

# Fluid Physics and Transport Phenomena Studies aboard the International Space Station: Planned Experiments

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**ABSTRACT.** This paper provides an overview of the microgravity fluid physics and transport phenomena experiments planned for the International Space Station. NASA's Office of Life and Microgravity Science and Applications has established a world-class research program in fluid physics and transport phenomena. This program combines the vast expertise of the world research community with NASA's unique microgravity facilities with the objectives of gaining new insight into fluid phenomena by removing the confounding effect of gravity. Due to its criticality to many terrestrial and space-based processes and phenomena, fluid physics and transport phenomena play a central role in the NASA's Microgravity Program. Through widely publicized research announcement and well established peer-reviews, the program has been able to attract a number of world-class researchers and acquired a critical mass of investigations that is now adding rapidly to this field. Currently there are a total of 106 ground-based and 20 candidate flight principal investigators conducting research in four major thrust areas in the program: complex flows, multiphase flow and phase change, interfacial phenomena, and dynamics and instabilities. The International Space Station (ISS) to be launched in 1998, provides the microgravity research community with a unprecedented opportunity to conduct long-duration microgravity experiments which can be controlled and operated from the Principal Investigators' own laboratory. Frequent planned shuttle flights to the Station will provide opportunities to conduct many more experiments than were previously possible. NASA Lewis Research Center is in the process of designing a Fluids and Combustion Facility (FCF) to be located in the Laboratory Module of the ISS that will not only accommodate multiple users but allow a broad range of fluid physics and transport phenomena experiments to be conducted in a cost effective manner.

## INTRODUCTION

The Microgravity Fluid Physics program currently has four major research thrust areas: *Complex Fluids, Interfacial Phenomena, Dynamics and Instabilities, and Multiphase Flows and Phase Change*. There are 106 ground-based and 20 flight/flight definition Principal Investigators (PIs) conducting experimental research as well as developing the theoretical framework for understanding the effects of gravity on processes involving fluids. Work in complex fluids covers colloids, foams, granular media, rheology of non-Newtonian fluids, and emulsions and suspensions. Interfacial phenomena includes liquid-vapor interface configurations, contact line dynamics, capillary driven flows and shape stability and break-up of liquid bridges and drops. Dynamics and instabilities include thermocapillary and thermosolutal flows, biofluid mechanics, geological fluid flows, pattern formation, and electrokinetics and electrochemistry. Multiphase flow and phase change include flow patterns in liquid-vapor/gas flows in microgravity, nucleate boiling and its control using acoustic and electric fields in microgravity, and flows of gas-solid and liquid-solid mixtures in microgravity.

The low-gravity environment of the Space Station nearly eliminates buoyancy and sedimentation and provides scientists near-ideal conditions to probe into flow phenomena otherwise too complex to study on Earth (such as physics of colloids and suspensions) and also allows study of flows (such as surface tension driven flows) that are nearly completely masked in Earth's normal gravity. This has the potential to revolutionize our understanding of growth of colloidal crystals that will enable tomorrow's photonic (using light in place of electrons) information technology. Understanding of liquid-vapor flows and heat transfer in microgravity is also vital to the design of spacecraft and life support systems needed for humans to explore and exploit the unlimited potential of space.

NASA Lewis Research Center is in the process of designing a Fluids and Combustion Facility (FCF) to be located in the Laboratory Module of the ISS that will not only accommodate multiple users but allow a broad range of fluid physics and transport phenomena experiments to be conducted in a cost effective manner. The FCF consists of three modules: Combustion Integrated Rack (CIR), Fluids Integrated Rack (FIR), and Science Augmentation Rack (SAR). A detailed discussion of FCF capabilities may be found in Corban and Winsa 1998. Most of the fluid physics and transport phenomena experiments planned to for the ISS will be conducted in the FIR of the FCF. In addition to FCF, the Microgravity Science Glovebox (MSG) and Expedited Processing of Experiments to Space Station (EXPRESS) rack will also be available for conducting fluid physics

experiments. All of these being multi-user facilities designed to maximize the scientific utilization of the Space Station.

The microgravity fluid physics and transport phenomena program is in the process of developing a number of experiments to be conducted using the ISS facilities mentioned above. This paper provides a list of all the planned experiments and details of some of the representative experiments. The program will continue to solicit new experiment ideas through NASA Research Announcements planned to be released on a two year cycle. The most recent NRA release is for November 1998.

## **PLANNED EXPERIMENTS ON ISS**

A list of the currently planned fluid physics and transport phenomena experiments is provided in Table 1. The table includes the descriptive title of the experiment, the Principal Investigator and Co-Investigator if any, and their affiliation.

These experiments are under various stages of design, definition, and non-advocate peer- reviews. The experiments that have mature science requirements and have completed a non-advocate peer-review are briefly described below.

### **Physics of Hard Spheres Experiment-2 (PH<sup>A</sup>SE-2):**

This experiment consists of microscopic and mesoscopic manipulation and control of colloidal samples to probe the essential features of the hard sphere disorder-order transition and the properties of the ordered solid phase that results. Many samples, in custom-designed microscope slide style cells that permit many different volume fractions and the application of external fields such as temperature gradients, periodic pattern imposition, and force application through the use of optical tweezers, will permit measurements from the disordered fluid phase, through the coexistence region, into the fully crystalline solid, and beyond into a glass-like phase. The dispersions will consist of colloidal hard spheres, in the 0.65 to 1.0  $\mu\text{m}$  diameter range, with controlled polydispersity, consisting of polymethyl-methacrylate in an index-matched fluid. (Chaikin and Russel 1998)

Microscopy will allow for the observation of the position of individual colloidal particles and thus the determination of local crystal line or liquid structure, defect structure, observation of nucleation and growth of individual crystallites, the spontaneous formation of dendrites, the effect of periodic and other imposed patterns, field induced local melting and freezing, and the dynamics of liquid – crystal, liquid-glass and solid-glass interfaces. The applied fields will allow for controlled nucleation and growth, induced metastable phases, susceptibility, and rheology measurements. A simple design with many 50 microliter samples in a single sample holder on the microscope platen will allow interchange between the many samples to be studied. Static and dynamic light scattering on the same samples will be done simultaneously by using a separate optical path allowing imaging of the back focal plane of the objective, which images the Fourier transform of the scattering from the samples. This image will be acquired with a CCD for Bragg scattering and structural studies. A small portion of the image, corresponding to a particular scattering wave vector will be acquired by a fiber optic and sent to a correlator for photon correlation spectroscopy.

Performing these experiments in reduced gravity will accomplish the full characterization desired without the gravitationally induced inhomogeneities that affect both the dynamics and the equilibrium state on earth. The information from this experiment will complement and build upon discoveries made in a previous space shuttle glovebox experiment, and a space shuttle express rack experiment (Zhu et al 1997). In particular, we expect to determine the volume fractions at which a fluid changes to a crystal, find the crystal structure of the equilibrium solid phase, contrast nucleation and growth in gravity and microgravity, especially in the region of the ground based glass transition (which was found not to occur in microgravity), quantitatively test the dendritic growth model, explore the role of polydispersity on the phase diagram and the structure of the different phases and explore the susceptibilities to external fields and the microrheology of the different phases.



Table 1

**International Space Station (ISS)  
Fluid Physics & Transport Phenomena Experiments (FPTP)**

<b>Experiment Title</b>	<b>Principal and Co-Inventor(s)</b>	<b>NASA Project Scientist</b>	<b>NASA Project Manager</b>	<b>Year Planned</b>
Physics of Hard Spheres Experiment - 2 (PHaSE-2)	Paul Chaikin and Bill Russel - Princeton	Bill Meyer	Mike Doherty	2003
PHaSE Augmentation Flight Experiment (CAFE)	Paul Chaikin and Bill Russel - Princeton	Bill Meyer	Amy Jankovsky	2002
Nucleate Boiling	Vijay Dhir - UCLA	Dave Chao	Mark Hickman	2004
Foam Optics and Mechanics (FOAM)	Douglas Durian - UCLA	Greg Zimmerli	Sue Moril	2004
Microscale Hydrodynamics Near Moving Contact Lines ( $\mu$ SCALE)	Stephen Garoff - Carnegie Mellon	Ray Skarda MaryJo Meyer - DepPS	John Caruso	2004
Particle Segregation in Collisional Shearing Flows ( $\mu$ SEG)	James Jenkins and Michel Y. Louge - Cornell	Enrique Ramé	Joe Balombin	2004
Field Induced Rheological Structural Transitions (FIRST)	Jing Liu - Cal State-Long Beach	K.C. Hsieh	Suzanne Saavedra	2004
Particle Interactions in $\mu$ g Flow Cell	Michel Y. Louge and James Jenkins - Cornell	Enrique Ramé	Joe Balombin	2004
Electrostatic Forces Controlling Granular Materials	John R. Marshall - NASA Ames	TBD	Tom Jacobson	2002
Dynamics of Miscible Interfaces	Tony Maxworthy - USC	R. Balasubramanian	Tom Jacobson	2005
Containerless Ripple Turbulence	Seth Putterman - UCLA	Walter Duval	Tom Jacobson	2004
Rapidly Sheared Bubbly Suspensions	Ashok Sangan (Syracuse) and Don Koch (Cornell)	Henry Nairn	Monica Hoffmann	2004
Cryogenic Capillary Pumped Loop & Heat Pipe	J. Seyed-Yagoobi - Texas A&M	Jeff Allen	Tom Jacobson	2005
Constrained Vapor Bubble Experiment (CVB)	Peter Wagner and Joel Plawsky - Rensselaer	Ray Skarda	Bill Postler	2002
Physics of Colloids in Space (PCS)	David Weitz - U. Penn	Rafat Ansari	John Koudelka Amy Jankovsky - DepPM	2000
Physics of Colloids in Space-2 (PCS-2)	David Weitz - U. Penn	Bala Sankaran	Mike Doherty John Sneed (DepPM)	2003
Colloidal Assembly in Binary Particle Suspensions	Arjun G. Yodh - U. Penn	Allen Wilkinson	John Sneed	2005

## Physics of Colloids in Space-2 (PCS-2)

This experiment is a direct follow-on to the Physics of Colloids in Space I (PCS-1) currently scheduled to fly in the International Space Station between 2000 and 2001. PCS-2 experiment will focus on two classes of colloidal samples. The first is binary alloys. These contain a mixture of two different colloidal particles. If their size ratio,  $r$ , and volume fraction,  $\phi$ , are adjusted appropriately, the particles will self-assemble into ordered binary alloy crystal structures. Colloidal particles of different materials will be used to make binary alloy crystals, significantly extending the applications of colloid engineering. The second set of samples will be a mixture of colloidal particles with polymers. The addition of the polymers induces a controllable attractive force, due to depletion, between the colloidal particles. This attractive force facilitates the formation of other structures. In addition, the presence of an attractive force induces new phase behavior in the colloidal suspensions.

The heart of this experiment is a microscope equipped to allow direct visualization of the particles in real space, using both bright field and differential interference contrast (DIC) imaging, as well as fluorescent imaging. In addition, it will allow both dynamic and static light scattering from the samples to determine Fourier space information. The microscope will also be equipped with laser tweezers to manipulate the structures formed to achieve specific effects. In addition, the plan is to include confocal microscopy to allow strongly scattering samples to be studied and to provide 3D real-space information. Finally, because of the very small sample volumes required, the apparatus will be able to contain between hundreds of samples in a very compact form, allowing the requisite sample variation to be achieved.

These experiments will provide a unique example of the use of colloid engineering to synthesize new materials with novel properties. The goal is to exploit the long range ordered structures formed using the self-assembly of colloidal particles. The use of mixtures of two different materials greatly increases the flexibility of the resultant structures; for example, the characteristic length scale of the structure can be set by one material, which could be an inert plastic, while the second material could have some completely different property, and could, for example, be an optically active semiconductor particle. This provides an opportunity to synthesize structures that are ordered on the length scale of light in all three dimensions, and such materials should have fascinating new properties. For example, they may be suitable for optical switches or filters, or as photonic band gap materials. Fabrication of 3D ordered structures with traditional lithographic methods is very difficult, and has not been done on the optical length scale; the use of colloidal materials allows the structures to be self-assembled, providing a new method for materials synthesis. In addition, we will study the phase behavior and crystallization properties of these binary alloys. This will provide additional insight into their growth allowing scientists to further tailor the crystal structure. (Weitz & Pusey, 1998)

## Constrained Vapor Bubble (CVB):

The thermophysical principles underlying change of phase heat transfer systems controlled by interfacial phenomena under microgravity conditions are not well understood. As a result, related passive engineering systems have not been optimized for space applications. This experiment in conjunction with the ongoing theoretical studies of the isothermal and nonisothermal constrained vapor bubble (CVB) under microgravity conditions will help remedy this undesirable situation. This proposed study is multifaceted: 1) it is a basic scientific study in interfacial phenomena, microgravity fluid physics and thermodynamics; 2) it is a basic study in thermal transport; and 3) it is a study of a passive heat exchanger. Facets (1) and (2) are emphasized. (Wayner & Plawsky, 1998)

Study of vapor bubble constrained in a transparent glass cell under both isothermal and nonisothermal conditions will increase the basic understanding of transport systems controlled by interfacial phenomena. The pressure gradient field will be obtained optically whereas the temperature field will be obtained using thermal sensors. Due to the sensitivity of systems of the proposed size to gravity and to small temperature and pressure gradients, these transport systems need to be studied under microgravitational conditions. Axisymmetric systems are required.

The immediate *microscopic* objective is to determine the interfacial characteristics of the system. The immediate *macroscopic* objectives are to determine the overall stability, fluid flow characteristics and heat conductance of the CVB as a function of the liquid volume and heat flow rate. Future *microscopic* objectives include the detailed evaluation of the transport processes in thin curved films. The augmented Young-Laplace and the Kelvin-Clapeyron models will be evaluated. Direct extensions to the microgravity environment of current earth based studies are proposed.

### **Microscale Hydrodynamics near Moving Contact Line:**

This low gravity experiments focus on the measurement of the fluid/vapor interface shape and flow field in the geometry-independent region near the contact line. These experiments will be the first characterization of geometry-independent properties as the length scale controlling the geometry dependent character of the fluid flow is varied. We will examine geometry-independent properties as we vary the relative importance of capillary, viscous, and inertial forces in the contact line region. In this experiment a rod moves down the central axis of a large square vessel. Simultaneous measurements of the shape of the liquid-vapor interface and the velocity field near the moving contact line are performed. Both microscopic (field of view 2mm x 2mm) and macroscopic views (field of view 5cm x 5cm) of the contact line region are required. Use of two liquids, one having a viscosity of 60,000 centistokes and the other 200 centistokes is planned. (Garnoff, 1998)

These experiments will shed new light on the unique hydrodynamics near moving contact lines. They will test the limits of the present analytical model for dynamic wetting and will provide the required input and validate evolving numerical solutions of this problem. Useful predictive models of spreading can only exist when geometry-independent properties extend to large enough distances from that contact line to be measured by known techniques. Our low gravity measurements will provide the first insight into the regimes where we can hope this occurs.

Dynamic wetting occurs in many natural and technological settings. It controls processes such as the migration of oil and water through a geological reservoir and film coating. Understanding the fundamental physics and chemistry governing moving contact lines and dynamic contact angles demands measuring geometry-independent properties, i.e., properties which are independent of the macroscopic shape of the moving fluid body. These properties must be determined if predictive models of spreading are to be realized and to be used in the design and optimization of technological processes. Since they are confined to a microscopic region near the contact line, they are difficult to determine. By expanding the distances over which geometry independence exists, low gravity is the essential tool in examining the crucial properties.

### **Foam Optics and Mechanics (FOAM):**

The unusual elastic character of foams will be quantified macroscopically by measurement of the shear stress as a function of shear strain rate and of time following a step strain; such data will be analyzed in terms of a yield stress, shear moduli, and dynamical time scales. The experiment will use a cone-plate rotating Couette rheometer that will permit video access radially through the cylindrical sidewall and optical measurements axially through the cone and plate of the rheometer. Microscopic information about bubble packing and rearrangement dynamics, from which these macroscopic non-Newtonian properties ultimately arise, will be obtained non-invasively by multiple-light scattering: diffuse-transmission spectroscopy (DTS) and diffusing-wave spectroscopy (DWS). Quantitative trends with materials parameters, most importantly average bubble size and liquid content, will be sought in order to elucidate the fundamental connection between the microscopic structure and dynamics and the macroscopic rheology. (Durian, 1998)

Aqueous foams are intrinsically nonequilibrium systems; with time, the gas and liquid components inexorably separate by some combination of coarsening (gas diffusion from smaller to larger bubbles), film rupture, and the gravitational drainage of liquid from in between gas bubbles. While coarsening is often slow and film rupture can

be eliminated, gravitational drainage cannot be prevented on earth since it is not possible to density match gas and liquid; furthermore, the rate of drainage increases rapidly with liquid content. This fundamentally precludes the possibility of ground-based study of foams near the melting transition. Prolonged microgravity conditions are therefore required in order to eliminate drainage for experimental study of the intrinsic structure, dynamics, and rheology of foams with liquid content varying up to, and beyond, the melting transition.

The utility and fascination of foams derive largely from the surprising fact that they have a solid like elastic character, in spite of being mostly gas with a few percent volume fraction of liquid, but can nevertheless flow under shear. The physical origin of such unusual rheology in terms of microscopic structure and dynamics is poorly understood and remains a subject of basic scientific interest to physicists, chemists, and chemical engineers. This experiment promises important new insight into these issues, and could also have significant consequences for our understanding of flow in other dense randomly-packed systems such as emulsions, colloidal suspensions, slurries, bubbly liquids, and granular materials. Furthermore, all foam applications are empirically based and results of this experiment may provide valuable fundamental guidance for the development of materials with more desirable rheology and stability characteristics.

### **Rapidly Sheared Bubbly Suspensions:**

Experimental measurements of bubble volume fraction in a cylindrical Couette device under microgravity conditions will provide a critical test of averaged equations for bubbly two-phase flows. The hydrodynamic interactions and direct collisions between suspended particles, drops or bubbles lead to random fluctuations in particle velocity and disperse phase stress, which includes a pressure and a viscous stress. The effective viscosity of the disperse phase may influence flow transitions such as transition to turbulence. The disperse phase pressure resists the accumulation of bubbles in certain regions of the flow. Buoyancy or centrifugal forces may drive this accumulation, for example. The segregation of bubbles, drops, and particles plays an important role in a variety of applications including boiling heat exchangers, bubbling reactors such as bioreactors, oil-gas-water mixtures in inclined wells, sediment transport, coal slurry pipeline flows, and the modification of turbulence by bubbles, drops or particles. Prediction of the extent of segregation in these situations requires knowledge of the disperse phase pressure. It is difficult to predict the disperse phase stress in most suspensions with microscale inertia. However, a theory has been developed based on the potential flow approximation for spherical, high Reynolds-number bubbles.

This theory will be tested in cylindrical Couette flows of suspensions of bubbles with diameter 2 to 3 mm. The bubbles will be suspended in an aqueous electrolyte solution to inhibit bubble-bubble coalescence. This experiment must be conducted under microgravity conditions to avoid the complicating effects of buoyancy-driven bubble motions. The centrifugal force will drive the bubbles toward the inner cylinder, while shear-induced bubble collision (disperse phase pressure) will resist this accumulation. Hot film probes will be used to measure bubble volume fraction and liquid velocity as a function of the radial position. Hot film probes mounted flush with the wall will measure the wall shear stress. The results of these measurements will be compared with theoretical predictions to test averaged equations of motion for a bubbly suspension including predictions for the magnitude of the disperse phase pressure and viscosity. A parametric study of the dependence of bubble pressure and viscosity on shear rate and bubble volume fraction and radius will be conducted. The experiment will also provide evidence as to whether the enhanced viscosity created by the bubbles' fluctuating motion delays the transition to turbulence. (Sangani & Koch, 1998)

### **Microgravity Segregation of Energetic Grains ( $\mu$ gSEG):**

The primary goal of this research is to carry out a physical experiment in which particle segregation is induced and maintained in a collisional flow of a binary mixture of two different types of spheres. The segregation will be driven in the absence of gravity by a spatial gradient in the kinetic energy of the velocity fluctuations of the mixture. The flow is to take place in a shear cell in the form of a racetrack in which the grains are sheared by the motion of the inner boundary relative to the outer. The gradient of the kinetic energy is to be maintained using

boundaries with different geometric features that result in different rates of conversion of the mean slip velocity into fluctuation energy at their surfaces.

In the experiment, a steady shearing flow will be maintained in shear cell by the relative motion of parallel, bumpy boundaries. The resulting profiles of mean velocity, fluctuation velocity, and concentration will be measured in a theory and those measured in computer simulations. Separate tests involving mixtures with special properties, e.g. spheres with identical masses but different diameters, but different masses, and spheres with identical masses but different diameters, will be used to interrogate different parts of the theory for segregation. We will also test simple analytical results for the mean velocity and fluctuation energy, obtained in a dense limit of the kinetic energy, against the experiment. The extent of agreement between the experiments, the theory, and the computer simulations will provide a test of the assumptions upon which the theory and the computer simulations are based. (Jenkins & Louge, 1998)

These experiments will isolate and investigate two different submechanisms of collisional segregation that usually occur together: the first is associated with differences in the inertia of the spheres. Attempt will be made to neutralize a third sub-mechanism associated with differences in collisional dissipation between the two different types of spheres. Inertial segregation will be studied in a system of spheres with different masses, but equal diameters, geometric segregation will be studied in a system different diameters, but equal masses.

The size segregation of flowing or shaken grains is a commonly observed phenomenon in industrial processes and in nature. In many industrial processes a homogeneous aggregate is desired; in these, size segregation is undesirable. However, in the mining industry, for example, segregation by size is exploited in some processing operations. Also, grain segregation is useful in understanding the origin of natural grain deposits; here it provides an indication of whether an aggregate of grains was deposited dry, with the larger grains above, or under water, with the larger grains below.

### **Nucleate Boiling in Microgravity:**

The proposed study of nucleate boiling heat transfer under microgravity conditions is planned in such a way that while providing basic knowledge of the phenomena, also leads to development of simulation models and correlations that can be used as design tools. In the study a building block type of approach is used and both pool and flow boiling are to be investigated. Starting with pool boiling experiments with a single bubble, the complexity of the experiments will be increased to three inline bubbles and to five bubbles placed on a 2 dimensional grid. Finally the experiments will be conducted when a large number of prespecified cavities nucleate on the heater and when a commercial surface is used. Silicon wafers will be used as test surfaces because on these surfaces cavities of desired size and shape can be fabricated in the absence of any undesired nucleation sites. In the experiments liquid subcooling will be varied parametrically. Two fluids will be used so that the effect of surface tension and wettability can be investigated. The system pressure in the experiments will vary over a narrow range around one atmosphere. However, the liquid to vapor density ratio of the two liquids will differ by at least an order of magnitude. In the experiments heater surface temperature will be maintained nearly constant by controlling power input to different regions on the heater. Data will be taken for heater temperatures, power input to heaters and liquid temperature in the pool. Visual observations will provide quantitative data on bubble inception, bubble growth, bubble merger and bubble departure processes. If possible, interferometry will be used to determine temperature distribution under and around the bubble and particle velocimetry to measure velocity in the pool during bubble growth. The experiments with three and five bubbles will provide data on bubble merger process in the lateral direction and for the effect of neighboring bubbles on bubble detachment from a particular site. (Dhir & Hasan, 1998)

In order to establish quasi-static conditions, experiments will last several bubble growth and departure cycles and will provide data which could be used to obtain spatially and temporally averaged heat transfer coefficients in nucleate boiling. The minimum duration of microgravity required to establish quasi-static conditions is several minutes. In the experiments with large number of active cavities data will be taken up to critical heat flux condition. Boiling is known to be a very efficient mode of heat transfer, and as such, it is employed in component

cooling and in various energy conversion systems. For space applications, boiling is the heat transfer mode of choice; since for a given power rating the size of the components can be significantly reduced. For any space mission, the size and, in turn, the weight of the components plays an important role in the economics of the mission.

## **DISCUSSION:**

These descriptions are intended to provide a brief overview of the experiment and the scientific objectives of each experiment. This should show the breadth of the microgravity fluid physics and transport phenomena discipline and value of the long-duration microgravity environment in making significant new contributions in the form of fundamental new knowledge that cannot be attained under Earth's gravitational environment. This knowledge is valuable for understanding and improving terrestrial processes and in providing data applicable for design of new and improved spacecraft and space-based systems.

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\*Science Requirements Document in NASA document available either from the PI from Microgravity Science Division of NASA Lewis Research Center, Cleveland, OH