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RESEARCH PROGRESS AND ACCOMPLISHMENTS ON ISS

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Abstract

The first research payloads reached the International Space Station (ISS) more than two years ago, with research operating continuously since March 2001. Seven research racks are currently on-orbit, with three more arriving soon to expand science capabilities. Through the first five expeditions, 60 unique NASA-managed investigations from 11 nations have been supported, many continuing into later missions. More than 90,000 experiment hours have been completed, and more than 1,000 hours of crew time have been dedicated to research, numbers that grow daily. The multidisciplinary program includes research in life sciences, physical sciences, biotechnology, Earth sciences, technology demonstrations as well as commercial endeavors and educational activities. The Payload Operations and Integration Center monitors the onboard activities around the clock, working with numerous Principal Investigators and Payload Developers at their remote sites. Future years will see expansion of the station with research modules provided by the European Space Agency and Japan, which will be outfitted with additional research racks.

Introduction

The International Space Station (ISS) provides truly unique opportunities for advancements in many fields of science and opens doors for commercial endeavors in space. Although construction of ISS began nearly four years ago, and research has been ongoing for nearly half that time, we are still early in the overall life of the facility. The progress we have made to date, and the accomplishments we have achieved, give cause for optimism. Along with the successes, we have also learned the limitations of the facility and its supporting infrastructure, and the continuing challenge has been to overcome those limitations, present and future, and maximize the capabilities of this truly unique facility. One major challenge has been to begin outfitting the station with research facilities and conducting research and commercial activities, while construction of the overall platform is still in progress. To date, the US Laboratory module *Destiny* has been outfitted with seven research racks, to enable research in a wide variety of scientific and commercial endeavors. Three more racks will arrive in 2003 to complete the research outfitting prior to US Core Complete. Through the end of Expedition 5, 60 unique investigations have been completed or are in progress (see attached Table), with 24 new ones planned to be added during the next four expeditions. Results of some of the investigations are already being published in peer-reviewed scientific journals, with others in print and in preparation. Over the next few years, addition of the European *Columbus* and Japanese *Kibo* modules will allow the station to complete its research outfitting. In addition, sites on the station's exterior will allow the placement of experiments requiring that unique vantage point. And finally, the Centrifuge Accommodation Module will bring the capability to conduct variable gravity experiments on ISS.

Challenges

Conducting research during the assembly phase of ISS is not without its challenges. Certainly, building the facility and improving its overall capabilities has top priority in terms of resources. Dynamics inherent to such a complex program, such as changing vehicle launch dates, stage and increment durations, and unexpected situations requiring immediate or delayed action, provide additional challenges to executing a stable research program. However, based on experience to date, it is clear that significant high quality research can be accomplished in this time frame, and the lessons learned will certainly ensure a greater research return as the station matures.

The end result of the challenges summarized above is limited resources available for research in two distinct areas: crew time during the expedition and powered middeck lockers on the Shuttle. The reasons for the limitations on crew time are rather straightforward: the various activities required to assemble and maintain the station, as well as the health of the crewmembers themselves, given a crew size of three, allows only a limited amount of time to conduct the research. Stated another way, if these systems activities were not performed, the station could potentially degrade to the point where no research could be carried out at all. On average, the ISS program estimates that the crew time available for all research is approximately 20 hours/week. Certain activities, such as extravehicular activities (EVAs), joint work with visiting vehicles, whether with a Shuttle assembly mission, a Soyuz taxi mission, or a Progress cargo vehicle exchange, tend to be crew time intensive, and therefore time available for research tends to be significantly reduced during those time periods. Therefore, overall crew time available for research on any given expedition is dependent to a significant degree on the number of those types of activities. It should be clearly stated that not all research requires crew time; therefore, crew time limitations selectively affect the types of research that by their nature require crew involvement, such as human investigations, plant biology, cellular biotechnology, and other complex experiments. It must be stressed that every crew has been extremely dedicated to performing as much science as possible, and are often willing to devote extra time to maximize the success of the research program.

The causes for the limitations on powered middecks are somewhat more complex, since a variety of factors contribute to the availability of middeck stowage as well as power. These factors include but are not limited to the overall layout of the specific mission, for example the type of cargo carried in the payload bay, the mass of the cargo, the mission duration, the number of crewmembers, the number of EVAs to be carried out, and whether the mission plan includes an ISS crew exchange. The ascent performance of the Shuttle itself is a factor, such as the performance of its main engines and even the time of year, which has a bearing on the performance of the Solid Rocket Boosters. The ISS program attempts to preserve 5 powered middeck lockers on every Shuttle flight, but it is often challenging to meet this commitment. Figure 1 shows a historical as well as a prospective summary of the number of middeck lockers available for research. For past missions, the number of middecks planned about one year prior to the mission is compared with the number actually flown. A similar comparison is made for future missions, comparing the L-12-month plan with the most recent plan for each flight. Historically, it is apparent that L-12-month plans can and do change, in some cases dramatically, by the time the mission actually flies. It can also be seen that for the missions in 2003, a very busy assembly phase during which large and heavy truss segment elements will be added to the station, current planning limits research to 5 middeck lockers. On the other hand, these assembly missions also will add new solar arrays to the station, to enable its further expansion by the addition of the International Partner research modules.

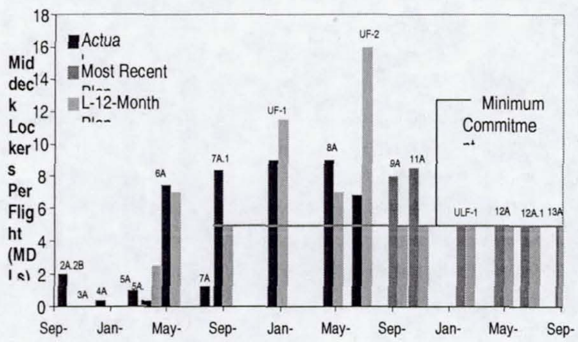

Figure 1. Summary of the number of middeck lockers per Shuttle flight.

Research Outfitting

Research on ISS can be categorized into two overlapping phases: outfitting and utilization. Outfitting refers to developing the on-orbit infrastructure to enable research to take place. Typically, this refers to launching the various research racks, roughly refrigerator-size facilities that can be dedicated to a certain type of research or multi-use platforms, to ISS and installing them inside the research modules. These racks are launched inside the Multi-purpose Logistics Module (MPLM), a large Italian-built carrier that fits inside the Shuttle cargo bay and is temporarily berthed to ISS to allow transfer of the racks and other hardware; the MPLM is also used to return hardware items from station. Once the racks are in place, activated and checked out, the various sub-rack payloads and experiments must then be launched, operated and returned to Earth – this is the utilization phase. As outfitting and utilization progress, racks and experiments often compete with each other as well as with station systems equipment for the limited capacity to launch hardware to orbit.

Of the 24 rack locations in *Destiny*, ten are currently dedicated to research (see Figure 2 for rack layout). The outfitting of *Destiny* with research racks began in March 2001, with the launch of the Human Research Facility Rack 1 (HRF 1) on the STS 102/5A.1 mission, the flight that also brought the second long-duration crew to ISS. *Destiny* itself had reached ISS just a month earlier, on the previous Shuttle mission. The purpose of the HRF 1 rack is to support a variety of investigations in the area of human life sciences. At launch, the rack contained a computer Workstation (WS) for experiment control and data management, an Ultrasound system similar to those found in clinical settings on Earth, a gas analysis system (GASMAP) used to measure exhaled gases to be used in cardio-pulmonary investigations, and a laptop for controlling various experiments. Additional items can be added to the rack, and it contains stowage drawers for investigators requiring their own unique additional experiment hardware. To date, this facility has supported eight different investigations in radiation monitoring, pulmonary function, neurovestibular function, and psychology. A second complementary rack will arrive in 2003 with additional hardware to support more complex investigations.

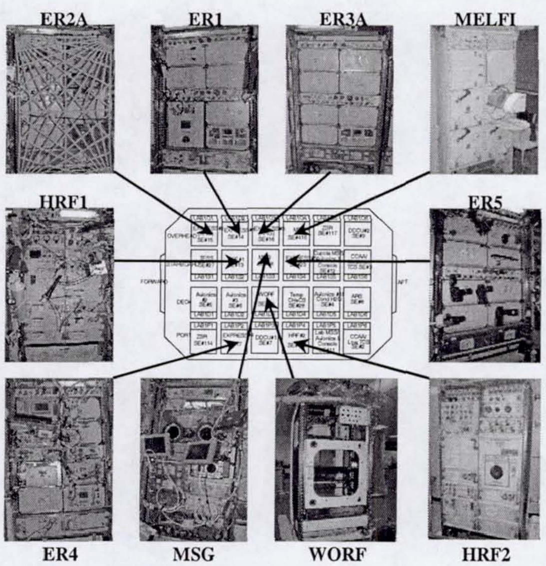

Figure 2. Distribution of research racks in US Laboratory module Destiny. Acronyms are defined in the text.

In April 2001, two more research racks were launched to ISS, on the STS 100/6A mission that also brought up the Canadarm2 remote manipulator system. These were the first two EXPRESS racks, short for EXpedite the Processing of REsearch for Space Station. These racks, containing eight Shuttle middeck locker size locations plus two smaller drawers to house individual experiments, provide services such as power, thermal control, data, and nitrogen purge to the payloads. Experiments can be moved in and out of EXPRESS racks in modular fashion, arriving and returning on Shuttle flights based on the duration needs of the specific payloads. One of these two initial EXPRESS racks is configured with the Active Rack Isolation System (ARIS) to provide attenuation of micro-acceleration disturbances for sensitive experiments. Both of these racks were put to near immediate use to support an initial suite of nine payloads, four of which required continuous power immediately after their transfer to *Destiny* to support thermally conditioned experiments.

The STS 105/7A.1 mission that carried the third expedition crew to ISS in August 2001 also carried two additional EXPRESS racks. One of these became the continuously powered EXPRESS rack, a function it has been faithfully executing essentially without pause for over a year. The other EXPRESS rack is initially being used for stowage, but will house a large commercial materials processing facility beginning in 2003.

The next two racks arrived in June 2002 on STS 111/UF2 along with the fifth expedition crew and the station's Mobile Base System. The Microgravity Sciences Glovebox (MSG), built by the European Space Agency (ESA), provides an enclosed work environment for experiments for which containment is desirable. The rack also provides power, data, and video capability for specific glovebox experiments. The second rack was another EXPRESS rack, the second one equipped with ARIS. It is currently being used for stowage, but will be used in the future to support experiments.

In March 2003, the STS 114/ULF1 mission will deliver the seventh ISS crew as well as three additional research racks, bringing the total to 10, the full allocation prior to the arrival of the International Partner laboratory modules. As noted above, a second HRF rack will expand the capability for conducting biomedical research. New hardware arriving in the rack includes a Space Linear Acceleration Mass Measurement Device (SLAMMD), a new WS, a Pulmonary Function System (PFS), and a refrigerated centrifuge. The second rack, the Window Observation Research Facility (WORF), will be installed in the rack location of the 20-cm diameter optical quality window. This window has been used to date for handheld crew photography; WORF will allow more sophisticated observation instruments to continue to monitor Earth's environment from the station's unique vantage point. The third rack is the Minus Eighty-degree Laboratory Freezer for ISS (MELFI), an ESA-provided facility dedicated to the cold stowage of scientific samples. Four Dewars in the MELFI can store samples at -80° C, -26° C, and +4° C.

The launch of Node 2 in early-2004 will complete the US Core Complete portion of the ISS Assembly Sequence. It will also allow for two additional research racks to be placed in the Destiny, by moving two systems racks into the Node 2. It is currently envisioned that the sixth EXPRESS Rack and the Combustion Integrated Rack (CIR) will be launched in mid-2004. Subsequent facilities will enhance the station's capabilities in conducting research in fluid physics, materials sciences and fundamental biology.

The ESA-provided *Columbus* module is currently planned for launch in late 2004. With the arrival of *Columbus*, the total allocation of research racks on ISS rises to 22, with four or five new racks arriving with the module. These and additional racks will augment the station's capability to conduct a wider range of research in life and physical sciences. The *Columbus* also affords external attach points for payloads requiring exposure.

Once the truss segments are completed in 2004, four sites will be available to attach external payloads. The first EXPRESS Pallet is planned to be launched in 2005, as is the Alpha Magnetic Spectrometer experiment, designed to investigate antimatter in the universe.

The Japanese *Kibo* module is planned to launch in 2006, bringing the number of available research rack sites to 33. Later launch of an exposed pallet will provide additional sites for external payloads.

In 2007, the Centrifuge Accommodation Module (CAM) will be added to ISS. This important facility will enable variable gravity investigations, particularly in the life sciences, to be conducted.

Research Accomplishments

As outfitting of ISS with research racks continues, the investigations conducted has grown in numbers and sophistication. To date, 60 unique investigations in a variety of research disciplines have been completed or are in progress, many of them spanning multiple expeditions. As experiments are completed, we are already beginning to see their results appearing in the scientific literature, with many more in the preparation and pre-publication phase. The overall success of the program, once initial "start-up" issues were resolved, has been gratifying (Figure 3): Of the 60 investigations supported by ISS, 21 are still in progress. Of the remaining 39, 36 were supported successfully, and the other three met with at least partial success. In one of those cases, the experiment's supporting hardware failed on its first attempt, but was reflown and was ultimately completed successfully.

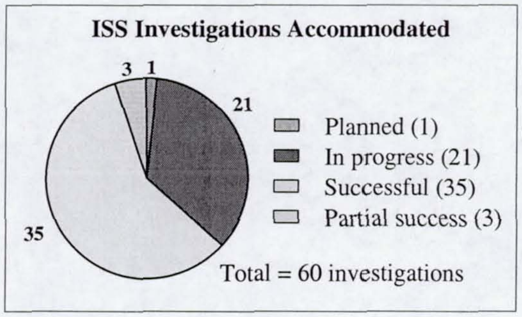

Figure 3. Summary of investigations accommodated by ISS through the end of Expedition 5.

Early research

Experiments were on ISS even before the first research rack arrived, indeed even before the first expedition crew arrived. In 2000, a Shuttle mission was inserted into the assembly sequence, allowing a unique opportunity to launch some simple payloads. This was achieved in about nine months from the announcement of the opportunity to the experiments reaching ISS in September 2000 aboard STS 106/2A.2B. Given the state of the program and the capabilities of the ISS at this time, these were relatively simple payloads. One flew as a sortie (i.e., was not transferred to ISS, but remained in the Shuttle middeck) and included two separate peer-reviewed investigations in a Commercial Generic Bioprocessing Apparatus (CGBA), a Bioserve, Inc., provided hardware that had flown numerous times on the Space Shuttle and twice on the Russian space station *Mir*. The CGBA had been intended to fly on ISS, and indeed has done so three times so far. A second payload, from the University of California, Irvine, was the Protein Crystal Growth-Enhanced Gaseous Nitrogen Dewar (PCG-EGN), an enhancement of a passive protein crystallization facility that had flown seven times on *Mir*. The apparatus requires no power and no crew involvement other than transfer to and from ISS, and was therefore suitable for this time period. The PCG-EGN, containing 635 samples of 21 different proteins, was transferred to the *Zarya* module, where the crystallization process took place, and then returned on the next Shuttle flight, for a total space flight duration of 46 days. Some of the results of this experiment have been published in the scientific literature (Barnes, *Acta Crystallogr D Biol Crystallogr* 2002). The third payload, a joint Air Force Research Lab/Massachusetts Institute of Technology investigation called Middeck Active Control Experiment-II (MACE-II), was prepositioned on ISS, and eventually operated successfully by the Expedition 1 and 2 crews.

Expedition 1

A few other experiments were flown on ISS prior to the arrival of the first research rack. Another PCG-EGN flew for 42 days between STS 98/5A and STS 102/5A.1, this one including 674 samples of 20 different substances. Crew Earth Observations (CEO), a continuation of crewmember hand-held photography of Earth targets carried it on all human space flights since the Mercury Program, resumed when the Expedition 1 crew took up residence in November 2000 (Figure 4). The crew's successful use of an 800-mm effective focal length lens to achieve 6-meter ground resolution was documented in a publication (Robinson, *EOS* 2002). An educational payload

Figure 4. Expedition 1 Flight Engineer Sergey Krikalyov conducting Crew Earth Observations in Zvezda module.

called Soybean and Corn Germination in Space (SEEDS for short) involved documenting the germination of seeds via electronic still camera images that were downlinked to the ground so schoolchildren could compare that process with seeds growing on Earth. Another educational payload, called Earth Knowledge Acquired for Middle schools (EarthKAM), was scheduled to conduct a hardware test during Expedition 1, but due to crew time limitations, this test was deferred to and successfully completed during Expedition 2. As noted above, the MACE-II experiment was planned to be completed during Expedition 1, but due to unexpected station maintenance activities limiting time available for research as well as anomalies with the experiment hardware itself, this was not possible. It was decided to leave the hardware on orbit for an additional expedition and the next crew was able to complete all the experiment's primary objectives. These two examples highlight a significant advantage of a permanent platform in space for conducting research, namely the greater flexibility of recovering from unexpected events and still complete research objectives.

Expedition 2

The arrival of the first research racks during Expedition 2 heralded a quantum increase in the quantity and sophistication of science activities on ISS. During the second expedition, 20 investigations were carried out, most of them in the HRF Rack 1 and EXPRESS Racks 1 and 2, compared to 4 investigations during the first expedition when the station's capabilities were more limited. These investigations were supported by experiment hardware that was launched to ISS on three different Shuttle missions.

There were multiple ISS systems anomalies, particularly early during the expedition, that hindered successful implementation of the planned research program. Several of these were attributable to multiple new and complex systems being operated for the first time. Significant amounts of crew time were required to resolve the anomalies, deferring many research activities. In addition, other system anomalies interfered with the ability to downlink data as planned. Once the systems anomalies were resolved, research resumed apace, and the eventual extension of the expedition by about four weeks because of delays in Shuttle launches allowed many objectives to be recovered. Extensive use of the "task list" by the crew, in which non time critical activities were made available to the crew to perform at their discretion, also significantly helped to complete as many research objectives as possible.

Arriving with the HRF Rack 1 on the STS 102/5A.1 mission were two components of an international suite of radiation monitoring investigations; the third component arrived on the next flight, STS 100/6A. The three experiments Dosimetric Mapping (DOSMAP), Bonner Ball Neutron Detector (BBND) and PHANTOM TORSO, provided by ESA, Japan and NASA, respectively, were at least partially

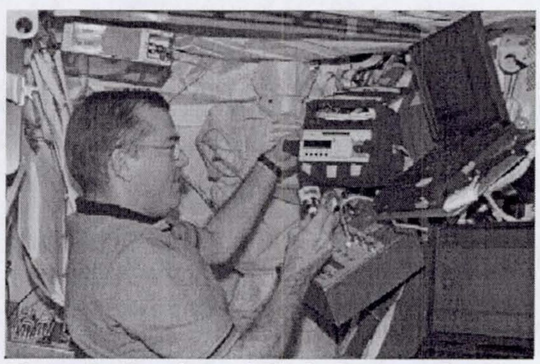

Figure 5. Expedition 2 Flight Engineer Jim Voss working with the radiation suite of experiments.

successful, although initial delays at deploying time-sensitive active dosimeters caused irretrievable data losses. Anomalies with the experiment hardware also contributed to data losses. The Hoffman Reflex (HREFLEX) experiment, to study changes in neuromuscular reflexes during long-duration space flight, was completed successfully. Another biomedical investigation, INTERACTIONS, which studies interactions among the crewmembers and between the crew and the ground control teams, was partially successful, data losses occurring primarily due to lack of crew time, particularly early in the expedition. The SUBREGIONAL BONE experiment, which required data collection only before and after flight, was completely successful. Initial activation and checkout of the HRF Rack itself was delayed several weeks due to lack of crew time, and the checkout of the Workstation planned for early in the expedition to support data downlink of BBND data had to be deferred to near the end of the expedition.

The two EXPRESS racks that arrived on STS 100/6A contained several payloads in research areas such as microgravity measurements, biotechnology, fluid physics as well as the first commercial payloads on ISS. EXPRESS Rack 1 was transferred and activated during the docked phase, and four powered payloads, CGBA, Commercial Protein Crystal Growth (CPCG) and two Protein Crystal Growth-Single-locker Thermal Enclosure System (PCG-STES) units, were transferred to it from the Shuttle middeck. The rack provided continuous power and data connections to the payloads for their duration on ISS. The CGBA, a commercial payload, contained an experiment provided by Bristol Myers Squibb to study bacterial fermentation and antibiotic production in microgravity. Unfortunately, due to an internal software problem, the CGBA failed after a few weeks, prematurely terminating the experiment. The experiment was eventually reflown during Expedition 4 and successfully completed. The CPCG, another commercial payload, contained 1,008 protein samples, and was successfully returned during the STS 105/7A.1 mission after 125 days in space. The two PCG-STES units contained three protein crystallization experiments, and both were successfully operated and returned on the STS 104/7A mission after 96 days in space. Another commercial experiment, Advanced Astroculture (ADVASC), was installed later in the rack, and successfully completed a plant growth experiment using *Arabidopsis* plants. The plants developed through an entire growth cycle and produced viable seeds. Due to delays in the subsequent two Shuttle missions, the return of the ADVASC was accelerated by one mission to ensure not exceeding the maximum on-orbit duration constraint of the experiment.

EXPRESS Rack 2 is configured with the ARIS, a system that provides active dampening of microgravity disturbances to sensitive payloads. One of the investigations, called ARIS-ISS Characterization Experiment (ARIS-ICE) was designed to characterize the performance of the ARIS in microgravity compared to preflight projections. The activation of EXPRESS Rack 2 was delayed due to unavailability of crew time, delaying the start of the characterization, an experiment originally planned only for Expedition 2 but eventually extended through Expedition 4. The delayed activation of the rack also delayed that start of operations of the two microgravity measurement payloads, the Microgravity Accelerations Measurement System (MAMS) and the Space Acceleration Measurement System (SAMS), as well as the fluid physics investigation, Experiment Physics of Colloids in Space (EXPPCS). However, once activated, these experiments required minimal to no crew time, and were controlled from the ground and data collection proceeded well. The EXPPCS experiment, studying the behavior of colloids in microgravity, was particularly successful once it was activated, achieving virtually all its objectives planned for the expedition via telescience.

Four experiments did not require the use of any of the research racks. The third flight of the PCG-EGN, containing 201 samples of 10 different proteins, occurred on STS 104/7A. The experiment was stowed in the *Zarya* module, and successfully returned on STS 105/7A.1 after a 41-day flight. The MACE-II experiment, extended from Expedition 1, was completed, and because its sessions were not time critical, it was an ideal experiment to be worked from the task list. The first operational session of the EarthKAM educational payload was completed, returning nearly 300 images to the participating schools. Imagery for CEO was successfully obtained primarily by use of the task list.

Expedition 2 was the first experience on ISS with a robust research program. Despite the initial difficulties, the expedition was overall highly successful. Of the 20 investigations attempted, only one failed due to an internal software problem, five were at least partially successful, and 14 were successful. Fifteen of the investigations performed during Expedition 2 continued in later missions.

Expedition 3

In August 2001, the STS 105/7A.1 mission that brought the Expedition 3 crew to ISS and returned the Expedition 2 crew to Earth also launched two additional EXPRESS Racks and 7 new payloads to ISS, and returned several of the Expedition 2 payloads as well as samples and data products back to Earth. Challenges to completing the research program during Expedition 3 were relatively minimal, the investigations accomplished more or less according to plan. Crew availability was an issue during certain phases of the mission, particularly around EVA's and visiting vehicles. Near the end of the mission, an unplanned EVA to inspect a docking port caused minor perturbations to the plan, but no science loss occurred. Anomalies with the EXPRESS racks were resolved early in the mission with software upgrades.

During the course of the third expedition, 28 investigations were performed, 18 of them new to the program. Of note, the first external payloads, the Materials on ISS Experiment (MISSE), were placed on the outside of the *Quest* Joint Airlock module during a space walk. The two MISSE assemblies contained 951 samples of a variety of materials to test the effects of the ISS external environment during the approximately 1-1.5 years of exposure. These two MISSE containers will be exchanged with two new ones during the STS 114/ULF1 mission in 2003.

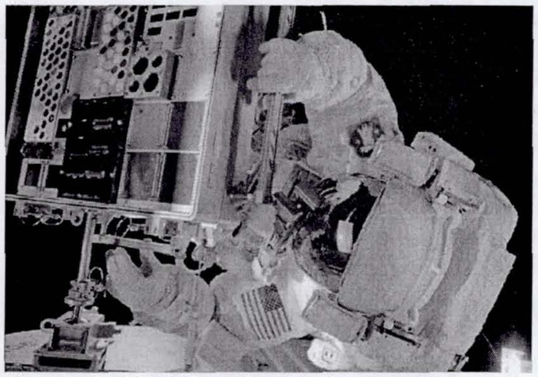

Figure 6. MISSE payload being installed on the exterior of the Quest Joint Airlock module.

Four biomedical investigations continued from Expedition 2, SUBREGIONAL BONE, HREFLEX, INTERACTIONS, and BBND, the last of which was completed and returned at the end of the expedition. Based on the results from Expedition 2, the HREFLEX PI requested, and was granted, an additional in-flight session to provide a better time course for the changes in the reflex. INTERACTIONS was partially successful, due to some missing data. Three new biomedical investigations were begun on Expedition 3. The XENON1 experiment, investigating changes in peripheral circulation as a possible cause of postflight orthostatic intolerance, required data collection only before and after flight, and was completed successfully. A study of pulmonary function in long-duration space flight, as well as after EVA, called PUFF, was completed successfully. The RENAL STONE experiment, assessing the risk of crewmembers developing kidney stones in flight, as well as evaluating a possible pharmacological countermeasure, was partially successful. While all urine collections were performed as planned, the countermeasure pills were not taken with enough frequency to meet study objectives.

Microgravity measurements using MAMS and SAMS, as well as characterization of ARIS, continued during Expedition 3. Data were obtained during station quiescent periods as well as during several docking and undocking events. The EXPPCS colloids experiment also continued from Expedition 2, and was able to achieve its planned objectives during the mission via telescience. The crew obtained valuable imagery to satisfy the CEO experiment's objectives. The EarthKAM educational payload obtained 647 images for 18 schools during its operational cycle.

A new payload for ISS, the Cellular Biotechnology Operations Support System (CBOSS) contained four investigations to study cell growth in microgravity, involving colon cancer, pheochromocytoma, ovarian cancer, and renal cells. This was the most complex and crew intensive experiment flown to ISS to date, and was successfully completed during the first two weeks of the expedition. The cells were then placed in an onboard refrigerator and finally returned on the STS 108/UF1 mission in December 2001.

Two different experiments studied protein crystallization in microgravity. The Dynamically Controlled Protein Crystal Growth (DCPCG) investigation not only observed the crystallization process, but also attempted to manipulate it by modulating vapor pressure. The experiment was primarily tele-operated by ground controllers. The Advance Protein Crystallization Facility (APCF) experiment, sponsored by the Italian Space Agency (ASI), contained eight different investigations from various European universities. Both experiments were completed successfully, and were returned on STS 108/UF1.

DREAMTIME was a commercial payload, to demonstrate High-Definition Television (HDTV) technology in space. The crew documented various aspects of life aboard ISS, including daily activities, as well as Shuttle dockings and joint crew operations. All payload objectives were met.

The research on Expedition 3 was highly successful: of the 28 investigations planned, two were partially successful and the other 26 achieved primary objectives. Fourteen of the investigations continued into later expeditions.

Expedition 4

Expedition 4, by virtue of two Shuttle flights including one carrying an MPLM which significantly increases the amount of research material carried to ISS, conducted the most investigations of any ISS expedition to date, 31, ten of them new to ISS. Some of these were also the most complex and crew intensive attempted to date in this program. A new facility, a middeck-locker size refrigerator-freezer called ARCTIC, and operating in an EXPRESS rack, was launched on STS 110/8A in April 2002, to provide a small cold stowage facility prior to the arrival of the rack-size MELFI. The EXPRESS Rack 4 that arrived at the beginning of Expedition 3 was put into service as the continuously powered rack, taking over those duties from EXPRESS Rack 1.

Several challenges during Expedition 4 were overcome to achieve an outstanding degree of success. Changes in Shuttle launch dates resulted in both stages of the expedition, indeed the expedition itself, to be extended. This required revisions of the research program during the expedition, and particularly for the 8A Stage this proved highly beneficial since with the original duration, it would have been difficult to complete all planned objectives. An unplanned EVA was added during the mission, which forced some replanning but also provided data to two investigations studying EVA-related changes. There were two events that resulted in a load-shed situation, in which station non-critical systems had to be powered down. This resulted in two separate periods during which critical payloads were without power for 6 hours and 1 hour, respectively. The full impacts of these events on science samples are still being evaluated.

Six of the seven biomedical investigations on Expedition 4 (SUBREGIONAL BONE, INTERACTIONS, HREFLEX, XENON1, PUFF, and RENAL STONE) were continued from earlier missions. All met their science objectives, and due to the mission extension, INTERACTIONS, HREFLEX and PUFF obtained more data than planned. The HREFLEX experiment was completed on Expedition 4, exceeding the minimum number of subjects. A new investigation, called EVA Radiation Monitoring (EVARM), was designed to measure radiation doses inside the US EVA suit at three locations, to approximate doses crewmembers receive during EVA's. The experiment's Expedition 4 objectives were met.

Two fundamental biology payloads were successfully flown during Expedition 4. The Avian Development Facility (ADF), flown as a sortie during the STS 108/UF1 mission, included two investigations to study embryologic development of Japanese quail. The Biomass Processing System (BPS), a payload flown

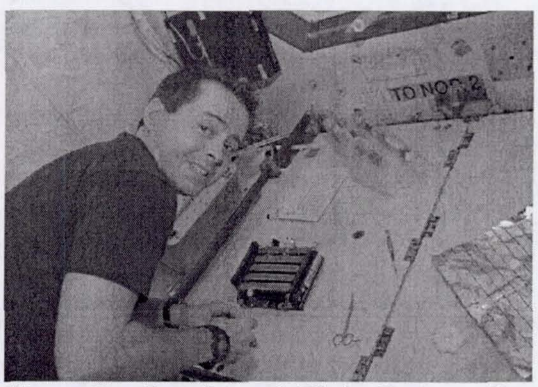

Figure 7. Expedition 4 Flight Engineer Dan Bursch performing pollination of Brassica plants in BPS experiment.

during the 8A Stage, was a hardware demonstration for future space-based plant growth facilities, using dwarf wheat and *Brassica rapa* as study species, and also included an experiment designed to study photosynthesis in dwarf wheat. Significant anomalies with the hardware were successfully overcome to achieve primary objectives, and the extension of the mission provided for additional plant growth cycles and additional data.

Microgravity measurements continued essentially continuously with the MAMS and SAMS hardware, although SAMS experienced an internal data communications problem that prevented data collection for approximately three weeks. Data were acquired during quiescent station modes as well as during visiting vehicle docking and undocking events. The ARIS characterization was completed during Expedition 4, having met all objectives of the project. Based on data obtained, the ARIS performance was judged equal to or better than predicted for virtually all frequency ranges. The ARIS provided its first operational support to an experiment, Zeolite Crystal Growth (ZCG), during Expedition 4. The MISSE external payload continued to expose the samples to the external environment, and during an EVA, the Expedition 4 crew took close up photographs to document any observable changes.

The EXPPCS colloids experiment suffered a non-recoverable software failure in its control unit during Expedition 4. Still, more than 85% of the original science objectives were met during the experiment's 9-month course during Expeditions 2, 3 and 4. In addition, due to the flexible nature of the experiment, additional objectives were developed and completed during its execution. The hardware was returned on the STS 111/UF2 mission in June 2002, will be refurbished and reflown to ISS to support investigations on later expeditions.

Three protein crystallization payloads were flown during Expedition 4. Two PCG-STES units were launched on STS 108/UF1, containing three investigations. The units operated nominally, and during a 6-hour powerdown period maintained the required set temperature. They were returned on STS 110/8A. The fourth PCG-EGN flew to ISS on STS 110/8A, carrying 351 samples, was stowed in *Zarya*, and successfully returned on STS 111/UF2. The second ISS flight of the commercial CPCG, carrying about 1,000 samples, was successfully completed between STS 110/8A and STS 111/UF2, a duration of 72 days.

The second operation of the CBOSS payload occurred in the two weeks following STS 108/UF1, containing three investigations to study microgravity growth of renal and tonsillar cells and the production of the hormone erythropoietin. The cell culturing portion of the experiment was carried out successfully and the cells placed in cold stowage. During a 6-hour powerdown, some of the samples may have been compromised by a rise in temperature above the required set point. Near the end of the cold stowage phase, the refrigerator experienced anomalies that caused additional warming of the samples. The samples were returned on STS 110/8A for postflight analysis.

The CGBA launched on STS 110/8A was a reflight of the Bristol Myers Squibb experiment on bacterial fermentation and antibiotic production that failed during Expedition 2. On this flight, the hardware operated normally and the experiment was successfully returned on STS 111/UF2. The ADVASC commercial payload continued the study of *Arabidopsis* growth in microgravity begun on Expedition 2, launching on STS 108/UF1 and returning on STS 110/8A. Indeed, some seeds produced in space during the earlier experiment were flown again, and germinated in space. The hardware was also modified to allow in-flight sampling of the plants.

A commercial payload new to ISS, called ZCG, studies the formation of zeolites and other industrially important substances in microgravity. The furnace unit was launched on STS 108/UF1, installed in EXPRESS Rack 2, and checked out early during Expedition 4. The samples, contained in 19 ampoules, were launched on STS 110/8A and processed for 14 days during the stage. The ARIS was required, since the processing of the samples, particularly the first few hours, is highly sensitive to microgravity disturbances. The furnace operated successfully and ARIS provided the required isolation, and the samples were returned on STS 111/UF2.

A new commercial payload, Commercial Biomedical Testing Module (CBTM), flew as a sortie on STS 108/UF1. It contained an experiment to investigate the role of a novel protein in osteoporosis. The experiment was completed successfully.

Crew Earth Observations continued during Expedition 4, with the largest return of images of any ISS mission to date. The EarthKAM education payload, during two operational cycles, returned 1,268 images for participating schools in the United States, Germany and Japan. A new educational payload, Education Payload Operations (EPO), was conducted during Expedition 4. The crew videotaped various physical processes in microgravity, as well as provided insight into living in space. The material will be used to produce educational documentary programs.

As noted above, the research program for Expedition 4 was the most ambitious to date. It was also highly successful: of the 31 investigations, all but one achieved their objectives. Only one was partially successful on the expedition, but since it operated over three expeditions, overall it achieved most of its preflight objectives. Nineteen of the investigations are planned to continue on future expeditions.

Expedition 5

The current ISS mission, Expedition 5, began in June 2002, with the launch of STS 111/UF2. This mission also brought two new research racks to ISS, the second ARIS-equipped EXPRESS rack and the ESA-built Microgravity Sciences Glovebox (MSG), bringing the number of research facilities to seven. A second ARCTIC refrigerator/freezer was also launched on this mission, to expand cold stowage capabilities. Of the 24 investigations planned for this expedition, nine are new to the ISS Program. Major challenges during this expedition have been few, of note is the extension of the UF2 Stage and the overall mission caused by delayed Shuttle flights. This extension had the effect that the Soyuz visiting mission that had been planned for Expedition 6 will now be in this expedition. This visiting mission has the unique feature that one of the crewmembers will be operating ESA-sponsored experiments, launched on a Russian vehicle, in the ESA-built MSG in the US Laboratory, a novel type of international cooperation and a probable preview of future activities.

The MSG rack was activated and checked out shortly after the mission began, and was put to active use supporting the first glovebox investigation, a materials experiment called Solidifcation Using Baffles in Sealed Ampoules (SUBSA). Although a few of the SUBSA samples encountered cracks, putting the MSG to good use as a containment device, the experiment was ultimately able to be completed. Shortly thereafter, the second investigation, another materials experiment called Pore Formation and Mobility Investigation (PFMI), was begun and is planned to continue into Expedition 6.

Several payloads continued from earlier expeditions. The MAMS and SAMS microgravity measurement devices continued their recordings essentially continuously, recording during station quiet periods as well as during more dynamic events such as vehicle docking and undocking events. The crew continued the CEO experiment, imaging pre-selected sites as well as transient phenomena. A continuation of the EPO experiment had the crew demonstrate and film a variety of activities, such as different sports, in microgravity, the footage to be used in future documentaries. The EarthKAM educational payload conducted their next operational session near the end of the expedition. The samples in the MISSE external payload continued their exposure, and will be returned on the STS 114/ULF1 mission in 2003.

Of the 10 biomedical investigations, six (SUBREGIONAL BONE, INTERACTIONS, XENON1, PUFF, RENAL STONE, and EVARM) are continued from earlier expeditions, with XENON1 being completed on this mission, meeting the investigator's science requirements. The four new ones all have only preflight and postflight data collection requirements, and are designed to study changes in muscle structure and function (BIOPSY), changes in locomotor function (MOBILITY), changes in immune function (EPSTEIN-BARR), and test a possible countermeasure to postflight orthostatic intolerance (MIDODRINE).

In protein crystallization research, a PCG-STES unit containing three investigations was launched on STS 111/UF2, operated successfully and was returned on STS 112/9A. A second unit was launched on STS 112/9A and will be returned on the next flight, STS 113/11A.

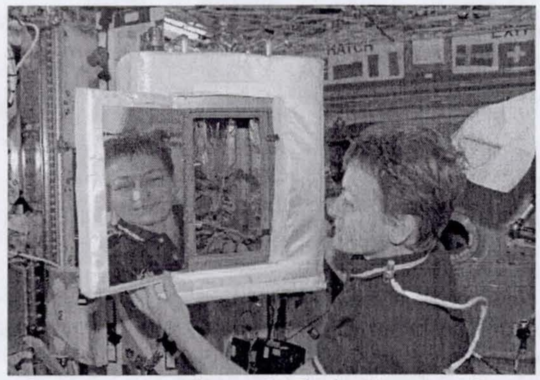

Figure 8. Expedition 5 Flight Engineer Peggy Whitson inspecting the soybeans growing in ADVASC.

The ADVASC commercial payload on Expedition 5 contained an experiment to study the growth of soybeans, a leading source of protein and also widely used in other products, in microgravity. The experiment was activated shortly after launch on STS 111/UF2 and grew healthy-looking plants that produced seeds. It was returned on the STS 112/9A mission.

The ZCG commercial experiment processed 19 new ampoules during the UF2 Stage, once again supported by ARIS. Because of delays in the Shuttle flight that returned the samples, seven of the more sensitive ones were placed in one of the ARCTIC refrigerators to help minimize possible degradation of the samples during the additional time on orbit. A second set of ampoules is being processed during the 9A Stage, to be returned on the STS 113/11A mission.

A new commercial experiment called Microencapsulation Electrostatic Processing System (MEPS) was launched on STS 111/UF2. The goal of this experiment is to study production of microencapsulated drugs in space, previous studies showing this can be enhanced in microgravity. Eight different samples were successfully processed and returned on STS 112/9A. Another new commercial experiment called STELSYS cultured human liver cells in space and study the production of certain substances by the cells. The investigation essentially used the CBOSS hardware that was used on Expeditions 3 and 4. The cells and other samples, placed in the ARCTIC 1 freezer for onboard storage, were returned on STS 112/9A.

The Plant Generic Bioprocessing Apparatus (PGBA) commercial payload was flown to ISS for the first time on STS 112/9A. It is studying the growth of *Arabidopsis* plants, some of which will be harvested in flight and placed in cold stowage for postflight analysis while others will be returned live to the ground, on STS 113/11A.

While Expedition 5 is still underway, to date it has been highly successful. Five of the 24 investigations have already been completed successfully. Twenty of the investigations will continue on future expeditions.

Near-term plans

The ISS faces a tremendous technical challenge over the next 18 months as the most complex series of assembly tasks will be undertaken. These primarily involve the piece by piece construction of the 365-foot truss, the backbone of the station, the addition of three new solar arrays and the relocation of the current array, as well as additions to the cooling system. While these assembly tasks are critical to the further construction of the station, including the addition of the International Partner modules, during this time frame the ability to resupply the research racks with experiments will be somewhat constrained. During some expeditions, extensive EVA work will also limit the crew time available to research.

The ISS Program Office is acutely aware of the need to maximize the resources available to research and has instituted formal efforts in this regard. A crew time steering team has been established to evaluate options to maximize the crew time available for research, including redefining the crew's work day plan, formalizing the task list concept to allow for extra science to be performed, and encouraging the planning of additional science activities that could be performed if additional time were to free up. A middeck optimization study has been initiated, working with the Space Shuttle Program, to evaluate specific actions that could increase the resources available to research in the middeck. These efforts should lead to increased science productivity of ISS.

Summary

The first research payloads arrived at ISS more than two years ago, and continuous science has been ongoing for more than one and a half years. During this time, the research capabilities have been tremendously increased, even as assembly of the overall platform continues. Despite significant challenges along the way, ISS continues to successfully support a large number of investigations in a variety of research disciplines. The results of some of the early investigations are reaching the publication stage. The near future looms with new challenges, but experience to date and dedicated efforts give reason to be optimistic that the challenges will be overcome and that new and greater successes will be added to past ones.

Table – List of ISS investigations through Expedition 5.

Expedition 0	1	2	3	4	5	Investigation title	Investigator/Affiliation	Payload
				■		Development and Function of the Avian Otolith System in Normal and Altered Gravity Environments	J. David Dickman, Washington University	ADF
				■		Skeletal Development in Embryonic Quail	Stephen Doty, Hospital for Special Surgery	ADF
				■		Biomass Processing System Technology Validation Test	Robert Morrow, Orbital Technology Corp.	BPS
				■		Photosynthesis Experiment and System Testing Operation	Gary Stutte, Dynamac Corp.	BPS
		■	■			Bonner Ball Neutron Detector	Tateo Goka, National Space Development Agency of Japan	BBND
					■	Effect of Prolonged Spaceflight on Human Skeletal Muscle	Robert Fitts	BIOPSY
		■				Dosimetric Mapping	Gunther Reitz, DLR Institute of Aerospace Medicine	DOSMAP
					■	Space Flight Induced Reactivation of Epstein-Barr Virus	Raymond Stowe	EPSTEIN-BARR
				■	■	A Study of Radiation Doses Experienced by Astronauts in EVA	Ian Thomson, Thomson & Nielson Electronics LTD	EVARM
		■	■	■		Effects of Altered Gravity on Spinal Cord Excitability	Doug Watt, McGill University, Montreal	HREFLEX
		■	■	■	■	Crewmember and Crew-Ground Interactions During ISS Missions	Nick Kanas, University of California and VA Medical Center	INTERACTIONS
					■	Test of Midodrine as a Countermeasure against Postflight Orthostatic Hypotension	Janice Meck	MIDODRINE
					■	Promoting Sensorimotor Response Generalizability: A Countermeasure to Mitigate Locomotor Dysfunction After Long-Duration Space Flight	Jacob Bloomberg	MOBILITY
			■	■	■	The Effects of EVA and Long-term Exposure to Microgravity on Pulmonary Function	John West, University of California San Diego	PUFF
			■	■	■	Renal Stone Risk During Space Flight: Assessment and Countermeasure Validation	Peggy Whitson, NASA-JSC	RENAL STONE
		■	■	■	■	Sub-regional Assessment of Bone Loss in the Axial Skeleton in Long-Term Space Flight	Thomas Lang, University of California San Francisco	SUBREGIONAL BONE
		■				Organ Dose Measurements Using a Phantom Torso	Francis Cucinotta, NASA-JSC	TORSO
			■	■	■	Effect of Microgravity on the Peripheral Subcutaneous Veno-Arteriolar Reflex in Humans	Anders Gabrielsen, National University Hospital, Copenhagen	XENON1

Expedition						Investigation title	Investigator/Affiliation	Payload
0	1	2	3	4	5			
			■			Evaluation of Ovarian Tumor Cell Growth and Gene Expression	Jeanne Becker, University of South Florida	CBOSS
			■	■		Renal Cell Differentiation and Hormone Production from Human Renal Cortical Cells	Timothy Hammond, Tulane University Medical Center	CBOSS
			■			Use of NASA Bioreactor to Study Cell Cycle Regulation Mechanisms of Colon Carcinoma Metastasis in Microgravity	J. Milburn Jessup, University of Texas Health Science Center, San Antonio	CBOSS
			■			PC12 Pheochromocytoma Cells: A Proven Model System for Optimizing 3-D Cell Culture Biotechnology in Space	Peter Lelkes, Drexel University	CBOSS
				■		Production of Recombinant Human Erythropoietin by Mammalian Cells Cultured in Simulated Microgravity	Arthur Sytkowski, Harvard Medical School	CBOSS
				■		Simulated Microgravity Antigen Synthesis in Tonsillar B Cells	Joshua Zimmerberg, National Institutes of Health	CBOSS
			■			Dynamically Controlled Protein Crystal Growth	Larry DeLucas, University of Alabama, Birmingham	DCPCG
		■	■	■		Physics of Colloids in Space	David Weitz, Harvard University	EXPPCS
		■	■	■	■	Microgravity Acceleration Measurement System	Richard DeLombard, NASA-GRC	MAMS
					■	Pore Formation and Mobility Investigation	Richard Grugel	MSG-PFMI
					■	Solidification Using Baffles in Sealed Ampoules	Alexander Ostrogorsky	MSG-SUBSA
■	■	■		■		Protein Crystal Growth-Enhanced Gaseous Nitrogen Dewar	Alex McPherson, University of California Irvine	PCG-EGN
		■		■	■	Facility-Based Hardware Science and Applications	Dan Carter, New Century Pharmaceuticals, Huntsville	PCG-STES
		■		■	■	Improved Diffraction Quality of Crystals	Craig Kundrot, NASA-MSFC	PCG-STES
		■		■	■	Vapor Equilibration Studies	Aniruddha Achari, NASA-MSFC	PCG-STES
		■	■	■	■	Space Acceleration Measurement System	Richard DeLombard, NASA-GRC	SAMS

Expedition						Investigation title	Investigator/Affiliation	Payload
0	1	2	3	4	5			
			■			Crystallization of Human Low Density Lipoprotein (LDL) Subfractions in Microgravity	M. Baumstark, University of Freiburg	APCF
			■			Crystallization of Rhodopsin in Microgravity	W. de Grip, University of Nijmegen	APCF
			■			Effect of Different Growth Conditions on the Quality of Thaumatin and Aspartyl-tRNA Synthetase Crystals Grown in Microgravity	R. Giege, CNRS Strasbourg	APCF
			■			Crystallization of the Next Generation of Octarellins	J. Martial, University of Liege	APCF
			■			Testing New Trends in Microgravity Protein Crystallization	F. Otalora, University of Granada	APCF
			■			Solution Flows and Molecular Disorder of Protein Crystals: Growth of High Quality Crystals, Motions of Lumazin Crystals, and Growth of Ferritin Crystals	S. Weinkauf, Technical University Munich	APCF
			■			Extraordinary Structural Features of Antibodies from Camelids	L. Wyns, Free University Brussels	APCF
			■			Protein Crystallization in Microgravity, Collagen Model (X-Y-Gly) Polypeptides: the case of (Pro-Pro-Gly) 10	A. Zagari, University of Naples	APCF
		■	■	■		Active Rack Isolation System - ISS Characterization Experiment	Glenn Bushnell, Ian Fialho, The Boeing Company	ARIS-ICE
	■	■	■	■	■	Crew Earth Observations	Kamlesh Lulla, NASA-JSC	CEO
		■	■	■	■	Earth Knowledge Acquired by Middle Schools	Sally Ride, University of California San Diego	EARTHKAM
				■	■	Education Outreach	Patience Smith, NASA-JSC	EPO
	■	■				Middeck Active Control Experiment-Reflight Program	Rory Ninneman, Air Force Research Lab, Albuquerque	MACE-II
			■	■	■	Materials on International Space Station Experiment	William Kinard, NASA-LaRC	MISSE
	■					Soybean and Corn Seed Germination in Space	Howard Levine, Dynamac Corporation	SEEDS
		■		■	■	Microgravity Impact on Plant Seed-to-Seed Production	Weijia Zhou, Wisconsin Center for Space Automation and Robotics	ADVASC
				■		Commercial Biomedical Testing Module	Ted Bateman, Bioserve Space Technologies	CBTM

Expedition						Investigation title	Investigator/Affiliation	Payload
0	1	2	3	4	5			
■						Neurolab Reflight	Timothy Hammond, Tulane University Medical Center	CGBA
■						Effects of Spaceflight of Drosophila Neural Development	Haig Keshishian, Yale University	CGBA
		■		■		Commercial Generic Biopressing Apparatus	David Klaus, Bioserve Space Technologies	CGBA
		■		■		Commercial Protein Crystal Growth	Larry DeLucas, University of Alabama, Birmingham	CPCG-H
			■			Long Duration HDTV Camcorder Experiment-Video	Ben Mason, Dreamtime Holdings, Inc	DREAMTIME
					■	Microencapsulation Electrostatic Processing System	Dennis Morrison	MEPS
					■	Plant Generic Bioprocessing Apparatus Liver Cell Function in Microgravity	Alex Hoehn Albert Li	PGBA STELSYS
				■	■	Zeolite Crystal Growth	Al Sacco, CAMMP, Northeastern University	ZCG