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Microscope-Based Fluid Physics Experiments in the Fluids and Combustion Facility on ISS

Michael P. Doherty, Susan M. Motil, John H. Snead, and Diane C. Malarik
Glenn Research Center, Cleveland, Ohio

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ABSTRACT

At the NASA Glenn Research Center, the Microgravity Science Program is planning to conduct a large number of experiments on the International Space Station in both the Fluid Physics and Combustion Science disciplines, and is developing flight experiment hardware for use within the International Space Station's Fluids and Combustion Facility. Four fluids physics experiments that require an optical microscope will be sequentially conducted within a subrack payload to the Fluids Integrated Rack of the Fluids and Combustion Facility called the Light Microscopy Module, which will provide the containment, changeout, and diagnostic capabilities to perform the experiments. The Light Microscopy Module is planned as a fully remotely controllable on-orbit microscope facility, allowing flexible scheduling and control of experiments within International Space Station resources. This paper will focus on the four microscope-based experiments, specifically, their objectives and the sample cell and instrument hardware to accommodate their requirements.

INTRODUCTION

The Fluids Integrated Rack (FIR) of the Fluids and Combustion Facility (FCF) is a facility being designed by NASA's Glenn Research Center (GRC), specifically to support a wide range of fluids experiments in the International Space Station (ISS) environment of little crew time availability and other limited resources.[1] Within the FIR, the first four fluids physics experiments will utilize a flight instrument built around a light microscope. These experiments are: the "Constrained Vapor Bubble (CVB)" experiment (Peter C. Wayner of Rensselaer Polytechnic Institute), the "Physics of Hard Spheres Experiment-2 (PHaSE-2)" (Paul M. Chaikin of Princeton University), the "Physics of Colloids in Space-2 (PCS-2)" experiment (David A. Weitz of Harvard University), and the "Low Volume Fraction Colloidal Assembly (LϕCA)" experiment (Arjun G. Yodh of the University of Pennsylvania). CVB investigates heat conductance in microgravity as a function of liquid volume and heat flow rate to determine, in detail, the transport process characteristics in a curved liquid film. PHaSE-2, PCS-2, and LϕCA investigate the nucleation, growth, structure, and properties of colloidal crystals in microgravity and the effects of micro-manipulation upon their properties. All four experiments will be conducted within a subrack payload to the FIR, called the Light Microscopy Module (LMM), which will provide the containment, changeout, and diagnostic capabilities to perform the experiments.

Key diagnostic capabilities for meeting the science requirements of the four experiments include: video microscopy to observe sample features including basic structures and dynamics, interferometry to measure vapor bubble thin film thickness, laser tweezers for colloidal particle manipulation and patterning, confocal microscopy to provide enhanced three-dimensional visualization of colloidal structures, and spectrophotometry to measure colloidal crystal photonic properties. This paper will discuss the experiment objectives of these four microscope-based experiments, describe the sample cell hardware, and present the diagnostic capabilities and the design of the LMM to accommodate the science requirements.

EXPERIMENT OBJECTIVES

The common thread that each of the four experiments, CVB, PHaSE-2, PCS-2, and LϕCA, share is that all are microgravity fluid physics experiments managed by GRC and all plan to employ a microscope as the basic diagnostic tool for acquiring their science data. CVB is a multi-faceted study of interfacial phenomena, fluid physics, thermodynamics and thermal transport. This fundamental scientific research proposes to study passive heat exchangers for use in space-based thermal control systems.

Beyond this, PHaSE-2, PCS-2, and LφCA (as a group, referred to as P-2L) have a further common thread in that all are experiments within the discipline of the physics of complex fluids (in particular colloidal suspensions), an emerging subfield of condensed matter physics. Complex fluids are soft materials such as colloidal suspensions, emulsions, and polymer solutions. A colloidal suspension, or colloid, consists of fine particles, often having complex interactions, suspended in a liquid, with paint, ink, and milk being examples of colloids found in everyday life.[2]

This section will introduce each experiment itself, make mention of the application of the research, and explain the general and specific objectives of the experiment that the Principal Investigator wants to accomplish in microgravity.

Constrained Vapor Bubble (CVB)

Peter C. Wayner, Jr. (Principal Investigator) and Joel L. Plawsky (Co-Investigator) of Rensselaer Polytechnic Institute propose basic experimental and theoretical studies of a constrained vapor bubble under microgravity conditions to better understand thermophysical principles controlling heat transfer systems. Many papers have been published on both the experimental investigations on and the modeling of micro heat pipes.[3–5] For CVB, the macroscopic objectives are to determine the overall stability, the fluid flow characteristics, the average heat transfer coefficient in the evaporator of the heat pipe, and heat conductance of the constrained vapor bubble as a function of vapor volume and heat flow rate. More specifically, evaluation of change-of-phase heat transfer under microgravity conditions will lead to a fuller understanding of stability and transport processes controlled by interfacial forces.

The use of interfacial free energy gradients to control fluid flow naturally leads to simpler and lighter heat transfer systems because of the absence of mechanical pumps. Therefore, "passive" engineering systems based on this principle are ideal candidates for the space program. In this context, "passive" refers to the natural pressure field due to the intermolecular force field under either an imposed non-isothermal or isothermal temperature field. This force field is a function of shape, temperature, and composition of the system. For example, heat pipes that rely on these forces have been frequently proposed to optimize heat transfer under microgravity conditions. However, the basic thermophysical principles controlling these systems are not well understood and as a result they have under performed. In general, the full potential of interfacial forces has not been realized in transport phenomena. The CVB microgravity experiment seeks to remedy this situation.

Wayner, Plawsky, DasGupta, and affiliates have proposed that the performance of micro heat pipes can be modeled and have begun to experimentally demonstrate model validity.[6–9] The CVB experiment's objectives are as follows: 1) verify, under microgravity conditions, that the shape of the constrained vapor bubble over a large range of conditions is described by the extended Young-Laplace equation, 2) verify that the shape dependent interfacial intermolecular force field passively controls fluid flow and heat transfer, and that these non-equilibrium effects can analyzed using the Kelvin-Clapeyron transport model, and 3) verify that the Kelvin-Clapeyron model can be evaluated using the constrained vapor bubble under microgravity conditions. To meet these objectives, the flight experiment will study a relatively large constrained vapor bubble with relatively small pressure gradients under microgravity conditions where the system will be symmetric with respect to the axis. Symmetric systems with small interfacial pressure jumps (large radii of curvature) cannot be obtained in earth's gravitational field. Due to the sensitivity of the system to small pressure and temperature gradients and gravity, these thermal control systems will be studied under microgravity conditions.

The following seven quantities will be directly measured or calculated from measured values: the film thickness profile based on the fringe data, the temperature profile obtained directly from the thermocouples, the pressure level in the cell obtained directly from the pressure transducer, the power input at one end of the cell and power output at the other end of the cell based on the power into the heaters and calculations of losses, the general location of the vapor bubble, the shape of the dry area, oscillations, cavitation, and instabilities if present, and, before launch, the Hamaker constant, the radiative characteristics, the liquid vapor volume ratio, and the purity in the CVB Test Module.

In order to achieve the CVB objectives, cuvette-based liquid samples (pentane and ethanol) with local heater, cooler, thermal control, thermocouples, and pressure transducer, as well as an optical microscope having both interferometry and macro-imaging capability are required.

PHaSE-2

Paul M. Chaikin (Principal Investigator) and William B. Russel (Co-Investigator) of Princeton University study colloidal suspensions of sub-micron sized polymethyl-methacrylate (PMMA) spheres, which have been tailored to reduce all attractive forces. Figure 1 is an image of a colloidal crystal system comprised of 2.3 micrometer (μm) diameter PMMA spheres. Such systems of monodisperse hard spheres share a fundamental characteristic with atomic systems[10] —both undergo a transition from a disordered liquid state to an ordered solid state under the proper conditions, just as when water molecules become ordered to form ice. The hard sphere phase transition is driven purely by configurational entropy and results from the packing of impenetrable particles at moderate to high densities. For hard spheres, the phase diagram (liquid, co-existence, solid, glass) is dependent only upon hard sphere volume fraction. This transition underlies all other fluid-solid transitions and provides a reference upon which much theory and computation in condensed matter physics builds. The ultimate payoff will be a definitive set of data on this most fundamental of liquid-solid transitions, plus the understanding required to control or modify the structure of densely packed media.

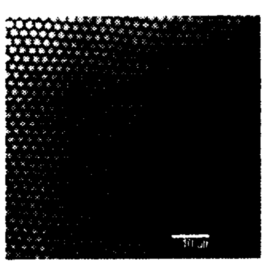

Figure 1. Confocal microscopy image of 2.3 micron diameter fluorescent PMMA particles showing a colloidal crystal system.

Chaikin and Russel previously flew PHaSE on the Space Shuttle (MSL-1, STS-83 and STS-94). PHaSE involved a multifunction light-scattering instrument and milliliter-sized sample cell volumes of 684 nanometer diameter monodisperse hard sphere colloids.[11] The instrument performed both static and dynamic light scattering, with sample oscillation for determining rheological properties. After local homogenization of the sample, scattered light from a 532-nm laser was recorded either by a 10-bit charge-coupled device (CCD) camera or by sensitive avalanche photodiode detectors. Significant research findings from 1-g experiments, their CDOT glovebox experiment,[12] and PHaSE include: calculating the growth instabilities of hard sphere colloids and the early nature of dendrites,[13] demonstrating experimentally the absence of a glass phase in the hard sphere phase diagram,[14] measuring nucleation and growth rates for several volume fractions and demonstrating differences between 1-g and micro-g,[15] making definitive measurements of shear modulus of hard sphere dispersions throughout the crystalline region,[16] and using temperature gradients to control density and grow the world's largest hard sphere colloidal crystal.[17,18]

In PHaSE-2, Chaikin and Russel will carry out further investigation of critical fundamental questions in colloid science relative to nucleation, growth, structure, dynamics, and rheology of colloidal crystals, and will investigate how colloidal systems respond to a variety of applied fields which may force them into non-equilibrium configurations or help them order. Colloidal growth and growth rate are to be controlled with temperature gradients, while liquid-crystal interface motion and the onset of dendritic instability are to be observed using a translatable hot region within the sample. The frequency dependent elasticity and viscosity of colloidal crystals are to be measured by: 1) directly recording the position and motion of probe particles (typically much larger than the basic particle), and 2) grabbing a probe particle and moving it either at a steady velocity or at a fixed oscillation frequency. Inducing the colloidal layer next to the cell surface into a specific two-dimensional arrangement is planned to measure the susceptibility of the homogenized hard sphere system to form non-equilibrium structures and/or to observe strain fields within a previously grown crystal.

In order to achieve these objectives, a thin cell sample, a local cell heater/ cooler, a local sample homogenization system, and an optical microscope having the capabilities of confocal microscopy and laser tweezers are required.

PCS-2

David A. Weitz (Principal Investigator) of Harvard University and Peter N. Pusey (Co-Investigator) of University of Edinburgh, UK study the physics of soft condensed matter, materials which are easily deformed by external stresses, electric, magnetic or gravitational fields, or even by thermal fluctuations.[19–23] One goal of the research is to probe and understand the relationship between the structure and dynamics at the mesoscopic scales and the macroscopic physical properties. Among the soft matter systems Weitz and Pusey study, two systems of great interest are binary colloidal and colloidal-polymer systems. Binary colloids have two different sized spheres dispersed in the liquid. When such systems crystallize, they form superlattice structures, with their phase diagram being dependent not only upon volume fraction, but particle size ratio. Binary colloidal systems may one day become useful in communications technologies as optical filters or displays. Colloidal polymers are similar to binary colloids, but with one of the constituents being a chainlike polymer particle. Polymers, being often added to colloids to control their properties and adjust their behavior (i.e., polymers control the way the paint spreads across a surface), could be optimized if we better understood the underlying reasons for their fundamental properties. The work of Weitz and Pusey is motivated both by the desire to model the properties of individual materials as well as the fundamental interest and important applications of these systems to create novel structures.

Weitz and Pusey have done extensive ground-based experimentation, have flown a number of 'glovebox' precursor experiments on MIR and Shuttle to study PMMA-based binary colloids and colloidal polymers, and are preparing to fly an ExPRESS Rack payload, the Physics of Colloids in Space (PCS), during ISS Increments 2, 3, and 4. PCS will perform macroscopic light scattering investigations of PMMA-based binary colloid, colloidal polymer, and fractal aggregate samples.[24]

In PCS-2, Weitz and Pusey seek to carry out further investigation of critical fundamental problems in colloid science and to more fully develop the evolving field of "colloid engineering," to create materials with novel properties using colloidal particles as precursors. For binary colloids, the PCS-2 experiment intends to obtain more extensive information on the phase behavior of binary colloidal crystals and to synthesize superlattice structures utilizing particle materials other than PMMA, such as silica, gold, or semiconductor or nematic liquid crystal droplets, in order to create structures that exhibit novel optical properties. For colloid-polymers, the PCS-2 experiment intends to examine the most interesting features of the colloid-polymer phase diagrams, in particular the regions of coexistence between several different phases (gas, fluid, solid). Attaining these objectives requires measurements of sample nucleation and growth, three-dimensional structure, and dynamics, inducing of defects and local modification of structures, and possibly the measurement of the stop bands of resulting photonic crystals.

In order to achieve these objectives, a thin cell sample, a local sample homogenization system, and an optical microscope having the capabilities of confocal microscopy, laser tweezers, and spectrophotometry are required.

LϕCA

Arjun G. Yodh (Principal Investigator) of the University of Pennsylvania studies entropically driven low volume fraction binary systems. This research topic differs from much of the previous investigators' work (Chaikin's hard sphere colloids and Weitz' binary colloids), which rely on the high volume fraction or space filling approach. In the space filling approach, crystals fill the entire sample cell and packing constraints provide the dominant forces. In Yodh's experiments, crystallization of the large spheres occurs in the low-volume fraction binary suspensions by the attractive particle interactions brought about by the depletion effect,[25] thus creating conditions for growth more closely resembling that which happens on the atomic and molecular scale. Yodh's interest in investigating colloidal crystal growth and formation includes the creation of novel structures and materials of industrial importance. Such structures or materials may be optical filters, switches, photonic band-gap materials, or strong ceramics.

Photonic band-gap materials are photonic crystals in which certain frequencies of light cannot freely propagate in the crystal in any spatial direction. Photonic crystals are three dimensionally periodic composites of dielectric materials, with lattice constants on the order of the wavelength of light. Light that travels through such crystals experiences a periodic variation of the refractive index, analogous to the periodic potential energy of an electron in an atomic crystal.[26] Under optimum conditions (e.g., the correct real space structure, and large index mismatches) it is possible for a band-gap for photons to form, meaning frequency stop bands where the propagating wave is highly attenuated. The band-gaps are separated by frequency pass-bands, where the wave propagates freely along the structure. Such a control over the electromagnetic wave propagation allows a wide range of applications in novel frequency selective surfaces.[27] Photonic band gaps are being vigorously pursued. Although full photonic band-gap materials have not yet been made in the visible range, it is expected that, in the near future, such photonic crystal systems will be realized and will allow us to perform many functions with light that ordinary crystals do with electrons.[28]

Photonic properties are pronounced when the index of refraction of the large spheres is highly mismatched from the surrounding solvent and small spheres. Sample systems being investigated for this research include, hollow latex spheres (air filled with index of refraction of 1.0), zinc sulfate (ZnS) spheres with index of refraction of 2.4, and other metal particles such as titanium dioxide (TiO_2) with even higher indices of refraction. This choice of particles poses a problem with regard to particle densities. Because particle densities vary between 1.0 for air filled particles to 4.1 for the ZnS particles (and even higher for other metal particles), settling and sedimentation occur on earth, influencing the formation of crystal growth. This influence will be greatly reduced in a microgravity environment.

The depletion effect can be understood as follows. In mixtures of different size spherical particles, an ordered arrangement of large spheres (typically 400nm to 3um) can increase the total entropy of the system by increasing the entropy of the small spheres (which are typically 5 to 10 times smaller than the large spheres). Because the center of mass of a small sphere cannot penetrate within half a 'small sphere' diameter of the large sphere surface, a region of excluded volume surrounds each large sphere. When the surfaces of two large spheres approach within a small sphere diameter, the total volume available to the small spheres thus increases, resulting in an attractive depletion force between the large spheres. The depletion effect also applies to large particles near the walls in the sample cell, with surface crystals forming. Because of this, the use of surface templates (special patterns to bias colloidal crystal growth) is a possibility for specifying how structures will grow.[29] This approach (low-volume fraction entropically driven binary systems) could lead to growing larger crystals that vary in particle size, particle density, and material with fewer defects and creating a methodology for colloidal "lithography" by using surface templates.

Under LφCA, Yodh seeks to create new colloidal crystalline materials from high and low density particles in low volume fraction binary particle suspensions, to study the assembly of these materials, to measure their optical properties, and to solidify the resulting structures so that they can be brought back and studied on earth. Specific objectives and measurements include determining the volume fractions at which surface nucleation occurs in microgravity, evaluating the structure of the resulting crystals, measuring the stop bands of the resulting crystals (versus both frequency and incidence angle), determining the relationship of the electromagnetic properties to variations (defects) in the colloidal crystal morphology, and solidification of the resulting structures in situ.

In order to achieve these objectives, a thin cell sample, a local sample homogenization system, a means to solidify the samples, and an optical microscope having the capabilities of spectrophotometry and confocal microscopy are required.

SAMPLE CELL HARDWARE

This section will provide detailed descriptions of the sample unique hardware.

CVB Cell and Principal Investigator Ancillary Hardware

The CVB Test Module is comprised of a cuvette, heater, cooler, thermal control, thermocouples, pressure transducer, and insulation (see Figure 2). The heater is at one end of the cuvette and the cooler at the other end. The heater and cooler will be controlled to create the required heat flux through the cuvette. The thermocouples will be used to obtain a temperature profile along the length of the cuvette. The pressure transducer will measure the vapor pressure of the fluid inside the cuvette to verify fluid purity. Fluid purity is very important to the success of CVB. Particulate matter, non-condensable, dissolved chemicals, and similar chemicals can affect the results. Particulate matter, for example, attached to the substrate in the contact line region distorts the fringe pattern.

The CVB test module cuvettes will be filled with either pentane (completely wetting) or ethanol (partially wetting). CVB will provide five test modules, with each cuvette representing a particular vapor/liquid volume ratio to be tested individually. The first test module will be dry so as to evaluate, calibrate, and compare the magnitude of radiative cooling to ground-based studies. A total of three cuvettes will contain a vapor/liquid pentane mixture, and the final cuvette will contain a vapor/liquid ethanol mixture. The ethanol mixture will ensure the observations of instabilities, and will provide comparisons with results obtained using the completely wetting fluid.

By using a set of liquid/vapor volume ratios, a systematic evaluation of the effect of liquid shear stress on the evaporative heat flux will be obtained. The shear stress is inversely proportional to the liquid film thickness at a given heat flux. The dominant design considerations are: 1) cell cleanliness and fluid purity, 2) a symmetric steady state test environment, 3) accurate control of both heat input and heat output, 4) accurate measurement of the liquid film thickness, the temperature profile along the sample cell, and the vapor pressure, and 5) optimum light level and alignment for sharp interference fringes with an optical microscope.

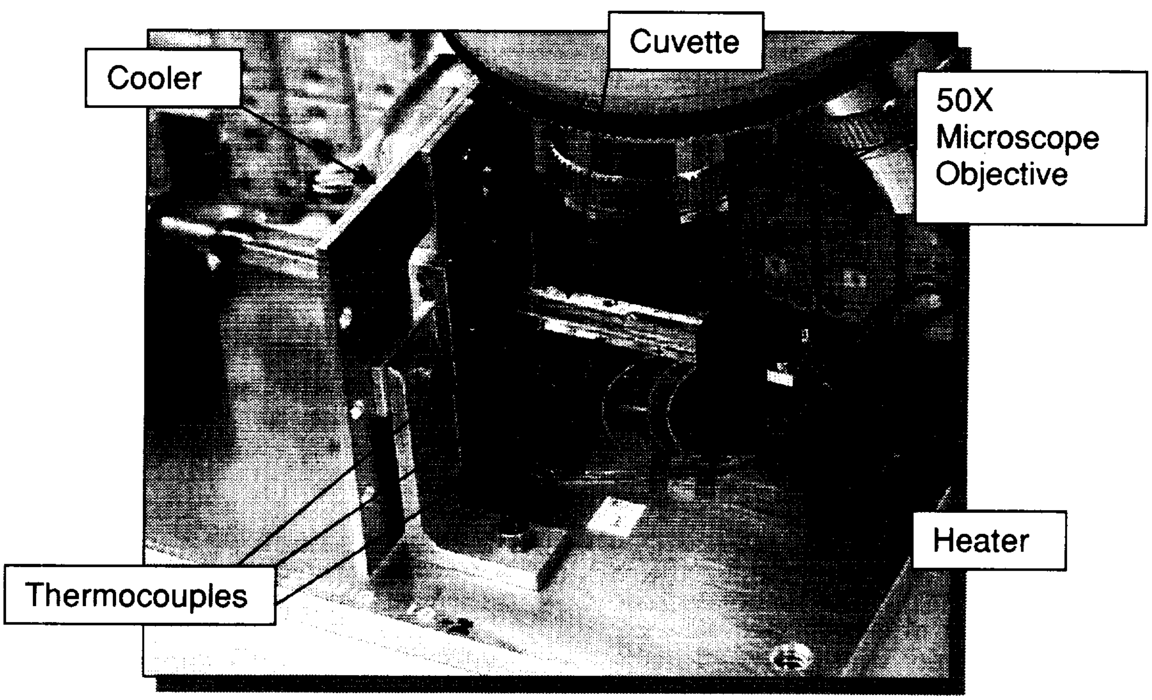

Figure 2. CVB Test Module in Microscope.

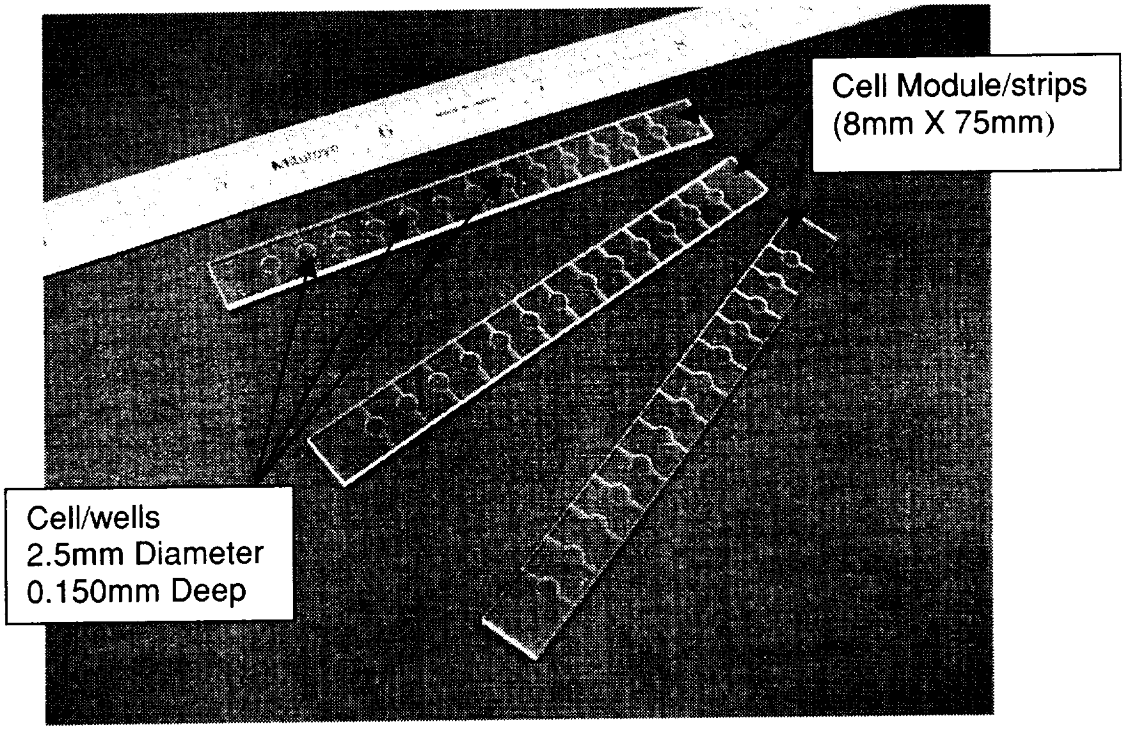

Figure 3. PHaSE-2, PCS-2, and LϕCA Sample Cells.

P-2L Cell and Ancillary Principal Investigator Hardware

Each of the P-2L Principal Investigators is requiring about 200 colloidal samples available for examination on-orbit. Sample volumes are to range from 1 - 5 microliters. To accommodate this range, a typical cell/well will have a diameter of 2.5mm (or greater) and a depth of 0.15mm.

Most of the requirements appear to be met by a sample cell having a round cell/well, fabricated as a one-piece cell module/ strip. Figure 3 shows three such prototype one-piece cell module/ strips. Each module/ strip, containing 13 cell/ wells, has nominal dimensions of 8mm by 75mm (thus three of these strips placed side by side have roughly the same dimensions as a standard microscope slide). The cell module/ strip is comprised of three layers of fused-silica, that are bonded together at 1000 deg C, and then lapped to the final dimensions. The middle layer (0.150mm thick) contains the 2.5mm diameter cell/ wells which are accessed on either side by 0.150mm by 0.5mm wide channels for cell/ well filling. The upper layer is typically lapped to have a thickness of 0.170mm (standard microscope cover slide thickness).

Cell/ wells are filled by capillary action of the colloidal suspension, and then are sealed using a small dab of epoxy to cover the channel openings. To accommodate local sample homogenization, a small piece of alumel thermocouple wire for use as a stir bar is inserted into the cell/ well through the channel before filling with sample. During the operations, a magnetic source external to the sample cell/ well will be utilized to agitate the stir bar and homogenize (or mix) the sample.

Variations in the sample cell to accommodate the P-2L science requirements include: a two-piece cell that is epoxied together after a surface template is applied to the inside of the cover slide, local heaters and coolers for temperature gradient studies, and specialized coatings on the cell to allow local sample heating via a high power directed laser beam. For LϕCA's in situ solidification of samples, a small fixture to expose the samples to ultra-violet light is envisioned.

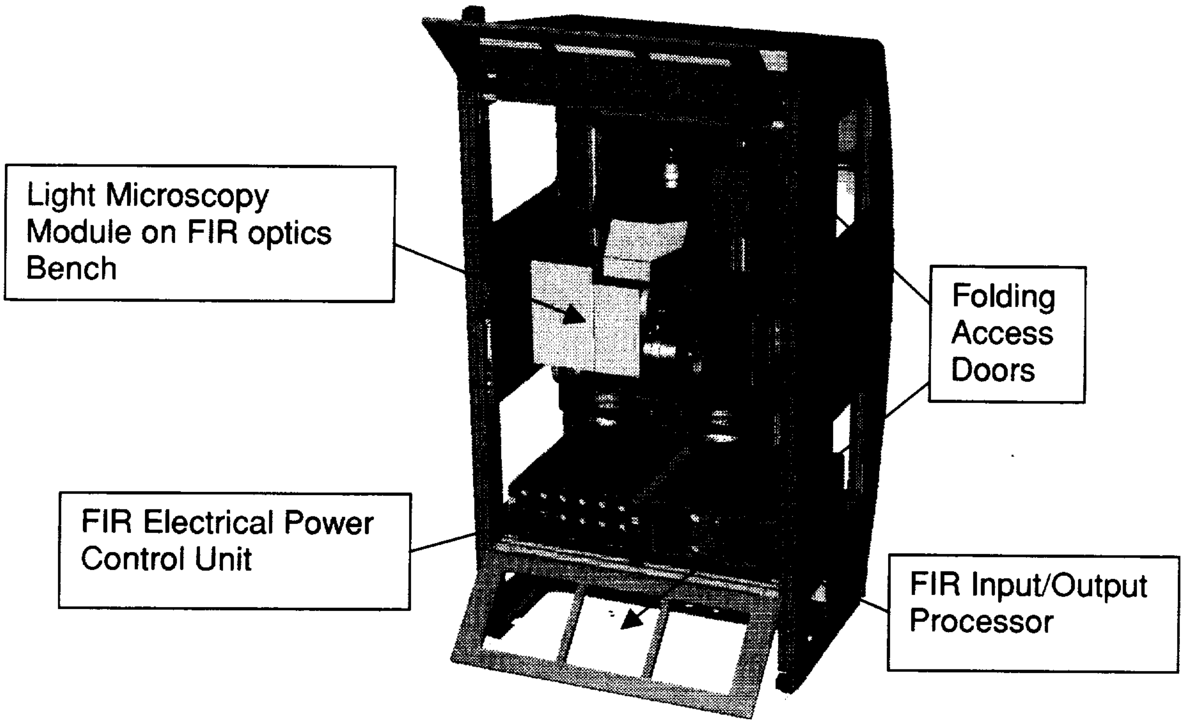

Figure 4. Light Microscopy Module in the Fluids Integrated Rack.

A four-slide sample platen is currently planned for the LMM, implying that ~140 samples (1 microliter in volume) would be accessable on a single platen. Thus, more than one platen will likely be required for each P-2L Principal Investigator.

LIGHT MICROSCOPY MODULE IN THE FLUIDS AND COMBUSTION FACILITY

As a subrack payload to the Fluids Integrated Rack (FIR) of the Fluids and Combustion Facility (FCF), the Light Microscopy Module (LMM) will be supported by the systems of the FIR (Figure 4). The FIR is a modular and reconfigurable rack facility in ISS providing laser sources, cameras, optics, computer control, communication, electrical power, temperature measurement and control, image processing and compression, and other support electronics.[30] Just as the FIR allows its common support hardware to be re-used by a wide range of experiments, so does the LMM allow many Principal Investigators (PIs) to use a powerful, well-configured fluids research microscope with only minor changes in sample cell design and instrumentation.[31]

The key diagnostic capabilities for meeting the science requirements of the four experiments are video microscopy, interferometry, laser tweezers, confocal microscopy, spectrophotometry, and macro-imaging. A more detailed discussion of each of these techniques follows. Given limited crew time as well as other resources on ISS, a fully remotely controllable on-orbit facility is the design goal, allowing as much ground control of the CVB, PHaSE-2, PCS-2, and LϕCA experiments as is possible. In addition to the science and operational requirements, the LMM must satisfy derived requirements from other sources, such as the ISS and FIR. The most restrictive to the LMM are: volume (limited to 300 liters), mass (may not exceed 65 kg), power draw (limited to approximately 500 watts of power), and containment (the LMM must provide at least one level of fluids and frangibles containment, and at least one level of containment for all light sources).

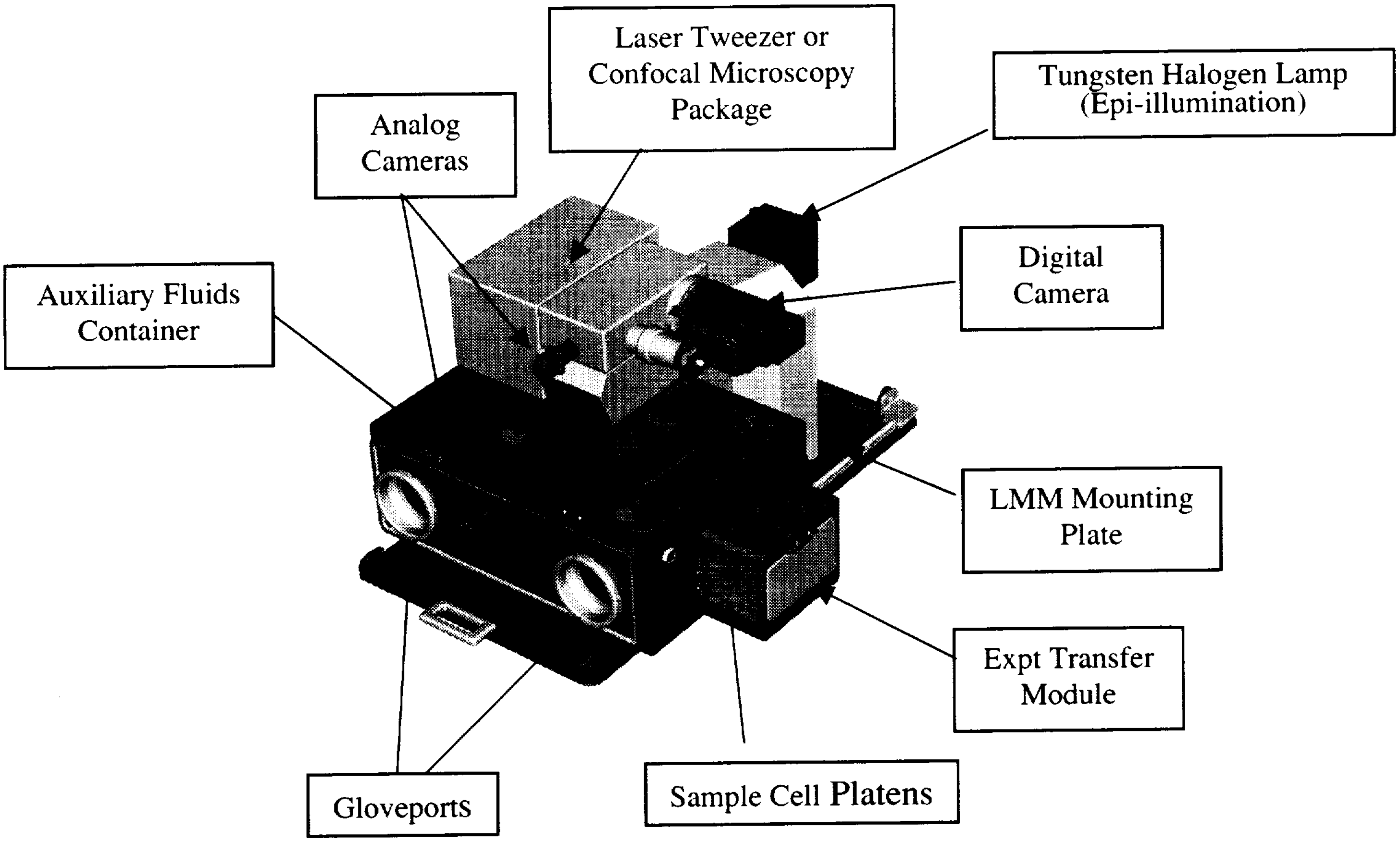

Figure 5. LMM on FIR Rotating Mounting Plate.

LMM Design

The LMM concept is built around a commercially available Leica DM-RXA microscope, which is an upright style microscope. The microscope will house several different objectives corresponding to magnifications of 10X, 50X, 63X, and 100X. The 100x objectives are oil immersion objectives (high Numerical Aperture for enhanced light collection and high resolution), which require the LMM to include a motorized oil deployment mechanism.

The microscope provides illumination sources in two different paths, one in the trans-illumination path and one in the so-called epi-illumination path. Trans-illumination illuminates the sample from underneath (through the sample) via a condenser and requires a reasonably transmissive sample material. Video microscopy, [32] the viewing of microscopic images at video rates of 30 frames per second or more, will be performed in trans-illumination. Epi-illumination illuminates the sample from above (from the same side of the sample as the camera) using the objective lens both as an illuminator and collector. The epi-illumination light path will be used for thin film interferometry, laser tweezers, confocal microscopy, and spectrophotometry. Incoherent light in both trans- and epi- illumination will be provided by tungsten halogen lamps.

A closeup view of the LMM is shown in Figure 5. Visible features include: a 12-bit digital monochrome camera, two 3-chip color (8 bits per color) analog cameras, a removable laser tweezer (or confocal) package, tungsten halogen lamps, an Auxiliary Fluids Container (AFC) with gloveports, an Experiment Transfer Module (ETM), and a rotating mounting plate. The multi-port imaging head on the top of the microscope provides a motorized slider to select the sensor or sensors to which the images are directed. The rotating mounting platform allows the LMM to be rotated for easy access to the sample area when in a non-operating mode. The AFC prevents liquid droplets (immersion oil or leaking sample material) from escaping into the cabin or into

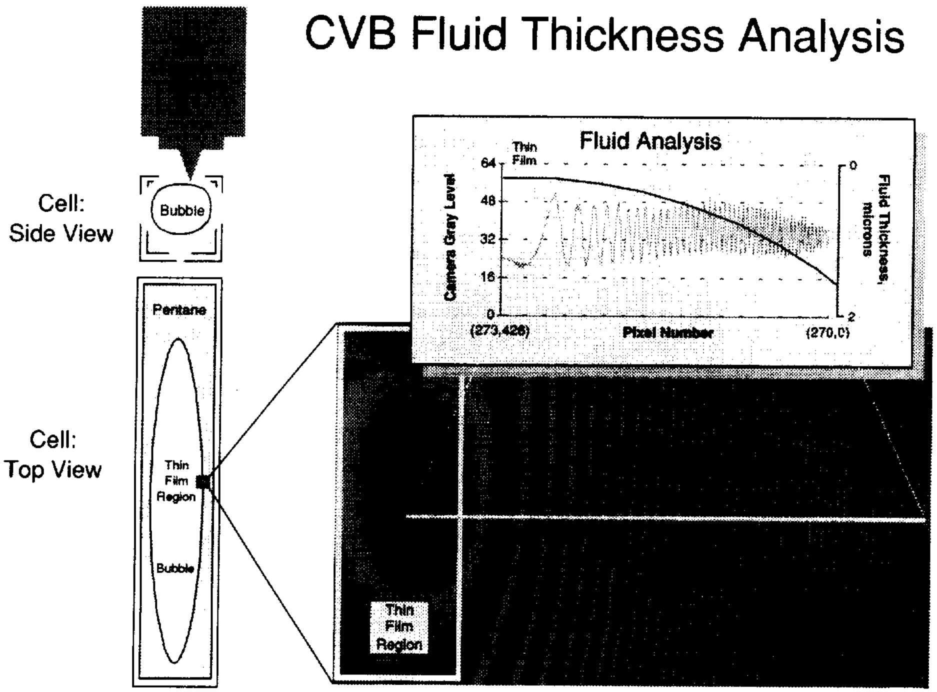

Figure 6. CVB Film Thickness Measurement.

electronics in the FIR. Likewise, the AFC is also capable of containing any potential glass shards (frangibles) from cells, which might break during operation. Glove ports allow cleaning access to the sample area before opening the box for sample changeout or reconfiguration. The ETM can accommodate up to 5 sample cell platens, and is configured adjacent to the AFC, which has a pass-through for the samples. The transfer box will be loaded with sample trays on the ground, and will provide contained storage until the samples are used in the experiment.

Video Microscopy

Video microscopy will be performed via trans-illumination imaging techniques already resident within the Leica RXA microscope itself, namely, bright field, dark field, phase contrast, and differential interference contrast (DIC). A variety of sophisticated condenser apertures, objectives, and prisms are required to support these techniques, but commercial microscopes come well suited for the task. Optical microscopy of colloidal suspensions, a well documented technique in the literature,[33,34] will be performed using the four transillumination techniques.

The microscope will be configured to have a 0.9 Numerical Aperture (NA) condenser and microscope objectives up to 100x and 1.4 NA (oil immersion) to support the required transillumination techniques. The light source for Kohler illumination is to be provided by a Tungsten Halogen bulb. The color analog camera on the multi-port imaging head will capture the images for downlinking and processing.

Interferometry

To understand the CVB bubble shape, measurement of the film curvature is required. Interferometry will be performed to measure the thickness of the liquid film, utilizing the 50x objective (Figure 6). The tungsten halogen light source in epi-illumination provides the required wavelengths to create the interference fringes. The light passes through the liquid and partially reflects at all interfaces: the glass-liquid interface and liquid-vapor interface. The greater the discontinuity between the two materials, the greater the reflection. The light from the two reflections interferes to form fringes that represent an increase in fluid thickness of half the wavelength of light for each bright and dark pair. The color analog camera on the multi-port imaging head will capture the images for downlinking and processing. Analyzing the interferometry images will yield a film thickness profile. This profile gives the curvature profile, and therefore the pressure field for liquid flow in the liquid film. The curvature will be measured at 10 axial positions along the cuvette.

Data is planned to be obtained under both steady state conditions and periodic oscillatory conditions. In a given test with varying heat input rates, steady state data will be obtained first as a function of the heat input rate and until oscillations occur. Then the test will continue with the data recorded under oscillatory conditions. In CVB's case, the definition of steady state will be based on the local value of the curvature associated with the first four destructive interference fringes near the contact line in the middle of the vapor bubble.

Laser Tweezers

Laser tweezers will be implemented using a custom built system based upon a 1064nm Nd:YAG laser, beam focusing optics, and two acousto-optic deflectors to steer the trap within the field of view of the microscope. The microscope's reflected light turret will contain a dichroic mirror to reflect the 1064nm light down to the sample and simultaneously pass visible light in trans-illumination up to the color analog camera on the multi-port imaging head, thereby allowing both the tweezer beam and the surrounding colloidal crystal to be imaged. Laser tweezers simply is the trapping of a colloidal particle using radiation pressure by focusing a laser beam through a high NA lens and striking a particle with a higher refractive index than the surrounding medium.[35] (Ashkin[36] was the first to trap a particle using radiation pressure).

Once the colloidal crystals have formed, tweezers can be employed to displace a particle by one lattice constant from its equilibrium position or to remove the particle entirely. The tweezers also can be scanned through a fixed array of points across the field of view. This can be performed on either a newly homogenized sample, to induce patterns that are either commensurate or incommensurate with the equilibrium configuration of the crystal, or on a sample that has already crystallized. The goal of the former is to observe the type of order (if any) the system assumes based upon these initial conditions, while the goal of the latter is to observe strain fields within a previously grown crystal. For sample cells with heat absorbing coatings, the 1064nm beam will be utilized for local heating to re-homogenize the sample for local recrystallization. Finally, laser tweezers appear useful for measuring the viscosity of the fluid. A particle is trapped and video images taken as it is translated in an oscillatory fashion through the field of view. The velocity just before the particle falls out of the trap is measured from the video record and, along with the known force and particle diameter, used to calculate the dynamic viscosity.

Confocal Microscopy

Confocal microscopy will be implemented using a 532nm frequency-doubled Nd:YAG laser, a Yokogawa Model CSU10 Confocal Scanner, and the 12 bit digital CCD camera.

The Yokogawa CSU10 confocal unit employed is a Nipkow disk based scanner (as opposed to a laser scanning device). The Nipkow disk version of confocal microscopy was chosen for the LMM due to its inherent stability and speed. This method uses a spinning array of apertures and lenses to individually map regions of the sample onto the CCD array, analogous to the raster scan of an electron beam on a cathode ray tube. The rotational speed of the scanner will allow 30 frames per second of confocal images to the CCD camera. Confocal is normally used on a fluorescent-dyed sample. The crystal three-dimensional structure is reconstructed by assembling the slices with an image analysis program, from which colloidal growth, structure, and dynamics can be measured. The confocal module will be attached and aligned to the side of the LMM using slide rails, and will access the sample though an auxiliary port on the Leica RXA. The microscope's reflected light turret will contain a reflecting mirror to direct the light to and from the sample.

The confocal microscopy technique should be a great augmentation to the video microscopy, providing certain advantages over brightfield, darkfield, phase contrast, and DIC due to the enhanced rejection of out-of-focus light provided by the confocal technique. (The disadvantage is that confocal microscopy requires exposure times, which affect its suitability for studying dynamics.) It results in a much finer resolution in the sectioning dimension (through the sample), allowing better reconstruction of crystal structure and lattice positions, even within somewhat turbid samples.

Spectrophotometry

Spectrophotometry will be implemented using the tungsten halogen lamp in epi-illumination, a liquid crystal tunable filter, a translating pinhole in the aperture plane, and either the 12 bit digital CCD camera or the color analog camera (Figure 7). The Liquid Crystal Tunable Filter (LCTF) is used to select narrow-band visible light (10nm bandwidth) from the collimated light in the epi-illumination path and pass it to the pinhole and on to the sample. The translating pinhole is planned to be adjustable in the X and Y directions to vary the angle of incidence (up to +/- 65 for normal incidence angle) at the sample. Since this technique is looking at the reflected light coming back from the sample, the detector will be seeing the stop bands of the photonic crystals (Bragg reflected). When the LCTF is tuned to a wavelength that is in the pass band of the photonic crystal, the light will pass through the crystal and only non-specular reflection will reach the detector.

Macro-imaging will be performed via the color camera located on the front of the AFC. Its chief purpose is to provide an overall view of the CVB test module, or to provide a visual check on test setups for the P-2L PIs.

CVB is planned as the first fluid physics experiment to be performed in the LMM (completed by approximately 5 months after on-orbit installation of the LMM), thereby being the first experiment performed in the FIR. For CVB operations, the microscope's condenser will not be present, allowing the larger CVB test module to fit under the objective stage. Subsequently then, in somewhat consecutive order, PHaSE-2, PCS-2, and LϕCA will be performed over a 6 month period of time. For P-2L science operations, the AFC will contain the motorized sample stage, the oil deployment mechanism, and the magnetic source for sample homogenization. Therefore, between experiments, the ISS crew will be needed for

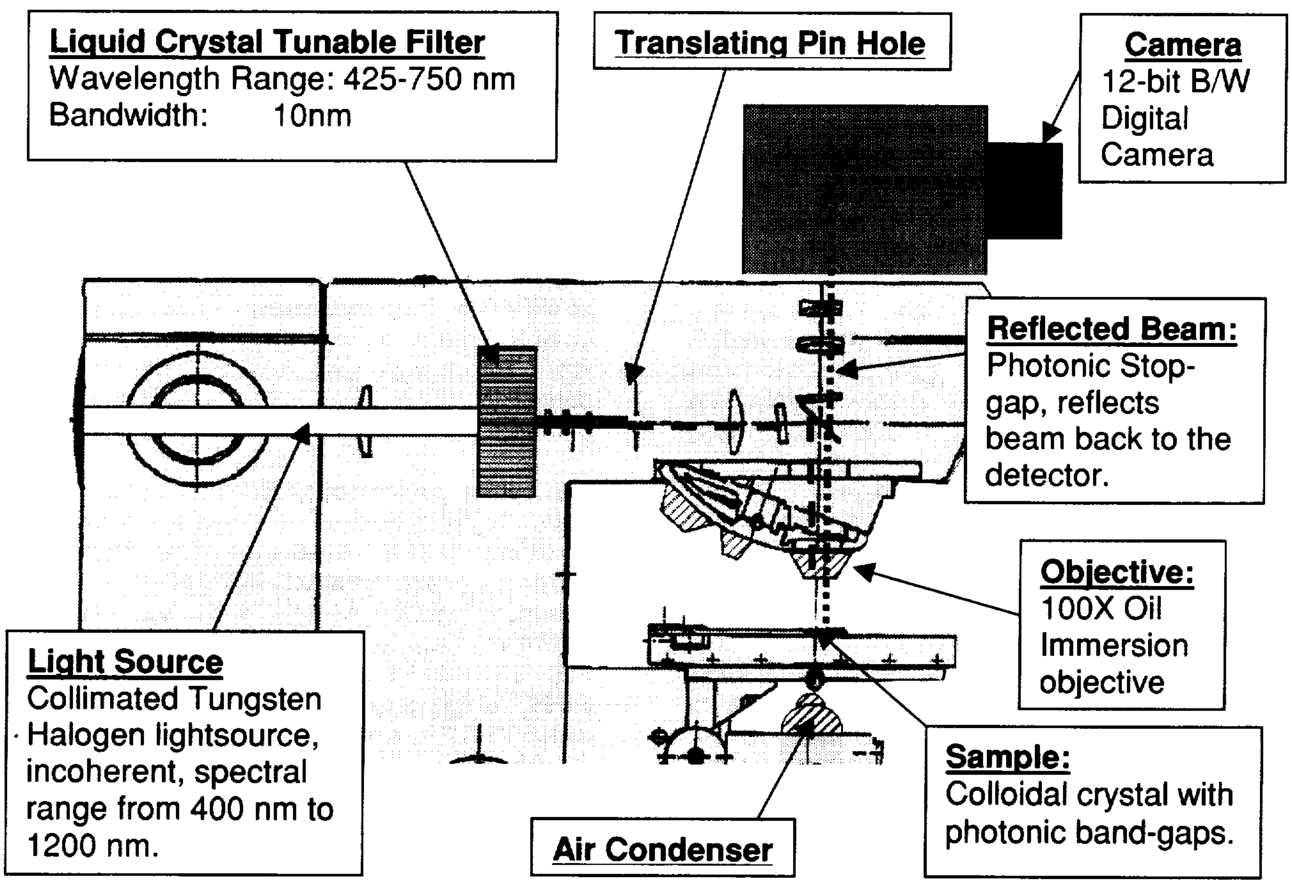

Figure 7. Spectrophotometry Concept for LMM.

reconfiguration of the LMM test setups. Also, new test modules and sample platens (some of which are launched after initial P-2L operations have been undertaken) will be introduced and changed out by the crew over the course of the LMM on-orbit operations via the pass-through for the samples. Crew time, therefore, will be an important resource. Although configuration and maintenance procedures will be conducted by the ISS crew, the LMM will primarily operate remotely from NASA and PI ground sites through the use of World Wide Web technologies. This will conserve precious on-orbit resources, as well as allow very specific experiment protocols to be easily modified by the PI in near real time. Control of the experiments and telemetry, and data acquisition, management, and transmission will be conducted via the LMM and FIR. Subsets of representative data will be downlinked via FIR and ISS subsystems to evaluate progress and direct experiment operations, and the remaining data will be later brought down on exchangeable physical hard drives.

LMM Status

Currently, the LMM project is in the requirements definition and preliminary design phase. A Preliminary Design Review (PDR) will be conducted in mid-2001. At that time, the engineering requirements will be baselined, and an engineering model of the LMM will be fabricated. The Critical Design Review (CDR) will occur in 2002, and the LMM Flight Unit will be ready for shipment to Kennedy Space Center by late 2003. The LMM is tentatively manifested to launch on the UF-5 flight to ISS. It will be installed in the FIR and remain on-orbit for up to 21 months, during which time, the four PI's will acquire their science data.

SUMMARY

In summary, the Light Microscopy Module is a fully remotely controllable microscope, planned for the Fluids Integrated Rack in the U.S. Laboratory on the International Space Station, allowing flexibility in scheduling experimental runs within the constrained resources of the ISS. It offers key capabilities of video microscopy, interferometry, laser tweezers, confocal microscopy, and spectrophotometry. The LMM provides coherent and incoherent light sources, filters, detectors, exposure control, sample manipulation, sample homogenization, oil immersion, and containment. The CVB, PHaSE-2, PCS-2, and LϕCA experiments will utilize the LMM over a 21-month on-orbit period starting at UF-5. The experiment-unique sample cells, procedures, and any specialized measurements (e.g. cell instrumentation, special light source, etc.) are customized within the constraints of the LMM, FIR, and ISS for each Principal Investigator. Such an arrangement allows cost and time savings on each experiment by reusing modular facility test equipment, rather than the traditional approach of designing stand-alone experiments for each Principal Investigator.

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At the NASA Glenn Research Center, the Microgravity Science Program is planning to conduct a large number of experiments on the International Space Station in both the Fluid Physics and Combustion Science disciplines, and is developing flight experiment hardware for use within the International Space Station's Fluids and Combustion Facility. Four fluids physics experiments that require an optical microscope will be sequentially conducted within a subrack payload to the Fluids Integrated Rack of the Fluids and Combustion Facility called the Light Microscopy Module, which will provide the containment, changeout, and diagnostic capabilities to perform the experiments. The Light Microscopy Module is planned as a fully remotely controllable on-orbit microscope facility, allowing flexible scheduling and control of experiments within International Space Station resources. This paper will focus on the four microscope-based experiments, specifically, their objectives and the sample cell and instrument hardware to accommodate their requirements.

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