

# **International Space Station Research Summary Through Expedition 10**

*Julie A. Robinson, Jennifer L. Rhatigan, and David K. Baumann  
Office of the International Space Station Program Scientist  
NASA Johnson Space Center, Houston, Texas*

*Judy Tate and Tracy Thumm  
Engineering & Science Contract Group, Houston, Texas*

## THE NASA STI PROGRAM OFFICE . . . IN PROFILE

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

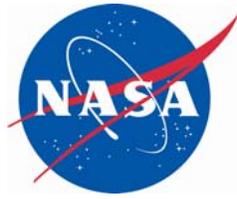
The NASA STI Program Office is operated by Langley Research Center, the lead center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also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

- **TECHNICAL PUBLICATION.** Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA's counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.
- **TECHNICAL MEMORANDUM.** Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.
- **CONTRACTOR REPORT.** Scientific and technical findings by NASA-sponsored contractors and grantees.
- **CONFERENCE PUBLICATION.** Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.
- **SPECIAL PUBLICATION.** Scientific, technical, or historical information from NASA programs, projects, and mission, often concerned with subjects having substantial public interest.
- **TECHNICAL TRANSLATION.** English-language translations of foreign scientific and technical material pertinent to NASA's mission.

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

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

- Access the NASA STI Program Home Page at <http://www.sti.nasa.gov>
- E-mail your question via the Internet to [help@sti.nasa.gov](mailto:help@sti.nasa.gov)
- Fax your question to the NASA Access Help Desk at (301) 621-0134
- Telephone the NASA Access Help Desk at (301) 621-0390
- Write to:  
NASA Access Help Desk  
NASA Center for AeroSpace Information  
7121 Standard  
Hanover, MD 21076-1320



# **International Space Station Research Summary Through Expedition 10**

*Julie A. Robinson, Jennifer L. Rhatigan, and David K. Baumann  
NASA Johnson Space Center, Houston, Texas*

*Judy Tate and Tracy Thumm  
Engineering & Science Contract Group, Houston, Texas*

Available from:

NASA Center for AeroSpace Information  
7121 Standard Drive  
Hanover, MD 21076-1320  
301-621-0390

National Technical Information Service  
5285 Port Royal Road  
Springfield, VA 22161  
703-605-6000

This report is also available in electronic form at <http://ston.jsc.nasa.gov/collections/TRS/>

## Contents

<b>Introduction</b> .....	<b>1</b>
<b>Human Research and Countermeasure Development for Exploration</b>	
<i>Physiological Studies—Bone and Muscle</i>	
Effect of Prolonged Space Flight on Human Skeletal Muscle (BIOPSY) .....	7
Commercial Biomedical Testing Module (CBTM): Effects of Osteoprotegerin (OPG) on Bone Maintenance in Microgravity .....	9
Foot/Ground Reaction Forces During Space Flight (FOOT) .....	11
Effects of Altered Gravity on Spinal Cord Excitability (H-REFLEX) .....	12
Hand Posture Analyzer (HPA) .....	14
Renal Stone Risk During Space Flight: Assessment and Countermeasure Validation (RENAL STONE) .....	15
Subregional Assessment of Bone Loss in the Axial Skeleton in Long-term Space Flight (SUBREGIONAL BONE) .....	16
<i>Physiological Studies—Other Effects of Space Flight</i>	
Advanced Diagnostic Ultrasound in Microgravity (ADUM) .....	18
Space Flight-induced Reactivation of Latent Epstein-Barr Virus (EPSTEIN-BARR) .....	20
Postflight Orthostatic Hypotension (MIDODRINE) .....	21
Promoting Sensorimotor Response Generalizability: A Countermeasure to Mitigate Locomotor Dysfunction After Long-duration Space Flight (MOBILITY) .....	22
Effects of EVA and Long-term Exposure to Microgravity on Pulmonary Function (PUFF) .....	23
Test of Midodrine as a Countermeasure Against Effect of Microgravity on the Peripheral Subcutaneous Veno-arteriolar Reflex in Humans (XENON-1) .....	24
<i>Psycho-social Studies</i>	
Crewmember and Crew-Ground Interaction During International Space Station Missions (INTERACTIONS) .....	26
Behavioral Issues Associated with Isolation and Confinement: Review and Analysis of ISS Crew Journals (JOURNALS) .....	28
<i>Radiation Studies</i>	
Bonner Ball Neutron Detector (BBND) .....	30
Chromosomal Aberrations in Blood Lymphocytes of Astronauts (CHROMOSOME) .....	31
Dosimetric Mapping (DOSMAP) .....	32
A Study of Radiation Doses Experienced by Astronauts in EVA (EVARM) .....	33
Organ Dose Measurement Using a Phantom Torso (TORSO) .....	34
<b>Physical and Biological Sciences in Microgravity</b>	
<i>Physical Sciences</i>	
Binary Colloidal Alloy Test-3 (BCAT-3) .....	37
Coarsening in Solid Liquid Mixtures-2 (CSLM-2) .....	39
EXPRESS Physics of Colloids in Space (EXPPCS) .....	40
Fluid Merging Viscosity Measurement (FMVM) .....	42
Viscous Liquid Foam-Bulk Metallic Glass (FOAM) .....	43
Investigating the Structure of Paramagnetic Aggregates from Colloidal Emulsions (INSPACE) .....	44
Miscible Fluids in Microgravity (MFMG) .....	45
Toward Understanding Pore Formation and Mobility During Controlled Directional Solidification in a Microgravity Environment (PFMI) .....	46
Solidification Using Baffle in Sealed Ampoules (SUBSA) .....	48
Zeolite Crystal Growth (ZCG) .....	49

### *Proteins Crystal Growth*

Advanced Protein Crystallization Facility (APCF), Eight Investigations .....	52
Commercial Generic Protein Crystal Growth-High Density (CPCG-H) .....	54
Dynamically Controlled Protein Crystal Growth (DCPCG) .....	56
Protein Crystal Growth-Enhanced Gaseous Nitrogen Ewer (PCG-EGN) .....	57
Protein Crystal Growth-Single Locker Thermal Enclosure System (PCG-STES) Nine Investigations .....	58

### *Cellular Biology and Biotechnology*

Avian Development Facility (ADF), Two Investigations .....	64
Cellular Biotechnology Operations Support System (CBOSS), Seven Investigations .....	66
Commercial Generic Bioprocessing Apparatus (CGBA), Three Investigations .....	70
Microencapsulation of Anti-tumor Drugs (MEPS) .....	72
StelSys Liver Cell Function Research (STELSYS) .....	73
Yeast-Group Activation Packs (YEAST-GAP) .....	74

### *Plant Biology in Microgravity*

Advanced Astroculture (ADVASC) .....	76
Biomass Production System (BPS) .....	78
Photosynthesis Experiment and System Testing and Operation (PESTO) .....	79
Plant Generic Bioprocessing Apparatus (PGBA) .....	81

## **Technology Development**

### *Spacecraft Materials and Systems*

Capillary Flow Experiment-Contact Line (CFE-CL) .....	85
Dust and Aerosol Measurement Feasibility Test (DAFT) .....	87
In-space Soldering Experiment (ISSI) .....	88
Materials International Space Station Experiment-1 and -2 (MISSE-1 and -2) .....	89
Synchronized Position Hold, Engage, Reorient, Experimental Satellites (SPHERES) .....	90
Serial Network Flow Monitor (SNFM) .....	91

### *Characterizing the Microgravity Environment on ISS*

Active Rack Isolation System-ISS Characterization Experiment (ARIS-ICE) .....	94
Middeck Active Control Experiment-II (MACE-II) .....	96
Microgravity Acceleration Measurement System (MAMS) and Space Acceleration Measurement System II (SAMS-II), Two Investigations .....	97

## **Observing the Earth and Educational Activities**

Crew Earth Observations (CEO) .....	100
Earth Knowledge Acquired by Middle School Students (EARTHKAM) .....	103
Space Exposed Experiment Developed for Students (EDUCATION-SEEDS) .....	105
Education Payload Operations (EPO) .....	106
Space Experiment Module (SEM) .....	107
DreamTime (DREAMTIME) .....	108

## **Results from ISS Operations**

Environmental Monitoring of ISS .....	110
Medical Monitoring of ISS Crewmembers .....	111
Exploration Lessons Learned from the Operation of ISS .....	112

<b>Summary .....</b>	<b>113</b>
<i>Appendix: The Expeditions Summarized</i>	
Expedition 1 (Nov 2, 2000 – Mar 18, 2001) .....	116
Expedition 2 (Mar 10, 2001 – Aug 20, 2001) .....	117
Expedition 3 (Aug 12, 2001 – Dec 12, 2001) .....	118
Expedition 4 (Dec 7, 2001 – Jun 15, 2002).....	119
Expedition 5 (Jun 7, 2002 – Dec 2, 2002).....	120
Expedition 6 (Nov 25, 2002 – May 3, 2003) .....	121
Expedition 7 (Apr 28, 2003 – Oct 27, 2003).....	122
Expedition 8 (Oct 20, 2003 – Apr 29, 2004).....	123
Expedition 9 (Apr 21, 2004 – Oct 23, 2004).....	124
Expedition 10 (Oct 15, 2004 – Apr 25, 2005).....	125
<b>Acknowledgments.....</b>	<b>126</b>

## Acronyms and Abbreviations

ADF	Avian Development Facility
ADUM	Advanced Diagnostic Ultrasound in Microgravity
AdvAsC	Advanced Astroculture
AEA	ancillary equipment area
AEM	animal enclosure module
AFRL	Air Force Research Laboratory
AIAA	American Institute of Aeronautics and Astronautics
ALARA	as low as reasonably achievable
APCF	Advanced Protein Crystallization Facility
ARIS	active rack isolation system
ASI	Italian Space Agency (Agenzia Spaziale Italiana)
BARS	brefeldin A-ADP ribosylated substra
BBND	Bonner Ball Neutron Detector
BCAT-3	Binary Colloidal Alloy Test-3
BCSS	Biotechnology Cell Science Stowage
bFGF	basic fibroblast growth factor
BPS	Biomass Production System
BSTC	biotechnology specimen temperature controller
CBOSS	Cellular Biotechnology Operations Support System
CBTM	Commercial Biological Testing Module
cDNA	complementary deoxyribonucleic acid
CEA	carcinoembryonic antigen
CEO	Crew Earth Observations
CEV	crew exploration vehicle
CFE	Capillary Flown Experiment
CFE-CL	CFE-Contact Line
CFE-ICF	CFE-Interior Corner Flow
CFE-VG	CFE-Vane Gap
CGBA	Commercial Generic Bioprocessing Apparatus
CGBA-APS	CGBA-Antibiotic Production in Space
CGBA-KCGE	CGBA-Kidney Cell Gene Expression
CGBA-SM	CGBA-Synaptogenesis in Microgravity
CIU	control and interface unit
CNRS	Centre National de la Recherche Scientifique
CO <sub>2</sub>	carbon dioxide
COTS	commercial off-the-shelf
CPCG-H	Commercial Protein Crystal Growth – High-density
CPDS	charged particle directional spectrometer
CSLM-2	Coarsening in Solid-Liquid Mixtures-2
CTP	citrate transporter protein
DAFT	Dust and Aerosol Measurement Feasibility Test
DCAM	Diffusion-Controlled Crystallization Apparatus for Microgravity
DcoH	4a-hydroxy-tetrahydropterin dehydratase
DCPCG	Dynamically Controlled Protein Crystal Growth
DCS	decompression sickness
DEXA	dual-energy X-ray absorptiometry
DLR	Deutsches Zentrum für Luft und Raumfahrt
DNA	deoxyribonucleic acid
DOSMAP	Dosimetric Mapping
DOSTEL	dosimetry telescope
DU	detector unit (for BBND)

EarthKAM	Earth Knowledge Acquired by Middle-School Students
EBV	Epstein-Barr Virus
ECG	electrocardiogram
<i>E. coli</i>	<i>Escherichia coli</i>
EDA	education demonstration activity
EGN	enhanced gaseous nitrogen
EM	electromagnetic
EMA	epithelial membrane antigen
EMG	electromyography
EMU	extravehicular mobility unit
EPO	Education Payload Operations
ESA	European Space Agency
ESM	experiment support module
EVA	extravehicular activity
EVARM	EVA Radiation Monitoring
EXPPCS	EXPRESS Physics of Colloids in Space
FAST	Focused Assessment with Sonography for Trauma
FDA	Food and Drug Administration
FDI	Fluid Dynamics Investigation
FMVM	Fluid Merging Viscosity Measurement
FSB	fundamental space biology
GAP	group activation pack
GASMAP	gas analyzer system for metabolic analysis physiology
GCR	galactic cosmic ray
GLA	general lighting assembly
HDPCG	High-density Protein Crystal Growth
HDTV	high-definition television
HEPA	high-efficiency particulate accumulator
HiRAP	high-resolution accelerometer package
HIV	Human Immunodeficiency Virus
HLT	human lymphoid tissue
HPA	Hand Posture Analyzer
HRF	Human Research Facility
IAA	International Academy of Astronautics
ICE	ISS Characterization Experiment
ICES	International Conference on Environmental Systems
ICM	isothermal containment module
IFRECOR	l'Initiative Française pour les Récifs Corallines
InSb	indium antimonide
InSPACE	Investigating the Structure of Paramagnetic Aggregates from Colloidal Emulsions
IR	infrared
ISS	International Space Station
ISSI	In-space Soldering Experiment
IVA	intravehicular activity
IZECS	Improved Zeolite Electronic Control System
JES	joint excursion sensor
K-cit	potassium citrate
KSC	Kennedy Space Center

LAN	local area network
LBNP	lower body negative pressure
LCD	liquid crystal display
LDL	low-density lipoprotein
LEMS	lower extremity monitoring suit
LET	linear energy transfer
LLC	limited liability company
MACE-II	Middeck Active Control Experiment-II
MAMS	microgravity acceleration measurement system
mBAND	Multicolor Banding Fluorescence In-Situ Hybridization
MBP	multi-body platform
MDU	mobile dosimetry unit
MEPS	microcapsulation electrostatic processing system
MESA	miniature electro-static accelerometer
MeV	million electron volts
mFISH	Multicolor Fluorescence In-Situ Hybridization
MFMG	Miscible Fluids in Microgravity
MISSE	Materials International Space Station Experiment
MIT	Massachusetts Institute of Technology
ML-I	mistletoe lectin-I
MnSOD	manganese superoxide dismutase
MOSFET	metal oxide semiconductor field effect transistor
MPV	Meerwein-Pohhdorf-Verley
MR	magnetorheological
mRNA	messenger ribonucleic acid
MSFC	Marshall Space Flight Center
MSG	microgravity sciences glovebox
NOAA	National Oceanic and Atmospheric Administration
NTDP	nuclear tracking detector package
OPG	osteoprotegerin
OTc	heart-rate-corrected objective test interval
PCAM	Protein Crystallization Apparatus for Microgravity
PCG-EGN	Protein Crystal Growth-Enhanced Gaseous Nitrogen
PCG-STES	Protein Crystal Growth-Single Locker Thermal Enclosure System
PCG-STES-IDQC	PCG-STES Improve the Diffraction Quality of Problematic Biomacromolecular Crystals
PCG-STES-IMP	PCG-STES Integral Membrane Protein
PCG-STES-MM	PCG-STES Mosaicity Measurements
PCG-STES-MMTP	PCG-STES Mitochondrial Metabolite Transport Proteins
PCG-STES-MS	PCG-STES Material Science
PCG-STES-RDP	PCG-STES Ribozyme for Diffraction Properties
PCG-STES-RGE	PCG-STES Regulation of Gene Expression
PCG-STES-SA	PCG-STES Science and Applications
PCG-STES-VEKS	PCG-STES Vapor Equilibrium Kinetic Studies
PCS	Physics of Colloids in Space
PESTO	Photosynthesis Experiment and System Testing and Operation
PFMI	Pore Formation in Microgravity
PGC	plant growth chamber
PGBA	Plant Generic Bioprocessing Apparatus
PPG <sup>10</sup>	(Pro-Pro-Gly) <sup>10</sup>
PRDX5	peroxiredoxin 5
PS	physical science
PuFF	Pulmonary Function in Flight

QCT	quantitative computed tomography
QTCMA	Quad Tissue Culture Module Assembly
QUS	quantitative ultrasound
RNA	ribonucleic acid
RPA	Replication Protein A
RPI	Rensselaer Polytechnic Institute
RPM	revolutions per minute
rRNA	ribosomal ribonucleic acid
RTS	remote triaxial sensor
RWV	rotating wall vessel
SAA	South Atlantic Anomaly
SAE	Society of American Engineers
SAME	Smoke and Aerosol Measurement Experiment
SAMS-II	Space Acceleration Measurement System-II
SCN	succinonitrile
SeaWiFS	sea-viewing wide field-of-view sensor
SEEDS	Space Exposed Experiment Development for Students
SEM	Space Experiment Module
SF	space flight
SGSM	slow growth sample module
SMADOS	small active dosimeters
SNFM	Serial Network Flow Monitor
Sn-Pb	tin-lead
SOD	superoxide dismutase
SPD	space product development
SPE	solar particle event
SPHERES	Synchronized Position Hold, Engage, Reorient, Experimental Satellites
STES	Single-locker Thermal Enclosure System
SUBSA	Solidification Using Baffle in Sealed Ampoules
Sv	sieverts
TCM	tissue culture module
TCS	thermal control system
TEPC	tissue equivalent proportional counter
TF-FGI	total force-foot ground interface
TLD	thermoluminescence dosimeter
tRNA	transfer ribonucleic acid
TVIS	treadmill vibration isolation system
US	ultrasound
VEE	Venezuelan Equine Encephalitis
VTR	videotape recorder
ZCG	Zeolite Crystal Growth



# INTRODUCTION

The launch of Expedition 1 to the International Space Station (ISS) opened a new chapter in the history of human space flight and international cooperation. Permanent human presence on board ISS began with the arrival of Bill Shepard, Sergei Krikalev, and Yuri Gidzenko on Nov 2, 2000. The first ten Expeditions marked a period of initial assembly, daily operations, and scientific activities. The completion of Expedition 10 on Apr 25, 2005 marked 1635 days (four and a half years) of continuous crewed operations.

Although construction and maintenance of the space station has been the primary objective during these early years, a wide range of research projects has also been conducted on board ISS. Twenty-six astronauts and cosmonauts have occupied ISS through Expedition 10, with stays ranging from four to six months. Crewmembers of the first ten Expeditions have completed work on 85 formal U.S. experiments—some over multiple years and crews. Expedition crews conduct science daily across a wide variety of fields including human research, physical and life sciences, technology demonstrations, Earth observations, and education activities.



STS113-336-015 — Backdropped by a blue-and-white-Earth, this full view of ISS was photographed by a crewmember on board space shuttle *Endeavour* following the undocking of the two spacecraft. *Endeavour* pulled away from the complex on December 2, 2002 as the spacecraft flew over northwestern Australia.

During these first ten Expeditions, events shaped the ability and capacity of the ISS for performing space research, as well as the focus of the ISS research itself.

- The ISS has been under continuous assembly during this time period, and is approximately 60% complete at this writing. The U.S. Destiny laboratory was deployed in early 2001. Major research outfitting includes five multipurpose ExPRESS [Expedite the Processing of Experiments to Space Station] racks and two Human Research Facility racks (the second brought in July 2005).
- The space shuttle fleet was grounded following the *Columbia* accident, halting ISS assembly. Prior to the *Columbia* accident, more than 6600 kg (14,600 lbs) of research equipment and facilities had been brought to ISS. Between the accident and the return to flight of the space shuttle *Discovery* in July 2005, 75 kg (165 lbs) of research supplies had been brought up on Russian Progress and Soyuz vehicles. The crew of the ISS was also reduced from three to two, and the research program was drastically adjusted to accommodate these changes.
- The focus of NASA's ISS research has changed strategically to support the *Vision for Space Exploration* announced by the President on Jan 14, 2004. While still including some fundamental research in micro-gravity, emphasis has shifted from fundamental studies of space phenomena to programs targeted at reducing the risks to Exploration missions to the moon, Mars, and beyond.

This report summarizes the NASA research accomplishments on ISS through the first ten Expeditions. When the research programs for the early Expeditions were established, five administrative organizations were executing research on ISS: bioastronautics research, fundamental space biology, physical science, space product development, and space flight. The *Vision for Space Exploration* has led to changes in NASA's administrative structures, and so we have grouped experiments topically by their scientific themes, even when these do not correspond to the administrative structure at the time at which they were completed. The research organizations at the time at which the experiments flew are preserved in the appendix of this document.

By scientific theme, the investigations are collected as follows:

- Human Research for Exploration—human medical research to develop the knowledge needed to send humans on Exploration missions beyond Earth orbit. These studies focused on the effect of living in space on human health and countermeasures to reduce health risks incurred by living in space in future. Areas of emphasis included physiological studies related to the effects of microgravity on bone and muscle, other physiological effects of space flight, psycho-social studies, and radiation studies.
- Physical and Biological Sciences—studies of physics, chemistry, biology, and other using microgravity conditions to gain insight into the effect of the space environment on living organisms. Areas of emphasis included growth of proteins and crystals in microgravity, physical properties in microgravity, cellular biology and biotechnology, and plant biology.
- Technology Development—studies tested and established new technologies for use in future Exploration missions. Areas of emphasis included spacecraft materials and systems, and characterization and control of the microgravity environment on ISS.
- Observing the Earth and Educating and Inspiring the Next Generation—these activities and investigations allowed students and the public to connect with the ISS mission, inspired students to excel in science, technology, engineering and math, and shared the astronauts' unique view of the Earth system with scientists and the public. A detailed summary of all educational activities on ISS is also available (Thomas et al. 2006).

These early investigations on ISS have laid the groundwork for research planning for the Expeditions to come. Humans performing scientific investigations on ISS, even while they test new hardware and build and maintain a livable habitat, serve as a model for the goals of future Exploration missions. The success of a wide variety of investigations is an important hallmark of early research on ISS. Of the investigations summarized here, some are completed with results released, some are completed with preliminary results, and some remain ongoing. For each case we provide an overview of the research objectives and the results returned through Expedition 10, and indicate whether additional activities were completed on Expeditions 11 and 12 or were planned for future ISS missions at the time of writing. Investigations are arranged topically within the four major research thrusts listed above, and alphabetically within each topical section. For interested readers, the appendix provides a chronological listing of investigations performed in each Expedition.

During the first ten Expeditions, a number of reviews and updates on ISS science have been written (Pellis et al. 2003, Rhatigan 2003, Rhatigan et al. 2005, Robinson et al. 2005, Robinson and Thomas 2006). This NASA Technical Publication is intended to provide an archival record of United States-sponsored ISS research accomplished through Expedition 10, both as part of formal investigations or “payloads” and from early scientific analysis of data collected as part of operating ISS. Additional research conducted independently by the International Partners on ISS, especially the Russian Space Agency and European Space Agency, is not included. Results from many of the investigations summarized continue to be released. Continuously updated information on ISS research and results is available on the NASA Portal at <http://exploration.nasa.gov/programs/station/>.

## REFERENCES

Pellis NR, North RM. Recent NASA Research Accomplishments Aboard ISS. 54<sup>th</sup> International Astronautical Congress of the International Astronautical Federation, the IAA, and the International Institute of Space Law, Bremen, Germany. IAC-03-T.4.07, Sep 29–Oct 3, 2003.

Rhatigan J. Research Accomplishments on the International Space Station. AIAA/ICAS International Air and Space Symposium and Exposition: The Next 100 Years, Dayton, Ohio. AIAA 2003-2703, 2003.

Rhatigan JL, Robinson JA, Sawin CF. Exploration-Related Research on ISS: Connecting Science Results to Future Missions. NASA/TP-2005-213166. 1–34, 2005. (Also published at the 44<sup>th</sup> AIAA Meeting, 2006-344, 2006.)

Robinson JA, Rhatigan JL, Baumann DK. Recent Research Accomplishments on the International Space Station. Proceedings of the IEEE Aerospace Conference, Big Sky, Mont. Paper no. 310, Mar 5–12, 2005.

Robinson JA., Thomas DA. NASA Utilization of the International Space Station and the *Vision for Space Exploration*, ISTS 2006-o-1-06, International Symposium on Space Technology and Science, Kanazawa, Japan, Jun 4–10, 2006, pp. 1–6.

Thomas DA, Robinson JA, Tate J, Thumm T. Inspiring the Next Generation: Student Experiments and Educational Activities on the International Space Station, 2000–2006. NASA/TP-2006-213721. Lyndon B. Johnson Space Center, Houston, Texas, 108 pp., 2006.



STS114-E-7221 — Backdropped against the Caspian Sea, this full view of ISS was photographed by a crewmember on board space shuttle *Discovery* after the undocking of the two spacecraft in August 2005.



## **HUMAN RESEARCH AND COUNTERMEASURE DEVELOPMENT FOR EXPLORATION**

*ISS is being used to study the risks to human health that are inherent in space exploration. Focal research questions address the mechanisms of the risks and develop and test countermeasures to reduce these risks. Research on space station addresses the major risks to human health from residence in a long-duration microgravity environment. Results from this research are key enablers for missions to the lunar surface and future Mars Exploration missions.*

## **PHYSIOLOGICAL STUDIES— BONE AND MUSCLE**

*When astronauts spend months in a microgravity environment, they experience significant physiological effects on bone, muscle, and calcium. The primary countermeasure to loss of bone and muscle while on space station has been exercise. Exercise equipment deployed on ISS is more mature and the prescribed exercise regimens are more rigorous than for any previous U.S. space flights. Early station studies have evaluated effects of long-duration space flight on bone and muscle in the context of these exercise protocols. The transit to Mars from Earth will be equivalent in duration to the typical six-month space station Expedition. This allows us to draw insight into the health status that can be expected when a crew lands on Mars.*

## EFFECT OF PROLONGED SPACE FLIGHT ON HUMAN SKELETAL MUSCLE (BIOPSY)

Principal Investigator(s): Robert Fitts, Marquette University, Milwaukee, Wis.  
Expeditions 5–7, 9–11

**Research Area** Human Research for Exploration



It is well established that space flight can result in loss of skeletal muscle mass and strength. This atrophy continues throughout a crew's mission, even if crewmembers adhere to a strict exercise regime. What researchers do not understand, however, are the effects that prolonged stays in microgravity have on skeletal muscles. Biopsy will evaluate changes in calf muscle function over long-duration space flights (30 to 180 days).

ISS004E6331 – Expedition 4 commander Yury Onufrienko exercises on a treadmill in the Zvezda service module.

In Biopsy, a specially designed torque velocity dynamometer is used to measure muscle strength before and after flight. Biopsies are also taken from the soleus and gastrocnemius muscles of participants. This allows determination of the cell size and the structural properties of individual fast and slow muscle fibers. Chemical analysis of the biopsies determines muscle fiber structural changes involving myosin, a protein “molecular motor” that drives muscle contractions and cell divisions, enzymes, and substrates. Electron microscopy determines the relationship between thick and thin filament, the amount of myofilament loss, and changes in membrane-associated protein complexes found in skeletal muscle fibers and connective tissue that help the muscle resist stretch-induced damage.

### RESULTS

Preliminary results were presented at the 2004 American Physiological Society Intersociety Meeting: Integrative Biology of Exercise in three abstracts (see Publications on next page). Summarizing data collected from the first five subjects, microgravity produced a 47% decrease in the peak power of postflight muscle fiber samples compared to preflight muscle fiber samples. This decrease was due to the combined effects of reduced fiber size and a decline in the size of the myofibrils that make up the fiber.

Further examination of the data collected from the crew indicated that astronauts who performed high treadmill exercise (greater than 200 minutes/week) vs. low treadmill exercise (less than 100 minutes/week) exhibited a smaller decrease in peak power. Astronauts who performed high treadmill exercise showed a 13% decrease compared to a 51% decrease in peak power of astronauts who performed low treadmill exercise. Sample analysis of the muscle fibers indicated that the ratio of myosin and actin proteins in the muscle fibers was not affected by long-duration space flight. Although exercise slowed the onset of atrophy and loss of strength in muscle fibers, a significant amount of muscle volume and strength loss still occurred on long-duration missions.

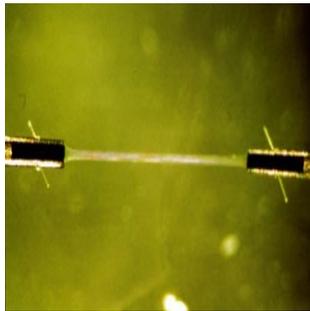
Of the exercise countermeasures currently being employed, treadmill exercise appeared the most effective in protecting the calf muscles from loss of strength and atrophy. Final publication is pending the collection of data from the final subjects during Expedition 11.

## PUBLICATION(S)

Fitts RH, Romatowski JG, Lim W-M, Gallagher P, Trappe S, Costill D, Riley DA. Microgravity, exercise countermeasures, and human single muscle fiber function (Abstract). Paper 21.16, American Physiological Society Intersociety Meeting: Integrative Biology of Exercise. *The Physiologist*. 47(4):320, 2004.

Gallagher P, Trappe S, Costill D, Riley DA, LeBlanc A, Evans H, Peters JR, Fitts RH. Human muscle volume and performance: the effect of 6-mo of microgravity (Abstract). Paper 21.19, American Physiological Society Intersociety Meeting: Integrative Biology of Exercise. *The Physiologist*. 47(4):321, 2004.

Riley DA, Bain JL, Gallagher P, Trappe S, Costill D, Fitts RH. The effect of 6-mo microgravity on human skeletal muscle structure (Abstract). Paper 21.17, American Physiological Society Intersociety Meeting: Integrative Biology of Exercise. *The Physiologist*. 47(4):320, 2004.



A single muscle fiber. Each muscle is composed of thousands of these fibers. Samples of muscle fibers will be extracted and tested as part of the Biopsy experiment.

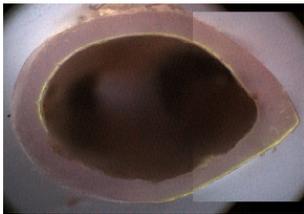
## COMMERCIAL BIOMEDICAL TESTING MODULE (CBTM): EFFECTS OF OSTEOPROTEGERIN (OPG) ON BONE MAINTENANCE IN MICROGRAVITY

Principal Investigator(s): Ted Bateman, BioServe Space Technologies, Boulder, Colo.  
Expedition 4

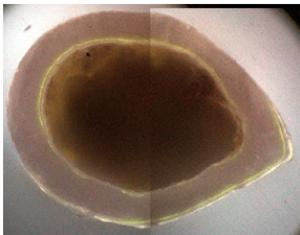
### Research Area Human Research for Exploration

Osteoporosis is a debilitating disease that afflicts millions worldwide. One of the physiological changes experienced by space crews during space flight is the accelerated loss of bone mass due to the lack of gravitational loading on the skeleton—a loss that is similar to that experienced by the elderly population on Earth. Osteoprotegerin (OPG), which is a bone metabolism regulator, is being evaluated by the Food and Drug Administration (FDA) as a new treatment for osteoporosis.

The Commercial Biomedical Testing Module (CBTM) examined the effects of OPG on bone maintenance in space using aged mice (older than nine months) as test subjects. The bone changes observed in older mice more closely reflect the bone changes observed in older humans. The mice were housed in three animal enclosure modules (AEMs), which provide the animal subjects with everything necessary to maintain health. Half of the mice were treated with OPG, a novel protein that regulates bone resorption, and half were treated with a placebo.



Fluorescent image of femur diaphysis from space flight placebo-treated mouse, indicating greatly decreased bone formation (calcein label indicates where bone was forming at the time of launch, which allows quantification of bone formation rates during flight).



Fluorescent image of femur diaphysis from ground control placebo-treated mouse, indicating greatly decreased bone formation (calcein label indicates where bone was forming at the time of launch, which allows quantification of bone formation rates during flight).

### RESULTS

During ISS Expedition 4, 24 female mice were flown to ISS on shuttle flight STS-108 in three AEMs. The AEMs remained on STS-108 throughout the 12-day mission.

Mice exposed to microgravity exhibited a 15–20% decline in femur elastic strength and a 40–60% decrease in bone formation when compared to the controls. The femur elastic strength decline was caused by three mechanisms: reduced bone formation, increased bone resorption, and inhibition of mineralization. Mice exposed to microgravity treated with OPG exhibited no discernable decline in femur elastic strength, and bone resorption was significantly increased (Bateman 2004). Mechanical testing data were complimented by serum, messenger ribonucleic acid (mRNA), and histological analyses that indicated a decline in bone formation and an increase in bone resorption in addition to an inhibition of mineralization. OPG mitigated the decline in mechanical strength by preventing increase in resorption and maintaining mineralization. In addition to this detailed analysis of skeletal properties, a secondary analysis of calf muscles from placebo-treated specimens was performed to collect baseline data to validate space-flown mice as an appropriate model for sarcopenia (age-related muscle loss). Space flight caused a 15–30% decline in muscle fiber diameter size compared to appropriate ground controls (Harrison et al. 2003).

Data obtained from the mice following return to Earth indicated some alternations in immune functions. Analysis of the spleenocytes (immune cells produced by the spleen) indicated an increase in B-cell (white blood cell that matures in the bone marrow and, when stimulated by an antigen, differentiates into plasma cells) production compared to T-cells (white blood cells that complete maturation in the thymus and have various roles in the immune system). A slightly lower white blood-cell count in the flight animals compared to the controls was not statistically significant. The spleen mass was 18–28% lower in flight mice compared to controls. Results also indicated that flight mice weighed 10–12% less than ground controls (Pecaut et al. 2003).

The ability to survive a major physical trauma in microgravity may be compromised due to an altered immune system. Platelets (constituent of blood that promotes clotting at the site of injury) are the primary cells involved in the wound healing process. The animals studied had significantly higher platelet levels but low volume compared to the controls. This indicates that the lack of platelets in the wound healing process is not a problem, but that platelets formed in microgravity have a decreased functionality in the wound healing process. Data indicated that a short stay in microgravity can induce significant changes in immune defense mechanisms, hematopoiesis (blood cell formation), and other aspects of health (Gridley et al. 2003).

#### **PUBLICATION(S)**

Bateman TA, Morony S, Ferguson VL, Simske SJ, Lacey DL, Warmington KS, Geng Z, Tan HL, Shalhoub V, Dunstan CR, Kostenuik PJ. Molecular therapies for disuse osteoporosis. *Gravitational and Space Biology Bulletin*. 17:83–89, 2004.

Gridley DS, Nelson GA, Peters LL, Kostenuik PJ, Bateman TA, Morony S, Stodieck LS, Lacey DL, Simske SJ, Pecaut MJ. Genetic models in applied physiology: selected contribution: effects of spaceflight on immunity in the C57BL/6 mouse. II. Activation, cytokines, erythrocytes, and platelets. *Journal of Applied Physiology*. 94(5):2095–2103, 2003.

Harrison BC, Allen DL, Girten B, Stodieck LS, Kostenuik PJ, Bateman TA, Morony S, Lacey DL, Leinwand LA. Skeletal muscle adaptations to microgravity exposure in the mouse. *Journal of Applied Physiology*. 95(6):2462–2470, 2003.

Pecaut MJ, Nelson GA, Peters LL, Kostenuik PJ, Bateman TA, Morony S, Stodieck LS, Lacey DL, Simske SJ, Gridley DS. Genetic models in applied physiology: selected contribution: effects of spaceflight on immunity in the C57BL/6 mouse. I. Immune population distributions. *Journal of Applied Physiology*. 94(5):2085–094, 2003.

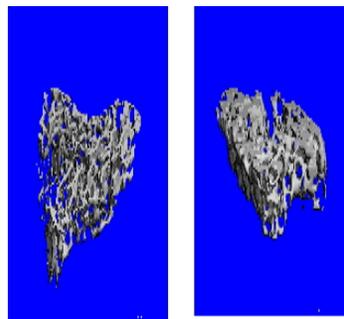


Image on the left shows a microCT image of trabecular bone from proximal tibia from space flight mouse compared to ground control mouse on right.

## FOOT/GROUND REACTION FORCES DURING SPACE FLIGHT (FOOT)

Principal Investigator(s): Peter R. Cavanagh, The Cleveland Clinic Foundation, Cleveland, Ohio  
Expeditions 6, 8, 11, 12

### Research Area Human Research for Exploration

The human body is designed to bear weight. Without the stimulation caused by placing weight on lower extremities, whether due to the microgravity environment or lack of use on Earth, bone will lose mass and muscles will lose strength. The Foot experiment characterizes the load placed on lower extremities during daily activities on station and examines to what degree mechanical load stimulus, via an in-flight exercise routine, could prevent the muscle atrophy and bone loss associated with space flight.

To achieve this, Foot has several sensors mounted in a special pair of Lycra exercise pants, the lower extremity monitoring suit (LEMS). The total force-foot ground interface (TF-FGI) serves as an insole that, when placed inside a shoe, measures the amount of force placed on the bottom of the foot. Joint excursion sensors (JESs) record joint angles at the ankle, knee, and hip. Electromyography (EMG) electrodes record muscle activity, including net neural drive, along the leg (the vastus medialis, rectus femoris, biceps femoris, gastrocnemius, and tibial anterior) and in the right arm (the biceps brachii and triceps brachii). Information is collected by an ambulatory data acquisition system and downloaded into the Human Research Facility (HRF) laptop on board ISS after each session.

### RESULTS

Results provide insight into the processes of loss of bone mineral density and muscle mass during long-duration stays on orbit. Knee-joint motion in space is reduced compared to that on Earth, and this has an effect on muscle action. In preliminary data analyses of the first subject, significant loss of bone mass was observed. Measurements of forces during exercise suggested that much less force was experienced than would be experienced when exercising on Earth. Detailed data were collected on loads across all exercise hardware settings during Expeditions 11 and 12. Final analysis will help in determining exercise prescriptions for station crewmembers and in the design of future exercise devices for Exploration missions.

### PUBLICATION(S)

Cavanagh PR, Maender C, Rice AJ, Gene KO, Ochia RS, Snedeker JG. Lower-Extremity Loading During Exercise on the International Space Station. Transactions of the Annual Meeting of the Orthopaedic Research Society 0395, 2004.

Pierre MC, Gene KO, Litow M, Humphreys B, Rice A, Maender CC, Cavanagh PR. Comparison of Knee Motion on Earth and in Space: An Observational Study. *Journal of NeuroEngineering and Rehabilitation*. 3:8, 2006.



ISS006E11011 — View of the body harness for the treadmill vibration isolation system (TVIS) and the LEMS for the Foot experiment in the Zvezda service module. The apparatus is shown worn by Expedition 6 commander Ken Bowersox.



ISS006E11018 — Expedition 6 commander Kenneth Bowersox, wearing a body harness, runs on the TVIS as part of the Foot experiment in the Zvezda service module.

## EFFECTS OF ALTERED GRAVITY ON SPINAL CORD EXCITABILITY (H-REFLEX)

Principal Investigator(s): Douglas Watt, McGill University, Montréal, Canada  
Expeditions 2–4

### Research Area Human Research for Exploration

In the weightlessness of low Earth orbit, the body loses muscle mass and bone density. The only known countermeasure for this atrophy is exercise. However, as astronauts spend longer durations in space, will exercise continue to be an effective countermeasure? Along with changes in muscle and bone, the neurovestibular system (the complex sensory system that maintains posture, balance, and coordination) adapts to changes in gravity. Researchers hypothesize that, as part of this neurovestibular system adaptation, spinal cord excitability decreases and the spinal cord reacts less to stimuli. If this hypothesis is correct, exercise may become less effective the longer astronauts stay in microgravity, and researchers may have to adjust exercise programs accordingly.

H-Reflex tested this hypothesis by measuring muscle response to mild electrical shocks (40–90 volts). Nerves in the leg perceive the electrical shock and send a signal along the spinal cord to the brain. The signal stimulates motoneurons in the brain, which, in turn, send signals that cause leg muscles to contract. The bigger the contraction, the more the neurons are stimulated, indicating the level of spinal cord excitability. Researchers compared measurements taken before, during, and after flight to determine whether the spinal cord's ability to respond to stimuli changed over time. The H-Reflex equipment recorded the EMG activity in the muscle—the electrical activity that caused the muscle to move—rather than the movement that follows the electrical activity (as a knee-tap test would), allowing researchers to take more precise measurements.

### RESULTS

This study of spinal cord excitability using the Hoffman reflex was completed by a total of eight subjects over ISS Expeditions 2–4. H-Reflex measured how excitable the nerve cells were by applying small electrical shocks behind the knee. Each shock produced a reflex response in the calf muscles (the H-reflex response); the data collected indicated that this response decreased significantly while in microgravity. The study found that spinal cord excitability decreased by about 35% in weightlessness, and stayed at this new level for the duration of the mission. Although there was notable improvement in the H-reflex response the day after landing, it took about ten days back on Earth for astronauts to fully recover their muscle strength and spinal cord excitability (Watt and Lefebvre 2001; Watt 2003). Additional analysis and final publication of results is pending.

This difference in excitability means that only a portion of muscle fiber units are contracting in response to signals from the nervous system and explains functionally why muscle mass declines in weightlessness, even with exercise. Reduced excitability means that there might be limits on the degree to which heart muscle strength, leg muscle tone, and bone density (for which muscle contraction is an important regulating factor) can be maintained through exercise on long-duration missions. Because this decrease in excitability is only observed on orbit and not during bed rest, an analogue for weightless space travel, the results highlight the possibility that reduced excitability with corresponding loss of muscle and bone might be partly a nervous system response and not simply due to disuse of the legs.



ISS003-330-006 — Cosmonaut Vladimir Dezhurov on ISS Expedition 3 performing H-Reflex activity in the U.S. Destiny laboratory.

Based on the results of this study, decreased spinal cord excitability could be an issue for long-duration stays in partial-gravity environments such as are found on the moon and Mars. Future designs of exercise equipment that provide feedback on work actually performed would help crewmembers compensate for decreases in exercise efficiency.

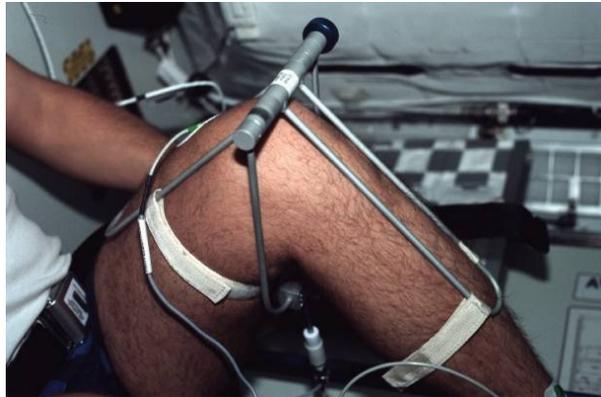
#### **PUBLICATION(S)**

Watt DG, Lefebvre L. Effects of altered gravity on spinal cord excitability. First Research on the International Space Station, Conference and Exhibit on International Space Station Utilization, Cape Canaveral, Fla. AIAA 2001-4939, Oct 15–18, 2001.

Watt DG. Effects of altered gravity on spinal cord excitability (final results). Proceedings of the Bioastronautics Investigators' Workshop, Galveston, Texas. Jan 2003.

Watt DG. Effects of prolonged exposure to microgravity on H-reflex loop excitability. Proceedings of the 14<sup>th</sup> IAA Humans in Space Symposium, Banff, Alberta, Canada. May 2003.

ISS003003011 — Close-up of H-Reflex hardware on the knee of cosmonaut Vladimir Dezhurov during ISS Expedition 3.



Still frame from a video of Expedition 2 showing astronauts Jim Voss and Susan Helms performing the H-Reflex experiment in the shuttle middeck.

## HAND POSTURE ANALYZER (HPA)

Principal Investigator(s): Valfredo Zolesi, Kayser Italia SRL, Livorno, Italy  
Expeditions 7, 8, 11

### Research Area Human Research for Exploration

The Hand Posture Analyzer (HPA) examines the way hand and arm muscles are used differently during grasping and reaching tasks in weightlessness. Measurements are compared to those taken both before and after flight. In this way, the HPA study will lead to a better understanding of the effects of long-duration space flight on muscle fatigue.

### RESULTS

The HPA was launched to ISS on 12 Progress in August 2003, and was performed during Expeditions 7 and 8 on ISS by astronauts Ed Lu and Michael Foale. Data from six HPA sessions were collected during Expedition 7 from one crewmember; two preflight collections, two in-flight collections, and two postflight collections. At the end of Expedition 10, European Space Agency (ESA) astronaut Roberto Vittori performed in-flight data collection with the HPA hardware. These data are being combined with data from the preliminary version of the same hardware (CHIRO) that was used on board ISS during an earlier “Marco Polo” mission with astronaut Roberto Vittori in 2002. Together, these experiments assessed the short- and long-term effects of weightlessness on upper limb performance. Additional data collection is planned for future flights.



ISS008E21605 — NASA science officer Mike Foale, was photographed during ISS Expedition 8 as he used hand/wrist position tracking via the hand posture acquisition glove during HPA operations.



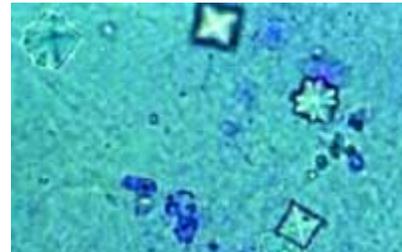
Hand grip dynamometer used for the muscle fatigue experiment that was part of the HPA investigation on board station.

## RENAL STONE RISK DURING SPACE FLIGHT: ASSESSMENT AND COUNTERMEASURE VALIDATION (RENAL STONE)

Principal Investigator(s): Peggy A. Whitson, NASA Johnson Space Center, Houston, Texas  
Expeditions 3–6, 8, 11, 12, ongoing

### Research Area Human Research for Exploration

The loss of calcium from bone combined with decreased fluid intake in flight increases the probability for kidney stone formation during and after flight. Development of a kidney (or renal) stone in an astronaut can have serious consequences since it cannot be treated in flight as it would be on the ground. Therefore, quantification of renal stone formation potential and recovery is necessary to reduce this risk. This study studies the potential development of renal stones in space crews and the efficacy of a pharmaceutical countermeasure.



This micrograph shows calcium oxalate crystals in urine. These small crystals can develop to form renal stones.

Potassium citrate (K-cit) is a proven ground-based treatment for patients suffering from renal stones. In this study, from three days before launch and continuing through 14 days after landing each crewmember takes either two K-cit tablets or two placebos daily. They collect urine samples during 24-hour periods when in flight, once at the beginning, midway point, and end of a mission. In addition to taking pills and collecting urine samples, crewmembers maintain handwritten logs of their daily food and fluid intake, exercise, and medication during the time of the urine collections. These log books act as a backup to the barcode reader records that are part of the inventory management system with which crews typically record food intake and medication.

Ultimately, these data will not only help long-duration space flight crews but also will aid those on Earth in understanding how renal stones form in otherwise healthy persons. This should also provide insight into stone-forming diseases on Earth.

### RESULTS

Urine samples were collected and analyzed before, during, and after flights, as was dietary information from crewmembers. Since the experiment design calls for the combination and comparative analysis of data from all Expeditions, final results are not yet available.



ISS011E13500 — ISS commander Sergei Krikalev with Renal Stone sample collection hardware during ISS Expedition 11.

## SUBREGIONAL ASSESSMENT OF BONE LOSS IN THE AXIAL SKELETON IN LONG-TERM SPACE FLIGHT (SUBREGIONAL BONE)

Principal Investigator(s): Thomas F. Lang, University of California, San Francisco, Calif.  
Expeditions 2–8

### Research Area Human Research for Exploration

Bone loss is one of the known risks of exposure to reduced gravity—a risk that increases with the length of stay in that environment. Although healthy bone can repair damage done to itself, researchers are yet unsure how much bone is replaced after crewmembers return to Earth. Is bone mass recovered one year after flight? Is there a difference in the subregional distribution of bone prior to flight and one year after flight? Subregional Bone measured the amount of bone lost during space flight and recovered postflight in an effort to answer these questions.

Subregional Bone hardware consisted of several devices used before and after flight. Dual-energy X-ray absorptiometry (DEXA) provided a two-dimensional measurement of the entire bone mass of the hip, spine, and heel. These measurements were compared to quantitative computed tomography (QCT), which examined cortical (the bone's dense outer layer) and trabecular (the bone's inner, spongy looking layer) bone separately and three-dimensionally to determine the extent of bone loss in the hip and spine. QCT measurements allow researchers to determine whether loss is localized in a subregion of the bone. DEXA and QCT measurements were also compared to quantitative ultrasound (QUS) of the heel to evaluate ultrasound as a possible alternative to X-ray measurements.



DEXA scan of a human hip

### RESULTS

This experiment determined the distribution of bone loss in the spine and hip in long-duration space flight using QCT and assessed how bone is recovered after return. One of the first Bioastronautics research investigations to begin on ISS, this study recruited 14 subjects between Expedition 2 and Expedition 8. The first publication in the *Journal of Bone and Mineral Research* included eight subjects who had been back long enough to measure their bone density one year postflight. On ISS, bone mineral density was lost at an average rate of about 0.9% per month in the lumbar spine and 1.4% per month in the femoral neck. For comparison, a post-menopausal woman experiences losses of bone mineral on the order of 1% per year. The experiment provides insight into the process of bone loss because it is the first study to differentiate the loss in the cortical bone (the outer part of the bone) and the trabecular bone (the inner parts of the bone). For example, in the hip losses of mass in the cortical bone averaged around 1.6–1.7% per month whereas losses in the trabecular bone averaged 2.2–2.5% per month. Analyses of postflight measurements of bone recovery will soon be complete (Lang et al. 2004).

### PUBLICATION(S)

Lang T, LeBlanc A, Evans H, Lu Y, Gennant H, Yu A. Cortical and Trabecular Bone Mineral Loss from the Spine and Hip in Long-duration Spaceflight. *Journal of Bone and Mineral Research*. 19(6):1006–12, 2004.

## **PHYSIOLOGICAL STUDIES— OTHER EFFECTS OF SPACE FLIGHT**

*When astronauts move between different gravity environments a number of acute physiological responses can affect their health and performance. Studies of the process of adapting to changes in gravity are important for mission success for future Exploration missions as astronauts may transition from Earth to interplanetary transit, to the moon or Mars, and back. Other physiological changes in microgravity—from changes in immune function, pharmacology, and clinical diagnostic measures—are also key areas of study.*

## ADVANCED DIAGNOSTIC ULTRASOUND IN MICROGRAVITY (ADUM)

Principal Investigator(s): Scott A. Dulchavsky, Henry Ford Health System, Detroit, Mich.  
Expeditions 8–11

**Research Area** Human Research for Exploration



Screen shot of the ADUM on-board proficiency enhancer used to teach crewmembers how to conduct an ultrasound scan of a new organ or system.

Advanced Diagnostic Ultrasound in Microgravity (ADUM) tests the accuracy of using ultrasound technology in the novel clinical situation of space flight. This investigation includes assessing health problems in the eyes and bones, as well as sinus infections and abdominal injuries. ADUM further tests the feasibility of using an in-flight ultrasound to monitor bone density during long-duration space flights. Another objective of the experiment is determining how well nonmedical crewmembers can learn to use an ultrasound device with CD-ROM training manuals and remote guidance from Earth. The intent of the ADUM investigation is to develop methods by which an individual who is untrained in medicine can use an ultrasound machine with remote diagnostician assistance to evaluate a vast array of medical problems.

Expedition crews used the ISS HRF ultrasound machine and four scan sets: the cardio/thoracic scan, which focuses on the heart but also can scan the lungs; the abdominal/retro-peritoneal scan, which focuses on the organs of the abdomen, including the liver, spleen, kidneys, and bladder; the dental scan, which can image the mouth, teeth, gums, facial bones and sinuses, and eyes; and the bone scan, which images bones and characterizes bone loss during flight. In addition to the ultrasound machine and probes, another key component of ADUM on station is the on-board proficiency enhancer—a software application that is used to train crewmembers on the methods employed for each scan.

## RESULTS

The ISS crews, which began their work with ADUM on Expedition 8 and completed it during Expedition 11, have demonstrated that minimal training along with audio guidance from a certified sonographer can produce ultrasound imagery of diagnostic quality. The ISS crewmembers, acting as operators and subjects, have completed comprehensive scans of the cardiothoracic and abdominal organs as well as limited scans of the dental, sinus, and eye structures. They also have completed multiple musculoskeletal exams, including a detailed exam of the shoulder muscles. To date, analysis of ultrasound video downlinked to ground teams at the NASA Johnson Space Center TeleScience Center has yielded excellent results that are beginning to appear in the scientific literature.

Ultrasound technology is now used in many trauma centers around the world as a first-line diagnostic procedure with which to assess abdominal trauma and has been accurate when performed by non-radiologists. Expanding ultrasound technology use by non-radiologists in remote locations to provide diagnostic information on acute clinical conditions has been investigated by many researchers. The use of ultrasound technology as a diagnostic tool on station required an on-board proficiency enhancement program, visual cue cards, procedures, and direction from ground-based trained radiological personnel. The Expedition 8 crew was able to capture high-fidelity images of the thoracic, cardiac, and vascular systems with minimally trained nonmedical personnel. This investigation has laid the groundwork for using ultrasound as a diagnostic tool in microgravity and remote locations on Earth when a physician is not readily available. A scientific paper discussing these results was submitted by the crewmembers directly from orbit (Foale et al. 2005).

Ultrasound images of the shoulder during Expedition 9 showed that ultrasound performed by crewmembers obtained diagnostic-quality imagery for evaluation of shoulder integrity. An application of this technology would be if a crewmember were to injure his/her shoulder during a strenuous extravehicular activity (EVA, or spacewalk), these techniques would allow evaluation and diagnosis of possible injuries (Fincke et al. 2005).

Following a traumatic event to the head or face, eye examination is a very important component of the physical examination. This examination may be difficult due to significant orbital or facial swelling. The Expedition 10 crew used ultrasound technology to examine the eye through a closed eyelid. This examination could determine a number of problems with the eye that are signs of other more significant trauma of the head (Chiao et al. 2005).

In addition to the importance of establishing ultrasound techniques for examination and diagnosis on ISS, this study is establishing ultrasound as a key tool for clinical medicine on future vehicles, the moon, and eventually Mars. The success of ADUM may also lead to additional applications of ultrasound on Earth. The remote guidance paradigm can be adapted on Earth for patients in rural/remote areas, disaster relief, and the military. Using existing communication systems, a person (e.g., nurse, physician's assistant, military medic) who is minimally trained in ultrasound could perform an ultrasound exam on a patient with guidance from an expert at a medical facility hundreds or thousands of miles away. This would expand the tools for the rural medical community, provide the ability to triage a mass casualty, and help in the decisions to conduct medical transport of patients.



#### **PUBLICATION(S)**

Chiao L, Sharipov S, Sargsyan AE, Melton S, Hamilton DR, McFarlin K, Dulchavsky SA. Ocular examination for trauma; clinical ultrasound aboard the International Space Station. *Journal of Trauma*. 58(1):35–39, 2005.

Fincke EM, Padalka G, Lee D, van Holsbeeck M, Sargsyan AE, Hamilton DR, Martin D, Melton SL, McFarlin K, Dulchavsky SA. Evaluation of Shoulder Integrity in Space: First Report of Musculoskeletal US on the International Space Station. *Radiology*. 234(2):319–322, 2005.

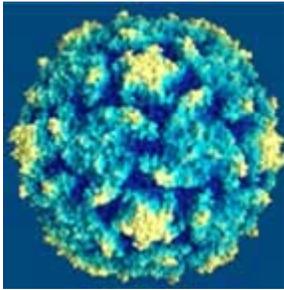
Foale CM, Kaleri AY, Sargsyan AE, Hamilton DR, Melton S, Margin D, Dulchavsky SA. Diagnostic instrumentation aboard ISS: just in time training for non-physician crewmembers. *Aviation Space and Environmental Medicine*. 76:594–598, 2005.

ISS010E18770 —ISS commander and science officer Leroy Chiao performs an ADUM scan on the eye of flight engineer Salizhan Sharipov during ISS Expedition 10.

## SPACE FLIGHT-INDUCED REACTIVATION OF LATENT EPSTEIN-BARR VIRUS (EPSTEIN-BARR)

Principal Investigator(s): Raymond Stowe, Microgen Labs, Galveston, Texas  
Expeditions 5–7, 11, 12, ongoing

**Research Area** Human Research for Exploration



A colored, scanning electron micrograph of an Epstein-Barr particle.

In the United States, approximately 95% of adults have been infected with Epstein-Barr Virus (EBV), one of the most common of human viruses and a member of the herpes virus family. EBV is an initial infection that establishes a lifelong dormant infection inside the body that can be reactivated by illness or stress. Once active, EBV causes infectious mononucleosis, cancers, and other disorders associated with the lymphatic system in people with a compromised immune system.

Decreased cellular immune function, likely caused by a combination of the microgravity environment and the stresses associated with a mission, is experienced by astronauts in space flight. With longer-duration missions, it is hypothesized that latent viruses are more likely to be reactivated, placing the crew at risk of developing and spreading infectious illnesses and jeopardizing the mission. Preliminary studies of astronauts have shown increased EBV shedding (the means by which viruses reproduce) in the saliva and increased antibody titers to the virus's proteins.

This study is examining the levels to which the crew's immune systems are suppressed during space flight and identifying conditions under which the virus will reactivate. To conduct Epstein-Barr, investigators collect urine and blood samples preflight and again postflight. The samples are analyzed for stress hormones and cytokines (messengers of the immune system), EBV replication, and virus-specific T-cell immune function. Epstein-Barr will determine the levels to which the crew's immune systems are suppressed during space flight and identify conditions under which EBV will reactivate. The investigators will analyze stress hormones and cytokines, which are the messengers of the immune system. They will also analyze EBV replication and determine virus-specific T-cell immune function.

### RESULTS

This experiment is still being conducted aboard the ISS. Earlier studies aboard space shuttle, which were the predecessors to this one, suggested that virus reactivation results from decreased T-cell function. If Epstein-Barr yields similar results, it will allow for a very specific focus on developing drug therapies that will allow for more rapid treatment for space travelers as well as for those on Earth.

## POSTFLIGHT ORTHOSTATIC HYPOTENSION (MIDODRINE)

Principal Investigator(s): Janice Meck, NASA Johnson Space Center, Houston, Texas  
Expedition 5, ongoing

### **Research Area** Human Research for Exploration

Many astronauts experience postflight orthostatic hypotension, a condition where the blood pressure drops when an individual stands up, resulting in presyncope (lightheadedness) or syncope (fainting). Approximately 20% of crews on short-duration missions and 83% of crews on longer-duration missions experience some degree of orthostatic intolerance after return to Earth. To date, the countermeasures tested—such as fluid loading, the use of lower body negative pressure (LBNP), and Fluronef—have not successfully eliminated postflight orthostatic hypotension.

On Earth, the drug Midodrine has been used extensively to treat low blood pressure. This investigation studies the effectiveness of Midodrine for the treatment of postflight orthostatic hypotension (dizziness or faintness following space flight). Midodrine has been previously tested as a pharmaceutical countermeasure by shuttle crewmembers. This experiment is the first test of the effectiveness of Midodrine following longer-duration flights.

### **RESULTS**

Midodrine has been shown to successfully reduce orthostatic hypotension in patients on Earth, as orthostatic hypotension affects people other than astronauts. To date, this investigation has been performed on some space shuttle crewmembers and on an Expedition 5 crewmember. Further Expeditions will involve testing on more subjects before conclusive results can be determined.



MSFC-0302205 — Posed inside Soyuz TMA-3 vehicle in a processing facility at Baikonur Cosmodrome, Kazakhstan, during a prelaunch inspection are (shown left to right): Expedition-8 crewmembers Michael C. Foale, mission commander and NASA ISS science officer; cosmonaut Alexander Y. Kaleri, Soyuz commander and flight engineer; and ESA astronaut Pedro Duque of Spain. Tight quarters, body position, entry suits, and G-forces all affect blood fluid distribution in the body during entry, contributing to postflight orthostatic hypotension.

## PROMOTING SENSORIMOTOR RESPONSE GENERALIZABILITY: A COUNTERMEASURE TO MITIGATE LOCOMOTOR DYSFUNCTION AFTER LONG-DURATION SPACE FLIGHT (MOBILITY)

Principal Investigator(s): Jacob Bloomberg, NASA Johnson Space Center, Houston, Texas  
Expeditions 5–12, planned ongoing

### Research Area Human Research for Exploration



Following space flight, astronauts experience disturbances in balance and walking control during the postflight readaptation period, due in part to changes in the way the central nervous system processes sensory information as a result of prolonged exposure to microgravity. The goal of this study is to develop an in-flight treadmill training program that facilitates recovery of locomotor function after long-duration space flight.

The proposed training program is based on the concept of adaptive generalization. During this type of training, the subject gains experience producing the appropriate adaptive behavior under a variety of sensory conditions and balance challenges. As a result of this training, the subject learns to solve a class of balance and walking problems rather than producing a single solution to one problem. Therefore, the subject gains the ability to “learn to learn” under a variety of conditions that challenge the balance and walking control systems.

JSC2002E33153 – A participant performs a treadmill motion analysis test. This test tracks the participant's body placement and balance, elements of locomotion that undergo alterations during space flight. Mobility participants undergo similar testing before and after their Expeditions.

This study will develop an in-flight countermeasure built around ISS treadmill exercise activities. By manipulating the sensory conditions of exercise (e.g., varying visual flow patterns during walking), this training regimen will systematically and repeatedly promote adaptive change in walking performance, improving the ability of the astronaut to adapt to a novel grav-

ity environment. It is anticipated that this training regimen will facilitate neural adaptation to unit (Earth) and partial (Mars) gravity after long-duration space flight.

The Mobility protocol is performed by two sets of ISS subjects comprising control and experimental groups. All participating subjects (control and experimental) perform two tests of locomotor performance both preflight and postflight: the Integrated Treadmill Locomotion Test and the Functional Mobility Test. The experimental group will also perform the in-flight training protocol throughout the Expedition. Comparisons will then be made between recovery rates in the control vs. experimental groups.

### RESULTS

Data have been collected on control subjects (who do not have access to the virtual-reality display) since ISS Expedition 5. The display is planned for launch on Expedition 14, after which additional observations will be made on the experimental subjects.

ISS010E24001 —Astronaut Leroy Chiao, Expedition 10 commander and NASA ISS science officer, equipped with a bungee harness, exercises on the TVIS in the Zvezda service module of ISS. Crewmembers that complete standard exercise protocols on ISS are the experimental controls for the Mobility experiment.



## EFFECTS OF EVA AND LONG-TERM EXPOSURE TO MICROGRAVITY ON PULMONARY FUNCTION (PUFF)

Principal Investigator(s): John B. West, University of California-San Diego, La Jolla, Calif.  
Expeditions 3–6

### Research Area Human Research for Exploration

This experiment examined the effect of long-term exposure to microgravity and EVA on pulmonary function by studying crewmembers before and after they performed EVAs. It examined whether pulmonary function was affected by long-term exposure to noxious gases or to particulate matter that may accumulate in the atmosphere of ISS.

There is a large difference in pressure between the inside of ISS and in the spacesuit used for EVAs. The effects of this difference in pressure pose a significant risk of decompression sickness (DCS)—known in the diving world as “the bends”—for spacewalkers, including bubble formation within the blood. Even if the symptoms of DCS do not occur, venous gas microbubbles can alter pulmonary function, increasing the risk of forming a venous embolism.

Each Pulmonary Function in Flight (PuFF) session consisted of five noninvasive tests with the crew breathing only cabin air. The tests measured the pulmonary system’s ability to exchange gases, the amount of air inspired and expired as a function of time, and the maximum pressure of the air inhaled and exhaled. The analysis looked for markers that indicate that the lungs have been weakened from exposure to microgravity, or that the body’s ability to exchange and distribute gases has been disrupted.



ISS006348005 — Astronaut Donald R. Pettit, Expedition 6 NASA ISS science officer, uses a camera during a spacewalk on Jan 15, 2003.

PuFF hardware, including a manual breathing valve and flow meter, was attached to the HRF gas analyzer system for metabolic analysis physiology (GASMAP) hardware, physiological signal conditioners, and the HRF computer. GASMAP measured the volume of gases inspired and expired, frequency of respiration, and ambient barometric pressure.

### RESULTS

Excellent quality data were collected from the crews on all four Expeditions. Data from the EVA portion of the study have been analyzed and preliminary results presented at the 2004 meeting of the Aerospace Medical Association. Because measurements could only be performed on the day following EVA due to logistical constraints, the researchers were unable to determine an acute effect of EVA on lung function. However, the small effect observed on the day following EVA suggests that current denitrogenation protocols prevent the decompression stress associated with EVA from causing any major lasting disruption to gas exchange in the lung.



ISS006E07133 — Donald R. Pettit sets up PuFF hardware in preparation for an HRF experiment in the U.S. Destiny laboratory on station during Expedition 6.

## TEST OF MIDODRINE AS A COUNTERMEASURE AGAINST EFFECT OF MICROGRAVITY ON THE PERIPHERAL SUBCUTANEOUS VENO-ARTERIOLAR REFLEX IN HUMANS (XENON-1)

Principal Investigator(s): Anders Gabrielsen, Danish Aerospace Medical Center of Research National University Hospital (Rigshospitalet), Copenhagen, Denmark  
Expeditions 3–5

### **Research Area** Human Research for Exploration

When we lower our legs in relationship to our heart, the body triggers what is called a local veno-arteriolar reflex, where small subcutaneous (below the surface of the skin) blood vessels constrict, forcing blood from our feet toward our head. If this reflex is not properly triggered or if blood circulation is impeded, the blood pressure drops, causing dizziness and, possibly, fainting. This effect is called orthostatic intolerance. Due to a number of possible reasons—reduced fluid volume, muscle atrophy, neurovestibular adaptation—astronauts suffer from orthostatic intolerance during entry and landing, and for a few days postflight, interfering with their ability to perform entry and landing tasks and prolonging their recovery period. Xenon-1 will test the local veno-arteriolar reflex in an effort to understand the source of, and ways to combat, postflight orthostatic intolerance.

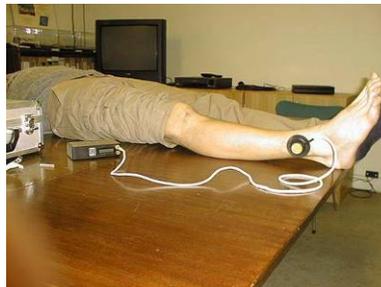


Injection of the tracer into a subject's leg.

Prior to and following Expeditions 3, 4, and 5, station crewmembers were placed on a gurney as a small amount of Xenon-133, a radioactive isotope dissolved in sterile saline solution, was injected into the subcutaneous tissue of their lower legs. Arterial blood pressure was recorded by a continuous pressure device on the crewmember's index finger. This measurement, which was taken with the Xenon-1 detector unit, was used to trace the movement of the Xenon tracer following injection. As the measurements were taken, the Xenon memory box recorded and displayed the counting rate.

### **RESULTS**

The last group of subjects for this experiment returned after Expedition 5. Data from all subjects were collected successfully. Preliminary results, reported to NASA by the principal investigator, indicate that the veno-arteriolar reflex is preserved and unaffected following weightlessness of as much as 195 days on ISS. This suggests that the veno-arteriolar reflex is not a contributor to postflight orthostatic intolerance.



A Xenon detector unit is attached to each crewmember's leg, slightly above the ankle, as shown here.

## **PSYCHO-SOCIAL STUDIES**

*Long-duration space missions, by their very nature, include many pressures on groups and individuals that could compromise mission success. Studies of behavior of individuals and teams under the conditions of space flight are important for determining the best team composition and interaction models for future Exploration missions.*

## CREWMEMBER AND CREW-GROUND INTERACTIONS DURING INTERNATIONAL SPACE STATION MISSIONS (INTERACTIONS)

Principal Investigator(s): Nick A. Kanas, University of California and Veterans Affairs Medical Center, San Francisco, Calif.  
Expeditions 2–5, 7–9

**Research Area** Human Research for Exploration

Isolated in the microgravity and vacuum of near-Earth orbit, ISS is a potentially dangerous place in which to work and live. Mission success and crew safety rely on the ability of station crews to communicate and get along with their fellows, regardless of their age, gender, nationality, or personal beliefs and preferences. It is also critical that the station crew has good interactions with members of ground operations.

The Interactions study recorded crew and crew-ground activities in an effort to fully understand group dynamics, individual psychological health, and factors that both hinder and help daily life on station. The study consisted primarily of a computerized questionnaire filled out weekly by crewmembers in space and by ground personnel at the NASA Johnson Space Center, the NASA Marshall Space Flight Center, and the Russian Mission Control Center in Moscow. The questionnaire software included a series of questions from three standard mood and interpersonal group climate questionnaires as well as a critical incident log.



JSC2004E25790 — Expedition 9 crewmembers, ISS science officer Michael Fincke (right) and ISS commander Gennady Padalka (left), use video and audio channels to communicate with the Mission Control Center-Houston on Jun 18, 2004. Everyone is celebrating the recent birth of Fincke's daughter. The primary focus of the Interactions investigation is to improve communications between the support personnel and the Expedition crew.

### RESULTS

The Interactions experiment observed the day-to-day relations between the ISS crew and the ground support teams in Houston, Texas, Huntsville, Ala., and Moscow, Russia. Data were collected over a period of four years during ISS Expeditions 2–9. ISS crewmembers and Mission Control personnel responded to questions from three standard mood and interpersonal group climate questionnaires (Profile of Mood States, Group Environment Scale, and Work Environment Scale) and maintained critical incident logs. The questionnaires used well-established psychometric measurements (measures of psychological variables; for example, intelligence, aptitude, and personality traits).

Preliminary results were presented in two papers by (Kanas et al. 2005) and (Ritscher et al. 2005) at the 15<sup>th</sup> International Academy of Astronautics (IAA) Humans in Space Symposium and were submitted for publication.

Previous studies of crew interactions, when U.S. crewmembers were added to the Russian space station Mir crews, identified important patterns of responses in interactions between and among crews and ground personnel. Not surprisingly, the investigation is also identifying differences in mood and group perceptions between Americans and Russians as well as between crewmembers and Mission Control personnel. In a separate but related study conducted by this research team, ISS crewmembers show evidence of an improvement in mental health as they adjust to the environment (adaptation). The study indicates that crewmembers improve in mood and social climate over the course of their missions. Post-mission surveys of crewmembers are being used to evaluate strategies to enhance crewmembers' in-flight stress tolerance and postflight adjustment.

Many of the behavioral factors studied in this experiment (communication styles, multicultural teams, operational systems) will be important in planning operations systems and relationships between Exploration crews and ground personnel for lunar and Mars missions. Complete and final analysis of the questionnaires is still being conducted.

### PUBLICATION(S)

Clement J, Ritscher JB. Operating the ISS: Cultural and leadership challenges. 56<sup>th</sup> International Astronautical Congress. Fukuoka, Japan, IAC-05-A1.5.05. Oct 17–21, 2005.

Kanas N, Ritscher J. Leadership Issues with Multicultural Crews on the International Space Station: Lessons learned from Shuttle/Mir. *Acta Astronautica*. 56:932–936, 2005.

Kanas N, Salnitskiy VP, Ritscher JB, Gushin VI, Weiss DS, Saylor S, Marmar C. Human interactions in space: ISS versus Shuttle/Mir. 56<sup>th</sup> International Astronautical Congress. Fukuoka, Japan, IAC-05-A1.5.02. Oct 17–21, 2005.

Ritscher JB, Kanas N, Gushin VI, Saylor S. Cultural differences in patterns of mood states onboard the International Space Station. 56<sup>th</sup> International Astronautical Congress. Fukuoka, Japan, IAC-05-A1.5.03. Oct 17–21, 2005.



JSC2003E59333 — Overview of the station flight control room in NASA Johnson Space Center's Mission Control Center. This photograph was taken during rendezvous and docking operations between the Soyuz TMA-3 spacecraft and the ISS.



ISS007E18044 — Astronaut Edward T. Lu (at musical keyboard), Expedition 7 NASA ISS science officer and flight engineer, and ESA astronaut Pedro Duque of Spain share a light moment during off-shift time in the U.S. Destiny laboratory.

## BEHAVIORAL ISSUES ASSOCIATED WITH ISOLATION AND CONFINEMENT: REVIEW AND ANALYSIS OF ISS CREW JOURNALS (JOURNALS)

Principal Investigator(s): Jack W. Stuster, Anacapa Sciences, Inc., Santa Barbara, Calif.  
Expeditions 8–12, ongoing

### **Research Area** Human Research for Exploration

A previous content analysis of journals maintained during long-duration expeditions on Earth (e.g., to the Antarctic) provided quantitative data on which to base a rank-ordering of behavioral issues in terms of importance. Journals uses the same content evaluation techniques on journals kept by ISS crewmembers. The objective is to identify equipment, habitat, and procedural features that can help humans when adjusting to isolation and confinement while ensuring they remain effective and productive during future long-duration space flights.

While on orbit, crewmembers make journal entries at least three times a week in a personal journal. In format, their journal can be either electronic (i.e., using an ISS laptop) or paper. In addition to the journal entries, participating crewmembers also complete a brief electronic questionnaire at the mid-point of their Expeditions.

ISS008E22350 —  
Astronaut Edward M.  
(Mike) Fincke, Expedition 9  
NASA ISS science officer  
and flight engineer, works  
in the U.S. Destiny  
laboratory.



Studies on Earth have shown that analyzing the content of journals and diaries is an effective means of identifying issues that are most important to the person recording his or her thoughts. The method is based on the assumption that the frequency with which an issue is mentioned in a journal reflects the importance of that issue or category to the writer. The tone of each entry (positive, negative, or neutral) and phase of the Expedition are also variables of interest. Study results will lead to recommendations for the design of equipment, facilities, procedures, and training to help sustain behavioral adjustment and performance during long-duration Expeditions on ISS, or to the moon, Mars, and beyond. These studies can also assist on Earth with Antarctic missions, service on submarines, etc.—anywhere humans choose to work in confinement or isolation.

### **RESULTS**

Data collection is ongoing, and the results will be analyzed when all of the journals are available.



ISS010E6816 — Expedition 10 crewmembers Leroy Chiao and Salizhan Sharipov participated in the Journals investigation.

## **RADIATION STUDIES**

*Cosmic radiation is one of the most critical risks to human health in space flight. Once we stray beyond the protective shielding of the Earth's atmosphere we are exposed to a wider spectrum of radiation that does not normally threaten us. Exposure to radiation found in low Earth orbit and beyond can cause cataracts and cancer, damage the reproductive organs and nervous system, and cause genetic damage.*

## BONNER BALL NEUTRON DETECTOR (BBND)

Principal Investigator(s): Tateo Goka, Japan Aerospace Exploration Agency, Tokyo, Japan  
Expeditions 2, 3

### Research Area Human Research for Exploration

Radiation is one of the many risks faced by astronauts. Large doses of radiation, from increased solar activity or long-duration space travel, can damage and kill cells and tissue, cause cancer and eye cataracts, injure the central nervous system, reduce fertility, and alter genetics. Radiation monitoring devices have flown on shuttle missions and on the Russian Mir station, but these devices were designed to detect radiation affecting the body's exterior. Thermal neutrons account for up to 20% of radiation affecting low Earth orbit missions. In space or on other planets, where there is little or no atmosphere to act as a protective barrier, thermal neutrons can penetrate deep into the body, affecting blood-forming bone marrow. Also, thermal neutrons are moderated by hydrogen-rich materials, such as water, so they not only damage deep body structures but can also be stopped by organs with high-water composition, such as the kidneys, liver, and spleen. The Bonner Ball Neutron Detector (BBND), which initially flew on shuttle mission STS-89, was the first space-based experiment designed to specifically detect neutron radiation. BBND was also the first radiation experiment that allowed researchers to examine data while the experiment was still in orbit. Previous experiments required that the detection media be returned to Earth for analysis.

BBND experiment hardware consists of two assemblies: the BBND control unit, which stores radiation measurements and controls data quality; and the BBND detector unit (DU), which measures neutron radiation via a series of six stainless-steel spherical shells. Four spheres are thermal neutron detectors covered in polyethylene of different thickness, one detector is covered in gadolinium; and one detector is uncovered. The gadolinium-covered sphere acts as a control; neutrons are unable to penetrate the dense gadolinium, and the data collected by the sphere are used to determine the difference between pulses created by neutrons and protons. Data collected from the polyethylene-covered spheres will show how the amount of hydrogen surrounding the detector affects the amount of radiation penetration.



ISS002E5714 — Astronaut James S. Voss, Expedition 2 flight engineer, sets up the BBND inside the U.S. Destiny laboratory. He holds the control unit (nearest the wall) and the detector unit (in his hands).

### RESULTS

BBND characterized the neutron radiation on ISS during Expeditions 2 and 3 and determined that galactic cosmic rays were the major cause of secondary neutrons measured inside ISS. The average dose-equivalent rate<sup>1</sup> observed through the investigation was 3.9 micro Sv/hour, with the highest rate at 96 micro Sv/hour, which occurred in the South Atlantic Anomaly region. Although this experiment did not characterize the neutron radiation environment outside of Earth's magnetic field, the BBND sampling equipment provided results without return of equipment to Earth and proved that similar measurement systems could be used on missions to the moon and Mars to monitor real-time radiation risks.

### PUBLICATION(S)

Koshiishi H, Matsumoto H, Koga K, Goka T. Evaluation of Low-Energy Neutron Environment inside the International Space Station. Technical Report of Institute of Electronics, Information, and Communications Engineers SANE2003-79:11–14, 2003. [*in Japanese*]

<sup>1</sup>To provide context for these measurements, radiation damage to the human body is indicated by dose-equivalent amount absorbed in living tissue and measured in sieverts. An average background radiation dose received on Earth can be approximately 1000 micro Sv/year without causing serious harm, while an exposure of 1 Sv/hour can result in radiation poisoning.

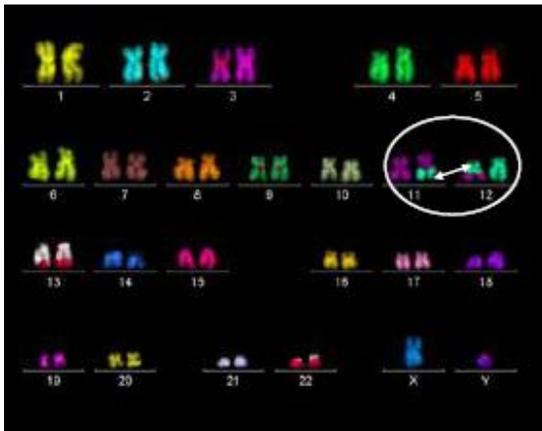
## CHROMOSOMAL ABERRATIONS IN BLOOD LYMPHOCYTES OF ASTRONAUTS (CHROMOSOME)

Principal Investigator(s): Günter Obe, Markus Horstmann, Christian Johannes, and Wolfgang Goedecke,  
University of Essen, Essen, Germany  
Expeditions 6–11, ongoing

### Research Area Human Research for Exploration

Crewmembers are exposed to radiation when they leave the protection of Earth's atmosphere. Ionizing radiation in particular can damage chromosomes, causing mutations such as chromosome aberrations. To assess the genetic impact of this radiation, blood is drawn before and immediately after flight by venous puncture. The blood is then cultured and the lymphocytes are stimulated to undergo mitosis (the process of cell division). In the first mitosis, at about 48 hours of incubation, the process is stopped and the chromosomes are prepared and stained using three different methods of microscopic analysis to assess all types of aberrations induced by ionizing radiations. These methods are:

- Classic Giesma staining, which allows the researcher to investigate changes in the morphology of the chromosomes. Chromosomes have a natural x-shape. Structural changes detected using Giesma include dicentric (the two chromatids of each chromosome are attached twice) and ring chromosomes or fragments (chromosome pieces without a centromere).
- Multicolor Fluorescence In-Situ Hybridization (mFISH), which scores reciprocal translocations and insertions (exchange of parts between different chromosomes).
- Multicolor Banding Fluorescence In-Situ Hybridization (mBAND) of the selected chromosome pair 5, which scores for inversions and translocations between homologous chromosomes (exchange or relocation of deoxyribonucleic acid (DNA) parts within the same chromosome pair).



A quantitative comparison between preflight and post-flight aberration values will give information about the chromosome-breaking effects of cosmic radiation in blood lymphocytes of space travelers. Information will be generated concerning the participation of each chromosome pair in aberration formation as well as the inter- and intrachromosomal distribution of different aberration types. The association of chromosomal aberrations with an enhanced cancer risk stresses the importance of the planned research.

This photo shows that a reciprocal exchange (translocation between chromosomes 11 and 12) has taken place in the blood lymphocytes of a crewmember after space flight.

### RESULTS

In each Expedition where the experiment has been conducted, preflight and postflight blood samples were drawn from each crewmember. To ensure high-quality results, the blood samples arrive at the laboratory within 72 hours after collection. Researchers are currently measuring changes in the genetic material and analyzing their significance and will release preliminary conclusions soon. From this study scientists may be able to better assess risk factors for genetic damage in space. Understanding and reducing the risk of radiation is important for safe long-duration travel in space, including stays on the moon and journeys to Mars.

## DOSIMETRIC MAPPING (DOSMAP)

Principal Investigator(s): Günther Reitz, Deutsches Zentrum für Luft und Raumfahrt (DLR) Institute for Aerospace Medicine, Cologne, Germany  
Expedition 2

### Research Area Human Research for Exploration

Dosimetric Mapping (DOSMAP) consisted of four types of dosimeters that measured absorbed dose, neutron dose, and heavy ion fluences as well as spectral composition with respect to charge, energy, and linear energy transfer (LET). Although the space program has produced a good deal of data on radiation since its beginning in the 1960s, there are insufficient data on radiation types and doses inside spacecraft. ISS provides an opportunity to fully characterize the nature and distribution of radiation over a long period of time. Nuclear tracking detector packages (NTDPs) measure the amount of radiation absorbed, the level of neutrons present, and the angle of entry into a variety of radiation-shielding materials. NTDPs were placed in different locations around ISS to monitor incoming radiation. Each package contained three strips of CR39 plastic film. As high-energy particles passed through the film, they left tracks that could be analyzed by researchers after NTDPs were returned to Earth.

Dosimetry telescopes (DOSTELs), placed near each other in an empty rack, measured ion flow. Additionally, crewmembers used mobile dosimetry units (MDUs) as personal dosimeters. The control and interface unit (CIU) provided power for recharging the MDUs and an interface for downloading data to the HRF laptop.

Twelve thermoluminescence dosimeters (TLDs) consist of a set of bulbs that measures dose rates for ionizing radiation and neutrons. Neutrons (low-energy, uncharged particles with the ability to penetrate deep into the body) are moderated by hydrogen. This means that neutrons can harm organs, such as the kidneys, that contain large quantities of hydrogen-containing water.

## RESULTS



ISS002E7814 — James S. Voss, Expedition 2 flight engineer, sets up the HRF DOSMAP power distribution unit in the U.S. Destiny laboratory.

DOSMAP measured integrated total absorbed doses and dose rates for ionizing radiation and neutrons at four different locations in the U.S. Destiny laboratory and Node 1. LET spectra were measured during Expedition 2, and were partitioned into the contributions due to galactic radiation, radiation belt particles, and the solar particle event (SPE) that occurred on Apr 15, 2001. The different radiation dosimeters used by the experiment showed good agreement comparing dose rates, particle fluxes, and LET spectra. Small technical difficulties with some dosimeters were overcome, and the data yield was over 95%.

The dose of the ionizing part of the radiation field that was measured with TLDs was lower than what has been measured on previous shuttle missions and on the

Russian space station Mir. Measurements were also taken during orbits that passed through the SAA that showed an increase in detections during this time.

The radiation observed by DOSMAP sensors during Expedition 2 can be converted into an average dose equivalent rate of 532 micro Sv/day (44.3 micro Sv/hour, 187 micro Gy/day), which is significantly lower than measurements on previous space shuttle missions and Mir and indicates low risk of acute harm to the crew.

## PUBLICATION(S)

Reitz G, Beaujean R, Dachev Ts, Deme S, Luszik-Bhadra M, Heinrich W, Olko P. Dosimetric Mapping. Conference and Exhibit on International Space Station Utilization, Cape Canaveral, Fla. AIAA-2001-4903, Oct 15–18, 2001.

## A STUDY OF RADIATION DOSES EXPERIENCED BY ASTRONAUTS IN EVA (EVARM)

Principal Investigator(s): Ian Thomson, Thomson & Nielsen Electronics, Ontario, Canada  
Expeditions 4–6

### Research Area Human Research for Exploration



ISS005E22017 — ISS Expedition 5 commander Valery Korzun during an EVA. The EVARM experiment measured the amount of radiation that spacewalkers absorb during EVAs.

Extravehicular mobility units (EMUs, or spacesuits), which are worn by spacewalking astronauts, provide less shielding from radiation than the spacecraft. This means that spacewalkers are exposed to higher radiation levels during EVAs than at other times on orbit. When planning EVAs, teams take into account mission parameters, estimated duration, and ISS altitude and inclination and information on space weather conditions (e.g., solar activity, geomagnetic field conditions, proton flux) anticipated for that day.

In addition to specific lifetime radiation limits, medical standards specify that radiation doses achieved by astronauts should be as low as reasonably achievable (ALARA). To create new and improved shielding for EVAs, researchers must know the type and flux of radiation inside the EMU. The EVA Radiation Monitoring (EVARM) study investigated the dose received by dif-

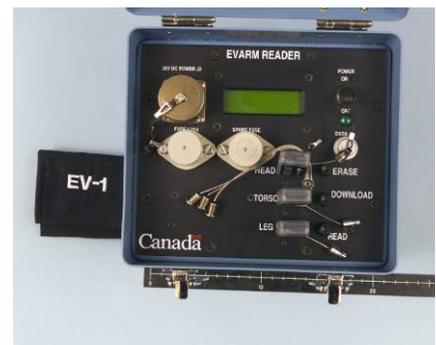
ferent parts of the body (skin, eyes, blood-forming organs) during an EVA by measuring dose rate, based on the time and position of EVAs as compared to the orbit, altitude, and attitude of the ISS.

As part of EVARM, spacewalkers wore dosimeters placed in small pockets along the EMU undergarments. Two dosimeters were placed either inside the thermal comfort undergarment or the liquid-cooled ventilation garment, one dosimeter was placed around the calf to measure absorbed dose to skin, and another dosimeter was worn above the eye inside the communications carrier assembly. EVARM used tiny metal oxide semiconductor field effect transistor (MOSFET) dosimeters, a 0.04-in<sup>2</sup> silicon chip placed on a badge made of aluminum. When a MOSFET is exposed to ionizing radiation, a positive charge builds up on the silicon surface, creating a negative shift in threshold voltage. Measurements were taken by comparing the change in threshold voltage with the radiation dose, which was recorded using a photodiode. New dosimeters were worn by the crew during each EVA.

### RESULTS

EVARM results have shown that geomagnetic storms increase the radiation doses to which spacewalking astronauts are exposed, although these storms are not very common. At the same time, shielding from the station significantly affected the dose of radiation each badge received. Finally, to determine radiation doses received by specific organs, one torso badge was not enough. Results also showed that badges must be placed more accurately near the organ to be monitored.

EVARM hardware. The device shown records and processes data sent by radiation detectors in the spacesuits of spacewalkers during EVAs.



## ORGAN DOSE MEASUREMENT USING A PHANTOM TORSO (TORSO)

Principal Investigator(s): Gautam D. Badhwar, NASA Johnson Space Center, Houston, Texas  
Expedition 2

### Research Area Human Research for Exploration

The most critical risk to humans in space is radiation exposure (see <http://bioastroroadmap.nasa.gov/index.jsp>, NASA's *Bioastronautics Roadmap*, for a ranked list of risks and countermeasures). Outside the protection of Earth's atmosphere, space crews are exposed to a wide range of particles, including neutrons, that are not normally a threat on Earth. Exposure to radiation found in low Earth orbit and beyond can cause cataracts, cancer, damage to reproductive organs and the nervous system, and changes in heredity.

Three experiments—BBND, DOSMAP, and Torso—flew on station in 2001 to measure the type and dose levels of radiation penetrating the station's interior. Torso was unique because, by mimicking the human body, it allowed researchers to measure the radiation dose received by the crew, not just inside the station.

Torso is a plastic equivalent anatomical model of a male head and torso composed of a Nomex "skin." It contains passive dosimeters in more than 350 locations throughout five layers. Five small active dosimeters (SMADOS) are located in the head, neck, heart, stomach, and colon regions. A common battery, located in Torso's abdomen pocket, powers the SMADOS. The SMADOS measure absorbed dose and dose-equivalent, and the returned data are calculated based on the duration of the measurements.



ISS002E5952 — Image of Torso on station during Expedition 2.

The tissue equivalent proportional counter (TEPC) consists of a spectrometer and cylindrical detector with which to measure external radiation doses. The TEPC is a microdosimetric instrument that measures radiation dose and dose equivalent in complex radiation fields (fields containing a mixture of particle types). The charged particle directional spectrometer (CPDS) measures particle energy and direction inside ISS. Both the TEPC and the CPDS remained within 1–1.5 feet (30.48–45.72 cm) of Torso during its operation on station.

### RESULTS

The results of the Torso experiment show that models of space radiation transport developed by the NASA Langley Research Center and the NASA Johnson Space Center are in good agreement with the measured organ doses. The largest differences observed are less than 15% between measurements and calculations. The majority of organ biological doses (80%) on station were from GCRs because trapped protons were well attenuated by the spacecraft and skin and because of the higher biological effectiveness of the GCR. The average quality factor (a measure of the impact of space radiation compared to X rays) was shown to have a value of about 2.6 on ISS.

NASA uses a risk assessment model that employs orbital inclination, altitude, phase in the solar cycle, vehicle-shielding, and body-shielding when calculating the risk from radiation. Data from the Phantom Torso experiment indicated the prediction of radiation dose and dose equivalent by the model to have an accuracy of  $\pm 25\%$ . Torso results also indicate the need to improve the measurements on secondary neutrons in space flight.

### PUBLICATION(S)

Cucinotta FA, Wu H, Semones EJ, Gibbons F, Atwell W, Shavers MR, George KL, Badhwar GD. Astronauts organ doses from 1962–2002: space validation with phantom torso experiments (Abstract), Proceedings of the Bioastronautics Investigators' Workshop, Galveston, Texas. Jan 2003.

## **PHYSICAL AND BIOLOGICAL SCIENCES IN MICROGRAVITY**

*Using a laboratory environment found nowhere else, the U.S. Destiny laboratory on space station provides the only place to study long-term physical effects in the absence of gravity. This unique microgravity environment allows different physical properties to dominate systems, and these have been harnessed for a wide variety of investigations in the physical and biological sciences.*

## **PHYSICAL SCIENCES**

*Much of our understanding of physics is based on the inclusion of gravity in fundamental equations. By conducting experiments in a microgravity environment, scientists can remove the effects of gravity-related processes such as sedimentation and convection. This allows testing of physical hypotheses that cannot be tested in any other environment.*

## **BINARY COLLOIDAL ALLOY TEST-3 (BCAT-3)**

Principal Investigator(s): David A. Weitz and Peter Lu, Harvard University, Cambridge, Mass. (Critical Point Experiment)  
Peter Pusey and Andrew Schofield, University of Edinburgh, Scotland (Binary Alloys Experiment)  
Arjun Yodh and Jian Zhang, University of Pennsylvania, University Park, Penn. (Surface Crystallization Experiment)  
Expeditions 8–10, 12, ongoing

### **Research Area** Physical and Biological Sciences



ISS008E20610 — Astronaut C. Michael Foale, Expedition 8 commander and NASA ISS science officer, uses a digital still camera to photograph a slow growth sample module (SGSM) for the BCAT-3 experiment. The SGSM is on a mounting bracket attached to the maintenance work area table set up in the U.S. Destiny laboratory.

The Binary Colloidal Alloy Test-3 (BCAT-3) hardware supported three investigations in which ISS crews photographed samples of colloidal particles (tiny nanoscale spheres suspended in liquid) to document liquid/gas phase changes, growth of binary crystals, and the formation of colloidal crystals confined to a surface. Colloids are small enough that in a microgravity environment without sedimentation and convection, they behave much as atoms and so can be used to model all sorts of phenomena because their size, shape, and interactions can be controlled.

The BCAT-3 payload consists of ten small samples of colloid alloys in which the microscopic colloid particles are mixed together into a liquid. These ten samples are contained within a small case that is the size of a school textbook. At the start of an experiment run, all ten samples are shaken to completely remix the colloid samples, much in the same way that salad dressing must be shaken to remix oil and vinegar. After the samples are mixed, what remains is periodically photo-

graphed using a digital camera until the colloid and liquid components of those samples have separated or the polymers have formed crystals. The samples can be remixed to repeat the experiment.

The ten samples in BCAT-3 were selected as part of three separate experiments examining different physical processes: critical point, binary alloys, and surface crystallization.

### **CRITICAL POINT EXPERIMENT (WEITZ AND LU)**

In an ordinary pot of boiling water, bubbles of water vapor coalesce on the bottom of the pot, growing until they detach and float to the surface where they escape into the atmosphere. At boiling temperature water exists simultaneously in two distinct phases—liquid and gas. But, what should the mixture look like in the absence of gravity, when the vapor no longer floats to the top? Further, the behavior changes with increasing pressure: seal the pot, as in a pressure cooker, and the boiling temperature rises. Continue the pressure increase and the mixture will reach its critical point, a unique pressure and temperature value where the properties of liquid and gas merge. Just above the critical point is the supercritical regime where there are no distinct phases but rather a homogeneous supercritical fluid. The BCAT-3 samples model this behavior in a colloidal system, where the phases analogous to liquid and gas can be seen as two different colors.

Supercritical fluids are technologically important because they uniquely combine the properties of liquids and gases, flowing easily (as gases) yet still having tremendous power to transport dissolved materials and thermal energy (like liquids). A better understanding of critical behavior as a result of microgravity experiments such as BCAT-3 might thus facilitate the development of new drugs, cleaner power, and interplanetary transportation.

Understanding critical phenomena was an important theoretical advance in physics during the last half century, but ground-based experiments have been limited by gravity, which invariably causes the denser liquid phase to fall to the bottom of any container, precluding direct observation of phase separation alone. BCAT-3 is the first experiment to systematically attempt to precisely locate the critical point and visualize the behavior around it.

### BINARY ALLOYS EXPERIMENT (PUSEY AND SCHOFIELD)

Colloids are also technologically interesting because they are the right size to manipulate light. Natural opal is likely the oldest and best known of the “photonic” crystals that direct light. Shine white light on the opal and a rainbow appears, demonstrating how colors of light are split up and sent in different directions. The ability to better control the movement of light is a major technological goal, not only to build computers operating on light instead of electricity but also to harness the full capabilities of existing fiber-optic networks for improving communications. Crystal structures built from only one building block—e.g., the arrangement of colloidal silica spheres in an opal—are well understood, but their optical properties are limited. More useful photonic crystals can be built from two different types of building blocks mixed together, yielding a binary alloy. The resulting structures and their optical properties are vast, as both the size and the proportion of the two building blocks can be varied. How crystallization is affected by these changes is only beginning to be explored. Theoretical studies suggest that desired optical properties require more complicated crystal structures, but this has not been well explored experimentally. Microgravity is crucial to the binary crystal experiments, allowing the growth of crystals far larger than those created on the surface of the Earth. The BCAT-3 binary alloy sample furthers previous investigations on binary growth in space.



BCAT-3 sample holder affixed to a wall inside ISS on Expedition 9.

### SURFACE CRYSTALLIZATION EXPERIMENT (YODH AND ZHANG)

Crystal structures are affected not only by constituent building blocks, but also by the geometrical environment in which they grow. The long, thin blades of ice on the surface of a freezing puddle are far different from the solid blocks in a freezer ice cube tray and the six-sided needles in a snowflake. BCAT-3 includes several samples to study the formation of colloidal crystals confined to a surface, allowing comparison with bulk three-dimensional crystallization to begin teasing out how geometry affects the crystallization itself.

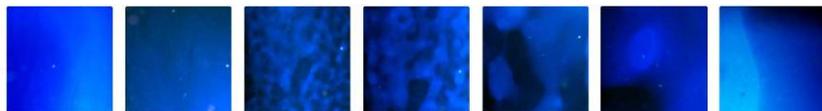
### RESULTS

**Critical Point:** The phase separation rates of the different samples were measured. The data gave some surprising results about the rates. The samples have been remixed for another session to verify the observations using a remote-controlled camera system from the EarthKAM educational payload to get more frequent images. Final results will not be available until the experiment is complete on ISS Expedition 13.

These dynamic data will help determine the boundary conditions for future models of critical behavior. Present observations also include a determination of the shape of the interface and which part of the sample wets the cell. The long-term observation of which samples phase separate will allow precise determination of the critical point of this colloidal mixture, and will allow inference of the fundamental physics underlying critical point behavior.

**Binary Alloy:** The sample dried out and was unavailable for further experiments.

**Surface Crystallization:** Crystal formation was observed in at least one sample. The samples have been remixed for another session to verify the observations.



Example of a time progression of separation of the colloids in one sample cell during the Critical Point experiment.

## COARSENING IN SOLID LIQUID MIXTURES-2 (CSLM-2)

Principal Investigator(s): Peter Voorhees, Northwestern University, Evanston, Ill.  
Expedition 7

### Research Area Physical and Biological Sciences

Coarsening is an increase in the size of grains in a metal, usually during heating at elevated temperatures. The process occurs in nearly any two-phase mixture ranging from raindrops in clouds to industrial metallic alloys. It is important in industry because it affects the strength of metal alloys. The objective of the Coarsening in Solid Liquid Mixtures-2 (CSLM-2) experiment was to assess the validity of the theory of coarsening that has been used to design materials. By operating on ISS, all material transport phenomena besides coarsening are eliminated, allowing the science team to focus on the effects of coarsening alone.



ISS007E10472 — Front view of the CSLM-2 hardware following setup in the microgravity sciences glovebox (MSG) before operation on Expedition 7.

During cooling of an alloy of several metals, the different constituent metals may cool at different rates, causing competitive particle growth—a process called Ostwald ripening. During Ostwald ripening, coarsening occurs with large particles growing at the expense of smaller ones in a matrix, with the large particles stealing atoms from smaller ones. Eventually, the sample consists of a few large particles crowded around a few remaining small particles. Materials that contain a few large particles rather than many small particles are structurally weaker.

In gravity, sedimentation will draw denser particles to the bottom and light particles to the top of the sample. As a result, the sample not only coarsens, it coarsens unevenly, thereby producing areas in the material that are much weaker than other areas in the material. Processing the sample in microgravity will not prevent coarsening, but it will allow researchers to observe coarsening without the phenomena of convection and sedimentation influencing the arrangement of particles in the two-phase mixtures.

In CSLM-2, samples were heated inside a large, cylindrical sample chamber inside the MSG. After a sample was completed, pressurized water was pumped into the chamber to quench the sample, cooling it for removal. This system can quench samples from 185°C (365°F) (the temperature required to initiate coarsening in tin-lead [Sn-Pb] samples) to 120°C (248°F) in only six seconds.

### RESULTS

Sample return from the CSLM-2 experiment was delayed due to the *Columbia* accident. The samples were eventually returned on STS-114 in 2005. Researchers had assumed that the data were lost because the samples were not kept under refrigeration. To their delight and surprise, samples were suitable for analysis in spite of the extended storage at room temperature. The furnace performed as designed, and investigators are now analyzing the microstructure of the samples. This will allow them to obtain new spatial distribution information on coarsening that is impossible to obtain using Earth-processed samples.

## EXPRESS PHYSICS OF COLLOIDS IN SPACE (EXPPCS)

Principal Investigator(s): David A. Weitz, Harvard University, Cambridge, Mass.; Peter N. Pusey, University of Edinburgh, Edinburgh, Scotland  
Expeditions 2–4

### Research Area Physical and Biological Sciences

Colloids can be defined as fluids with other particles dispersed in them, particularly particles of size between 1 nanometer and 1 micrometer. Since colloids have widespread uses in nature and industry, understanding of the underlying physics that controls their behavior is important. Under the proper conditions, colloidal particles can self-assemble to form ordered arrays, or crystals. On Earth, the ordering of these particles is mostly directed by gravitational effects, sedimentation, and buoyancy. Self-assembly does not occur. Thus, the weightlessness of low Earth orbit is an important element in the study of colloids.

Physics of Colloids in Space (PCS) focused on the growth, dynamics, and basic physical properties of four classes of colloids: binary colloidal crystals, colloid-polymer mixtures, fractal gels, and glass. These were studied using static light scattering (for size or positions of the colloids or structures formed), dynamic light scattering (to measure motions of particles or structures), rheological (flow) measurement, and still imaging.

### RESULTS

Results are discussed by class of colloid material studied. Analyses are still under way.

**Binary colloidal crystals:** These alloy samples are dispersions of two differently sized particles in an index-matching fluid. Two samples were studied: an  $AB_{13}$  crystal structure and an  $AB_6$  crystal structure. Due to a hardware failure late in Expedition 4, the  $AB_6$  experiment was not completed.

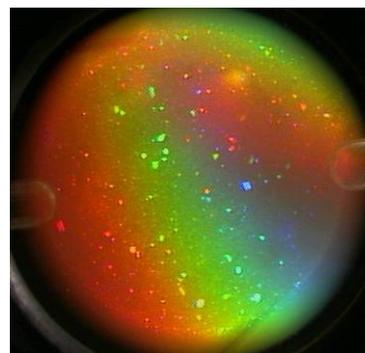
Unexpected “power law” growth behavior that is still under investigation was observed in the  $AB_{13}$  crystal structure sample.

**Colloid-polymer mixtures:** These mixtures induce a weak attractive interaction that allows precise tuning of the phase behavior of the mixtures. The phase behavior is controlled by the concentration of the colloid, the concentration of the polymer, and the relative size of the colloid and the polymer.

**Colloid-polymer gels:** This sample was expected to be in a fluid-cluster state, but unexpectedly formed a solid gel. The elastic modulus, which was estimated using the experiment’s rheology capabilities, will be compared to ground samples. “Aging” characteristics of this gel were found to be similar to those formed on Earth.

**Colloid-polymer critical point:** Immediately after mixing, the colloid-polymer critical point sample began to separate into two phases—one that resembled a gas and one that resembled a liquid, except that the particles were colloids and not atoms. The colloid-poor regions (the colloidal “gas” phase) grew bigger until, finally, complete phase separation was achieved and there was just one region of each—a colloid-rich phase and a colloid-poor phase. None of this behavior can be observed in the sample on Earth because sedimentation would cause the colloids to fall to the bottom of the cell faster than the de-mixing process could occur. Knowledge gained from these runs was used to develop the BCAT-3 later operated on ISS.

**Fractal gels:** Fractal gels may form when charged colloids have their electrostatic repulsions screened out by the addition of a salt solution, permitting aggregation. These can be formed at very low volume fractions and form highly tenuous aggregates that exhibit a remarkable scaling property—their structure appears the same on all length scales up to a cluster size, and so can be described as a fractal. It was thought that the samples studied (colloidal polystyrene and silica gel) would, in the absence of sedimentation effects, ultimately form a continuous network of fractal aggregate; the polystyrene fractal sample never fully gelled as expected however. Initial indications are that the volume fraction tested was too low. Large fractal clusters did nevertheless grow (larger than they do on



One of the first images from the PCS on ISS. During Expedition 2, sample  $AB_6$  was illuminated with white light to produce this image. The colored regions result from refraction of white light by the sample and sample cell, splitting the light into its component colors.

Earth), allowing measurement of the internal vibration modes of these structures. The silica gel is thought to have gelled, and is currently being evaluated.

**Colloidal glass:** These samples are still under evaluation. Comparison to samples formed in one-g in the laboratory were needed to understand whether the crystallization observed was due to poor mixing or was a true microgravity phenomena.

#### **PUBLICATION(S)**

Manley S, Cipelletti L, Trappe V, Bailey AE, Christianson RJ, Gasser U, Prasad V, Segre PN, Doherty MP, Sankaran S, Jankovsky AL, Shiley B, Bowen J, Eggers J, Kurta C, Lorik T, Weitz DA. Limits to Gelation in Colloidal Aggregation. *Physical Review Letters*. 93(10):108302, 2004.

Manley S, Davidovitch B, Davies NR, Cipelletti L, Bailey AE, Christianson RJ, Gasser U, Prasad V, Segre PN, Doherty MP, Sankaran S, Jankovsky AL, Shiley B, Bowen J, Eggers J, Kurta C, Lorik T, Weitz DA. Time-Dependent Strength of Colloidal Gels. *Physical Review Letters*. 95(4):048302(4), 2005.

Weitz D, Bailey A, Manley A, Prasad V, Christianson R, Sankaran S, Doherty M, Jankovsky A, Lorik T, Shiley W, Bowen J, Kurta C, Eggers J, Gasser U, Serge P, Cipelletti L, Schofield A, Pusey P. Results from the Physics of Colloids Experiment on ISS. NASA TM-2002-212011: IAC-02-J.6.04, 2002.

## FLUID MERGING VISCOSITY MEASUREMENT (FMVM)

Principal Investigator(s): Edwin Ethridge, NASA Marshall Space Flight Center, Huntsville, Ala.  
Expeditions 9, 11

**Research Area** Physical and Biological Sciences



ISS009E14560 — Mike Fincke, Expedition 9 science officer, is shown deploying one of the drops of liquid onto Nomex thread during FMVM testing.

The Fluid Merging Viscosity Measurement (FMVM) experiment was developed rapidly after the *Columbia* accident to provide a low-mass experiment using hardware already on board ISS. The purpose of FMVM is to measure the rate of coalescence of two highly viscous liquid drops and correlate the results with liquid viscosity and surface tension. The FMVM experiment will verify a new method for measuring the viscosity of highly viscous liquids by measuring the time it takes for two spheres of liquid to coalesce into a single spherical drop, where the time constant is proportional to the viscosity.

If this new method of measuring viscosity is validated, it could provide a method by which to measure viscosities of materials that cannot currently be measured. An example of this is liquid (molten) glass that crystallizes while cooling from liquid to solid. The viscosity in most of the crystallization range

cannot be measured using current, Earth-based technology in spite of the fact that this is the most interesting range for the study of crystallization.

To obtain accurate data for precise models, it is best to measure viscosity in liquid that is free-floating and uncontained. The station's microgravity environment is an excellent testbed for this procedure because drops float freely in low gravity. The simple test apparatus was constructed of materials already on board ISS, and sample liquids, representing a range of viscosities, were deployed to station on a Russian Progress vehicle. These liquids consisted of glycerin, silicone oil (high and low viscosities), honey, honey mixed with water, corn syrup, and corn syrup mixed with water.

### RESULTS

Preliminary results were based on downlink video. The original data tapes were returned to Earth on shuttle flight STS-114/LF-1 and are still undergoing analysis. Glycerin proved difficult to deploy as planned (the viscosity was too low and/or the surface tension was too high), but the two different silicone oil viscosity calibration liquids were deployed easily, and five coalescence experiments were recorded with the two liquids. A range of drop sizes from 0.5 cc to 4 cc was coalesced. Since the honey had crystallized, the ISS food warmer was used to eliminate crystallization and the honey experiments were completed. Two corn syrup liquids formed a stiff skin. Real-time discussions with the astronaut resulted in a quick change to the procedure. New drops were deployed rapidly so as to avoid skin formation. Several successful coalescence runs were obtained with the corn syrup.

Preliminary results from data analysis indicate a very good agreement with the predicted coalescence time. Scientists believe that the final analysis will validate the model for this new viscosity measurement method. Final analysis and report of the results are pending.

### PUBLICATION(S)

Ethridge E, Kaukler W, Antar B. Preliminary Results of the Fluid Merging Viscosity Measurement Space Station Experiment, Proceedings of the 44<sup>th</sup> AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nev. AIAA 2006-1142, Jan 9–12, 2006.

## **VISCOUS LIQUID FOAM-BULK METALLIC GLASS (FOAM)**

Principal Investigator(s): William Johnson and Chris Veazey, California Institute of Technology, Pasadena, Calif.  
Expedition 9

**Research Area** Physical and Biological Sciences.

Bulk metallic glasses are a special class of metallic materials created by rapid solidification that causes them to form glass-like structures that are light but very strong. This experiment investigates the formation and structure of foams made from bulk metallic glass. Because the effects of buoyancy are minimized in space, more uniform foam structures with unique properties can be produced. These new materials have potential applications for use in future moon or Mars space structures (due to their high strength and low weight) as well as for potential shielding against micrometeorites and space debris impacts on spacecraft.

### **RESULTS**

Three planned runs for the Foam experiment were successfully completed on station during Expedition 9. Samples, which were returned to Earth in late August 2005, are being analyzed.



ISS009E1479 — Expedition 9 flight engineer and science officer Edward M. (Mike) Fincke performs the Foam experiment in the maintenance work area of space station.

## INVESTIGATING THE STRUCTURE OF PARAMAGNETIC AGGREGATES FROM COLLOIDAL EMULSIONS (INSPACE)

Principal Investigator(s): Alice P. Gast, Massachusetts Institute of Technology (MIT), Cambridge, Mass.  
Expeditions 6, 7, 12, planned ongoing

### Research Area Physical and Biological Sciences

Magnetorheological (MR) fluids are suspensions of magnetizable particles whose properties can be controlled by magnetic fields. These fluids are classified as “smart materials” that transition to a solid-like state by the formation and cross-linking of microstructures in the presence of a magnetic field. On Earth these materials are used for vibration dampening systems that can be turned on or off. The Investigating the Structure of Paramagnetic Aggregates from Colloidal Emulsion (InSPACE) experiment will visually study the final, fine structure of MR fluids in a pulsed (alternating on and off) magnetic field. This study will help researchers understand the competing forces that govern the final shape of the structures.

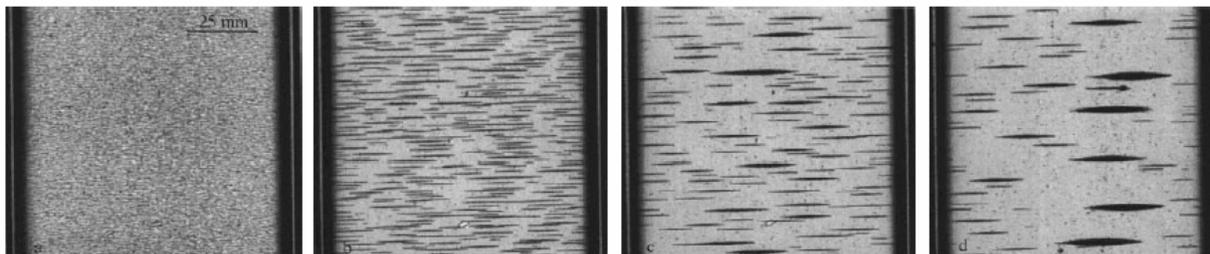
The InSPACE coil assembly holds a Helmholtz coil assembly containing sealed vials of MR fluid, the camera/lens assemblies, and the power control. The coil assembly is attached to the “floor” of the MSG. The magnetic fields are applied to the various samples, and the operation of the experiment is monitored via video.

### RESULTS

InSPACE was performed in the MSG during Expeditions 6 and 7. Nine tests were performed for each Helmholtz coil for a total of 27 experimental runs. The collected data were used to test theoretical models of the microstructures. Furthermore, understanding the complex properties of the fluids and the interaction of the microparticles will enable the development of more sophisticated methods for controlling and use of these fluids. Data are still undergoing analysis. During Expedition 12, the samples will be checked and verified suitable for future analysis. Additional runs are planned during upcoming Expeditions.



ISS006E41778 — During Expedition 6, flight engineer Donald R. Pettit works with the InSpace samples in the MSG in the U.S. Destiny laboratory.



Structure evolution in a magnetorheological fluid over time while an alternating magnetic field is applied. The far left image shows the fluid after one second of exposure to a high-frequency-pulsed magnetic field. The suspended particles form a strong network. The images to the right show the fluid after three minutes, 15 minutes, and one hour of exposure. The particles have formed aggregates that offer little structural support and are in the lowest energy state.

## MISCIBLE FLUIDS IN MICROGRAVITY (MFMG)

Principal Investigator(s): John Pojman, University of Southern Mississippi, Hattiesburg, Miss.  
Expeditions 8–11

### Research Area Physical and Biological Sciences

The goal of the Miscible Fluids in Microgravity (MFMG) experiment is to test the fluid dynamics between two miscible (or mixable) liquids in a microgravity environment provided by ISS. The interaction between two miscible liquids here on Earth would be masked by the effects of either gravity or density, and, in effect, the two miscible liquids would combine into one relatively homogenous (or equally distributed) solution. In microgravity, miscible liquids may behave completely differently, potentially taking on properties more akin to immiscible (or non-mixable) liquids, and supporting a theory proposed by Korteweg over 100 years ago. Testing Korteweg's hypothesis is challenging on Earth because the force of gravity overwhelms surface tension, but the microgravity environment on station provides an ideal opportunity to do so.



Edward M. (Mike) Fincke, Expedition 9 science officer and flight engineer, uses syringes to inject honey into water to test the mixing ability of the two liquids for the MFMG experiment.

This experiment originated from a call for simple experiments requiring little upmass following the grounding of the space shuttle fleet after the loss of *Columbia*. The MFMG experiment was proposed as a simple study of miscible fluids limited to the use of ordinary items already on board ISS (unused syringes, water, honey, Ziploc bags, a still camera, and a video camera). In the isothermal experiment (where diffusive forces predominate in microgravity), a stream of either honey or water was introduced into a syringe of the opposite fluid to observe the transient behavior of the miscible fluids. In the thermal experiment, a temperature gradient was created across the syringe holding one of the fluids, and a second fluid was introduced at ambient temperature.

and surface tension would cause the fluid to have as little surface area as possible for a given volume. The droplets that form as the stream breaks apart would have less surface area than a cylinder (stream) of the same volume—an effect known as Rayleigh instability. The experiment will determine whether the stream exhibits the Rayleigh instability characteristic of immiscible fluids.

Korteweg's theory predicts that miscible fluids will demonstrate interfacial tension transiently until diffusion prevails. Under normal gravity, the stream of honey would break apart under its own weight

### RESULTS

MFMG results from Expeditions 8 and 9 are reported here. Later runs of the experiment are still being analyzed.

**Isothermal results:** Four sessions were performed with no observation of Korteweg's prediction of the Rayleigh instability. It was found that the honey did not break into small drops, neither did it change its shape when injected. The behavior that was exhibited was that of simple diffusion, which is seen on Earth when mixing two miscible fluids.

**Thermal results:** Two sessions of MFMG were performed with a thermal gradient introduced. The stream migrated towards the warmer side of the temperature gradient, which may indicate the presence of Korteweg's predicted behavior. Further sessions with thermal gradients are still being analyzed.

### PUBLICATION(S)

Pojman JA. Miscible Fluids in Microgravity (MFMG): A Zero-Upmass Experiment on the International Space Station. Proceedings of the 43<sup>rd</sup> AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nev. AIAA 2005-718, Jan 10–13, 2005.

## TOWARD UNDERSTANDING PORE FORMATION AND MOBILITY DURING CONTROLLED DIRECTIONAL SOLIDIFICATION IN A MICROGRAVITY ENVIRONMENT (PFMI)

Principal Investigator(s): Richard Grugel, NASA Marshall Space Flight Center, Huntsville, Ala. Expeditions 5, 7, 8

### Research Area Physical and Biological Sciences

On Earth, bubbles that form in molten materials rise to the surface and release trapped gas prior to solidification. In microgravity, where there is no buoyancy or convection, bubbles can become trapped inside the material, leaving pores as the material solidifies. These pores can greatly reduce the finished material's strength and structural integrity, making it a less desirable product. The goal of the Pore Formation in Microgravity (PFMI) experiments was to learn how bubbles form and move during phase change (from liquid to solid) inside molten material, in this case succinonitrile (SCN), a clear organic compound that is a transparent metal analog material, and SCN water (1%) mixtures. The PFMI experiments methodically investigated pore formation and growth using SCN loaded with an excess amount of dissolved nitrogen gas. To eliminate the porosity problem in space processing, the role of thermocapillary forces in transporting the bubbles away from the solidification interface was examined.

Experiments were conducted inside the MSG, a sealed and ventilated work volume in the U.S. Destiny laboratory. The samples were melted inside a thermal chamber with temperature-controlled hot zones and one thermoelectric cold zone. Flow visualization technology was used in support of the experiment to observe bubble movement.

### RESULTS

The PFMI experiment used glass tubes (1 cm inner diameter and 30 cm in length) filled with SCN and water in concentrations ranging from pure SCN to 1% SCN water mixture. The data from this experiment were provided by downlinked images during real-time operations on ISS. In addition, images were recorded using a videotape recorder (VTR) inside the MSG.

Grugel et al. (2004) observed bubble migration up the temperature gradient due to thermocapillary forces and reported that thermocapillary forces do play a role in bubble removal during solidification, thereby providing a potential mechanism for avoiding porosity in space processing.

Strutzenberg et al. examined the morphological evolution of the solidification of the PFMI samples (0.25% water to SCN mixture and 0.50% water to SCN mixture). Direct comparison between the ground-based thin (two-dimensional) samples and the flight bulk (three-dimensional) samples showed significant differences in the interface morphology. The flight samples achieved planar growth, an emergence of dendrites (crystallizes in the shape of a tree or branch), in less time than ground-based samples. When comparing the planar interface recoil, the flight sample was steeper than the ground-based sample. Additionally, the dendrite spacings in the flight bulk samples were closer together than the ground-based thin samples. This highlights the researchers' premise that the use of two-dimensional (thin) samples in one-g to obtain quantitative data for comparison with theoretical models has significant shortcomings.

Strutzenberg et al. concluded that the thin samples are not adequate to provide data on the initial planar front dynamics, the dynamical condition for the planar interface instability, and the steady-state primary dendrite spacing. Solidification of bulk samples in a microgravity environment and in the lab setting is necessary for a suitable comparison. The flow visualization images obtained for the PFMI experiment allowed Grugel et al. (2005) to study bubble formation in SCN. The bulk solidification samples, which were filled with SCN, were melted and re-



ISS008E06301 — C. Michael Foale, Expedition 8 mission commander and ISS science officer, installs equipment in the MSG for the PFMI experiment.

solidified to observe the bubbles that formed. During controlled re-solidification, aligned tubes of gas were seen to be growing perpendicular to the planar solid/liquid interface, inferring that the nitrogen previously dissolved into the liquid SCN was now coming out at the solid/liquid interface and forming the little-studied liquid=solid+gas eutectic-type reaction. The flight sample results could not be duplicated in the ground-based samples.

Cox et al. are now attempting to better replicate the space phenomena in a ground-based lab by using small-diameter channels to minimize bulk convection and buoyant bubble rise effects.

#### **PUBLICATION(S)**

Cox MC, Anilkumar AV, Grugel RN, Hofmeister WH. Isolated Wormhole Growth and Evolution during Directional Solidification in Small Diameter Cylindrical Channels: Preliminary Experiments, Proceedings of the 44<sup>th</sup> AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nev. AIAA 2006-1140, Jan 9–12, 2006.

Grugel RN, Anilkumar AV, Lee CP. Direct observation of pore formation and bubble mobility during controlled melting and re-solidification in microgravity, solidification processes and microstructures. A Symposium in Honor of Wilfried Kurz. The Metallurgical Society, Warrendale, Penn. 111–116, 2004.

Grugel RN, Anilkumar AV. Bubble Formation and Transport during Microgravity Materials Processing: Model Experiments on the Space Station. Proceedings of the 42<sup>nd</sup> AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nev. AIAA 2004-0627, Jan 5–8, 2004.

Grugel RN, Anilkumar AV, Cox MC. Morphological Evolution of Directional Solidification Interface in Microgravity: An Analysis of Model Experiments Performed on the International Space Station. Proceedings of the 43<sup>rd</sup> AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nev. AIAA 2005-917, Jan 10–13, 2005.

Strutzenberg LL, Grugel RN, Trivedi R. Observation of an Aligned Gas-Solid Eutectic during Controlled Directional Solidification aboard the International Space Station—Comparison with Ground-based Studies. Proceedings of the 43<sup>rd</sup> AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nev. AIAA 2005-919, Jan 10–13, 2005.

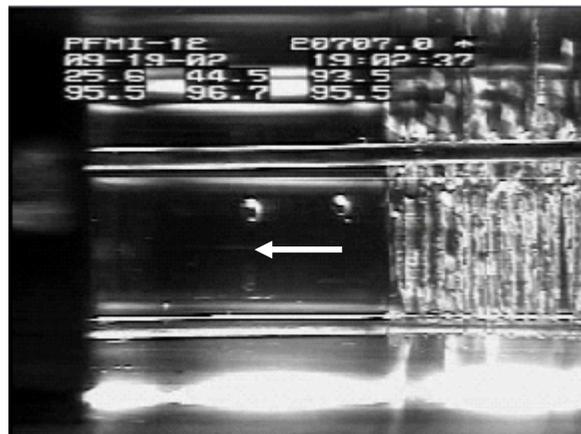


Image of the solid liquid interface of the PFMI experiment. Bubbles detach from the interface and move up the temperature gradient (right to left), courtesy of Dr. Richard Grugel, NASA Marshall Space Flight Center.

## SOLIDIFICATION USING BAFFLE IN SEALED AMPOULES (SUBSA)

Principal Investigator(s): Alexander Ostrogorsky, Rensselaer Polytechnic Institute (RPI), Troy, N.Y.  
Expedition 5

### Research Area Physical and Biological Sciences

Material melt-growth experiments have been difficult to run in the space environment because there is just enough residual micro-acceleration (g-jitter) to produce natural convection that interferes with the structure and purity of the material. This convection is responsible for the lack of reliable and reproducible solidification data and, thus, for gaps in the solidification theory. The Solidification Using Baffle in Sealed Ampoules (SUBSA) experiment tested an automatically moving baffle (driven by melt expansion during freezing) that was designed to reduce thermal convection inside an ampoule to determine whether the baffle significantly reduces convection. Ground studies showed that the baffle reduces the movement of the material during its liquid phase, making the process easier to analyze and allowing more homogenous crystals to form.

The key goal of SUBSA was to clarify the origin of the melt convection in space and to reduce the magnitude to the point that it does not interfere with the transport phenomena.

### RESULTS

The baffle proved successful. Eight single crystals of indium antimonide (InSb), doped with tellurium and zinc, were directionally solidified in microgravity. The molten semiconductor material solidified as expected, without separating from the ampoule walls or releasing the undesirable bubbles that have been reported in several previous microgravity investigations. Semiconductor crystals with reproducible, nearly identical composition were obtained for the first time in space.

### PUBLICATION(S)

Churilov A, Ostrogorsky A. Solidification of Te and Zn Doped InSb in Space. Proceedings of the 42<sup>nd</sup> AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nev. AIAA 2004-1388, Jan 5–8, 2004.

Churilov AG, Ostrogorsky A. Model of Tellurium- and Zinc-Doped Indium Antimonide Solidification in Space. *Journal of Thermophysics and Heat Transfer*. 0887-8722, 19(4):5420–541, 2005.

Ostrogorsky A. Solidification Using a Baffle in Sealed Ampoules (SUBSA). Proceedings of the 41<sup>st</sup> AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nev. AIAA-2003-1309, Jan 6–9, 2003.

Spivey RA, Gilley S, Ostrogorsky A, Grugel R, Smith G, Luz P. SUBSA nad PFMI Transparent Furnace Systems Currently in use in the International Space Station Microgravity Science Glovebox. 41<sup>st</sup> Aerospace Sciences Meeting and Exhibit, Reno, Nev. AIAA 2003-1362, Jan 6–9, 2003.



ISS005E07172 — Astronaut Peggy Whitson, NASA science officer, is shown in front of the MSG as she works on SUBSA during Expedition 5.

## ZEOLITE CRYSTAL GROWTH (ZCG)

Principal Investigator(s): Albert Sacco, Jr., Northeastern University, Boston, Mass.  
Expeditions 4–6

### Research Area Physical and Biological Sciences

Zeolites, which are mineral crystals of aluminosilicates, have a rigid crystalline structure with a network of interconnected tunnels and cages that is similar to a honeycomb. A sort of mineral sponge, zeolites have the ability to absorb and release liquids and gases such as petroleum or hydrogen while remaining as hard as rock.

Zeolites are important for many industrial processes, and are used as commercial ion exchangers, adsorbents, and catalysts. Virtually all the world's gasoline is produced or upgraded using zeolites. Zeotype ETS titanosilicates contain natural quantum wires in their structures, which are of great potential in electronic and optical applications and in photochemistry. There is insufficient understanding of how zeolite and zeotype materials grow, however, making it difficult for scientists to independently control structure characteristics such as size, morphology, and purity. Growing zeolite crystals in microgravity minimizes the role of convection and sedimentation, and may allow production of crystals with fewer defects.

The Zeolite Crystal Growth (ZCG) furnace, which was designed for the and derived from earlier shuttle models, can grow zeolites, zeotype titanosilicate materials, ferroelectrics, and silver halides—all materials of commercial interest. The unit consists of a cylinder-shaped furnace, the Improved Zeolite Electronic Control System (IZECS), which includes a touchpad and data display as well as autoclaves. Two precursor growth solutions are placed into each autoclave, which mix during their stay in the furnace.

Zeolite Beta was grown from precursor solutions of sodium aluminate and colloidal silica heated to 403 K (130°C) on station. The samples were characterized by X-ray diffraction to determine the crystal structure. The performance of zeolite Beta as a Lewis acid catalyst was evaluated using a standard set of chemical reduction reactions known as the Meerwein-Pohhdorf-Verley (MPV) reactions.

## RESULTS



ISS005E19055 — Peggy Whitson, Expedition 5 flight engineer, places a cartridge into the ZCG experiment in the U.S. Destiny laboratory.

ZCG produced zeolite crystals with a high degree of crystalline perfection in microgravity. During ISS Expedition 6, 19 zeolite samples were mixed and incubated. These samples were returned to Earth at the conclusion of Expedition 6 and sent back to the principal investigator for analysis.

Results from the samples mixed on ISS suggest that the Lewis acid catalytic sites are altered in microgravity, as indicated by lower catalytic activity in the MPV probe reaction compared to Earth-grown zeolite. This further suggests that the control of fluid dynamics during crystallization may be important in making better industrial catalysts. Although space-grown zeolites had the same particle morphology and identical surface framework as zeolites grown on Earth, the average zeolite size of the space-grown crystals was 10% larger than crystals grown on Earth (Akata et al. 2004).

Larger zeolite crystals allow researchers to better define the structure and understand how they work, with a goal of producing improved crystals on Earth. Improved zeolites may have applications in storing hydrogen fuel, reduction of hazardous byproducts from chemical processing, and more efficient techniques for petroleum processing.

## PUBLICATION(S)

Akata B, Yilmaz B, Jirapnoghphan SS, Warzywoda J, Sacco Jr. A. Characterization of zeolite Beta grown in microgravity. *Microporous and Mesoporous Materials*. 71:1–9, 2004.



## **PROTEIN CRYSTAL GROWTH**

*Growing protein crystals in space, free from the gravitational effects of sedimentation and convection, provides an opportunity to grow crystals that are larger or more pure than crystals grown on Earth. Crystallization experiments on ISS have examined proteins, viruses, and other microbiological molecules to better understand their structure and function for maintaining human health and fighting disease.*

## ADVANCED PROTEIN CRYSTALLIZATION FACILITY (APCF), EIGHT INVESTIGATIONS

Payload developer: Italian Space Agency (ASI) for the European Space Agency Expedition 3

Principal Investigator(s): Richard Giegé, Centre National de la Recherche Scientifique (CNRS), Strasbourg, France; Effect of Different Growth Conditions on the Quality of Thaumatin and Aspartyl-tRNA Synthetase Crystals Grown in Microgravity

Manfred W. Baumstark, University of Freiburg, Germany; Crystallization of Human Low Density Lipoprotein (LDL) Subfractions in Microgravity

Willem J de Grip, University of Nijmegen, Netherlands; Crystallization of Rhodopsin in Microgravity

Joseph. Martial, University of Liege, France; Crystallization of the Next Generation of Octarellins

Fermin Otalora, University of Granada, Spain; Testing New Trends in Microgravity Protein Crystallization

Sevil Weinkauff, Technical University Munich, Germany; Solution Flows and Molecular Disorder of Protein Crystals: Growth of High Quality Crystals, Motions of Lumazine Crystals, and Growth of Ferritin Crystals

Lode Wyns, Free University Brussels, Belgium; Extraordinary Structural Features of Antibodies from Camelids

Adriana Zagari, University of Naples, Italy; Protein Crystallization in Microgravity, Collagen Model (X-Y-Gly) Polypeptides: the case of (Pro-Pro-Gly)<sup>10</sup>

### Research Area Physical and Biological Sciences



S105E5161 — Astronauts Frederick W. Sturckow and Scott J. Horowitz of the shuttle STS-105 crew pose with the APCF by the middeck locker during Expedition 3.

vapor diffusion, and dialysis. Liquid-liquid diffusion was not used during Expedition 3. In the vapor diffusion method, a crystal forms in a protein solution as a precipitant draws moisture in a surrounding reservoir. In the dialysis method, salt draws moisture away from the protein solution via a membrane separating the two, forming crystals. ESA has announced that due to potential difficulties with the vapor diffusion method that could cause experiment failure, it will no longer propose the use of this method with the APCF.

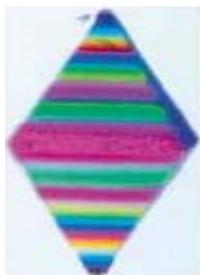
### RESULTS

Initial analysis of crystals returned from station support the findings of earlier APCF flights: comparative crystallographic analysis indicates that space-grown crystals are superior in every way to control-group crystals grown on Earth under identical conditions (except the critical space environment). Crystals grown in microgravity generally have improved morphology, larger volume, higher diffraction limit, and lower mosaicity as compared to

Understanding proteins is basic to understanding the processes of living things. While we know the chemical formulae of proteins, learning the chemical structure of these macromolecules is more difficult. Mapping the three-dimensional structure of proteins, DNA, ribonucleic acid (RNA), carbohydrates, and viruses provides information concerning their functions and behavior. This knowledge is fundamental to the emerging field of rational drug design, replacing the trial-and-error method of drug development. Microgravity provides a unique environment for growing crystals—an environment that is free of the gravitational properties that can crush the delicate structures of crystals. Currently, several test facilities are used to grow crystals.

The Advanced Protein Crystallization Facility (APCF) can support three crystal-growth methods: liquid-liquid diffusion,

Earth-grown crystals. The researchers reported that the electron-density maps calculated from diffraction data contained considerably more detail, allowing them to produce more accurate three-dimensional models.



A thaumin crystal, grown in microgravity during Expedition 3, displays interference patterns in polarized light.

Although many of the investigators have not completed their analysis and modeling, early published results have come out for crystals of (Pro-Pro-Gly)<sup>10</sup> (PPG<sup>10</sup>). PPG<sup>10</sup> is a collagen protein found in many tissues. This collagen is particularly concentrated in the skin, joints, and bones. Video that was collected during Expedition 3 showed the small movements within the crystallizing solutions. A direct correlation between crystal motion and acceleration from events on station (such as docking, venting, and crew movement) was determined for the first time. The PPG<sup>10</sup> crystals were independently studied by X-ray diffraction in various labs; the best resolution attained for microgravity-grown crystals from ISS was 1.5Å, superior to the 1.7Å obtained on the ground. The teams of APCF scientists are combining data from previous space flights, the ground, and the station to get the best possible information on protein structures for applications in pharmaceutical and physiological research.

### PUBLICATION(S)

Berisio R, Vitagliano L, Vergara A, Sorrentino G, Mazzarella L, Zagari A. Crystallization of the collagen-like polypeptide (PPG)<sup>10</sup> aboard the International Space Station. 2. Comparison of crystal quality by X-ray diffraction. *Acta Crystallography*, Section D Biological Crystallography. 58:1695–1699, 2002.

Castagnolo D, Piccolo C, Carotenuto L, Vegara A, Zagari A. Crystallization of the collagen-like polypeptide (PPG)<sup>10</sup> aboard the International Space Station. 3. Analysis of residual acceleration-induced motion. *Acta Crystallographica*. Section D, Biological Crystallography. 59(pt4):773–776, 2003.

Lorber B. The crystallization of biological macromolecules under microgravity: a way to more accurate three-dimensional structures? *Biochimica et Biophysica Acta*. 1599(1–2):1–8, 2002.

Vergara A, Corvino E, Sorrentino G, Piccolo C, Tortora A, Caritenuto L, Mazzarella L, Zagari A. Crystallization of the collagen-like polypeptide (PPG)<sup>10</sup> aboard the International Space Station. 1. Video observation. *Acta Crystallography*, Section D Biological Crystallography. 58:1690–1694, 2002.

Vergara A, Lorber B, Zagari A, Giege R. Physical aspects of protein crystal growth investigated with the Advanced Protein Crystallization Facility in reduced gravity environments. *Acta Crystallographica*, Section D. 59:2–15, 2002.

Vergara A, Lorber B, Sauter C, Giege R, Zagari A. Lessons from crystals grown in the Advanced Protein Crystallization Facility for conventional crystallization applied to structural biology. *Biophysical Chemistry*. 118:102–112, 2005.



Camelid crystals, complexed with lysozyme, grown in the APCF during ISS Expedition 3.

## COMMERCIAL GENERIC PROTEIN CRYSTAL GROWTH-HIGH DENSITY (CPCG-H)

Principal Investigator(s): Lawrence DeLucas, Center for Biophysical Sciences and Engineering, University of Alabama, Birmingham, Ala.  
Expeditions 2, 4

### Research Area Physical and Biological Sciences

Proteins provide the building blocks of our bodies. Some proteins make it possible for red blood cells to carry oxygen while other proteins help transmit nerve impulses that allow us to see, hear, smell, and touch. Still other proteins play crucial roles in causing diseases. Pharmaceutical companies may be able to develop new or improved drugs to fight those diseases once the exact structure of the proteins are known.

The goal of the Commercial Protein Crystal Growth–High-density (CPCG-H) payload is to grow high-quality crystals of selected proteins so that their molecular structures can be studied. On Earth, gravity often has a negative impact on growing protein crystals. In microgravity, however, gravitational disturbances are removed, thus allowing some crystals to grow in a more regular and perfect form. During ISS Expeditions 2 and 4, CPCG-H was outfitted with High-density Protein Crystal Growth (HDPCG) hardware. HDPCG was a vapor-diffusion facility that could process as many as 1008 individual protein samples. The entire HDPCG assembly had four trays that held 252 protein crystal growth blocks, each consisting of six chambers. The chambers had a protein reservoir, a precipitant reservoir, and an optically clear access cap. The chambers were designed to reduce sedimentation problems and to produce highly uniform, single crystals.

The primary proteins involved in the testing of the CPCG-H hardware during ISS Expeditions 2 and 4 were mistletoe lectin-I (ML-I), *Thermus flavus* 5S RNA, brefeldin A-ADP ribosylated substrate (BARS), and a triple mutant myoglobin (Mb-YQR). ML-I is a ribosome inactivating protein that can stop protein biosynthesis (creation of proteins) in cells, and is also a major component of drugs used in the treatment of cancer. Although the study of *Thermus flavus* 5S RNA has been ongoing for well over 30 years, the exact function of this protein remains obscure. Scientists believe that the crystallization of different domains of this protein may reveal functional properties. BARS is an enzyme involved in membrane fission, catalyzing the formation of phosphatidic acid by transfer. Mb-YQR was studied to assess the functional role of packing defects in proteins. The elucidation of these protein structures will provide valuable insight into the role of these proteins for application in the pharmaceutical industry.



ISS004E10827 — Astronaut Carl E. Walz, Expedition 4 flight engineer, works in the U.S. Destiny laboratory installing the CRIM-M. CRIM-M provides the temperature control that is critical to the success of CPCG-H experiments.

### RESULTS

Preliminary analysis indicated that at least 65% of the macromolecules flown in the CPCG-H experiments produced diffraction-sized crystals. X-ray diffraction studies of these crystals were conducted, and the data were used to determine and refine the three-dimensional structures of these macromolecules. Three benchmark proteins, ML-I, *Thermus flavus* 5S RNA, and BARS, were flown to validate the performance of the hardware. Diffraction-quality crystals, which were obtained from all of these proteins, crystals yielded X-ray diffraction data comparable to those previously collected on Earth-grown crystals. Since the structure of each of the benchmark proteins is known

to high resolution, these results indicate that the new HDPCG assembly worked very well, successfully producing high-quality crystals of the benchmark proteins.

Synchrotron diffraction data collected from the space crystals of the BARS protein were comparable in resolution but more intense and showed significantly less mosaicity than data from Earth-grown crystals. This indicates that the space-grown crystals had a higher order at the molecular level, and the X-ray diffraction data from the space crystals produced a more complete data set. These results contributed significantly to the structural study of BARS (Nardini et al. 2002).

ML-I is an enzyme that has the ability to inactivate ribosomes and inhibit cell replication. It is a target for new cancer treatments. Crystals of the protein attached to adenine (one of five building blocks of DNA or RNA) were flown, and these crystals yielded X-ray data to 1.9 Å. These data were used to refine the structure of the complex and were especially valuable in refining the active site conformation (Krauspenhaar et al. 2002).

Perhaps the most exciting results from the macromolecular crystallization experiments conducted in the CPCG-H hardware were obtained from the *Thermus flavus* 5S rRNA [ribosomal ribonucleic acid] experiments. These experiments involved a synthetic RNA duplex of 5S rRNA, which is a model system for the study of the binding of ribosomal RNA to proteins. Crystallization under microgravity provided crystals of significantly higher quality than those grown in one-g. The space crystals diffracted to a maximum resolution of 2.6 Å in contrast to the best Earth-grown crystals, which diffracted to 2.9 Å. The improved X-ray data facilitated the completion of the structure of the RNA segment (Vallazza et al. 2002).

To understand the true function of a protein, the structure must be determined. The model of the structure must be accurate to allow scientists to create compounds that bind to the protein. The elucidation of the protein structure is of major importance with complex proteins (proteins that have significant folding). The three-dimensional structure of the triple mutant protein Mb-YQR was solved by growing the protein on ISS during Expeditions 2 and 4. Following return to Earth, three-dimensional models were created of the Mb-YQR proteins grown in space using X-ray crystallography techniques (Miele et al. 2004).

Structural studies of microgravity-grown crystals have provided important information for the development of new drugs. For example, previous studies conducted using crystals grown on shuttle flights have been used in the design of inhibitors, which may serve as broad-spectrum antibiotics. The CPCG-H payload offers a great increase in the amount of space available for protein crystal growth, enhancing the space station's research capabilities and commercial potential.

#### **PUBLICATION(S)**

Krauspenhaar R, Rypniewski W, Kalkura N, Moore K, DeLucas L, Stoeva S, Mikhailov A, Voelter W, Betzel C. Crystallisation under microgravity of mistletoe lectin-I from *Viscum album* with adenine monophosphate and the crystal structure at 1.9Å resolution. *Acta Crystallographica*. Section D, Biological Crystallography. 58:1704–1707, 2002.

Miele AE, Federici L, Sciara G, Draghi F, Brunori M, Vallone B. Analysis of the effect of microgravity on protein crystal quality: the case of a myoglobin triple mutant. *Acta Crystallographica*. Section D, Biological Crystallography. D59:928–988, 2004.

Nardini M, Spano S, Cericola C, Pesce A, Damonte G, Luini A, Corda D, Bolognesi M. Crystallization and preliminary X-ray diffraction analysis of brefeldin A-ADP ribosylated substrate (BARS). *Acta Crystallographica*. Section D, Biological Crystallography. 58:1068–1070, 2002.

Vallazza M, Banumathi S, Perbandt M, Moore K, DeLucas L, Betzel C, Erdmann V. Crystallization and Structure Analysis of *Thermus flavus* 5S rRNA helix B. *Acta Crystallographica*. Section D, Biological Crystallography. 58:1700–1703, 2002.

## DYNAMICALLY CONTROLLED PROTEIN CRYSTAL GROWTH (DCPCG)

Principal Investigator(s): Lawrence DeLucas, University of Alabama, Birmingham, Ala.  
Expedition 3

### Research Area Physical and Biological Sciences

Researchers have found that it is possible to grow high-quality protein crystals in the weightlessness of low Earth orbit, where gravitational forces will not distort or destroy a crystal's delicate structure. When crystals are returned to Earth, their structure is examined by sending X rays through them and using the resulting data to create computer-based models.

The goal of the Dynamically Controlled Protein Crystal Growth (DCPCG) experiment was to control and improve the crystallization process by dynamically controlling the elements that influence crystal growth. Current growth methods provide little or no control over growth rate and separation of the nucleation and growth phases. The DCPCG system provided researchers real-time control of the diffusion process (supersaturation) through control of the protein concentration. It also determined the differences in vapor diffusion rates (the speed at which the liquid surrounding a protein solution evaporates, leaving behind a protein crystal) between experiments conducted in microgravity and similar experiments conducted on Earth. DCPCG quantified the basic differences between crystal growth on Earth and in space, differences in growth rate and in the way crystals moved and organized in the two environments, thereby allowing researchers to assess in detail the best systems with which to grow high-quality crystals and how to optimize those systems.

Four different proteins were flown in DCPCG during Expedition 3. These proteins were glucose isomerase (an enzyme that catalyzes the conversion of glucose to fructose), equine serum albumin (a blood plasma protein that is produced in the liver and forms a large proportion of all plasma proteins), VEE capsid (target protein in the development of antiviral drugs to fight Venezuelan Equine Encephalitis (VEE)), and a chaperone protein that catalyzes the correct folding of newly synthesized proteins. DCPCG consists of a Vapor Locker (V-Locker) connected to a Command and Data Management Locker (C-Locker) installed in EXPRESS Rack 1. The V-Locker contained 38 growth chambers surrounded by a closed-loop nitrogen management subsystem. Dry nitrogen flowing through the subsystem caused liquid to evaporate from the growth chambers. An in-line moisture sensor provided feedback as to how much of the liquid had evaporated. A static light-scattering sensor allowed researchers to modify the rate of evaporation, giving them far more control over the crystal growth process than is afforded by other methods. The C-Locker housed the electronics and data ports for the experiment. A large portion of the C-Locker is the ancillary equipment area (AEA) drawer, which contains a selection of tools and equipment for the experiment: a CD-ROM, spare flash disks, connector covers, and a tool for activating the experiment hardware.



ISS003E8171 — Close-up image of DCPCG hardware, the V-Locker, and the C-Locker in EXPRESS Rack 1 on ISS Expedition 3.

### RESULTS

DCPCG was the first flight test of an apparatus designed to control the crystal growth process by controlling the rate of evaporation. The apparatus worked on orbit, and crystals were grown for the test proteins; however, the investigators determined that the growth could have been better. The same apparatus was used in extensive testing on the ground. Researchers tested a selection of protein solutions, including insulin (a hormone produced by the pancreas to regulate the metabolism and use of sugar), serum albumin, and lysozyme (an enzyme that attacks bacteria) and found that a slower evaporation rate yielded better results than a more rapid evaporation rate. While the results of the ground tests were published, the DCPCG experiment investigators did not seek to publish any structures from crystals grown in orbit.

### PUBLICATION(S)

Collingsworth OD, Bray L, Christopher GK. Crystal growth via computer controlled vapor diffusion. *Journal of Crystal Growth*. 219:283-289, 2000. (Results from ground controls grown in parallel with ISS samples.)

## PROTEIN CRYSTAL GROWTH-ENHANCED GASEOUS NITROGEN (PCG-EGN)

Principal Investigator(s): Alexander McPherson, University of California, Irvine, California  
Expeditions 0 (prior to human occupation of ISS), 1, 2, 4

### Research Area Physical and Biological Sciences



Crystal of trypsin that was grown in microgravity during ISS Expedition 4.

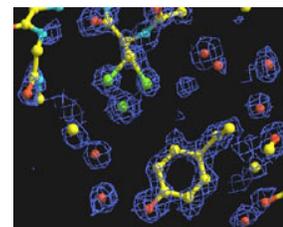
The microgravity environment on board the ISS is relatively free from the effects of sedimentation and convection and can provide an exceptional environment for crystal growth. Uniform, large, crystals are key for determining the structure of protein and other large biological molecules.

The primary purpose of this experiment was to provide a simple trial platform for the production of a large number of crystals of various biological macromolecules. A second objective was an education program called “Student Access to Space” in which students participated in preparing some of the samples that were flown on orbit and learned about crystallization, the methods of analysis of crystals, and the impact of studies of crystals on advancing biotechnology, medicine, and basic research in structural biology. Through the Student Access to Space program, more than 500 samples were mixed by middle and high schools across the United States.

Protein Crystal Growth-Enhanced Gaseous Nitrogen (PCG-EGN) samples were brought to station frozen in liquid nitrogen in a Dewar (a stainless-steel and aluminum container assembly that is similar to a Thermos bottle) at  $-196^{\circ}\text{C}$  ( $-321^{\circ}\text{F}$ ) in sealed plastic capillary tubes. On board ISS, the nitrogen warmed and boiled off, turning into a gas, and the samples began to thaw. After eight days, when the samples had reached the station ambient temperature of  $22^{\circ}\text{C}$  ( $71.6^{\circ}\text{F}$ ), crystals began to form.

### RESULTS

Successful crystallization rates were as follows: Expedition 0 (prior to permanent human occupation of ISS), ten of 24 proteins and viruses; Expedition 1, four of 23 proteins and viruses; Expedition 2, six of eight proteins and both viruses; Expedition 4, three of nine proteins and zero of two viruses. Major crystals obtained included Bence-Jones protein, Bromegrass Mosaic Virus, canavalin, lysozyme, pea lectin, thaumatin, trypsin, and 4a-hydroxy-tetrahydropterin dehydratase (DcoH). Overall the rate of successful crystallizations was not as high as expected. Although many of the crystals produced were no better than those obtained in the ground laboratory, there were still some significant structural results.



Electron density map of thaumatin crystal grown on ISS during Expedition 2.

When compared to their Earth-grown counterparts, the space-grown thaumatin crystals diffracted to a higher resolution, and some crystals showed as much as 40% more intensity during the diffraction process. This resulted in a more accurate protein structure model (electron density map) being produced from the space-grown crystal data. The pea lectin crystals also diffracted to higher resolution than their Earth-grown counterparts. Data from the space-grown crystals were the best obtained, giving rise to the highest resolution structure for pea lectin. A refinement for the structural model of pea lectin is in progress. DcoH crystals grown on Expedition 1 also appeared to be of better quality than those grown on Earth.

Student investigations across the four Expeditions were successful in crystallizing a number of proteins. Although many of the crystals did not appear to be better than previously analyzed crystals, some of the crystals from Expedition 2 were used for microscopic observation and X-ray examination.

### PUBLICATION(S)

Barnes CL, Snell EH, Kundrot CE. Thaumatin crystallization aboard the International Space Station using liquid-liquid diffusion in the Enhanced Gaseous Nitrogen Dewar (EGN). *Acta Crystallographica*. Section D, Biological Crystallography. 58(Pt 5):751–760, 2002.

Ciszak E, Hammons AS, Hong YS. Use of Capillaries for Macromolecular Crystallization in a Cryogenic Dewar. *Crystal Growth & Design*. 2(3):235–238, 2002.

## **PROTEIN CRYSTAL GROWTH-SINGLE LOCKER THERMAL ENCLOSURE SYSTEM (PCG-STES), NINE INVESTIGATIONS**

- Payload Developer: Marshall Space Flight Center, Huntsville, Ala.  
Expeditions 2, 4–6, samples held on board and returned during Expedition 11
- Principal Investigator(s): Daniel Carter, New Century Pharmaceuticals, Inc., Huntsville, Ala., Protein Crystal Growth Facility-based Hardware: Science and Applications (PCG-STES-SA, Expeditions 2, 4–6)
- Aniruddha Achari (Technical Investigator), Raytheon, Huntsville, Ala., Vapor Equilibration Kinetic Studies (PCG-STES-VEKS, Expeditions 2, 4–6)
- Craig Kundrot, Marshall Space Flight Center, Huntsville, Ala., Optimizing the Use of Microgravity to Improve the Diffraction Quality of Problematic Biomacromolecular Crystals (PCG-STES-IDQC, Expeditions 2, 4–6)
- Gloria Borgstahl, University of Toledo, Toledo, Ohio, and the University of Nebraska Medical Center, Omaha, Neb., Searching for the Best Protein Crystals: Synchrotron Based Mosaicity Measurements of Crystal Quality and Theoretical Modeling, and Searching for the Best Crystals: Integration of Synchrotron-Based Crystal Quality Measurements and Structure Determination (PCG-STES-MM, Expeditions 4, 5)
- Geoffrey Chang, Scripps Research Institute, La Jolla, Calif., Crystallization of the Integral Membrane Protein Using Microgravity (PCG-STES-IMP, Expedition 5)
- Barbara Golden, Purdue University, West Lafayette, Ind., Engineering a Ribozyme for Diffraction Properties (PCG-STES-RDP, Expedition 5)
- Ronald Kaplan, The Chicago Medical School, Chicago, Ill., Crystallization of the Mitochondrial Metabolite Transport Proteins (PCG-STES-MMTP, Expedition 5)
- Bill Thomas, Universities Space Research Association, Huntsville, Ala., Crystal Growth Model System for Material Science (PCG-STES-MS, Expedition 6)
- Gerald Bunick, Oak Ridge National Laboratory, Oak Ridge, Tenn., Regulation of Gene Expression (PCG-STES-RGE, Expedition 6)
- Associate Investigators: Wayne Shultz, Hauptman-Woodward Institute, Buffalo, N.Y.; Debashis Ghosh, Hauptman-Woodward Institute, Buffalo, N.Y.; D. A. A. Myles, European Molecular Biology Laboratory, Grenoble, France; Naomi Chayen, Imperial College, London; Jean-Paul Declercq, University of Louvain, Louvain-la-Neuve, Belgium

### **Research Area** Physical and Biological Sciences

The Protein Crystal Growth-Single Locker Thermal Enclosure System (PCG-STES) is a suite of protein crystal growth investigations performed in the station's U.S. Destiny laboratory. Multiple independent and collaborating principal investigators contributed samples and evaluated the technology for crystal growth in space. In general these studies sought to grow crystals of target proteins that would be of superior quality to similar crystals grown on the ground. The sedimentation and convection forces that cause many Earth-grown crystals to be irregular in shape and small in size are absent in microgravity.

### **SCIENCE AND APPLICATIONS (CARTER)**

These investigations focused on the hardware that provided a suitable environment for crystal growth in microgravity. Samples were housed in the PCG-STES and within two different types of crystallization hardware: the Protein Crystallization Apparatus for Microgravity (PCAM) or the Diffusion-Controlled Crystallization Apparatus for Microgravity (DCAM).

PCAMs consist of nine trays, each containing seven vapor-equilibration wells. The nine trays are sealed inside a cylinder. Crystals are formed by the "sitting drop" method of vapor diffusion. Each sample well holds a drop of protein solution and precipitant (salts or organic solvents, which draw water away from the protein solution) mixed

together. A surrounding moat holds a reservoir, filled with an absorbent fluid, that draws moisture away from the mixed solution. Crystals form as the moisture is absorbed. A rubber seal pressed into the lip of the reservoir keeps crystals from forming on Earth or from bouncing out of their wells during transport. Each cylinder holds 63 experiments for a total of 378 experiments inside the Single-locker Thermal Enclosure System (STES). PCAM was used for all samples during Expeditions 2, 4, and 5.

DCAMs, which are slightly smaller than a 35mm film canister, each contained two cylindrical chambers that are connected by a tunnel. One chamber holds the precipitant solution and the other contains the protein sample. A thin semipermeable membrane covers the protein sample that allowed the precipitant to pass through at a controlled rate. The rate of diffusion was controlled by a porous plug that separates the two chambers. This is referred to as the liquid-liquid diffusion method. Eighty-one DCAMs, which were housed inside the STES, were used for all samples during Expedition 6.

The STES provides a controlled temperature environment between 1°C and 40°C in which to grow large, high-quality crystals. Its thermal control system (TCS) regulates the temperature inside the payload chamber. A fan pulls cabin air through an intake on the front panel, causing the air to flow across the heat exchanger fans and then out the rear left side of the unit. Pushbuttons and a liquid crystal display (LCD) on the front panel allow the station crew to command the unit. STES can also be commanded from the ground.

These investigations also focused on key proteins of the circulatory system such as human serum albumin, human antithrombin III, and human peroxiredoxin 5 (PRDX5). In addition, S-layer protein from *Bacillus sphaericus*, cytochrome p450, and c-phycoerythrin from *Synechococcus elongatus* were flown as part of associate investigations during Expedition 5.

#### **VAPOR EQUILIBRATION KINETIC STUDIES (ACHARI)**

In a technical investigation associated with the use of PCG-STES, crystallization conditions were varied experimentally, including days to activate the crystallization, droplet volumes, and different precipitants. By characterizing the time crystallization took to reach equilibrium in microgravity, the goal was to help identify optimum crystallization conditions.

#### **IMPROVED DIFFRACTION QUALITY OF CRYSTALS (KUNDROT)**

These experiments focused on the growth of better quality crystals for X-ray diffractions analysis. During ISS Expedition 2, two types of samples were selected. The first was a complex of basic fibroblast growth factor (bFGF) (a fibroblast is a cell from which connective tissue develops) and 19t2mod, a 42-nucleotide DNA that inhibits bFGF activity (inhibition of bFGF activity is a type of anti-cancer therapy). The second sample type was the plant protein thaumatin. Thaumatin, which is a protein from the katemfe fruit of West Africa, is an extremely potent sweetener. The objective of this sample type was to determine whether some of the chemical conditions that do not produce crystals on Earth would produce crystals in microgravity. In addition to the samples above, two further proteins, rDerf2 and glucocerebrosidase, were flown as part of an associate investigation during Expeditions 4 and 5. A deficiency of  $\beta$ -glucocerebrosidase leads to Gaucher's disease, which is a rare chronic disorder of cerebrosidase metabolism that is characterized by enlargement of the spleen, skin pigmentation, and bone lesions.

#### **SUPEROXIDE DISMUTASE (BORGSTAHL)**

During Expedition 4, this investigation focused on the crystallization of human Replication Protein A (RPA) and manganese superoxide dismutase (SOD) to be used in ground-based X-ray diffraction studies to understand the atomic structure. Human RPA is a single-stranded DNA binding protein that is used in DNA metabolism (replication, transcription, recombination, and repair). SODs are antioxidant enzymes that protect living cells against oxide radicals that are associated with cell damage.

#### **INTEGRAL MEMBRANE PROTEINS (CHANG)**

This Expedition 5 investigation focused on the crystallization of two transporter proteins, *Escherichia coli* (*E. coli*) MsbA and EmrE. *E. coli* MsbA is a protein transporter responsible for transporting lipopolysaccharides and phospholipids from the inner membrane of the bacteria cell to the outer membrane, increasing the cell wall strength. It is theorized that antibiotics are transported out of the bacteria cells using this type of transporter protein and that knowledge of the structure of this protein could help develop a new class of drugs to supplement antibiotics. *E. coli* EmrE is of interest because its production is associated with antibiotic resistance.

### **RIBOZYME FOR DIFFRACTION PROPERTIES (GOLDEN)**

This Expedition 5 investigation focused on the crystallization of a molecular engineered RNA enzyme. RNA enzyme, which is also called a ribozyme, is an RNA molecule that is responsible for catalyzing its own cleavage or the cleavage of other RNA strands. For this investigation, a ribozyme was engineered to be used to examine the Group I introns (a segment of RNA that is not coded for a gene) through X-ray crystallography to get a detailed view of the ribozyme active site at the atomic level.

### **MITOCHONDRIAL METABOLITE TRANSPORT PROTEINS (KAPLAN)**

This Expedition 5 investigation focused on the crystallization of the mitochondrial citrate transporter protein (CTP). Mitochondria are round or rod-shaped organelles that are located in most cells and that produce enzymes for the metabolic conversion of food to energy (citric acid cycle). CTP is an important part in cellular metabolism.

### **CRYSTAL GROWTH MODEL SYSTEM (THOMAS)**

This Expedition 6 investigation used Ferritin and Apoferritin as a crystal growth model system to look at fundamental protein biochemistry.

### **REGULATION OF GENE EXPRESSION (BUNICK)**

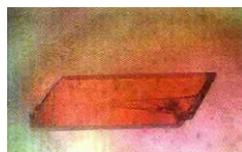
This Expedition 6 investigation focused on the crystallization of two different proteins, nucleosome core particle and D-xylose ketol-isomerase (xylose isomerase). The nucleosome core particle is a building block of chromatin, which is found in the nucleus and is responsible for gene expression and housing DNA. This investigation examined the structure-function relationship in chromatin. Xylose isomerase is an enzyme that is used in the food industry to convert glucose to fructose.

### **RESULTS**

PCG-STES is a suite of nine experiments with additional shared samples for associated investigators. Samples were taken to and from station five times for crystallization during Expeditions 2, 4, 5, and 6. The logistical considerations of space flight affected some of the results, as flight delays compromised some samples, and a jarring drop of the hardware shortly after return on 11A/STS-113 probably destroyed any larger crystals that had formed during that set of runs. PCG-STES samples in DCAM were on orbit prior to the space shuttle *Columbia* accident, and then spent an unprecedented 981 days (Nov 2002–Aug 2005) on ISS before being returned on the next space shuttle flight.



DCAM trays shown in the STES.



A manganese superoxide dismutase (MnSOD) crystal grown in microgravity. The pink color is a result of oxidized manganese in the active site.



- (a) PCAM trays with seven experimental cells.
- (b) Nine trays are housed in one cylinder.
- (c) Six cylinders fit into a thermal carrier and are housed in an EXPRESS Rack on board ISS.

Not surprisingly, given the wide array of materials and objectives, some samples did produce large crystals, while other samples produced crystals no better than those produced on Earth. Yet other samples failed to crystallize at all.

Crystals of MnSOD, produced during Expedition 4, exhibited an 80-fold volume increase when compared to the crystals produced on Earth. The crystals that were produced in orbit ranged from small, needle-like crystals to large three-dimensional crystals. These crystals were used for Synchrotron X-ray analysis, the use of a high-energy, adjustable particle beam used for crystal diffraction. Through this analysis it was determined that the diffraction resolution and quality of data for the crystals produced in microgravity were increased when compared to the diffraction resolution of the crystals grown on Earth (Vahedi-Faridi et al. 2003).

High-resolution structural data were also obtained from human albumin and human antithrombin III crystals, and publications of new structural information is anticipated. Analyses of the samples returned in August 2005 is ongoing.

#### **PUBLICATION(S)**

Vahedi-Faridi A, Porta J, Borgstahl G. Improved three-dimensional growth of manganese superoxide dismutase crystals on the International Space Station. *Acta Crystallographica*. Section D, Biological Crystallography. 59:385–388, 2003.



ISS005E21531 — Astronaut Peggy A. Whitson, Expedition 5 science officer, works the PCG-STES hardware on board ISS.



## **CELLULAR BIOLOGY AND BIOTECHNOLOGY**

*In a microgravity environment, physical controls on the directionality and geometry of cell and tissue growth can be dramatically different to those on Earth. Various experiments have used the culture of cells, tissues, embryos, and small organisms on orbit as a tool to increase our understanding of biological processes in microgravity.*

## AVIAN DEVELOPMENT FACILITY (ADF), TWO INVESTIGATIONS

Principal Investigator(s): J. David Dickman, Washington University, St. Louis, Mo. , Development and Function of the Avian Otolith System in Normal and Altered Gravity Environments (ADF-Otolith)

Stephen B. Doty, Hospital for Special Surgery, New York, N.Y., Avian Development Facility- Skeletal Development In Embryonic Quail (ADF Skeletal)

Expedition 4

**Research Area** Physical and Biological Sciences



The avian hatching habitat with the exterior panels removed.

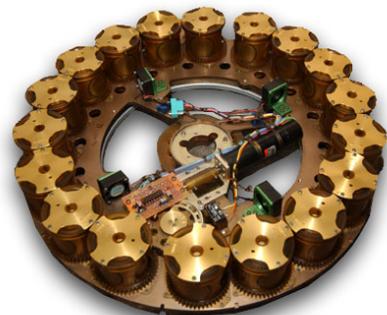
The avian development biology experiment, which is a tool for the study of embryogenesis in space, provides the support hardware needed for researchers to better understand and mitigate or nullify the forces of altered gravity on embryo development. Avian eggs are ideal for studying embryo development since they are self-contained and self-sustaining and can be nurtured without a maternal host. The Avian Development Facility (ADF) allows incubation of avian eggs under controlled conditions (humidity, temperature, and gas environment) on orbit and the fixation of the eggs for study while minimizing the effects of launch and landing. Up to 36 eggs in centrifuge carousels can be exposed to simulated gravity of zero-g to one-g in 0.1-g increments.

During its flight on space shuttle mission STS-108 to the ISS, the ADF housed two investigations: the Development and Function of the Avian Otolith System in Normal and Altered Gravity Environments (ADF-Otolith) and the Skeletal Development in Embryonic Quail on the ISS (ADF-Skeletal) investigations.

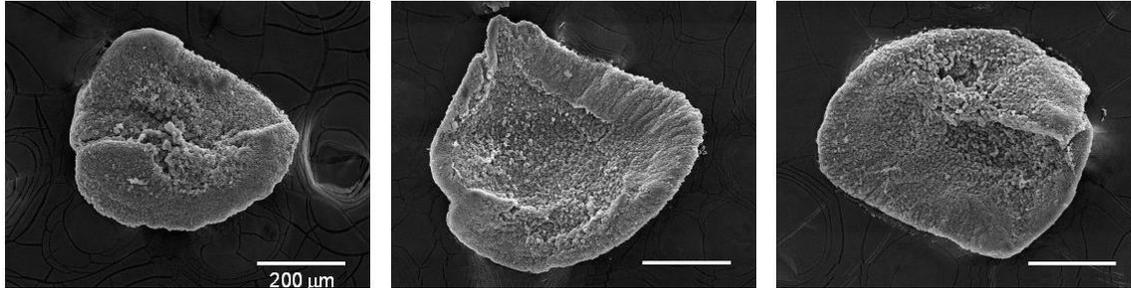
### ADF-OTOLITH (DICKMAN)

The otolith system (small bones of the inner ear) in all vertebrates functions to detect head position and movement relative to gravity depending on neuromotor responses. The avian otolith system offers an excellent model with which to study the effects of gravity upon development due to the short maturation period following fertilization and due to the extensive knowledge of otolith system structure and function in birds.

One of two ADF carousels, each featuring 18 sample containers. During space missions, one carousel rotates at 77.3 revolutions per minute (RPM) to simulate a one-g gravity field. The other carousel remains motionless to provide a microgravity environment for the specimens inside. In addition to eggs, the ADF can carry fish, plants, insects, or cells in its sample containers.



Otoliths are part of the vestibular system (balance system) in vertebrates and are an essential component in the production of movement-related responses that are critical for daily function and survival. During space flight, vestibular disturbances are frequently reported by astronauts, with approximately 80–90% of current astronauts experiencing some symptoms of space motion sickness (disorientation and nausea) during the first 48–72 hours of weightlessness.



Scanning electron micrographs of fused otoconial stones from embryonic day 12 quail embryos. Three saccule stones are shown, one each from an embryo raised from fertilization in zero-g (left), one-g flight (middle), and two-g laboratory centrifugation (right).

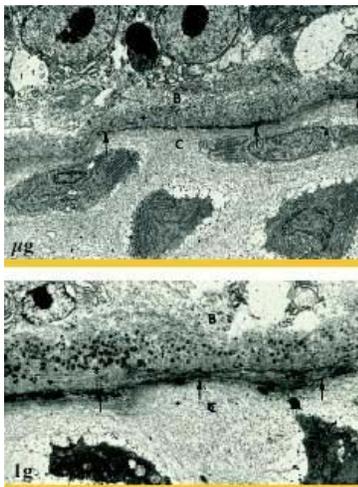
Many scientists have suggested that lack of gravity as a constant stimulus during space flight produces significant changes in vestibular system function. Preliminary studies indicate that the structure and function of the vestibular system is affected by exposure to microgravity. For example, changes in size of otoconia in the receptor-afferent morphology, hair cell conductance, vestibular afferent responsiveness, vestibular central pathways, and vestibular-related neuromotor responses have all been observed in both adult and developing animals that are exposed for brief periods to either microgravity or hypergravity.

## RESULTS

The inner ear bones in the embryos that developed in microgravity appear to be larger than those found in the controls that remained on Earth. There are some indications that the fan-shaped arrangement of receptor cells may also be altered under the influence of microgravity. Conclusive data from this investigation are pending further analysis.

## ADF-SKELETAL (DOTY)

The objective of this experiment was to define the effects of space flight on embryonic skeletal development. This investigation was a stepping-stone in determining the effect of microgravity on the molecular and cellular biology of bone formation and loss. Many of the biological processes observed in bone formation during embryogenesis (development and growth of an embryo) also occur in the adult skeleton during fracture repair. Furthermore, previous space flight studies identified bone demineralization and bone density loss in embryo quails, which was similar to what is observed in adult humans with osteoporosis. However, up to a certain developmental age embryonic quail bones will rapidly recover from this condition when re-exposed to gravity; whereas humans suffering from bone loss can take years to recover. Therefore, the data gained from this study should provide a foundation of future studies on bone demineralization and density loss and provide insight into the mechanisms involved in the full re-mineralization of bones.



Electron micrographs of quail limb bones formed under the influence of microgravity show decreased mineralization compared to bones formed in normal gravity. The bone that developed during space flight (top) shows less mineral compared to the control sample (bottom); the control sample clearly shows mineral deposits (dark spots) that are absent in the space flight sample.

## RESULTS

No space flight effects were observed for osteocalcin levels in the day 12 embryos, based on bone matrix staining. Since osteocalcin reflects the degree of bone mineralization, this would suggest that mineralization is not affected in an older embryo. However, direct mineralization quantitative studies have not been reported for day 7 and day 12 embryos, which should provide definitive evidence for whether osteocalcin-associated processes are affected.

The second finding was that the space flight embryos on the spinning carousel or stationary carousel had a reduced level of collagen-synthesizing activity as compared to the ground control specimens, although the sample size was small. If this trend is validated, it would suggest that space flight has a component that can affect collagen synthesis that is not correctable by an applied one-g force. These insights might be important for the development of appropriate countermeasures for space travel. Final analyses and publication of results are pending.

## CELLULAR BIOTECHNOLOGY OPERATIONS SUPPORT SYSTEM (CBOSS), SEVEN INVESTIGATIONS

Payload Developer: Johnson Space Center, Houston, Tex.  
Expeditions 3, 4 for cell cultures, Expeditions 8, 10, 12, ongoing for Fluid Dynamics Investigation

Principal Investigator(s): Timothy G. Hammond, Tulane University Medical Center, New Orleans, La., Human Renal Cortical Cell Differentiation and Hormone Production (CBOSS 01 02-RENAL, Expeditions 3, 4)

J. Milburn Jessup, Georgetown University Medical Center, Washington, D.C., Use of NASA Bioreactor to Study Cell Cycle Regulation Mechanisms of Colon Carcinoma Metastasis In Microgravity (CBOSS-01-Colon, Expedition 3)

Jeanne L. Becker, University of South Florida, Tampa, Fla., Evaluation of Ovarian Tumor Cell Growth and Gene Expression (CBOSS-01-Ovarian, Expedition 3)

Peter Lelkes, Drexel University, Philadelphia, Penn., PC12 Pheochromocytoma Cells: A Proven Model System for Optimizing Three Dimensional Cell Culture Biotechnology in Space (CBOSS-01-PC12, Expedition 3)

Arthur J. Sytkowski, Beth Israel Deaconess Medical Center, Boston, Mass., Production of Recombinant Human Erythropoietin by Mammalian Cells (CBOSS-02-Erythropoietin, Expedition 4)

Joshua Zimmerberg, National Institutes of Health, Bethesda, Md., Simulated Microgravity Applications Towards the Study Of HIV: The Effect of Microgravity on the Immune Function of Human Lymphoid Tissue (CBOSS-02-HLT, Expedition 4)

J. Milburn Jessup, Georgetown University Medical Center, Washington, D.C., Joshua Zimmerberg, National Institutes of Health, Bethesda, Md., Cellular Biotechnology Operations Support Systems: Fluid Dynamics Investigation (CBOSS-FDI, Expeditions 8, 10, 12, ongoing)

### **Research Area** Physical and Biological Sciences

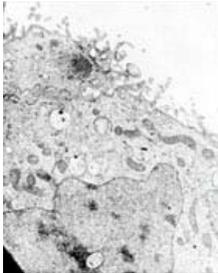
The purpose of the Cellular Biotechnology Operations Support System (CBOSS) study was to support biotechnological research on board ISS by providing a stable environment in which to grow cells. The system was a multi-component cell incubator intended to grow three-dimensional clusters of cells in microgravity. A self-contained apparatus, CBOSS was designed to allow multiple experiments to be performed, thereby enabling scientists to study various types of cells operating simultaneously.



ISS003328030 — Frank L. Culbertson, Jr., Expedition 3 mission commander, works at the biotechnology specimen temperature controller (BSTC) for the CBOSS in the U.S. Destiny laboratory on ISS.

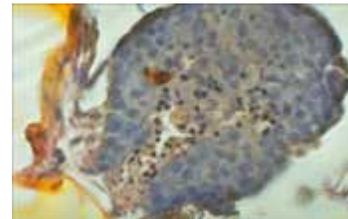
In the human body, cells normally grow within a scaffolding of protein and carbohydrate fibers that creates a three-dimensional structure. But outside the body, cells tend to grow in flat sheets and are incapable of duplicating the structure they normally hold, which can make them behave differently in the laboratory than they would in the body. Past research has shown that cells grown in a microgravity environment arrange themselves into three-dimensional shapes that more closely duplicate how they would behave in the body. Cell culture in microgravity thus becomes a tool for studying cells in a state that is closer to that which occurs normally in the body.

#### **HUMAN RENAL CORTICAL CELLS (HAMMOND)**



Microscopic image of human renal cortical epithelial cells.

To better understand the mechanisms that cause several kidney disorders, human renal cortical epithelial cell lines were grown on station. This experiment used kidney cells to study the mechanism by which the kidney reabsorbs proteins that are filtered from the blood. The goal of this ISS experiment was to again create three-dimensional growth of normal human renal cells, and to assess the production of erythropoietin and vitamin D<sub>3</sub> while assessing the model for production of commercial applications.



Microscopic image of colon carcinoma cell.

#### **COLON CARCINOMA CELLS (JESSUP)**

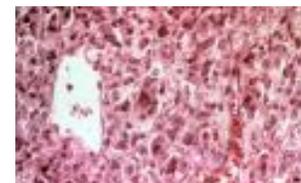
Human colorectal carcinoma cells were grown to test the hypothesis that three-dimensional growth in microgravity facilitates the reprogramming of signal transduction pathways and gene expression as cells differentiate into the two major colonic cell lineages. This differentiation is important because it may inhibit cancer growth and, if applied to developing cancers, may block the emergence of new cancer formation. The unique environment of microgravity can provide insight into growth, maturation, and death of this type of cancer cells.

#### **OVARIAN TUMOR CELLS (BECKER)**

The goal of this study was to characterize the complex three-dimensional development of the human Müllerian ovarian (LN1) tumor cell line to characterize morphological changes that occur during three-dimensional growth. This study also sought to determine accompanying alterations in cell cycle kinetics, cell cycle proteins, and cellular oncoproteins. Cells were preserved in RNAlater, a fixative that allows cells to remain stable at refrigerator temperatures (4°C, 39°F) for up to 30 days. Following return to Earth after three months on ISS, the cells were analyzed for antigenic stability after removal of RNA using the RNAqueous kit. Knowledge gained from this experiment could help define mechanisms in tumor cell development that can be targeted for treatment of patients with ovarian cancer.

#### **PC12 PHEOCHROMOCYTOMA CELLS (LELKES)**

Neuroendocrine cells (PC12) are cells that receive electric signals from the nervous system and chemical signals secreted from glands. As they differentiate, the cells are known to produce catecholamines, which are key to normal function and pain suppression. Evidence of differentiation is seen in ground-based (simulated) microgravity rotating wall systems. In this experiment, the ability and extent of the differentiation in actual microgravity was assessed by the growth and subculture of these cells to provide a greater understanding of neural regeneration and pain suppression.



Stained microscopic image of neuroendocrine cells.

#### **ERYTHROLEUKEMIA CELLS (SYTKOWSKI)**

Reduced immune system function and anemia related to decreased red blood cell production are two problems that face astronauts after extended durations in space. This experiment was designed to study cells in space to gain insight into the way microgravity affects blood cell formation. EMS-3 cells are Rauscher murine erythroleukemia cells, derived originally from mice infected with the virus that causes erythroleukemia. The EMS-3 cell line serves as an important model system for studying the cellular and molecular aspects of erythropoiesis (red blood cell formation), including the mechanism of action of erythropoietin in vitro under controlled conditions. EMS-3 cells were selected for culture in CBOSS to advance our knowledge of effects of microgravity on the hematopoietic system and to suggest possible in-flight countermeasures and treatments for ground-based disease states.

### HUMAN LYMPHOID TISSUE (ZIMMERBERG)

Impaired immune function has been observed in astronauts during flight, and these observations are bolstered by evidence of lymphocyte dysfunction in the rotating wall vessel (RWV) culture system (the ground-based analog or model for cell culture in microgravity conditions). Using human lymphoid tissue cells that have been isolated from human tonsils and derived from five donors for the experiment, the goal of this study was to determine whether microgravity was detrimental to the immune responses of human lymphoid tissue cell suspensions.

### FLUID DYNAMICS INVESTIGATION (JESSUP AND ZIMMERBERG)

When cells arrive for culture on ISS, they are thawed, injected into a static tissue culture module (TCM) with media (nutrition), and then additional media is added at different times while waste liquid is removed. When these cells are injected or additional media is added to the TCM, it is important that the entire contents of the TCM be uniformly distributed. If cells in one corner of the TCM are not receiving nutrients they will die, causing a leaching of waste products that can be toxic to other cells. There is also the potential for bubble formation in the semi-permeable TCM, which could be deleterious to cells in culture, so procedures are also being developed for their removal. CBOSS-FDI involves a series of experiments aimed at optimizing CBOSS fluid-mixing and bubble-removal operations while contributing to the characterization of the CBOSS stationary bioreactor vessel (the TCM) in terms of fluid dynamics in microgravity. These experiments will validate the most efficient fluid-mixing and bubble-removal techniques on orbit; these techniques are essential to conducting cellular research in microgravity and will enhance the probability of success for future investigations.

### RESULTS

The CBOSS hardware supported six cell culture investigations with different detailed scientific objectives. There were problems in the growth and preservation of all of the cell lines grown on Expeditions 3 and 4. The PC12 and erythroleukemia cells did not survive well in long term culture, so no scientific results are expected from these experiments. It was found that there was more bubble formation than expected that may lead to cell death at the air-liquid interface. Although not well documented in this experiment, it was noted that poor mixing of cells/tissues and medium occurred in the other CBOSS payloads as well. Both the poor mixing and greater than expected bubble formation were important lessons learned that led to the addition of the CBOSS-Fluid Dynamics Investigation (CBOSS-FDI) to study mixing and bubble formation in microgravity on later Expeditions.

Renal cortical cells returned were treated with an RNA stabilizing agent (RNAlater-Ambion) that enabled analyses of both RNA and immunoreactive proteins. The space and ground control cell cultures exhibited similar immunoreactivity profiles for the antibodies tested. These data provide evidence that the techniques used can be generalized to other cell lines, and that RNAlater will provide long-term storage of proteins at 4°C (39°F) for long-duration investigations (Hammond et al. 2006).

Analyses of the returned colon carcinoma cells revealed that the cells had died on orbit. However, ground-based research led to an appreciation of a novel mechanism by which microgravity may kill cells as well as of the role of tumor marker carcinoembryonic antigen (CEA) on preventing cell death. It has been shown that CEA interacts with death receptors on the cell membrane to reduce cell death. Since CEA is important to many of the cancers that afflict men and women in the United States, this is a critical finding that was in large part initiated by studies of growth in simulated microgravity. These results are not yet published, but were presented by Jessup at the Keystone Symposium on “Stem Cells, Senescence and Apoptosis” (Singapore, Oct 25–30, 2005).



ISS004E5210 — Image of the Quad Tissue Culture Module Assembly (QTCMA)-5 on ISS Expedition 4 after activation of the cells. A syringe was used to inject cells into the pink nutrient growth media. When the samples completed their growth cycle, the crew transferred the cells from the incubator to the biotechnology refrigerator, where they were stored until they were examined at a ground-based laboratory.



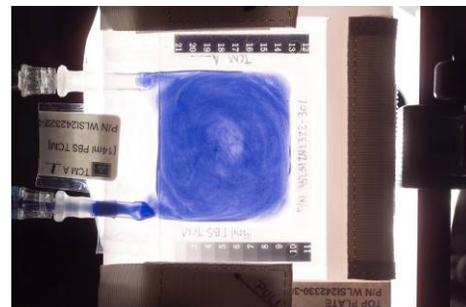
Scanning electron micrograph of a human Müllerian ovarian cell cancer nurtured in microgravity conditions. The three-dimensional structure shown is much closer in true size and form and natural tumor cells found in cancer patients.

The LN1 ovarian cell cultures on board station did not survive in long-term culture. However, the cells grown on ISS were found to have produced reduced amounts of cytokines (small secreted proteins that mediate and regulate immunity, inflammation, and hematopoiesis) compared to the ground controls. The proteins were recovered after the RNA had been removed from the cells via filtration. The novel proteins, vimentin and epithelial membrane antigen (EMA) proteins, were extracted from filtrate of the RNA extraction. Vimentin is the main intermediate filament protein in embryonic cells. It plays an important role in the differential diagnosis of undifferentiated neoplasms (abnormal tissue growths). EMA, which belongs to a family of proteins known as human milk fat globule membrane proteins, is considered a broad spectrum antibody that is reactive against many types of adenocarcinomas. The data obtained from the protein extraction indicate the presence of the antigenic proteins, vimentin and EMA, in RNA-stabilized LN1 cells following long-duration storage at 4°C (39°F). The vimentin and EMA proteins showed similar profiles at different times between the flight and ground

samples. These data provide confirmation that the techniques used can be generalized to other cell lines and that RNA later will provide long-term storage of proteins at 4°C (39°F) for long-duration investigations (Hammond et al. 2005).

The human lymphoid tissue cultures were activated on board station but did not survive in longer-term culture. Early preliminary results, which were in agreement with RWV ground studies (microgravity simulation), indicated that the human tonsil cell suspensions show impaired immune responses in microgravity and that the extent of impairment depended on the activation state of the cells. Cells in all conditions showed metabolic activity, indicating that they were alive. Cells that were activated in microgravity did not demonstrate any increases in antibody or cytokine production; however, if the cells were activated prior to exposure to microgravity, they did demonstrate such responses. These results indicated that microgravity suppresses humoral immune responses in a not dissimilar fashion to that of Human Immunodeficiency Virus on Earth, and that this phenomenon may reflect immune dysfunction observed in astronauts during space flights (Fitzgerald et al. 2006).

For CBOSS-FDI, a series of procedures was performed on Expeditions 8, 10, and 12 to optimize particle mixing and bubble removal. A mixing protocol for particles has been found that appears to be effective and time-efficient, and crew feedback has been very valuable in these studies. Two bubble removal methods were tested. Future experiments will help determine their effectiveness, and a protocol for bubble removal can be created for future tissue culture investigations. This investigation is critical for optimizing cell culture in space and ensuring the success of future investigations.



ISS008E09941 — A CBOSS FDI tissue culture module photographed during Expedition 8.

#### PUBLICATION(S)

Hammond DK, Elliott TF, Holubec K, Baker TL, Allen PL, Hammond TG, Love JE. Proteomic Retrieval from Nucleic Acid Depleted Space-Flown Human Cells. *Gravitational and Space Biology*. 19(2), Jun 2006.

Hammond DK, Becker J, Elliot TF, Holubec K, Baker TL, Love JE. Antigenic Protein in Microgravity-Grown Human Mixed Müllerian Ovarian Tumor (LN1) Cells Preserved in a RNA Stabilizing Agent. *Gravitational and Space Biology*. 18(2):99–100, 2005.

## COMMERCIAL GENERIC BIOPROCESSING APPARATUS (CGBA), THREE INVESTIGATIONS

- Payload Developer: BioServe Space Technologies, Boulder, Colo., Antibiotic Production in Space Expeditions 0 (prior to human occupation of ISS), 2, 4
- Principal Investigator(s): Timothy G. Hammond, Tulane University Medical Center, New Orleans, La., Kidney Cell Gene Expression (CGBA-KCGE, Expedition 0 [prior to permanent human occupation of ISS])
- Haig Keshishian, Yale University, New Haven, Conn., Synaptogenesis In Microgravity (CGBA-SM, Expedition 0 [prior to permanent human occupation of ISS])
- Louis Stodlieck and David Klaus, BioServe Space Technologies, Boulder, Colo., Antibiotic Production in Space (CGBA-APS, Expeditions 2, 4)

### **Research Area** Physical and Biological Sciences

The Commercial Generic Bioprocessing Apparatus (CGBA) provided automated processing for biological experiments. The CGBA can contain up to eight containers that house the experiments, and each container is programmable and temperature controlled between 4°C (39°F) and 37°C (99°F). The CGBA was equipped with data, video, and telemetry electronics to allow telepresence remote operation. Three experiments, discussed below, were conducted in the CGBA.



ISS004E11048 — The CGBA isothermal containment module (ICM) v.3, installed in EXPRESS rack just above astronaut Dan Bursch's extended left arm; photograph taken during Expedition 4.

### **KIDNEY CELL GENE EXPRESSION (HAMMOND)**

The primary objective of CGBA-KCGE was to assess how microgravity alters the genes that control protein production in kidney cells. The investigator hoped to be able to manipulate the kidney cells to produce specific tissues that can be used in models when developing medicines or in humans. The kidney cell samples were drawn into the test tubes containing a preservative, approximately two hours after reaching orbit. Once the samples were drawn, a messenger RNA (mRNA) preservative was added to the cell cultures for postflight analysis.

### **SYNAPTOGENESIS IN MICROGRAVITY (KESHISHIAN)**

CGBA-Synaptogenesis in Microgravity (SM) used the CGBA hardware to examine how microgravity affects the neuronal development of fruit flies, *Drosophila melanogaster*. This investigation used *D. melanogaster* embryos and larvae to observe how nerves that control movement navigate through an embryonic central nervous system and attach to muscle fibers. Investigators observed how the synapses, the junction



The adult *Drosophila melanogaster* is a species of fruit fly that was used in the CGBA-SM investigation.

between two nerve cells where signals are transferred from one nerve to another, developed both during and after the embryonic stage.

### ANTIBIOTIC PRODUCTION IN SPACE (STODIECK AND KLAUS)

Previous research, conducted during short-duration shuttle flights, identified significant potential for antibiotic production by microorganisms in orbit. The CGBA-Antibiotic Production in Space (APS) experiment was the first ISS investigation to test whether long-duration exposure to microgravity stimulated antibiotic production in microorganisms. CGBA-APS spent a total of 72 days in orbit on ISS. The experiment used *Streptomyces plicatus* to produce the antibiotic compound actinomycin D. Actinomycin D is an anti-tumor antibiotic used to treat tumors of the bone, urogenital tract, skeletal muscle, kidney, and testis.

### RESULTS

Preliminary results indicated that that an average of 60% of the kidney cell samples from CGBA-KCGE were drawn into the Vacutainers. Although the sample size was smaller, the samples were sufficient for postflight analysis. For the synaptogenesis experiment with fruit flies, preliminary results indicated that although the CGBA hardware operated successfully, there were unexpected temperature drifts above the planned temperature in two of the seven containers. While ground tests were completed for comparison to the in-flight samples, final data analysis has not been released.



CGBA ICM with eight containers. The ICM provides both the computer and the thermal control for the samples.



Postflight images show MOBIAS tray with waste bag and samples visible (dark substance indicates actinomycin D).

CGBA-APS originally flew on Expedition 2 but was not able to function due to technical issues. Its re-flight took place during Expedition 4 where the hardware performed as planned. Samples of antibiotic were taken at four-day intervals. A total of 48 samples of *Streptomyces plicatus* were used to produce the antibiotic compound actinomycin D for a span of 72 days on orbit. The initial production of actinomycin D from on-orbit samples was higher than those produced during the ground tests. This was true for samples that were taken on day 8 (15.6 % increase) and day 12 (28.5% increase) of the investigation. Beginning at day 16, the ground experiment produced more antibiotic than the on-orbit experiment. This trend continued for the remainder of the experiment. The causes for the higher yield during the first 12 days of the experiment are still unknown. One theory is that there is a shorter lag phase, which allowed ISS samples to reach the growth and production phases sooner than the ground samples (Benoit et al. 2005).

Identifying the mechanism that caused increased production of antibiotics while in microgravity and applying them to production on Earth could be advantageous to the pharmaceutical industry. A method for transferring the microgravity research results to Earth-based production has not yet been identified.

### PUBLICATION(S)

Benoit MR, Li W, Stodieck LS, Lam KS, Winther CL, Roane TM, Klaus DM. Microbial antibiotic production aboard the International Space Station. *Applied Microbiology Biotechnology*. Online:10–9, 2005.

## MICROENCAPSULATION OF ANTI-TUMOR DRUGS (MEPS)

Principal Investigator(s): Dennis Morrison, NASA Johnson Space Center, Houston, Texas  
Expedition 5

**Research Area** Physical and Biological Sciences



Micro-balloons containing anti-tumor drugs and small amounts of radio-contrast oil were created during MEPS operations. This oil, which is traceable by radiograph, allows doctors to follow the microcapsules as they travel to the tumor. The permeable outer skin releases the drug slowly, giving the microcapsule plenty of time to reach its destination. This slow release prevents artery damage as the drug travels to its destination.

The microcapsulation electrostatic processing system (MEPS) is an automated system that is used to produce liquid-filled micro-balloons. It works through the use of microcapsules, unique capsules resembling miniature liquid-filled balloons the size of blood cells, that deliver FDA-approved anti-cancer drugs by injection into the bloodstream. The microgravity environment on ISS is vital to the development of these capsules because the station environment enables the pharmaceutical and its outer membrane to form spontaneously.

MEPS was designed with flexibility in mind. The system can process a wide range of experiments. For example, it can handle volumetric proportions of up to six chemical constituents; it can transfer liquids back and forth, at variable rates, between its six reservoirs and two main chambers; it can apply different electrical fields to the enclosed experiments; and it can be programmed to use filters or membranes of different porosity between chambers. Electrical fields charge the surface of the microcapsules, making it less recognizable as a foreign invader to the immune system.

The use of microcapsules will benefit the treatment of several diseases. For example, to eliminate daily insulin shots diabetes patients can use implanted microcapsules as treatment. A further Earth application is the microcapsules can be used as a substitution for chemotherapy. Traditional anti-cancer treatment involves large quantities of drugs that affect the entire body. The microcapsules contain a smaller dose of medication that directly targets tumors. Also, they reduce the unwanted side effects currently produced by chemotherapy.

### RESULTS

MEPS experiments were conducted during Expedition 5. Eight samples were processed using various methods to mix dissimilar liquids to form micro-balloons/microcapsules. The recovered micro-balloons were analyzed for size and drug content. Additionally, studies included the effects of temperature and internal pressure on the size of the micro-balloons. Ground-based medical investigations revealed that when using these microcapsules, the growth of human prostate and lung tumors can be inhibited with only a few local injections. When anti-cancer microcapsules are injected following cryosurgery, the combined treatment can completely destroy 1- to 2-cm-size tumors in just three weeks.

### PUBLICATION(S)

Le Pivert P, Haddad RS, Aller A, Titus K, Doulat J, Renard M, Morrison DR. Ultrasound Guided, Combined Cryoablation and Microencapsulated 5-Fluorouracil, Inhibits Growth of Human Prostate Tumors in Xenogenic Mouse Model Assessed by Fluorescence Imaging. *Technology in Cancer Research and Treatment*. 3(2):135-42, 2004.

Morrison DR, Haddad RS, Ficht A. Microencapsulation of Drugs: New cancer therapies and improved drug delivery derived from microgravity research. Proceedings of the 40<sup>th</sup> Space Congress, Cape Canaveral, Fla. Apr 2003.

## STELSYS LIVER CELL FUNCTION RESEARCH (STELSYS)

Principal Investigator(s): Albert Li, StelSys LLC, Baltimore, Md.  
Expedition 5

### **Research Area** Physical and Biological Sciences

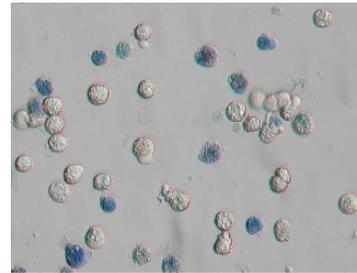
The liver filters potentially harmful substances from the blood and breaks these substances down into water-soluble forms that can be washed from the body. It is therefore a difficult organ to treat because medications can be broken down and removed before they have an opportunity to provide effective treatment. The purpose of this experiment was to allow the investigator to observe how human liver cells react to the presence of drugs in microgravity, and to compare these results to a control experiment conducted on the ground.

To do this, human liver cells were launched inside a caddy held at freezing temperatures within a Dewar. The experiments were conducted in the CBOSS, including the BSTC, the gas supply module, and syringes. Individual cell cultures were grown in the temperature-controlled environment of the BSTC. When the experiments were complete, they were stored in the ARCTIC freezer until the end of the Expedition.

### **RESULTS**

The samples returned from space were analyzed by specialized mass spectrometry equipment to determine the amount of drug metabolites formed by the liver cells from the drug substances added. Overall this analysis showed that the rate of metabolism by the liver cells in space was lower than that of the liver cells maintained under similar conditions on Earth. This was true for all of the drug substances tested as well as for cells from three different liver donors. These results indicate that microgravity may well retard the rate of drug metabolism in the human liver, although the mechanism for this effect is yet unknown.

Returned samples were also analyzed by gene array to determine whether genetic expression differed for cells in microgravity. Differences were found, including 9200 of 13,000 genes that had at least two-fold greater expression in space as compared to Earth and 9800 genes that had decreased expression in space. This large body of data is being analyzed for clues as to how liver cell function changes in specific ways in the microgravity environment of space.



Human liver cells at the completion of a ground-control experiment. A stain has been applied to indicate the live vs. dead (blue-colored) cells.

## YEAST-GROUP ACTIVATION PACKS (YEAST-GAP)

Principal Investigator(s): Cheryl A. Nickerson, Arizona State University, Tempe, Ariz.  
Expedition 8

### **Research Area** Physical and Biological Sciences

This experiment was designed to study how individual genes respond to microgravity conditions. To achieve this, scientists studied yeast cells—eukaryotic cells, or cells that contain a distinct nucleus bound by a cell membrane. Mammalian cells have a similar eukaryotic structure, and the results of this experiment could aid in understanding more complex mammalian cell response to microgravity. Yeast cells are far simpler than mammalian cells because they have a well-characterized, much smaller genome. This makes it easier for scientists to study how microgravity alters the makeup of the cells and their potential function.

Yeast is an ideal candidate for such a study because it is hardy enough to resist the rigors of flight, requires no refrigeration, and poses little risk to ISS crewmembers. The experiment used genetically engineered cells of brewer's yeast (*Saccharomyces cerevisiae*) and a special cell growth chamber called a group activation pack (GAP) developed by BioServe Space Technologies. The goal is to identify the precise genes of yeast that are affected by growth in microgravity to understand differences in the growth of yeast cells in space and on Earth.

### **RESULTS**

Samples were returned on space shuttle flight STS-114/LF1 in August 2005. Further analysis is ongoing.



ISS008E14397 — ISS science officer Mike Foale is holding the GAP for the Yeast-GAP experiment during Expedition 8.

## ***PLANT BIOLOGY IN MICROGRAVITY***

*Studies of plant physiology in microgravity provide insight into the basic biology of plants, and into how plants might be used as part of future Exploration missions. Successfully growing plants in microgravity presents challenges, from predictable distribution of water and nutrients to the reliability of biomass production.*

## ADVANCED ASTROCULTURE (ADVASC)

Principal Investigator(s): Weijia Zhou, Wisconsin Center for Space Automation and Robotics,  
University of Wisconsin at Madison, Wis.  
Expeditions 2, 4, 5

### Research Area Physical and Biological Sciences

Advanced Astroculture (AdvAsC) was a commercially sponsored payload that provided precise control of environmental parameters for plant growth, including temperature, relative humidity, light, fluid nutrient delivery, and carbon dioxide (CO<sub>2</sub>) and ethylene concentrations. AdvAsC hardware was used in a series of tests over three Expeditions (2, 4, and 5). First, AdvAsC demonstrated the first “seed-to-seed” experiment in space, growing *Arabidopsis thaliana* through a complete life cycle. (*Arabidopsis thaliana* (thale cress) is a model system in plant biology studies with a short life cycle, a completely sequenced genome, and a history of space experiments.) Next, 35% of the space-grown seeds and 65% of wild *Arabidopsis* seeds were grown. Finally, soybean plants were also grown through an entire life cycle.



ISS002E6300 — James S. Voss, Expedition 2 flight engineer, works with the AdvAsC condensate fluid syringe at the AdvAsC growth chamber in the U.S. Destiny laboratory.



ISS005E07209 — Astronaut Peggy A. Whitson, Expedition 5 NASA ISS science officer, displays a first crop of soybeans growing inside the AdvAsC. Photos of the growing plant have been a useful tool for the ground-based science team, which uses them to determine optimal time for cross-pollination and harvesting.

## RESULTS

*Arabidopsis thaliana* was successfully grown from seed to seed on ISS. During a two-month growth period, the plants progressed from seed hydration to germination, vegetative, and reproductive stages, producing mature seeds. Ninety percent of the seeds germinated in space, although only 70% of the plants grew to maturity.

Some of the seeds that were harvested from the plants grown in microgravity were planted in a ground study. These seeds produced typical plants without any visible abnormalities (Link et al. 2003). During a second AdvAsC run, second-generation seeds were produced and tissues were harvested and preserved for RNA and complementary deoxyribonucleic acid (cDNA) analysis. Detailed results of the germination and harvesting of space-grown seeds in the AdvAsC growth chamber in the U.S. Destiny laboratory have not been released.

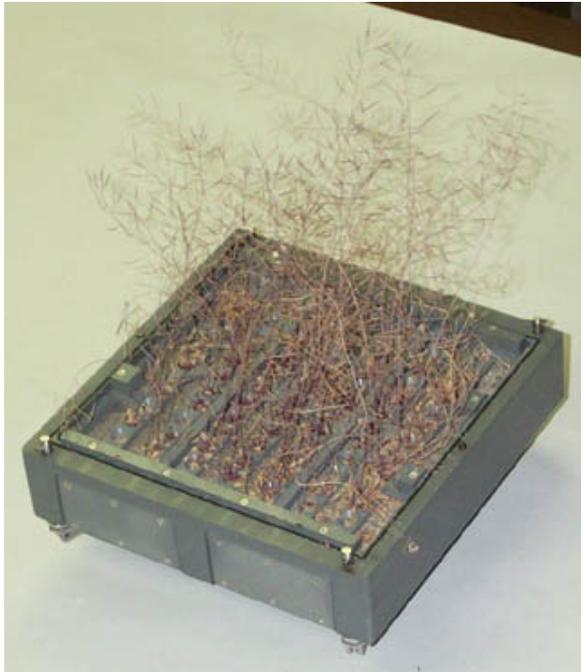
In the third AdvAsC run, which took place over approximately 95 days on ISS, soybeans were grown from seed to seed for the first time in space. Biomass production in the space seeds was approximately 4% larger than ground controls. Flight and ground controls produced nearly identical numbers of seeds, but the space seeds were larger on average. Scientists found that the seeds produced in space were healthy, the germination rates were comparable to those on Earth, and no major morphological differences were evident. Phytochemical analysis of commercially important components such as oils, amino acids, proteins, carbohydrates, and phytoestrogens have not yet been released.

### PUBLICATION(S)

Link BM, Durst SJ, Zhou W, Stankovic B. Seed-to-seed growth of *Arabidopsis thaliana* on the International Space Station. *Advances in Space Research*. 31(10):2237–2243, 2003.

Zhou W, Durst SJ, DeMars M, Stankovic B, Link BM, Tellez G, Meyers RA, Sandstrom PW, Abba JR. Performance of the Advanced Astroculture™ plant growth unit during ISS-6A/7A mission. SAE Technical Paper Series. Paper no. 02ICES-267, 2002.

Zhou W. Advanced Astroculture™ Plant Growth Unit: Capabilities and Performances. 35<sup>th</sup> International Conference on Environmental Systems, Rome, Italy. Jul 11–14, 2005.



Dried *Arabidopsis thaliana* plants, from ISS Expedition 4, upon their return to Earth.

## BIOMASS PRODUCTION SYSTEM (BPS)

Principal Investigator(s): Robert C. Morrow, Orbital Technologies Corporation Space Center, Madison, Wis.  
Expedition 4

### Research Area Physical and Biological Sciences

The Biomass Production System (BPS) was developed as a precursor to systems capable of maintaining plant growth in microgravity for more than 90 days (e.g., planetary missions). The BPS objective was to validate plant growth system hardware functionality and performance, plant productivity and health, information acquisition, and experiment operations and support in microgravity. The BPS housed two experiments: the Technology Verification experiment and the Photosynthesis Experiment and System Testing and Operation (PESTO) experiment.



ISS004E11721 — View of Brassica plants from PGC 2 being harvested as part of the technical validation test of the BPS conducted during ISS Expedition 4.

*Brassica rapa* (field mustard) was the test species for the BPS. The BPS plant growth chambers (PGCs) contained plants that were started on the ground and that had already developed their photosynthetic apparatus, such as stoma, guard cells, and other structures found in the leaves. Samples taken from the plants were compared to data taken from previous ground-based experiments conducted using BPS.

BPS tested the hypothesis that environmental control subsystems would provide a stress-free growing environment in microgravity. These technology validation studies provide a foundation on which to base the design of future plant growth units for station or future Exploration missions. These results can lead to the development of regenerative life support systems on future missions to the moon or Mars. While creating useful technology and science, BPS allowed

students in grades Kindergarten through twelve to work as co-investigators on real space research. This research, known as “Farming in Space,” examined the basic principles and concepts related to plant biology, agricultural production, ecology, and the space environment. Activities associated with this research encouraged curiosity in the sciences while teaching good scientific methodology.

### RESULTS

Thirty-two germinating *Brassica rapa* plants were launched inside the BPS for the technology validation test of the hardware. The *Brassica rapa* plants were grown over two growth cycles on ISS. *Brassica rapa* tissue from BPS was analyzed for general morphology, seed anatomy and storage reserves, foliar carbohydrates, and chlorophyll and root zone hypoxia analysis. Overall the BPS hardware performed as expected, and may provide a viable use in the development for regenerative life support systems for future spacecraft development.

Gross measure of growth, leaf chlorophyll, starch, and soluble carbohydrates confirmed comparable performance by the plants on the station with ground controls. Of particular interest were the differences between the immature seedlings. Immature seeds from station had higher concentrations of chlorophyll, starch, and soluble carbohydrates than the ground controls. Seed protein was significantly lower in the ISS material. Also, microscopy of immature seeds fixed on ISS showed embryos to be at a range of developmental stages, while ground control embryos had all reached the same stage of development. These differences could be attributable to differences in water delivery or reduced gas exchange due to lack of convection. These results suggest that the microgravity environment may affect flavor and nutritional quality on potential space produce (Musgrave et al. 2005).



Video screen shot of *Brassica rapa*, 36 days after planting on ISS during Expedition 4.

### PUBLICATION(S)

Musgrave ME, Kuang A, Tuominen LK, Levine LH, Morrow RC. Seed Storage Reserves and Glucosinolates in *Brassica rapa* L. Grown on the International Space Station. *Journal of the American Society for Horticultural Science*. 130(6): 848–856, 2005.

## PHOTOSYNTHESIS EXPERIMENT AND SYSTEM TESTING AND OPERATION (PESTO)

Principal Investigator(s): Gary Stutte, Dynamac Corporation, NASA Kennedy Space Center, Fla.  
Expedition 4

### Research Area Physical and Biological Sciences



Video screen shot of *Triticum aestivum* 20 days after planting inside the BPS on station during Expedition 4.

The PESTO investigation, conducted in concert with technology verification for the BPS hardware, measured the canopy photosynthesis (the production of oxygen and carbohydrates from CO<sub>2</sub> and water in the environment) of *Triticum aestivum* (super dwarf wheat). The wheat was grown under high light and controlled CO<sub>2</sub> conditions in microgravity. The investigation also measured the metabolic effects on the photosynthetic apparatus to quantify the effects on metabolism and to model the impact of microgravity on biological approaches to atmospheric regeneration.

To test the hypothesis that the carbon exchange rates would be the same in microgravity as on Earth, investigators measured and characterized the CO<sub>2</sub> and light response curves for a wheat photosynthetic canopy grown in microgravity. Data came from various sources: gas samples taken from

the closed atmosphere inside the chambers; liquid samples taken through ports in the chambers; plant tissue samples extracted by the crew during different points in the growth cycle; and, finally, plant tissue extracted from the live plants returned to Earth inside the BPS. The investigators analyzed the plant tissue postflight for primary photosynthesis parameters, such as electron transport, carbohydrate partitioning, and photosystem (the biochemical pathway for photosynthesis). Measurements were taken over a range of relative humidity conditions to discover whether atmospheric vapor pressure deficits affect gas exchange in microgravity.

### RESULTS

During ISS Expedition 4, PESTO grew 32 plants for 73 days inside the plant growth chambers of BPS. Following return to Earth, these plants were compared to ground controls that were grown in BPS plant growth chambers on Earth.



ISS004E10138 — Close-up view of apogee wheat plants with a scale as backdrop to exhibit the development of the plants grown as part of the PESTO experiment on ISS Expedition 4.

The PESTO investigation had three dimensions that resulted in a more complete picture of microgravity influences on photosynthesis: gas exchange, partitioning and metabolism. CO<sub>2</sub> and light response curves allowed researchers to establish whether canopy photosynthetic responses were affected by space conditions. This is noteworthy since plants can be used to regenerate the atmosphere in space conditions through removal of CO<sub>2</sub> and production of oxygen. In addition, the tests that evaluated movement of water via transpiration are important since they are indicative of the stomatal responses that regulate photosynthesis. Further, the impact of microgravity on transpiration was significant since plants can be used to purify water under space flight conditions. These studies involving gas exchange at elevated CO<sub>2</sub> concentrations increased our understanding of the biological impacts of increasing levels of atmospheric

CO<sub>2</sub> on Earth-based ecosystems. Furthermore, an understanding of plant responses under a range of CO<sub>2</sub> and light conditions has potential benefits to commercial-controlled environment agriculture industries.

The growth and development of the dwarf wheat plants on the space station was similar to the growth and development of plants on Earth. Analysis of the plants indicated that the microgravity-grown plants were 10% taller than plants grown on Earth, although the growth rate of dwarf wheat leaves was very similar to the plants grown on Earth. The near-real-time video data provided by BPS allowed for validation of the growth data in micro-

gravity when compared to the controls. Design applications can be made to the BPS to allow for successful plant production on ISS and future long-duration missions to the moon and Mars (Stutte et al. 2003).

To effectively farm in space, multiple redundant plant growth chambers will be needed to acquire the maximum yield of food, oxygen, and water. PESTO evaluated the transpiration (water) and photosynthesis (oxygen) processes of the dwarf wheat plant in microgravity and found that microgravity did not affect either the transpiration or the photosynthesis processes of the plants (Monje et al. 2005).

When environmental controls such as temperature, relative humidity, CO<sub>2</sub>, and water are effectively maintained, microgravity does not affect canopy growth of dwarf wheat plants. Slight differences in photosystem I (photosynthesis in which light of up to 700 nm is absorbed and reduced to create energy) and photosystem II (photosynthesis in which light of up to 680 nm is absorbed and its energy is used to split water molecules, giving rise to oxygen) were noted and are being evaluated further (Stutte et al. 2005).

When conducting biological studies, it is important to maintain the integrity of the samples. The standard method to preserve samples is quick freezing at low temperatures (−80°C (−112°F) and below), but strict temperature control of samples on station is not always uniform or possible. Therefore a preservative is needed that will maintain the integrity of biological samples before cooling. RNAlater was used to preserve some of the PESTO samples on station. The viability of the samples preserved with RNAlater was greater than that of the samples preserved using formalin. To carry out long-term studies aboard ISS, a fixative such as RNAlater is needed to maintain the integrity of samples at the varying temperatures that are experienced in microgravity (Paul et al. 2005).

#### **PUBLICATION(S)**

Monje O, Stutte GW, Goins GD, Porterfield DM, Bingham GE. Farming in Space: Environmental and Biochemical Concerns. *Advances in Space Research*. 31:151–167, 2003.

Monje O, Stutte G, Chapman D. Microgravity does not alter plant stand gas exchange of wheat at moderate light levels and saturating CO<sub>2</sub> concentration. *Planta*. Online, Jun 2005.

Paul A, Levine HG, McLamb W, Norwood KL, Reed D, Stutte GW, Wells HW, Ferl RJ. Plant molecular biology in the space station era: Utilization of KSC fixation tubes with RNAlater. *Acta Astronautica*. 56:623–628, 2005.

Stutte GW, Monje O, Anderson S. Wheat (*Triticum Aesativum* L. cv. USU Apogee) Growth Onboard the International Space Station (ISS): Germination and Early Development. *Proceedings of the Plant Growth Regulation Society of America*. 30:66–71, 2003.

Stutte GW, Monje O, Goins GD, Tripathy BC. Microgravity effects on thylakoid, single leaf, and whole canopy photosynthesis on dwarf wheat. *Planta*. 1–11, 2005.

## PLANT GENERIC BIOPROCESSING APPARATUS (PGBA)

Principal Investigator(s): Gerard Heÿenga, NASA Ames Research Center, Moffett Field, Calif.  
Expedition 5

### Research Area Physical and Biological Sciences

The Plant Generic Bioprocessing Apparatus (PGBA) is used to grow and monitor plants in microgravity experiments. PGBA is a self-contained plant growth chamber that provides preset or remotely controlled temperature, humidity, nutrient delivery, and light. The PGBA venting system also supplies the plants with ambient air and controls ethylene buildup.

The objective during Expedition 5 was to grow two crops of *Arabidopsis thaliana* (thale cress). The first crop was to be harvested when it reached maturity and placed into cold storage. The second crop was to be started at the harvest of the first crop and returned to Earth while it was still growing. Scientific objectives were focused on understanding lignin production.



*Arabidopsis thaliana* (Brassica family) plants grown under controlled conditions in a plant cultivation module in the Bioserve Laboratories.

### RESULTS

The returned plant material did not develop in a normal manner, and the primary scientific objectives were not met. The study did, however, help to identify the need for greater regulation of air quality within a PGC to ensure uniform plant growth. Although no results will be published from this ISS activity, lessons learned from this study are being applied to the development of subsequent plant growth investigations and improved space flight plant chamber design (Heÿenga et al. 2005).

### PUBLICATION(S)

Heÿenga G, Stodieck L, Hoehn A, Kliss M, Blackford C. Approaches in the Design of a Space Plant Cultivation Facility for *Arabidopsis thaliana*. 34<sup>th</sup> International Conference on Environmental Systems (ICES), Jul 2004, Colorado Springs, Colo., SAE-paper no. 2004-01-2459, 2004. (*New designs influenced by lessons learned.*)

Heÿenga G, Kliss M, Blackford C. The Performance of a Miniature Plant Cultivation System Designed for Space Flight Application. 35<sup>th</sup> International Conference on Environmental Systems, Rome, Italy, SAE 2005-01-2844, 2005. (*New designs influenced by lessons learned.*)



## TECHNOLOGY DEVELOPMENT

*Future exploration—the return to the moon and human exploration of Mars—presents many technological challenges. Studies on the ISS can test a variety of technologies, systems, and materials that will be needed for future Exploration missions.*

## **SPACECRAFT MATERIALS AND SYSTEMS**

*ISS provides a testbed for a variety of spacecraft systems. Results of studies on station help to determine which materials are most resistant to the conditions of the space environment, provide insight into in-space repairs, test satellite control algorithms, and give information on physical processes underlying systems as diverse as fire suppression and propellant tank design.*

## CAPILLARY FLOW EXPERIMENT-CONTACT LINE (CFE-CL)

Principal Investigator(s): Mark M. Weislogel, Portland State University, Portland, Ore.  
Expeditions 9, 12, ongoing

### Research Area Technology Development

The Capillary Flow Experiments (CFEs) are a suite of fluid physics experiments whose purpose is to investigate capillary flows and phenomena in low gravity. The CFE data to be obtained will be crucial to future space exploration because they provide a foundation for physical models of fluids management in microgravity, including fuel tanks and cryogen storage systems, TCSs (e.g., water recycling), and materials processing in the liquid state. NASA's current plans for Exploration missions assume the use of larger liquid propellant masses than have ever flown before. Under low-gravity conditions, capillary forces can be exploited to control fluid orientation so that such large mission-critical systems perform predictably.

The handheld experiments common to the suite aim to provide results of critical interest to the capillary flow community that cannot be achieved in ground-based tests; for example, dynamic effects associated with a moving contact boundary condition, capillary driven flow in interior corner networks, and critical wetting phenomena in complex geometries. Specific applications of the results center on particular fluids challenges concerning propellant tanks. The knowledge gained will help spacecraft fluid systems designers increase system reliability, decrease system mass, and reduce overall system complexity.

CFE encompasses three experiments, CFE-Contact Line (CFE-CL), CFE-Interior Corner Flow (CFE-ICF), and CFE-Vane Gap (CFE-VG), with two unique experimental apparatuses per experiment. There are multiple tests per experiment. Each of the experiments employs conditions and test cell dimensions that cannot be achieved in ground-based experiments. All of the units use similar fluid injection hardware made of Lucite, have simple and similarly sized test chambers, and rely solely on video for highly quantitative data. Silicone oil is used as the fluid. Differences between units are primarily fluid properties, wetting conditions (determined by the coating inside the test chamber), and test cell cross section.



ISS009E23445 — ISS science officer Edward M. (Mike) Fincke is pictured next to CFE-CL2 in the U.S. Destiny laboratory aboard ISS during Expedition 9.

CFE-CL investigates the properties of the contact line (the boundary between the liquid and the solid surface of the container). The contact line controls the interface shape, stability, and dynamics of capillary systems in low gravity. CFE-ICF studies capillary flow in interior corners. Structured inside tanks providing interior corners are used in the design of fuel tanks so that the fuel will always flow to the outlet of the tank in the absence of gravity. The equations governing the process are known but, to date, have not been solved analytically because of a lack of experimental data identifying the appropriate boundary conditions for the flow problem. Experimental results will guide the analysis by providing the necessary boundary conditions as a function of container cross section and fill fraction. The benchmarked theory can then be used to improve propellant management aboard spacecraft. CFE-VG studies capillary flow when there is a gap between interior corners, such as in the gap formed by an interior vane and tank wall of a large propellant storage tank or the near intersection of vanes in a tank with complex vane network.

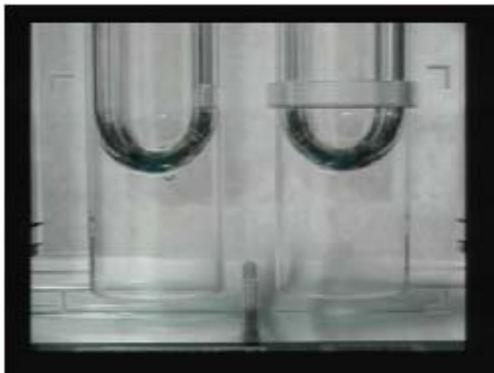
During each experimental run a crewmember will disturb the fluids by tapping the container, moving the vanes, etc. By digitizing and quantitatively analyzing video data of the resulting oscillations, natural frequencies and damping rates will be determined. The effects of partial wetting, the lag before contact angle changes, and fluid properties such as surface tension and viscosity will be quantified. Transient flow rates, stability limits, and coalescence time scales will be measured.

## RESULTS

One (of two) contact line apparatus, CFE-CL2 (pictured on previous page with astronaut Mike Fincke), was tested during ISS Expeditions 9 and 12. During Expedition 9, in excess of 136 individual test were performed and downlinked via video by the crew. A number of tests were repeated during Expedition 12. Preliminary analysis of the CFE-CL2 data has begun using the low-resolution video downlinked from ISS during real-time operations. Experts are debating whether current fluid dynamics models can accurately predict fluid behavior at contact lines in microgravity. Numerical analysts from the United States and Europe were given data (hardware descriptions and fluid properties of the CFE-CL2 system) with which to create computer predictions of the experimental properties. Final data analysis is pending analysis of the high-resolution videotapes of the CFE-CL2 sessions, returned on the shuttle in late 2005. Current fluid dynamic models will then be compared to experimental results to determine the fidelity of current models and the need for future research (Weislogel 2005).

## PUBLICATION(S)

Weislogel MM. Preliminary Results from the Capillary Flow Experiment Aboard ISS: The Moving Contact Line Boundary Condition. Proceedings of the 43<sup>rd</sup> AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nev. AIAA 2005-1439, Jan 10–13, 2005.



Video screen shot of the CFE contact line-2 setup and initial condition on board ISS during Increment 9. The light blue liquid is in two narrow tubes, shown side by side, forming a meniscus in each tube.



Video screen shot of CFE CL-2 bubble test 1 on board ISS during Increment 9.

## DUST AND AEROSOL MEASUREMENT FEASIBILITY TEST (DAFT)

Principal Investigator(s): David Urban, NASA Glenn Research Center, Cleveland, Ohio  
Expeditions 10, planned 13

### Research Area Technology Development

Our understanding of how fires burn in a spacecraft has evolved since the fire detection equipment on space shuttle and space station was developed. One thing we have learned is that smoke particles that form in microgravity can be larger than those formed on Earth. Since smoke detectors are gauged to detect certain sizes of particles, this knowledge could help design more accurate smoke detectors for future spacecraft. The Smoke and Aerosol Measurement Experiment (SAME) is planned to gather particulate size information on ISS. The DAFT experiment, which was initiated after the *Columbia* accident, is to be used to obtain data in preparation for SAME using very little upmass.



Video screen shot of ISS commander and science officer Leroy Chiao performing DAFT operations on station during Expedition 10.

DAFT is intended to assess and characterize the distribution of particles in the air inside ISS to allow assessment of the suitability of current shuttle and ISS smoke detectors. This experiment was begun on Expedition 10 and is planned for completion during Expedition 13. DAFT is designed to test the effectiveness of the P-Trak Ultrafine Particle Counter, a device that counts ultra-fine dust particles in a microgravity environment. Most particle counters work by using a laser to record instances when the beam is interrupted; however, this method will not record ultra-fine particles that are much smaller than the wavelength of the light. P-Trak works by passing dust-laden air through a chamber of vaporous isopropyl alcohol. When a droplet of alcohol condenses over an ultra-fine dust particle, the particle becomes large enough to break the light beam and be counted. The alcohol is then recycled as it condenses on sidewalls and gravity pulls the alcohol back to the saturator. If the results are satisfactory, P-Trak will be used in SAME, which requires counts of particles ranging from 0.2–1 micron.

### RESULTS

Preliminary results, based on two DAFT sessions performed on station in 2005, indicate very low levels of particulate in the ISS environment relative to that previously measured on shuttle. This low particulate level is not surprising due to the current two-person crew on ISS (vs. the typical seven-person crew on shuttle) and the high-efficiency particulate accumulator (HEPA) filtration system of ISS. It is suspected that the particulate level will rise once station hosts a larger crew. As this experiment is a proof of the technology, it is also possible that the particulates are not being detected. Upcoming runs of the experiment will use known dust sources to confirm that the equipment is functioning accurately on orbit. Sampling will also be done at more locations throughout ISS to draw definitive conclusions. Once the median particulate level throughout ISS is known, it can be used to design future smoke detectors that accurately distinguish normal dust from the presence of dangerous smoke particles.

### PUBLICATION(S)

Urban D, Griffin D, Ruff G, Cleary T, Yang J, Mulholland G, Yuan Z. Detection of Smoke from Microgravity Fires. Proceedings of the International Conference on Environmental Systems. 2005-01-2930, 2005.

## IN-SPACE SOLDERING EXPERIMENT (ISSI)

Principal Investigator(s): Richard Grugel, NASA Marshall Space Flight Center, Huntsville, Ala.  
Expeditions 7–10

**Research Area** Technology Development



Video screen shot of ISS science officer Mike Fincke using a soldering iron to perform the ISSI experiment on station during Expedition 9.

The In-space Soldering Experiment (ISSI) is another payload that was rapidly developed after the *Columbia* accident to provide a low-mass experiment using hardware already on board station. It was designed to promote understanding of joining techniques, shape equilibrium, wetting phenomena, and micro-structural development in space. Its primary objective was to better understand the effects and consequences of soldering in a microgravity environment such as that found on ISS. In Earth's gravity, soldering has a defined behavior and is reliant on gravity and convection to assist in solidification, joint shape, integrity, and microstructure. Unfortunately, on Earth detrimental gas bubbles (void spaces) are still found in the solder joint and at contact surfaces. These voids reduce the thermal and electrical conductivity and provide sites for crack initiation. Bubbles have less chance to escape in the reduced-gravity environment of space and, therefore, are likely to

be more of a problem. To better understand this potential problem, a systematic series of soldering samples was designed to investigate and understand porosity development, surface wetting, and equilibrium shape formation. After the samples were heated on orbit, they were returned to Earth for property testing and metallographic examination.

### RESULTS

The experiment samples were returned to the investigator team in late 2005, so analysis of these samples has just begun. The samples will be evaluated nondestructively first and then destructively.

Real-time downlink video of the experiment yielded direct observation of the solder melting, equilibrium shape attainment by the liquid, and flux movement. The flux movement was particularly noteworthy because it was entirely unexpected. When the flux was released from the solder during heating, it formed a droplet that spun around the larger solder drop. This surprising movement is driven by thermocapillary flow induced by the temperature gradient. This type of behavior cannot be duplicated on Earth.



ISS009E14472 — Astronaut Edward M. (Mike) Fincke, Expedition 9 science officer and flight engineer, works on the ISSI in the U.S. Destiny laboratory.

### PUBLICATION(S)

Grugel R, Cotton LJ, Segre PN, Ogle JA, Funkhouser G, Parris F, Murphy L, Gillies D, Hua F, Anilkumar AV. The In-Space Soldering Investigation (ISSI): Melting and Solidification Experiments Aboard the International Space Station. Proceedings of the 44<sup>th</sup> AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nev. AIAA 2006-521, Jan 9–12, 2006.

## MATERIALS INTERNATIONAL SPACE STATION EXPERIMENT-1 AND -2 (MISSE-1 AND -2)

Principal Investigator(s): William H. Kinard, NASA Langley Research Center, Hampton, Va.  
Expeditions 3–11, other MISSE experiments ongoing

### Research Area Technology Development

Researchers from the private and public sector prepared a wide range of samples for the first externally mounted experiment on ISS. Materials International Space Station Experiment (MISSE)-1 and -2 are testbeds for more than 400 materials and coatings samples, testing their survivability under the corrosive effects of the space environment; including micrometeoroid and orbital debris strikes, atomic oxygen attack, intense ultraviolet radiation from the sun, and extreme temperature swings. Results will provide a better understanding of the durability of various materials in this environment. Many of the materials may have applications in the design of future spacecraft.



ISS009E22435 — MISSE on ISS, over cloud tops.

Both MISSE-1 and -2 were deployed in August 2001 on Expedition 3 and were planned for a one-year exposure. Due to the delays incurred following the *Columbia* accident, they were not retrieved until four years later during ISS Expedition 11 in August 2005. Follow-on samples are now on board station (MISSE-5) or are planned for the future (MISSE-3, MISSE-4, and MISSE-6).

### RESULTS

In late 2005, 35 investigators taking part in MISSE-1 and -2 traveled to NASA Langley Research Center to inspect their samples and prepare them for return to their respective laboratories for further analysis. Researchers taking part in this investigation have interests in polymers, thermal control coatings, nano-composites, radiation shielding, environmental monitors, and marking processes designed to label parts that will be exposed to the space environment. The primary data from MISSE will be obtained by comparing the preflight laboratory characterization of the test specimens with postflight laboratory characterizations made after the specimens are retrieved.

While the samples are still under investigation, researchers indicate that over 100 micrometeoroid and space debris strikes were found. Many polymer film samples were completely eroded by atomic oxygen, but some samples survived and are undergoing analysis. Some particulate contamination was observed. Optical property changes in thermal control materials were also observed. Several materials did well in the harsh environment. Lack of widespread molecular contamination on MISSE gives confidence in using station for future material studies. A number of results are anticipated to be released over the next few years.



ISS009E22432 – Close-up of MISSE with Earth backdrop.

### PUBLICATIONS

Finckenor M. The Materials on International Space Station Experiment (MISSE): First Results from MSFC Investigations, Proceedings of the 44<sup>th</sup> AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nev. AIAA 2006-472, Jan 9–12, 2006.

## SYNCHRONIZED POSITION HOLD, ENGAGE, REORIENT, EXPERIMENTAL SATELLITES (SPHERES)

Principal Investigator(s): David Miller, MIT, Cambridge, Mass.  
Expedition 8, planned 13 and ongoing

### Research Area Technology Development

SPHERES is a testbed for formation flying by satellites—the theories and calculations that coordinate the motion of multiple bodies maneuvering in microgravity. To achieve this inside the ISS cabin, bowling-ball-sized spheres perform various maneuvers (or protocols), with one to three spheres operating simultaneously. The Synchronized Position Hold, Engage, Reorient, Experimental Satellites (SPHERES) experiment will test relative attitude control and station-keeping between satellites, re-targeting and image plane filling maneuvers, collision avoidance and fuel balancing algorithms, and an array of geometry estimators used in various missions.

SPHERES consists of three self-contained satellites, which are 18-sided polyhedrons that are 0.2 meter in diameter and weigh 3.5 kilograms. Each satellite contains an internal propulsion system, power, avionics, software, communications, and metrology subsystems. The propulsion system uses CO<sub>2</sub>, which is expelled through the thrusters. SPHERES satellites are powered by AA batteries. The metrology subsystem provides real-time position and attitude information. To simulate ground station-keeping, a laptop will be used to transmit navigational data and formation flying algorithms. Once these data are uploaded, the satellites will perform autonomously and hold the formation until a new command is given.

### RESULTS

During Expedition 8, preliminary interference tests were conducted to characterize the effects of lights and other sources of electromagnetic (EM) radiation. The “Beacon-Beacon Test” used a beacon (with mount) and a beacon tester to demonstrate the functionality of the ultrasound/infrared (IR) positioning system of the SPHERES experiment. This portion of the investigation is a risk mitigation experiment for the SPHERES investigation to determine whether any sources of IR radiation or ultrasound exist in the work area that may interfere with SPHERES operations. IR interference was detected from a general lighting assembly (GLA) and from the 760DX laptop in Node 1. A second unplanned test session was performed to better quantify this IR interference. Based on the results of this test, SPHERES will use the newer A31P laptop and dim the GLAs in the workspace to 25% during operations. Operations of the formation-flying objectives with one, two, and three spheres are planned to begin during Expedition 13.



SPHERES team testing flying of 3 satellites in tandem during freefall of a parabolic flight on the KC-135 aircraft. Flights were in July/August 2002 and February 2003.



ISS0008E19135 — Expedition 8 commander Mike Foale holds the SPHERES ultrasound beacon and beacon tester as he performs functionality checks between the Beacon-Beacon tester and its proximity to a general luminaire assembly in Unity Node 1.

## SERIAL NETWORK FLOW MONITOR (SNFM)

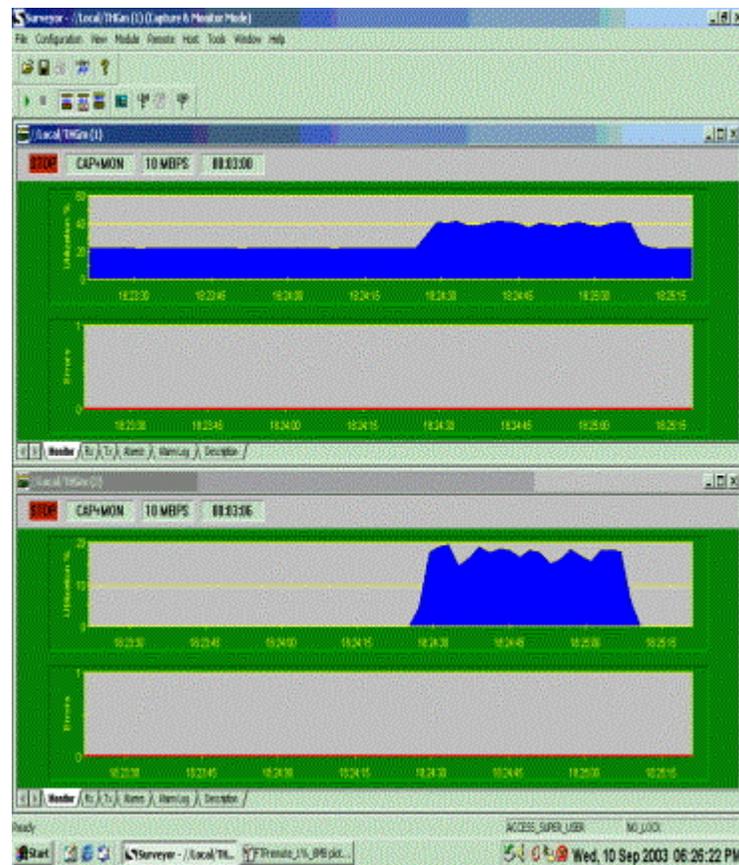
Principal Investigator(s): Carl Konkel, The Boeing Company, Houston, Texas  
Expeditions 9–11

### Research Area Technology Development

The Serial Network Flow Monitor (SNFM) is a commercial off-the-shelf (COTS) software package that monitors packet traffic through the payload Ethernet local area networks (LANs) on board station. The SNFM experiment characterized the network equivalent of data traffic jams on board ISS. The SNFM team targeted historical problem areas including the Space Acceleration Measurement System-II (SAMS-II) communication issues, data transmissions from ISS to the ground teams, and multiple users on the network at the same time. By looking at how various users interact with each other on the network, conflicts can be identified and work can begin on solutions.

### RESULTS

SNFM data are still being analyzed, and will provide “lessons learned” for ongoing network operations on space station and future spacecraft systems.



Computer screen capture image provides a graphic example of network load monitoring.



## **CHARACTERIZING THE MICROGRAVITY ENVIRONMENT ON ISS**

*Many people think of ISS as a “zero-gravity” environment because the continuous free-fall as ISS orbits the Earth simulates the absence of gravity. However, tiny vibrational disturbances aboard station from aerodynamic drag, venting of air or water, movement of solar arrays and antennas, dockings, reboosts, and crew activity all exert forces on station. Experiments have monitored the microgravity environment and evaluated technical solutions to protect ISS experiments from unwanted forces.*

## ACTIVE RACK ISOLATION SYSTEM-ISS CHARACTERIZATION EXPERIMENT (ARIS-ICE)

Principal Investigator(s): Glenn S. Bushnell and Ian J. Fialho, The Boeing Company, Seattle, Wash.  
Expeditions 2–4

### Research Area Technology Development

Constant microgravity conditions are essential for some ISS experiments. Sources of disturbance can include minor changes in acceleration, the movement of hardware such as the space station remote manipulator system (the robotic arm), or even normal crew activities, any of which can cause subtle vibrations to be transferred through station. The active rack isolation system (ARIS) protects equipment by absorbing the shock of motion before it can affect an experiment.

ARIS is installed in two EXPRESS racks on ISS (EXPRESS Rack 2 and EXPRESS Rack 3), where it reduces vibrations using a combination of sensors and actuators. When the sensors detect a disturbance, the actuators counter the effect by sending a reactive force between the EXPRESS rack and the laboratory module, much as a shock absorber on an automobile would—except this “smart” shock absorber is finely tuned to react to, and cancel out, very minute vibrations. Accelerometer assemblies measure the disturbances and send data to the ARIS electronic control unit. The electronic control unit signals pushrods to press against the framework of station, stabilizing the rack. A microgravity rack barrier prevents accidental disturbances to the active ARIS rack. ARIS is designed to isolate all frequencies greater than 0.01 Hz, and is most effective in the 0.05- to 300-Hz range.

The ARIS-ISS Characterization Experiment (ICE) was a payload activity to characterize the ARIS on-orbit performance by monitoring the ambient vibration environment and by generating disturbances. The shaker unit provided a precise, measurable disturbance that simulated possible station vibrations. The other major component of ICE is the payload on-orbit processor, which executed characterization tests and acquired, synchronized, and processed ICE and SAMS-II data for downlink.



SS003327013 — Cosmonaut Vladimir Dezhurov performs ARIS-ICE hammer tests in the U.S. Destiny laboratory during Expedition 3.

### RESULTS

ARIS-ICE operations were performed for over a year during ISS Expeditions 2–4. During that period more than 1700 test runs were completed, ranging from short 1-second stability tests to 5-hour isolation characterization tests. Station vibrations were isolated to levels well below the science requirements of investigations in EXPRESS racks equipped with ARIS (Bushnell et al. 2002a). The ARIS-ICE command and data handling architecture helped to streamline the operational efficiency of the ARIS system. The level of testing needed was greatly reduced by this system (Bushnell et al. 2002b). Quick-control design cycles were able to facilitate on-orbit payload operations, allowing ease of performing ARIS-ICE (Fialho et al. 2003).

The investigators determined, through a series of acceleration characterization experiments conducted during ARIS-ICE, that the ARIS facility provides the ability to predict and prevent the potentially damaging effect of station vibrations. It was also determined that sensitive experiments installed in ARIS would be isolated and

protected from both vibrational and acceleration movements. These capabilities are critical to make ISS a unique, world-class research laboratory in microgravity.

#### **PUBLICATION(S)**

Bushnell GS, Fialho IJ, McDavid T, Allen JL, Quraishi N. Ground and On-Orbit Command and Data Handling Architectures for the Active Rack Isolation System Microgravity Flight Experiment. AIAA 53<sup>rd</sup> International Astronautical Congress, The World Space Congress, Houston, Texas. IAC-02-J.5.07, Oct 10–19, 2002a.

Bushnell GS, Fialho IJ, Allen JL, Quraishi N. Microgravity Flight Characterization of the International Space Station Active Rack Isolation System. AIAA Microgravity Measurements Group Meeting, The World Space Congress, Houston, Texas. Oct 10–11, 2002b.

Fialho IJ, Bushnell GS, Allen JL, Quraishi N. Taking H-infinity to the International Space Station: Design, Implementation and On-orbit Evaluation of Robust Controllers for Active Microgravity Isolation. AIAA Guidance, Navigation and Control Conference, Austin, Texas. Aug 2003.



JSC2001E34286 — Astronaut James Voss performing ARIS-ICE hammer operations in the U.S. Destiny laboratory on EXPRESS Rack 2.

## MIDDECK ACTIVE CONTROL EXPERIMENT-II (MACE-II)

Principal Investigator(s): R. Rory Ninneman, Air Force Research Laboratory (AFRL), Kirtland Air Force Base, N.M.  
Expeditions 1, 2

### Research Area Technology Development

The Middeck Active Control Experiment-II (MACE-II) will allow engineers to design future spacecraft and facilities with lightweight, inexpensive structures and materials without sacrificing the stability demanded by sensitive payloads. MACE-II, the first hands-on experiment on board station, consists of two basic parts designed to detect and compensate for vibrations. The multi-body platform (MBP) test article, which is the structure undergoing tests, has four 1-inch-diameter struts connected to five nodes. It is loosely tethered in the aisle between racks during operations and is stowed between operations. The entire platform has 20 separate sensors that monitor vibration. The experiment support module (ESM) is a self-contained computer with a power interface to the EXPRESS rack and an umbilical connection to the MBP.

During experiments scientists used a gimbal on the MBP to create a disturbance at one end of the platform. The ESM detected these movements and, using an adaptable set of algorithms, calculated the opposing forces to be applied at the opposite gimbal, thereby stabilizing the platform. The algorithms could be adapted to changes due to moving parts, variations in temperature, and normal wear and tear on mechanical systems.

A collaborating team at MIT planned to study how control systems such as that used for MACE-II can be applied to hardware and systems that change over time, such as telescopes, antennas, and robotic arms that must be moved to perform specific duties.

### RESULTS

MACE-II provided data autonomously (no human intervention or prior knowledge of the system), decreasing the effects of vibration in moving structures in space. Algorithms were developed to control mechanical systems in real time using only information from on-board sensors and actuators to respond to changes in the system. The system was able to reduce unwanted vibrations without human intervention once it was turned on. These algorithms were able to “adapt” whenever they sensed changes in vibration or the loss of a sensor or actuator.



ISS002E6721 —Susan Helms, Expedition 2 flight engineer, works with MACE-II, which is shown “floating” in the microgravity environment of station.

Fourteen test protocols were completed during Expedition 1, and an additional 62 test protocols were completed during Expedition 2. The MACE-II unit, which was returned on shuttle flight STS-105, successfully completed all its experiment objectives associated with the AFRL Science Team while on station. On orbit they demonstrated a decrease in vibration by a factor of ten while the system was under control. They then showed that their system could adapt to failure of a primary actuator on the system and still decrease vibration by a factor of six.

However, due to data downlink constraints, the MIT Science Team was unable to meet its science objectives. The MIT team required downlink of specific on-orbit tests to build its control algorithms. By the time data were provided to the university, there was insufficient time to uplink the commands to run the critical experiments.

### PUBLICATION(S)

Davis L. Economical and Reliable Adaptive Disturbance Cancellation. AFRL-VS-TR-2002-1118 Vol. I, AFRL-VS-TR-2002-1118 Vol. II Pt. 1, AFRL-VS-TR-2002-1118 Vol. II Pt. 2, AFRL-VS-TR-2002-1118 Vol. II Pt. 3, Sep 2002. (*Department of Defense clearance required to view this paper.*)

Ninneman R, Founds D, Davis L, Greeley S, King J. Middeck Active Control Experiment Reflight (MACE II) Program: Adventures in Space. AIAA Space 2003 Conference and Exhibition, Long Beach, Calif. AIAA 2003-6243, 2003.

## MICROGRAVITY ACCELERATION MEASUREMENT SYSTEM (MAMS) AND SPACE ACCELERATION MEASUREMENT SYSTEM II (SAMS-II), TWO INVESTIGATIONS

Principal Investigator(s): Richard DeLombard, NASA Glenn Research Center, Cleveland, Ohio  
Expeditions 2–12, ongoing

### **Research Area** Technology Development

Apparent weightlessness is created as the station circles and falls around the Earth; its continuous free-fall simulates the absence of gravity. A number of scientific investigations on station rely on the absence of gravity for successful completion. However, tiny disturbances aboard ISS, including the reboosts required to maintain the station's orbit, mimic the effects of gravity.

Vibrational disturbances occur within the frequency range of 0.01–300 Hz. Two different hardware systems measure and record these vibrations. SAMS-II measures vibrations from vehicle acceleration, systems operations, crew movements, and thermal expansion and contraction. The microgravity acceleration measurement system (MAMS) complements the data by recording accelerations caused by aerodynamic drag and ISS movements caused by small attitude adjustments, gravity gradient, and the venting of water. These quasi-steady state accelerations occur in the frequency range below 1 Hz.

ISS006E42571 — This view features a reboost of station. Ground controllers at Mission Control Moscow ignited the thrusters of a Progress rocket that was docked to the Zvezda service module. This 14-minute firing raised the average altitude of ISS by about 3 km.



MAMS consists of a low-frequency triaxial accelerometer, the miniature electro-static accelerometer (MESA), a high-frequency accelerometer, the high-resolution accelerometer package (HiRAP), and associated computer, power, and signal processing subsystems contained within a double middeck locker enclosure. SAMS-II has multiple remote triaxial sensor (RTS) systems that are used to monitor individual experiments. Each RTS is capable of measuring between 0.01 Hz to beyond 300 Hz of vibration, also known as g-jitter.

### **RESULTS**

MAMS data have been analyzed to examine the quasi-steady regime on station with a frequency below 0.01 Hz. These are related to aerodynamic drag, gravity gradient and rotational effects, venting of air or water, and appendage movement, such as that of the solar arrays and antennas. Characteristics were found in the data that were unexplainable for a short period of time. Analysts determined that the movement of the Ku-band antenna was the source of the unusual characteristics in the quasi-steady data collected by MAMS. (A Ku-band antenna is used to transmit payload science data and video.) The correlation was made after comparing the data with real-time observations from ISS.

A special study using MAMS data was performed by ISS science officer Don Pettit during Expedition 6 as a part of Saturday Science. Pettit examined the motion of air bubbles in water to see how it correlated with quasi-steady accelerations. (Quasi-steady accelerations are vibrations that are at or below a frequency of 0.01 Hz for a period greater than 100 seconds.)

SAMS-II has been used in microgravity and non-microgravity modes of ISS operations to measure vibratory acceleration disturbances. Current data indicate that space station is not meeting its microgravity mode design requirement, and that there is no clear reduction in these disturbances during crew sleep periods.

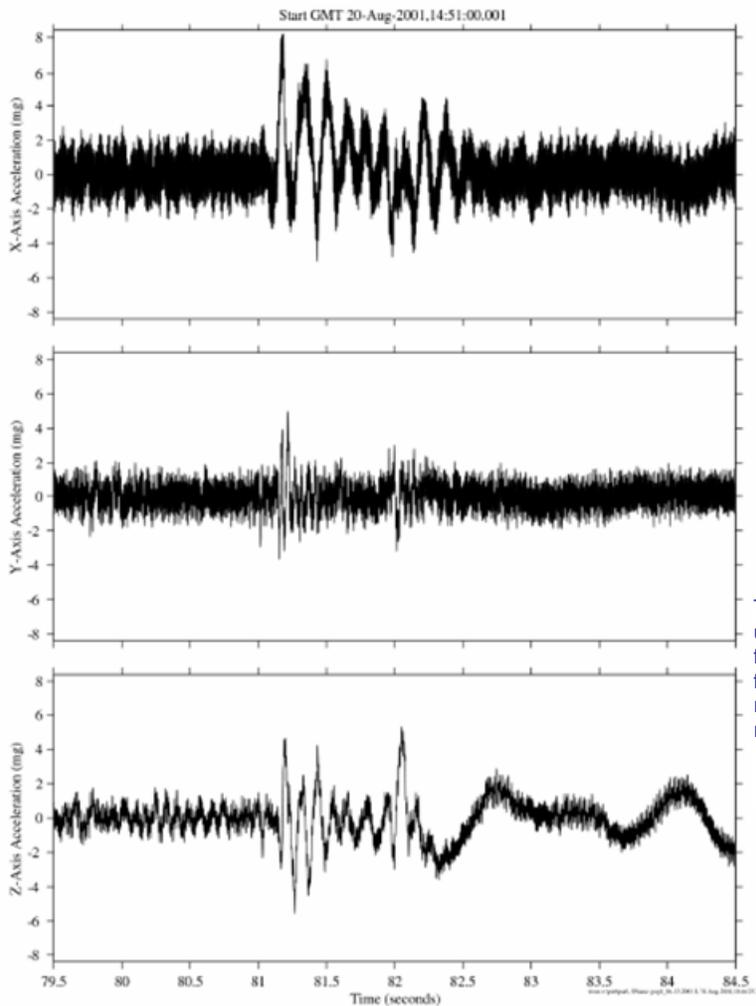
MAMS is currently being activated intermittently to meet operational requests for data during major mission events such as dockings by Soyuz and Progress vehicles. SAMS-II, which began having computer difficulties at the beginning of Expedition 12 (Oct 2005), is still on-orbit but is deactivated.

**PUBLICATION(S)**

Del Basso S, Laible M, O’Keefe E, Steelman A, Scheer S, Thampi S. Capitalization of Early ISS Data for Assembly Complete Microgravity Performance. Proceedings of the 40<sup>th</sup> AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nev. AIAA 2002-606, Jan 14–17, 2002.

DeLombard R, Kelly EM, Hrovat K, Nelson ES, Pettit DR. Motion of Air Bubbles in Water Subjected to Microgravity Accelerations. Proceedings of the 43<sup>rd</sup> AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nev. AIAA 2005-722, Jan 10–13, 2005.

DeLombard R, Hrovat K, Kelly EM, Humphreys B. Interpreting the International Space Station Microgravity Environment. Proceedings of the 43<sup>rd</sup> AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nev. AIAA 2005-0727, Jan 10–13, 2005.



Time series of vibrations produced by the undocking of shuttle flight STS-105 (7A.1) from ISS during Expedition 2. Data are from the HiRAP sensor with graphs representing the X-, Y-, and Z-axes respectively.

## OBSERVING THE EARTH AND EDUCATIONAL ACTIVITIES

*The tradition of Earth observations from orbit was born in 1961 when a Project Mercury astronaut packed the first Hasselblad 500C aboard his capsule to take photographs of the Earth. These images changed our view of ourselves and our relationship to the Earth. Even with the many satellites now orbiting the Earth, ISS continues to provide unique views of our planet.*

*ISS provides a unique platform for inspiring students to excel in mathematics and science. Station educational activities have had a positive impact on thousands of students by involving them in station research, and by using the station to teach them the science and engineering behind space exploration.*

## CREW EARTH OBSERVATIONS (CEO)

Principal Investigator(s): Kamlesh Lulla and Sue Runco, NASA Johnson Space Center, Houston, Texas  
Expeditions 1–12, ongoing

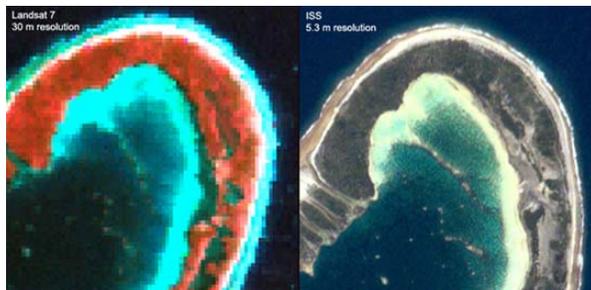
### Research Area Observing the Earth

Space station crewmembers use handheld cameras and a variety of lenses (including an 800mm lens equivalent) to take Earth observation photographs. Scientists on the ground train the crew in basic areas of Earth system science and provide to the crew a daily list of targets of the greatest scientific interest. Crewmembers take these photographs as time is available and during their leisure time. These digital photographs are downlinked and their location identified for use as educational and research tools, as well as historical records of global environmental change, special geological and weather events, and the growth and change of human-made features, such as cities. Crew Earth Observations (CEO) can be conducted from any available window on space station, but is conducted primarily from the nadir-viewing, optical-quality window in the U.S. Destiny laboratory module and from the windows in the Russian Zvezda service module.

### RESULTS

ISS provides a unique opportunity to capture a variety of sites on Earth by providing repeated overflight passes of the Earth. Through CEO, ISS crewmembers share their view of the Earth with the public and take pictures of some of the most dramatic examples of change on the Earth's surface. These sites have included major deltas in south and east Asia, coral reefs, cities, smog over industrial regions, areas that typically experience floods or droughts triggered by El Niño cycles, alpine glaciers, tectonic structures, and features on Earth, such as impact craters, that are analogs to structures on other planets. Some of the unique images of Earth taken by astronauts from station from 2000–2003 that provide information concerning the Earth not available from any other source are available in an online collection of ISS Greatest Hits. In 2004 and 2005, station astronauts took key photographs of the four Florida hurricanes, the December 2004 tsunami, and Hurricanes Katrina and Wilma.

From Expedition 1 through December 2005, ISS crewmembers took more than 180,000 images of Earth, almost one-third of the total number of images taken from orbit by astronauts since the first Gemini missions. Scientists and the public around the world have access to CEO images captured by astronauts on station through the Gateway to Astronaut Photography of Earth Web site (<http://eol.jsc.nasa.gov>). Approximately 700,000 to 800,000 NASA digital photographs of Earth are downloaded by the public each month. The Web site also features an “Image of the Week” and searchable access to all the photographs. Scientific analyses using CEO data have been published in scientific journals in a wide variety of disciplines. A few highlights of these publications are summarized here.



This comparison of Landsat 7 ETM+ (left) and digital photography from station (ISS002E6372, right) illustrates how astronaut photography can be an important source of supplemental data to studies using satellite imagery. At Landsat's 30-meter spatial resolution, there is not enough information about the lagoon structure. Detailed photographs of reefs taken from ISS are being used around the world. The high spatial resolution of the images (about 5 meters/pixel) make them highly suited for comparison to what is seen by divers in the water.

gathered indicated that landscape parameter estimates were fairly accurate regardless of spatial resolution changes from 5 to 30 meters. This study of ISS imagery showed that spatial resolution, as well as spectral resolution, is of equal importance when studying these formations (Andréfouët et al. 2003). The most detailed images of Fangatau

Spatial resolution is a measure of the smallest object that can be resolved by the sensor, or the size of the area on the ground represented by each pixel determined by geometric properties of the altitude of the spacecraft, lens magnification, size of the original image, and look angle. To achieve maximum potential spatial resolution, a camera system must capture information at sufficient speed to eliminate the effects of relative ground motion. Using handheld motion compensation, station crewmembers have achieved a spatial resolution of less than 6 meters in photographs of Earth from ISS. The ISS provides great potential as a remote-sensing platform capable of providing high-resolution imagery of the Earth's surface (Robinson and Evans 2002).

CEO images captured from ISS of Pacific Ocean atolls (islands consisting of a circular coral reef surrounding a lagoon) allowed for an assessment of spatial resolution on estimates of landscape parameters of the atolls. Data

atoll, taken from ISS, were used to measure the biomass of the giant clam fishery at Fangatau Atoll with accuracy similar to that obtained from aerial photography (Andréfouët et al. 2005). Astronaut photographs of reefs in the Indian Ocean have been used as base maps for dive surveys of reef resources in the region (Quod et al. 2002).

Extracting clear water depths from a variety of sources allows the examination and mapping of shallow water from global to local scales. Scientists from the National Oceanic and Atmospheric Administration (NOAA) used four sources of data to map shallow water bathymetry near U.S. coral reef areas. These included the sea-viewing wide field-of-view sensor (SeaWiFS) on board the OrbView 2 Satellite (SeaWiFS, allows global mapping within 1-kilometer pixels), the IKONOS satellite (global mapping within 4 meters), the Landsat Satellite (global mapping within 30 meter pixels), and handheld photography by the ISS crew (CEO local mapping within 6 meters). A new technique was applied to the blue and green bands from astronaut photography, allowing construction of a bathymetry map for Pearl and Hermes reef with accuracies similar to that obtained from IKONOS (Stumpf et al. 2003).

High-resolution astronaut photography collected from station has provided useful data for urban analysis, especially vegetation measurements. The accuracy of the data obtained from the astronaut photographs was similar to the data obtained by satellite remote sensors. The high-resolution astronaut photography obtained by the CEO investigation gives insights into vegetation density in urban areas (Stefanov and Robinson 2003).

Imagery captured during ISS Expedition 6 by astronaut Don Pettit (example, right) has led to potential applications for urban analyses and modeling of cities at night. ISS photographs of cities at night are unique because they provide greater spatial resolution than any other source of city light data. Images of cities captured at night clearly provide data for urban density modeling and enhancing census estimates (Lulla 2003).



ISS006E24987 — ISS Expedition 6 science officer Don Pettit pioneered an approach using a homemade tracking system to track the ground as it moves relative to station; this allowed him to acquire long-exposure images under low-light conditions using very long exposures. This image shows the lights of Argentina's capital city, Buenos Aires.

#### **PUBLICATION(S)**

Andréfouët S, Robinson JA, Hu C, Salvat B, Payri C, Muller-Karger FE. Influence of the spatial resolution of SeaWiFS, Landsat 7, SPOT and International Space Station data on landscape parameters of Pacific Ocean atolls. *Canadian Journal of Remote Sensing*. 29:210–218, 2003.

Andrefouet S, Gilbert A, Yan L, Remoissenet G, Payri C, Chancerelle Y. The remarkable population size of the endangered clam *Tridacna maxima* assessed in Fangatau Atoll using in situ remote sensing data. *ICES Journal of Marine Science*. 62(6):1037-1048, 2005.

Cembella AD, Ibarra DA, Diogene J, Dahl E. Harmful Algal Blooms and their Assessment in Fjords and Coastal Embayments. *Oceanography*. 18(2):160–173, 2005.

Lulla K. 2003 Nighttime Urban Imagery from International Space Station: Potential Applications for Urban Analyses and Modeling. *Photogrammetric Engineering and Remote Sensing*. 69:941–942, 2003.

Quod J-P, Bigot L, Blanchot J, Chabanet P, Durville P, Nicet J-B, Wendling B. Research and monitoring of the coral reefs of the French islands of the Indian Ocean. Assessment activities in 2002. Mission carried out in Glorieuses. *Réunion: IFRECOR (l'Initiative Française pour les Récifs Corallines)*. 2, 2002. [in French]

Robinson JA, Evans CA. Space Station Allows Remote Sensing of Earth to within Six Meters. *Eos, Transactions of the American Geophysical Union*. 83:185–188, 2002.

Stefanov WL, Robinson JA. Vegetation Density Measurements From Digital Astronaut Photography. International Archives of the Photogrammetry, Remote Sensing, and Spatial Information Sciences. 34:185–189, 2003.

Stumpf RP, Holderied K, Robinson JA, Feldman G, Kuring N. Mapping water depths in clear water from space. Proceedings of the 13<sup>th</sup> Biennial Coastal Zone Conference. Baltimore, Maryland, Jul 13–17, 2003.



ISS003E5588 — This still image, taken from ISS, shows the World Trade Center smoke plume rising from lower Manhattan. It was taken by Expedition 3 commander Frank Culbertson as station flew over New York City shortly after the collapse of the towers. The ISS crew was at an altitude of approximately 250 miles.



ISS006E44305 — Astronaut Donald R. Pettit, Expedition 6 NASA ISS science officer, runs a drill while looking through EarthKAM mounted on the nadir window in the U.S. Destiny laboratory. The device is called a “barn door tracker.” The drill turns the screw, which moves the camera and its spotting scope.



ISS008E16355 — A massive sandstorm over the Persian Gulf state of Qatar blows southward toward southeastern Saudi Arabia and the United Arab Emirates. This photograph was taken by an Expedition 8 crewmember on board station.

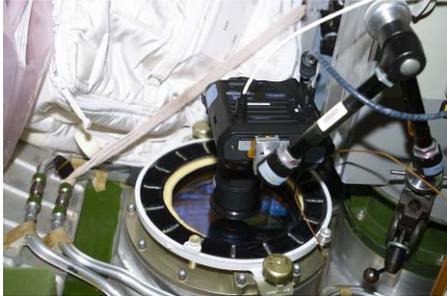


ISS007E14745 — Astronaut Ed Lu snapped this photograph of the eye of Hurricane Isabel from ISS on Sep 13, 2003. At the time, Isabel was located about 450 miles northeast of Puerto Rico. Meteorologists have used astronaut photography of hurricane eye walls as a unique, high-resolution view of the structure during changes in intensity.

## EARTH KNOWLEDGE ACQUIRED BY MIDDLE SCHOOL STUDENTS (EARTHKAM)

Principal Investigator(s): Sally Ride, University of California at San Diego, La Jolla, Calif.  
Expeditions 2, 4–12, ongoing

**Research Area** Educating and inspiring the next generation



The EarthKAM equipment is mounted in one of the windows of the ISS service module.

Earth Knowledge Acquired by Middle School Students (EarthKAM) is a NASA-sponsored education program that enables thousands of students to photograph and examine Earth from the unique perspective of space. The purpose of EarthKAM is to integrate the excitement of ISS with middle-school education. EarthKAM invites schools from around the world to take advantage of this exceptional educational opportunity. In addition to the many schools in the United States, schools from 12 countries have also participated.

Middle-school students learn about spacecraft orbits and Earth photography, and then target and request their desired images by tracking the orbit of the station, referencing maps and atlases, and checking weather. Their requests are then collected and compiled by

students at the University of California, San Diego, Calif. With help from representatives at NASA Johnson Space Center in Houston, compiled requests are uplinked to a computer on board ISS. This computer records the requests and transmits them to the digital camera, which takes the desired images and transfers them back to the computer. The images are then downlinked to EarthKAM computers on the ground. Within hours, the EarthKAM team makes the photographs available on the World Wide Web for easy access by participating schools as well as the general public. Schools then explore the images in support of national, state, and local education standards. Students learn to recognize and research features in the images, place the images in global context using maps and atlases, and make connections with the topics and subjects they are studying.

### RESULTS

As of April 2006, 65,648 students from 1062 schools worldwide, as well as members of the general public, have used EarthKAM to investigate every corner of the globe. Images taken by the participating schools are posted on the EarthKAM Web site at <http://www.earthkam.ucsd.edu/> for use by the public and participating classrooms around the world. Started in 1996, EarthKAM has conducted 19 missions on ISS and offers more than 20,000 photos of the Earth. No other NASA program gives students such direct control of an instrument flying on a spacecraft orbiting Earth, and as a result, students assume an unparalleled personal ownership in the study and analysis of their Earth photography.



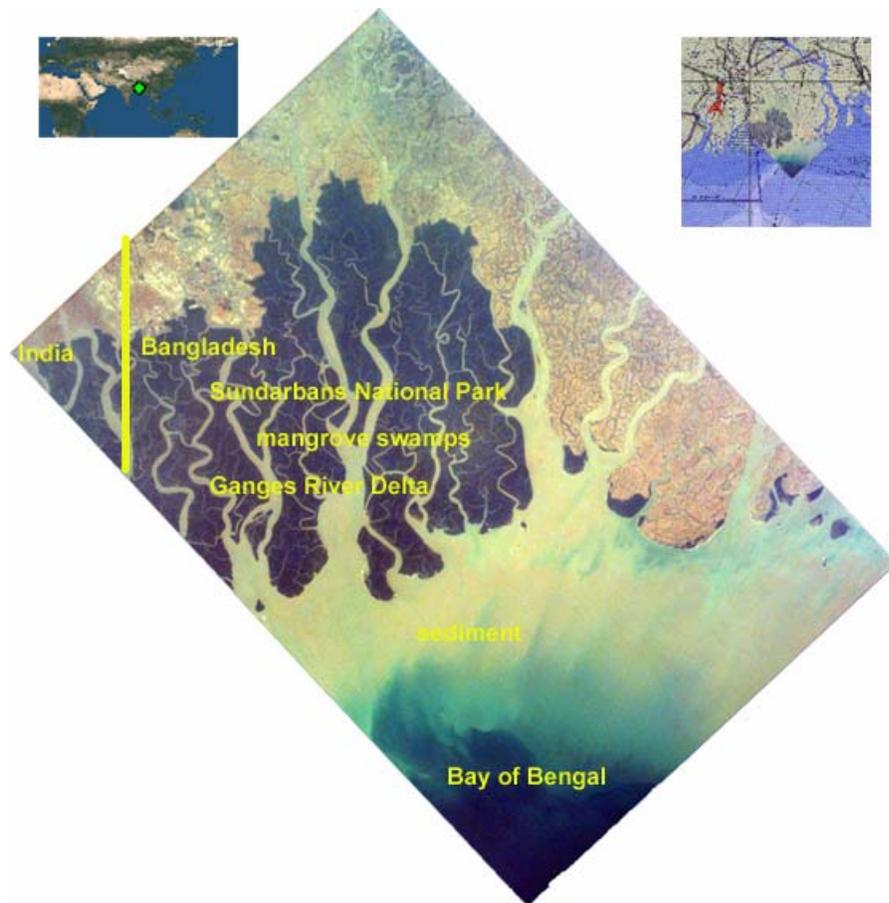
Edward T. Lu, Expedition 7 flight engineer, participates in EarthKAM training in the Space Vehicle Mockup Facility at NASA Johnson Space Center.



EarthKAM students determine photo locations by referencing maps and atlases, and by matching these to a display of the upcoming orbit tracks for ISS to generate their image requests.

## PUBLICATION(S)

Hurwicz M. Case Study: Attack of The Space Data – Down To Earth Data Management At ISS EarthKAM. *New Architect.* 38, Aug 1, 2002.



The above image was acquired by ISS EarthKam, annotated, and captioned by students. The caption produced by the students is as follows:

South of the confluence of the Ganges and Brahmaputra Rivers (not shown in this image) and north of the Bay of Bengal lies the vast Ganges Delta, which is about 220 miles (350 kilometers) wide. As the rivers empty, they carry large quantities of sediment into the Bay of Bengal. Parts of this delta—the world's largest—lie in both Bangladesh and the State of West Bengal, India. The very dark part of the delta is the Sundarbans, a vast wildlife preserve and abundant mangrove swamp that is the largest remaining habitat of the Bengal tiger. The entire low-lying region is plagued almost yearly by severe storm surges and powerful low-pressure cyclones (the monsoons) that arrive from the Bay of Bengal. Summer monsoon causes flooding, heavy damage to crops and shelters, and loss of human life. The Ganges River is the most sacred river of India. Many Hindus come to get healed, to wash away their sins, or to die at the river if they are ill or elderly. When a person dies, they are taken to the "purifying stream" and are then dipped in the Ganges before being cremated. The Hindus then scatter the ashes across the river.



Expedition 10 science officer and commander Leroy Chiao in front of the EarthKAM camera holding a student greeting from Wissahickon Middle School, Ambler, Penn.

## SPACE EXPOSED EXPERIMENT DEVELOPMENT FOR STUDENTS (EDUCATION-SEEDS)

Principal Investigator(s): Howard Levine, NASA Kennedy Space Center, Cape Canaveral, Fla., and Fredrick Smith, NASA Johnson Space Center, Houston, Texas  
Expedition 1

**Research Area** Educating and inspiring the next generation

During the Education-Space Exposed Experiment Development for Students (SEEDS) experiment, eight pouches of soybean and corn seeds flew on station and germinated under either dark or lighted conditions. A grid along the side of the pouch allowed the crew to determine the amount of growth without opening the pouches. In addition, microgravity-exposed seeds were distributed to schools in Fall 2001 and students conducted germination experiments comparing them with seeds that had not flown in space.

### RESULTS

The Education-SEEDS investigation, which was part of the Jason XI mission, was the first plant experiment to be performed on station. This experiment studied the effects of microgravity and light on the germination of corn and soybean seeds.

The corn seedlings that were exposed to light appeared to show phototropism (or growth towards light). The shoots grew toward the light and were green, demonstrating chlorophyll synthesis (the creation of the green pigment that is used in photosynthesis). The corn seedlings that were not exposed to light did not turn green and did not grow towards the light. The soybean seedlings grown in the light were slightly greener than the seedlings grown in the dark. The phototropic effect was more evident in the corn seedlings than in the soybean seedlings. On Earth, gravity influences the roots of plants to grow in a downward direction (gravitropism). While on orbit the seedlings grew in a microgravity environment. Whether grown in light or dark, the corn roots grew in random directions. The roots of the soybean seeds also grew in random directions (Levine et al 2001).

Examination of the seeds after their stay on ISS revealed that the nutritional and epidermal layers of the space-exposed seeds were more porous than those of the ground-based control seeds. This might allow nutrients to disperse through the seeds more quickly and explain the faster germination and growth rates observed in the space-exposed seeds.

Simple space flight experiments suitable for ISS can have significant science impact in the classroom. A total of 750,000 students across the U.S. participated in the experiments, growing corn and soybean seeds in their classrooms to compare with the results from station, and participating in live broadcasts.

### PUBLICATION(S)

Levine HG, Norwood KLL, Tynes GK, Levine LH. Soybean and Corn Seed Germination in Space: The First Plant Study Conducted on Space Station Alpha. Proceedings of the 38<sup>th</sup> Space Congress, Cape Canaveral, Fla. 181–187, May 2001.

Expedition 1 commander Bill Shepherd is shown with a SEEDS pouch. Additional pouches are hanging from the ISS "wall" above the "Astronauts At Work" sign.



## EDUCATION PAYLOAD OPERATIONS (EPO)

Principal Investigator(s): Cynthia McArthur, NASA Johnson Space Center, Houston, Texas  
Expeditions 4, 5, 7–10, 12, ongoing

**Research Area** Educating and inspiring the next generation



Expedition 3 science officer Mike Foale uses small and large magnets to show the pull of the Earth's magnetic field on ISS as part of an EPO event.

The objective of the Education Payload Operations (EPO) investigation is to use toys, tools, and other common items in the microgravity environment of ISS to create educational video and multimedia products that inspire the next generation of engineers, mathematicians, physicists, and other scientists. The products are used for demonstrations, and to support curriculum materials that are distributed across the United States and internationally. The individual EPO projects are designed to explore physical phenomena such as force, motion, and energy. Each Expedition involves different on-orbit activities and themes, as well as different partners, such as museums, universities, and public school districts.

The EPO payloads are small, weighing less than 6.8 kg (15 lbs) each. Whenever possible, the demonstrations use materials and objects already available on station. Some of the activities cover physical properties, such as Newton's Laws of Motion or Bernoulli's Principle for air pressure, and others are specific to life in space, such as explaining how ISS solar panels work or demonstrating EVAs.

Specific activities are as follows:

- Education demonstration activities (EDAs) showed basic physics, such as of Weight vs. Mass, Center of Mass.
- EDAs illustrated aspects of living in space, such as Tools in Space, and Pouring Liquid into a Container.
- International Toys in Space developed a DVD for use in classrooms around the United States based on the physics behind a variety of toys.
- Tomatosphere II, exposed 1.5 million tomato seeds to the space environment. The seeds have been distributed to classrooms throughout Canada. Students will measure the germination rates, growth patterns, and vigor of growth of the seeds.
- EDAs for use by science museums included a harmonica, puzzles, dexterity puzzles, and a balsa wood Wright Flyer.

## RESULTS

EPO has been a successful education program on ISS. By using simple objects and the microgravity environment, NASA is able to produce videos that demonstrate physical properties, such as force, motion, and energy, that may be obscured by gravity on Earth. To date, over 500 videos, DVDs, and video clips have been produced and distributed to science teachers and schools throughout the United States. About 1500 teachers each year are trained to use the materials in their classrooms. An additional 30.9 million students have had the opportunity to participate in live downlink events where their classmates pose questions of ISS crews on orbit.

The 1.5 million Tomatosphere-II seeds from Expedition 9 were divided and distributed to 160,000 students in 6000 classrooms across Canada.



Expedition 8 science officer Mike Foale demonstrates the use of tools on station for an EPO event.

## PUBLICATION(S)

National Aeronautics and Space Administration Educational Product. International Toys in Space – Science on the Station DVD. ED-2004-06-001-JSC, 2004.

## SPACE EXPERIMENT MODULE (SEM)

Principal Investigator(s): Ruthan Lewis, NASA Goddard Space Flight Center, Greenbelt, Md.  
Expeditions 10, 11, planned 13

**Research Area** Educating and inspiring the next generation



ISS010E12594 0— This image shows an integrated SEM used during Expedition 10; the photograph was taken by ISS commander Leroy Chiao.

Kevlar, silk, ultraviolet beads, chicken bones, copper, plastic, dextrose, yeast, over-the-counter medications, human hair, mineral samples, light bulbs, and brine shrimp eggs. Many students will test for seed growth after microgravity exposure; other students will test how materials protect against radiation exposure and survival rates of microscopic life forms.

### RESULTS

Eleven schools and 300 students developed experiments for SEM Satchel 001. The satchel was launched during ISS Expedition 10 in December 2004 and returned to Earth on space shuttle *Discovery* (STS-114) in August 2005. The sample vials will be returned to the students for analysis.



Students from Mott Hall School, New York City, N.Y. wrap fabrics around radiation dosimeters as they prepare samples for the Wearable Radiation Protection Experiment that was part of SEM-2.

## DREAMTIME (DREAMTIME)

Principal Investigator(s): Ben Mason, Dreamtime Holdings Inc., Moffett Field, Calif.  
Expedition 3

**Research Area** Educating and inspiring the next generation

As part of the DreamTime project a commercial high-definition television (HDTV) system was flown on ISS. The camera's COTS battery system and a dedicated cable were modified to allow the batteries to interface with station on-board EVA tool charger. When compared to standard television video, high-definition video appears four times sharper, giving a considerably more detailed image. The audio is also improved with HDTV, which records on 5.1 channels vs. the standard two channels in typical stereo systems, in effect providing surround-sound capability. Dreamtime was used on ISS to provide these enhanced images and audio for ground-based observers.

### RESULTS

In developing the original public-private partnership, NASA had hoped that DreamTime would play a role in developing commercial products based on the historic activities on ISS. Lacking commercial direction from DreamTime, yet recognizing the historical significance of activities on the station, NASA took the initiative and developed scenarios and created storyboards for the flight crew to record ISS documentary footage of outstanding quality during the mission. The result of this effort returned over 500 minutes of HDTV footage, suitable for commercial purposes, and far exceeding the expected imagery return. The private company that originally sponsored DreamTime was short-lived, and no results were generated. The Bioastronautics Research Program has created the video "Secrets of Science in Outer Space" using some of the DreamTime footage.



ISS003-E-5826 — Cosmonaut Vladimir N. Dezhurov, Expedition 3 flight engineer, works with camera equipment in the Zvezda service module.

## RESULTS FROM ISS OPERATIONS

*Although not part of a formal investigation or payload on ISS, medical and engineering data collected as part of the operation of ISS is an important source of information for scientific study. We therefore summarize the results of three major areas of information-gathering to date: environmental monitoring, medical monitoring of crewmembers, and lessons learned from the operation of station that are relevant to future mission designs.*

## ENVIRONMENTAL MONITORING OF ISS

Environmental monitoring research has been performed on all ISS Expeditions and will continue to be performed on future station missions to ensure the health of the spacecraft as well as of the crew.

### RESULTS

During one study of the ISS atmosphere 12 bacterial strains were isolated and fingerprinted from the ISS water system. These bacteria consisted of common strains and were encountered at levels below 10,000 colony-forming units/10 cm<sup>2</sup>, well below the minimum of bacteria needed to cause illness. These data represent the beginning of ISS habitation and indicate that the lessons learned from previous Mir and Skylab missions were implemented and have been effective in keeping station a safe place in which to live and work (Castro et al. 2004).

Other studies performed an in-depth microbial examination of the drinking water in various stages (from the NASA Kennedy Space Center, Cape Canaveral, Fla. to the ISS ports). These studies have revealed that NASA policy for biocide treatment has effectively removed pathogenic microbes traveling to space (La Duc et al. 2004; Plumlee et al. 2002; Plumlee et al. 2003). Studies on station air quality found that the active (volatile organics analyzer) and passive (HEPA filters) controls in place on ISS are effective in controlling trace contaminants of volatile organic compounds on space station (James 2003; Perry 2003).

### PUBLICATION(S)

Castro VA, Thrasher AN, Healy M, Ott CM, Pierson DL. Microbial Characterization during the Early Habitation of the International Space Station. *Microbial Ecology*. 47:119–126, 2004.

James J. Toxicological Assessment of the International Space Station Atmosphere with Emphasis on Metox Canister Regeneration. 33<sup>rd</sup> International Conference on Environmental Systems, Vancouver, Canada. SAE Technical Paper 2003-01-2647, Jul 2003.

La Duc MT, Sumner R, Pierson D, Venkat P, Venkateswaran K. Evidence of pathogenic microbes in the International Space Station drinking water: reason for concern? *Habitation*. 10:39–48, 2004.

Perry J, Peterson B. Cabin Air Quality Dynamics on Board the International Space Station. 33<sup>rd</sup> International Conference on Environmental Systems, Vancouver, Canada. SAE Technical Paper 2003-01-2650, Jul 2003.

Plumlee D, Mudgett PD, Schultz JR. Chemical Sampling and Analysis of ISS Potable Water: Expeditions 1–3. 32<sup>nd</sup> International Conference on Environmental Systems, San Antonio, Texas. SAE Technical Paper 2002-01-2537, 2002.

Plumlee D, Mudgett P, Schultz J, James J. ISS Potable Water Sampling and Chemical Analysis: Expeditions 4–6. 33<sup>rd</sup> International Conference on Environmental Systems, Vancouver, Canada. SAE Technical Paper 2003-01-2401, Jul 2003.

## MEDICAL MONITORING OF ISS CREWMEMBERS

Medical monitoring of ISS crewmembers includes tests before, during, and after space flight to follow the effects of space flight on their health and to ensure that they receive proper medical care. Nutritional assessments ensure adequate intake of energy, protein, and vitamins during missions. Scientists use the information to understand the connections between nutrition and human health during space flight, and to develop effective dietary strategies to reduce adverse health impacts. Electrocardiograms or Holter monitor tracings obtained from astronauts during their time in space are analyzed to provide insight into cardiac function in microgravity. In addition, some assessments of new hardware such as the ultrasound equipment, mass-measurement devices, and gas analyzers have led to scientific findings.

### RESULTS

Results of nutritional status monitoring were compiled and analyzed for crewmembers on ISS Expeditions 1–8. Intake of energy (relative to World Health Organization standards) was observed to generally decrease over time during missions. However, when dietary counseling was provided to a single astronaut during flight, adequate energy intake was thereafter maintained throughout the mission. Body weight, total bone mineral content, and bone mineral density decreased during flight. Antioxidant capacity decreased during flight, leading to increased susceptibility to genetic damage from radiation. Vitamin D concentration in crew bone was decreased, and bone resorption increased by long exposure to microgravity (Smith et al. 2005). Future flight research is in development to acquire more information on the effect of the space flight environment on vitamin and drug potency, and to gather additional information on the importance of nutrition as a countermeasure for the effects of space flight on the human body.

A very limited retrospective study of electrocardiograms (ECGs) from astronauts on short-duration (space shuttle) and long-duration (ISS and Mir) missions indicated that long-duration, not short-duration, space flight was associated with prolonged cardiac conduction and repolarization. Long-duration flight was associated with heart-rate-corrected objective test interval (QTc) interval prolongation that might increase susceptibility to cardiac arrhythmia (D'Aunno et al. 2003). A systematic collection of ECGs from ISS crewmembers is planned for the future to better evaluate whether there is a significant risk of arrhythmia from long-duration stays in a microgravity environment.

As part of the testing of ultrasound equipment when it was first brought to ISS, the Focused Assessment with Sonography for Trauma (FAST) examinations were performed by an ISS crewmember with minimal sonography training. Even with a significantly reduced video frame rate and a two-second communication latency, the quality of the ultrasound video were excellent and would have allowed clinical decision-making in a trauma contingency (Sargsyan et al. 2005). This preliminary work was followed by the formal ADUM experiment.

### PUBLICATION(S)

D'Aunno DS, Dougherty AH, DeBlock HF, Meck JV. Effect of Short- and Long-Duration Spaceflight on QTc Intervals in Healthy Astronauts. *The American Journal of Cardiology*. 91:494–497, 2003.

Sargsyan AE, Hamilton DR, Jones JA, Melton S, Whitson PA, Kirkpatrick AW, Martin D, Dulchavsky SA. FAST at Mach 20: Clinical Ultrasound Aboard the International Space Station. *The Journal of Trauma, Injury, Infection, and Critical Care*. 58(1):35–39, 2005.

Smith S, Zwart SR, Block G, Rice BL, Davis-Street JE. The nutritional status of astronauts is altered after long-term space flight aboard the International Space Station. *Journal of Nutrition*. 135(3):437–443, 2005.

## **EXPLORATION LESSONS LEARNED FROM THE OPERATION OF ISS**

Constructing and operating ISS serves as a testbed for new technologies and techniques in support of the crew exploration vehicle (CEV) and lunar mission hardware design and development. Lessons learned from the operation of life support technologies on station are directly applicable to the selection and operation of systems for future Exploration vehicles. The limited resupply following the *Columbia* accident served as a model for operation of future Exploration missions to the moon and Mars. Lessons learned from ISS are directly applicable to the design, development, operations, and management of future Exploration missions.

### **PUBLICATION(S)**

Carrasquillo RL. ISS ECLSS Technology Evolution for Exploration Proceedings of the 43<sup>rd</sup> AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nev. AIAA-200-0337 Jan 10–13, 2005.

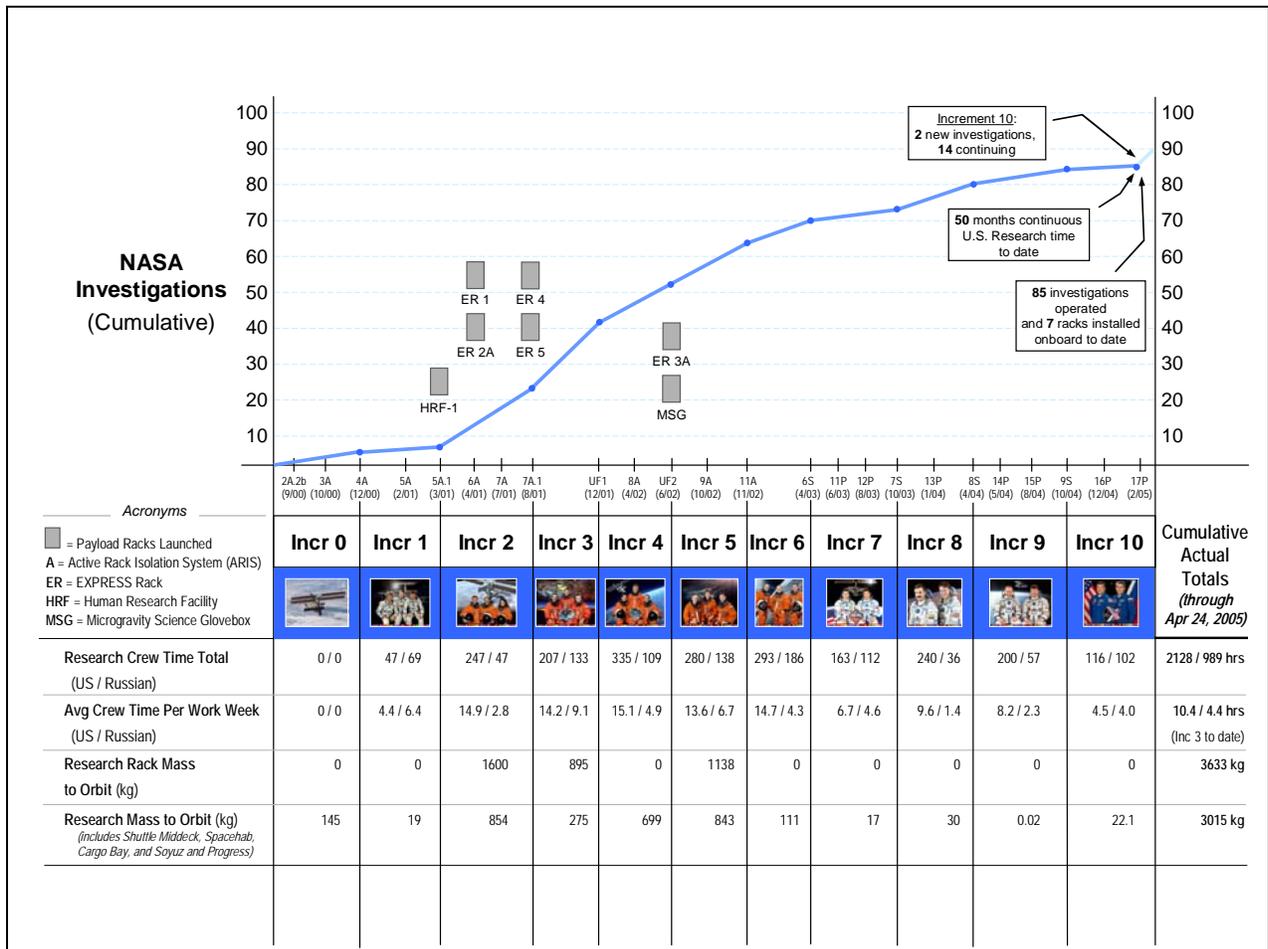
Kitmacher GH, Rosenberg I, Gerstenmaier W. ISS: A partner in enabling space exploration through reduction of risk. Proceedings of the 1<sup>st</sup> Space Exploration Conference, Orlando, Fla. AIAA 2005-2550, Jan 30–Feb 5, 2005.

Sanchez MJ, Voss JS. From ISS to the Moon, Mars, and Beyond—applying lessons learned. Proceedings of the 43<sup>rd</sup> AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nev. AIAA 2005-705, Jan 10–13, 2005.

Walz C, Uri J, Baumann D. Far from home—human presence on the ISS as a preparation for a lunar base and beyond. Proceedings of the 1<sup>st</sup> Space Exploration Conference, Orlando, Fla. AIAA 2005-2549, Jan 30–Feb 1, 2005.

# SUMMARY

In this report we summarized the objectives and results of research on the International Space Station from its beginning through Expedition 10 (2000–April 2005). Over this four-and-one-half-year period, the primary emphasis was on station assembly, not on completing research. A total of 85 experiments were conducted on ISS, covering a wide range of research topics from fundamental physics to applied human health research. NASA’s international partners completed additional research under their own programs. The engineers, doctors, and scientists responsible for operating station and ensuring the wellbeing of its crews have also been actively collecting and analyzing scientific data to improve the technologies and operational approaches for future ISS Expeditions and future Exploration missions.



Summary of the crew time and research mass to orbit during early assembly of ISS from Expeditions 0–10.

Given the time that it takes from the conclusion of data collection to the complete publication of scientific results, we are only just beginning to see the fruits of early scientific labors on station. In this report, we summarized 110 scientific publications (listed by detailed category in Table 1). Many of the payloads summarized here are expected to have published additional scientific articles concerning them as their analyses are completed.

**TABLE 1. SCIENTIFIC PUBLICATIONS FROM ISS RESEARCH IN THIS REPORT, THROUGH JUNE 2006.**

<i>Type of Activity</i>	<i>No. of Publications</i>
Experiments (formal utilization activities or payloads)*	87
Experiments on shuttle sorties to ISS that were part of the station research portfolio	4
Scientific analysis of data collected as part of station operations	9
Lessons learned from station operations	4
Summaries and reviews of ISS science activities	6
<b>Total</b>	<b>110</b>

\*Includes four abstracts with significant data content, one publication based on ground controls, and two publications of new designs created from ISS experience.

A number of accomplishments in different fields have been summarized in this report. Although it is a challenge to choose among these, we have subjectively identified what we believe are some of the top accomplishments from the first ten Expeditions.

1. ***Significant advances have been made in understanding the processes of bone loss in microgravity.*** The Subregional Bone experiment identified significant loss of bone in spite of exercise by crewmembers. In addition, the study found that that bone was lost disproportionately from the trabecular (interior) bone. As ISS exercise equipment was repaired and improved, the Foot/Ground Reaction Forces during Space Flight study measured the actual foot forces and joint angles, and found that replacement forces on the devices were not adequate to replace forces that would have been experienced on Earth. These data will allow improved exercise prescriptions in the future, and are particularly important as we look forward to launch of the advanced resistive exercise device and tests of additional mechanical and pharmaceutical countermeasures in future investigations.

2. ***Improvements in telemedicine capabilities have improved medical care during long-duration space flights.*** The Advanced Ultrasound study established the feasibility of using “just-in-time” training to get diagnostic-quality medical imaging should a crewmember be injured in space. Remote medical capability will be a key requirement for long stays on the moon and any Mars expedition. Medical Monitoring of ISS Crewmembers to protect the health of the crew on ISS has been the pathfinder for medical care on any long-duration space Exploration mission. Results from medical monitoring are being used to drive the next steps in medical research on station.

3. ***Early results of physical sciences experiments indicate strong potential for new understanding of basic physical processes in several different areas.*** Results from the originally planned runs of the Binary Colloidal Alloy Experiment were so surprising that an entire set of experiment runs was repeated using the EarthKam camera system to get more frequent time-lapse imagery. Additional concentrations of colloid mixtures are now planned to be flown in future to expand the understanding of this model of the behavior of fluids near the critical point. Runs of the first apparatus for the Capillary Flow Experiment were also repeated to improve the measurement of physical parameters. The unique experiment chambers in this apparatus allow very detailed measurement of fluid flows in microgravity and are providing new data that are relevant to the design of fuel tanks and other spacecraft systems. Five additional chambers in various configurations are planned for future experimentation.

4. ***Tests of material exposure to the space environment are increasing our understanding of the robustness of spacecraft materials.*** The Materials International Space Station Experiment (MISSE-1 and 2) carriers exposed hundreds of different samples effects of radiation and atomic oxygen. Although planned for one year of exposure, the materials were left in orbit for an unprecedented four years. The results are expected to change the choice of materials for use in satellites and human spacecraft, and improve our theoretical knowledge of the effects of the space environment. MISSE-5 is now on board ISS testing performance of new solar cells. MISSE carriers are also testing materials specifically for use on the CEV.

5. ***Student experiments and educational activities on ISS have reached millions.*** Educational activities on ISS include student-developed experiments, students performing classroom versions of ISS experiments, students participating in NASA investigator experiments, students participating in ISS engineering activities, and educational demonstrations and activities. A review (Thomas et al. 2006, cited on p.3) of all activities from 2000–April 2006 identified 24 unique types of educational programs involving 31.8 million students, and more than 12,500 teachers participating in ISS-based education workshops. Some key examples are the EarthKAM experiment where nearly 1000 schools and 66,000 middle school students have controlled a digital camera on board ISS to photograph

features of the Earth. The students have investigated a wide range of topics such as deforestation, urbanization, volcanoes, river deltas, and pollution. The Crew Earth Observations activity has made imagery of Earth from ISS accessible to scientists, educators, and the public, hundreds of thousands of photographs taken by crewmembers, and about half a million images downloaded from the “Gateway to Astronaut Photography of Earth” (<http://eol.jsc.nasa.gov>) each month. In-flight Education Downlinks (part of Education Payload Operations) have linked crewmembers on board ISS with students around the world. The students have studied the science activities on ISS and living and working in space in preparation for asking questions of the crewmembers. Through broadcasts sponsored by Channel One and the U.S. Department of Education, more than 30 million students have been able to watch the interviews.

Although NASA’s focus for ISS will remain its assembly, the forecast for research on the next ten Expeditions is a positive one. NASA will be focusing on three main areas for its utilization of ISS (2006, The National Aeronautics and Space Administration (NASA) Research and Utilization Plan for the International Space Station (ISS), NASA Headquarters, Washington, DC.):

- Astronaut health and countermeasure development to protect crews from the space environment during long-duration voyages
- Testing research and technology developments for future Exploration missions
- Developing and validating operational procedures for long-duration space missions

In addition, select studies in the physical and biological sciences will be conducted that take advantage of the unique microgravity environment on ISS. Significant results that have been achieved during the many challenges of assembly and operations during the first ten Expeditions on station make us confident that similar results can continue to be achieved during the remainder of station assembly. All of this early research lays the groundwork for full utilization of ISS when facilities developed by NASA and the international partners are complete.

## APPENDIX: THE EXPEDITIONS SUMMARIZED

### EXPEDITION 1 (NOV 2, 2000 – MAR 18, 2001)

“... these technical demands that we have—flying in space, keeping humans healthy and able to work up there—have huge side benefits to the way that we live and the style of life we enjoy [on Earth].” – Bill Shepherd, Expedition 1 commander

When the three-man Expedition 1 crew moved into ISS, they began not only a habitation that continues to this day but also became part of a station that was a work-in-progress.

The Zvezda service module provided their early living quarters. At this time the ISS also consisted of the Zarya module (the Functional Cargo Block), Node 1 (the Unity module), and a Soyuz spacecraft (in which the crew had arrived and which supplied their assured crew return capability). Later in Expedition 1, the U.S. Destiny laboratory was installed. Yet despite the Spartan living conditions and the sense of working on a platform under construction, the crew made significant advances in four experiments into physical science (PS), space product development (SPD), space flight (SF), and fundamental space biology (FSB):

- Protein Crystal Growth-Enhanced Gaseous Nitrogen Ewer (PS),
- Middeck Active Control Experiment-II (SPD),
- Crew Earth Observations (SF), and
- Space Exposed Experiment Developed for Students (FSB).

While some of these experiments are unique to only one or two Expeditions (Education-SEEDS, for example), others continued to be run—and CEO is running yet—through several Expeditions.



ISS01E5086 — Cosmonaut Sergei K. Krikalev, Expedition 1 flight engineer, prepares to photograph some geographic targets of opportunity through a viewing port on the Zvezda service module.



ISS01E5325 — Cosmonaut Yuri P. Gidzenko, Expedition 1 Soyuz commander, stands near the hatch leading from the Unity node into the U.S. Destiny laboratory. This picture was taken on the day the hatch was opened.



ISS01E5129 — Astronaut Bill Shepherd, Expedition 1 commander, works on the ward room table in the Zvezda service module.

## EXPEDITION 2 (MAR 10, 2001 – AUG 20, 2001)

“... I know that the research that we’re doing will make us take steps forward that eventually will help us to solve many of the problems that we face here on Earth. ... I think we can only imagine what will happen on board the International Space Station as we continue to do research and explore.” – James S. Voss, Expedition 2 Flight Engineer

As ISS continued to grow and expand with the installation of new experiment facilities and hardware on the U.S. Destiny laboratory, the capacity for research on board station increased accordingly. From the original four experiments conducted on Expedition 1, Expedition 2 expanded the research potential vastly to include experiments in bioastronautics research (BR), physical science (PS), space product development (SPD), and space flight (SF):

- Bonner Bell Neutron Detector (BR),
- Crewmember and Crew-Ground Interaction During International Space Station Missions (BR),
- Dosimetric Mapping (BR),
- Effects of Altered Gravity on Spinal Cord Excitability (BR),
- Organ Dose Measurement Using the Phantom Torso (BR),
- Subregional Assessment of Bone Loss in the Axial Skeleton in Long-term Space Flight (BR),
- Commercial Protein Crystal Growth-High-Density (PS),
- Experiment Physics of Colloids in Space (PS),
- Protein Crystal Growth-Enhanced Gaseous Nitrogen (PS),
- Protein Crystal Growth-Single Locker Thermal Enclosure System (PS),
- Active Rack Isolation System-ISS Characterization Experiment (SPD),
- Advanced Astroculture-TM (SPD),
- Microgravity Acceleration Measurement System (SPD),
- Middeck Active Control Experiment-II (SPD),
- Space Acceleration Measurement System –II (SPD),
- Crew Earth Observations (SF), and
- Earth Knowledge Acquired by Middle-School Students (SF).



ISS002E5246 – Astronaut James S. Voss (left) Expedition 2 flight engineer, unpacks a stowage bag in the U.S. Destiny laboratory while cosmonaut Yury V. Usachev, Expedition 2 mission commander (right), takes notes.



ISS002E5511 — Astronaut Susan J. Helms, Expedition 3 flight engineer, pauses while moving through the Node 1/Unity module to pose for this photograph.

## EXPEDITION 3 (AUG 12, 2001 – DEC 12, 2001)

“We need a space station because we need a frontier. We need to keep pushing the human race to expand beyond the current boundaries that we have.” – Frank L. Culbertson, Jr., Expedition 3 Commander

As with other Expedition crews, the Expedition 3 crew focused on expansion and scientific matters. While various experiments naturally carried over from previous Expeditions—thereby establishing a pattern of building on earlier work that carries forward to this day—the crew also conducted new experiments in bioastronautics research (BR), physical science (PS), space product development (SPD), space flight (SF), and fundamental space biology (FSB):

- Bonner Bell Neutron Detector (BR),
- Crewmember and Crew-Ground Interactions During International Space Station Missions (BR),
- Effect of Microgravity on the Peripheral Subcutaneous Veno-arteriolar Reflex in Humans (BR),
- Effects of Altered Gravity on Spinal Cord Excitability (BR),
- Effects of EVA and Long-term Exposure to Microgravity on Pulmonary Function (BR),
- Renal Stone Risk During Space Flight: Assessment and Countermeasure Validation (BR),
- Subregional Assessment of Bone Loss in the Axial Skeleton in Long-term Space Flight (BR),
- Advanced Protein Crystallization Facility (PS),
- Cellular Biotechnology Operations Support System (PS),
- Dynamically Controlled Protein Crystal Growth (PS),
- Evaluation of Ovarian Tumor Cell Growth and Gene Expression (PS),
- Experiment Physics of Colloids in Space (PS),
- Human Renal Cortical Cell Differentiation and Hormone Production (PS),
- PC12 Pheochromocytoma Cells (PS),
- Materials International Space Station Experiment (SPD),
- Microgravity Acceleration Measurement System (SPD),
- Space Acceleration Measurement System-II (SPD),
- Crew Earth Observations (SF), and
- DreamTime (FSB).



ISS003E5498 — Cosmonauts Mikhail Tyurin (left) and Vladimir Dezhurov (right), Expedition 3 flight engineers, pose for a photograph in the Zvezda service module.



ISS003E5566 — Astronaut Frank L. Culbertson Jr., Expedition 3 mission commander, assembles a temporary sleep station in the U.S. Destiny laboratory.

## EXPEDITION 4 (7 DEC 2001 – 15 JUN 2002)

“... I think the culmination of our participation ... will allow us to really make some headway and get some answers to some ... scientific questions.” – Carl E. Walz, Expedition 3 Flight Engineer

The Expedition 4 three-man crew continued to maintain focus not only on ongoing experiments, several of which had already carried through Expeditions 2 and 3, but also turned their focus to new experiments in bioastronautics research (BR), physical science (PS), space product development (SPD), space flight (SF), and fundamental space biology (FSB). Or in the words of Carl Walz (above), this crew continued to “make some headway”:

- A Study of Radiation Doses Experienced by Astronauts in EVA (BR),
- Crewmember and Crew-Ground Interactions During International Space Station Missions (BR),
- Effect of Microgravity on the Peripheral Subcutaneous Venous-arteriolar Reflex in Humans (BR),
- Effects of Altered Gravity on Spinal Cord Excitability (BR),
- Effects of EVA and Long-term Exposure to Microgravity on Pulmonary Function (BR),
- Renal Stone Risk During Space Flight: Assessment and Countermeasure Evaluation (BR),



STS108E5401 — Astronaut Daniel W. Bursch (left), Expedition 4 flight engineer, cosmonaut Yuri L. Onufrienko, mission commander, and astronaut Carl E. Walz, flight engineer, pose for a photograph in the U.S. Destiny laboratory.

- Subregional Assessment of Bone Loss in the Axial Skeleton in Long-term Space Flight (BR),
- Biomass Production System-Photosynthesis Experiment and Systems Testing (PS),
- Cellular Biotechnology Operations Support Systems (PS),
- Commercial Generic Bioprocessing Apparatus: Antibiotic Production in Space (PS),
- Commercial Protein Crystal Growth-High-Density (PS),
- Development and Function of the Avian Otolith System in Normal and Altered Gravity Environments (PS),
- Experiment Physics of Colloids in Space (PS),
- Protein Crystal Growth-Enhanced Gaseous Nitrogen Ewer (PS),
- Protein Crystal Growth-Single Locker Thermal Enclosure System (PS),
- Zeolite Crystal Growth Furnace (PS),
- Active Rack Isolation System ISS Characterization Experiment (SPD),
- Advanced Astroculture TM (SPD),
- Materials International Space Station Experiment (SPD),
- Microgravity Acceleration Measurement System (SPD),
- Space Acceleration Measurement System-II (SPD),
- Crew Earth Observations (SF),
- Earth Knowledge Acquired by Middle-School Students (FSB), and
- Education Payload Operations (FSB).

## EXPEDITION 5 (JUN 7, 2002 – DEC 2, 2002)

"[The] ISS is the one step for future investigation, future science experiments ..." – Sergei Y. Treschev, Expedition 5 Flight Engineer

As ISS continued to grow and expand, so too did the scientific workload for the Expedition crews—especially, and critically, augmented by the installation of the MSG. The Expedition 5 crew arrived on station faced with the largest workload to date of both continuing and new experiments in bioastronautics research (BR), physical science (PS), space product development (SPD), space flight (SF), and fundamental space biology (FSB):

- A Study of Radiation Doses Experienced by Astronauts in EVA (BR),
- Crewmember and Crew-Ground Interactions During International Space Station Missions (BR),
- Effect of Microgravity on the Peripheral Subcutaneous Venous-arteriolar Reflex in Humans (BR),
- Effect of Prolonged Space Flight on Human Skeletal Muscle (BR),
- Effects of EVA and Long-term Exposure to Microgravity on Pulmonary Function (BR),
- Promoting Sensorimotor Response Generalizability (BR),
- Renal Stone Risk During Space Flight: Assessment and Countermeasure Evaluation (BR),
- Space Flight-induced Reactivation of Latent Epstein-Barr Virus (BR),
- Subregional Assessment of Bone Loss in the Axial Skeleton in Long-term Space Flight (BR),
- Test of Midodrine as a Countermeasure Against Postflight Orthostatic Hypotension (BR),
- Microencapsulation Electrostatic Processing System (PS),
- Protein Crystal Growth-Single Locker Thermal Enclosure System (PS),
- Solidification Using a Baffle in Sealed Ampoules (PS),
- StelSys Liver Cell Function Research (PS),
- Toward Understanding Pore Formation and Mobility During Controlled Directional Solidification in a Microgravity Environment (PS),
- Active Rack Isolation System-ISS Characterization Experiment (SPD),
- Advanced Astroculture-TM (SPD),
- Materials International Space Station Experiment (SPD),
- Microgravity Acceleration Measurement System (SPD),
- Plant Generic Bioprocessing Apparatus (SPD),
- Space Acceleration Measurement System-II (SPD),
- Crew Earth Observations (SF),
- Earth Knowledge Acquired by Middle School Students (FSB), and
- Education Payload Operations (FSB).



ISS005E08808 — Cosmonaut Sergei Y. Treschev (left) and astronaut Peggy A. Whitson (right), Expedition 5 flight engineers, perform maintenance on the treadmill vibration isolation system in the Zvezda service module.



ISS005E11311 — Cosmonaut Valery G. Korzun, Expedition 5 commander, uses an amateur radio in the Functional Cargo Block.

## EXPEDITION 6 (NOV 25, 2002 – MAY 3, 2003)

“... [Experiments] done on space station are designed around the reduction in the gravitational force so that you can see other forces manifest themselves, and you can make new observations that are very difficult, if not impossible, to make any other way.” – Donald R. Pettit, Expedition 6 Flight Engineer

As station entered its third year of continuous operations, the scientific workload continued to occupy a significant amount of the Expedition crews' time. The Expedition 6 crew worked unremittingly on the scientific mission in face of the changes wrought following the loss of *Columbia*, conducting experiments in bioastronautics research (BR), physical science (PS), space product development (SPD), space flight (SF), and fundamental space biology (FSB):

- A Study of Radiation Doses Experienced by Astronauts in EVA (BR),
- Chromosomal Aberrations in Blood Lymphocytes of Astronauts (BR),
- Effect of Prolonged Space Flight on Human Skeletal Muscle (BR),
- Effects of EVA and Long-term Exposure to Microgravity on Pulmonary Function (BR),
- Foot/Ground Reaction Forces During Space Flight (BR),
- Promoting Sensorimotor Response Generalizability (BR),
- Renal Stone Risk During Space Flight (BR),
- Space Flight-induced Reactivation of Latent Epstein-Barr Virus (BR),
- Subregional Assessment of Bone Loss in the Axial Skeleton in Long-term Space Flight (BR),
- Investigating the Structure of Paramagnetic Aggregates from Colloidal Emulsions (PS),
- Protein Crystal Growth-Single Locker Thermal Enclosure System (PS),
- Zeolite Crystal Growth (PS),
- Materials International Space Station Experiment (SPD),
- Microgravity Acceleration Measurement System (SPD),
- Space Acceleration Measurement System-II (SPD),
- Crew Earth Observations (SF), and
- Earth Knowledge Acquired by Middle-School Students (FSB).



ISS006E30084 — Astronauts Kenneth D. Bowersox (right) and Donald R. Pettit (left), Expedition 6 mission commander and NASA ISS science officer respectively, participate in a scheduled EVA in the Quest Airlock. This test demonstrated the ability of two crewmembers to don safely a U.S. spacesuit without the assistance of a third crewmember.



ISS006E45319 — Cosmonaut Nikolai M. Budarin, Expedition 6 flight engineer, floats near the Potok 150MK air decontamination equipment in the Zvezda service module.

## EXPEDITION 7 (APR 28, 2003 – OCT 27, 2003)

“... [although] the science program will be reduced ... the most exciting results so far ... will be continued. ... [For example,] it does seem possible to reduce or even eliminate ... calcium loss in bones from astronauts.” – Edward T. Lu, Expedition 7 Flight Engineer

The Expedition 7 crew was the first two-man crew to occupy space station, and the first crew to launch from Baikonur on board a Soyuz spacecraft. Despite the loss of one-third of the expected crew complement, this crew continued work to fulfill ISS’s scientific goals, conducting experiments in bioastronautics research (BR), physical science (PS), space product development (SPD), space flight (SF), and fundamental space biology (FSB):

- Chromosomal Aberrations in Bloody Lymphocytes of Astronauts (BR),
- Crewmember and Crew-Ground Interactions During International Space Station Missions (BR),
- Effect of Prolonged Space Flight on Human Skeletal Muscle (BR),
- Hand Posture Analyzer (BR),
- Promoting Sensorimotor Response Generalizability (BR),
- Subregional Assessment of Bone Loss in the Axial Skeleton in Long-term Space Flight (BR),
- Coarsening in Solid Liquid Mixtures-2 (PS),
- Investigating the Structure of Paramagnetic Aggregates from Colloidal Emulsions (PS),
- Protein Crystal Growth-Single Locker Thermal Enclosure System (PS),
- Toward Understanding Pore Formation and Mobility During Controlled Directional Solidification in a Microgravity Environment (PS),
- In-space Soldering Experiment (SPD),
- Materials International Space Station Experiment (SPD),
- Microgravity Acceleration Measurement System (SPD),
- Space Acceleration Measurement System-II (SPD),
- Crew Earth Observations (SF),
- Earth Knowledge Acquired by Middle School Students (FSB), and
- Education Payload Operations (FSB).



ISS007E11507 — Cosmonaut Yuri I. Malenchenko, Expedition 7 commander, works in the transfer compartment of the Zvezda service module.



ISS007E09679 — Astronaut Edward T. Lu, Expedition 7 NASA ISS science officer and the flight engineer, exercises on the TVIS in the Zvezda service module.

## EXPEDITION 8 (OCT 20, 2003 – APR 29, 2004)

“... I think [our scientific mission is] going to be advanced quite significantly ... [That's] a ... bold statement, but it's supported by the fact that I have many investigations to carry out on board the station.” – C. Michael Foale, Expedition 8 Commander and ISS Science Officer

As compared to the scientific workload borne by Expedition 7 as the crewmembers accustomed themselves to working with a reduced number, the Expedition 8 crew carried a heavier workload in bioastronautics research (BR), physical science (PS), space product development (SPD), space flight (SF), and fundamental space biology (FSB):

- Advanced Diagnostic Ultrasound in Microgravity (BR),
- Behavioral Issues Associated with Isolation and Confinement (BR),
- Chromosomal Aberrations in Blood Lymphocytes of Astronauts (BR),
- Crewmember and Crew-Ground Interactions During International Space Station Missions (BR),
- Foot/Ground Reaction Forces During Space Flight (BR),
- Hand Posture Analyzer (BR),
- Promoting Sensorimotor Response Generalizability (BR),
- Renal Stone Risk During Space Flight: Assessment and Countermeasure Validation (BR),
- Subregional Assessment of Bone Loss in the Axial Skeleton in Long-term Space Flight (BR),
- Binary Colloidal Alloy Test-3 (PS),
- Miscible Fluids in Microgravity-Isothermal (PS),
- Protein Crystal Growth-Single Locker Thermal Enclosure System (PS),
- Toward Understanding Pore Formation and Mobility During Controlled Directional Solidification in a Microgravity Environment (PFMI) (PS),
- Yeast-Group Activation Packs (PS),
- Materials International Space Station Experiment (SPD),
- Microgravity Acceleration Measurement System (SPD),
- Space Acceleration Measurement System-II (SPD),
- Synchronized Position Hold, Engage Reorient, Experimental Satellites (SPD),
- Crew Earth Observations (SF),
- Earth Knowledge Acquired by Middle School Students (FSB), and
- Education Payload Operations (FSB).



ISS008E06301 — Astronaut C. Michael Foale, Expedition 8 commander and NASA ISS science officer, installs equipment in the MSG in the U.S. Destiny laboratory.



ISS008E05179 — Cosmonaut Alexander Y. Kaleri, Expedition 8 flight engineer, works with the Russian biomedical “Pilot” experiment (MBI-15) in the Zvezda service module.

## EXPEDITION 9 (APR 21, 2004 – OCT 23, 2004)

“... we’re hoping that we show on our mission the value of working together, the value of team-work, the value of knowing one’s job, and a good work ethic ...” – Edward Michael (Mike) Fincke, Expedition 9 Flight Engineer and ISS Science Officer

For the Expedition 9 crew of Gennady Padalka and Mike Fincke, scientific research was a ruling passion. Accordingly and in keeping with the pattern established by earlier Expeditions, they conducted experiments in bioastronautics research (BR), physical science (PS), space product development (SPD), space flight (SF), and fundamental space biology (FSB):

- Advanced Diagnostic Ultrasound in Microgravity (BR),
- Behavioral Issues Associated with Isolation and Confinement (BR),
- Chromosomal Aberrations in Blood Lymphocytes of Astronauts (BR),
- Crewmember and Crew-Ground Interactions During International Space Station Missions (BR),
- Effect of Prolonged Space Flight on Human Skeletal Muscle (BR),
- Promoting Sensorimotor Response Generalizability (BR),
- Serial Network Flow Monitor (BR),
- Binary Colloidal Alloy Test-3 (PS),
- Miscible Fluids in Microgravity-Isothermal (PS),
- Protein Crystal Growth-Single Locker Thermal Enclosure System (PS),
- Viscous Liquid Foam – Bulk Metallic Glass (PS),
- Yeast Group Activation (PS),
- Capillary Flow Experiment (SPD),
- Capillary Flow Experiment Contact Line (SPD),
- Capillary Flow Experiment Interior Corner Flow (SPD),
- Capillary Flow Experiment Vane Gap (SPD),
- Fluid Merging Viscosity Measurement (SPD),
- In-space Soldering Experiment (SPD),
- Materials International Space Station Experiment (SPD),
- Microgravity Acceleration Measurement System (SPD),
- Space Acceleration Measurement System-II (SPD),
- Crew Earth Observations (SF),
- Earth Knowledge Acquired by middle School Students (FSB), and
- Education Payload Operations (FSB).



ISS009E13739 — Cosmonaut Gennady I. Padalka, Expedition 9 commander, works with the Cardiocog experiment, which studies the human cardiovascular system in microgravity, as expressed in the peripheral arteries, and by the vegetative regulation of arterial blood pressure and heart rate.



ISS009E08863 — Astronaut Edward M. (Mike) Fincke, Expedition 9 NASA ISS science officer and flight engineer, is pictured near free-floating fruit in the Zvezda service module.

## EXPEDITION 10 (OCT 15, 2004 – APR 25, 2005)

“If we’re going to go to the moon and Mars, we’re going to have to know how ... [and] the space station is an ideal platform for ... that kind of work.” – Leroy Chiao, Expedition 10 Commander and ISS Science Officer

For the Expedition 10 crew of Salizhan Sharipov and Leroy Chiao, the focus was on “knowing how” to work for long durations in space and to continue to develop methods and technologies that would aid the space program in a future return to the moon and exploration of Mars. Accordingly and in keeping with the pattern established by earlier Expeditions, they conducted experiments in bioastronautics research (BR), physical science (PS), space product development (SPD), space flight (SF), and fundamental space biology (FSB):

- Advanced Diagnostic Ultrasound in Microgravity (BR),
- Behavioral Issues Associated with Isolation and Confinement (BR),
- Chromosomal Aberrations in Blood Lymphocytes of Astronauts (BR),
- Effect of Prolonged Space Flight on Human Skeletal Muscle (BR),
- Promoting Sensorimotor Response Generalizability (BR),
- Binary Colloidal Alloy Test-3 (PS),
- Miscible Fluids in Microgravity-Isothermal (PS),
- In-space Soldering Experiment (SPD),
- Materials International Space Station Experiment (SPD),
- Microgravity Acceleration Measurement System (SPD),
- Space Acceleration Measurement System-II (SPD),
- Crew Earth Observations (SF),
- Serial Network Flow Monitor (SF),
- Earth Knowledge Acquired by Middle School Students (FSB), and
- Education Payload Operations (FSB).



ISS010E06638 — Astronaut Leroy Chiao, Expedition 10 commander and NASA ISS science officer, conducts a session with the BCAT-3 in the U. S. Destiny laboratory of ISS.



ISS010E18952 — Cosmonaut Salizhan S. Sharipov, Expedition 10 flight engineer, floats in the U.S. Destiny laboratory on ISS.

## ACKNOWLEDGMENTS

We are especially grateful to the ISS crewmembers who have been dedicated to making the most of research activities, even in the years of ISS assembly when there are so many maintenance and construction tasks. We would like to the Associate Administrator for Space Operations and former head of the ISS Program, Bill Gerstenmaier, and the ISS Program Scientist, Don Thomas, for their unwavering support of our efforts to assemble complete information on ISS research and results. We thank the many scientists who have shared information on their station research and supported us in tracking their results and publications. We thank them, too, for reviewing the evolving versions of descriptions in the database and for their patience as we tried to describe their work for a general audience. We want to thank those in the Mission Science group of Lockheed Martin who drew the information together for the first draft of the database, especially Peggy Delaney, Pasha Morshedi, Andy Self, and Wes Tarkington. Our original NASA internal Web site and database structure was developed by Wes Tarkington. The system evolved, and dynamic updates to the NASA Portal Web site were made possible by the efforts of Ryan Elliott of the Engineering & Science Contract Group and Alex Pline, NASA Headquarters, and his colleagues. Last, but not least, we want to thank Sharon Hecht of TES for her editorial help in making this NASA Technical Publication a reality. Her patience with our continued updates and her gentle reminders kept this project on track.



REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE September 2006	3. REPORT TYPE AND DATES COVERED Technical Paper		
4. TITLE AND SUBTITLE International Space Station Research Summary Through Expedition 10			5. FUNDING NUMBERS	
6. AUTHOR(S) Julie A. Robinson,* Jennifer L. Rhatigan,* David K. Baumann,* Judy Tate,** Tracy Thumm**				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) *Lyndon B. Johnson Space Center, Houston, Texas 77058 **Engineering & Science Contract Group, Houston, Texas 77058			8. PERFORMING ORGANIZATION REPORT NUMBERS S-978	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, D.C. 20546-0001			10. SPONSORING/MONITORING AGENCY REPORT NUMBER TP-2006-213146	
11. SUPPLEMENTARY NOTES				
12a. DISTRIBUTION/AVAILABILITY STATEMENT  Unclassified/Unlimited Available from the NASA Center for AeroSpace Information (CASI) 7121 Standard Hanover, MD 21076-1320 Category: 99			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words)  This report summarizes research accomplishments on the International Space Station (ISS) through the first ten Expeditions. When research programs for early Expeditions were established, five administrative organizations were executing research on ISS: bioastronautics research, fundamental space biology, physical science, space product development, and space flight. The Vision for Space Exploration led to changes in NASA's administrative structures, so we have grouped experiments topically by scientific themes—human research for exploration, physical and biological sciences, technology development, observing the Earth, and educating and inspiring the next generation—even when these do not correspond to the administrative structure at the time at which they were completed. The research organizations at the time at which the experiments flew are preserved in the appendix of this document. These early investigations on ISS have laid the groundwork for research planning for Expeditions to come. Humans performing scientific investigations on ISS serve as a model for the goals of future Exploration missions. The success of a wide variety of investigations is an important hallmark of early research on ISS. Of the investigations summarized here, some are completed with results released, some are completed with preliminary results, and some remain ongoing.				
14. SUBJECT TERMS  International Space Station; research facilities; bioastronautics; space technology experiments; biology; physical science; space flight; technology assessment			15. NUMBER OF PAGES  142	16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT  Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE  Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT  Unclassified	20. LIMITATION OF ABSTRACT  Unlimited	



---