International Space Station – A Unique Place for Research

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Abstract—Since March 2001, International Space Station has supported continuous research operations. The facility actually opened for the business of science in September 2000, when the first experiments were launched to the outpost, even prior to the start of a permanent human presence. Since that time, even as construction of ISS has continued, several dozen unique investigations have been completed or are still in progress. Most of the experiments are stored and operated in research racks inside the US Laboratory module Destiny. These investigations in a variety of research disciplines take advantage of at least two unique aspects of ISS: a long-duration platform to study effects of microgravity, and a vantage point in low-Earth orbit for observations of our home planet and the Universe. Experiments conducted to date have: studied the effects of long-duration microgravity on biological systems, including plants and the crewmembers themselves; taken advantage of long-duration microgravity to determine whether the production of various substances can be improved in space for basic science as well as possible commercial endeavors; studied various physical and chemical processes in microgravity; studied the internal and external environment of the space station; observed short- and long-term changes on Earth; and sought to educate and inspire students of various age groups. To date, the construction of ISS and the research conducted aboard have been remarkably successful. Future years will see an expansion of the facility as International Partners add their own research modules.

1. INTRODUCTION

The International Space Station (ISS) is a unique, permanent platform for conducting research in a variety of disciplines. It should be viewed as offering significant advantages over previous vehicles that were used to conduct research in Low Earth Orbit. Compared to the US Space Shuttle, and the Spacelab and Spacehab modules carried in its cargo bay, ISS offers one significant advantage: long duration. This enables research that was previously impossible to carry out, due to the maximum Space Shuttle flight time of about 18 days. Many physical and biological processes require longer periods for adequate study. A long-duration platform also allows investigators to conduct one phase of a study, analyze the data, and with the experiment hardware still in space, modify experimental protocols, thereby building on earlier results – this is a hallmark of the scientific process. The permanent platform also provides a vantage point for long-term monitoring of changes on Earth as well as observations of other phenomena of the near-Earth environment.

Compared to the Russian space station Mir, which had an outstanding career as humanity’s outpost in space from 1986 to 2001, including extensive international cooperation such as the joint US-Russian missions during the Phase 1 Program (1995-8), ISS provides several advantages. Among these are: larger size, accommodating a much greater volume of research facilities and of greater sophistication; greater power generating capability to support the research activities; and extensive telemetry and commanding capability to enable telescience.

Although the ISS Program is still relatively new compared to its overall projected 15-year lifetime, and construction of the facility is still well underway with many challenging milestones yet to come, significant research continues to be accomplished in many research disciplines, and several fledgling commercial endeavors have proven successful. Results from early experiments are already reaching publication in peer-reviewed journals, with others in print or in preparation. To date, both construction of the facility and research have met with extraordinary success.

2. CONSTRUCTION

Assembly of ISS began in November 1998 with launch of the Russian Zarya module, followed a month later by the first Shuttle mission, carrying the Unity Node 1 module. Since then, the station has been expanded with the addition of five modules and five major elements and resupplied by numerous US and Russian vehicles, summarized in Tables 1 and 2. Many of the assembly tasks were accomplished by
crewmembers performing Extra-Vehicular Activities (EVA's). Human occupancy began in November 2000; since then six long-duration crews have taken up residence. To date, the most important element for the conduct of research has been the US Laboratory module Destiny. It was brought to ISS during the STS 98/5A mission in February 2001, and in addition to containing station systems equipment such as life support and control centers for the remote manipulator, it currently has the capability to house up to 10 research racks. The outfitting of Destiny with these racks began shortly after its arrival and still continues.

Table 1. Summary of vehicles that have visited ISS, as of December 10, 2002.

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Number flown</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soyuz</td>
<td>5</td>
<td>Crew transport; escape vehicle</td>
</tr>
<tr>
<td>Progress</td>
<td>9</td>
<td>Unmanned resupply</td>
</tr>
<tr>
<td>Shuttle</td>
<td>16</td>
<td>Crew transport; resupply; assembly</td>
</tr>
</tbody>
</table>

Table 2. Summary of major ISS on-orbit elements, as of December 10, 2002.

<table>
<thead>
<tr>
<th>Element</th>
<th>Date</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zarya</td>
<td>Nov 1998</td>
<td>Functional Cargo Block (FGB)</td>
</tr>
<tr>
<td>Unity</td>
<td>Dec 1998</td>
<td>Node 1</td>
</tr>
<tr>
<td>Zvezda</td>
<td>Jul 2000</td>
<td>Service Module</td>
</tr>
<tr>
<td>Z1 truss</td>
<td>Oct 2000</td>
<td>Zenith truss segment</td>
</tr>
<tr>
<td>P6 arrays</td>
<td>Nov 2000</td>
<td>First US arrays</td>
</tr>
<tr>
<td>Destiny</td>
<td>Feb 2001</td>
<td>US Laboratory Module</td>
</tr>
<tr>
<td>Canadarm2</td>
<td>Apr 2001</td>
<td>Remote Manipulator System</td>
</tr>
<tr>
<td>Quest</td>
<td>Jul 2001</td>
<td>Joint Airlock</td>
</tr>
<tr>
<td>Pirs</td>
<td>Sep 2001</td>
<td>Docking Compartment-1</td>
</tr>
<tr>
<td>S0 truss</td>
<td>Apr 2002</td>
<td>Center truss segment</td>
</tr>
<tr>
<td>S1 truss</td>
<td>Oct 2002</td>
<td>First starboard truss segment</td>
</tr>
<tr>
<td>P1 truss</td>
<td>Nov 2002</td>
<td>First port truss segment</td>
</tr>
</tbody>
</table>

Assembly of ISS is the most complex space endeavor ever attempted. As can be glimpsed from the tables, which do not reflect the complexity of the construction tasks, or the number of EVA's (49 totaling more than 300 hours to date) that have been required to accomplish them as well as other maintenance activities, it has been a very challenging effort by several nations. It has also been highly successful. From 2002 through 2004, the main goal of construction is the assembly of the truss elements, to allow the placement of additional solar arrays, providing adequate power to the larger station to come and the research to be conducted. The trusses will also allow the placement of large external payloads. In 2004, addition of Node 2 will finish the U.S. Core Complete configuration. After that, International Partner modules, beginning with the ESA Columbus module in 2004 through the Japanese components in 2006, will be added. Finally, the Centrifuge Accommodation Module (CAM), allowing variable gravity research, will be added in 2007.

While construction has provided the enabling infrastructure (facility, power, life support) for the conduct of research, it also requires a large proportion of the available resources, crew time and upmass in particular. The research program, both the outfitting of the station with the specific research facilities and the resupply of those facilities with experiment hardware and consumables, therefore competes with critical station assembly components. In terms of crew time for performing research, that resource is also limited by critical station assembly and maintenance tasks.

3. OUTFITTING

The majority of research on ISS is conducted in large refrigerator-size facilities called racks that are delivered inside the Multi Purpose Logistics Module (MPLM), carried in the Space Shuttle cargo bay. Some racks are dedicated to a single research discipline, such as human life sciences, fundamental biology, or microgravity sciences. Other racks, called EXPRESS racks, short for EXPedite the Processing of RFsearch for Space Station, are multi-user facilities. Once the racks are installed in the laboratory modules, they become essentially permanent facilities, providing power, thermal and data interfaces to experiments that, typically brought to ISS and returned to Earth on Space Shuttles, may spend weeks, months or even years in the racks.

Figure 1. Expedition 2 Flight Engineer Susan Helms activating HRF Rack 1.

A month after Destiny's launch in February 2001, the first research rack arrived at ISS. The STS 102/5A.1 mission that also brought the station's second long-duration crew, carried the Human Research Facility (HRF) Rack 1 to ISS (Figure 1). This rack is designed to support a variety of human life sciences investigations, by both providing an intrinsic capability with support systems such as a computer workstation and a laptop for data management and experiment control, a gas analyzer system for pulmonary function studies, and an Ultrasound device similar to those found in clinical settings for both research purposes and medical diagnosis. The rack also contains stowage drawers for investigators' unique experiment hardware. The rack is...
designed so that future upgrades are easily accommodated. A second HRF Rack, with additional equipment, will expand biomedical research capabilities when it arrives in 2003.

The first two EXPRESS racks arrived on station in April 2001, delivered by the STS 100/6A mission (Figure 2). Almost immediately after installation in Destiny, EXPRESS Rack 1 was put into service supporting experiments that required continuous power for temperature control. EXPRESS Rack 2, although transferred and installed during the same mission, was not activated until a few weeks later. This rack is configured with the Active Rack Isolation System (ARIS), a system of accelerometers, actuators and pushrods that, when in active mode, isolates sensitive payloads from microgravity disturbances.

EXPRESS Rack 3 is currently being used for stowage and will support active experiments in the near future.

EXPRESS Rack 3 beginning its transfer from the MPLM to Destiny during the STS 100/6A mission in April 2001.

Another pair of EXPRESS racks arrived in August 2001 on the STS 105/7A.1 mission that exchanged the second and third resident crews. EXPRESS Rack 4 was activated right after transfer to accommodate a 14-day cell science experiment, and beginning on Expedition 4, became the continuously powered rack. EXPRESS Rack 5 is currently being used for stowage, but will accommodate a large commercial materials processing facility beginning with Expedition 7.

The next mission to deliver racks to ISS was STS 111/UF2 in June 2002, the flight that also exchanged the fourth and fifth expedition crews. It delivered the Microgravity Sciences Glovebox (MSG), built by the European Space Agency (ESA), and EXPRESS Rack 3, the second ARIS-configured EXPRESS rack. The MSG provides a containment volume accessible via several ports, power and data connections, and video support for experiments, primarily in the microgravity sciences such as fluid physics, materials science and combustion physics (Figure 3).

The start of Expedition 7 (STS 114/ULF1) will see the arrival of three new research racks, bringing the total complement to ten (Figure 4). The HRF Rack 2 will augment the capability to conduct human life sciences investigations with the addition of a sensitive human mass measurement device, a refrigerated centrifuge, an upgraded computer workstation, and additional equipment for pulmonary physiology testing. The Window Observational Research Facility (WORF) will be placed in the rack location around Destiny's 20-cm optical quality window.

Figure 3. Expedition 5 Flight Engineer Peggy Whitson activating the MSG rack.

Figure 4. Layout of research racks in Destiny through 2003.
The facility will allow the placement of a variety of cameras and remote-sensing instruments at the window site, and provide the required support to the experiments. The ESA-provided Minus Eighty-degree Laboratory Freezer for ISS (MELFI) will provide cold stowage capability for science samples, with four Dewars at set points of -80°C, -22°C and +4°C.

Two additional research racks will arrive on the ULF2 mission in 2004. Current planning foresees the sixth EXPRESS Rack and the Combustion Integrated Rack (CIR) added to Destiny, bringing the complement to 12, the extra locations made available by the transfer of two systems racks to Node 2. The IP modules will provide additional capability for internal racks, up to 33 total sites by 2006, as well as attach points for external payloads.

4. RESEARCH

Through the beginning of Expedition 6, ISS has supported 69 unique investigations. Of these, 23 are still in progress, while 46 have been completed. The ISS supported the completion of the major objectives of 43 of the completed investigations, and supported the partial completion of the other three. A large variety of research disciplines have been represented by these investigations, and additional disciplines, for example combustion science and fundamental physics, will be represented by experiments in the near future.

Bioastronautics

As of this writing (Expedition 6), 16 different investigations in bioastronautics have been completed or are still in progress. Of these, six involve data collection only during the preflight and postflight time periods, with no in-flight crew involvement. The main goal of these investigations is to study the effects of long-duration space flight on human physiology. Better understanding of underlying physiological mechanisms will lead to development of more effective countermeasures to the more deleterious effects of long-duration space flight, required to safely maintain a human presence in space.

The first set of investigations, begun early during Expedition 2, was a suite of radiation monitoring hardware provided by three of ISS’s Partners (Figure 5). A variety of active and passive dosimeters to record radiation in multiple spectra was launched on STS 102/5A.1 in March 2001 as part of the Dosimetric Mapping (DOSMAP) experiment provided by ESA and the Bonner Ball Neutron Detector (BBND) experiment provided by the Japanese space agency NASDA. These were joined on STS 100/6A by the US-provided PHANTOM TORSO experiment, which contained dosimeters in a simulated human body to estimate doses absorbed by various organs and tissues. DOSMAP and TORSO were completed during Expedition 2, while BBND continued collecting data through Expedition 3.

Figure 5. Expedition 2 Flight Engineer Jim Voss working with the radiation suite of experiments.

Another radiation monitoring experiment, a Canadian investigation called EVA Radiation Monitoring (EVARM), was conducted during Expeditions 4 through 6, and consisted of dosimeters placed inside the US EVA suit to record doses near important tissues. A German biodosimetric experiment called CHROMOSOME was begun during Expedition 6, studying chromosomal aberrations in crewmembers' lymphocytes as an indicator of the mutagenic impact of ionizing radiation.

The musculoskeletal system, both structurally as well as its neurological control, is known to be affected by long-duration space flight, and several investigations on ISS are performed to better understand these changes. The SUBREGIONAL BONE experiment, begun on Expedition 2, uses ultrasound, computer tomography and dual X-ray absorptiometry techniques to measure changes in the human skeleton. The BIOPSY experiment, begun on Expedition 5, monitors changes in muscle structure at the microscopic level and muscle function using exercise protocols. The Canadian HREFLEX experiment, completed during Expeditions 2-4, studied changes in the Hoffman Reflex, a simple neuromuscular reflex, brought about by space flight, while the MOBILITY investigation, begun on Expedition 5, assesses crewmembers' posture and locomotion after space flight. The FOOT experiment, begun during Expedition 6, is characterizing the loads, positions and muscle activity of lower extremities during long-term space flight.

Another known consequence of space flight, caused by in-flight fluid redistribution, is postflight orthostatic intolerance or hypotension. The XENON1 experiment from Denmark, completed on Expeditions 3-5, uses a radioactive isotope of Xenon as a tracer to measure changes in peripheral vascular circulation after long-duration space flight as a possible contributing factor to orthostatic intolerance. Another experiment, called MIDODRINE and begun on Expedition 5, tests the efficacy of the drug Midodrine as a possible countermeasure to orthostatic intolerance.
Possibly related to space-flight induced changes in fluid distribution and metabolism, it has been observed in earlier space flight experiments that crewmembers can become more susceptible to developing certain types of kidney stones. The RENAL STONE investigation, begun during Expedition 3, not only continues assessing this susceptibility but, in a double-blind study is also evaluating the effectiveness of potassium citrate, a commonly used drug on the ground, as a possible preventive measure against kidney stones in space.

One aspect of human physiology that has not been studied in great detail in long-duration space flight is pulmonary function. The PUFF experiment, conducted on Expeditions 3-6, studies changes in various parameters of pulmonary function by monthly evaluations of lung volumes, flow rates and other values. In addition, the experiment also studies any possible changes in pulmonary function that may be caused by EVA, during which crewmembers breathe 100% O2 at low pressure for up to 8 hours.

One of the important aspects of long-duration space flight is maintenance of the crew's psychological well-being as well as their productiveness. The INTERACTIONS experiment, begun on Expedition 2, is a continuation of an experiment conducted on Mir, and uses standard questionnaires to weekly assess the crewmembers' psychological state, how they perceive their interactions with their crewmates as well as the ground controllers, who in turn complete the same weekly questionnaires.

A study looking at changes in human immune function, the EPSTEIN-BARR experiment begun on Expedition 5, assesses whether the stresses of space flight can induce a reactivation of the Epstein-Barr virus, which is latent in 90% of the population. The virus levels are measured in preflight and postflight blood and urine samples.

**Fundamental biology**

Experiments in fundamental biology strive to understand how basic biological processes in plant and animal models are affected by long-duration space flight. Investigations to date have either made use of a Shuttle flight or an EXPRESS Rack on ISS, but facilities dedicated to fundamental biology studies, as well as the CAM, will be delivered to station later in the assembly. For many of these experiments, a long-duration platform is absolutely essential, since growth and development phases under study are often measured in weeks or months.

The Avian Development Facility (ADF) flew as a sortie on the STS 108/UF1 mission in December 2001. The sortie mode was chosen because the 12-day mission was the ideal duration for the two experiments contained in ADF, which studied embryological development in Japanese quail. One experiment studied development of the avian otolith system in microgravity, while the other investigated skeletal development in the embryos.

The Biomass Production System (BPS) payload flew during Expedition 4. One primary objective of BPS was the demonstration of technologies to be used in future facilities to support plant growth investigations. The hardware demonstrated successfully supported growth of dwarf wheat and *Brassica rapa* plants (Figure 6) in two of four growth chambers. Another objective was the support of a science investigation, studying photosynthesis and development of wheat in the two other growth chambers. Both objectives were successfully accomplished, with additional science gained from additional time in space, demonstrating the usefulness of ISS as a platform for conducting long-duration experiments in fundamental biology, as well as the value of a trained crewmember to recover from anomalies.

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**Figure 6. Brassica rapa** plants grown aboard ISS in the BPS experiment during Expedition 4.

**Fluid physics**

To date, one investigation has been conducted in the field of fluid physics. The Experiment Physics of Colloids in Space (EXPPCS) was conducted during Expeditions 2-4, with the objective to study nucleation, growth and properties of various colloidal suspensions and fractal aggregates. Long-term microgravity was required for this experiment because most of the structures under study required extensive periods of time to nucleate and grow, during which sedimentation effects had to be eliminated. The experiment was highly successful, demonstrating the value of a long-term study by allowing changes in protocols based on information gained earlier in the experiment, until a non-recoverable software failure ended operations after nine of the planned 12 months; still, more than 85% of preflight objectives were accomplished. The hardware was returned to Earth, and after failure analysis and problem correction will be reflown to ISS to support future investigations in colloid physics.
Microgravity measurements

Characterization of the microgravity environment of ISS is critical, since many types of experiments (e.g., protein crystallization, materials science) are sensitive to disturbances, both constant and transient. Two main systems were placed aboard ISS during Expedition 2 and will likely remain on ISS for its lifetime. The Microgravity Acceleration Measurement System (MAMS), located in EXPRESS Rack 1, contains a low-frequency sensor (up to 1 Hz) to measure the quasi-steady state environment, as well as a sensor to characterize the vibratory environment up to 100 Hz. The Space Acceleration Measurement System (SAMS) uses multiple triaxial sensor heads to measure vibratory and transient accelerations caused by ISS itself, crewmembers and other experiments in the frequency range of 0.01 to 300 Hz. The sensor heads are moveable to accommodate specific needs, as was done when a sensor head was installed in the MSG to support materials science experiments. Recordings with MAMS and SAMS are made nearly continuously, during quiescent periods as well as during active events such as vehicle dockings, and throughout the assembly phase as the station’s overall mass increases and its configuration changes. These results are made available to all interested investigators by the Principal Investigator Microgravity Services (PIMS) group at the NASA Glenn Research Center.

As noted previously, EXPRESS Racks 2 and 3 are configured with the ARIS to provide attenuation of microgravity disturbances for sensitive experiments. The ARIS ISS Characterization Experiment (ARIS-ICE) was conducted during Expeditions 2-4 to evaluate the performance of ARIS in EXPRESS Rack 2 against preflight predictions across a range of frequencies and during normal quiescent periods and crewmember-induced disturbances. Preliminary results indicate that ARIS performance meets or exceeds predictions at nearly all frequencies tested. After characterization was completed, ARIS provided its first operational support to an experiment during Expedition 4.

Structural biochemistry

Previous experiments on the Space Shuttle have shown that long-term microgravity can provide improvements in the quality of macromolecular crystals. These highly-ordered crystals can then be used to determine their three-dimensional molecular structure using X-ray diffraction methods, the information important to fields in biotechnology such as protein engineering and rational drug design. Several payloads on ISS serve to grow large numbers of macromolecular crystals, to better understand the crystallization process, and to improve the process to yield higher quality products. A long-term platform such as ISS is ideal for these investigations, since many types of crystals require several weeks for optimum growth.

One of the first payloads flown to ISS, even prior to human occupancy, was the Protein Crystal Growth-Enhanced Gaseous Nitrogen (PCG-EGN), an improvement over the Dewars that flew seven times on Mir. The PCG-EGN, a passive payload containing samples in Tygon capillary tubes in liquid nitrogen, has now flown four times on ISS, flying nearly two thousand samples of dozens of proteins. Once the Dewar is placed in a quiescent location on ISS, typically behind a panel in the Zarya module, boil off of the nitrogen allows the samples to thaw, initiating the crystallization process, which may take place over days or weeks. The Dewar containing the samples is then returned on the next Shuttle flight. Results from the early missions have been published by Barnes et al. [1]. High school students from across the United States are active participants in the PCG-EGN program, learning the sample preparation and analysis process and even contributing their own samples.

The Protein Crystal Growth-Single-locker Thermal Enclosure System (PCG-STES) is a payload that has flown numerous times on the Shuttle, and provides a thermally controlled environment for optimal growth of macromolecules (Figure 7). Seven units have now flown on ISS, supporting nine different investigations with various scientific objectives ranging from production of higher quality crystals to improve the understanding of macromolecular crystal growth in microgravity.

The Advanced Protein Crystallization Facility (APCF) flown during Expedition 3 for the Italian Space Agency (ASI) can accommodate up to 48 growth chambers and was used for eight vapor diffusion and dialysis experiments from various European universities. The growth process can be monitored in 10 of the chambers by video and in five chambers by interferometry.

The goal of the Dynamically Controlled Protein Crystal Growth (DCPCG) experiment, flown during Expedition 3, was to test the effects that controlling and changing the supersaturation level of protein solutions have on crystallization results. The experiment used vapor diffusion...
control to optimize the crystal growth process, which was monitored by video cameras that provided near-realtime feedback.

**Materials science**

Materials science investigations on ISS were begun after the MSG was installed in mid-2002, the facility providing an ideal sealed work environment for this type of research. The first of these was the Solidification Using Baffles in Sealed Ampoules (SUBSA), an experiment using directional solidification to form single crystals from molten samples. Better understanding of the process that leads to a more uniform distribution of dopant can yield improvements in semiconductor production. The MSG provided near-realtime video of the melting and solidification process, allowing the investigator to optimize conditions from sample to sample.

The second materials science experiment is called Pore Formation and Mobility Investigation (PFMI) and was begun during Expedition 5. This investigation studies the formation of bubbles, or porosity, and their movement in the samples as they are melted and resolidified. Porosity can diminish a material’s strength and usefulness, and understanding the process can lead to ways to minimize the defects. Near the very end of Expedition 5, the MSG suffered a power failure that interrupted operations with PFMI. The failed rack component was returned to Earth, and as of this writing, a recovery plan is being finalized to allow resumption of MSG science activities.

**Cell biology**

Microgravity allows culturing of cells into three-dimensional arrays not possible in ground-based experiments, as shown by precursor experiments in tissue culturing flown on Shuttle and Mir. The Cellular Biotechnology Operations Support System (CBOSS), consisting of an incubator, a gas supply system, refrigerated stowage, and cryogenic transport hardware, provides the capability to culture mammalian cells on ISS (Figure 9). Six experiments during Expeditions 3 and 4 cultured the following cell lines: human ovarian tumor; human colon carcinoma; pheochromocytoma; renal cortical epithelium; erythroleukemia; and human tonsillar tissue. Components of the CBOSS hardware were used to conduct a commercial cell culture experiment during Expedition 5, described below.

![Figure 8. Expedition 5 Flight Engineer Peggy Whitson and Expedition 6 Flight Engineer Don Pettit working with MSG during STS 113/11A handover activities.](image)

![Figure 9. Expedition 3 Commander Frank Culbertson working with the CBOSS cell science experiment.](image)

**Commercial endeavors**

Commercial activities form a significant portion of the research program on ISS. The majority of the commercial projects are managed through NASA’s 15 Commercial Space Centers (CSC’s), consortia of academia, government and industry. The CSC’s work with companies in diverse fields to develop new or improved products and services. Other companies approach NASA directly, and enter into reimbursable agreements to conduct research in space.

The Advanced Astroculture (ADVASC) commercial plant growth payload is an improvement over similar experiments flown on Shuttle and Mir, and has now flown three times on ISS. The first two missions (Expedition 2 and 4) involved growing *Arabidopsis* plants from seed to seed, with seeds produced during the first flight flown and germinated successfully during the second. The second mission also saw the hardware upgraded with a sample port, allowing in-flight sampling and preservation of growing plants. The returned plants and samples were analyzed for structural changes as well as for gene expression alterations. The third flight (Expedition 5) successfully grew soybeans, a commercially and industrially important plant species, from seed to seed.

The Commercial Protein Crystal Growth (CPCG) payload was very successful on numerous Shuttle missions, and was adapted for long-duration flights on ISS, particularly for...
those macromolecules that required more than 2-3 weeks for crystal formation. The crystal growth hardware, capable of housing up to 1,008 samples and contained in a Commercial Refrigerator Incubator Module (CRIM), has flown successfully twice on ISS, during Expeditions 2 and 4.

The Commercial Generic Bioprocessing Apparatus (CGBA) had a successful career on Shuttle and two long duration experiences on Mir. It was one of a trio of payloads that took advantage of a new flight opportunity to conduct research early in the ISS Program. On its first ISS mission, STS 106/2A.2B in September 2000, CGBA flew as a sortie and contained two investigations, one studying neural changes in Drosophila, the other culturing human kidney cells. During the second CGBA mission on Expedition 2, the hardware suffered a non-recoverable software error, and the commercial experiment studying bacterial fermentation and antibiotic production in microgravity could not be completed. However, after failure analysis and correction, the hardware and the experiment were reflown successfully during Expedition 4, demonstrating the value of a long-duration research platform to rapidly recover from failures.

The Plant Generic Bioprocessing Apparatus (PGBA), an earlier version of which flew on Shuttle, made its first ISS flight during Expedition 5. The hardware maintains proper environmental control to allow growth of Arabidopsis thaliana, a well-characterized plant species that has been used in other space flight experiments, and spinach. Unfortunately, due to as yet undetermined causes the plants did not reach the expected maturity levels.

Zeolites are important materials used in the chemical processing industry, such as gasoline production. Zeolites have a rigid honeycomb-like structure that allows them to absorb liquids or gases but remain hard. Zeolite crystals of higher quality, such as may be produced in microgravity, could have significant economic impact. The Zeolite Crystal Growth (ZCG) experiment, begun during Expedition 4, seeks to find ways to create more perfect crystals. This experiment was the first to use ARIS operationally. Two sets of new samples were processed in the on-board ZCG furnace during Expedition 5, and as of this writing, another set of new samples is to be processed during Expedition 6.

Osteoporosis is a potentially crippling disease that affects millions. In the Commercial Biomedical Testing Module (CBTM), the effectiveness of a protein involved in bone metabolism as a possible treatment for osteoporosis was evaluated. The experiment, which consisted of three Animal Enclosure Modules, was flown successfully as a sortie on STS 108/UFL.

Microencapsulation, a process in which a drug is enclosed in miniature liquid filled balloons, has been shown to provide more effective drug delivery and treatment, for example for some solid tumors. The Microencapsulation Electrostatic Processing System (MEPS) is an automated apparatus to form such drug filled microballoons. It is believed that this process is improved in microgravity. The experiment was conducted during Expedition 5.

The first commercial reimbursable experiment on ISS was DREAMTIME, flown on Expedition 3. It consisted of a High-Definition TV (HDTV) camera, which the crew used to record everyday activities aboard ISS as well as special events such as Shuttle arrivals and crew visits.

Another commercial reimbursable experiment, called STELSYS and flown during Expedition 5, involved culturing of human liver cells and evaluating their metabolic function in microgravity. The experiment used components of the CBSS payload.

Earth observations

Crew Earth observations using hand-held cameras have been an integral part of human space flight since the first missions in 1961. Observations and recording of images of pre-selected Earth targets as well as targets of opportunity have been very useful in tracking long-term planetary changes, such as climatic variations, agricultural land-use, and urban sprawl, as well as events often first noted by the on-orbit crew, such as fires and dust storms. On ISS, the usual 35-mm and 70-mm film cameras are supplemented by digital cameras that allow for near-real time downlinking of images. This is especially useful for ephemeral events (e.g., weather events, volcanic eruptions), where it is important to have imagery available prior to the film products' return on the next Shuttle flight, which could be weeks or even months away. Starting on Expedition 1 (Figure 10), crews have been using lens combinations giving an effective focal length of 800 mm, providing up to 6-meter ground resolution. Early results of these activities have been published by Robinson and Evans [2].
Educational activities

A long-duration crewed platform such as ISS is an ideal venue for conducting educational projects. Everyday life in microgravity can be easily demonstrated by onboard crewmembers, as can basic physical laws and other processes. Students can be active participants in some of these activities, by preparing simple experiment protocols and subjects for demonstrations, and receiving and analyzing data, samples and other products.

During Expedition 1, an educational experiment called SEEDS for short, involved crewmembers growing and photographing corn and soybean seeds. The images were downlinked near real-time, allowing the students to compare the development in microgravity with similar plants grown in their classrooms. Educational video products were generated by crewmembers on Expeditions 4 and 5, demonstrating common Earth-based activities, such as games and sports, in the unique microgravity environment. Physical phenomena such as conservation of angular momentum, how fluids behave in microgravity, and even the basic concept of weightlessness were also recorded by the crews, the footage to be used to generate documentaries.

In another activity called Earth Knowledge Acquired by Middle schools (EarthKAM), an electronic still camera is mounted in an ISS Earth-facing window for several days, and high school and college students on the ground can direct it to image selected Earth sites. The images are downlinked and placed on the Internet for wide distribution. To date, about three thousand images have been returned, with participating schools in the United States, Germany and Japan.

Technology demonstration

One of the first payloads to reach ISS, even prior to human occupancy, was the Middeck Active Control Experiment-II (MACE-II). The experiment was launched on STS 106/2A.2B in September 2000 as a pre-positioned item, and became the first active science experiment when it was operated by the Expedition 1 crew. Due to limited crew time during the first expedition, the experiment was extended into Expedition 2 (Figure 11), and its objectives ultimately completed, demonstrating the valuable nature of a long-duration research platform. The goal of the experiment was to provide data on decreasing the effects of vibration in moving structures in space. The experiment hardware demonstrated advanced control technologies to suppress unwanted vibration. The results of this experiment will allow future spacecraft to be designed with lighter weight structures.

External payloads

The first ISS external payload is the Materials on ISS Experiment (MISSE), delivered during the STS 105/7A.1 mission in August 2001. The payload, a collaboration among NASA, the U.S. Air Force and private industry, consists of two suitcase-size containers, holding 951 samples. The goal of the experiment is to evaluate the effects of long-term exposure to the low Earth orbit environment on the samples, which include paints, lubricants, thermal coatings, solar cell materials, polymers and other materials. The first two containers were placed on the outside of the Quest Joint Airlock during an EVA (Figure 12), for an anticipated 1-1.5-year exposure. In 2003, these two containers will be retrieved during an EVA, and replaced by two new containers with new samples, which will be exposed for a planned 3 years.

Figure 11. Expedition 2 Flight Engineer Susan Helms working with the MACE-II experiment in *Unity*.

Figure 12. Crewmembers deploy the MISSE experiment containers during the STS 105 mission.
5. SUMMARY

Construction of ISS is the most complex space project ever attempted, establishing a truly unique place for research. Even while the assembly is progressing, significant science is being conducted, taking advantage of the special characteristics of a long-duration research platform. The U.S. Laboratory module Destiny is being outfitted with research facilities, and once the International Partner modules arrive, there will be additional capability for research, both inside and outside the station. While challenging, both the assembly and the research have been remarkably successful to date, with ISS supporting the successful completion of the major objectives of the great majority of the investigations attempted to date. The publication of the results of the early experiments carried out on ISS has begun, a positive sign that valuable science is being accomplished. Although challenges remain as the assembly continues, the ISS Program is dedicated to maximizing the research output of the station.

And we are still relatively early in the overall lifetime of the station, giving cause for optimism.

6. ACKNOWLEDGMENTS

The authors would like to recognize the outstanding efforts of all the ISS crewmembers, past, present and future, who are the operators and sometimes the subjects for the science investigations. They clearly recognize firsthand the valuable platform that ISS is for conducting research, and often dedicate extra time to ensure the output is as great as it can be. The authors also wish to recognize the numerous investigators, especially those that came early in this program, for their patience and perseverance – we certainly hope that it was worth the wait.

7. REFERENCES
