NASA Sponsored Fluid Physics Experiments Conducted on the Mir Space Station

Jeffrey S. Allen *
National Center for Microgravity Research, Cleveland, OH 44135

Suzanne Saavedra †
NASA Lewis Research Center, Cleveland, OH 44135

An overview of the NASA sponsored fluid physics experiments conducted on the Mir Space Station beginning with the launch of the Priroda module in April, 1996 is presented. The NASA sponsored fluid physics experiments on Mir have studied free surface behavior, capillary-driven flows, and colloidal science. The experiments discussed are the Interfacial Configuration Experiment (ICE), the Technological Evaluation of the Microgravity Isolation Mount (TEM-1 & 2), the Angular Liquid Bridge (ALB) experiment, the Binary Colloidal Alloy Tests (BCAT-1 & 2), the Colloidal GELation (CGEL) experiment, the Passive Accelerometer System (PAS), and the Growth and Morphology of Supercritical Fluids (GMSF) experiment. This review discusses the scope, conduct, and results of these experiments. In addition, the lessons learned with respect to remote operation of experiments on the Mir Space Station are discussed.

Acronyms

ALB	Angular Liquid Bridge experiment
ALICE	French critical point facility on Mir
BCAT	Binary Colloidal Alloy Tests
CGEL	Colloidal Gelation experiment
CNES	Centre National des Etudes Spatiales
EVA	Extra-Vehicular Activity
GMSF	Growth Morphology of Supercritical Fluids
ICE	Interface Configuration Experiment
ISS	International Space Station
MGBX	Microgravity GloveBoX facility
MIM	Microgravity Isolation Mount
MIPS	Mir Interface Payload System
NASA	National Aeronautics and Space Administration
PAS	Passive Accelerometer System
PCS	Physics of Colloids in Space
RSA	Russian Space Agency
STS	Space Transportation System (i.e., Shuttle)
TEM	Technological Evaluation of the MIM

Introduction

Phase 1 of the NASA-Mir Program was intended to provide a mechanism for collaboration and exchange of information between the National Aeronautics and Space Administration (NASA) and the Russian Space Agency (RSA) with respect to long-duration space flights. The Phase 1 program consisted of two components; Phase 1A and Phase 1B. The Phase 1A program began and ended with Astronaut Norman Thaggard's stay on Mir from March 14, 1995 to July 4, 1995. During Phase 1A, twenty-eight research investigations were conducted in seven disciplines, though none in the microgravity fluid physics discipline which is pertinent to this discussion.

The science investigations and technology demonstrations conducted during the Phase 1B program were divided among nine disciplines: Advanced Technology, Earth Sciences, Fundamental Biology, Microgravity, Human Life Sciences, Space Medicine Program, Space Sciences, International Space Station Risk Mitigation, and Life Support Risk Mitigation. Phase 1B began when Astronaut Shannon Lucid entered the Mir Space Station on March 24, 1996 and ended when Astronaut Andrew Thomas left Mir on STS-91 on June 8, 1998. Lucid's mission, referred to as NASA 2, included the launch and docking of the Priroda module in which most of the microgravity science experiments were performed. Astronaut John Blaha replaced Shannon Lucid in September of 1996 and thus began the NASA 3 increment. The exchange of NASA astronauts on Mir continued through June of 1998; resulting in six increments during the Phase 1B program.

The objectives of the NASA-Mir Phase 1B program[1] were:

1. Obtain engineering and operational experience conducting research on an orbital space station.
2. Conduct experiments and demonstrations of technology pertinent to the International Space Station (ISS) development.
3. Provide EVA demonstrations for space station hardware and tasks.
4. Characterize the Mir environment relative to scientific investigations and conduct scientific investigations and demonstrations.

It should be noted that conducting scientific research was lowest in priority among these objectives.

*NCMR Staff Scientist

†Space Experiments Project Manager

Table 1 Phase 1B fluid physics experiments performed on Mir during each of the NASA missions.

Phase 1B Mission	Experiment(s)
NASA 2 (4/96–9/96)	ICE, TEM-1
NASA 3 (9/96–1/97)	PAS, BCAT-1
NASA 4 (1/97–5/97)	ALB
NASA 5 (5/97–9/97)	CGEL
NASA 6 (9/97–1/98)	BCAT-2
NASA 7 (1/98–6/98)	n/a
Post-Phase 1B (1/99)	GMSF

This paper describes nine experiments which were conducted under the Microgravity Science program during the NASA-Mir Phase 1B program. The experiments described herein are those experiments which were funded through the NASA Microgravity Science Division as fluid physics experiments. There are experiments funded through other NASA programs which may appear to be more "fluid-like" than some of those described here, but the scope of this paper will be limited to NASA programmatic distinctions. These experiments studied diverse phenomena ranging from capillary-driven flows to characterization of accelerations to colloidal science. Of the nine experiments to be discussed, two (TEM-1 & TEM-2) are considered to be technology evaluation for lack of an independent peer review.

The objectives of this paper are twofold. The first objective is to describe the various experiments and the way in which each experiment is conducted. This is not intended to give a detailed description of the science or present the results of the experiments. The bibliography provides suitable references which may direct the reader to more thorough discussion on each of the experiments. Rather, the intent is to describe the manner in which the experiment is setup and operated. There is great variety in the manner in which the experiments are conducted; some being fully automated and others requiring extensive astronaut interaction.

The second objective of this paper is to assess effectiveness of each type of experiment; noting weaknesses and strengths in the *style* of the experiment in order to assist scientists and engineers in designing long-duration, low-gravity fluid physics experiments for the International Space Station (ISS). The objective is, in essence, a "lessons learned" from an experimentalists' point of view; as opposed to that of program management, political, etc. This discussion should not be viewed as a critique of the NASA-Mir Phase 1B program. One of the program objectives was to learn how to conduct experiments on a space station with an international partner. The issues raised in this discussion are presented in that spirit.

The Experiments

The NASA sponsored fluid physics experiments conducted on the Mir Space Station are PAS, ICE, ALB, TEM-1 & 2, BCAT-1 & 2, CGEL, and GMSF. (See Acronyms section for the complete name of each experiment.) Table 1 lists the fluid physics experiments performed during each of the NASA-Mir Phase 1B missions. Additional mission details for each individual experiment are provided in Table 2.

ICE, *Interface Configuration Experiment*

The Interface Configuration Experiment, or ICE, was designed to investigate the theoretical prediction of a stable, non-axisymmetric liquid surface shape in an axisymmetric container in the absence of gravity.[2] ICE was launched from Russia as part of the Priroda module which docked with the Mir space station in April, 1996. Astronaut Shannon Lucid conducted the ICE experiment in the Microgravity Glovebox (MGBX)[‡] during the NASA 2 increment. (See Tables 1 and 2.)

There were three main objectives of ICE.[2] The first was to investigate the configuration of low-gravity liquid-vapor interfaces in "exotic" containers. The second objective was to observe the location and relative stability of metastable surface shapes. And the third objective was to compare the low-gravity interface shape with theoretical and numerical results. The ICE vessels consisted of a fluid reservoir and a test section which resembled a right circular cylinder with a toroidal-like bulge at its midpoint. The fluid was an immersion oil indexed matched to the acrylic test chamber. The MGBX was utilized for video recording the ICE vessels during testing.

To begin the experiment, a crew member setup the MGBX for ICE which included video preparation and the installation of a fixture in the MGBX with which to secure an ICE vessel. After an ICE vessel was attached to the fixture, the fluid was manually transferred to the test section by rotating a knob which displaced a piston within the reservoir. After the fluid transfer was complete, time was allowed for the liquid surface to fully stabilize. A crew member then disturbed the liquid surface by gently tapping the side of the vessel with a finger. All new surface shapes which formed during the tapping process were given time to stabilize and were recorded on video. The imposed disturbances continued to increase in force until the surface

[‡]The Microgravity GloveBoX, or MGBX, is a multi-user facility originally developed for conducting experiments on Spacelab or in the Space Shuttle Middeck. The Mir version of the Glovebox was launched as part of the Priroda module which docked with the Mir Space Station in April, 1996. The MGBX was developed to accommodate hands-on experiments in biological, fluid physics, combustion, and materials sciences. The MGBX provides a level of containment for powders, splinters, liquids, or bioparticles that could result from such experiments; whether accidentally or purposefully. Thus, a crew member may carry out experiments involving small quantities of toxic, irritating, or potentially infectious materials which could not be allowed to contaminate the spacecraft atmosphere. The MGBX also provides conditioned power and video camera/recording capabilities. The Middeck/Mir Glovebox was developed by Bradford Engineering of the Netherlands and by Teledyne Brown Engineering of Huntsville, Alabama under contract to NASA Marshall Space Flight Center.

either broke up or consistently returned to a particular configuration.

During the experiment, four different interface shapes were observed. All four surface shapes were stable and only one was rotationally symmetric. The remaining three asymmetric surfaces are described as "spoon-right","potato chip", and "spoon-left". The rotationally symmetric surface appeared during the fluid transfer from the reservoir to the test section. The "spoon-right" surface appeared as soon as the crew member removed her hands from the ICE vessel following the fluid transfer process. This surface configuration was extremely stable. The liquid would reform the "spoon-right" surface after very large disturbances were imposed on the ICE cell. After several oscillations imposed at near the natural frequency of the surface, the liquid reoriented into the "potato-chip" configuration, where again the surface shape was quite stable. After further disturbances, the liquid surface retracted into the "spoon-left" configuration. These surface shapes matched the numerically predicted surface shapes.

ICE was a hands-on experiment, requiring the crew member to set up the test facility, the adjust the cameras and video recorders, and the experiment. The experiment required direct action by the crew member in order to affect changes in the liquid surface. Also, the crew member was required to judge not only the effect of the imposed disturbance on the liquid surface, but also to determine the disturbance with which to proceed. There was no communication between the investigators and the crew member during the conduct of the experiment. In this, the investigators were extremely fortunate. The investigators would have halted the experiment much earlier than did the crew member and would not have observed the third and fourth surface shapes.[3] In this instance, the lack of communication resulted in success of the experiment.

TEM-1*, Technological Evaluation of the MIM – 1*

The first Technological Evaluation of the MIM (TEM-1) was a technology demonstration experiment designed to investigate the feasibility of using the Microgravity Isolation Mount (MIM)[§] for vibration isolation of fluid physics experiments in a low-gravity environment. TEM-1 investigated both the vibration isolation and the controlled motion capabilities of the MIM by studying the natural frequency and damping characteristics of a liquid surface in low gravity.[4] The MIM and TEM-1 were launched from Russia as part of the Priroda Module which docked with the Mir Space Station in April, 1996. Astronaut Shannon Lucid performed the TEM-1 experiment during the NASA 2 increment in July and August of 1996. (See Tables 1 and 2.)

There were three objectives of TEM-1.[4] The first objective was to demonstrate the effect of g-jitter on low-gravity fluid physics experiments. The second objective was to demonstrate utility of MIM to isolate fluid physics experiments from g-jitter and evaluate the controlled displacement capabilities of the MIM. And the third objective was to gather new information on the damping characteristics of liquid surfaces in a low-gravity environment.

The basis of the TEM-1 experiment is a cylinder half-filled with liquid exposed to the residual accelerations of the Mir or to the imposed accelerations of the MIM. TEM-1 consisted of two test cells and a baseplate. The baseplate was used to secure the test cells to the MIM. The two test cells were identical except for an interior coating on one test cell which resulted in a change in the contact angle. The change in contact angle between the test cells allowed for study of the effect of curvature and contact angle on the natural frequency and damping of liquid surface oscillations. The fluid used was an immersion oil which was indexed matched to the acrylic test chamber. The index matching allowed for an undistorted view of the free surface behavior. Attached to the exterior of the housing was a CCD camera sensor and lens which could be connected to the Glovebox (MGBX)[¶] facility for recording video of the response of the liquid surface to accelerations. Acceleration (both imposed and ambient) and position data were recorded on a computer hard drive located in the MIM.

The TEM-1 experiment was semi-automated. A crew member was required to setup the MIM and MGBX facilities and to install the TEM-1 experiment on the MIM. Installation of the TEM-1 experiment included securing a TEM-1 test cell to the MIM flotor using the TEM-1 baseplate and transferring the test fluid from the reservoir to the cylindrical test chamber; filling the chamber approximately half full. Then the TEM specific configuration files were loaded into the MIM processor and the experiment began. These files instructed the MIM to oscillate sinusoidally at a fixed frequency, amplitude, and direction for a short period of time and then return to the vibration isolation mode. This sequence of oscillation/isolation was conducted over a wide range of frequencies and acceleration levels automatically. The crew member was not required again until the end of a complete set of imposed oscillations which required approximately 30 minutes to complete. At the end of the sequence, a crew member would transfer the MIM data to an optical disk for storage. Then, a new set of configuration files would be loaded into the MIM processor and another sequence of imposed oscillations performed.

During the NASA 2 mission, 6 sequences of imposed oscillations were performed on each of the TEM-1 test cells. Unfortunately, due to an error in translating and back-translating the TEM-1 experiment procedures, all of the acceleration data for one of the test cells was lost. The experiment was rerun on this test cell, but the fluid in the test cell had become broken into many surfaces and drops. Therefore, for this test cell there exists video data of the liquid surface during one run and acceleration data during another run. Correlation between the two runs is on going.

[§]The Microgravity Isolation Mount (MIM), provided by the Canadian Space Agency, actively isolates an experiment from vibration through the use of Lorentz coils. In addition to vibration isolation, the MIM can also superimpose controlled oscillations on a vibration isolated experiment. The MIM flotor is approximately 14 inches square and the working volume for an experiment is the size of a single middeck locker. The frequency range of isolation is 0.01 Hz to 100 Hz subject to a flotor displacement of ± 9 mm. A force of up to 10 N can be exerted on an experiment package perpendicular to the flotor and up to 5 N in the plane of flotor. The MIM can interact with an experiment through 4 control channels and can record experiment data through 8 data channels. In addition, the MIM can record flotor/stator accelerometer data and flotor position data.

[¶]See footnote on page 2 for a description of the MGBX

The video data of the two test cells indicates that the dissipation of energy, or damping, is greater in the low contact angle system (wetting) than in the high contact angle system (less wetting). In addition, the natural frequency of the low contact angle system was less than that of the high contact angle system.

The TEM-1 experiment was a simple concept, but was greatly complicated by using three separate facilities for conducting the experiment. The MIM, the MGBX for video recording, and a third facility, MIPS, used for storing the MIM acceleration data on optical disk. The complexities of simultaneous development of facilities and experiments lead to undefined interfaces between them. The complications were exacerbated by the translation of the procedures into Russian and then back into English. The crew member, Shannon Lucid, went to great lengths to sort out the confusion, but errors and last minute changes in the crew procedures resulted in a loss of data. These errors and mistakes may have been overcome but for the lack of real-time communication between investigators and the crew on Mir.

TEM-2*, Technological Evaluation of the MIM – 2*

The second Technological Evaluation of the MIM, or TEM-2, was designed to evaluate the capabilities of the MIM in a different parameter range than that of TEM-1.[4] TEM-2 was transferred to Mir from STS-79 in September, 1996. TEM-2 remained on Mir through the NASA 6 increment, but was never conducted.

As with TEM-1, TEM-2 consisted of two identical test cells differing only in contact angle. The test fluid was a mixture of decalin and tetralin and was indexed matched to the acrylic test chamber so as to allow for clear observation of the oscillating free surface. Variations in surface curvature between the test cells occurred as a result of the difference in contact angle. TEM-2 was a much less viscous system than TEM-1. This was affected by enlarging the test chamber diameter and by using a less viscous fluid. TEM-1 used an immersion oil which had a viscosity of about 27 cSt. The decalin/tetralin mixture used in TEM-2 had a viscosity of about 2 cSt. Therefore, TEM-2 would have been able to evaluate the capabilities of MIM to much lower accelerations than TEM-1.

TEM-2 was never performed because it was deemed of lower priority than other experiments and mission activities; particularly following the series of mishaps on Mir during the summer of 1997.

BCAT-1*, Binary Colloidal Alloy Tests*

The Binary Colloidal Alloy Test, or BCAT-1, was designed as a precursor experiment to the Physics of Colloids in Space (PCS), whose ultimate goal is to improve fundamental understanding of colloidal science, and to synthesize novel structures. In that vein, BCAT was designed to test theories of crystal growth and gel formation in space and to optimize the sample selection for PCS.[5] BCAT was transferred to the Mir Space Station from STS-79 in September, 1996. The experiment was conducted by John Blaha during the NASA 3 increment. (See Tables 1 and 2.)

The study was divided into two parts: slow growth crystals and rapid growth gels. The rapid growth portion of the experiment was conducted in the Glovebox (MGBX)[‖] and the slow growth portion was a fully automated, stand-alone experiment. There were three objectives for the BCAT experiment. The first was to observe the slow growth of crystal alloys in microgravity. The second objective was to observe the rapid growth of gel structures in microgravity. And the third objective was to determine the colloidal systems and their resultant microgravity structures.

The slow growth hardware consists of ten samples in a cell holder; back lighting and an automated 35mm camera for photographing the samples at prescribed time intervals. Growth of the crystals was qualitatively recorded by a series of 250 photographs. The different sample types and volume fractions were chosen to test as wide of a range of sample as possible in order to define the optimum sample set to be studied for PCS.

The experiment was initiated by a crew member homogenizing the samples and then pressing the start button. The experiment was then left undisturbed while the samples crystallized and were periodically photographed for 90 days. After the pictures were taken the crew member removed the cell holder and shot several additional roles of film.

The data gathered for the automated slow growth experiment was good. However, the film shot by the crew member was under exposed and was of little use. The results were varied depending on the type of sample studied, but did, in general, provide new information of colloidal growth and will be critical in the sample selection for PCS. However results were limited by the bubbles that developed in samples after delivery of the flight hardware for launch and by the hardware design; lighting was less then optimum.[5,6,7]

The fast growth experimental set-up used a five sample cell holder that was placed inside of the glovebox. Video was taken of the samples through a microscopic lens and camera system after mixing was initiated. The gels formed almost immediately and video was then acquired over the next twenty-four hours to watch the collapse of the gel structure. The crew was required for hardware set-up, camera focus, and turning the video on and off.

The results of the rapid growth portion of the experiment showed that gel collapse did not occur in the 24 hour observation period in microgravity. This leads to the conclusion that the collapse of the gels on earth is indeed driven by gravity, confirming that the tests planned for PCS are feasible and that microgravity is needed to obtain meaningful data.

The BCAT experiment was designed to be as simple and as automated as possible. Where crew interaction was required the experiment hardware was designed to not put the crew member in a position to have to make decisions that would directly effect the science results. Hardware was specifically designed in this manner due to fears that the crew could not be properly trained with the severe limits on crew training time, not to mention the long time elapsed between crew training and experiment operations. This strategy work well. The few disappointing results from the experiment were not due to crew errors but limitations and compromises that were made during the hardware design

[‖]See footnote on page 2 for a description of the MGBX.

due to budget constraints and the extremely short development cycle of the experiment hardware.

***PAS**, Passive Accelerometer System*

The Passive Accelerometer System, or PAS, was designed to measure the quasi- steady accelerations due to atmospheric drag and the earth's gravity gradient which occur on a low-earth-orbit spacecraft.[8] The PAS experiment was transferred to the Mir Space Station from STS-76 in March, 1996 and was conducted during the NASA 3 increment by Astronaut John Blaha between October and December of 1996. (See Tables 1 and 2.)

The PAS experiment consisted of a small steel sphere in a graduated tube filled with liquid. The graduated tube was 2 cm in diameter, the steel sphere was 0.4 cm in diameter and the liquid was water. The PAS tube assembly was attached to a modified camera tripod head to allow for a full range of orientations and the tripod head was mounted onto a steel plate backed with Velcro strips to allow for easy mounting to surfaces in the spacecraft. A pencil magnet was used to reposition the ball inside the tube. The residual accelerations were measured by recording the average velocity and trajectory of the sphere over a suitable time period. Strictly speaking, the PAS would operate optimally in a gravity gradient attitude whereas the Mir operates in a solar-inertial attitude. However, the average velocity of the sphere can yield a reasonable estimate of the quasi-steady residual acceleration provided that the tube is oriented along the net acceleration vector and that the net acceleration vector does not significantly change orientation over the measurement period.

To conduct the experiment, the PAS cell was oriented such that the graduated tube axis was, as close as possible, parallel to the direction of the acceleration. The sphere was then positioned at the end of the tube via the magnet. The starting position of the sphere was recorded and a timer was started. At 1–2 minute intervals a crew member checked that the trajectory of the sphere still lay along the tube axis and recorded the time and position of the sphere. If the angular deviation of the sphere's trajectory from the tube axis was greater than 10 degrees, the tube was reoriented such that its axis was parallel to the trajectory of the sphere. Each run was considered complete when the sphere had traversed at least 3 cm.

During the NASA 3 mission, 10 measurement attempts were made with the PAS. Six of those attempts produced definitive measurements of residual accelerations which were between $5 \cdot 10^{-2}\mu g$ and $1.9\mu g$. The remaining 4 PAS measurement attempts produced no visible motion over periods of 10–15 minutes. This indicates that there are periods of time in excess of 15 minutes for which the *local* quasi-steady acceleration was below $1\mu g$. In addition, the PAS experiment measured accelerations which varied by an order of magnitude between measurement attempts for the same location in Mir. Several explanations are provided for the large variation in acceleration measurements. Further clarification may develop as information is still being gathered on the location of the center of mass for Mir during the periods of PAS operation.[8,9]

The PAS experiment was a hands-on experiment which required a crew member to make judgments on orientation and location of the PAS cell during setup, manually collect data, make judgments and adjustments during the data collection, note anomalies and attempt to isolate sources of anomalies. The PAS was a simple experiment and easy to build and transport. However, it was difficult to properly set up the experiment and proved to be susceptible to ill-defined environmental factors; primarily location and orientation of the PAS cell. There was little or no real-time communication between the investigator and the crew member which might have addressed some of these problems.

***ALB**, Angular Liquid Bridge experiment*

The Angular Liquid Bridge experiment, or ALB, was designed to investigate the behavior of liquid surfaces in a low-gravity environment where small changes in container shape or contact angle may result in significant changes in the configuration of the liquid.[10,11] ALB was transferred to Mir from STS-81 in January, 1997 and was performed by Astronaut Jerry Lineger during the NASA 4 increment. (See Tables 1 and 2.)

Two different types of test vessels were used for the ALB experiment. The first was referred to as the Movable Wedge Vessel and the second was the Angular Liquid Bridge Vessel. The ALB experiments using both vessels utilized the MGBX** for recording video of the liquid configurations.

The Movable Wedge Vessel was a "pie-slice" section of a right circular cylinder in which the internal angle of the section could be varied. The test fluid was an immersion oil indexed matched to the acrylic test chamber in order to minimize optical distortion. The experiment with this ALB vessel began by dispensing liquid from the vessel reservoir into the wedge section. The internal angle of the wedge section was then slowly increased and decreased, with the apex of the wedge passing through the critical wetting angle, in order to study the effects of hysteresis on liquid wicking.

The results of the ALB experiment were limited. For the Movable Wedge Vessel experiments, the desired initial liquid configuration was not obtained prior to changing the wedge angle. That is, the liquid fill was asymmetric and additional time, or tapping, would have been needed to bring symmetry to the liquid configuration. During the experiments with the Movable Wedge Vessel the crew member worked through the operational procedures very quickly and time was not allowed to overcome the effects of hysteresis.[3,11]

The Angular Liquid Bridge Vessel consisted of a roughly cubic acrylic box within which the behavior of liquid drops (either water or indexed matched immersion oil) between two plates could be observed. The two plates could be parallel or tilted with respect to one another. The hinged door of the vessel served as a stationary plate. The movable plate was supported within the vessel by an adjustable fixture which could translate, tilt, and/or pivot the plate. The experiment with this vessel began by applying a particular coating to the pair of plates. This coating provided a pristine surface with the desired wetting properties. Following the coating process, liquid drops of a controlled volume were deployed on the interior surface of the vessel door. The door was then closed and secured thus becoming

**See footnote on page 2 for a description of the MGBX.

the stationary plate. Then the movable plate operations proceeded which included forming a liquid bridge between parallel plates or between tilted plates of varying angle. Other movable plate operations were tilting the movable plate with a liquid bridge in place and pivoting the movable plate about a vertex. The intent of experiments with this vessel was to examine the effect of hysteresis in the reorientation of a liquid bridge when the static conditions are changed. Multiple drops of varying volume in different geometries were tested.

Two sets of tests were performed using the Angular Liquid Bridge Vessel; wetting and non-wetting. During the wetting tests, drop motion occurred as the crew member was attempting to get a closer view with the video camera. Subsequently, the camera was not in focus when the experiment was initiated. In addition, the crew member was unaware that drops had begun to move and continued to change the tilt angle. Therefore, it is difficult to quantify the critical wetting angles and the rate of flow. The non-wetting tests using the Angular Liquid Bridge Vessel experienced similar problems to the tests using the movable wedge vessel. Time to overcome hysteresis effects was not allowed nor was the vessel tapped in order to initiate drop movement. Drop motion was observed, but only at the end of the experiment as the crew member was disassembling the setup. The lack of allowed hysteresis time and tapping may have been due, in part, to two control tests in which nothing was expected to have happened. It may not have been clear to the crew member that these were control tests. Thus, the expectations of the experiment behavior may not have been the same for the crew member as that for the investigators.[3,11]

ALB was a crew intensive, hands on experiment. This experiment required very careful attention to detail and a thorough understanding of the scientific results being sought. The lack of communications between investigators and the crew member prevented clarification of experiment procedures which may have assisted in the conduct of the experiment.

CGEL, *Colloidal Gelation experiment*

The Colloidal Gelation, or CGEL, was another Glovebox**experiment designed to study fundamental properties of colloids, emulsions and polymers. It is an extension of the BCAT experiment specifically designed to quantitatively study crystal growth using static light scattering techniques to analyze the crystal structure and density. The results of CGEL, like BCAT, are to be used to aid in the selection of samples for PCS, a more in-depth, definitive and longer-term study of colloids.[12,13] CGEL was transferred to Mir from STS–84 in May of 1997 and was performed by Astronaut Mike Foale during the NASA 5 increment. (See Tables 1 and 2.)

In addition to the goal of gaining sample information for PCS, there were three science of objectives for CGEL. The first objective was to further the understanding of the basic physics of colloid suspensions. The second objective was to observe the growth and behavior of colloidal crystals and gels in microgravity. The final objective was to understand the structure and properties of the materials produced in order to develop a model for the behavior of colloids.

Several samples of differing volume fractions of binary colloidal alloys, polymer colloidal samples and fractal colloidal gels were flown in sealed test tubes. The fractal gels were house in a special test tubes that kept reactant materials separate until the experiment was started and aggregating was desired.

Once the hardware was set-up, crystallization was initiated by a crew member homogenizing each sample. The samples were then inserted into the experiment module, which included a laser and a scattering screen to collect scattered light. The static light scattering patterns were then recorded by a video camera. A laptop computer with correlator cards then processed and stored the data. Additionally, an avalanche photomultiplier was located at ninety degrees to gather exact photon counts. The experiment module also incorporated motors to allow for translation of the sample for ensemble averaging and for oscillation of the sample to determine resonant frequency of the crystal structures. Data was to be collected at varying stages of crystal growth for each of the samples. Samples were also to be photographed by the crew member using a 35mm camera.

Due to Progress-Mir collision in June of 1997, only half of the samples were homogenized and photographed. No light scattering measurements were taken and no fractal aggregate samples were processed. Subsequently, the science objectives were not met for the CGEL experiment. Though qualitative, the data which was collected is considered to be very good by the experiment team.[6,7,12,13]

BCAT-2, *Binary Colloidal Alloy Tests – 2*

The second Binary Colloidal Alloy Test, or BCAT-2, used identical hardware and had the same objectives as that of BCAT-1. That is, it was designed as a precursor experiment to the Physics of Colloids in Space (PCS).[6,7] BCAT-2 was transferred to the Mir Space Station from STS–86 in May, 1997. was conducted by Astronaut Dave Wolf during the NASA 6 increment. (See Tables 1 and 2.)

BCAT-2 consisted of nearly identical hardware to BCAT-1 with the exception of a adapter which allowed the BCAT-2 sample cells to be secured in the CGEL camera fixture. This adapter allowed for improved crew photography of the BCAT-2 sample cells as compared to BCAT-1. The sample cells for BCAT-2 were of different volume fraction than those of BCAT-1 and/or contained different solutions. The results of BCAT-2 are similar to BCAT-1 and the experiment was considered to be a success.[6,7]

GMSF, *Growth & Morphology of Supercritical Fluids*

Growth and Morphology of Supercritical Fluids (GMSF) was designed to study fluids near the critical point.[14,15] The experiment was transferred to Mir from STS-91 in June of 1998 and is currently being conducted.

GMSF consists of three samples (thermostat units) which are processed in a critical point facility (ALICE II) developed by the French Space Agency, CNES. The three sample cells designed for GMSF allow for volume adjustments so that the off-critical density of the fluid could be varied. One of the cells also incorporates a design which provides a 20X magnification.

The operation of the ALICE II facility is fully automated and requires very little crew interaction. Programs were created to operate the furnace in a series of predetermnined and controlled temperature changes. The test cells specific to GMSF, however, are designed such that the density of the sample can be manually adjusted by a crew member. Additionally, a crew member is required for quenching the samples. Crew interaction is necessary for set-up, sample and video tape change, and for sample volume change. The crew is not required to make any critical decision regarding scientific outcome.

The GMSF experiment includes three different types of tests. The first examines the relationship between the morphology and the growth rates of droplets during phase separations. The second type of test studies supercritical boiling. The third study is a quantitative determination of the size distribution of density fluctuations. Currently, there are 40 days of testing planned for GMSF. The first 20 days of the experiment are scheduled to begin January 10, 1999.[6]

Summary of the Experiments

The fluid physics experiments are grouped into three categories; automated, semi-automated, and hands-on. The automated experiments required a crew member to turn on power and check on the status of the experiment, but little else. The semi-automated experiments required a crew member to properly set up the experiment, align cameras, fill test chambers, etc., but did not require a crew member to make any decisions or judgements related to the science being investigated. The hands on experiments required a crew member to act as a surrogate for the investigators; having to evaluate the results as the experiment progressed and make adjustments accordingly. All three styles of experiment experienced successes and disappointments.

The slow growth investigations of BCAT-1 & 2 were the only automated tests in this group of experiments. Although the slow growth experiments of BCAT-1 were considered to be successful, some of the samples developed bubbles and the liqhting conditions were poor. These problems were primarily hardware design issues and were largely overcome with BCAT-2. The advantages inherent with an automated experiment is that little crew time is required. This allows for longer test times and fewer restrictions on scheduling. The disadvantages are that the phenomena being studied must be well known. There is little or no recourse when unexpected behavior occurs and in microgravity science the unexpected is routine. In addition, automation can, potentially, increase the cost and complexity of the experiment hardware.

Most of the experiments were of the semi-automated variety. These include TEM-1 & 2, CGEL, the rapid growth experiments of BCAT-1 & 2, and GMSF. These experiments also experienced successes and failures. The experiment failures occurred for a variety of reasons. TEM-1 failures occurred because of errors in translating the experiment procedures. TEM-2 was not conducted because of scheduling problems. CGEL fell victim to the Mir-Progress collision and the subsequent power loss on Mir. Yet, the rapid growth tests of BCAT-1 & 2 were successful and all indications are that GMSF will be successful. In most instances, the failures associated with the semi-automated experiments were not hardware or crew related, but were due to programmatic issues.

The semi-automated experiments all used a separate facility to handle experiment power, video recording, data acquisition, etc. This approach is a more efficient use of limited space and resources than is a stand-alone experiment. Use of a multi-purpose or multi-experiment facility also allows for quick, inexpensive development of the experiment hardware, streamlined verification and safety reviews, and flexibility in experiment scheduling. However, the experiments may be limited by the capabilities of the facility; especially as the facility ages.

The hands-on experiments of ICE, PAS, and ALB are quite distinct from the automated and semi-automated experiments. These three experiments required decisions of the crew members which could directly affect the outcome of the investigation. For ICE, as discussed earlier, this was fortuitous. However, an in-depth understanding of the science was not a prerequisite for good judgements during the operation of ICE. This was not the case for the ALB and PAS experiments which required complex decisions that were critical to the experiment outcome. There was, particularly for ALB, too little training of the crew member on both the hardware operation and science to effectively perform the experiments. In addition, there was up to several months lag time between the crew training sessions and the actual operation of the experiments. The operation of the hands-on experiments was compromised by the complexity of the experiment details and by inadequate training.

The hands-on style of experiment allows for quick hardware development and recovery from experimental anomalies. In order for the experiment to be successful, though, intensive crew training is required as is greater communication between investigator and crew.

Issues Resulting From Mir Experiences

Hardware Development

In general, the fluid physics experiments described herein were simple, small, cheap, and designed for limited scientific studies. The hardware had to be designed under very tight delivery schedules. Some experiments had less than eight months to design, fabricate, and pass both NASA and RSA verification and safety requirements. Hardware developed in this situation is less than optimal and can lead to compromises in design which, in turn, lead to complicated or non-efficient operation procedures for the crew to implement.

In many cases, programmatic considerations did not allow for extensive testing and modifications of the hardware. In particular, there was no time to modify the hardware interfaces based upon crew suggestions. This is normally a critical step in the successful operation of an experiment.

If the space station program is willing to live with failures induced by these constraints, the benefits can be shorter development cycles and lower costs for experiments. However, failure acceptable to the program may not be acceptable to an investigator for which a particular experiment may be their one and only opportunity to test in long-duration microgravity.

Crew Preparation

The preparation, or training, of the crew for operating the experiments on Mir was a very serious issue. In general, a crew member received one or two hours of training on an experiment several months before the experiment would be operated. Specific experiment details and operation techniques could not be remembered under these circumstances. In one instance, a crew member did not even recognize the name of the experiment when it appeared on the daily schedule. This issue is, in part, due to the nature of a long-duration mission. In addition, a space station is a very complex assembly of systems and much of the crews' training and attention has to be given to maintaining these systems. Towards the end of the NASA-Mir Phase 1B program, there was an attempt to have the crew review informational materials in orbit before operation of an experiment. This has great benefit in a crew member become refamiliar with the experiment.

However, being familiar with an experiment does not ensure correct operation of the hardware. The check-list format of the crew procedures was designed to allow execution of each step in a timely, orderly and blind fashion. This format was not condusive to helping the crew member analyze observations and make appropriate decisions. Additionally, the format did not allow for a scientific description or overview which could have assisted the crew member in operation and analysis. The operation of experiments on the International Space Station would be facilitated by a more deliberative procedure format.

The crew procedures were further complicated by translation into Russian and then back-translation into English. The crew member was required to operate the experiment using the back-translated English version of the procedures. To correct errors arising from the dual translation, an English correction would be translated into Russian and then back into English; in some instances becoming the same error it was intended to correct. This resulted in great frustration on the part of investigator and crew alike. Presumably this will not be as big of an issue with the International Space Station for English speaking investigators.

Experiment Operations

A number of experiment failures could have easily been resolved if the Mir crews had the ability to communicate real-time with the investigators during experiment operations. The voice communication which did occur was limited to approximately two hours total per day in ten minute intervals. And most of the communication time was allotted for timeline and housekeeping/maintenance information, very little time was available for discussing science issues. This small allocation of communication for science is, however, in keeping with the priorities of the space station program. In contrast to Mir, there is a significant real-time communication between investigators and crew during Shuttle missions which can and does make up for deficits in crew training, experiment anomalies, and hardware malfunctions.

In addition, while the Mir crew members had technical backgrounds, the microgravity fluid physics investigations were not in their areas of expertise. Scientific investigations on the Shuttle often use a mission specialist for conducting experiment in a given discipline.

Conclusions

In conclusion, the experience of conducting microgravity fluid physics experiments on the Mir Space Station has shown that the long-duration microgravity environment offered by the Internation Space Station (ISS) can be excellent experiment platforms – provided that the space station program address several key issues relevant to microgravity experimentation. These issues include adequate lead time to develop and debug experiment hardware, enough time and resources to ensure that the crew is competently trained in both the science and the operation of the hardware, and greater communication between the investigator and the crew member during the operation of the experiment.

Acknowledgements

The authors would like to thank Dr. Iwan Alexander, Dr. Rafat Ansari, Monica Hoffman, Dr. Subramanian Sankaran, Dr. Bhim Singh, Brian Trach, and Dr. Mark Weislogel for their assistance in preparing this paper.

References/Bibliography

[1]Uri, J. and Levy, J., eds., 6th Quarterly Report of the Phase 1 Shuttle-Mir Research Program, August, 1998.

[2]Concus, P., Finn, R., Weislogel, M., and Saavedra, S., "Final Report for the Interface Configuration Experiment on Mir/NASA 2", 1997.

[3]Weislogel, M., personal communications, 1998.

[4]Allen, J., "One Year Report for the Technological Evaluation of the MIM (TEM)", 1997.

[5]Weitz, D., Pusey, P., and Ansari, R., "One Year Report for Binary Colloid Alloy Tests (BCAT)", 1998.

[6]Hoffman, M., personal communications, 1999.

[7]Ansari, R., personal communications, 1998.

[8]Alexander, J. I., "Final Report for the Passive Accelerometer System on Mir/NASA 3", 1997.

[9]Alexander, J. I., personal communications, 1999.

[10]Concus, P., Finn, R., and Weislogel, M., "Operational Accomplishments Report for the Angular Liquid Bridge (ALB) Experiment on Mir/NASA 4", 3rd Phase 1 Research Program Quarterly Report, 1998.

[11]Concus, P., Finn, R., and Weislogel, M., "Final Report for the Angular Liquid Bridge (ALB) Experiment on Mir/NASA 4", 1998.

[12]Weitz, D., "NASA 5 Operational Accomplishments Report for Colloidal Gelation (CGEL)", 4th Phase 1 Research Program Quarterly Report, 1998.

[13]Weitz, D., Pusey, P., and Ansari, R., "One Year Report for the Colloidal Gelation (CGEL) Experiment on Mir/NASA 5", 1998.

[14]Hegseth, J., "Growth and Morphology, Boiling and Critical Fluctuations in Phase Separating Super Critical Fluids (GMSF)", Science Requirements Document, 1997.

[15]Hegseth, Nikolayev, Beysens, Garrabos, and Chabot, "Growth and Morphology of Phase Separating Supercritical Fluids (GMSF), Boiling in Subcritical Fluids, and Critical Fluctuations", Fourth Microgravity Fluid Physics & Transport Phenomena Conference, Cleveland, Ohio, August, 1998.

Table 2 Timeline of NASA sponsored fluid physics experiments conducted on the Mir Space Station during the Phase 1B program.

Experiment	Investigator(s)	Launch	Mission	Land	Experiment Style
Interface Configuration Experiment (ICE)	P. Concus, U. C. Berkeley R. Finn, Stanford U. M. Weislogel[a], NASA Lewis	Priroda 4/96	NASA 2 Shannon Lucid 3/96 – 9/96	STS–79 9/96	hands on
Technological Evaluation of the MIM (TEM)	J. Allen[b], U. Dayton	Priroda 4/96	NASA 2 Shannon Lucid 3/96 – 9/96	STS–79 9/96	semi-automated
Technological Evaluation of the MIM–2 (TEM–2)	J. Allen[b], U. Dayton	STS–79 9/96	experiment was not conducted	STS–89 1/98	semi-automated
Binary Colloidal Alloy Tests (BCAT)	D. Weitz, U. Pennsylvania P. Pusey, U. Edinburgh	STS–79 9/96	NASA 3 John Blaha 9/96 - 1/97	STS–81 1/97	semi-automated & fully-automated
Passive Accelerometer System (PAS)	J. Iwan Alexander[c] U. Alabama–Huntsville	STS–76 3/96	NASA 3 John Blaha 9/96 – 1/97		hands on
Angular Liquid Bridge Experiment (ALB)	P. Concus, U. C. Berkeley R. Finn, Stanford U. M. Weislogel[a], NASA Lewis	STS–81 1/97	NASA 4 Jerry Lineger 1/97 – 5/97	STS–84 5/97	hands on
Colloidal Gelation (CGEL)	D. Weitz, U. Pennsylvania P. Pusey, U. Edinburgh	STS–84 5/97	NASA 5 Mike Foale 5/97-9/97	STS–86 9/97	semi-automated
Binary Colloidal Alloy Tests – 2 (BCAT–2)	D. Weitz, U. Pennsylvania P. Pusey, U. Edinburgh	STS–86 9/97	NASA 6 Dave Wolf 9/97 - 1/98	STS–89 1/98	semi-automated & fully-automated
Growth & Morphology of Supercritical Fluids (GMSF)	J. Hegseth, U. New Orleans D. Beysens[d] Y. Garrabos[e], C. Chabot[e]	STS–91 6/98	post Phase 1B 1/99		semi-automated

[a]Currently Senior Engineer at TDA Research, Inc., Colorado.
[b]Currently Staff Scientist at the National Center for Microgravity Science, Cleveland, Ohio.
[c]Currently Senior Staff Scientist at the National Center for Microgravity Science, Cleveland, Ohio.
[d]Commissariat à l'Energie Atomique, CEA-Grenoble, France.
[e]Institut de Chimie de la Matière Condensée, CNRS-Université Bordeaux I Château Brivazac, France.