studies to consider issues relevant to energy and fuel efficiency by including complexities:
 - Multicomponent fuels,
 - Binary droplet arrays
 - Convective airflow
- FLEX-2J is a collaboration with JAXA, Nihon University and Yamaguchi University
 - Ignition of linear droplet arrays
- FLEX-ICE-GA is a collaboration with ASI and Istituto Motori of National Research Center (CNR, Naples, Italy)
 - Surrogate fuels (idealized bio-fuels)



(Left) FLEX Chamber Insert Assembly Apparatus. (Right) Mike Fincke operating the CIR.



(Left) FLEX Chamber Insert Assembly Apparatus. (Right) Mike Fincke operating the CIR.

Droplet Combustion (continued)



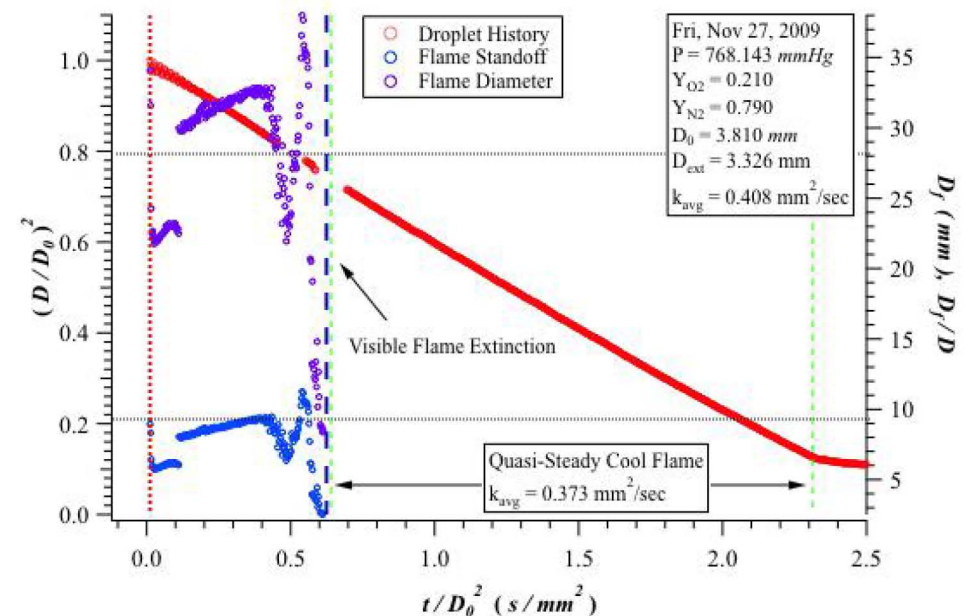
FLEX – Major Research Accomplishments

Methanol

- Stable droplet burning in 0.125/0.875 O₂/N₂, 1.0 atm, much lower than in 1-g
 - Validation of detailed numerical models of methanol combustion (building block for real fuel models)
- Flammability boundary at 0.15/0.35/0.50 O₂/N₂/CO₂, 0.7 atm
 - NFPA standard for portable CO₂ extinguishers not conservative enough for enriched O₂ (e.g., EVA pre-breathe), microgravity environment.
- Observed unique pre-extinction flame oscillations

Heptane

- Flammability boundary at approximately 0.15/0.85 O₂/N₂, much lower than in 1-g
- Unique observation of pre-extinction flame oscillations
 - Only for radiative extinction, more prevalent than for methanol
- Unique observation of low temperature chemical reaction after visible flame extinction
 - New observation; shows previous beliefs about cool flames are wrong.
 - Low temperature chemistry important in internal combustion engines (i.e. engine knock)



Gaseous Diffusion Flames (MSG)



Smoke Point in Co-flow Experiment (SPICE) – 2010

Soot control remains one of the major unsolved issues in combustion. Soot:

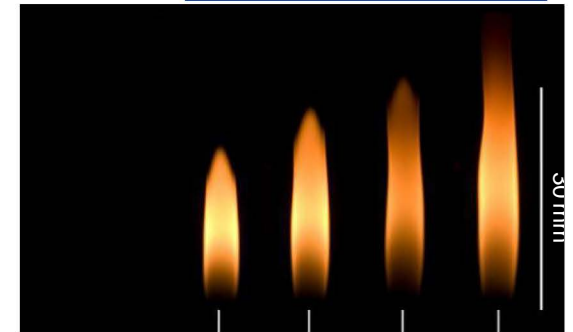
- Is the dominant source of radiant heat
- Is a major pollutant and health risk
- Is desired in some combustors and not in others.

Soot emission in flames is the result of the interplay of soot formation and soot oxidation kinetics. The smoke point is a long standing measure of the sooting propensity of fuels used in fuel selection and flame radiation modeling.

Initially deemed not possible in reduced gravity, the smoke point has been found to be substantially different in reduced gravity.

SPICE has extended this observation to consider the impact of the coflowing air stream on the smoke point

SPICE Experiment Assembly



Still images showing the onset of the smoke point

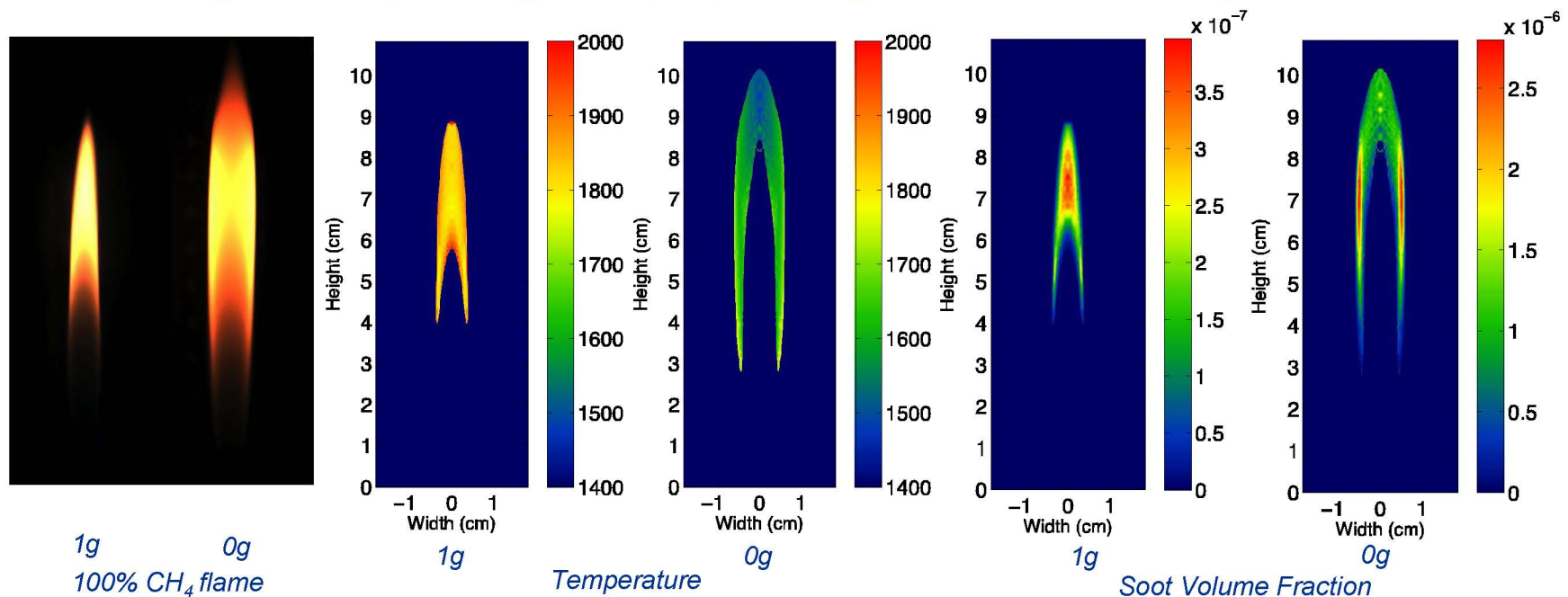


Gaseous Diffusion Flames (MSG)



The Structure & Liftoff In Combustion Experiment (SLICE) – 2012

- Study of flame structure and stability limits conducted using the SPICE hardware.
- Results will enable (1) a refinement of the ACME Coflow Laminar Diffusion Flame (CLD Flame) experiment, increasing its scientific return, and (2) improved design capability for terrestrial combustion devices through the validation of combustion models over a wider parameter range.
- Preliminary structure data reveals lower flame temperatures and dramatically increased soot concentrations in the microgravity (0g) flames as compared to normal gravity (1g); see below.
- Preliminary stability data indicates that the 0g/1g difference in forced air flow at liftoff is comparable to the buoyant velocity in the 1g flames, i.e., where 0g flames destabilize at higher forced air flows.



Solid Fuel Combustion-Material Flammability



The Burning and Suppression of Solids Experiment (BASS) – 2012 in process now

Recent Results:

With BASS we can measure material flammability in microgravity to compare with normal gravity flammability NASA-STD-6001 Test # 1. Results to date indicate that Test 1 is not conservative, and materials can burn at lower oxygen levels in microgravity than on Earth.

BASS also assesses the effectiveness of N_2 inert extinguishing agent in putting out flames over different materials, geometries, and flow. Results to date indicate that local application of suppressant is not adequate to fully extinguish the flames. The local jet entrains air and sustains the flame even when the ambient air flow is turned off.

Relevance/Impact:

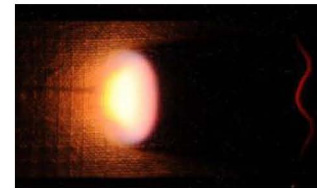
Spacecraft fires are a significant risk factor for human exploration.

Understanding material flammability and suppression in actual spacecraft environments relative to 1g materials screening is needed to mitigate this risk.

The PMMA material burned in BASS is being considered for MPCV windows.

JSC was surprised that this thick sample ignited easily and burned well in air.

Ground-based drop tower testing provides some data, but long-duration microgravity data is needed to study flammability limits for all but the thinnest films.



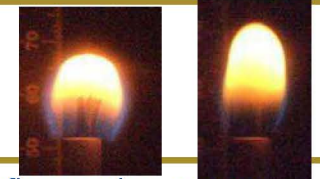
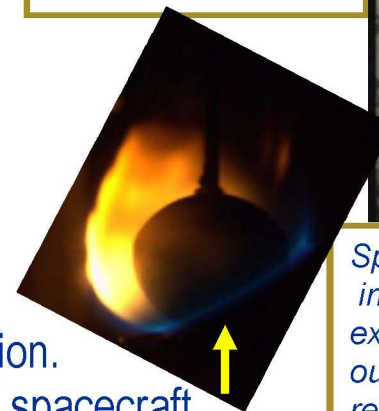
Nomex III burning in BASS in air. This material will not burn in air on earth.



*BASS in MSG
Don Pettit running BASS*



Spherical PMMA sample in BASS. N_2 Jet does not extinguish flame, only blows out stagnation region. Wake region continues to burn.



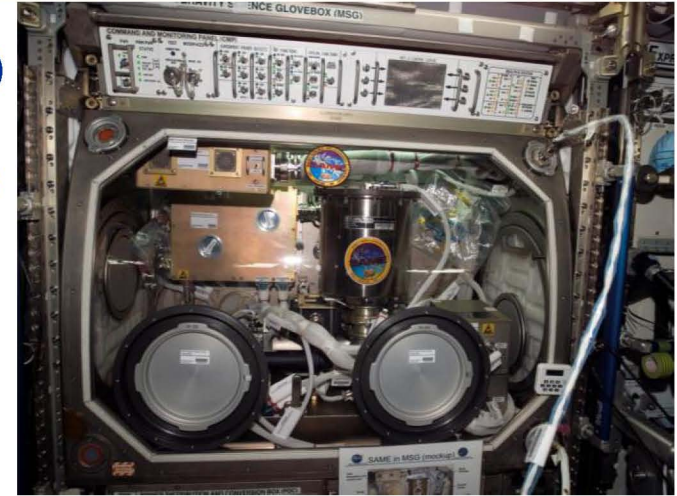
N_2 flow makes candle flame longer, it does not put it out.

Spacecraft Fire Safety

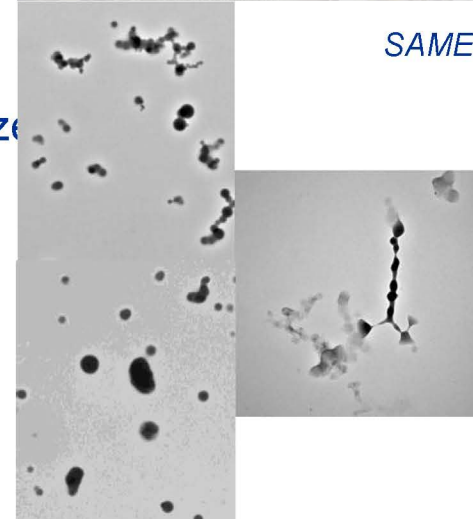


The Smoke Aerosol Measurement Experiment (SAME) 2007 & 2010

- Spacecraft fire is a recognized risk however there has been limited study of fires in 0-gravity.
- Current fire detection and suppression systems are consequently based on 1-g experience e not 0-g fires
- The reduced airflow seen in low-gravity enhances the smoke residence time near the source, enabling enhanced particle growth.
- SAME pyrolyzed 5 materials commonly found in spacecraft and made measurements of the particle size distribution
- Smoke particles produced in low gravity are typically twice the size on those produced in normal gravity however the overall morphologies are similar.
- These measurements will enable rational design of spacecraft smoke detectors.



SAME in MSG

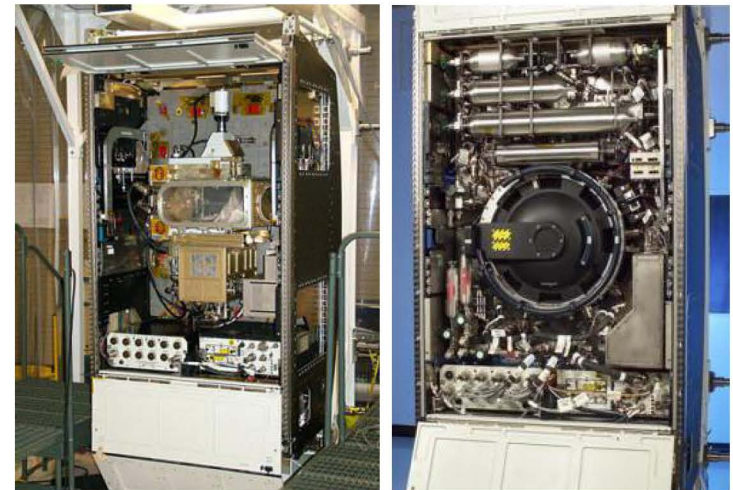


TEM photos of smoke particles from different materials (clockwise from the top: Pyrell, Teflon and Cotton) Horizontal dimension of images ~ 2 microns

Conclusions



- The past 12 years have produced significant results in microgravity research in Fluid Physics, Combustion Science and Complex Fluids
- These results have applications to terrestrial human health, pollution, energy, and commercial products in addition to NASA's exploration mission
- Future years can be expected to produce even more advances in diverse areas such as
 - Two phase flow
 - Packed bed reactors
 - Gaseous diffusion flames
 - Solid fuel flames
 - Long-term propellant storage tank pressurization and control
 - Suspended liquid crystals
 - Fire detection
 - Rheology of foams



Fluids Integrated Rack (left) and Combustion Integrated Rack

