NASA/TM—2002-212009 IAC–02–T.4.02

The NASA Microgravity Fluid Physics Program—Knowledge for Use on Earth and Future Space Missions

Fred J. Kohl and Bhim S. Singh
Glenn Research Center, Cleveland, Ohio

J. Iwan Alexander
National Center for Microgravity Research, Cleveland, Ohio

Nancy J. Shaw, Myron E. Hill, and Frank G. Gati
Glenn Research Center, Cleveland, Ohio

December 2002

The NASA STI Program Office . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the Lead Center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA's counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results . . . even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI Program Home Page at ***http://www.sti.nasa.gov***

- E-mail your question via the Internet to help@sti.nasa.gov

- Fax your question to the NASA Access Help Desk at 301–621–0134

- Telephone the NASA Access Help Desk at 301–621–0390

- Write to:
  NASA Access Help Desk
  NASA Center for AeroSpace Information
  7121 Standard Drive
  Hanover, MD 21076

NASA/TM—2002-212009 IAC–02–T.4.02

The NASA Microgravity Fluid Physics Program—Knowledge for Use on Earth and Future Space Missions

Fred J. Kohl and Bhim S. Singh
Glenn Research Center, Cleveland, Ohio

J. Iwan Alexander
National Center for Microgravity Research, Cleveland, Ohio

Nancy J. Shaw, Myron E. Hill, and Frank G. Gati
Glenn Research Center, Cleveland, Ohio

Prepared for the
53rd International Astronautical Congress
cosponsored by the International Astronautical Federation (IAF), the International Academy of Astronautics (IAA), and the International Institute of Space Law (IISL)
Houston, Texas, October 10–19, 2002

National Aeronautics and
Space Administration

Glenn Research Center

December 2002

Available from

NASA Center for Aerospace Information
7121 Standard Drive
Hanover, MD 21076

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22100

Available electronically at http://gltrs.grc.nasa.gov

THE NASA MICROGRAVITY FLUID PHYSICS PROGRAM—KNOWLEDGE FOR USE ON EARTH AND FUTURE SPACE MISSIONS

Fred J. Kohl and Bhim S. Singh
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

J. Iwan Alexander
National Center for Microgravity Research
Cleveland, Ohio 44106

Nancy J. Shaw, Myron E. Hill, and Frank G. Gati
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

ABSTRACT

Building on over four decades of research and technology development related to the behavior of fluids in low gravity environments, the current NASA Microgravity Fluid Physics Program continues the quest for knowledge to further understand and design better fluids systems for use on earth and in space. The purpose of the Fluid Physics Program is to support the goals of NASA's Biological and Physical Research Enterprise which seeks to exploit the space environment to conduct research and to develop commercial opportunities, while building the vital knowledge base needed to enable efficient and effective systems for protecting and sustaining humans during extended space flights.

There are currently five major research areas in the Microgravity Fluid Physics Program: complex fluids, multiphase flows and phase change, interfacial phenomena, biofluid mechanics, and dynamics and instabilities. Numerous investigations into these areas are being conducted in both ground-based laboratories and facilities and in the flight experiments program. Most of the future NASA-sponsored fluid physics and transport phenomena studies will be carried out on the International Space Station in the Fluids Integrated Rack, in the Microgravity Science Glovebox, in EXPRESS racks, and in other facilities provided by international partners. This paper will present an overview of the near- and long-term visions for NASA's Microgravity Fluid Physics Research Program and brief descriptions of hardware systems planned to achieve this research.

INTRODUCTION

Many of the biological, environmental, and industrial processes required to support life take place in the fluid phase. Fluid motion accounts for most transport and mixing in natural and industrial processes as well as in living organisms. A detailed understanding of fluid dynamics over a broad range of length and time scales is essential for progress in many emerging research areas of physical and biological sciences. The low-gravity environment of space offers a unique opportunity for the study of fluid physics and transport phenomena, as the nearly weightless conditions allow researchers to observe and control fluid phenomena in ways that are not possible on Earth. In addition, detailed knowledge of fluid flows is essential for the design of practical space systems for propulsion, power, and life support.

NASA's Office of Biological and Physical Research (OBPR) seeks to exploit the space environment to conduct research and to develop commercial opportunities, while building the vital knowledge base needed to enable efficient and effective systems for protecting and sustaining humans during extended space flights.[1] OBPR addresses the two fundamental challenges associated with human space flight: 1) understanding nature's forces in space; and 2) understanding the human experience in space. The specific thrusts of the OBPR Physical Sciences Research Division Program in fluid physics are to conduct peer-reviewed research based on scientific value that exploits the advantages of the microgravity environment of space and research based on applications that are relevant to future human and robotic space exploration.[2] Thus the NASA Microgravity Fluid Physics Program provides a significant component of the foundation for the broad range of diverse NASA OBPR-sponsored research activities.

Previous experiments conducted on the ground and in low-earth orbit over the past four decades have yielded rich results that have provided valuable insights into fundamental fluid behavior that apply to both terrestrial and space environments.[3–8] Many results were unexpected or could not have been observed in Earth-based laboratories. For example, in the Physics of Colloids in Space (PCS) experiment on the International Space Station (ISS), de-mixing of the colloid-polymer critical point sample could be studied over four decades of length scale, from one micron to one centimeter, as this sample phase-separated into two phases.[9] Such behavior cannot be observed in this type of sample on Earth because sedimentation would cause the colloids to fall to the bottom of the cell faster than the de-mixing process could occur. Another example comes from the study of granular materials: in microgravity, granular materials exhibited strengths nearly 80% higher than conventional design and analysis concepts had predicted.[10] Reexamination of existing theories in light of this observation is expected to yield improved theories for soil mechanics. The impact on foundation engineering could result in more effective designs and lower costs.

Research on fluids management and heat transfer, the results of which are applied to propulsion, power and life support systems, has contributed greatly to U. S. leadership in space exploration. One example is the Pool Boiling Experiment,[11] that examined the fundamental mechanisms that constitute nucleate pool boiling, specifically its characteristics under the buoyancy-free conditions of microgravity. The experiments were part of a systematic theoretical and experimental study of the heat transfer and vapor bubble dynamics associated with nucleation and bubble growth, departure, motion, collapse, and subsequent rewetting of a heated surface. All high-heat-flux cases exhibited the expected boiling pattern; however, the low-heat-flux experiments produced results quite different from those found under terrestrial conditions, and also quite different from what one would have anticipated in microgravity. These differences were caused by the existence of a large vapor bubble attached to the heater surface. Within this bubble, small bubbles merged and subsequently condensed because of high subcooling. A thin layer of liquid persisted under the bubble, causing rewetting of the heater surface. These results also indicated the potential for quasisteady nucleate pool boiling in long-term microgravity, with certain combinations of heat flux and bulk liquid subcooling. These simple experiments provided evidence that nucleate pool boiling may be achievable in a microgravity environment.

Ground-based researchers have recently reported the first-ever experimental observation of Marangoni-Bénard long-wavelength instability in investigations using very thin liquid layers where the effect of gravity is negligible.[12,13] The short-wavelength Bénard instability results in formation of well-known hexagonal cells. Although this long-wavelength instability was predicted 35 years ago, it had not been observed. Researchers have also developed a numerical simulation whose results are in qualitative agreement with experimental observations. This instability could become the primary one in a microgravity environment.

Building on a history of diverse and productive fundamental microgravity research carried out over more than four decades, and with the recent availability of research facilities on the ISS, the current NASA Microgravity Fluid Physics Program promises to continue in that tradition.

MICROGRAVITY FLUID PHYSICS THEME AREAS

The Microgravity Fluid Physics Program currently consists of five major research areas: complex fluids, interfacial phenomena, biofluid mechanics, dynamics and instabilities, and multiphase flows and phase change. Work in complex fluids covers colloids, foams, granular media, rheology of non-Newtonian fluids, and emulsions and suspensions. Interfacial phenomena include liquid-vapor interface configurations, contact line dynamics, capillary-driven flows, and the shape stability and breakup of liquid bridges and drops. Biofluid mechanics includes fluid flow and transport in biological systems at cellular, organ and organism level. Dynamics and instabilities include thermocapillary and thermosolutal flows, geological fluid flows, pattern formation, and electro-kinetics and electrochemistry. Multiphase flows 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.

As NASA undertakes new technology development for exploration of space (e.g., the Nuclear Systems

Initiative (NSI)), many microgravity fluid physics and transport issues need to be successfully addressed. This creates the need for strategic mission-driven needs for research in areas like phase change heat transfer in partial- and reduced-gravity, fluid management in low-gravity, long-term cryogenic fluid storage and handling in low-gravity, and fluid flow and transport in the human body to facilitate development of effective countermeasures for sustained human presence in space.

MICROGRAVITY FLUID PHYSICS GROUND-BASED PROGRAM

The program currently has a total of 106 ground-based and 16 candidate flight principal investigators (PI). Ground-based research can either be conducted in a PI's own lab or at NASA Glenn Research Center using its unique suite of low-gravity facilities. These facilities include a 2.2-Second Drop Tower, 5.2-second Zero Gravity Facility, and NASA's low-gravity aircraft. The ground-based program provides the intellectual underpinning and spawning for the flight program. Many of the flight PIs start-out in the ground-based program and exhaust the use of terrestrial capabilities before moving to the flight program. Because of its larger base the ground-based program also serves as a catch-net to attract the scientific community to the Microgravity Research Program. The Fluid Physics Program has attracted and engaged many of the top notch internationally recognized fluid physicists. The Proceedings of the Sixth Microgravity Fluid Physics and Transport Phenomena Conference provide an overview of most of the research currently supported by the program.[14] The ground-based program has produced a large body of peer-reviewed publications that have appeared in some of the most prestigious journals such as *Science, Nature, Physical Review Letters, Journal of Fluid Mechanics, Physics of Fluids* and many others. The NASA Research Announcement NRA-01-OBPR-08-D released in December 2001 is currently open for submitting proposals. Proposals submitted to the Fluid Physics research area are due December 2, 2002.

More information can be found at: http://research.hq.nasa.gov/code_u/nra/current/NRA-01-OBPR-08/index.html

MICROGRAVITY FLUID PHYSICS FLIGHT EXPERIMENTS PROGRAM

The current Microgravity Fluid Physics flight experiments program is comprised of a set of experiments to be carried out on both a dedicated Space Shuttle (STS) research mission and on the International Space Station (ISS).

Non-ISS Flight Experiments

Beginning in the early 1980s, the ensuing two decades included many STS missions that were dedicated to low-gravity research, most noteworthy of which was the series of Spacelab missions. Only the STS-107 research mission now remains on the NASA manifest of missions dedicated to low-gravity research.

The Mechanics of Granular Materials-III experiment (MGM-III) (Principal Investigator (PI) – Stein Sture, University of Colorado)[10,15] will be conducted on this STS-107 mission, now scheduled for launch in January 2003. The objective of the MGM-III experiment is to continue the study of a number of hypotheses about soil behavior and to use the microgravity environment to obtain data on granular materials under very low effective confining pressures and stresses—conditions that cannot be duplicated on Earth. The MGM experiment will study load, deformation, and fluid pressures, as well as changes in soil structure, including the formation of shear bands and changes in density. Knowledge derived from these experiments will further the understanding of design models for soil movement under stresses. The models can then be applied to strengthening building foundations, managing undeveloped land, and handling powdered and granular materials in chemical, agricultural, and other industries. The knowledge obtained is also expected to be valuable in understanding technical issues in fields such as earthquake engineering, terrestrial and planetary geology, mining engineering, and coastal and off-shore engineering.

For more information on the MGM experiments, go to: http://mgm.msfc.nasa.gov/mgm.html

ISS-Based Flight Experiments

The Program Plan for Fluid Physics flight experiments on the ISS takes advantage of the availability of several major facility accommodations: the Fluids Integrated Rack (FIR), the Microgravity Science Glovebox (MSG), EXPRESS racks, and facilities provided by international partners. Each of these facilities and the associated experiments are described below. Figure 1 lays out the scenario of the current plan from FY2001 through FY2008. The most current version of this chart can be found on-line at:

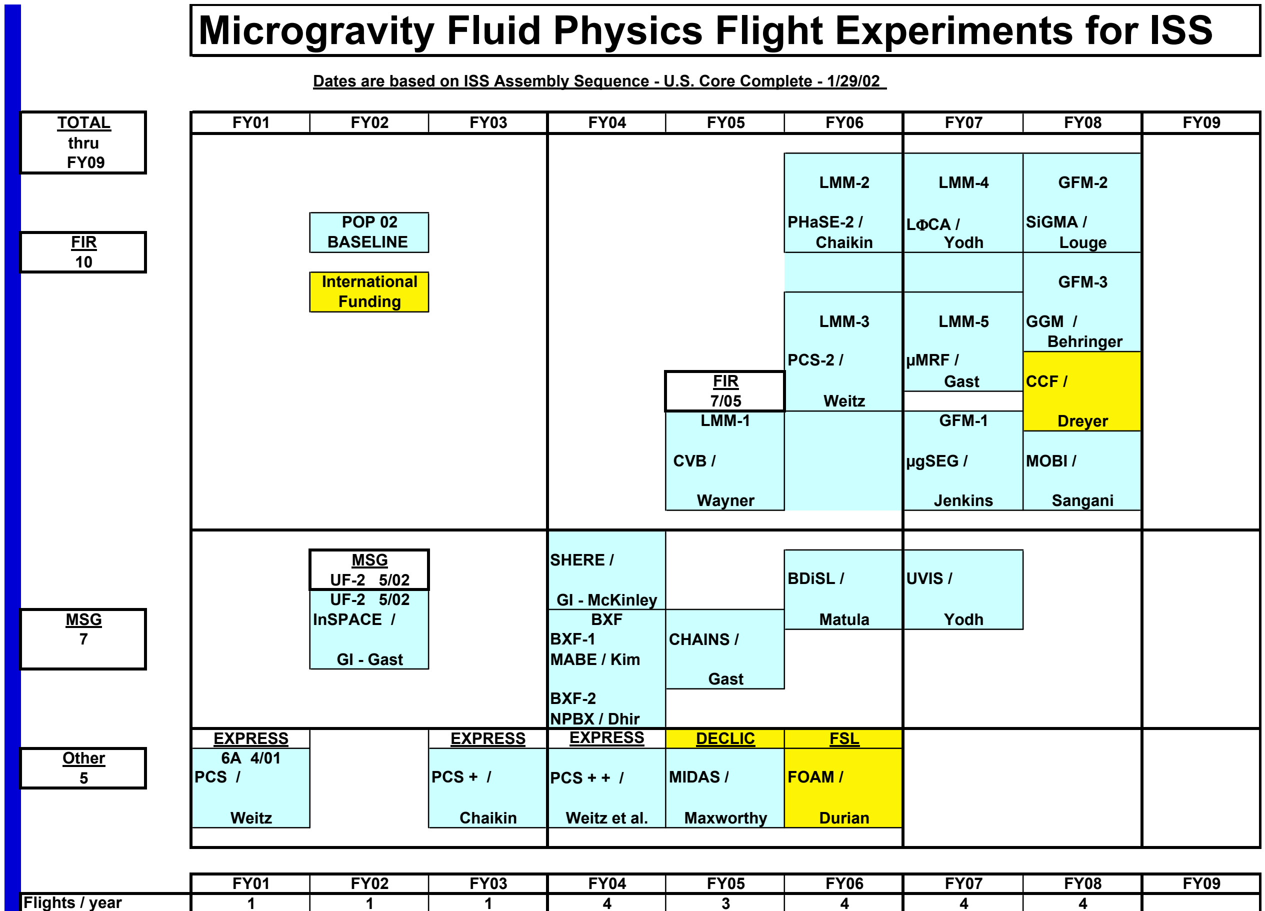

Figure 1 – Fluid Physics Flight Experiments for ISS

http://microgravity.grc.nasa.gov/willard/Flight_Rate_Core.PDF

The series of Fluid Physics investigations on the ISS began with the Physics of Colloids in Space (PCS) experiment in FY2001 and builds up to a steady state level of four experiments per year. The capacity of on-orbit facilities provides adequate accommodations to carry out several more experiments per year. However, the number of experiments developed and performed on the ISS is currently limited by a combination of budget constraints and limited resources such as upmass and crew time.

Fluids Integrated Rack

The Fluids and Combustion Facility (FCF)[16] will be a permanent facility onboard the ISS. The FCF will accommodate and facilitate sustained, systematic Microgravity Fluid Physics and Microgravity Combustion Science experimentation on the ISS. The Fluids Integrated Rack (FIR)[17,18] is one of the two racks that make up the Fluids and Combustion Facility. The primary mission of the FIR is to accommodate experiments in fluid physics disciplines. Furthermore, FIR's flexibility (i.e., large volume for experimental hardware, easily re-configurable diagnostics, customizable software) allows accommodation of experiments from other disciplines such as biotechnology. The FCF will occupy two International Standard Payload Racks (ISPRs) as shown in Figure 2. The

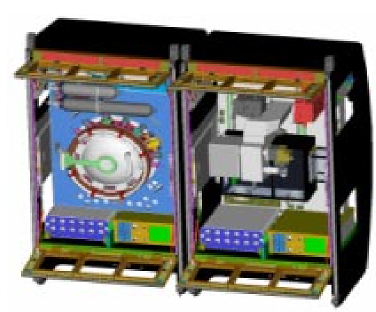

Figure 2 – Fluids and Combustion Facility

FIR is currently scheduled to be launched in July 2005 on the UF-5 mission.

One of the key design drivers for the FIR is to provide common laboratory diagnostic hardware, in a flexible environment, in order to accommodate a variety of imaging techniques commonly used in fluid physics experiments. With this in mind, the FIR is being designed to support various diagnostic techniques such as: Video Imaging, Video Microscopy, Light Scattering, Shadowgraphy, Particle Image Velocimetry, Interferometry, IR-imaging, Confocal Microscopy, Laser Tweezers, and Surface Profilometry. In addition, the design of the FIR infrastructure is such that experiment-unique cameras, light sources and optical hardware can be accommodated through standard interfaces if the FIR diagnostics tools are not sufficient for a particular diagnostic technique. In order to provide a flexible environment that can accommodate the various experimental test cells and the required diagnostics, the FIR provides a large volume for experimental payloads. Within this volume, experimental hardware can be precision-mounted directly to the FIR optics bench and supported with necessary cooling, power, command and data interfaces.

The FIR design allows for easy manipulation, installation and removal of FIR hardware by the ISS crew. The FIR can be operated by an ISS crew member through a laptop computer mounted outside of the rack. While the ISS crew will be available for experiment operations, their time will be limited, so the FIR is being designed for both autonomous and remote control operations. Control of the FIR will be primarily through the Telescience Support Center (TSC) at the Glenn Research Center.

The FIR will utilize six major subsystems to accommodate the broad scope of fluid physics experiments. The major subsystems are: structural, environmental, electrical, gaseous, command and data management, and diagnostics. These subsystems combined with payload unique hardware will allow the FIR to conduct world-class science.

Structural Subsystem The foundation of the FIR's structural subsystem is the ISPR. The ISPR will contain all of the FIR hardware and provide a standard interface to the ISS Destiny module.

The Active Rack Isolation System (ARIS) enhances the microgravity environment for

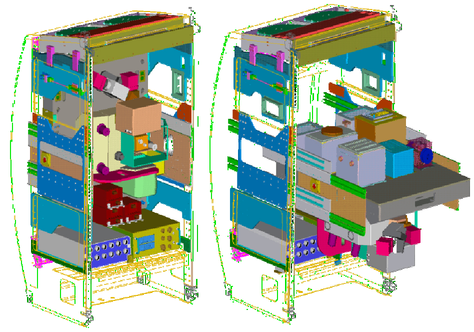

Figure 3 – FIR Optics Bench stowed and un-stowed positions

experiments in the FIR. ARIS, mounted in the ISPR, isolates the rack and minimizes vibratory transmission to and from the rack.

The centerpiece of the FIR structural subsystem is the optics bench. The optics bench provides a mounting surface for FIR light sources and avionics packages on the back of the bench and for payload hardware on the front.

The optics bench is designed so it can be translated out of the rack from its stowed position and rotated forward, as shown in Figure 3, to allow the crew easy access to hardware mounted on the optics bench for procedures such as replacing FIR hardware on the back of the bench or routing a fiber optic cable from the light sources on the back of the bench to payload hardware on the front.

Environmental Subsystem The environmental subsystem will utilize air and water to remove heat generated by the FIR and payload hardware. The air thermal control system will provide a temperature-controlled environment for the payload. The control set-point, which can be located anywhere within the payload volume, is selectable by the payload.

Cooling water from the ISS moderate temperature loop enters the rack and is split into two cooling loops. One loop is dedicated to the FIR hardware while the other loop is for payload hardware.

Gas Interface Subsystem The FIR will provide payloads with access to the ISS gaseous nitrogen and vacuum systems through the Gas Interface Panel (GIP) located on the side of the rack. These systems are available to support experiment operations such as the purging of experimental test cells and pressurizing or creating flows within experimental test cells.

Electrical Subsystem The Electrical Power Control Unit (EPCU) is the heart of the electrical subsystem. All power from ISS will flow through the EPCU. The EPCU will provide power management and control functions, as well as fault protection. The EPCU will take 120 VDC from the ISS power bus to provide 120 VDC and 28 VDC 4 Amp fault protected circuits to the FIR and payload hardware.

Command and Data Management Subsystem The FIR Command and Data Management subsystem (CDMS) provides command and data handling for both facility and payload hardware. The main components of the FIR CDMS are the Input Output Processor (IOP), the Image Processing and Storage Unit (IPSU), the Fluids Science Avionics Package (FSAP), and the Mass Data Storage Unit (MDSU).

The Input Output Processor (IOP) will provide the link from the FIR to the ISS command and data management. The Input Output Processor provides the overall command and data management functions for the FIR.

The FIR will be able to accommodate two Image Processing and Storage Units (IPSU). The IPSU will perform diagnostic control and image processing and storage functions. Payloads can use existing FIR software or generate custom software to process and compress image data. The IPSU will be capable of receiving raw image data at 64 MB/s. The IPSU will be capable of post processing images and performing automated real-time image analysis in order to support real-time activities such as object tracking.

The Fluids Science and Avionics Package (FSAP) will provide the primary control in carrying out an experiment. Through the FSAP the payload will be able to execute an experiment by controlling the FIR diagnostics and avionics packages as well as payload hardware. Payload developers will be able to download their own custom software into the FSAP for experiment control. The FSAP provides a standard set of computer data acquisition and control functions for use by the payload such as motion control, analog to digital channels, digital to analog channels, digital input and output, external and internal triggers, RS-422, analog frame grabber and CAN bus. The FSAP has two 18 GB hard drives for storing data.

The Mass Data Storage Unit (MDSU) provides supplemental data storage for the rack. The MDSU will have a data storage capacity of approximately 1 Tera Byte utilizing removable storage media.

Diagnostics Subsystem With the initial deployment of the FIR and through facility upgrades, the FIR will provide a suite of cameras and illumination sources to support a wide range of diagnostic capabilities typically required by fluid physics experiments. The FIR cameras will offer color and black and white imaging. These cameras will be capable of frame rates up to 32,000 frames per second and pixel densities of at least 1,024 pixels by 1,024 pixels. Lenses for these cameras will provide for macroscopic imaging. The FIR will provide two illumination sources, 532 nm Nd:YAG 150 mW laser and a white light source, containing two separate 50 W metal halide bulb subassemblies, for use with the FIR or payload cameras. Both the laser and white light have intensity control and measurement capabilities.

On-Orbit Operations Due to limited crew time, most of the powered up payload operations will be conducted from the Telescience Support Center (TSC) at the Glenn Research Center. A ground team made up of both the FIR and payload teams will operate the FIR and payload hardware from the TSC. These teams will be able to monitor the health and status of the FIR and payload hardware, issue commands and review data in near real time and posttest. Once testing is completed, the payload hardware will be removed and stowed until it can be returned to earth.

More information on the FIR can be found at:
http://fcf.grc.nasa.gov/pages/overview.html

Experiments for the FIR

Based on the current Physical Sciences Research Division ISS flight program plan, Fluid Physics payloads for the FIR have been planned out to FY 2008. The first payload will be the Light Microscopy Module, a multi-user, mini-facility designed to obtain science data for a number of investigations.

Light Microscopy Module The Light Microscopy Module (LMM) is a remotely controllable on-orbit microscope subrack facility designated for deployment on the FIR.[18,19] The current plan for the LMM/FIR combination will allow flexible scheduling and control of physical and biological sciences experiments with the LMM for about 30 months of on-orbit operation. LMM utilizes FIR-provided resources such as power, communications, air and water cooling, vacuum exhaust, avionics, image processing, and additional science diagnostic hardware. LMM will meet the needs of fluids, colloidal, and biological experiments with a standard set of science diagnostic equipment to reduce hardware development costs for Principal Investigators (PIs).

Key LMM diagnostic capabilities include: video microscopy to observe sample features including basic structures and dynamics, thin film interferometry, 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. In addition to using the confocal system, biological experiments can conduct fluorescence imaging by using the fiber-coupled output of a Nd:YAG laser operating at 532 nm or the 437nm line of a mercury arc or appropriate narrow-band filtering of the FIR-provided metal halide white light source.

More information on the LMM can be found at: http://microgravity.grc.nasa.gov/6712/lmm.html

An initial complement of five fluid physics experiments is scheduled to utilize the LMM instrument. These experiments are the Constrained Vapor Bubble (CVB) experiment (PI – Peter C. Wayner, Rensselaer Polytechnic Institute),[20] Physics of Hard Spheres–2 (PHaSE-2) experiment (PI – Paul M. Chaikin, Princeton University),[21] Physics of Colloids in Space–2 (PCS-2) experiment (PI – David A. Weitz, Harvard University),[22] Low Volume Fraction Colloidal Assembly (LΦCA) experiment (PI – Arjun G. Yodh, University of Pennsylvania),[23] and the Micromechanics of Magnetorheological Fluids (µMRF) experiment (PI – Alice P. Gast, Massachusetts Institute of Technology).[24]

The objective of the CVB experiment is to determine the overall stability, fluid flow characteristics, average heat transfer coefficient, and heat conductance of a constrained vapor bubble as a function of vapor volume and heat flow rate. The knowledge obtained from this experiment will aid in the development of passive, long-life, efficient and lightweight heat transfer devices for space-based and terrestrial applications.

The next three investigations focus on the area of colloid physics. Colloidal systems are found everywhere in nature and in biological and industrial processes. Aerosols, foams, paints, pigments, cosmetics, milk, salad dressings, and biological cells are examples of colloidal dispersions or suspensions.

PHaSE-2 will investigate the growth, structure, dynamics, rheology, and phase diagrams for hard sphere colloids. PCS-2 will extend the investigation of critical fundamental problems in colloid science to provide information to aid in the development of the field of "colloid engineering" for creating materials with novel properties that use colloids as precursors. The objective of the LΦCA experiment is to create photonic band-gap colloidal surface crystalline materials from high and low-density particles in low volume fraction binary particle suspensions using entropy-driven crystallization. The scientific results obtained from these experiments will add to the fundamental knowledge in colloid and condensed matter physics regarding the nature of transitions among gaseous, liquid, solid/crystal, and glassy states of matter. This knowledge will impact development of technologies in the field of optical materials (3-dimensional photonic materials, optical switches, and components for future computers) and biomedical applications (materials for novel drug delivery, biomimetic assemblies, encapsulating cells, and tissue culture).

The µMRF experiment will study the rheological properties and long-range lateral attraction of magnetic chains and coalesced chain structures in magnetorheological (MR) fluids and the rheological properties of composite chains formed through depletion-induced coalescence.

<u>Granular Flow Module</u> The second payload on the FIR will be the multi-user, mini-facility Granular Flow Module (GFM).[25] The GFM will utilize services provided by the FIR in addition to GFM-specific systems and diagnostics to study the flow of granular materials (simulated by simple spheres). There are two configurations being designed to accommodate the science teams' requirements. Both configurations are simultaneously contained in the GFM facility. An initial complement of three granular fluids experiments is scheduled to utilize the GFM instrument. These experiments are the Microgravity Particle Segregation in Collisional Shearing Flows Experiment (µgSEG) (PI – James T. Jenkins, Cornell University),[26] Studies of Gas-Particle Interactions in a Microgravity Flow Cell (SiGMA) experiment (PI – Michel Y. Louge, Cornell University),[27] and Gravity and Granular Materials (GGM) experiment (PI – Robert P.

Behringer, Duke University).[28] The first experiment chamber is a μgSEG-/SiGMA-specific annular Couette cell, with the spheres contained between two concentric cylinders. Anticipated diagnostic capabilities include normal and high-speed video imaging through an optical cover, as well as measurements of the rotational speed, ambient pressure and temperature. The second experiment chamber is a GGM-specific annular Couette cell with one rotating end cap and stress measurement sensors in the other end cap and cylinders.

The objective of the μgSEG is to obtain data on a system 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 SiGMA experiment will study the interaction between a flowing gas with relatively massive particles that collide with each other and with moving boundaries of the cell. Both co-current and counter-current flows will be used. GGM will study the properties of stress and force in quasi-static and fluid-like particle systems. The data from these experiments will prove useful in the fields of civil engineering, granular transport, and soil mechanics.

Microgravity Observations of Bubble Interactions The next payload on the FIR will be the Microgravity Observations of Bubble Interactions (MOBI) experiment (PI – Ashok S. Sangani, Syracuse University).[29] The PI-specific hardware will consist of a Couette cell with a gap that contains the bubble suspension, a bubble generation system to generate the bubble suspension, a two-phase separation system to separate the disperse phase from the continuous phase, sensors to determine bubble velocity, liquid velocity, bubble volume fraction distribution, the wall shear stress to determine the rheological properties of the suspension, and video imaging to record the dynamics of the flows. The objective of the MOBI experiment is to study and understand the physics of segregation and re-suspension of bubble suspensions. Potential applications of the results are improved understanding of oil and gas well flow rates, which are typically two- and three-phase flows complicated by gravity-induced segregation; improved understanding of bubble segregation in bioreactors, and the effect of bubble segregation on the efficiency of transporting oxygen to the cells being cultivated within the reactor; and fundamental knowledge valuable in the engineering and design of microgravity materials processing and life support systems for extended space flight.

For more information on MOBI, go to: http://microgravity.grc.nasa.gov/6712/multiph/bubbly.htm

Future Payloads for the FIR Beyond the experiments summarized so far, future FIR payloads may include experiments that take advantage of the following FIR-based capabilities: small scale multiphase flow experiments; boiling experiments[30] with multiple fluids, with and without electric fields; foams and suspensions that use rheometer-based measurements; investigations that require vibratory or rotational acceleration fields; and, biological experiments requiring microscopy under stringent environmental controls.

EXPRESS Rack

The Expedite the PRocessing of Experiments to Space Station (EXPRESS) Rack is a standardized payload rack system that transports, stores, and supports experiments aboard the ISS.[31] It provides the structure and subsystem hardware to accommodate payloads compatible with the Space Shuttle middeck, Spacehab, and Standard Interface Rack (SIR) drawers. It provides standard and simple interfaces that simplify the integration process of payloads into the rack. The volume of eight single middeck lockers and two SIR drawers are provided by the EXPRESS Rack for payload use. This system was developed specifically to maximize the Station's research capabilities.

For more information on the EXPRESS program, go to: http://spaceresearch.nasa.gov/research_projects/ros/express.html

Physics of Colloids in Space The first Fluid Physics payload to utilize the EXPRESS rack on the ISS was the Physics of Colloids in Space (PCS) experiment (PI – David A. Weitz, Harvard University).[9,32] The objective of PCS was to conduct fundamental studies of colloid physics in microgravity. The apparatus provided the ability to examine eight samples using static light scattering, dynamic light scattering, Bragg scattering, and high-resolution video color imaging. These features were used to study the formation of colloidal super lattices, large-scale fractal aggregates, and the physical properties and dynamics of these formations. Figure 4 shows the PCS experiment on-orbit in EXPRESS Rack 2.

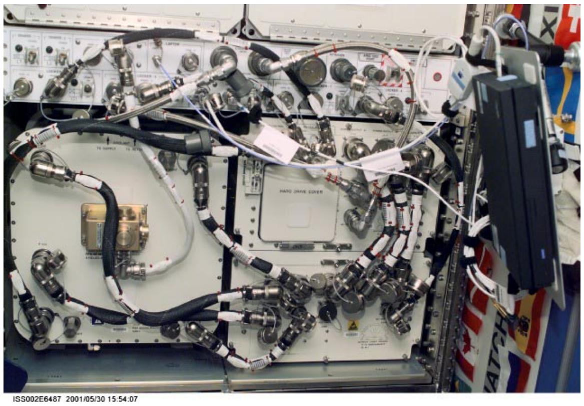

Figure 4 – PCS experiment in EXPRESS Rack 2

The apparatus operated for over 2,400 hours on the ISS between May 2001 and February 2002.[33] PCS was remotely operated from the NASA Glenn Research Center's Telescience Support Center in Cleveland, OH and at an established remote site at Harvard University in Cambridge, MA. The two locations permitted daily remote (telescience) operations of this unique experiment.

Follow-on flights of the PCS hardware, designated as PCS+ and PCS++, will take place in FY2003 and FY2004. The objective of PCS+ (PI – Paul M. Chaikin, Princeton University)[34] is to conduct light scattering and rheological measurements to probe the essential features of the colloidal hard sphere disorder-order transition and the properties of the ordered phase that results. PCS++ will continue to examine a series of samples for other investigators. The PCS series of investigations is complementary to the colloidal physics studies being carried out in the LMM. The potential payoffs of PCS are: improvements in the properties of paints, coatings, ceramics, and both food and drug delivery products, improved manufacturing of products requiring either colloidal suspensions for processing or as precursors, and important first steps in the research and development of an entirely new class of materials which passively affect the properties of light passing through them.

For more information on PCS, go to: http://microgravity.grc.nasa.gov/6712/pcs.htm or http://www.deas.harvard.edu/projects/weitzlab/research/nasaproj.html

Miscible Interface Dynamics and Simulation Another Fluid Physics experiment to be conducted in the EXPRESS rack is the Miscible Interface Dynamics and Simulation (MIDAS) experiment (PI - Tony Maxworthy, University of Southern California).[35–37] MIDAS will utilize the French-developed facility known as the Dispositif pour l'Etude de la Croissance et des Liquides Critiques (DECLIC).[38–40] The objective of MIDAS is to observe "finger-type" interface morphology between miscible fluids in flow regimes unattainable on Earth. The experiment will study the process of displacement of a viscous liquid by a miscible, less viscous liquid in a cylindrical tube. The goal is to measure the flow fields using particle image velocimetry and concentration fields in the vicinity of the moving interface by interferometry. These data will be used to test the Kroteweg model for quantitatively describing detailed stresses, which shape the interface. These data will be used to assess the importance of the additional fluid stresses caused by concentration gradients by comparing experimental results with numerical predictions. This information will be used to help develop new predictive tools important for enhanced oil recovery, to improve flows in porous media, and to improve understanding in the technologies of fixed bed regeneration and hydrology.

For more information on the DECLIC facility, go to:
http://131.176.49.1/spaceflight/map/fsl/declic.htm

Microgravity Science Glovebox

The ISS Microgravity Glovebox Facility (MSG) provides a double containment sealed laboratory with gloveports with a volume of 260 liters for carrying out crew-interactive experiments.[41] It provides video, power, thermal control, a vacuum vent, analog and digital data downlink, experiment commanding and telemetry, facility manipulation (lights, fans, air flow), ancillary equipment, and support for crew-operated and remote experiment and facility operations. The MSG was delivered to the ISS in June 2002 and is now operational.

For more information on the MSG, go to: http://msad.msfc.nasa.gov/gb/

Investigating the Structure of Paramagnetic Aggregates from Colloidal Emulsions The first Fluid Physics experiment to be conducted in the MSG is the Investigating the Structure of Paramagnetic Aggregates from Colloidal Emulsions (InSPACE) experiment (PI – Alice P. Gast, Massachusetts Institute of Technology).[42] InSPACE will conduct a microscopic video study of magnetorheological (MR) fluids in a pulsed magnetic field to determine the effect of varying magnetic field, pulse frequency, and particle size on the equilibrium microstructures. The microstructure of these fluids plays a significant role in determining their bulk rheological properties. Magnetorheological fluids are part of a new class of controllable fluids that have exciting implications for electromechanical devices such as robots, brake systems, suspension systems, tunable dampers and other devices where "smart materials" play a key role. Observations of the microscopic microstructures will yield a better understanding of the interplay of three competing effects: the demagnetizing field, surface energy, and repulsion between structures in MR suspensions.

Shear History Extensional Rheology Experiment The second Fluid Physics payload for the MSG is the Shear History Extensional Rheology Experiment (SHERE) (PI – Gareth H. McKinley, Massachusetts Institute of Technology).[43] This experiment will investigate the effect of preshearing on the stress/strain response of a non-Newtonian polymeric liquid being stretched in microgravity. The experiment will be accomplished by imposing a well-defined and controlled preshear history (from no preshear to very strong preshear) for a specified period of time. The shear flow is halted and an exponential increasing elongation profile is applied axially to the polymeric liquid bridge while measuring several key quantities: tensile force, midpoint radius and fluid filament profile evolution. The data should prove valuable for understanding the optimization of polymer processing operations that involve complex flows, i.e., both shearing/rotation and elongation/stretching. Applications include shearing in spinnerets prior to fiber spinning of both synthetic and natural polymers and the utilization of complex flows such as polymeric drag reduction and shearing and stretching in extruders and nozzles.

Boiling Experiment Facility The next Fluid Physics experiments planned for the MSG are the Microheater Array Boiling Experiment (MABE) (PI – Jungho Kim, University of Maryland)[44] and the Nucleate Pool Boiling Experiment (NPBX) (PI – Vijay K. Dhir, University of California, Los Angeles)[45] that will be conducted in the Boiling Experiment Facility (BXF) in the MSG. The facility will be able to study local boiling heat transfer mechanisms, transition boiling, and critical heat flux by means of temperature sensors and video recordings. These experiments are expected to yield data to validate numerical simulation tools for prediction of performance of boiling under variable gravity conditions. Boiling phase change heat transfer is used in heat exchangers for power systems on Earth and in space and for electronic component cooling systems.

Chain Aggregation Investigation by Scattering The Chain Aggregation Investigation by Scattering (CHAINS) experiment (PI – Alice P. Gast, Massachusetts Institute of Technology)[24,46] will study fluctuations and dynamics responsible for lateral cross-linking of dipolar chains in magnetorheological fluids. This study will help to determine if the long-range attraction between dipolar chains in MR fluids are brought about by these thermal fluctuations. Diffusing Wave Spectroscopy (DWS) will be used to measure the dynamics of an MR fluid over time and length scales that capture short wavelength motions. DWS experiments are very sensitive to sedimentation due to the higher particle concentrations needed to produce multiple scattering. A second aim, taking advantage of the unique conditions on the ISS, is to investigate the gelation transition of dipolar particles in MR fluids through a tunable external field. By conducting these experiments in low-gravity, sedimentation is nullified. Microgravity also permits larger as well as different types of particles to be studied. Understanding MR fluids will lead to advances in visco-elastic applications as those mentioned in the section on the InSPACE experiment above. The experiment will also lead to a better fundamental understanding of the dynamics of a suspension of particles interacting via a tunable anisotropic interaction. It is anticipated that using these fluids will enable a broad range of novel technologies. This investigation is a complement to the μMRF investigation being conducted in the LMM.

Buoyancy-Driven Instabilities in Single-Bubble Sonoluminescence The objective of the Buoyancy-Driven Instabilities in Single-Bubble Sonoluminescence (BDiSL) experiment (PI – Thomas J. Matula, University of Washington)[47] is to better understand the limits of energy focusing in cavitation bubbles. The experiment will quantify the role of instabilities, particularly buoyancy, as it pertains to emitted light intensity and bubble dynamics in single bubble sonoluminescence. It will also attempt to understand why a small amount of noble gas (such as helium, argon, or xenon) in the bubble increases the intensity of the emitted light dramatically. The experiment in the MSG will levitate a radially oscillating bubble that will emit a burst of light upon each collapse and perform ambient and maximum bubble size imaging under constant pressure conditions and during pressure ramp conditions through bubble extinction. It will also perform integrated light emission measurements under constant pressure conditions. The data will help to expand the understanding in the field of sonochemisrty, or the science that deals with the application of ultrasound. It could help to better explain the effects of ultrasound in life science and medicine, such as the technique of lithotripsy that uses shock waves to break up kidney stones, avoiding the need for invasive surgery. Another potential application of the data will be to improve the understanding of the models that describe plasmas.

Ultraviolet-Visible-Infrared Spectrophotometer The Ultraviolet-Visible-Infrared Spectrophotometer (UVIS) instrument (PI – Arjun G. Yodh, University of Pennsylvania)[23] will be used to measure the photonic properties of colloidal crystalline materials and also have the capability of examining biological samples. This instrument will be first used in the MSG in conjunction with the LΦCA experiment in the LMM. Operations will be coordinated with the observation of samples in the LMM so that complementary data over a broader spectral range will be obtained on common samples. Visible video microscopy will be used to locate and image sample regions to ~10 µm resolution over a 2 mm field of view. The instrument will measure transmission and reflectance spectra as a function of angle (±55 degrees in two orthogonal planes) and map out the photonic band structure of the materials over the range from 200 to 2,200 nm. Two CCD sensors and a focal plane array will view 0^{th} and 1^{st} order Bragg spots in the ultraviolet, visible, and infrared. The data obtained will contribute to the development of colloidal crystals as photonic materials.

Other Fluid Physics Experiments for the ISS

The current plan calls for hardware for two Fluid Physics experiments to be developed by NASA's international partners.

Foam Optics and Mechanics The objective of the Foam Optics and Mechanics (FOAM) experiment (PI – Douglas Durian, University of California, Los Angeles)[48] is to understand the complex rheology of foams in terms of the bubble-scale dynamics. The relationship between microscopic bubble motion and the macroscopic mechanical properties of foams will be studied by examining how bubble rearrangements due to coarsening and/or shear affect the macroscopic mechanical response of foams. Very wet foams act like a simple liquid; microgravity will enable the study of wet foams and the loss of rigidity as the liquid content is increased. The approach to obtaining the required data will employ simultaneous light scattering and rheology measurements. The PI-specific instruments will be housed in the ESA-developed Fluid Science Lab (FSL).[49] Foams are used in many industrial, consumer, and safety products. The understanding obtained from these experiments should help to enable the development of improved products and new lightweight materials.

Critical Velocities in Open Capillary Channel Flows The Critical Velocities in Open Capillary Channel Flows (CCF) experiment (PI –Michael Dreyer, Center of Applied Technology and Microgravity, University of Bremen)[50] will obtain data that will be used to enable design of spacecraft tanks that can supply gas-free propellant to spacecraft thrusters directly through capillary vanes, significantly reducing cost, weight, and reliability. The experiment will determine the shape of the free surface and find the maximum flow rate that may be achieved in an open channel without a collapse of the free surface. Current designs of spacecraft fuel tanks rely on an additional reservoir to prevent the ingestion of gas into engines during firing. This research is necessary because current theoretical design models do not adequately predict the maximum flow rate achievable through the capillary vanes. The data obtained here will lead to increased life and reliability of spacecraft and satellites by reducing the complexity of fuel tanks, and reduce cost and weight. The experiment will be designed, built, and funded by the German Space Agency (DLR) and be carried out in either the FIR or the MSG.

SUMMARY AND CONCLUSIONS

Fluid mechanics and thermal sciences provide the underpinning for most of the scientific investigations required for development of mission-enabling and enhancing technologies. With the vigorous ground-based and flight experiments program described above, the NASA Microgravity Fluid Physics Program is clearly poised to make significant contributions to the store of knowledge on the fundamental behavior of fluids that relate to both emerging new technologies and also more traditional ones. The current and future anticipated results in these diverse areas will extend the knowledge bases necessary for development of mission-critical technologies for space applications. This knowledge will also enable improvements in the efficiency and effectiveness of terrestrial processes, both man-made and natural.

NASA is currently undertaking development of new technologies (e.g., Nuclear Systems Initiative (NSI)) for space exploration. Some of the advanced power and propulsion concepts involve phase change and multiphase flows in microgravity. The Microgravity Fluid Physics Program is positioned to work with technology developers and conduct experiments on the ISS that will fill the critical knowledge gap to make these technologies viable.

Web Sites

More details on the Microgravity Fluid Physics ground-based and flight experiment projects are available at: http://microgravity.grc.nasa.gov/MSD/MSD_htmls/fluids.html and http://www.ncmr.org/events/fluids2002/

For information on the NASA Office of Biological and Physical Research, see: http://SpaceResearch.nasa.gov/

REFERENCES

1. Kicza, M., Erickson, K., and Trinh, E., "Research Priorities and Plans for the International Space Station," IAC-02-T.4.01, 53rd International Astronautical Congress, The World Space Congress 2002, October 2002.

2. Trinh, E., "Physical Sciences Research Plans for the International Space Station," IAC-02-T.5./J.6.01, 53rd International Astronautical Congress, The World Space Congress 2002, October 2002.

3. Antar, B. and Nuotio-Antar, V.S., *Fundamentals of Low Gravity Fluid Dynamics*, CRC, Boca Raton, FL, 1993.

4. Myshkis, A.D., Babskii, V.G., Kopachevskii, N.D., Slobozhanin, L.A., and Tyuptsov, A.D., *Low-Gravity Fluid Mechanics*, Springer-Verlag, New York, NY, 1987.

5. Koster, J.N. and Sani, R.L., editors, *Low-Gravity Fluid Mechanics and Transport Phenomena*, Progress in Astronautics and Aeronautics, Vol. 130, AIAA, Washington, DC, 1990.

6. Subramanian, R. S., and Balasubramanian, R., *The Motion of Bubbles and Drops in Reduced Gravity*, Cambridge University Press, New York, NY, 2001.

7. Langbein, D., *Capillary Surfaces, Shape – Stability – Dynamics, in Particular Under Weightlessness*, Springer-Verlag, New York, NY, 2002.

8. Singh, B.S., Kohl, F.J., and Alexander. J.I., "Going with the flow: Microgravity fluid physics," *Aerospace America*, October 2001, pp. 20–22.

9. Weitz, D.A., Doherty, M., Jankovsky, A., Sankaran, S., Lorik, T., Shiley, W., Bowen, J., Kurta, C., Eggers, J., Bailey, A., Manley, S., Prasad, V., Christianson, R., Gasser, U., Segre, P., Cipelletti, L., Schofield, A., and Pusey, P., "Results from the Physics of Colloids Experiment on ISS," IAC–02–T.5./J.6.04, 53rd International Astronautical Congress, The World Space Congress 2002, October 2002.

10. Sture, S., Costes, N., Batiste, S., Lankton, M., Alshibli, K., Jeremic, B., Swanson, R., and Frank, M., "Mechanics of Granular Materials at Low Effective Stresses," *ASC Journal of Aerospace Engineering*, 11 (3), 67–72 (1998).

11. Lee, H.S., Merte, Jr., H., and Chiaramonte F., "Pool Boiling Curve in Microgravity," *Journal of Thermophysics and Heat Transfer*, 11 (2), 216–222 (1997).

12. Schatz, M.F., VanHook, S.J., Swift, J.B., McCormick, W.D., and Swinney, H.L., "Onset of Hexagons in Surface Tension-Drive Bénard Convection," *Phys. Fluids*, 11 (9), 2577–2582 (1999).

13. VanHook, S.J., Schatz, M.F., Swift, J.B., McCormick, W.D., and Swinney, H.L., "Long-wavelength Marangoni-Bénard Convection: Experiment and Theory," *J. Fluid Mechanics*, 345, 45–78 (1997).

14. Proceedings of the Sixth Microgravity Fluid Physics and Transport Phenomena Conference, NASA/TM—2002-211211, August 2002; http://www.ncmr.org/events/fluids2002/

15. Alshibli, K.A., Sture, S., Costes, N.C., Frank, M., Lankton, M., Batiste, S., and Swanson, R., "Assessment of Localized Deformations in Sand Using x-ray Computed Tomography," *ASTM Geotechnical Testing Journal*, 23 (3), 274–299 (2000).

16. Zurawski, R.L., "The ISS Fluids and Combustion Facility: Microgravity Combustion Science and Fluid Physics Research Capability," AIAA–2001–4925, International Space Station Utilization—2001, October 2001.

17. Gati, F., and Hill, M., "The FCF Fluids Integrated Rack: Microgravity Fluid Physics Experimentation on Board the ISS," AIAA–2001–4926, International Space Station Utilization–2001 Conference, October 2001.

18. Motil, S.M., Gati, F.G., Snead, J.H., Griffin, D.W., Hill, M.E., and Hovenac, E.A., "The Fluids Integrated Rack and Light Microscopy Module Integrated Capabilities," IAC–02–J.5.06, 53rd International Astronautical Congress, The World Space Congress 2002, October 2002.

19. Motil, S., Snead, J. and Hovenac, E., "The Light Microscopy Module: An On-Orbit Multi-User Microscope Facility," AIAA–2001–4956, International Space Station Utilization–2001 Conference, October 2001.

20. Wang, Y., Zheng, L., Wayner, Jr., P. and Plawsky, J., "A Study of the Constrained Vapor Bubble Heat Exchanger," AIAA–2001–4957, International Space Station Utilization–2001 Conference, October 2001.

21. Chaikin, P., Russel, W., Harrison, C., Hollingsworth, A., and Megens, M., Sullivan, M., "Physics of Hard Spheres Experiment (PHaSE-2)," AIAA–2001–4958, International Space Station Utilization–2001 Conference, October 2001.

22. Sankaran, S., Gasser, U., Manley, S., Valentine, M., Prasad, V., and Rudhardt, D., "Physics of Colloids in Space-2 (PCS-2)," AIAA–2001–4959, International Space Station Utilization–2001 Conference, October 2001.

23. Yodh, A., "Entropically Driven Self-Assembly of Colloidal Crystals on Templates in Space," AIAA–2001–4960, International Space Station Utilization–2001 Conference, October 2001.

24. Agui, J. and Gast, A., "Anisotropic Colloidal Self-Assembly," AIAA–2001–5091, International Space Station Utilization–2001 Conference, October 2001.

25. Caruso, J. and Ramé, E., "Granular Flow Module Mini Facility Capabilities for Granular Flow Experiments on ISS," AIAA–2001–4983, International Space Station Utilization–2001 Conference, October 2001.

26. Jenkins, J. and Louge, M., "Particle Segregation in Collisional Shearing Flows," AIAA–2001–4990, International Space Station Utilization–2001 Conference, October 2001.

27. Xu, H., Louge, M., and Jenkins, J., "Flow Development of a Gas-Solid Suspension in a Microgravity Couette Apparatus," AIAA–2001–4992, International Space Station Utilization–2001 Conference, October 2001.

28. Behringer, R., "Fluctuations and Phase Transitions in Sheared Granular Materials," AIAA–2001–4993, International Space Station Utilization–2001 Conference, October 2001.

29. Sangani, A., Hoffmann, M., Koch, D., Kushch, V., Nahra, H., and Tsang, Y., "Behavior of Rapidly Sheared Bubble Suspensions," AIAA–2001–5018, International Space Station Utilization–2001 Conference, October 2001.

30. Logsdon, K., "Pool Boiling Module Multi-User Hardware Description," AIAA–2001–4994, International Space Station Utilization–2001 Conference, October 2001.

31. Sledd, A., "Express Rack Capabilities and On-orbit Lessons Learned," AIAA–2001–5056, International Space Station Utilization–2001 Conference, October 2001.

32. Weitz, D., Doherty, M., Jankovsky, A., Koudelka, J., Ansari, R., Lorik, T., Shiley, W., Bowen, J., Kurta, C., Eggers, J., Bambakidis, K., Hovenac, E., Segre, P., Bailey, A., Gasser, U., Manley, S., Prasad, V., Schofield, A., and Pusey, P., "The Physics of Colloids in Space," AIAA–2001–4900, International Space Station Utilization–2001 Conference, October 2001.

33. Doherty, M.P., Jankowsky, A., and Lorik, T., "Physics of Colloids in Space: Flight Hardware Operations on ISS," NASA/TM—2002-211371, AIAA–2002–0762, presented at the AIAA 40th Aerospace Sciences Meeting, January 14–17, 2002, Reno, NV.

34. Chaikin, P., Russel, W., van Blaaberen, A., Meyer, W., Doherty, M., and Kopacka, W., "Physics of Colloids in Space Plus (PCS+)," AIAA–2001–5058, International Space Station Utilization–2001 Conference, October 2001.

35. Maxworthy, T., Meiburg, E., Balasubramaniam, R., Rashidnia, N., and Lauver, R., "The Dynamics of Miscible Interfaces: A Space Flight Experiment (MIDAS)," AIAA–2001–5061, International Space Station Utilization–2001 Conference, October 2001.

36. Petitjeans, P. and Maxworthy, T., "Miscible Displacements in Capillary Tubes," Part 1. Experiments, *J. Fluid Mech.,* 326, 37 (1996).

37. Chen, C.Y. and Meiburg, E., "Miscible Displacements in Capillary Tubes," Part 2. Numerical Simulations, *J. Fluid Mech.,* 326, 57 (1996).

38. Marcout, R. and Cambon, G., "DECLIC, a Multipurpose Facility for Physical Sciences in Microgravity," IAC–02–J.5.04, 53rd International Astronautical Congress, The World Space Congress 2002, October 2002.

39. Cambon, G., Zappoli. B., Lauver, R., Beysens, D., Garrabos, Y., Lecoutre, C., Billa, B., Jamgotchian, H., and Bergeon, N., "DECLIC: The Experiment Program and its Potentialities," IAC–02–J.2.04, 53rd International Astronautical Congress, The World Space Congress 2002, October 2002.

40. Lauver, R. and Cambon, G., "DECLIC Facility: Research Capabilities for Microgravity Fluid Physics and Materials Science," AIAA–2001–4931, International Space Station Utilization–2001 Conference, October 2001.

41. Baugher, C., "The Microgravity Science Glovebox," AIAA–2001–5089, International Space Station Utilization–2001 Conference, October 2001.

42. Promislow, J.H.E. and Gast, A.P., "Low-energy Suspension Structure of a Magnetorheological Fluid," *Phys. Rev. E,* 56 (1), 642–651 (1997).

43. McKinley, G.H., Brauner, O. and Yao, M., "Kinematics of Filament Stretching in Dilute and Concentrated Polymer Solutions," *Korea-Aust. Rheol. J.*, 13 (1), 29–35 (2001).

44. Kim, J., McQuillen, J., and Balombin, J., "Microheater Array Boiling Experiment," AIAA–2001–5116, International Space Station Utilization–2001 Conference, October 2001.

45. Dhir, V., Qiu, D.-M., and Chao, D., "Bubble Dynamics and Heat Transfer Associated with Pool Nucleate Boiling Under Microgravity Conditions," AIAA–2001–4995, International Space Station Utilization–2001 Conference, October 2001.

46. Furst, E.M. and Gast, A.P., "Particle Dynamics in Magnetorheological Suspensions using Diffusing-wave Spectroscopy," *Phys. Rev. E*, 58 (3), 3372–3376 (1998).

47. Matula, T., "Buoyancy-Driven Instabilities in Single-Bubble Sonoluminescence," AIAA–2001–5118, International Space Station Utilization–2001 Conference, October 2001.

48. Zimmerli, G., Bandyopadhyay, R., and Durian, D., "Foam Optics and Mechanics in Microgravity," AIAA–2001–4961, International Space Station Utilization–2001 Conference, October 2001.

49. Zell, M., Jordan, M., and Fortezza, R., "The Development of the First Experiments for the European Fluid Physics laboratory on the International Space Station," IAC–02–T.5./J.6.06, 53rd International Astronautical Congress, The World Space Congress 2002, October 2002.

50. Rosendahl, U., Dreyer, M., Rath, H., and Motil, B., "Design of Critical Velocities in Open Capillary Flow Experiment," AIAA–2001–5021, International Space Station Utilization–2001 Conference, October 2001.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	December 2002	Technical Memorandum

4. TITLE AND SUBTITLE

The NASA Microgravity Fluid Physics Program—Knowledge for Use on Earth and Future Space Missions

5. FUNDING NUMBERS

WBS–22–400–35–80–01

6. AUTHOR(S)

Fred J. Kohl, Bhim S. Singh, J. Iwan Alexander, Nancy J. Shaw, Myron E. Hill, and Frank G. Gati

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135–3191

8. PERFORMING ORGANIZATION REPORT NUMBER

E–13698

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, DC 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA TM—2002-212009
IAC–02–T.4.02

11. SUPPLEMENTARY NOTES

Prepared for the 53rd International Astronautical Congress cosponsored by the International Astronautical Federation (IAF), the International Academy of Astronautics (IAA), and the International Institute of Space Law (IISL), Houston, Texas, October 10–19, 2002. Fred J. Kohl, Bhim S. Singh, Nancy J. Shaw, Myron E. Hill, and Frank G. Gati, NASA Glenn Research Center; J. Iwan Alexander, National Center for Microgravity Research, Cleveland, Ohio 44135. Responsible person, Fred J. Kohl, organization code 6700, 216–433–2866.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified - Unlimited
Subject Category: 34 Distribution: Nonstandard

Available electronically at http://gltrs.grc.nasa.gov

This publication is available from the NASA Center for AeroSpace Information, 301–621–0390.

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

Building on over four decades of research and technology development related to the behavior of fluids in low gravity environments, the current NASA Microgravity Fluid Physics Program continues the quest for knowledge to further understand and design better fluids systems for use on earth and in space. The purpose of the Fluid Physics Program is to support the goals of NASA's Biological and Physical Research Enterprise which seeks to exploit the space environment to conduct research and to develop commercial opportunities, while building the vital knowledge base needed to enable efficient and effective systems for protecting and sustaining humans during extended space flights. There are currently five major research areas in the Microgravity Fluid Physics Program: complex fluids, multiphase flows and phase change, interfacial phenomena, biofluid mechanics, and dynamics and instabilities. Numerous investigations into these areas are being conducted in both ground-based laboratories and facilities and in the flight experiments program. Most of the future NASA-sponsored fluid physics and transport phenomena studies will be carried out on the International Space Station in the Fluids Integrated Rack, in the Microgravity Science Glovebox, in EXPRESS racks, and in other facilities provided by international partners. This paper will present an overview of the near- and long-term visions for NASA's Microgravity Fluid Physics Research Program and brief descriptions of hardware systems planned to achieve this research.

14. SUBJECT TERMS

Microgravity; Fluid dynamics; Fluid physics; Fluid mechanics; Reduced gravity

15. NUMBER OF PAGES

20

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	