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NASA Utilization of the International Space Station and the *Vision for Space Exploration*[*]

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In response to the U.S. President's Vision for Space Exploration (January 14, 2004), NASA has revised its utilization plans for ISS to focus on (1) research on astronaut health and the development of countermeasures that will protect our crews from the space environment during long duration voyages, (2) ISS as a test bed for research and technology developments that will insure vehicle systems and operational practices are ready for future exploration missions, (3) developing and validating operational practices and procedures for long-duration space missions. In addition, NASA will continue a small amount of fundamental research in life and microgravity sciences. There have been significant research accomplishments that are important for achieving the Exploration Vision. Some of these have been formal research payloads, while others have come from research based on the operation of International Space Station (ISS). We will review a selection of these experiments and results, as well as outline some of ongoing and upcoming research. The ISS represents the only microgravity opportunity to perform on-orbit long-duration studies of human health and performance and technologies relevant for future long-duration missions planned during the next 25 years. Even as NASA focuses on developing the Orion spacecraft and return to the moon (2015-2020), research on and operation of the ISS is fundamental to the success of NASA's Exploration Vision.

I. Introduction

Prior to the announcement of President Bush's *Vision for Space Exploration*[1] on January 14, 2004, NASA's utilization plans for the International Space Station (ISS) focused on a diverse multi-disciplinary research program. This included any and all research, from fundamental to applied, from physical to biological science, and from academic to commercial. In response to the Exploration Vision, NASA has refocused its utilization plans for ISS to include three areas (see also 2, 3).

(1) Research on astronaut health and the development of countermeasures that will protect our crews from the space environment during long duration voyages.
(2) Testing of research and technology developments that will meet information and systems needs for future exploration missions.
(3) Developing and validating operational practices and procedures for long-duration space missions.

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In addition, NASA will continue a small amount of fundamental research in life and microgravity sciences. This insures that key fundamental science experiments can still be completed on ISS and sustains this capability for future post-assembly scientific utilization.

NASA's utilization plans for ISS must also be viewed in a programmatic context. Of necessity, completing assembly of ISS and developing the Orion crew exploration vehicle to replace the Space Shuttle must have priority. NASA research opportunities during assembly will be limited by utilization upmass, crew time, on-orbit stowage, and downmass even for the highest priority research. However, key research activities and utilization are still planned during assembly and will allow us to meet the information needs of the Exploration Vision.

In spite of the many challenges to utilizing ISS during the assembly phase, there have been significant research accomplishments that are important for achieving the Exploration Vision. As of the end of December 2006, a total of 97 U.S. investigations have been carried out on ISS, 19 of these ongoing. In this paper we highlight a selection of these experiments and results, as well as outline some of the ongoing and upcoming research that is important for future exploration.

II. Research on Astronaut Health—the ISS Medical Project

Getting suitable human physiological data for ISS crewmembers is critical, so that information from each human "subject" living on orbit can be used to better understand the effects of spaceflight on human physiology. Once cold stowage is in place, biological sample collection and return requires relatively little upmass and downmass, but has high potential payoff of information for planning future exploration missions.

Figure 1. Jeff Williams inserts a sample into the MELFI freezer onboard ISS. *One dewar door is open (left) and a tray partially extracted. (ISS013-E-64639).*

A complete programmatic review of NASAs human research program is underway. This review has examined all areas of space clinical physiology, including:

(1) Muscle and Bone Loss
(2) Cardiovascular Changes
(3) Neurovestibular Changes
(4) Behavioral Health and Performance
(5) Pharmacology
(6) Nutrition
(7) Immune System Changes
(8) Radiation and Human Health

The objective is to join research teams with the NASA flight surgeons that are responsible for overseeing the health of the crew. The evidence base for space effects on human health is being combined with the clinical implications to the mission and health of the crew. Finally, gaps in the existing research portfolio are being identified and prioritized so that the most important research for future exploration will be accomplished. Once research gaps are identified, an integrated project plan for the needed research will be developed across all research platforms: ground, on-orbit, and even future studies on the lunar surface. These plans will determine the research portfolio of NASA's Human Research Program, including the ISS Medical Project—the new organizational structure for all NASA human research on ISS.

Over the very near term, several gaps were identified and new ISS research studies initiated with expedited development for flight. The next sections provide more information on recently completed and new ISS experiments aimed at developing the medical knowledge and countermeasures to keep crews healthy and productive on ISS and on future exploration missions.

A. Freezers for Biological Samples

Two pieces of research equipment recently delivered to ISS provide new capabilities for human and biological research. The Human Research Facility Rack 2 (HRF-2), brought to ISS on STS-114 (July 2005), includes a refrigerated centrifuge that makes it possible to spin down samples such as whole blood, and increases the options for sample processing and analysis. The MELFI (Minus Eighty-degree Laboratory Freezer for ISS) rack, brought to

ISS on STS-121 (July 2006), provides the capability for long term storage of samples until they can be returned to Earth. The MELFI rack adds a system of four independently controlled dewars down to –80°C (Fig. 1), enabling a wide variety of storage options for biological samples.

During 2007, additional cold stowage and transportation options will become available including MERLIN (Microgravity Experiment Research Locker/ Incubator, +37°C to -15°C) and GLACIER (General Laboratory Active Cryogenic ISS Experiment Refrigerator, –80°C to –180°C). This hardware will increase the ability to collect and store biological samples on orbit and return them back to Earth for analysis.

B. Nutrition and Physiological Status

Prior to the availability of MELFI, major clinical monitoring of space-induced physiological changes was not possible. A set of standard parameters was measured before and after spaceflight, but there was very limited information on the time course of the observed changes. Information from pre- and postflight testing suggested significant detrimental physiological changes, especially excessive bone resorption, compromised vitamin D status, and oxidative damage[4].

An extramural panel reviewed NASA's current monitoring and made a series of recommendations for new tests to be conducted periodically during the mission. These new analyses are possible because whole blood can be spun down using the new refrigerated centrifuge, and the serum can be stored in MELFI for return to Earth and future analysis.

Additional markers of bone metabolism (helical peptide, OPG, RANKL, IGF-1) will be measured to better monitor bone health and countermeasure efficacy. New markers of oxidative damage will be measured (8-iso-prostaglandin F2a, protein carbonyls, oxidized and reduced glutathione) to better assess the type of oxidative insults during space flight. The array of nutritional assessment parameters will be expanded to include serum folate, plasma pyridoxal 5'-phosphate, and homocysteine to better understand changes in folate, vitamin B6 status, and related cardiovascular risk factors during and after flight. Additionally, stress hormones and hormones that affect bone and muscle metabolism will also be measured (DHEA, DHEA-S, cortisol, testosterone, estradiol).

This additional assessment for the "Nutrition Status Assessment" investigation (*Nutrition*, Scott M. Smith, NASA Johnson Space Center) began Expedition 14 crewmembers in September 2006. Sampling occurs on flight days 15 (±5 days), 30, 60, 120, and 180 (±14 days). Samples will be returned to earth for analysis within a year of being collected. This study will allow for better health monitoring, and more accurate recommendations to be made for crew rehabilitation and countermeasure development.

C. Vitamin and Drug Stability in Space

Another identified knowledge gap is the degradation of pharmaceuticals and vitamins in the space environment. Analysis of returned foods and drugs from ISS has indicated that some pharmaceuticals and vitamins are significantly degraded in space (L. Putcha, unpubl. data), and this may harm the health of crews on future exploration missions. The "Stability of Pharmacotherapeutic and Nutritional Compounds" investigation (*Stability*, Scott M. Smith and Lakshmi Putcha, NASA Johnson Space Center) will identify those pharmaceuticals, vitamins, and amino acids that degrade in space and collect controlled data on the time course of degradation of in space.

Figure 2. Stability kits inside the Orbital Environmental Simulator at the Kennedy Space Center. *Inset shows packages of pulls and foods inside the kit (courtesy of L. Putcha).*

Four identical sample kits (containing pharmaceuticals, food, dosimeter and a temperature sensor) were delivered to ISS during the STS-121 mission (July 2006). One kit made a shuttle roundtrip, the others will be returned in approximately 6, 9 and 12 months. In addition, a kit is being stored in the Orbital Environmental Simulator at the Kennedy Space Center (Fig. 2). This simulator follows the ISS temperature and humidity profiles, allowing investigators to distinguish degradation from the combined environment from that due to radiation.

The data gathered from Stability will support the development of mathematical models to predict shelf life of products for long duration exploration missions. This will be the foundation for future efforts for alternative formulation, packaging and shielding for medicines and foods to ensure the integrity and quality of products used by crews during exploration missions.

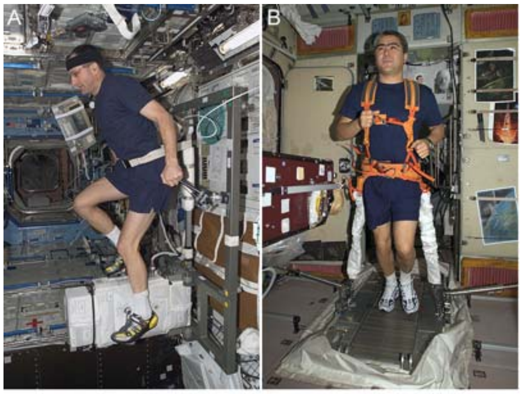
D. Bone Loss and Countermeasures

Results from two studies related to bone loss in ISS crewmembers have been published. These works significantly expand the evidence base for the effects of long duration flight on bone, and the efficacy of current countermeasures (particularly exercise). The first of these studies, “Sub-regional Assessment of Bone Loss in the Axial Skeleton in Long-Term Spaceflight” *(Sub-regional Bone,* Thomas F. Lang, University of California, San Francisco), provides the first insight into the degree and location of bone loss in ISS crewmembers.

Subregional Bone determined the distribution of bone loss in the spine and hip in long-duration spaceflight using quantitative computed tomography (QCT) and assessed how bone is recovered after return to Earth. One of the first bioastronautics research investigations to begin on ISS, this study recruited 14 subjects from Expedition 2 through Expedition 6. 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[5]. For comparison, a post-menopausal woman experiences losses of bone mineral on the order of 1% per year (e.g. 6). 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 0.5%/month whereas losses in the trabecular bone averaged 2.5%/month [5].

Post-flight measurements of bone recovery indicate that proximal femoral bone mass was substantially recovered in the year after spaceflight. Measures of the volumetric cortical bone mass and estimated bone strength showed only partial recovery[7]. The accompanying increases in the cross sectional area of the hip during the recovery period might partially (but not completely) offset of the risk for fracture in the year following return to gravity.

These results were from crewmembers who were participating in typical U.S. spaceflight exercise regimens (Fig 3); albeit with exercise routines for some subjects compromised by hardware limitations and failures[8]. Now that we better understand the distribution of bone loss, development of countermeasures to control these regional losses is paramount to assure successful human exploration. If Mars mission design includes a zero gravity transit, these countermeasures will be critical to insure that crewmembers are physically capable of completing tasks on Mars and making a safe return.



Cycle ergometer Treadmill

Resistive Exercise Device

Figure 3. Exercise modalities on ISS. *A. Astronaut Donald R. Pettit uses the Cycle Ergometer with Vibration Isolation System (CEVIS) in the Destiny laboratory, ISS006-E-13965, 2 January 2003. B. Cosmonaut Salizhan S. Sharipov, equipped with a bungee harness, exercises on the Treadmill Vibration Isolation System (TVIS) in the Zvezda Service Module, ISS010-E-05609, 31 October 2004. C. Astronaut Leroy Chiao, wearing squat harness pads, exercises using the Resistive Exercise Device (RED) equipment in the Unity node, ISS010-E-05325, 28 October 2004. D. Chiao uses the short bar on the SchRED to perform upper body strengthening pull-ups, ISS010-E-05343, 28 October 2004.*

The “Foot Reaction Forces during Space Flight” investigation (*Foot*, Peter Cavanaugh, The Cleveland Clinic), characterized the load placed on legs and feet during daily activities on the ISS. Each participating crewmember was instrumented with sensors—a calibrated force-sensing shoe insole, joint sensors that record angles at the ankle, knee, and hip, and electrodes to record muscle activity in leg muscles.

Once actual on-orbit loads are understood, more efficient and focused countermeasures to bone and muscle loss (such as better exercise regimens or equipment) can be developed for exploration missions.

The experiment was conducted on four subjects during Expeditions 6, 8, 11, and 12. During Expeditions 6, 11 and 12, special exercise sessions were completed to measure the forces experienced with various settings of the treadmill with vibration isolation system (TVIS), cycle ergometer with vibration isolation (CEVIS), and resistive exercise device (RED, see Fig. 3 for exercise hardware).

Preliminary results have already given us great insight into why bone is being lost by crewmembers during their stay on ISS in spite of the exercise protocols in place. Peak forces experienced during treadmill runs were approximately 63% of the forces that would have been experienced running on a treadmill on Earth. During 161 days in orbit, bone was lost at a rate of 0.72% and 2.31% per month in the total hip and lumbar spine regions, respectively[9], and similar to bone loss documented by the Sub-regional Bone experiment completed earlier on ISS [5].

Complete results of the exercise trials are already being used by NASA to improve exercise prescriptions and make design selections for the future loading devices for the future Advanced Resistive Exercise Device. The exercise results are expected to be published in the scientific literature shortly. These results and recommendations will be important not only for determining proper exercise prescriptions for future crewmembers on ISS, but also in the design and development of exercise countermeasures for exploration missions.

III. Research and Technology Development

Applied physical science research and tests of new technologies are being completed on ISS to facilitate information needs for design of future exploration vehicles. Short term needs such as the selection of a smoke detection system and specific materials for the Orion crew exploration vehicle are combined with longer-term needs to test exploration technology on ISS.

A. Smoke Detection

The results of the “Smoke and Aerosol Measurement Experiment” (*SAME*, David Urban, NASA Glenn Research Center), planned for 2007, will be important for final selection of the smoke detection system for CEV**.** This experiment will make measurements of the smoke properties (particle size distribution) from typical spacecraft fire smokes to identify ways to improve future smoke detectors. It will also compare the performance in microgravity of the two very different smoke detector technologies, in use on the Shuttle and ISS[10].

A technology precursor to the SAME experiment, the “Dust and Aerosol Measurement Feasibility Test” (*DAFT*, David Urban, NASA Glenn Research Center) was completed on ISS in August 2006. This precursor study tested the performance of commercial off-the-shelf dust and particle counters to establish that they would perform accurately in microgravity when used for the SAME experiment. DAFT sampling also determined that the particulate levels in the ISS are much lower than those observed in previous space vehicles, indicating the excellent performance of the HEPA filtration system[11].

B. Heat Transfer

Planned for 2008 are two experiments aimed at better understanding the process of boiling and heat transfer in microgravity. The two experiments are the “Microheater Array Boiling Experiment” (MABE, Jungho Kim, Ph.D., University of Maryland, College Park) and the “Nucleate Pool Boiling eXperiment” (NPBX, Vijay Dhir, Ph.D., University of California, Los Angeles). The data collected will be used to validate models developed for heat transfer coefficients, critical heat flux and pool boiling curves. The long term objective is the provide data that will be used to design safer and efficient means of cooling systems for future spacecraft.

C. Space Materials

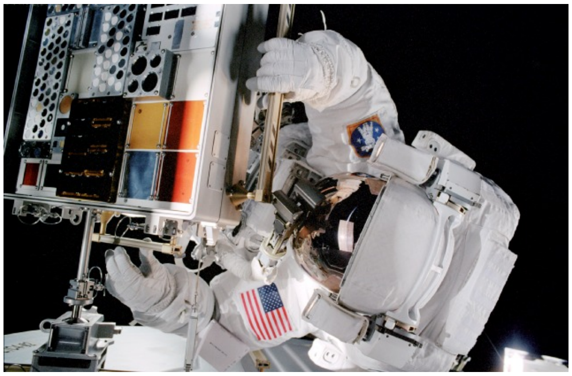


Figure 4. MISSE-2 on orbit. *Astronaut Patrick G. Forrester, during the second STS-105 extravehicular activity, with the MISSE installed outside of the Quest Airlock (STS105-346-007).*

A series of experiments have been mounted outside the ISS to test the performance and degradation of spacecraft materials. The Materials on the International Space Station Experiment (*MISSE*, William Kinard, NASA Langley Research Center, and Robert Walters, Naval Research Laboratory) have tested the effects of the space environment on a variety of materials directly exposed to atomic oxygen, ultraviolet rays, radiation, vacuum, thermal cycling, and micrometeroids. Since Expedition 3, MISSE Passive Experiment Containers (PECs) that house the many material samples have been mounted outside of the ISS (Table 1). Each PEC includes samples for dozens of investigations. Many of the materials that are tested will be used on communication and defense satellites as well as future crew exploration vehicles and extravehicular activity suit material.

MISSE-1 and 2 were originally scheduled to be deployed for one year, but due to the *Columbia* accident, experienced four years of exposure. Investigators are now in the process of analyzing their samples. Although a number of the samples had completely eroded away and the science was lost due to the length of the exposure, preliminary results have shown that many of the materials are behaving as the ground tests had predicted. Thermal control materials did have significant changes in optical properties; these data will help with long term durability studies. For example, the samples that were coated with silica appear to have the least amount of erosion.

Table 1. MISSE schedules for ISS. *History and planned deployments of MISSE packages outside ISS.*

MISSE	Launch	Deployment	Retrieval	Exposure, years	Return
1 and 2	STS-105 August 10, 2001	August 16, 2001	July 30, 2005	4	STS-114 Aug 9, 2005
5	STS-114 July 28, 2005	August 3, 2005	Sept. 15, 2006	1+	STS-115 Sept. 21, 2006
3 & 4	STS-121 July 4, 2006	August 3, 2006	Summer 2007	~ 1	Scheduled for STS-120, Sept. 2007
6A & 6B	In planning Late 2007			~ 1	

MISSE-5 contained three investigations. The first investigation measured the degradation of more than 200 materials in the space environment. PCSat-2 provided a communications system and tested the Amateur Satellite Service off-the-shelf solution for telemetry command and control. The Forward Technology Solar Cell Experiment tested the performance of 36 current and advanced generation solar cells for use on future spacecraft. Preliminary results show that there was close agreement between ground and on-orbit conditions, and proved the performance of the materials and solar cells during space exposure. Detailed materials analyses are ongoing.

One of the objectives of upcoming MISSE-6 (2007) will be to test three types of elastomer materials to decide what will be used to create the seals or O-rings for the Orion Advanced Docking and Berthing System/Low Impact Docking System (ADBS/LIDS). The seal samples that will be used for MISSE 6 are a scaled down version of what will ultimately be manufactured for the CEV. Some of the seals will be exposed to the space environment while others will be shielded. The shield is a metal cap and it is used to simulate a removable cover that could be placed over the docking system. The exposed seals will experience radiation, atomic oxygen, micrometeoroids, temperature and vacuum effects; whereas the shielded seals will only experience the temperature and vacuum effects. Another seal tested will be shielded with a metallic coating to determine if this approach will protect it from radiation and atomic oxygen damage. The results of the exposure will help engineers select the best-performing material to use for the Orion docking systems.

IV. Lessons Learned 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. Environmental monitoring, medical monitoring of crewmembers, testing of new technologies, and lessons learned from the operation of station (see summary[12]) are all important for future exploration.

A. Environmental Monitoring

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. During one study of the ISS atmosphere 12 bacterial strains were isolated from the ISS water system. These bacteria consisted of common strains and were encountered at levels below 10,000 colony-forming units/10 cm^2, well below the minimum of bacteria needed to cause illness. These data document the environment on

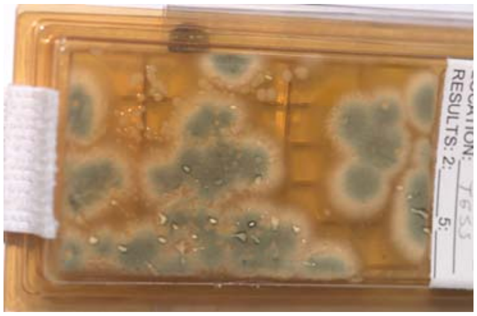


Figure 5. Example of a microbial sample. *This sample was grown as part of routine environmental monitoring on ISS (courtesy D. L. Pierson).*

ISS from the beginning of its 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[13].

Other studies performed an in-depth microbial examination of the drinking water in various stages (from the NASA Kennedy Space Center, Florida, to the ISS). These studies have revealed that NASA practices for biocide treatment has effectively removed pathogenic microbes traveling to space[14]. Studies on station air quality found that the onboard contamination controls and HEPA filters in place on ISS are effective in controlling trace contaminants of volatile organic compounds on space station[15, 16].

Gaps in the operational monitoring of microbes on ISS have also led to a scientific study, the "Surface, Water and Air Biocharacterization" investigation (SWAB, Duane L. Pierson, NASA Johnson Space Center). Scheduled to begin sampling ISS just prior to the STS-115 flight (planned for September 2006), the primary goal of this experiment is to use advanced molecular technologies to better understand the types of microrganisms that the crew could encounter, their sources, and assess the potential risks to the crew. A particular emphasis is on those organisms that would be harmful to the crew, but can only be identified by genetic analysis, and not through the standard culture testing used on ISS (Fig. 5).

B. Life Support Technologies for a 6-person Crew

One of the important ISS assembly milestones is to achieve the infrastructure needed to support 6 crewmembers on orbit. The successful operation of life support hardware will insure a safe environment for 6 crewmembers, and provide the hands to increase the amount of research conducted each day on ISS. An increase in the number of crewmembers from three to six is currently projected to double the amount of time for utilization on a per-crewmember basis, and yield an 4-fold increase in overall crewtime available for research (Table 2).

Table 2. Historical and projected crew time for U.S. research on ISS. *Volunteer time for science activities during leisure time is included. International partner utilization crewtime is not shown.*

Expedition	No. Crew	NASA Research Time, hrs
Historical Data:		
1	3	47
2	3	247
3	3	207
4	3	335
5	3	280
6	3	293
7	2	163
8	2	240
9	2	200
10	2	116
11	2	121
12	2	159
13	3	173 (final under review)
Average per expedition		*199*
Average per crewmember		*78*
Projected Data (subject to change):		
14	3	144
15	3	80
16	3	50
17	3	TBD
18	3	TBD
19	6	TBD

Life support systems are also important as technology developments in their own right, and will have important applications for future long duration spaceflight[17]. The Oxygen Generation System (OGS) was delivered to ISS on STS-121 (July 2006) and will be tested over the coming year. The Water Recovery System (WRS) is planned for the ULF2 flight in 2008.

C. Life and Physical Sciences in Microgravity

Although exploration research and technology testing are NASA's primary focus for ISS, a research capability in fundamental aspects of the life and physical sciences is being maintained. The STS-121 shuttle flight (July 2006) established new life science capability by bringing the European Modular Cultivation System (EMCS). This pair of small centrifuges will allow for a wide variety of plant growth experiments, with capabilities for microgravity and partial gravity studies.

The EMCS facility was commissioned on orbit in August 2006, and the first of these experiments, "Analysis of a Novel Sensory Mechanism in Root Phototropism" (Tropi, John Kiss, Miami University, Oxford, OH) began in October 2006 and is planned for completion in December 2006. This experiment will study the role of the dual phytochrome system by growing *Arabadopsis thaliana* (thale cress) seedlings in microgravity under different wavelengths of light and levels of partial gravity.

Fundamental physical sciences experiments that have recently been *completed* on orbit include a study of magnetorheological fluids (InSPACE), a study of pore formation during solidification (PFMI), and study of a colloid system as a model of the behavior of fluids near the critical point (BCAT-3, see full titles in Table 3). Follow-on studies of several of these investigations are planned for the future.

Table 3. Physical sciences experiments. *Experiments completed on ISS during 2006.*

Short Name	Title and Principal Investigator
BCAT-3	Binary Colloidal Alloy Test - 3: Critical Point, David Weitz and Peter Lu, Harvard University
InSPACE	Investigating the Structure of Paramagnetic Aggregates from Colloidal Emulsions, Alice P. Gast, Massachusetts Institute of Technology, Cambridge
PFMI	Toward Understanding Pore Formation and Mobility During Controlled Directional Solidification in a Microgravity Environment, Richard Grugel, NASA Marshall Space Flight Center

V. Conclusion

The ISS represents the only opportunity to perform on-orbit long-duration microgravity studies of human health and performance and technologies relevant for future long-duration missions planned during the next 25 years. It is also our prime opportunity to test systems readiness and operational practices for long duration space missions. The current NASA priority is on assembling the space station prior to space shuttle retirement in 2010. However, as new facilities are brought to orbit, they are rapidly put to use in early investigations.

In this paper we have only highlighted a few recent results and important upcoming activities. A more through review of all the results of ISS research carried out through Expedition 10 (April 2005) is available[18]. Similarly, we have not discussed the significant and ongoing educational impact of ISS, which has reached millions of students to date[19].

Because of the finite number of crewmembers that will live on ISS during its lifetime, it is particularly important that critical human research be carried out during the assembly timeframe. Since the Vision for Space Exploration was announced, a series of reviews have identified the highest priority research on human health to maximize the use of crewmembers as voluntary scientific subjects. Similarly, development of exploration vehicles is making it important to test key technologies and materials on ISS. NASA has scaled back, but not abandoned fundamental research during ISS assembly. Once assembly is complete, a broad array of facilities and suitable number of crewmembers will be available to maximize utilization of this unique laboratory.

Acknowledgments

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