

# From ISS to the Moon, Mars and Beyond – Applying Lessons Learned

Merri J. Sanchez\*

*NASA, Johnson Space Center, Houston, Texas, 77062*

James S. Voss†

*Auburn University, Auburn, Alabama, 36849*

**On January 14, 2004, the President of the United States announced a new and exciting direction for NASA's future with his space exploration initiative. This new policy includes the safe return to flight of the Space Shuttle in order to complete the assembly of the Space Station by the end of this decade and to meet our international obligations with the International Space Station. At that time the Space Shuttle fleet would be retired. In addition, the Orbital Space Plane program was cancelled and replaced by a new Crew Exploration Vehicle program, which will serve as both a crew transport to low Earth orbit, and beyond. The key element of the new policy is a return to the Moon by 2020. The expeditions to the Moon will be used to gain experience and knowledge to serve as a foundation for human exploration to Mars, and elsewhere in our solar system. But before we get to the Moon, we are already establishing a foundation of experience, knowledge, and lessons learned about long duration human space flight operations with the International Space Station, which has been in low Earth orbit for over six years. This paper highlights some of the lessons learned during the construction and operation of the Space Station that will help to take us to the Moon, Mars, and beyond.**

## I. Introduction

**C**ONSTRUCTING and operating the International Space Station (ISS) is a magnificent orchestration of varying methods, operations, hardware designs, and scientific research from different countries and engineering cultures. The Space Station is currently over 200 tons with 15 complex major components launched from different hemispheres after fabrication in four different countries, united together to form approximately 15,000 cubic feet of habitable volume.<sup>1,2</sup>

By the time construction is finished, the Space Station will weigh over 1 million pounds and include hardware and modules from the United States (U.S.), Russia, Europe, Japan, and Canada. What is often not appreciated, however, is the tremendous challenge of integrating the details involved in the hardware, computer software, command and control interfaces, crew procedures, logistics, ground support teams, and so on, with the added dimension of different languages and cultural paradigms – in the largest, most complex spacecraft ever devised. This technical challenge is certainly one of the most difficult any international partnership has ever faced.

Space is an unforgiving environment for both hardware and humans. Designs must address the often-hazardous operating conditions of vacuum, micro-gravity, temperature extremes, radiation exposure, etc. For spacecraft systems and hardware, the designs must be robust and on-orbit maintainable. For humans, the designs must address the countermeasures to radiation and micro-gravity, short and long term health maintenance, emergency care, ergonomics, as well as physical and psychological environments for work and recreation. These environmental factors become even more important design considerations and drivers when we go beyond Earth orbit. There are environmental hazards in space, and we will not have quick, if any resupply on an exploration mission. We will not have the capability for an emergency medical return in the event of a serious injury or illness of a crewmember. All of this must be planned for in designs and manifests.

---

\* NASA Increment Manager, Mission Integration and Operations Office, Mail Code OC3, AIAA Associate Fellow.

† Astronaut, currently Associate Dean, Samuel Ginn College of Engineering, 108 Ramsay Hall, AIAA Senior Member.

With the continuing Space Station daily operations, hardware failures, and innovative work-arounds we continue to add to our knowledge base through lessons learned. This experience base has been compounded and accelerated by the limited resupply available during the Space Shuttle down time. These lessons learned are directly applicable to the design, development, operations, and management of future exploration missions.

## II. Hardware Design

The Space Station is currently composed of what is referred to as the U.S. segment and the Russian segment. Given the cultural differences between the two major partners, it is not surprising that there are also cultural and philosophical differences in their approaches to hardware design and operation.

The Russian modules and systems use heritage hardware. Much of the Russian hardware used in the Space Station is identical to that used in the Russian Mir Station. Designs that are simple, robust, mechanical, and have stood the test of time through their various spaceflight programs. Many of their systems require frequent crew interaction for maintenance and operation. This design philosophy has plusses and minuses. The mechanical systems are often easier to operate and repair, and are usually very reliable. There is limited telemetry on system performance available for flight controllers on the ground, which gives the crew a level of independence from the ground that comes with the responsibility to ensure the systems remain operational. To avoid development overhead associated with failure analysis and the high cost of developing and building long lifetime items, Russian system reliability is based on periodic replacement of components. This initial savings in development costs, and at times, launch mass, becomes a logistics burden to keep the systems operational when they require the frequent change out of components either in routine or corrective maintenance.

The U.S. modules and systems have little to no heritage from our other spaceflight programs, and are more complex. There is a high degree of automation, with significant telemetry available to flight controllers that may not be available to the crew. Most of the U.S. hardware and systems require operational computers in order to function. Even something as simple as turning on or off the lights is controlled through a computer command. This allows the crew to rely on the flight control team to monitor the status of the various systems, and in many cases, to issue commands to operate hardware. The danger of relying too heavily on this philosophy was demonstrated in April 2001 during Expedition 2 when all of the command and control computers in the U.S. Laboratory failed. In that instance the Space Shuttle *Endeavour* was docked to the Space Station in support of Flight 6A. The Space Shuttle provided critical communications between the ground and the U.S. segment until it was reestablished through a resident program in the Node 1 computers. This computer program had the capability to provide a one use "backdoor" path to the laboratory computers that allowed restoring control of the U.S. segment. Fortunately neither the crew nor the Space Station was in danger, as the Russian segment still provided control of the Space Station.<sup>2</sup>

The computer control and data management system on the Space Station is a study in lessons learned itself. With any software there will be bugs. But the Space Station computer architecture has proven to be robust. On many occasions we have demonstrated the ability to rapidly and successfully uplink entirely new software, modify existing software, and reset parameters. This capability was demonstrated early in the Space Station life when the Space Station robotic arm experienced a series of anomalies with safing, brake release, and joint errors during the summer of 2001. The Program discussed delaying the installation of the Joint Airlock, scheduled on the next Space Shuttle flight, until a mechanical joint could be prepared, flown, and installed. This would have required a change in the sequence of the Space Shuttle flights. But ground personnel finally determined that a series of software patches would solve the major anomalies. This solution only required delaying the planned Space Shuttle launch several weeks to accommodate the development of the software patches.<sup>2</sup>

Use of laptops for crew interface to the command and data handling system has allowed phased upgrading the hardware by replacing the units with new models as they become available and certified. These laptops have been upgraded with little requirement to recode resident software.

Reliable operation of the life support systems in human spacecraft is critical. The different hardware design philosophies between the U.S. and Russian segments can nowhere be as clearly illustrated as in the life support system. Both segments maintain their unique systems, providing unlike redundancy for the Space Station. Since the *Columbia* accident we have had to rely at times on the components of each partner's system. When a component in one segment fails, the other segment can often pick up the burden of support. Within the U.S. carbon dioxide removal system we have seen excellent scrubbing capabilities, but the system is prone to zeolite contamination. The zeolite beds cannot be opened on orbit. With the Russian systems we see routine failures and reduced performance requiring frequent, but usually simple maintenance. Despite the frequent failures, between the two independent systems we have been able to maintain a safe, breathable atmosphere. This demonstrates a synergy between system development and operation that has become more evident as we gain long duration space flight experience.

Other smaller systems and hardware components also demonstrate the philosophical differences. The U.S. provided health maintenance and exercise hardware is technically sophisticated, with vibration isolation and exercise performance monitoring systems, yielding excellent human and hardware performance data to the ground physicians and engineers. But the hardware is not robust and is not designed for easy on-orbit maintenance. In many cases very large components must be flown as replacements, even when it is a small internal component that has actually failed. The Russian provided equipment is simpler, and more limited in the ability to monitor the benefit of the exercise, but is specifically designed for simplicity, robustness, and on-orbit repair.

Maintenance of equipment on long duration missions becomes its own area of specialization. There is significant crew time required to maintain hardware that was not designed for on orbit repair. Much precious volume is required to store system spares if we chose a replacement instead of a repair design philosophy. One example of a large critical spare stowed inside the pressurized volume on Space Station is the Bearing Motor and Roll Ring Module, which is over 18 cubic feet in volume. This spare was flown to the Space Station in August 2001 on Flight 7A after a solar array experienced several stalls in its rotation mechanism. After the spare was launched it was determined that it would be too difficult to install without the Space Shuttle docked. The balky arrays continue to function over three years later, the spare has never been installed and remains stowed on board. In addition, after a failed hardware component is removed, a decision must be made whether to return the component to the ground for failure analysis. Typically, most U.S. hardware is returned for ground inspection. Most Russian hardware is disposed of in the trash. For an exploration mission there will be limited stowage available for spares and no opportunity to return hardware for repair or failure analysis, so appropriate diagnostic, calibration and maintenance tools must be available to the crew.

There are two key lessons learned that are applicable across the board on hardware design for human spaceflight. First, is that we really do not fully know the exact operational environment the hardware will be exposed to until we actually start operating it after it is launched. There have been several occurrences where we have had to alter the operating parameters of hardware on orbit due to unpredicted thermal environments. The thermal environment on the external Space Station structure was difficult to fully predict preflight due to shadowing of equipment from structure, and the use of different flight attitudes than originally planned. We have also had to create “masks” or keep out zones for various antennas as we gain more insight into both the thermal environment and in signal multi-pathing from the structure. Hardware must be designed to collect an appropriate amount of performance data; to be able to be modified through operational constraints, software, or design to perform in newly defined environments; and to support field diagnosis and repair. The second is that a conscious design choice must be made that optimizes the trades between complexity, automation, reliability, repair, and replacement. Built into this trade space are variables such as crew training, crew time, stowage, logistics, and cost. In most cases, a modular system design with commonality between components may be the best choice.

The International Space Station continues to provide the unique opportunity of an on orbit test bed that allows proving and refining hardware and system designs for the exploration program before we have to use them on missions far from Earth.

### III. Resupply

Resupply and logistics have proven to be very important issues for the Space Station. Prior to the *Columbia* accident the plan was to fly U.S. provided consumable items as required on the Space Shuttle, and Russian provided consumable items on the Progress cargo vehicle. This arrangement of frequent visiting vehicles provided a constant supply line that allowed us meet the needs of the crew on orbit with less impact to on orbit stowage. The Russian cargo vehicle also carried a significant volume of replacement components as their hardware is designed for frequent maintenance. Critical U.S. hardware had prepositioned spares, and all other hardware was flown on an as needed basis. It was never desired to preposition all hardware on the Space Station due to the limited stowage space available. Stowage availability will continue to be a driver in the system design of exploration vehicles.

Since *Columbia*, the entire resupply of the Space Station has depended on the limited number of Progress cargo vehicles. This has prompted significant refining of our consumables rate, and reduction where possible. Over the past two years the ISS Program has carefully reevaluated the actual usage of the critical consumables of air, water, food, and propellant to exactly define our consumables rates. The resulting reduction in resupply rates has allowed continuing missions to the ISS.<sup>1</sup>

Reduction examples include a nearly 85% reduction in crew clothing, down from 12 cubic feet to just over 2 cubic feet per crew member for their six-month stay on orbit; a 25% reduction in food overage volume; replacing packing materials with soft goods such as towels and clothes; replacing film with digital cameras; using electronic procedures instead of paper procedures, etc. We are also recycling more water by fully drying out clothes and

towels prior to disposal, which has led to a reduced usage from 3 to 2 liters per day per person for consumption and hygiene needs.<sup>1,3</sup> In addition, engineers developed new lower drag profiles for positioning the solar arrays as they track the Sun, which allows a reduction in propellant resupply requirements. With the conservation efforts of the crew and the close tracking of actual consumables usage, we will be able to maintain two crewmembers on orbit for over two years using only Progress cargo vehicles until the Space Shuttle returns to flight.

The potential resupply of some items forces additional operational philosophy and hardware design trades. Do you continually supply clean clothes and towels, or provide laundry facilities? Do you supply all of your food, or grow some to supplement the diet? There are volumetric, environmental, nutritional, and psychological reasons to grow food, but do you depend on the ability to produce successful crops? Do you dispose of items in the trash or recycle them? Do you supply enough water for all needs or have a closed loop regenerative life support system? Do you launch hardware in carefully designed padding that can protect fragile components but also yields on orbit trash, or make due with using other required soft goods for padding that may offer less protection? Do you continue to package food in individual servings and containers as we do now, which are easy to use but volumetrically inefficient, or develop a new food storage methodology?

In this long duration mission operating environment inventory management has gained new importance. It is critical to understand what items are available on orbit, where they are stowed, and when resupply is required. A computerized inventory system relying on barcodes is used on the Space Station to track the hardware. All crewmembers living on Space Station have reported both the importance of the system, and the need to make architecture updates to make the system easier to use. Challenges of inventory management include maintaining an accurate database for thousands of items and keeping the crew workload low for maintenance of the system.

#### IV. Extravehicular Activity and Robotics

More complex space walk activity has occurred, and is planned, during the construction of the Space Station than at any other time in human space flight history. These tasks have been conducted from three different airlocks using two different styles of space suits.

The Expedition 2 crew performed the first Space Station-based extravehicular activity (EVA), utilizing the Russian segment and the Russian Orlan space suits. This was actually an internal EVA where the crew remained inside the depressurized compartment in order to prepare the Service Module nadir port for the docking of the Russian module Pirs, which would serve as both a docking compartment and airlock.<sup>2</sup>

The first U.S. segment EVA was performed after the Joint Airlock, Quest, was installed and activated while the Space Shuttle *Atlantis* was docked during Flight 7A. This EVA was the first use of the U.S. extravehicular mobility unit (EMU) space suits from the Space Station.<sup>2</sup>

There have been 25 Space Shuttle-based and 31 Space Station-based EVAs at the Space Station, totaling over 338 hours, with many more EVAs to come as the assembly continues. The majority of these were for assembly tasks, but several have been for maintenance and repairs. This can be compared to 74 non-ISS EVAs performed from the Space Shuttle (totaling nearly 472 hours) and 75 EVAs performed on the Russian Mir Station (totaling nearly 362 hours).

Having two different suit systems onboard the Space Station has been invaluable since the loss of Space Shuttle *Columbia*. The EMUs have reached the end of their on-orbit service life and new suits cannot be flown on the Russian Progress resupply vehicles. Two of the three EMU suits currently on orbit have had technical issues that have prevented their use in a spacewalk. But through the ingenuity of the engineers on the ground, and the skills of the crew on-orbit, the EMUs have been repaired on-orbit and are now serviceable if there is a need to use them. This is a break-through in the normal maintenance philosophy of the EMUs, as all critical maintenance had always been performed on the ground in the past. The ingenuity of the ground team and the crewmembers was demonstrated by developing the procedures to troubleshoot and repair the problem on orbit with no training and limited tool selection. During the time period that the EMUs were not usable, an external remote power controller module failed on the Space Station. This unit provides power to one of the control moment gyros that are used to maintain the orientation of the Space Station. Using the Orlan suits, the Expedition 9 crew successfully performed the EVA task and replaced the unit. This was the first EVA to be performed in the Russian Orlan suits for U.S. hardware on the U.S. segment. While the advantage of the two different space suits is evident, there are also disadvantages. Two suits means double the preflight training time in order to become proficient in both, double the on orbit stowage of the suits and support items, extra logistics to launch parts for two types of suits, and dedicated airlock hardware for each suit. In addition, while the U.S. Joint Airlock recovers the air during depressurization, the Russian Docking Compartment airlock vents the air into space. This air must be resupplied.

Space Shuttle EVA training philosophy has always been to train crewmembers on the specific tasks to be accomplished, in the specific order they will be performed. A Space Shuttle-based EVA is a well-practiced and carefully orchestrated ballet, where everyone knows his or her part by rote.

Space Station crews on the other hand may be faced with both planned and unplanned, or contingency, EVA tasks. There is limited time and resources to prepare the expedition crews for EVAs. In order to most efficiently use the available preflight crew time and training resources a different philosophy is slowly evolving based on crewmember recommendations. This new philosophy is to train the crewmembers on a skill set that is applicable to most EVA tasks they will encounter. If there is an especially complex task required of a crew, some specific task-based training may still be required. This skills-based philosophy well equips expedition crewmembers to be able to react to nearly any EVA contingency or repair task that might arise while they are on orbit. This philosophy has shown its value during several unplanned EVA tasks that were required to replace failed external hardware on the Space Station.

This skills-based training philosophy is also applicable for the robotic operations on the Space Station. It has been demonstrated that crewmembers with solid skills-based training are able to accomplish any robotic operations task. The training program is being adjusted to reinforce that philosophy. Now specific robotic task training is only given to Expedition crewmembers that will be required to perform planned critical and complex robotic tasks while on-orbit.

## V. Daily Operations

Round-the-clock long duration operations on the Space Station have required a different approach than the Space Shuttle program, both for the crew and the ground controllers. It is apparent that with 24-hour operations in a control center, there is a need to train flight controllers to be proficient in more than one system in order to reduce manpower requirements and workload induced burnout. The National Aeronautics and Space Administration (NASA) Mission Control Center team has successfully initiated this approach, but additional streamlining can still be implemented.

A Space Shuttle crew is used to having a rigid schedule, carefully optimized for maximum performance that leaves the crew weary at the end of their 1-2 week missions. This is not practical for a long duration crew. The expedition crew schedules are carefully balanced to provide not only dedicated work time, but also exercise, hygiene, sleep, and personal time. The standard workday schedule utilized by crews include information on task requirements and prerequisites, such as if ground monitoring is required during the task, and lets the crew have flexibility in performing the other daily tasks that have no requirements. Starting with Expedition 2, a “task list” approach was incorporated that gives the crew insight to other tasks that will need to be performed in the future, and allows the crew to work ahead at their own pace.<sup>2</sup> This schedule and task flexibility is critical in maintaining a refreshed crew, and has resulted in more work being performed by crews than could be accomplished with strict scheduling. To illustrate, the Expedition 2 crew of three, and the first to use the task list, accomplished 333 hours of official task list work, of which over 70 hours were for additional science activities. They also performed almost 80 additional hours in their personal time under the Crew Earth Observations program where crewmembers are requested to photographically document the Earth and its oceans for scientific study by specialists in the Earth sciences fields.<sup>4</sup> More recently, the Expedition 9 crew of two completed over 250 hours of task list work, with over 200 of those hours for science, including “Saturday morning science” where crewmembers used their personal time to demonstrate scientific principles in zero-gravity for later use as educational material.

In addition, new protocols have been developed for daily operations including scheduling, how frequently the ground contacts the crew, and how the crew lets the ground know that tasks have been completed. For example, with the Space Station there is a planned conference between the crew and the ground controllers at the start and end of each workday. Other than those planned conferences, the ground will not call the crew unless absolutely necessary. This allows the crew to work undisturbed and provides them the necessary flexibility in their workday schedule to accomplish tasks in a different order if they chose. This flexibility allows performing serially scheduled activities in parallel, and lets crews make use of space and hardware efficiencies not apparent to planners. The crew can call the ground any time they desire. Also, with the computerized work schedule, the crew is able to annotate if the task has been completed, and insert notes that might interest the ground controllers, such as how long the task took or if items were stowed differently than expected or if the task was more complex than anticipated. The crew comments are then automatically down linked when there is communications coverage. This allows the personnel on the ground to track the crew’s progress throughout the day without disturbing them. These all work together to make the Space Station research work more Earth-like, providing the crew more autonomy and greater enjoyment in

their workdays. The Russian segment activities are still more rigidly scheduled than those on the U.S. segment with the expectation that operations will be conducted on time and per the planned schedule.

It is important for a long duration crew to be able to be autonomous during routine operations. This is especially critical once we leave Earth orbit. A long duration vehicle should operate without crew intervention except during maintenance and repair. But crews still need the ability to control all systems due to the possibility of failure of automated systems, loss of communications with the ground controllers, or other failures. The complexity of the Space Station systems limits the ability of expedition crews to completely understand all levels of all systems.

New found flexibility in the control centers' response to crewmember suggestions has also been demonstrated. An example is the request by the Expedition 2 crew to complete some of their post-flight technical debriefs while still on orbit. The crew was allowed to use personal time to complete a limited number of debriefs. This concept was fully exploited by the Expedition 9 crew, which recently completed a significant number of their U.S. systems technical debriefs while on orbit, reducing their required post-flight debriefing schedule in the U.S. by half. This option has benefits of providing more timely technical information from the crew to the ground, allowing all crew members to make inputs to the debriefings without impacting their post-flight travel schedule, and freeing up precious post-flight time from the crew schedule.

One area to note in daily operations is the definition of what the crew workday hours will be. The time zone selected to anchor the crew day can have significant impacts on the ground personnel. For the Space Station, the crew workday was aligned with the standard workday in Moscow. This was due to the very real constraints of ensuring that the Russian flight controllers would have access to public transportation since most Russian citizens rely on the Russian Metro system, which does not operate 24-hours a day. The result of this is that the crew workday begins at 2:00 a.m. local time at the Mission Control Center in Houston, Texas. This makes one of the prime control center work shifts in Houston occur during the night, which results in the need for controllers to sleep shift, and can result in fatigue. The differing time zones for the two primary control centers makes it difficult for coordination between the flight controllers, engineers, and managers. Careful orchestration of schedules must be done in order to ensure that meetings can be conducted at times of day reasonable to all partners. Decisions on the crew day and the location of control centers have significant impact on program operations.

## **VI. Humans in the Loop**

### **A. Crew Compatibility**

Crew compatibility is probably the most important consideration for the selection of a crewmember for a long duration mission. Despite the early success of crews being compatible in the ISS Program, we need a way to select crew compositions to ensure that there are both personality and skills matches. There is a recognized need to establish criteria for evaluating individual and crew characteristics to ensure there are no significant problems between crewmembers during a long duration mission. This becomes more important the longer the mission. Factors strongly affecting the cohesiveness and compatibility of the crew include, but are not limited to, personality, cultural background, and to some extent, gender. NASA is doing extensive research into different methodologies to assess crew compatibility prior to crew assignments. Besides compatibility, each crewmember needs to possess skills that complement the team composition. Examples of skills may be computer skills, mechanical ability (handy with tools), scientific knowledge, medical knowledge, specific technical knowledge, skills such as robotics or EVA, etc.

### **B. Training**

Training for the Space Station, and future exploration missions requires significant investments in time, resources, and facilities due to the complexity of the spacecraft systems and mission requirements. Before a crew ever launches they spend two or more years in Space Station and expedition specific training. For the ISS, the multinational hardware components drive multinational training locations. This adds overhead and complexity to the training schedule, which if not effectively managed, this workload can result in crew fatigue prior to launch. For exploration, the systems and mission needs will be even more complex, resulting in even more extensive training requirements.

### **C. Psychological Support**

One of the key lessons learned with crews on long duration flights is that psychological support of the crewmembers is very important. Crewmembers have reported the real value of psychological support to their ability to maintain mental well-being. It is also important for the crewmembers to know that their family members are

being assisted and cared for while they are away. Not having to worry about their families is one less distraction that can differentiate between a fulfilling long duration mission and an ordeal to be endured. One valuable lesson learned in the area of psychological support is the delivery of “care packages” which are launched on each visiting vehicle to the Space Station. Items in the care packages are provided by family and friends, and typically include things such as cards and letters, small mementos and reminders from home, photographs, small children’s stuffed animals, music, movies, snack food, etc. While visiting vehicles are not possible during an exploration mission, attention must be paid to providing for these types of items.

Probably the most valued aspect of psychological support is the ability to have frequent contact with family and friends. The initial plan for the Space Station was to allow each crewmember one 15-minute teleconference or videoconference with his or her family per week. Having an amateur radio on board that could be used to contact ground stations augmented this plan. During Expedition 2 an off-the-shelf computer telephone capability was incorporated onto an on board laptop. Crewmembers can now make informal telephone calls to their family and friends worldwide whenever the communications coverage and their schedule permits. This almost daily contact has greatly enhanced the mental well being of both the crewmembers and their families.

#### **D. Food**

Another area of psychological as well as nutritional support is food. The psychological aspect of food becomes more important the longer the duration of the mission. Nearly every Space Station crewmember has returned from their mission with the same two inputs to the nutritional support people. Tastes change on orbit as time goes by, and there is never enough variety in the diet. The more choices that crewmembers have at mealtime, the happier they will feel about their food. Based on crew comments we now provide longer menu cycles before food repeats. There are also deeply cultural aspects to food. Nearly everyone who has made a foreign trip has at some point missed the food they are familiar with and most associate with home. Imagine what it is like in a confined environment on a long duration mission. Each crewmember needs to have an adequate supply of culturally familiar foods to choose from. We are seeing some effects of this currently on the Space Station where there is more Russian food available on orbit than U.S. food due to relying on Russian cargo vehicles. U.S. crewmembers flying with this food disparity have all reported wanting more of their own familiar food.

Another consideration of food is how it is stored. Early in the Space Station all food was stored by meal, with one day’s worth of meals for a crew in the same container. To no one’s surprise, crewmembers did not always want to eat what was on that day’s menu. After crew input, we now store much food “pantry” style, with courses separated. For example, drinks will be in one container, vegetables in another, and main courses in another allowing easier access to a variety of menu choices. Lastly, on Space Station we provide “bonus” food, where the crewmembers can select special foods outside the normal menu cycle, including snacks as well as menu favorites to supplement the standard meals.

#### **E. Environmental Hazards**

There are environmental hazards to living in space, and consideration must be given to providing as safe of living conditions as can reasonably be accommodated. The Space Station has an acceptable level of radiation protection given the fact that it remains in low Earth orbit protected by the Earth’s magnetic field, and given the restrictive screening and selection of long duration crewmembers. However, in the even harsher radiation environment of an exploration mission, the current shielding methods, the NASA human radiation standards, and the expected duration of exploration missions are not compatible with limiting radiation exposure to acceptable values. More effective shielding or other countermeasures still need to be developed before we leave Earth orbit for a long duration mission.

Acoustics is a real problem on the Space Station. Not all hardware and systems operating in the Space Station meet the sound level requirements defined by the ISS Program. Average mid-module sound levels vary from 55-69 dB, but a crew worn sound dosimeter has measured a 24-hour average of 72 dB. As a result, crewmembers often wear hearing protection while on orbit, while both sleeping and working. Crewmembers are provided with a variety of earplug styles as well as noise canceling headsets to use. Several Space Station expedition crewmembers have experienced permanent hearing loss after their missions.

Atmospheric control is also critical. Four on orbit fires have been reported in Russian space flight history, on Salyut 1, Salyut 6, Mir 16, and Mir 23.<sup>5</sup> While there are a variety of ways that the atmosphere inside a spacecraft can become toxic, fire is probably the most feared due to not only the destructive effects of the fire itself, but also the smoke and toxic by-products that can be produced. Provisions need to be made to both monitor the presence and level of toxic components in a closed environment, but also to scrub the toxins from the atmosphere. Currently on the Space Station we have lost the ability to perform real-time monitoring of the environment due to hardware

failures, including the U.S. provided volatile organics analyzer. Replacement hardware is delicate, and cannot be flown on the Progress cargo vehicle, so we are relying on small discrete samples returned to the ground every six months on the Soyuz spacecraft after each crew return. Higher reliability is imperative for exploration missions.

## **F. Health Maintenance**

Health maintenance requires a significant investment in design and crew time on orbit. We currently do not have the ability to have crews live for months in micro-gravity and be able to function at their normal preflight level of performance for weeks to months following return to a gravity environment. This is with our current experience of each crewmember exercising up to two hours per day. This becomes a more critical issue when you have a crew that may be in transit several months to a planetary body, and then be required to perform significant physical tasks as soon as they land on the surface. We must accept the risk to human health and degradation in human performance or find better ways to counter the effects of micro-gravity using pharmaceuticals or artificial gravity.

General health care must also be carefully planned. Currently on the Space Station we have at least one person on every crew trained to Emergency Medical Technical level so that they can provide care adequate for emergency stabilization of an injury or illness in preparation of an emergency return to Earth. We have the medical requirement of any crew rescue vehicle being able to complete a medical evacuation from the Space Station to a medical care facility within 24 hours. For a crew that leaves Earth orbit there will be a need to provide a higher level of emergency and long-term care since medical evacuation will likely not be possible. This can be accomplished through additional crew training, the use of telemedicine, or both. Telemedicine concepts are already being demonstrated on board the Space Station through ground physician monitoring of vitals and crew experiments in performing ultrasound imaging on themselves.

To date on the ISS, no crewmembers have experienced any injury more significant than cuts or bruises. There have been two recorded instances in the Russian space program of crew illness on orbit either cutting a mission short (Soyuz 21), or resulting in the return of a crew member to Earth (Salyut 7).<sup>5</sup> Medical conditions have occurred on short U.S. space missions which could have been life threatening if they occurred on an exploration mission with no possibility of a quick return to Earth. Medical evacuation risk analysis for a space station has been performed using actual medical events experienced during both the U.S. and Russian space programs, including the expected probability of other medical events. This risk must also be assessed for exploration missions where it may not be possible to return a crewmember to Earth for medical care. The space station analysis led to the following conclusions<sup>6</sup>:

- A space station crewmember has a 6% per year chance of requiring a medical evacuation.
- A space station crewmember has 1% chance per year of requiring a critical (unconscious) medical evacuation.
- On ISS there is a probability of one medical evacuation every 5.6 years when there are 3 crewmembers. That increases to one every 2.4 years with seven crewmembers.

## **G. Sleep Shifting**

Special on orbit operations often result in significant shifts in the work and sleep cycle of crews and ground support personnel. Care must be taken when ground personnel schedule critical activities such as a visiting vehicle docking or undocking or EVAs so that the crew sleep schedule is not adversely impacted. Both the Russian Soyuz and Progress vehicle dockings and undockings nearly always require the Space Station crew to perform a sleep shift. Russian EVAs also often require sleep shifts. These sleep shifts are required to ensure telemetry data is available through Russian ground sites during the activities. While the U.S. relies on the Tracking Data Relay Satellite System for excellent communications coverage with the Space Station, the Russians rely on ground stations throughout Asia due to the lack of a communication satellite constellation.

There have been several disagreements between the U.S. and Russia physicians over sleep shifting philosophies. The U.S. believes that a sleep shift should be performed gradually to ensure that the sleep nadir is moved outside the time period the activity will be performed. The Russians believe in “slam” shifting. The disagreements began during Expedition 2 when the crew was required to perform four sleep shifts in opposite directions in 15 days. The crew reported that their fatigue levels were a safety hazard.<sup>2</sup> During Expedition 7 agreement was reached that vehicle operations and EVAs were critical activities, and that special sleep shifting rules were required to ensure that the crew was not in a sleep nadir during a critical activity. Sleep shift protocols are still refined on a case-by-case basis. For exploration missions the implementation of regular schedules, which avoid sleep disruption, will improve operations and enhance safety.

## H. Workload

It is also important as we leave Earth orbit to ensure that a crew maintains a normal work schedule and workload. We currently function with conflicting requirements of: do not overload the crew, provide as normal of a workday as possible, and get as much work done as reasonable. There is little else for a crewmember to do in a confined environment like the Space Station. Giving the crew the option to do additional work provides an outlet for both mental stimulation and relaxation. This is much like someone working in their yard or garage on weekends and evenings, or doing home remodeling projects. Careful consideration must be given for long duration missions. Boredom can be as bad as over work. A variety of stimulating and relaxing activities need to be provided. Examples include work task lists, books, movies, games, etc. One possibility for a long duration mission to another planet would be for the crew to have the “normal job” of assembling the hardware they will need at their destination.

## I. Habitability

Habitability is not only a concern when providing a comfortable work environment, but is also a safety issue if not addressed correctly. Every crewmember needs to have their own private space and sleeping quarters. This was put into practice early on in the Space Station operations. The Space Station was launched with only two crew sleep stations, located in the Service Module, and it was planned to remain that way until the Habitation Module was launched later in the assembly sequence. Before the U.S. Laboratory was delivered and installed on Flight 5A, the Expedition 1 crew had no room for a third private sleep station, so they placed a sleeping bag in the corridor of the Functional Cargo Block module. The Expedition 2 crew found this unacceptable and used materials on orbit to design and build a third sleep station inside a stowage rack in the U.S. Laboratory so that each crewmember would have their own quarters. Other crews agreed that private space was necessary, and a more capable “temporary” sleep station was designed by ground engineers and launched with the Expedition 3 crew. This sleep station was also located in the U.S. Laboratory and included privacy doors, lighting, ventilation and additional radiation protection.

Crew members also report that a long duration environment needs to have the work and living quarters separated in order to allow the crew to mentally relax during their off duty time. More specifically, a visiting Russian crewmember complained early in the Space Station life that it is undesirable to have the toilet located so near the table and food preparation area, as it is in the Service Module. Generally, all expedition crews have reported that the Space Station as designed offers adequate, though spartan, living and hygiene facilities.

Another habitability concern on the Space Station is the lack of stowage volume. Both the U.S. and Russian segments have inadequate stowage volume. It was recognized early on that stowage would be an issue, but short of adding an on orbit “closet”, there was little that could be done. The buildup of supplies and items to be returned on the Shuttle for the last two years has exacerbated this problem. Photographs taken of the Space Station interior reveal that the crewmembers have stowed cargo in multiple layers on nearly every available surface. This is not only a living condition issue, but also potentially a safety issue. Shortly after the Expedition 7 crew arrived on Space Station, they reported that it took longer than expected to be able to access the fire ports in the equipment racks with portable fire extinguishers during a training drill. Upon closer inspection of the digital imagery provided by the crew, it was discovered that many key fire ports had been blocked by cargo bags. All of the bags in critical areas had to be relocated into areas that did not block fire ports or translation paths. Even when not a safety issue, the large volume of cargo to be stowed can create an excessive crew workload. Crewmembers have to move cargo to access equipment and additional stowage behind rack faces. The pressurized mating adapter that the Space Shuttle docks to is filled with cargo that must be relocated before a docking is possible. And both the Russian and U.S. airlocks are completely filled with cargo bags that must be moved prior to an EVA.

## J. Value of the Human

We need to use the human component for what we are best at – solving problems. As we have been forced to expand crew servicing and repair of equipment on orbit we have relearned a valuable lesson. The ground personnel and crew as a team are much more capable to overcome adversity and problems than we had planned into our system design. With the limited resupply of parts to the Space Station many are coming to accept, and rely on, the fact that the greatest benefit of humans on board spacecraft is their unique ability to deal with the unknown. History has repeatedly shown that mission success and reliability are improved with humans in the loop since they can respond to hardware failures and unanticipated natural events using both preplanned procedures, and when necessary, innovation. This knowledge should be used in the design of future systems. We have seen this concept continually repeated in the Space Station as crews have effectively dealt with hardware problems ranging from laptops to exercise equipment to EVA suits. All hardware for exploration systems should be designed with human operations and maintenance in mind.

## VII. International Partnerships

The Space Station is internationally designed, managed, supported, and operated. Both advantages and disadvantages come with an international partnership. Clearly, without our Russian partners being able to provide crew and cargo launch services, we would have had to abandon the Space Station after the *Columbia* accident. Partnerships obviously bring additional resources and assets to the design, development, assembly, and operation of a large space-based architecture like the ISS. As demonstrated in the hardware and EVA discussions, there can be benefits to different design philosophies and unlike system redundancies.

But an international partnership is also hard work, and there are hurdles that have to be overcome. Throughout the life cycle of the Space Station we have seen differences in not only design, but also in training, language, operations, management, and safety approaches. Some of these differences have created tension between the partners and have been difficult to work through. Some have created burdens on the crewmembers, flight controllers, engineers, and managers.

One of the obvious differences is that the Space Station is functionally a dual language facility. English is the official language of the ISS, however, the realities of the current Space Station is that it is dual language. As a result, crewmembers must become near fluent in two languages, Russian and English. Their systems training is in two languages, they must be able to perform procedures written in either language, and speak to the different control centers in the two languages. It requires a significant investment in training time for the crewmembers not only to learn the technical aspects of the Space Station, but also to learn an additional language, and space flight culture.

There have been times when one partner's control center approves or performs some action with which the other partner does not concur. While there has been no occurrence of a crewmember or hardware being harmed as a result of these actions, there have been violations of the established safety boundaries and/or rules of a partner. One example was during an Expedition 9 Russian segment EVA when the Russian control center directed the crew to dispose of excess hardware by jettisoning it instead of bringing the hardware inside the Space Station. NASA does not agree with jettisoning hardware if there are other options due to the potential of it becoming hazardous orbital debris. The jettison of the hardware was not coordinated before the space walk. A second example occurred during Expedition 7 when the Russian control center directed the crew to recharge a cellular telephone battery. NASA was still working to resolve several potential safety issues with the recharging process and had not yet approved the procedure. This telephone was newly considered critical rescue hardware for the Soyuz after the delay in locating the Expedition 6 crew when they landed at the ballistic landing site instead of the planned landing site. In a similar vein, NASA performed preflight vibration testing of replacement telephone batteries to a level that the Russian engineers considered could actually induce rather than identify potential problems. The Russians declined to fly these batteries on the Progress cargo vehicle. Probably the most public partnership conflict was over the flight of a tourist to ISS on a Russian Soyuz vehicle.<sup>2</sup> This philosophical disagreement at the highest levels of space program management was not resolved until the second tourist flight. Despite these examples, we have seen remarkable cooperation between diverse partners and with each disagreement we learn better how to work together.

Significant time and investments have been made by the ISS partnership in multinational negotiations and integration, both during the development phase, and now in the assembly phase. Daily discussion, negotiation, and coordination are required, and occur, to ensure the safe and continued operation of the Space Station. Multilateral decision and control boards are established, and meet at a frequency commensurate with the issues they are discussing. For example, the ISS Mission Management Team conducts a multilateral teleconference with all partners twice a week, with additional bilateral teleconferences as required. Other control boards, such as the Multilateral Mission Integration and Operations Control Board meet monthly to discuss requirements, operational processes, manifests, etc.

There are several significant recommendations based on observations from the history of international partnership activities of the Space Station to date. The ISS Program planned some of these, and some have become apparent as assembly and operations mature. The following should be incorporated in future exploration partnerships:

- A single management entity that is the senior partner with the authority to make binding decisions that all partners will respect and abide by.
- A single partner that performs the function of the lead integrator, with full technical and operational insight into all systems and hardware flown to the Space Station.
- A single lead operations center that is responsible for determining the operational course of action when differences occur.
- A single lead operational center that oversees the daily work and operations on the entire Space Station, thereby eliminating national boundaries between the crew and the segments.

- A single operational integration lead that ensures the Space Station operates within a framework that balances the available resources with all partner's national priorities, goals, and requirements to ensure interests are fairly addressed.
- A single agreed to set of mission requirements and guidelines.
- A single agreed to set of standards to certify hardware for use in the entire Space Station, and not a segment-by-segment approach.
- A single agreed to approach towards crew, vehicle, and mission safety.

Any international program needs time and effort initially invested to arrive at common approaches in as many areas as possible. These areas include management, integration, operations, software approach, hardware approach, certification, and safety. It should also be noted that there are a variety of approaches that can satisfy the approach toward a partnership. The responsibility of leadership can rest with a single partner, be shared among several partners with very clearly agreed-to authorities, or even rotated between partners as the program enters different phases or levels of maturity. A international partnership can be successful, rewarding, and achieve the goals that each brought into the arrangement.

### VIII. The Future

We are ever increasing our understanding of the requirements for the design, robustness, and maintainability of hardware, and how to increase the life cycles of that hardware. We are gaining an understanding of the human body that is exposed to long duration space flight. We are shifting our research priorities to better focus on using the Space Station as a test bed for future spacecraft leading toward expanded space exploration. We are gaining insight into the types of problems that can develop in round-the-clock operations. And we are validating the importance of the human in the total system integration of future space exploration hardware design. The lessons we have learned through the years of ISS partnership will be extremely valuable to other programs in the future of exploration of our solar system.

Continued operation and research on the Space Station will allow us to demonstrate enabling capabilities and technologies for exploration in areas such as exercise hardware, environmental monitoring, power generation, propulsion, avionics, and life support. We are building a knowledge infrastructure that will support the design decisions of the future exploration vehicles. The hardware and systems we design and test today are the heritage of the hardware required for tomorrow.

The new millennium promises unsurpassed accomplishments – and challenges – in the field of human space exploration, and we are learning valuable lessons from our past and present to apply toward our future.

### References

<sup>1</sup>Sanchez, M. J., "Keeping the International Space Station Flying: The Challenge Without Shuttles," AIAA Aerospace Sciences Meeting Paper AIAA-2004-0274, Jan. 2004.

<sup>2</sup>Sanchez, M. J., "International Space Station Program Increment 2 Overview Report," NASA SP-2004-55, S937, 2004 (to be published).

<sup>3</sup>Kitmacher, G. H., Gerstenmaier, W. H., Bartoe, J. F., Mustachio, N., "The International Space Station: A Pathway to the Future," *International Astronautical Congress*, Oct. 2004.

<sup>4</sup>Sanchez, M. J., "Post Increment Evaluation Report, Increment 2," NASA SSP 54302, Dec. 2002.

<sup>5</sup>Sanchez, M. J., "A Human Factors Evaluation of a Methodology For Pressurized Crew Module Acceptability for Zero-Gravity Ingress of Spacecraft," Ph.D. Dissertation, Industrial Engineering Dept., University of Houston, Houston, TX, Dec. 1999.

<sup>6</sup>Johnston, S L., Flight Surgeon, NASA Johnson Space Center, personal communication (1999).