

**Investigation Title:** Ambient Diffusion-Controlled Protein Crystal Growth  
**Principal Investigator:** Daniel C. Carter, Ph.D., New Century Pharmaceuticals, Inc.  
**Additional Investigators:** Dr. John Rosenberg, Dr. Mark Wardell, Dr. Gottfried Wagner, Dr. Gerard Bunick, Dr. Franz Rosenberger, Dr. Bill Thomas, Dr. B. C. Wang, Dr. Jean-Paul Declercq, Dr. Louis Delbaere, Dr. Don Frazier, and Dr. Bill Stallings

## INVESTIGATION OBJECTIVES

1. Evaluate experiment/hardware approach and produce high quality protein crystals for scientific applications.

## PHASE 1 MISSIONS

NASA 2 - NASA 5, NASA 7

## OPERATIONAL ACTIVITIES

Not provided by PI.

## RESULTS

Exceptionally large crystals of lysozyme (1.25 cm), albumin (0.8 to 1.0 cm), as well as the largest examples of crystals of the nucleosome core particle and histone octamer were produced. Crystals of the membrane associated protein bacteriorhodopsin were of improved size and quality. Additionally, crystals of several proteins have proved suitable for analysis and structure determination by neutron diffraction. This has produced the first completed protein structure determined by neutron diffraction as a direct result of microgravity (J. X. Ho, et al. unpublished results). To date, largely because of limitation in crystal size, only approximately one dozen protein structures have ever been determined by neutron diffraction. Experience gained from flight and ground-based experiments has proven essential to the proper utilization of the technology, as well as successful operations during periods of long-duration microgravity. One consequence of this success is that the technology has been licensed (1) and the hardware is now available commercially for ground-based applications.

Research involving a multi-disciplinary internationally recognized group of scientists has made key strides, both experimentally and theoretically, toward understanding the underlying role of microgravity in production of crystals with improved size and quality (2). A summary of the experiments and results has been published (3). Improved versions of the hardware have been selected through a recent NRA which will pave the way for future experiments on the International Space Station.

## CONCLUSIONS

DCAM, a specially designed hardware for the Mir experiment series, has proven to be a highly successful and valuable concept for the production of unusually large protein crystals. As a consequence, DCAM appears to have eliminated the barrier to the routine production of macroscopic centimeter sized protein crystals for neutron analysis. Insight into the role of microgravity in protein crystal growth promises to guide future applications.

## PUBLICATIONS

1. D. C. Carter U. S. Patent No. 5,641,681 (1997).
2. D. C. Carter, K. Lim, J. X. Ho, B. S. Wright, P. D. Twigg, T. Y. Miller, J. Chapman, K. Keeling, J. Ruble, P. G. Vekilov, B.R. Thomas, F. Rosenberger, and A. A. Chernov, "Lower dimer impurity incorporation may result in higher perfection of HEWL crystals grown in microgravity: A case study," J. Cryst. Growth, in press (1998).
3. D. C. Carter, B. Wright, T. Miller, J. Chapman, P. Twigg, K. Keeling, K. Moody, M. White, J. Click, J. R. Ruble, J. X. Ho, L. Adcock-Downey, G. Bunick, J.Harp, "Diffusion-controlled Crystallization Apparatus for Microgravity (DCAM): Flight and Ground-based Applications," J. Cryst. Growth, in press (1998).

**Investigation Title:** Angular Liquid Bridge Experiment in the Microgravity Glovebox (ALB)  
**Principal Investigator(s):** Paul Concus, University of California at Berkeley  
**Additional Investigators:** Robert Finn, Stanford University and Mark Weislogel, NASA Lewis Research Center

## INVESTIGATION OBJECTIVES

The objective of this experiment is to explore the behavior of liquid-vapor interfaces in a low-gravity environment, by comparing experimental with mathematical results that predict major shifts of liquid with small changes in container configuration or in contact angle. The particular configurations investigated were those of a liquid between parallel and tilted plates.

## PHASE 1 MISSION

Mir 23/NASA 4

## OPERATIONAL ACTIVITIES

Two test vessels were flown: The Movable Wedge Vessel and the Angular Liquid Bridge Vessel. Both vessels were constructed largely of acrylic plastic with aluminum fittings. Liquid drops were deployed on the plate surfaces by the crew member, in some cases after a fluoropolymer coating to achieve the desired wetting properties had been applied. Intersection angles between the plates were varied, and the liquid behavior was recorded on videotape, along with verbal comments by the crew member.

## RESULTS

The on-board procedures for applying coating to the plates worked successfully to achieve desired contact angles. Essentially all drops were deployed in a controlled fashion and exhibited a high degree of symmetry, despite drop sizes with diameters as large as 20 mm. Nevertheless, sufficient time to overcome hysteresis was not always allowed and additionally vessel tapping was not always introduced to initiate drop reorientation, so that the information obtained on drop transitions between the various configurations was incomplete.

## CONCLUSIONS

The procedure employed for on-board coating of the plates is effective and can be a useful tool for other space experiments. The experiment suffered, however, from lack of availability from Mir for communication between the ground-based investigators and the crew member during the course of the experiment.

## PUBLICATIONS

1. P. Concus and R. Finn, Discontinuous behavior of liquids between parallel and tilted plates, *Phys. Fluids*, 10 (1998), pp. 39-43.
2. P. Concus, R. Finn, and J. McCuan, A discontinuous dependence of liquid bridge configurations, Preprint PAM727, Center for Pure and Applied Mathematics, Univ. California, Berkeley, 1998, submitted *Zeit. Anal. Anwend.*
3. R. Finn, J-T. Chen, and E. Miersemann, Capillary surfaces in wedge domains: behavior at the vertex, continuity and discontinuity, asymptotic expansions, Univ. Leipzig preprint, 1998, submitted to *J. Math. Pures Appl.*
4. R. Finn and J. McCuan, Vertex theorems for capillary drops on support planes, MSRI preprint 1997-077, to appear in *Mathematische Nachrichten*.

**Investigation Title:** Binary Colloidal Alloy Tests (BCAT1, BCAT2)  
**Principal Investigator:** Dave A. Weitz, Ph.D., University of Pennsylvania  
**Additional Investigators:** Prof. P.N. Pusey and Dr. P.N. Segre

## **INVESTIGATION OBJECTIVES**

Study growth of binary colloidal alloy crystals and colloid-polymer gels by photography to assist in optimizing sample choice for future experiments, Physics of colloids in Space, scheduled to fly in the express rack on the ISS. The glovebox experiments help mitigate the risk of the ISS experiment.

## **PHASE 1 MISSIONS**

Mir

## **OPERATIONAL ACTIVITIES**

Photograph 10 samples about twice a day for 90 days; video colloid-polymer gels with low magnification microscope for several hours.

## **RESULTS**

Pictures of binary colloid alloys obtained; video of colloid-polymer gels obtained.

## **CONCLUSIONS**

Collapse of colloid polymer gels that is observed on the ground was confirmed to be due to gravity. In microgravity, no collapse was observed. Binary colloidal alloys were observed to grow more rapidly in microgravity than on Earth, and the concentration that yielded the best results was observed to be different than on the ground. This is essential information for judicious choice of samples for PCS. It also indicates that gravity plays a subtle role in the crystallization which is, as yet, not understood.

## **PUBLICATIONS**

NASA report, and several in preparation.

**Investigation Title:** Biochemistry of 3-D Tissue Engineering - BTS  
**Principal Investigator(s):** Timothy Hammond, M.B., B.S, Tulane Environmental Astrobiology Center  
**Additional investigators:** Thomas J. Goodwin M.A. and James H. Kaysen Ph.D.

## **INVESTIGATION OBJECTIVES**

Primary engineering objective: hardware validation.

- i. To determine the engineering performance of the BSTC during 105 days of inflight cell culture.

Secondary biotechnology objectives:

- i. To determine if cells will grow and propagate in culture in microgravity.
- ii. To validate procedures for cell transfer, refeeding and culture splitting in microgravity.
- iii. To investigate the mechanisms of differentiation of rat renal cells growing in microgravity culture.

## **PHASE 1 MISSIONS**

STS-86 to Mir with STS-89 return of samples.

## **OPERATIONAL ACTIVITIES**

I-STAT analysis of culture conditions.

## **RESULTS**

- F01. The BSTC supports cell culture in microgravity for prolonged periods.
- F02. Cells will grow and propagate in culture in microgravity.
- F03. Cell transfer, refeeding and culture splitting is efficacious in microgravity.
- F04. The mechanisms of differentiation of rat renal cells growing in microgravity culture and being analyzed.

## **CONCLUSIONS**

We have validated the engineering performance of the BSTC as flight hardware to support cell culture in microgravity, and identified components which require refurbishing. Cells grow and propagate in culture in microgravity, where cell transfer, refeeding and culture splitting can be performed with efficiency.

Mid experiment de obligation of funds for a flight experiment is devastating to timely completion of the analysis.

## **PUBLICATIONS**

Submitted Nature Medicine.

**Investigation Title:** Biotechnology System (BTS) CoCulture (COCULT)

**Principal Investigator(s):** Elliot M. Levine, Ph.D., Wistar Institute

**Additional Investigators:** Thomas Goodwin, NASA Johnson Space Center

#### **INVESTIGATION OBJECTIVES**

1. Demonstrate the ability to culture cells into tissues in the Mir environment, with regard to nominal operating procedures for Space Station.

#### **PHASE 1 MISSIONS**

NASA 7

#### **OPERATIONAL ACTIVITIES**

Human breast cancer cells and endothelial cells were inoculated on the ground at KSC and the culture transported by the Shuttle to Mir and allowed to grow during the NASA 7 mission.

#### **RESULTS**

At present, data analysis and evaluation is in progress. The samples are being processed.

#### **CONCLUSIONS**

No conclusions

#### **PUBLICATIONS**

No publications

**Investigation Title:** Biotechnology System (BTS) Diagnostic Experiment  
**Principal Investigators:** Steven R. Gonda, Ph.D., NASA/Johnson Space Center

**INVESTIGATION OBJECTIVES**

Verify and validate the Data Acquisition and Control System for the BioTechnology Facility on ISS. DACS is hardware, firmware and software designed to monitor, operate, and control experiment specific payloads and Facility systems, and to capture and archive experiment data and hardware performance data.

**PHASE 1 MISSIONS**

Increment	Location	Duration	Facility Components
Pre-2	<i>Spectr</i> Module	105 days	Passive PCMCIA Card
2	<i>Priroda</i> /BTS Facility	156 days	Powered DACS
3	<i>Priroda</i> /BTS Facility	130 days	Powered DACS with Bioreactor
4 & 5	<i>Priroda</i> /BTS Facility	263 days	Powered DACS
7	<i>Priroda</i> /BTS Facility	142 days	Powered DACS and Powered DACS with Bioreactor

**OPERATIONAL ACTIVITIES & PRELIMINARY CONCLUSIONS**

Increment	Facility Hardware	Activity Summary
Pre-2	Passive PCMCIA Card	<ul style="list-style-type: none"> <li>SRAM cards in stowage are susceptible to radiation induced SEU corruption</li> <li>Unpowered Flash PC-Cards in stowage are immune to SEU corruption at MIR radiation levels</li> </ul>
2	Powered DACS	<ul style="list-style-type: none"> <li>Powered Flash PC-Cards are immune to SEU corruption at MIR radiation levels</li> <li>Verified DACS integrated operation</li> </ul>
3	Powered DACS with Bioreactor	<ul style="list-style-type: none"> <li>Verified DACS control of experiment specific hardware</li> <li>Verified operation of DACS RRS</li> </ul>
4 & 5	Powered DACS	<ul style="list-style-type: none"> <li>Extended previous results for larger capacity flashcards and longer duration operations</li> <li>Detection of DRAM SEUs</li> </ul>
7	Powered DACS and Powered DACS with Bioreactor	<ul style="list-style-type: none"> <li>Verified DACS control of experiment specific hardware, including RRS</li> <li>Verified capability of DACS RRS to repair, monitor and protect SRAM PC-Cards in-flight</li> <li>Extended and reinforced previous results</li> </ul>

**PUBLICATIONS**

Not provide by PI.

**Investigation Title:** Biotechnology System (BTS) Facility Operations  
**Principal Investigators:** Steven R. Gonda, Ph.D., NASA/Johnson Space Center

**INVESTIGATION OBJECTIVES**

In order to conduct Risk Mitigation for the BioTechnology Facility on the ISS, the BTS was designed and flown on the Mir Space Station. The purpose of the BTS was multi-fold and included:

1. Demonstration of technology and systems to support biotechnology investigations.
2. Validation of BTF concepts and systems through long-duration operations.
3. Verification of BTF operational and training procedures.
4. Verification of the launch and transfer of operating experiments between orbiting spacecraft.
5. Fundamental Science investigations.

**PHASE 1 MISSIONS**

Increment	Location	Duration	Facility Components
Pre-2	<i>Spectr</i> Module	105 days	Passive PCMCIA Card
2	<i>Priroda</i> /BTS Facility	156 days	Powered DACS
3	<i>Priroda</i> /BTS Facility	130 days	Powered DACS with Bioreactor
4 & 5	<i>Priroda</i> /BTS Facility	263 days	Powered DACS
6	<i>Priroda</i> /BTS Facility	140 days	Bioreactor
7	<i>Priroda</i> /BTS Facility	142 days	Powered DACS and Powered DACS with Bioreactor

**OPERATIONAL ACTIVITIES**

Increment	Facility Hardware	Activity Summary
Pre-2	Passive PCMCIA Card	<ul style="list-style-type: none"> <li>• SRAM cards in stowage are susceptible to radiation induced SEU corruption</li> <li>• Unpowered Flash PC-Cards in stowage are immune to SEU corruption at MIR radiation levels</li> </ul>
2	Powered DACS	<ul style="list-style-type: none"> <li>• Powered Flash PC-Cards are immune to SEU corruption at MIR radiation levels</li> <li>• Verified DACS integrated operation</li> </ul>
3	Powered DACS with Bioreactor	<ul style="list-style-type: none"> <li>• Verified DACS control of experiment specific hardware</li> <li>• Verified operation of DACS RRS</li> </ul>
4 & 5	Powered DACS	<ul style="list-style-type: none"> <li>• Extended previous results for larger capacity flashcards and longer duration operations</li> <li>• Detection of DRAM SEUs</li> <li>• Verified DACS control of experiment specific hardware, including RRS</li> </ul>
7	Powered DACS and Powered DACS with Bioreactor	<ul style="list-style-type: none"> <li>• Verified capability of DACS RRS to repair, monitor and protect SRAM PC-Cards in-flight</li> <li>• Extended and reinforced previous results</li> </ul>

## **RESULTS**

Mir/BTS Technology and Systems Demonstration:

- Data Acquisition and Control System (ECC, Flashcards, recovery software)
- Gas Supply Module
- System performance, maintenance and extended operation
- Evaluation of monitoring (video, microscope) systems
- Experiment change-out procedures
- Data Acquisition, storage and downlink
- Bioreactor design and operations
- Bioreactor sensors and automation control systems
- Cell culture operations

Media preparation and storage

## **CONCLUSIONS**

Pending completion of analysis in FY99.

## **PUBLICATIONS**

Not provided by PI.

**Investigation Title:** Canadian Protein Crystallization Experiment (CAPE)

**Principal Investigator(s):** Jurgen Sygusch, University of Montreal

**Additional Investigators:** None reported.

### **INVESTIGATION OBJECTIVES**

1. To grow high-quality protein crystals in microgravity for the 15 university and industrial researchers involved with the mission.
2. To compare the resolution limits and mosaic spread between the space-grown crystals, ground-grown crystals, and space-grown crystals mounted on the Microgravity Isolation Mount (MIM).
3. To provide an opportunity for elementary and high school students to participate in a space experiment as part of an educational outreach program.

### **PHASE 1 MISSIONS**

Mir 24/NASA 6

### **OPERATIONAL ACTIVITIES**

Two identical sets of over 800 samples of 32 individual proteins will be grown in two separate crystallization units. The crystallization units use sliding blocks to mix protein solutions with precipitants. Certain cartridges of both sets have windows through which the growth process can be videotaped. One set of crystal growing chambers will be attached to the side of the Microgravity Isolation Mount (MIM) locker and subjected to Mir microaccelerations caused by crew movements, hardware activities and Mir operations. The second set will be located on top of the magnetic flotor of the MIM, which isolates experiments from external forces, such as microaccelerations. Data from these two sets, when compared, will show the effects of microgravity isolation on protein crystal growth.

### **RESULTS**

MIM optical disks and CAPE video tapes are in the process of being analyzed at this time. The CAPE hardware did produce a large number of crystals, which are in the process of being analyzed by x-ray diffraction techniques.

No results have been reported to date.

### **CONCLUSIONS**

No conclusions can be drawn at this time.

### **PUBLICATIONS**

None.

**Investigation Title:** Candle Flame in Microgravity (CFM) - MGBX  
**Principal Investigator:** Dr. Daniel L. Dietrich, NASA/Lewis Research Center  
**Additional Investigators:** Prof. James S. T'ien and Dr. Howard D. Ross

## **INVESTIGATION OBJECTIVES**

1. Determine if a quasi-steady candle flame can exist in a microgravity environment.
2. Determine the characteristics of the steady flame.
3. Study the previously observed pre-extinction oscillations.
4. Observe the interactions between two closely spaced candle flames.

## **PHASE 1 MISSIONS**

NASA 2

## **OPERATIONAL ACTIVITIES**

79 total candles burned, with three different wick diameters, two different candle diameters, and two different initial exposed wick lengths.

## **RESULTS**

Data consisted of primarily 35 mm photographs of the flame and crew audio commentary. Results compared favorably with a recently developed numerical model of the microgravity candle flame. Both showed very long flame lifetimes are possible and the existence of pre-extinction flame oscillations. Limited number of 2 candle tests performed in favor of more single candle tests. New behavior observed -- long-lived flame oscillations and postflight aerosol cloud.

## **CONCLUSIONS**

A steady flame is possible (at least in elevated oxygen concentrations) and pre-extinction flame oscillations are inherent to candle flames in microgravity.

## **PUBLICATIONS**

1. Ferkul, P.V., et al. "Combustion Experiments on the Mir Space Station," AIAA 99-0439.
2. Dietrich, D.L. et al. "Candle Flames in Non-Buoyant Atmospheres," in preparation.

**Investigation Title:** Cartilage in Space - BTS  
**Principal Investigator:** Lisa E. Freed, M.D., Ph.D., Massachusetts Institute of Technology (MIT)  
**Additional Investigators:** Gordana Vunjak-Novakovic, Ph.D., Neal R. Pellis, Ph.D., and the NASA/Johnson Space Center team working on BTS

## INVESTIGATION OBJECTIVES

Exposure of humans to microgravity affects cells and tissues at a variety of levels. Musculoskeletal changes (e.g. significant bone and muscle loss) occur even when astronauts exercise regularly, but the mechanisms are not yet understood. Previous flight experiments examined cells in monolayers and lasted 6-28 days. Tissue engineering, a new field enabling three-dimensional tissue equivalents to be created from isolated cells in conjunction with biomaterials and bioreactor culture vessels, can provide a basis for systematic, controlled in vitro studies. Cartilage was selected as a model musculoskeletal tissue for this first long-term space study because of its resilience and low metabolic requirements. Our working hypothesis was that in vitro cartilage formation is affected by space flight. Our specific objectives were two fold: (1) to maintain cell viability for four months in space and (2) to study effects of the space environment on the growth and function of tissue engineered cartilage.

## PHASE 1 MISSIONS

NASA 3

## OPERATIONAL ACTIVITIES

Preflight (MIT): Cell-polymer tissue “constructs” based on bovine calf articular chondrocytes and biodegradable polyglycolic acid scaffolds (5 million cells per 5 mm diameter x 2 mm thick scaffold) were cultured in rotating bioreactors for 3 months at 1 g prior to launch. Culture medium consisted of Dulbecco’s modified Eagle medium with 4.5 g/L glucose, 10% fetal bovine serum, 10 mM HEPES buffer, 0.1 mM nonessential amino acids, 0.4 mM proline, 50 mg/L ascorbic acid, 50 U/mL penicillin, 50 mg/mL streptomycin, and 0.5 mg/mL fungizone. After 3 months, constructs were transferred into each of two flight-qualified rotating, perfused bioreactors (the Biotechnology system, BTS) for an additional 4 months of cultivation on either the Mir Space Station or on Earth. Specifically, one BTS containing ten constructs was transferred to Mir via the US Space Shuttle STS-79 (9/16/96 launch) and brought back to Earth via STS-81 (1/22/97 landing). A second BTS with ten constructs served as an otherwise identical study conducted on Earth, at JSC.

Flight and ground control studies (astronaut John Blaha, NASA-JSC team): Medium was recirculated between the bioreactor and the gas exchanger at 4 mL/min for 20 min four times per day, and 50 to 100 mL of fresh medium were infused into the system approximately once per day. As a result, medium metabolic parameters were maintained within previously established target ranges (i.e. pH between 6.9 and 7.4, partial pressure of oxygen between 71 and 127 mmHg, and glucose concentration between 3.0 and 4.3 g/L) in both groups for the duration of the study, as assessed using portable cartridges. Concentration gradients within the bioreactor were minimized by differential rotation of the inner and outer vessel walls at 10 and 1 rpm, respectively, in microgravity, and by the convection associated with gravitational construct settling during solid body rotation of the bioreactor at 28 rpm in unit gravity. In the Mir group, gas bubbles were observed in the bioreactor between flight days 40 and 130. The amount of gas stabilized at approximately 20% of the total bioreactor volume, and the bubbles did not appear to come into direct contact with the constructs, as assessed by videography. An equal amount of gas was introduced into the bioreactor in the Earth group, in order to match conditions on Mir as closely as possible.

Postflight (MIT): Constructs were assessed at the time of launch (i.e. after 3 months of culture) and after 4 additional months on either Mir or Earth (i.e. after 7 months of culture), and compared to full thickness natural calf articular cartilage. Constructs were assessed with respect to the following parameter: (1) size and morphology (weight, histological/ultrastructural appearance); (2) biochemical composition (DNA, glycosaminoglycan (GAG), collagen type II, total collagen); (3) viability of reisolated cells (trypan blue exclusion, intracellular esterase activity); (4) tissue metabolism (incorporation of radiolabeled tracers into macromolecular GAG and collagen); (5) mechanical properties in confined compression (aggregate modulus, dynamic stiffness, hydraulic permeability).

## RESULTS

**Cellular viability:** Mir-grown constructs assessed 30 hours postflight were comparable to Earth-grown constructs with respect to cell viability and biosynthetic activity. Specifically, constructs from both groups consisted of 95-99% viable cells, as judged by trypan blue exclusion and by intracellular esterase activity, and incorporated radiolabeled tracers into macromolecules at comparable rates. The latter may represent a rebound in chondrocyte metabolism in the Mir-grown constructs, which were assayed following return from space.

**Construct shape:** Constructs grown on Mir tended to become more spherical while those grown on Earth maintained their initial discoid shape, as assessed histologically and from their respective aspect ratios (i.e. height to width) of  $0.72 \pm 0.08$  and  $0.62 \pm 0.03$  ( $p < 0.05$ ). These findings might be related to differences in cultivation conditions, i.e. videotapes showed that constructs floated freely in microgravity but settled and collided with the rotating vessel wall at 1 g.

**Construct structure:** Final samples from Mir and Earth appeared histologically cartilaginous throughout their entire cross-sections (5 - 8 mm thick), with the exception of fibrous outer capsules (0.15 - 0.45 mm thick), as assessed using safranin-O stain for GAG and immunohistochemical staining for collagen type II. Constructs grown on Earth appeared to have a more organized extracellular matrix with more uniform collagen orientation as compared to constructs grown on Mir, but the average collagen fiber diameter was similar in the two groups ( $22 \pm 2$  nm).

**Construct composition:** Constructs at the time of launch and after additional cultivation on Mir and on Earth contained  $13 \pm 1$ ,  $14 \pm 0.8$  and  $19 \pm 0.2$  million cells, respectively. On Earth, construct wet weights increased 1.7-fold between 3 and 7 months, which could be attributed to increasing amounts of cartilage-specific tissue components (i.e. GAG and collagen type II). In contrast, on Mir construct wet weights increased 1.3-fold over the same time interval, due to deposition of collagen and unspecified components that were not GAG. The polymer scaffold represented less than 0.3% of the final construct wet weight. The fraction of the total collagen that was type II decreased, but not significantly, from  $92 \pm 19\%$  at launch to  $78 \pm 4\%$  at landing, demonstrating relatively good maintenance of the chondrocytic phenotype.

**Construct function:** Construct mechanical properties improved both on Mir and on Earth resulting in an increase in aggregate modulus,  $H_A$ , and a decrease in hydraulic permeability,  $k$ . Dynamic stiffness also increased with culture time and showed the characteristic frequency dependence of natural cartilage. Mechanical properties of Mir-grown constructs were inferior to those of Earth-grown constructs. Specifically, the aggregate modulus of Earth-grown constructs was indistinguishable from natural calf cartilage and was three-fold higher than that of Mir-grown constructs.

## CONCLUSIONS

Tissue engineering is the creation of new tissues from component cells and biomaterial scaffolds. Our flight study was the first to demonstrate that engineered tissues can be grown for several months in space. Cartilaginous tissues grown on Mir were smaller, more spherical, and mechanically weaker than corresponding tissues grown on Earth. Our data is consistent with previous reports that space flight weakens the bones and muscles of experimental animals and humans. but ours was the first controlled comparison of isolated tissues grown on space or Earth for period of several months. Further studies of tissue engineering in space might help us understand, prevent or treat conditions such as osteoporosis that affect astronauts as well as bedridden and elderly people on Earth

## PUBLICATIONS

1. Tissue Engineering of Cartilage in Space. L.E. Freed, R. Langer, I. Martin, N.R. Pellis, G. Vunjak-Novakovic. Proc. Nat. Acad. Sci. U.S.A. 94: 13885-13890, 1997. This paper can be accessed at <http://www.pnas.org>. A commentary on this work appeared in the same PNAS issue on page 13380.
2. Freed, L.E., Pellis, N., Searby, N., de Luis, J., Preda, C., Bordonaro, J., Vunjak-Novakovic, G. Microgravity Cultivation of Cells and Tissues. Gravitational & Space Biology Bull. (invited article, submitted 10/98)

**Investigation Title:** Colloidal Gelatin  
**Principal Investigator:** Dave A. Weitz, Ph.D., University of Pennsylvania  
**Additional Investigators:** Prof. P.N. Pusey and Dr. P.N. Segre

## **INVESTIGATION OBJECTIVES**

Study growth of binary colloidal alloy crystals, colloid-polymer gels and fractal colloidal gels by static and dynamic light scattering. Some supplementary photography also planned. The primary goal of these experiments was to assist in optimizing sample choice for future experiments, Physics of colloids in Space, scheduled to fly in the express rack on the ISS. The glovebox experiments help mitigate the risk of the ISS experiment.

## **PHASE 1 MISSIONS**

NASA 5

## **OPERATIONAL ACTIVITIES**

All light scattering results were not performed due to the loss in power on Mir due to the collision. However, extensive photographs were taken, primarily of colloid-polymer mixtures, and also of binary alloy colloidal crystals.

## **RESULTS**

Pictures of binary colloid alloys obtained; pictures of colloid-polymer mixtures obtained.

## **CONCLUSIONS**

Unexpected structures were seen in the colloid-polymer mixtures. These structures suggest that the phase separation proceeds along different paths, that the crystals may grow out of the liquid in some instances, while out of the gas in other instances. Such results have never been observed on Earth because gravity leads to macroscopic phase separation, which obscures these results. These results have helped inspire new experiments, now planned primarily for PCS2.

## **PUBLICATIONS**

NASA report, and several in preparation.

**Investigation Title:** Forced Flow Flamespread Test (FFFT)  
**Principal Investigator:** Dr. Kurt Sacksteder, NASA/Lewis Research Center  
**Additional Investigators:** Prof. James S. T'ien, Mr. Paul S. Greenberg, and Dr. Paul V. Ferkul

## **INVESTIGATION OBJECTIVES**

Enhance the understanding of flame spreading over solid fuel surfaces in low-speed flows by: determining the structure of spreading flames in terms of temperature, species concentrations and velocity fields; and determining the mechanisms that induce flammability limits.

## **PHASE 1 MISSIONS**

NASA 2

## **OPERATIONAL ACTIVITIES**

In the Microgravity Glovebox, all samples successfully ignited and burned in very low speed airflow: Four flat cellulose samples of differing thicknesses, four samples of polyethylene wire insulation.

## **RESULTS**

Video and film images obtained for each sample. Fuel and flame temperatures measured. Comparison of flame structure with numerical simulation of thinnest cellulose sample complete and successful. Wire insulation samples show more complete burning in orbit than in Earth-bound tests.

## **CONCLUSIONS**

Glovebox environment useful for flame spread tests at the lowest airflow velocities.

## **PUBLICATIONS**

1. Ferkul, P.V., et al. "Combustion Experiments on the Mir Space Station," AIAA 37th Aerospace Sciences Meeting, AIAA-99-0439, January 1999.

**Investigation Title:** Interface Configuration Experiment (ICE) in the Microgravity Glovebox  
**Principal Investigator(s):** Paul Concus, University of California at Berkeley  
**Additional Investigators:** Robert Finn and Mark Weislogel

## INVESTIGATION OBJECTIVES

The objective of this experiment is to investigate symmetry breaking for liquid surfaces in microgravity by use of specifically designed containers, and to compare observed shapes with mathematical predictions. For the containers in the experiment, the liquid is predicted mathematically to have the striking property that any stable configuration it assumes cannot be rotationally symmetric, even though the containers themselves are rotationally symmetric; furthermore it is predicted that there can be more than one such asymmetric stable configuration for a prescribed liquid volume.

## PHASE 1 MISSION

Mir 21/NASA 2

## OPERATIONAL ACTIVITIES

Two identical vessels, made of acrylic plastic, were flown. The test portions of the vessels were in the shape of a right circular cylinder with a mathematically determined toroidal-like bulge near the midpoint. The reservoir portions contained the test liquid, an immersion oil indexed matched with the acrylic plastic. At the initiation of each test, the liquid was transferred to the test portion of the vessel. Subsequently, perturbations were applied by the crew member to induce the liquid to assume different configurations and to test stability. The liquid behavior was recorded on video tape, along with verbal comments of the crew member.

## RESULTS

The crew member (Dr. Lucid) skillfully and successfully found two distinct locally stable non-rotationally-symmetric configurations in the same container. Four static surfaces in all were formed: First the (unstable) rotationally symmetric configuration observed during the initial filling, then the apparent global minimizer like the one found numerically, then (following further carefully applied disturbances) another local minimizer that had also been found numerically. Finally, a further disturbance led once more to the minimizing surface, this time in reflected configuration.

## CONCLUSIONS

It was confirmed that stable equilibrium configurations of liquid in a rotationally symmetric container with symmetric boundary data (contact angles) need not themselves be rotationally symmetric. Thus symmetry breaking in capillary configurations must be expected physically. Additionally, more than one distinct asymmetric stable configuration can occur. These results communicate clearly the need for designers of in-space fluid management systems to take account of possible unusual behavior that may not be easy to anticipate.

## PUBLICATIONS

1. R. Finn, Non uniqueness and uniqueness of capillary surfaces, *Manuscr. Math.*, 61 (1988), pp. 347-372.
2. Callahan, M., Concus, P., Finn, R., Energy Minimizing Capillary Surfaces for Exotic Containers, in *Computing Optimal Geometries* (with accompanying video tape), J.E. Taylor Ed., AMS Selected Lectures in Mathematics, Amer. Math. Soc., Providence, RI, 1991, pp. 13-15.
3. Concus, P., Finn, R., Exotic Containers for Capillary Surfaces, *Journal of Fluid Mechanics*, Vol. 224, 1991, pp. 383-394; Corrigenda, *Journal of Fluid Mechanics*, Vol. 232, 1991, pp. 689-690.
4. P. Concus, R. Finn, and M. Weislogel, Drop-tower experiments for capillary surfaces in an exotic container, *AIAA J.*, Vol. 3, Jan. 1992, pp.134-137.

5. P. Concus, R. Finn, M. Weislogel; Interface Configuration Experiment: Preliminary Results, Joint Launch + One Year Science Review for USML-1 and USMP-1 with Microgravity Measurement Group, NASA CP-3272, Vol. 2, 1994, pp. 525-541.
6. P. Concus, R. Finn, and M. Weislogel, Capillary surfaces in an exotic container: results from space experiments, Report PAM737, Center for Pure and Applied Mathematics, Univ. California, Berkeley, 1998, submitted to J. Fluid Mech.

**Investigation Title:** Interferometric Study of Protein Crystal Growth in the Microgravity Glovebox  
**Principal Investigator(s):** Alexander McPherson, Ph.D., University of California at Irvine  
**Additional Investigators:** Stanley Koszelak

#### **INVESTIGATION OBJECTIVES**

1. Provide a technology demonstration and development effort of an interferometry system to study Protein Crystal Growth (PCG) in microgravity.
2. Study solute concentration gradients surrounding growing proteins crystals to obtain evidence regarding the role of growth unit aggregation in PCG.

#### **PHASE 1 MISSIONS**

NASA 6

#### **OPERATIONAL ACTIVITIES**

The IPCG hardware will be transported to Mir on STS-86. The IPCG hardware will then be installed in the Microgravity Glovebox for experiment operations. Once installed, the crew initiated experiment operations and utilized an optics system and computer software to collect optical data from the experiment. At the end of all the experiments, the IPCG hardware was removed from the glovebox and returned to stowage. The IPCG and associated hardware was returned on STS-89.

#### **RESULTS**

There were 492 images present on the IPCG computer in lieu of the expected 4,140 possible images. Power outages, possible environmental vibrations, and intermittent automatic camera digitization made the results less than desirable.

The IPCG hardware succeeded magnificently, especially with the commercial PC boards and the data acquisition and control system. Several lessons learned and minor redesigns of the fluid and optics systems should be implemented in any follow-on investigations.

#### **CONCLUSIONS**

No conclusions

#### **PUBLICATIONS**

No publications

**Investigation Title:** Liquid Metal Diffusion Experiment (LMD) - Microgravity Isolation Mount  
**Principal Investigator(s):** Franz Rosenberger, University of Alabama in Huntsville  
**Additional Investigators:** R.M. Banish

## INVESTIGATION OBJECTIVES

1. Measure the diffusion coefficient of In metal at 185° C.
2. Investigate the “wall effect”, i.e., transport differences between the bulk and wall regions of the sample.
3. Characterize the convective contamination of diffusivity measurements on Earth via using the MIM in its three operating modes: 3a.vibration isolation, 3b.programmed g-input and 3c.deactivated.

## PHASE 1 MISSIONS

NASA 4

## OPERATIONAL ACTIVITIES

The LMD apparatus was mounted to the Microgravity Isolation Mount (MIM) with four captive screws. The MIM was used to provide several different acceleration profiles to the LMD during the running of five samples on the Mir Space Station. The MIM oven is used to heat the samples up to 185 degrees Celsius and, the samples are allowed to diffuse for 96 hours. Following sample processing, data from the LMD is transferred to the MIPS system for data storage.

## RESULTS

The raw LMD data from the three completed diffusion runs have been processed. Diffusivity values have been obtained. Accelerometer data from the MIM has been received and reviewed. The diffusivity values obtained from experiments conducted on Mir/NASA 4 are within 5% (i.e., within the experimental error) of the terrestrial experiments. No effect of the container wall on diffusive transport was detected. The acceleration disturbances measured on the MIM floater platform (during sample processing) were generally less than  $10^{-4}$  g for the latched (deactivated) mode and  $10^{-6}$  g for the isolating mode. Thus, buoyancy-driven convection effects were minimal in our samples.

## CONCLUSIONS

Similarities between the self-diffusivity of Indium at 185°C between the terrestrial and space experiments was observed. At 185°C the temperature non-uniformities in the liquid indium were probably less than 0.05°C. The residual acceleration/g-jitter was typically less than  $10^{-4}$  g. Therefore, convective contamination was minimal. In addition, the scatter of all diffusivity values were well within the experimental error; which is not true for the ground-based measurements. The performance of our radiation detectors and our sample containment method was well within our expectations. Hence, these components will be used for future missions. Although increased background noise from the South Atlantic Anomaly was evident in the detector data, it did not interfere with the diffusivity measurements. These results will be published shortly.

## PUBLICATIONS

No publications

**Investigation Title:** Mechanics of Granular Materials (MGM)  
**Principal Investigator:** Stein Sture, Ph.D., University of Colorado at Boulder  
**Additional Investigators:** Dr. Nicholas C. Costes, Dr. Khalid AlShibli, Dr. Roy A. Swanson, Mr. Mark Lankton, Ms. Susan Batiste, Mr. Tae-Hyung Kim, and Ms. Maria P. Tchonkova

## INVESTIGATION OBJECTIVES

Not provide by PI.

## PHASE 1 MISSION

STS-79, STS-89

## OPERATIONAL ACTIVITIES, ETC.:

Since the time-fuse is very short, let me again refer to the web-site, which might help answer most of these:

<http://bechtel.colorado.edu/~batiste/>

## RESULTS

A set of nine very low effective confining stress level experiments, were conducted in the microgravity environment of the Space Shuttle (STS-79, September, 1996 and STS-89, January, 1998). Conventional triaxial one-way cyclic compression and compression-extension cyclic (small and large amplitude) experiments were conducted on medium dense cylindrical specimens measuring 75 mm diameter by 150 mm long on dry quartz sand under displacement rates of 35 mm/hr, to total axial strains of 25% at confining stresses in the range of 0.05 - 1.30 kPa. In the absence of cohesion, the friction angles observed were in the range of 75 (+/- 1) to 70 (+/- 1) degrees at the lowest confining stress level to 56 degrees at the highest level. The dilatancy angles for all experiments were in the range of 30 degrees. The deformations were relatively uniform in all cases right up to the maximum displacements. No shear bands or other forms of localized deformation were visible at the surfaces of the specimens. The overall behavior of the specimens was brittle-ductile with significant material instabilities only at the 0.05 kPa level, resulting in strain-softening. More ductile behavior was seen at the 0.52 and 1.30 kPa levels. X-ray computed tomography studies show relatively uniform internal structure with radial-turbine screw fan-like patterns appearing almost periodically, where the fans constitute zones of dilation. The specimens' overall nominal stress-strain response curves display periodic patterns of minor instability, with stress variations resembling stick-slips that were of a magnitude 5-10% of the overall stress levels. These periodic material instabilities appear to be independent of confining stresses in the ranges that were studied. All six experiments showed significant initial stiffnesses, which were comparable to the regularly spaced observed unloading-reloading stiffness responses. It appears that there is little or no coupling between the unloading-reloading stiffness modulus behavior, which is predominantly elastic, and the confining stress level, or the amount of inelastic deformations induced. Ground-based experiments were compared to the flight data, and it was shown that the in-space experiments showed consistently higher friction and dilatancy angles at the lower confining stresses. Analysis of the flight experiments and the terrestrial tests show that there is internal consistency in the material properties except for the very high dilatancy and friction angles, and elastic moduli seen in the microgravity experiments. These findings have large impact on engineering and science involving the mechanics of granular materials, such as Earthquake engineering, geotechnical engineering, coastal and ocean engineering, sediment transport, geophysics, storage and handling of bulk (granular) solids, etc.

## CONCLUSIONS

Not Provided by PI.

## PUBLICATIONS

### *Journal Articles*

1. Runesson, K., Larsson, R., and Sture, S. Localization in hyperelastic-plastic porous solids subjected to undrained conditions, *Int. J. Solids and Structures*, Pergamon Press, Vol. 35, No. 31-32, pp. 4239-4255, 1998.
2. Sture, S., Costes, N.C., Batiste, S.N., Lankton, M.R., Alshibli, K.A., Jeremic, B., Swanson, R.A., and Frank, M., Mechanics of granular materials at low effective stresses, *ASCE, J. of Aerospace Engineering*, Vol. 11, No. 2, July, pp. 67-72, 1998.
3. Jeremic, B., and Sture, S., Tensor objects in finite element programming, *Int. J. Numerical Methods in Engineering*, Vol. 41, 113-126, 1998.

### *Proceedings*

4. Jeremic, B., Runesson, K., and Sture, S., Large deformation elasto-plastic analysis of geomaterials: from experiment to numerical predictions, *Proc. Int. Conf. on Comp. Meth. and Advances in Geomech.*, Wuhan, PR China, November, 1997, Vol. 2, 678-692.
5. Alshibli, K.A., Swanson, R.A., Costes, N.C., Sture, S., Batiste, S.N., and Lankton, M.R., Mechanics of granular materials under very low effective stresses in a microgravity environment, *Proc. Am. Geophysical Union*, Boston, Massachusetts, April, T21B-8, 1998.
6. Swanson, R.A., Alshibli, K.A., Frank, M., Costes, N.C., Sture, S., Batiste, S.N., Lankton, M.R., and Jeremic, B., Mechanics of granular materials in microgravity at low effective stresses, *Proc. Am. Geophysical Union*, Boston, Massachusetts, April, T21B-7, 1998.
7. Alshibli, K.A., Sture, S., and Costes, N.C., Effect of inclusions on plane strain behavior of sand, *ASCE, Proc. 12th Engineering Mechanics Conference*, Univ. of California, San Diego, May, CD-ROM, 1998.
8. Costes, N.C., and Sture, S., A mobility concept for Martian exploration, *Proc. ASCE, 5th Int. Conference on Engineering, Construction and Operations in Space*, Vol. 1, 489-494, 1998.
9. Jeremic, B., Runesson, K., and Sture, S., Finite deformation hyperelasto-plasticity of geomaterials: Numerical integration algorithms, *Proc. 13th U.S. Natl. Congress of Applied Mechanics*, Univ. of Florida, MA9, June, 1998.
10. Sture, S., Modeling of granular materials at low stresses, *Proc. 13th U.S. Natl. Congress of Applied Mechanics*, Univ. of Florida, MB9, June, 1998.
11. Sture, S., and Costes, N.C., Mechanics of granular materials at very low effective stresses, *Proc. 13th U.S. National Congress of Applied Mechanics*, University of Florida, Gainesville, MB9, June, 1998.

### *Presentations*

12. Sture, S., "Experiments and Analysis of Granular Materials aboard the Space Shuttle", Invited Lecture, Colorado School of Mines, Department of Engineering, Golden, Colorado, March 31, 1998.
13. Sture, S., "Mechanics of Granular Materials under Low Effective Stresses and Static Conditions", Invited Lecture, Cornell University, Department of Theoretical and Applied Mechanics, April 15, 1998.
14. Sture, S., "Microgravity and Low Stress Experiments on Granular Materials aboard the Space Shuttle," Moran Lecture in Engineering, University of Notre Dame, Indiana, April 30, 1998.
15. Sture, S., "Mechanics of Granular Materials at Low Effective Stresses", Fourth Microgravity Fluid Physics and Transport Phenomena Conference, Cleveland, Ohio, August 14, 1998.
16. Sture, S., "Constitutive Issues in Soil Liquefaction, Int. Workshop on the Physics and Mechanics of Soil Liquefaction", NSF and Johns Hopkins University, Baltimore, Maryland, September 10, 1998.

(Lectures and proceedings papers related to NASA/JSC organized symposia in connection with 180-day results reports, 360-day reports, and NASA microgravity results symposia (organized by John Uri et al., at JSC, and

held at NASA Ames Research Center, April 1-3, 1998, etc. are not included. It is assumed that these have found their way into your database separately.)

17. Batiste, S.N., Lankton, M.R., and Sture, S., "Mechanics of Granular Materials: STS-89/Mir8 experiments," Second Phase 1 Research Program Results Symposium, NASA, Ames Research Center, April 1, 1998.

*Report*

18. Sture, S., Costes, N.C., Batiste, S.N. Lankton, M.R., Alshibli, K.A., and Swanson, R., 180-day Report: Mechanics of Granular Materials Experiment Research Results, Report to NASA, Johnson Space Center, June, 1998.

**Investigation Title:** Microgravity Glovebox (MGBX) Facility Operations  
**Principal Investigator(s):** Don Reiss, Ph.D., NASA/Marshall Space Flight Center  
**Additional Investigators:**

## **INVESTIGATION OBJECTIVES**

1. To provide a level of containment by providing a physical barrier between the MGBX working area and the ambient environment.
2. To maintain a negative pressure within the working area during normal operations.
3. To provide a working area in which to perform experiments with a window for viewing the experiments.
4. To store data on orbit to support experiment correlation with environmental status during operation of the experiments.

## **PHASE 1 MISSIONS**

NASA 2 - NASA 6

## **OPERATIONAL ACTIVITIES**

The glovebox facility was used on NASA 2, 3, 4, 5, and 6 to support multiple Microgravity science experiments. The glovebox facility was brought back to the ground on STS-89.

## **RESULTS**

NASA 2 - The experience gained on NASA 2 has been very valuable. The facility met all expectations. A total of 100 operational hours were accumulated.

NASA 4 - The NASA 4 investigation data has been reduced and supplied to the respective MGBx-housed investigative teams. The MGBx facility operated flawlessly during the 290 hours of accumulated time through NASA 4.

NASA 5 - The Mir GBX facility operated flawlessly during the 461 hours of accumulated time through NASA 5.

NASA 6 - NASA 6 was the final mission scheduled for Mir MGBx science operations. At the conclusion of this mission, the MGBx was cleaned and all experiment and facility hardware was stowed for return on STS-89. On return to MSFC, the facility was inspected and found to be in generally good condition, and was cleaner than originally expected due to the efforts of the crew. The expected amount of wear was evident, and some refurbishment would be required to prepare the facility for reflight.

## **CONCLUSIONS**

The Mir Glovebox (MGBX) for Microgravity Investigations was located in the Priroda module of the Mir Space Station. The glovebox provided work area for microgravity investigations that can be physically isolated from the crew environment. The air filtration system provided a negative pressure in the work area with respect to crew environment. Two separate banks of filters contained solid and liquid materials, preventing contamination of the crew environment.

## **PUBLICATIONS**

No publications

**Investigation Title:** Microgravity Isolation Mount (MIM)  
**Principal Investigator(s):** Bjarni Tryggvason, Ph.D., Canadian Space Agency (CSA)  
**Additional Investigators:**

## INVESTIGATION OBJECTIVES

1. Ensure that the Microgravity Isolation Mount (MIM) provides an isolated microgravity condition (free from acceleration disturbances) for conducting experiments.

## PHASE 1 MISSIONS

NASA 2 - NASA 7

## OPERATIONAL ACTIVITIES

NASA 2 - The MIM was operated in support of three experiments during NASA 2 on the Mir Space Station: (1) MIM Performance Verification Experiments (2) QUELD II Experiments and (3) The TEM experiment. NASA 3 - The MIM was operated in support of one experiment during NASA 3 on the Mir Space Station: (1) The MIM Performance Verification Experiment. NASA 4 - The MIM was operated in support of two experiments during the NASA 4 mission on Mir Space Station: (1) The Liquid Metal Diffusion Experiment and the (2) QUELD II experiment.

## RESULTS

NASA 2 - MIM data was copied to optical disks. These disks were returned to Earth on STS-79. The MIM and TEM experiments used their own optical disks. The QUELD experiment used optical disks supplied by the MIPS-2C. The MIM and TEM optical disks were returned to their respective PIs. The MIPS optical disks were returned to JSC. Copies of the data on the MIPS optical disks were made by NASA onto CD-ROMs and supplied to the CSA. Working copies of the data from the MIM and TEM disks were made to CD-ROMs at the Canadian Space Agency. For the TEM experiment three such copies have been made with one being returned to the TEM PI. The original flight optical disks for both the MIM and TEM have been placed in storage for future uses. At 30 days postflight, a summary of MIM runs, a summary of event files, a summary of experiment runs, optical disk and CD-ROM Listing, and a summary of analysis results has been prepared.

NASA 3 - Data analysis is ongoing. MIPS provided optical disks were used to archived the MIM data. These disks were returned to Earth on STS-81. The MIPS optical disks were returned to JSC. Copies of the data on the MIPS optical disks were made by NASA onto CD-ROMS and supplied to CSA, on March 14,1997. At 30 days postflight, a summary of MIM runs, a summary of event files, a summary of experiment runs, optical disk and CD-ROM Listing, and a summary of analysis results has been prepared.

NASA 4 - The MIM facility was used to support LMD and the QUELD experiment.

## CONCLUSIONS

NASA 2 - There were 63 QUELD runs. This compares to the 32 planned. Additional runs were required to operate the QUELD unit with only one of its two furnaces operating. There were 18 TEM runs compared to the 10 planned. Again extra runs were required in an attempt to recover data that was not stored properly.

NASA 4 - The MIM facility has accumulated more than 1200 hours of operations without any mechanical or electrical malfunctions. During the conduct of the LMD experiment operational difficulties have been encountered, an example is the discrepancy between estimated versus actual time to perform various tasks. The content of the MIM event files will be used to determine the reasons for the discrepancy and corrective measures will be implemented in future missions. Overall the MIM performed as planned and was capable of providing improved microgravity conditions over long periods of time, up to 96 continuous hours without interruption.

## PUBLICATIONS

No publications available

**Investigation Title:** Opposed Flow Flame Spreading over Cylindrical Surfaces (OFFS)  
**Principal Investigator:** Robert A. Altenkirch, Mississippi State University  
**Additional Investigators:** Dr. Kurt Sacksteder, Prof. Subratta Bhattacharjee, and Dr. Michael A. Delichatsios

## **INVESTIGATION OBJECTIVES**

Enhance the understanding of flame spreading over solid fuel surfaces in the presence of low-speed opposed flows; especially considering effects of radiation heat transfer from cylindrical fuels. Seek flammability limit in terms of air velocity for cylindrical samples.

## **PHASE 1 MISSIONS**

NASA 4

## **OPERATIONAL ACTIVITIES**

In the Microgravity Glovebox, four of eight samples successfully ignited and burned. Remaining samples judged to be not flammable under the test conditions.

## **RESULTS**

Video and film images obtained for four samples. Change in flame spread characteristics observed with change in air flow velocity. Observed flammability limit for thick cylindrical sample.

## **CONCLUSIONS**

Glovebox environment useful for flame spread tests at the lowest airflow velocities. Differences between flame spread characteristics for flat and cylindrical samples attributed to differences in radiative heat losses.

## **PUBLICATIONS**

1. Ferkul, P.V., et al. "Combustion Experiments on the Mir Space Station," AIAA 37th Aerospace Sciences Meeting, AIAA-99-0439, January 1999.

**Investigation Title:** Passive Accelerometer System (PAS) - MGBX  
**Principal Investigator:** J. Iwan D. Alexander, Case Western Reserve University

## **INVESTIGATION OBJECTIVES**

The objective of the passive accelerometer system (PAS) is to measure, at various locations in the spacecraft, the small ( $10^{-6}$   $\mu\text{g}$ ) quasi-steady residual acceleration caused by a combination of atmospheric drag effects and the gravity gradient.

## **PHASE 1 MISSIONS**

Mir 22/NASA 3

## **OPERATIONAL ACTIVITIES**

PAS was deployed on 10 separate occasions between October 20 and December 17, 1996. The acceleration measurement is obtained by recording the motion of a spherical proof mass along an oriented liquid-filled tube. Modified Stokes' Law uses trajectory and speed to calculate acceleration.

## **RESULTS**

Successful operation. Measured accelerations up to  $1.9 \mu\text{g}$  and as low as  $5 \times 10^{-2} \mu\text{g}$ . High and low accelerations measured at the same location but at different times.

## **CONCLUSIONS**

Higher acceleration values consistent with orbital attitude and estimated atmospheric drag. Lower values surprising. Explanation: simulations show that proximity to CG + quasi-inertial attitude can lead to periods of practically no proof mass motion when the drag accelerations are low enough ( $\Rightarrow$  low average acceleration)

## **PUBLICATIONS**

1. J. Iwan D. Alexander and M.J. B. Rogers, Passive Accelerometer Measurements on Mir and STS-50, to be submitted to Microgravity Science and Technology, 1999.

**Investigation Title:** Protein Crystal Growth (PCG) GN2 Dewar  
**Principal Investigator:** Alexander McPherson, Ph.D., University of California at Irvine  
**Additional Investigator:** Stan Koszelak, Ph.D.

## INVESTIGATION OBJECTIVES

1. Crystallize proteins, nucleic acids, viruses, and polypeptides in a microgravity environment taking advantage of the long duration afforded by Mir.
2. Crystallize a very large number of samples inexpensively, simply, with minimal flight resources.
3. Identify for most investigations the likelihood that microgravity will be a useful variable.
4. Provide a method for the optimization of crystallization conditions for particular sample types.
5. Improve the diffraction quality of macromolecule crystals for X-ray study on Earth.
6. Provide a system for the exploration and definition of ideal microgravity experiment configurations.

## PHASE 1 MISSIONS

STS-71, STS-74, STS-76, STS-79, STS-81, STS-84, STS-89

## OPERATIONAL ACTIVITIES:

### PCG/GN2 Dewar Flight History

Flight, date	# of samples	# of proteins
STS-71 (6-27-95)	183	19
STS-74 (11-5-95)	166	16
STS-76 (3-22-96)	275	20 (2 units flown)
STS-79 (9-16-96)	285	11
STS-81 (1-12-97)	220	8
STS-84 (5-15-97)	107	11
STS-89 (1-22-98)	150	16

## RESULTS

- Approximately 80% success in terms of obtaining crystals of different macromolecule samples.
- Significant size and/or X-ray quality enhancement for approximately 15% of macromolecules flown.

## CONCLUSIONS

- The Liquid-Liquid Diffusion and Batch Techniques for PCG are well suited to long-duration missions remaining stable for months.
- A very large number or volume of experiments can be performed with minimal hardware or on-orbit resources.

## PUBLICATIONS

1. Koszelak, S., Leja, C. and McPherson, A. Crystallization of biological macromolecules from flash frozen samples on the Russian Space Station Mir. *Biotechnology and Bioengineering* 52, 449-458 (1996).
2. McPherson, A. Macromolecular crystal growth in microgravity. *Crystallography Reviews*, 6(2) 157-308 (1996).
3. McPherson, A. Recent Advances in the Microgravity Crystallization of Biological Macromolecules. *Trends in Biotechnology TIBTECH*. 15 No. 6(161), pp. 197-237 (1997).

**Investigation Title:** Queen's University Experiment in Liquid Diffusion (QUELD)  
**Principal Investigator(s):** Reginald Smith, Queen's University, Kingston, Canada  
**Additional Investigators:** Kedar Tandon, University of Manitoba, Winnipeg, Canada; Robert Redden, Amistar R&D Inc, Victoria, Canada

## INVESTIGATION OBJECTIVES

1. To measure the diffusion coefficients in metallic binary systems under conditions of microgravity.
2. To provide further data and increase the understanding of the diffusion problem and of the experimental data.

## PHASE 1 MISSIONS

NASA 2, NASA 4, NASA 7

## OPERATIONAL ACTIVITIES

NASA 2 - The QUELD was upmassed on STS-76 on May 27, 1996 and operated during the NASA 2 mission. During the period from June 10, 1996 to August 27, 1996, crewmember Shannon Lucid processed a total of 50 samples of the 55 samples planned for this mission. All the samples were returned on STS-79 in September, 1996.  
NASA 4 - The QUELD FA-1 was upmassed on STS-81 in January, 1997 and operated during NASA 4. During the period from March 21 to May 4, 1997, crewmember Jerry Linenger processed or attempted to process a total of 102 samples, 36 samples more than planned for NASA 4. Of these 102 samples, only 6 samples seem to have been affected by anomalies. All 102 samples were returned on STS-84 in May, 1997.

## RESULTS

To date, 51 of the 55 samples have been evaluated. Of these 51 runs, 17 can be considered operational successes, the rest were affected by anomalies. The remaining 4 experiment runs are currently being evaluated. The Principal Investigators (PIs) have begun the analysis of their respective samples. Since their return from Mir, the samples have been visually inspected and re-tested for containment by vacuum test and X-ray inspection, as they were for flight qualification. This post-mission examination proved the complete integrity of the sample containment. The samples were then returned to the respective PIs. The time, temperature and acceleration data for each experiment was downloaded from the MIM optical disks. Due to the large volume of data generated by the experiments, the activity of computing and reporting the data is not yet complete - the data for 12 runs remain to be reduced. Some general results are:

- As desired, none of the samples were found to have internal shrinkage cavities.
- As desired, the X-ray inspection showed that during processing, the surface of the molten specimens had wetted the walls of the inner sheath, an indication that Marangoni convection was minimized.
- The preliminary examination of the oxide interference tints on the sample surfaces and a visual inspection of the specimen materials indicate that the experiments were highly reproducible (consistent).

NASA 4 - Samples have been visually inspected. This post-mission examination revealed that some of the samples had some external oxidation but that the integrity of the sample containment was maintained. The samples and the QUELD furnace temperatures at the midpoint of the processing sequence, as obtained from data collected by the memory modules, were returned to the respective Principal Investigators (PIs).

During NASA 4, the crew processed or attempted to process 102 QUELD samples, 36 more samples than planned. Of these 102 samples, 6 samples have been affected by operating anomalies. Five of these samples were not processed or partially processed because the QUELD thermal switch interrupted the sequence when it sensed that the safe touch temperature of the furnace module (50 C) was exceeded on the surface of the QUELD unit. One sample, sample 214, was returned, apparently without having been processed. No record of this experiment exists on the QUELD memory modules. The samples have been visually inspected by the CSA and found to have maintained containment integrity in spite of surface oxidation on some of the sample casings. The samples along with the temperature data stored on the QUELD memory modules were returned to the respective PIs. More in-depth analysis will occur once the QUELD data disks, on which the bulk of the mission data are stored, are returned to the CSA.

NASA 7 - The data disks containing data from MIM has been received and analyzed. A report was written on MIM Flight Data analysis for Queen's (CSA-MSP-MIM-QUELD/NASA7-001) and for University of Toronto (CSA-MSP-MIM-QUELD/NASA7-002). The report will be sent to Queen's along with the raw electronic data. The samples have not been yet analyzed by the PI. For University of Toronto, the samples as well as the report will be released when the PI will present a new proposal that would take into account the contamination factor . For the QUELD Furnace data, the analysis will start on reception of the Memory Modules in late August.

During NASA 7, the crew processed or attempted to process 50 QUELD samples. The 38 samples from Queen's have been visually inspected by the PI and CSA and 4 samples seems to have not been processed. The 12 samples from University of Toronto will not be further analyzed until a new proposal is submitted. All samples have maintained containment integrity in spite of surface oxidation on some of the sample casings. All MIM data have been analysed and a report for each PI has been written including all analysed data plots. The Queen's report will be sent to the PI along with the raw electronic data. More in-depth analysis will occur once the QUELD Memory Modules are returned to CSA.

## **CONCLUSIONS**

No conclusions

## **PUBLICATIONS**

No publications

**Investigation Title:** Space Acceleration Measurement System (SAMS) Operations

**Principal Investigator:** Richard Delombard, NASA/Lewis Research Center

## **INVESTIGATION OBJECTIVES**

1. Measure the microgravity acceleration environment on Mir in support of US and Russian Phase 1 investigations.
2. Characterize the microgravity environment and pass knowledge to Principal Investigators.

## **PHASE 1 MISSIONS**

SAMS launched to Mir on Progress vehicle in August 1994 (before N. Thaggard).

Intermittent operation as required until return on STS-91 in June 1998 (with A. Thomas).

## **OPERATIONAL ACTIVITIES**

- Measure accelerations near science experiments during their operations.
- Measure accelerations in support of Mir Structural Dynamics Experiment (MiSDE).

## **RESULTS**

SAMS acquired over 50 gigabytes of data which represents 3,500 hours of operations.

## **CONCLUSIONS**

- Mir microgravity acceleration levels generally similar to Shuttle.
- Different equipment give different characteristics.
- Major features: vehicle dockings, crew exercise, gyrodynes, Mir flight attitude, Mir subsystem equipment, crew daily cycle.

## **PUBLICATIONS**

Seven NASA Technical Memorandum reports.

One COSPAR paper and presentation.

**Investigation Title:** Technological Evaluation of the Microgravity Isolation Mount (TEM-1 & 2)

**Principal Investigator:** Jeff Allen, National Center for Microgravity Research

## INVESTIGATION OBJECTIVES

1. Demonstrate the effect of g-jitter on low-gravity fluid physics experiments.
2. Demonstrate utility of Canadian provided Microgravity Isolation Mount (MIM) to isolate fluids experiments from g-jitter and evaluate the controlled displacement capabilities of the MIM.
3. Gather new information on the damping characteristics of liquid surfaces in low-gravity.

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.

## PHASE 1 MISSIONS

TEM-1 experiment was launched on Priroda in April, 1996; conducted by Astronaut Shannon Lucid during the NASA 2 mission; and returned on STS-79 in September, 1996. TEM-2 experiment was launched on STS-79 in September, 1996; remained on Mir through the NASA 6 mission, but was never conducted; and returned on STS-89 in January, 1998.

## OPERATIONAL ACTIVITIES

The TEM experiment required the crewmember to setup the MIM and MGBX facilities and to install the TEM experiment on the MIM. Installation included securing a TEM test cell to the MIM flotor and transferring the test fluid from the reservoir to the cylindrical test chamber. 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 crewmember was not required again until the end of a complete set of imposed oscillations. At the end of the sequence, the crewmember 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.

## RESULTS

During the NASA 2 mission, 6 sequences of imposed oscillations were performed on each of the TEM-1 test cells. Unfortunately, all of the acceleration data for one of the test cells was lost due to an error in translating and back-translating the TEM-1 experiment procedures. 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 ongoing.

The video data of the two test cells indicates that the dissipation of energy, or damping, is greater by an order of magnitude 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.

## CONCLUSIONS

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 led to undefined interfaces between them. These complications were exacerbated by the translation of the procedures into Russian and then back into English. The crewmember, 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.

## **PUBLICATIONS**

1. Jeffrey S. Allen and Suzanne Saavedra, "NASA Sponsered Fluid Physics Experiments Conducted on the Mir Space Station", paper no. AIAA 99-0437, presented at the AIAA 37th Aerospace Sciences Meeting and Exhibit, January 11-14, 1999, Reno, Nevada.

Intent is to publish TEM-1 data and results in a NASA Technical Memorandum once the acceleration data is analyzed in Canada and the video is correlated.