Furthering Exploration – International Space Station Experience

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The International Space Station (ISS) is instrumental to the exploration of space. As we expand human presence from earth orbit, in the next decade to the Moon, and later, to Mars and beyond, we will face challenges in management; integration; remote, long duration, assembly and maintenance operations; science and engineering; and international culture and relationships. The ISS program has provided critical insight and amassed new knowledge in all of these areas.

The National Aeronautics and Space Administration (NASA) is at a critical juncture at this time, establishing the Exploration Program as ISS operations and assembly continue. Use of the expertise gained in the ISS Program can reduce risks in the Exploration Program. This paper discusses the applicability of the ISS experience to the Vision for Space Exploration, specifically in the areas of crew operations, spacecraft systems operations, and crew-system interface operations.

I. Introduction – the Vision for Space Exploration

On January 14, 2004, President Bush announced the Vision for Space Exploration (VSE). It establishes a course that expands the human presence beyond the earth - first, in near-Earth orbit on the ISS; then in the next decade, to the Moon; and later, to Mars and beyond. NASA has unveiled plans for the next generation spacecraft, the Crew Exploration Vehicle (CEV).

Completing assembly of the ISS by the end of the decade, and fulfilling commitments to the International Partners, is a crucial first step in human exploration. NASA has re-focused ISS research to meet the VSE requirements. As humans venture further from Earth, and as program timetables and mission logistics increase in time, distance and complexity, it will be crucial to have crews and vehicles that can be sustained with greater reliability in the harsh rigors of space. The <u>new</u> ISS mission objectives corresponding directly to these Agency needs are summarized as follows:

1. Develop, test and evaluate biomedical protocols to ensure human health and performance on long-duration space missions
2. Develop, test and evaluate systems to ensure readiness for long-duration space missions
3. Develop, demonstrate and validate operational practices and procedures for long-duration space missions

Are these real, defined somewhere ?

II. The International Space Station Experience

The International Space Station is a technological undertaking of global scope. Elements of the ISS are provided and operated by an international partnership of governments and their contractors. The principals are the space agencies of the United States, Russia, Europe, Japan, and Canada.

The ISS has been continuously crewed for more than five years and is about 50% complete with approximately 180 metric tons of mass on orbit. There are 15 elements in orbit today, 9 elements ready for launch at the Kennedy Space Center in Florida, and 7 elements in process at International Partner sites. When assembly is complete, the

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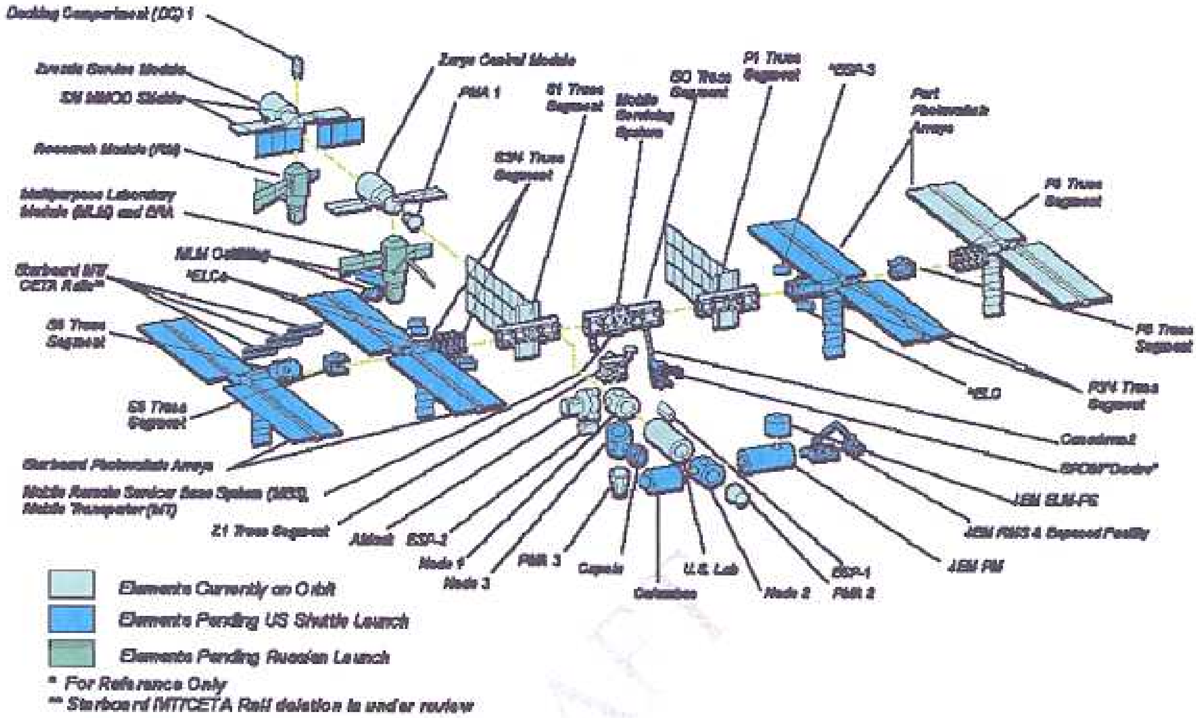
ISS will be comprised of nearly a million pounds of hardware, orbited in about 40 separate launch packages over the course of more a decade. To date, there have been over 50 flights to the ISS, including flights for assembly, resupply, and logistical support.



NASA will use the Space Shuttle, prior to its retirement in 2010, to complete the ISS assembly. Assembly priorities are to:

- Complete the truss segments.
- Establish the life support, thermal control and power systems that can sustain the assembly complete station.
- Attach the International Partner elements, including the Japanese Experiment Module (JEM), the European Columbus Module and the Canadian DEXTRE robotic manipulator.
- Provide the logistics to sustain the ISS.

The final ISS configuration will support growth to six crewmembers in 2009 with the delivery of additional crew quarters, galley and waste management systems. During this period, the Russian Progress vehicle will be used to augment Space Shuttle capacity and fill expected logistics shortfalls and the Russian Soyuz vehicle will be used for some crew rotations. Need to keep in mind Soyuz launch vechicle that carries Progress & Soyuz

Once the Shuttle is retired in late 2010, NASA and its International Partners will use a combination of their collective assets to support and maintain the ISS in orbit. The Russian Soyuz can be used to carry crew while the Russian Progress, European Automated Transfer Vehicle (ATV) and Japanese H-II Transport Vehicle (HTV) will be used to share the burden of logistics support. NASA is also seeking a commercial provider to supply logistics and crew transport to the ISS. Within two to four years after the Space Shuttle's last flight, the new NASA Crew Exploration Vehicle should be ready to support flights to and from the ISS.

The International Space Station Program has endured now for 22 years – a full generation of technical expertise that has designed, developed, operated and managed the Program. ISS personnel have successfully adapted to changing circumstances, whether driven by technical or operational difficulties, transportation shortfalls, budgetary considerations, or political redirections. This has included several major redesigns of the ISS vehicle, as well as major changes in ISS operations. For example, challenges in returning the Shuttle to flight over the last few years have taught ISS engineers and scientists how to deal with logistics shortfalls and to adapt the ISS research to new operations realities. Because of changing in up and down mass capability.

The Exploration program will not likely be completed within the lifetimes of the personnel now establishing it. The personnel who will implement the Mars landing may not yet have begun their careers. Through the experience of the ISS Program, personnel are developing the experience, knowledge and skills to overcome the inevitable contingencies that will arise in the Exploration Program. (Separate thoughts, not merged well)

As we expand human presence beyond the Earth, first in orbit, in the next decade to the Moon, and later, to Mars and beyond, the International Space Station experience will help to guide and serve as a measure of our success in Exploration. (How so?)

III. Areas of Applicability to the Exploration Program

Through the ISS Program, NASA and its Partners have acquired experience in building and operating complex space vehicles. The ISS has been a tremendous challenge of integrating the hardware, computer software, command and control interfaces, crew procedures, logistics, ground support teams, research, and so on, with the added dimension of dealing with 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.

Perhaps as significant as the technological sophistication is the complexity of the multinational and multi-organizational elements involved. The ISS has been the most politically and technically complex space exploration program ever undertaken. INTERNATIONAL PROJECT It involves multiple aerospace corporations and nearly every international space agency working as program partners. Further, it manages international flight crews, multiple launch vehicles, globally distributed launch/operations/training/engineering (or development) facilities, communications networks, and the international scientific research community. Here talk about hardware meeting one another for the first time, difficulty in meeting interfaces

The ISS Program's greatest accomplishment is as much a human achievement as it is technological in nature – how best to plan, coordinate, and monitor the multitudinous (?) and varied activities of the program's many organizations. Getting all of the personnel elements to effectively work together has been a continuing challenge for the program management, regardless of whether they were from the US or other nations, the various NASA centers, or civil service or industry. The various communities often have differing priorities and compete for the same resources. The Program has succeeded by developing management processes which address the needs and constraints of the various organizational elements. Roles/responsibilities and interfaces were negotiated and documented. Control boards, reviews, documentation, procedures, and information systems were designed to facilitate program management and coordination. These ISS operations management processes and tools have continually evolved to accommodate changing needs, to address problem areas, and to take advantage of potential efficiencies. Some examples are given below.

The ISS Program provides valuable lessons for current and future engineers and managers. ISS provides real world examples of what works and what does not work in space.

Specific operational areas in which the ISS experience can be applied to the VSE include: *Crew Operations*, *Spacecraft Systems Operations*, and *Crew-System Interface Operations*.

A. Crew Operations

High performing crews are critical to successful long duration missions. Mission failures can result from degradation of human performance, either physiologically or psychologically, after long duration exposure to the space environment and to the stress of isolation. Specialized skills and training of international crew members, as well as advanced protocols, procedures and tools were developed for the ISS and can be used to reduce the risks to future exploration missions.

The interaction of the crew with mission control is also a significant element that can make a space mission highly successful or bring work to a standstill. The ISS provides an environment to improve the interaction between crew and ground and make missions safer and more effective. Working for months with crew members from other countries and cultures is an important aspect of the ISS program. Developing methods to work with our partners on the ground and in space is critical to providing innovative solutions to operations challenges.

1. Long Duration Crew Operations

By necessity, the ISS Program adopted crew operations philosophies and support tools that are conducive to long duration operations.

If the crew had a big input into the plan, there is a lot of pride of ownership

Unlike rigidly scheduled short duration missions, long duration crew schedules must be carefully balanced to provide dedicated work time in addition to crewmember time for exercise, hygiene, rest and sleep, and personal time. The number of tasks required to be performed according to a predefined schedule has been minimized; the crew has the flexibility to execute other routine, non-critical, and non-hazardous tasks from a pre-defined "task list". The increased scheduling flexibility permits the crew to better manage their own activities and time. This makes work on the Space Station more Earth-like, providing the crew more autonomy, a heightened sense of professionalism, and greater enjoyment and an enhanced feeling of accomplishment. It has also frequently been beneficial in terms of the quantity of work performed.

Planned daily conferences at the start of each workday permit flight and ground crews to identify tasks requiring attention, and at the end of each workday, to identify tasks that have been completed. This allows the ground to track the progress throughout the mission while keeping unnecessary communications to a minimum.

Because current versions of paper crew procedures and flight plans cannot be maintained onboard, the Program implemented software systems to electronically view and manage this information. Any needed updates to the procedures are made on the ground then uploaded to the ISS for immediate access by the crew. The onboard crew also has an electronic version of the ISS flight plan. Capabilities are provided for the crew to make annotations on their planned activities and to perform some limited plan editing. Updates to the crew flight plan are uploaded on a daily basis.

The extent of crew-controlled task scheduling and the degree of crew autonomy will become more critical as missions become longer, as missions take place at greater distances, and as the potential for any interruption in communications grows. The Exploration crews will build on the ISS experience with task scheduling and will need even more robust capabilities to manage their flight plans. The ISS has been a cornerstone in advancing knowledge about how to live and work in space for long, continuous periods of time and will remain critical to our future exploratory journeys.

2. Crew Training

The international ISS crew must be trained in both nominal and off-nominal operations. This requires general training on the onboard hardware and systems as well as specific training on the procedures to be performed. Effective training is essential since the crews may be required to control/restore systems in the event of automated systems failures, loss of communications with the ground controllers, or other malfunctions/emergencies. In some instances, ISS systems were designed to an unnecessary level of complexity, or the design and operation of a system was incompletely documented. This has sometimes limited the ability of ISS crewmembers to completely understand or deal with contingencies.

Skill vs task should be discussed here

TVIS should be here

The Crew On-Orbit Support System, developed initially for use on Mir, provides on-board training capability for the flight crew. A library of software provides lessons covering many systems and critical operations and is available for crew use and review. The ability to effectively train on-board will be a key to future exploration missions. For long duration missions, "refresher" training is especially important prior to complex, critical, or hazardous operations, since the crew's training on the operation may have been months before.

The international nature of the ISS necessitated a training program that is geographically distributed. Each Partner is responsible for training the crew on the operations of their elements/systems. There are, therefore, training facilities in the US, Russia, Europe, Japan, and Canada. Scientific equipment training further widens the distributed nature of the training requirements. This adds overhead and complexity to the training schedule, which, if not effectively managed, can result in crew fatigue prior to launch.

The ISS experience has shown that US and Russian training methods for flight crew and ground personnel differ considerably. US training focuses more on specific task and procedural training while Russian training focuses on overall understanding of design functionality and operations of systems. Advantages can be seen in both approaches. Generic training on system design and functionality provides a knowledge base which the crew can use when dealing with unforeseen events, while specific task training is beneficial for very complex or hazardous operations.

ISS training requires significant investment in resources and facilities due to the complexity of the spacecraft systems and mission requirements. For the ISS, the multinational hardware components drive multinational training locations. A two year or longer training regimen is required by each long duration crew. For the Exploration Program, the systems and mission needs will be even more complex, resulting in even more extensive training requirements.

3. Extravehicular Activity (EVA) Operations

To date, there have been 28 Space Shuttle-based and 36 Space Station-based EVAs at the Space Station, totaling over 385 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, repairs, and science. These tasks were conducted from three different airlocks using two different styles of space suits, the US Extravehicular Mobility Unit (EMU) and the Russian Orlan suit.

Spell out the airlocks, Shuttle, ISS Joint , Russian

Talk about RPCM change out and repair – Russian suits on US segment and two different control teams leading depending on when/where-two systems hardware, procedures,m controllers all working together to solve one issue

One major lesson the ISS Program learned is the importance of designing EVA equipment for longer lifetimes, with the capability to perform on-orbit maintenance. The EMUs are normally planned to be returned to earth on the Shuttle for servicing. During the Shuttle down time after the Columbia accident, two of the three EMU suits on orbit, as well as the US Joint Airlock, experienced technical issues that prevented their use in a spacewalk. Root cause of the loss was contaminants in the suit and airlock coolant water that blocked filters and disrupted magnetic coupling of the suit pump rotor. Water pump rotors also de-bonded over time. The Russian Airlock and Orlan suits were relied upon to conduct ISS EVAs during this period. But through the ingenuity of the engineers on the ground, and the skills of the crew on-orbit, the EMUs were repaired on-orbit and made serviceable should there be a need to use them. However, a plan for re-certification of hardware while in space was never established, so nominal use of the suit was not planned. Nevertheless, 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 EMU cooling pump impellers on orbit with no training and limited tool selection. US EVA capability on the ISS has now been fully restored. The two EMUs were replaced during the July 2005 Shuttle flight, and the third unit is scheduled for replacement on an upcoming flight. A filter/iodinization kit delivered by the Shuttle was successfully used to complete airlock restoration and will continue to be used in the future to assure EVA readiness. The Exploration Program must avoid design features that are prone to failure in long duration flights, and plan for on-orbit repair and servicing of its EVA equipment.

The ISS experience with EVA training is also highly applicable to other long-duration missions, such as a Shuttle task training was ~ 10 hrs / hr in-flight and for general skills they tare trying to get to a lower number ??journey to Mars. The Space Shuttle EVA training philosophy has been to train crewmembers on the specific tasks to be accomplished, in the specific order they would be performed. A Space Shuttle-based EVA is a well-practiced and carefully orchestrated ballet, where everyone knows his or her part by rote. ISS 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 ISS expedition crews for EVAs. In order to most efficiently use the available preflight crew time and training resources a different philosophy has evolved 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 (prepares) 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 repeatedly shown its value during several unplanned EVA tasks that were required to replace failed external hardware on the ISS.

Preflight EVA training is augmented with on-orbit training. Each EVA is preceded by a training session, in which the EVA crewmembers review their procedures and practice the EVA, including donning/doffing of the suits. These sessions can be used to train the crew on-the-fly for EVA tasks that were not planned preflight.

It should be noted that each EVA requires a significant amount of crew time in addition to the actual EVA. Besides the preflight and on-orbit training requirements, numerous operations must occur immediately before and after an EVA, including preparing the airlock, inspecting the suits, pre-breathe protocol procedures, servicing the suit after an EVA, and closing out the airlock. This additional overhead should be considered when defining EVA requirements and strategies for the Exploration Program.

As ISS crew size was reduced from 3 to 2 in the wake of the Columbia accident and the resulting reductions in logistics capabilities without the Shuttle, EVAs have become two person operations during which there is no one in addition to [preparing the Station for the EVA, the station must be prepared to be left unmanned in case crew could not get back in remaining inside. This kind of operation is not new to either the US or Russia. During the Apollo moon landings the crew worked on the moon's surface while ground controllers monitored the spacecraft systems. During Salyut and Mir, Russian cosmonauts routinely left the spacecraft without a crew during spacewalks. On ISS, when three people were available, EVAs were planned to have a crew member inside support the EVA; but with only two crew, necessity required that systems monitoring and some spacecraft operations be turned over to mission control. This mode of operation is possible as long as the ground has the ability to command and control the vehicle while the crew is outside.

Exploration missions will require a new EVA suit, more appropriate to the environments on the Moon and Mars. However, the operational lessons of the ISS, e.g., in the areas of EVA suit maintainability, training and shelf-life, will be even more critical for long duration exploratory missions which venture even further from the Earth.

B. Spacecraft Systems Operations

Efficient, reliable spacecraft systems are critical to reducing crew and mission risks. Optimizing systems performance and characterizing system performance in space will reduce mission risks and advance capabilities in long distance and autonomous vehicle and systems management.

Demonstrating and developing confidence in systems for water and waste recovery, oxygen generation, and environmental monitoring technologies are important as the distance and time away from Earth is extended. The ISS is NASA's closed loop life support test bed for demonstrating these advanced capabilities in the space environment. Maintaining crew health is key for long duration flights and ISS provides demonstration and continuous operation of the systems that support this health maintenance function. Already, much has been learned about developing exercise equipment and its effectiveness for maintaining crew fitness in zero-g. More must be learned before long duration missions on the Moon or to Mars are attempted.

Operations protocols and support tools which minimize the ground support infrastructure needed to monitor and control spacecraft systems are also essential for long duration missions. The ISS operations concepts and ground facilities continue to evolve due to ongoing efforts to minimize operations costs.

1. System Design for Long-term Operations

The US and Russia evolved different approaches to system design and operations. The ISS experience has shown that, for long term operations, there are advantages and disadvantages to both approaches.

The Russian modules and systems of ISS are essentially identical to those used in the Russian Mir Station and were developed beginning with the Salyut designs of the early 1970s. Russian design philosophy embraces simplicity and robustness. Many of the systems, however, require frequent crew interaction for maintenance and operation. The systems are usually reliable and easy to operate and, when maintenance is required, permit crew access and interaction. Emphasis is placed on operability and functionality, but the minimal telemetry means that systems unexpectedly malfunction before corrective measures are planned (confused wording). The on-orbit crew is expected to operate with a level of independence from the ground that also requires the crew to take on the responsibility to ensure the systems remain operational. Russian system reliability is based on periodic maintenance and component replacement.

Most of the US modules and systems now part of ISS have little heritage from prior spaceflight programs. The US systems tend to be more complex than their Russian counterparts. The US systems provide considerable data to flight controllers via telemetry. This allows the crew to rely on the flight control team to monitor the performance of the systems. Frequently ground controllers have more data than the on-board crew and they may have more control than the on-board crew. Most of the US systems are integrated with digital controllers. This permits a high degree of automation, but this also means the systems may not operate at all unless computers and software operate without any problems. Even turning on or off the lights is controlled through a computer command.

The risk of relying too heavily on this philosophy was demonstrated early in the program when the US Laboratory module was attached to the station. Initially all of the command computers in the US Laboratory failed resulting in the loss of critical control functions and communications. The Space Shuttle was able to provide critical communications until the Node computers could be used to restore the Laboratory computers, thereby regaining control of the US segment. The Russian segment was able to provide all critical functions so neither the crew nor the station was in any danger.

Laptop computers are used as the crew interface to the Data Management System (DMS). This had not even been conceived at the time the ISS DMS was first defined. But the use of laptops has permitted phased upgrading of the hardware by replacement with new models as they are developed and certified.

The maintenance of avionics software on ISS has been another success story. The software upgrade process was originally launch-driven, with software upgrades sent up in batches on Shuttle flights. After the Columbia accident, the process was changed to allow periodic uploads of software patches to the ISS. Virtually all of the Space Station's US and Russian software has been upgraded at least once since the Columbia accident in February 2003. The new process has shown several advantages over the original process. Because the software staffing plan is more level, the team can live within budget allocations. In addition, the number of software bugs gets continuously reduced in a steady process, allowing the operations organization to remove workarounds in procedures at a predicable rate. Many of the workarounds identified for software issues at the time of the Columbia accident were eliminated via telemetered software patches, even with no access to the ISS via the Space Shuttle (confused wording/intent).

2. Habitation and Life Support

The ISS is demonstrating the importance of habitability in sustaining crews and spacecraft operations over the long time periods that will be critical for lunar/planetary habitats and Mars transit vehicles. Habitability is important for making the crew habitat livable, for maintaining crew health, and feelings of well-being. Inadequate attention to habitability presents serious mission and safety risk.

In the case of the ISS, volumetric requirements for hardware and provisions stowage were addressed early in the program. However, as a cost savings measure, the primary on-orbit stowage module was eliminated. Cargo is now stowed in multiple layers on nearly every available surface. The interior of the US modules was designed to permit racks to be swung rapidly away from the module pressure shell in the case of micrometeorite punctures. Stowage and other deployed hardware now blocks the racks and inhibit access. Use of manually operated fire extinguishers is a planned means of fighting fires, but stowage blocks access to fire ports. Program has been mindful to take corrective measures and maintain access Stowage usually occupies the volume of modules that are used less frequently, such as the US and Russian Airlocks and the Pressurized Mating Adapter to which the Shuttle docks. This incurs a penalty in terms of normal accessibility, difficulty in locating hardware and provisions, and increased crew time required to locate, unpack and repack stowage areas. Stowage issues need new solutions on long duration missions.

Noise levels were a concern from the outset of the ISS program, beginning with requirements definition. Inadequate attention in the design and development stages and, in some cases, use of decades-old technologies, led to a noisy environment in which personal hearing protection for the crew has become the norm. The noisy environment makes it difficult for crews to communicate with one another and with the ground and can cause safety hazards when alarms cannot be heard. As systems are replaced, this noise problem is being reduced, but on long distance missions upgrades are not an option.

Reliable operation of the life support systems in human spacecraft is critical and will become much more significant as crews and spacecraft become much more distant in time and space from their logistics source on earth. The US and Russia used different hardware design reliability philosophies. As previously noted, the Russian designs evolved over the course of the Salyut and Mir programs in the 1970s and 1980s. The Russian systems are made of modular, standalone hardware. Though these components endure periodic failures and anomalies that reduce performance, frequent, simple maintenance can keep the systems operating, and when there are more significant problems, replacement components or assemblies can be launched on Progress logistics missions. The US systems were designed independently from the Russian systems, are more complex, experienced different operational failure modes and required varied maintenance and repair solutions..

The Russian "Elektron" system, for example, has been the primary generator of oxygen onboard ISS. Its major component, the "Liquid Unit" generates breathing oxygen by electrolysis of water recovered from the cabin air and separation into oxygen and hydrogen. A series of failures of the fluid micropumps, caused by air bubbles and contaminants in the fluid lines, occurred during the Shuttle down period. The failures necessitated the change-out of three Liquid Units in succession, and then considerable hands-on maintenance by the crewmembers in order to maintain partial operability. The Russian backup system, the solid-fuel oxygen generators (SFOGs), was also pressed into service. Another back-up capability is provided by US and Russian EVA bottled oxygen. Replacing these Liquid Units creates severe manifesting problems on Progress resupply missions.

The Carbon Dioxide Removal Assembly (CDRA), in the US segment, processes the cabin air to remove carbon dioxide, as does the Vozdukh system in the Russian segment. Failure of the desiccant containment, valve contamination and corrosion resulted in some partial failures of the CDRA. However, by using new and innovative cleaning processes and by prepositioning key spare components the system was maintained throughout the Shuttle down period. The advantage of having two totally different designs, one US and one Russian, for CO2 removal was evidenced during this time.

In the wake of the Columbia accident, as logistics constrained the number of environmental samples being returned from ISS, environmental monitoring systems, such as the Major Constituents Analyzer (MCA) have had to be used less frequently and for only the most critical measurements. When the Volatile Organics Analyzer (VOA) failed, the US and Russia shared returned air samples for analysis and monitoring of the cabin atmosphere. In order to reduce the number of environmental samples being returned, the crew performed previously unplanned microbiological measurements in-situ to verify water quality.

When either a US or Russian component has failed, the other country's system has always been relied upon for support. Despite the failures, the two independent systems have proven complementary and have maintained a safe, breathable atmosphere and a potable water supply. Dissimilar redundancy should be a strong consideration for Exploration systems. Really significant and major point this is one of the top 3 lessons from ISS

Probably need a summary section that identifies the big points

Other systems also demonstrate the philosophical differences. The US provided health maintenance and exercise hardware is technically sophisticated, with vibration isolation and exercise performance monitoring systems, and provides excellent human and hardware performance data to the ground physicians and engineers. But the hardware was under-designed and inadequately tested prior to flight and failures were seen soon after the first crew took up residence on-board. The Russian provided equipment is simpler and has limited monitoring or downlink capability, but it is specifically designed for simplicity, robustness, and on-orbit repair.

The sophisticated US exercise hardware was not designed for on-orbit maintenance. At the outset, entire systems were designed for periodic return to earth and replacement with new systems launched on the Space Shuttle. However, the failed components are frequently small and on-orbit crews have learned to maintain the systems in orbit. The Resistive Exercise Device (RED) and the Treadmill required maintenance through crew replacement of much smaller components than had ever been planned for repair in orbit. The maintenance operations necessitated some special zero-g considerations. For instance, the large gyroscope and flywheel of the Treadmill Vibration Isolation System (TVIS) had to be disassembled from the treadmill assembly. The Vibration Isolation and Stabilization (VIS) system isolates the TVIS from the ISS structure, enabling crewmembers to run without transferring vibrations to the station or to sensitive experiments. On the ground this maintenance procedure is done on a workbench in a tightly controlled environment and with components resting on specially cleaned workbenches and with specially built restraints. But in orbit, magnetic forces pushed apart the components, and caused the components to fly away from one another. The crewmembers had to physically restrain the components and use considerable force to overcome magnetic forces during reassembly and disassembly.

The increased on-orbit maintenance requirements and its sometimes unexpected difficulty have enhanced our knowledge of the kinds of operations astronauts can be relied upon to perform during long duration exploration missions and they have reduced the launch mass required to support maintenance.

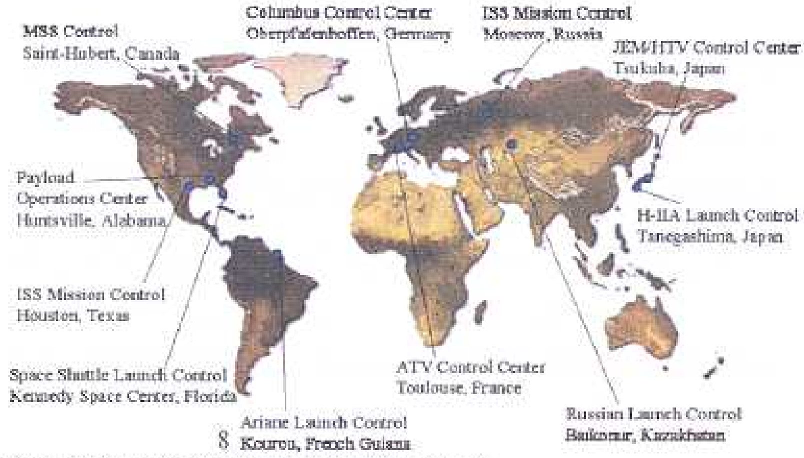
3. *Spacecraft Operations and Ground Support*

One of the big challenges for long duration missions is the design of the ground support infrastructure needed to monitor and control the spacecraft systems.

Control center transfers like for hurricanes, where we transferred capability and responsibility to Russia

Because the ISS is an international program, it faces unusual complexities in the area of real-time flight operations. Operations functions for ISS have been decentralized, with each Partner taking on significant roles relating primarily to the hardware/systems they have developed. Over time, as the ISS has moved into its operational phase, interdependencies have increased and they will do so to an even greater extent in the future.

Real-time operations and control of the ISS is geographically distributed across countries and International Partners. Each Partner will eventually have an operations control center participating in flight operations, in addition to a launch control center for its transportation elements. Currently there are three control centers operating 24 hours/day, seven days/week supporting ISS: the Johnson Space Center (JSC) Mission Control Center (MCC) in Houston, Texas, MCC-Moscow, and the Payload Operations and Integration Center (POIC) located at Marshall Space Flight Center (MSFC) in Huntsville, Alabama. The Mobile Servicing System (MSS) Operations Complex in Saint-Hubert, Quebec, supports operations of the Canadian robotics systems. The Columbus Control Center in Oberpfafenhoffen, Germany, and the JEM Control Center in Tsukuba, Japan, will come on line when the European and Japanese elements are launched. The control centers are interconnected, and each has its own unique functions and responsibilities. They are not fully redundant. MCC-Houston and MCC-Moscow are responsible for the US and Russian segments of the ISS, respectively. The POIC is responsible for NASA payload operations, and generally falls under the authority of MCC-Houston. In addition to these prime control centers, there are



also a variety of smaller operations centers supporting the research community.

Flight operations concepts must accommodate the additional interfaces, complexities, and coordination that are introduced with multiple flight operations centers. New tools had to be developed to facilitate distributed planning and operations information distribution. Cooperative software development and sharing of software tools across NASA centers and Partners, where feasible, is being used to reduce overall ground development costs.

Long duration, round-the-clock operations require a different approach than is used for short duration missions such as the Space Shuttle. A prime consideration is the need to minimize overall costs for the ground support facilities and flight control teams. Because of continued budget pressures, the ISS Program has attempted to reduce mission operations costs wherever possible, without sacrificing safety. Efficiencies have been realized in both the ground support facilities and the flight control teams.

Reductions in the number of flight control personnel have been achieved by adopting different operational paradigms. Have one FD and a couple flt controllers – is there a name for this ?? For example, one strategy is to train flight controllers to be proficient in more than one system in order to reduce manpower requirements and workload induced burnout. NASA has successfully initiated this approach, and it is possible that more streamlining can be done in the future. The flight control team can also be reduced through increased automation for routine monitoring of spacecraft systems.

Another strategy is to reduce or simplify the "pre-mission" operations preparations activities that must be performed. A good example is the mission planning approach that has been adopted for the ISS. In contrast to the Space Shuttle Program, where detailed flight plans are developed long in advance of the flight, the ISS Program produces long term plans at a much less detailed level. These plans allocate flight activities to days, but do not assign specific times. The very detailed flight plans are not generated until a week or two before they are to be executed. The template for generating the long term plans has also been reduced. Initial concepts were to have three iterations of the plan. Over time, the Program has reduced the number of iterations, thus reducing the overall time and manpower required. Reductions in both the level of detail and the planning template have helped to minimize the manpower requirements for this activity.

Another prime consideration for flight control team staffing on a long-duration mission is the human factors aspect. Long periods with shift or weekend work can disrupt family life, cause personnel burnout and high turnover. A variety of strategies have been employed to minimize these impacts to the flight control teams, such as reducing support on the weekends and off-shifts. Some flight teams cycle personnel on and off console. During the periods when they are not performing shift work, these controllers cycle back into planning or other operations support activities. The ISS prime shift hours were even driven by the very real constraint of the Russian flight controllers to utilize the Moscow mass transportation system, which does not operate from late evening to early morning. The Exploration Program will face some of the same challenges.

The NASA ground support facilities continue to pursue reductions in sustaining costs, while increasing capabilities for the flight control teams. Both the MCC-Houston and the MSFC POIC have been migrating legacy hardware/software to readily available and cheaper desktop systems, and have created internet versions of many basic flight control tools (e.g., voice distribution systems, information systems for flight support). This not only reduces facility sustaining costs, but allows more and more operations to be performed away from the control centers. MSFC has created a suite of low cost tools, including the Telescience Resource Kit (TReK) and the Internet Voice Distribution System (IVODS), which enable US science users to remotely monitor and command their payloads from their home sites. Because of the progress made in these remote operations support tools, JSC MCC personnel were able to continue monitoring of ISS operations even after evacuating the MCC-Houston during recent hurricanes. Crew has gone crazy over use of IP phone-incorporating existing technology develop commercially and its win-win for everybody;

Through these experiences, the ISS Program has learned many valuable lessons in the areas of long term flight operations, ground facility/software development and distributed operations that will have applicability to the very complex and long-term Exploration missions.

- Crew personal family conferences, audio and video very important for psych support

C. Crew-System Interface Operations

Demonstration and validation of the human-machine interfaces will enable sustained spacecraft operations over long periods of time. Advances in crew and robotic operations, on orbit maintenance and repair, and in space assembly are essential to expand beyond low Earth orbit.

The Canadarm 2 robotic arm provides the ability to assemble large, massive ISS elements on-orbit. Ground control of certain robotic activities enables more efficient use of valuable crew time. Development of displays and control are important for future spacecraft systems' designs. Software tools, such as virtual reality, play a role in helping crews to practice EVA or robotic tasks before ever donning a spacesuit or powering up the robotic arm.

ISS also provides a real world laboratory for logistics and maintenance concepts for future spacecraft. ISS crews have had to demonstrate repair capabilities as an indirect result of the Columbia accident and the reduced flow of logistics for the ISS. Crews and their ground maintenance counterparts have devised unique solutions that have kept the ISS functioning despite logistic shortfalls. (repetitious of previous)

1. Systems Maintenance and Repair (repetitious, need to tie-in that this is an improved crew/system interface)

The ISS Program is demonstrating new capabilities to sustain spacecraft operations over long time periods which will be critical for lunar/planetary habitats and Mars transit vehicles.

The lifespan of hardware is frequently limited by performance and materials constraints. Hardware may be designed to remain in space without maintenance or replacement, designed for periodic maintenance or replacement, or designed with a specific certification lifespan. The ISS Program uses a combination of analysis, testing, and simulations to define life limits. System performance is being tracked to understand the degradation of the vehicle and systems over time.

As a result of the Shuttle loss and the resulting interruption of logistics support, all of these design features have been tested. Major challenges were posed by the limitations on size and mass of cargoes that could be launched to orbit, and by the inability to return failed hardware to the ground for failure analysis and refurbishment.

Control Moment Gyroscopes (CMG) maneuver the ISS, using naturally replenished solar-energy-generated electrical power to operate the motion control system, in addition to rocket engines burning fuel. The use of CMGs dramatically reduces the amount of propellant that must be re-supplied from the ground. The system consists of 4 CMGs, although only three are required for full operation and two CMG's can provide adequate control. When CMG #1 malfunctioned, the remainder of the CMG system could continue to maintain vehicle attitude control. When a second CMG shut down because a Remote Power Controller Module (RPCM) failed, planning for an EVA to change out the RPCM started immediately.

Sun slicer, solar array pointing unplanned new ops in order to conserve fuel…

The cause of the failure of the rotational bearing of CMG #1 could not be resolved through telemetry transmitted to the ground. During the Discovery return to flight mission, astronauts conducted an EVA to replace the failed CMG, getting the system back into fully operating condition. The failed CMG was returned to the ground for failure analysis. Significant crew time and stowage volume was required to maintain hardware that was not designed for on-orbit repair.

An example of a spare inconveniently stowed inside a module on ISS is the Bearing Motor and Roll Ring Module for a solar array. It is over 18 cubic feet in volume. After a solar array experienced several stalls in its rotation mechanism, shortly after the array was installed, the spare was launched. It was determined that it would be too difficult to install without the Space Shuttle docked and the Shuttle has not been available for three years. To date, the spare has been in storage for five years. While the original balky rotation mechanism continues to function, another lesson in maintenance planning for long duration missions. For an Exploration mission there will be limited stowage available for spares and no opportunity to return hardware for failure analysis, so appropriate performance and diagnostic data must be available to support insitu diagnosis and repair.

Maintenance tools must be available to the crew. Trades must optimize between complexity, automation, reliability, repair, and replacement. Factors that must be considered in the trade include crew training, crew time, stowage, logistics, costs and vehicle functionality. Modular systems with commonality maximized across hardware and systems may be the best choice. The ISS is an ideal testbed for new maintenance methodologies and tools.

2. Logistics and 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 US 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 to 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 the Russian hardware is designed for frequent maintenance. Critical US hardware had pre-positioned spares, but all other hardware was flown on an as needed basis. It was undesirable to preposition all hardware on the Space Station due to the limited stowage space available.

In the wake of the Columbia accident, the resupply of the ISS has depended primarily on a limited number of Progress cargo vehicles. Micromanagement of supplies to .1 l of consumption of water, pay much closer attention…This has prompted significant refining of our consumables rates, and reductions where possible. Out of necessity, 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 occupancy and operation of the ISS.

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. More water is recycled 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.

New lower drag profiles were developed 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, the program was able to maintain two crewmembers on orbit using only Progress cargo vehicles.

The potential resupply of some items forces operational, philosophical and hardware design trades. For example, should some food be grown to supplement the diet? How much trash and waste can be recycled? To what extent can you depend upon a closed loop regenerative water or oxygen life support system? Can clothes and soft goods packing or food packaging be made more efficient?

In the closed, stowage-challenged, and critical spares environment of the planetary spaceship, inventory management gains critical significance. The items available on-board, their stowed location, and their rate of use or lifespan must be tracked, forecast, and carefully planned. The computerized barcode inventory system used on the Space Station has been inefficient and has proven only as good as the discipline of the crewmembers. The importance of the function was brought home in late 2004 as crewmembers came close to running out of food; a situation which would have necessitated abandonment of the ISS. Did we really get that far ? Maybe says more than we need to. Perhaps, Radio-Frequency Identifier Devices (RFIDs) should be explored.

3. In-Space Assembly Operations

The size and complexity of the ISS presented a unique challenge to operations. The ISS at assembly complete will have a mass four times larger than any previous vehicle in orbit, and will be larger than a football field. The complexity, size and mass of the on-orbit vehicle prevented assembly of the ISS on the ground. Even using a heavy lift booster such as a Saturn V, many launch and assembly flights would be required, but with launch capacity restricted to Shuttle performance, a series of nearly fifty assembly flights was needed.

The ISS international partnership introduced new challenges because elements and modules were designed and built by various International Partners using their unique techniques and components in their respective countries. And ISS is being assembled over an extended period. Components are being designed and built now, and won't be in orbit until ten years after the launch of the first elements. Many of the components will have never seen one another on the ground.

The first time the elements, including those produced by International Partners, will be joined together and operated will be on orbit. The on-orbit construction of the ISS, starting from an initial single module, to the assembly complete configuration, will take over a decade; however, the ISS was required to be operational during all phases of construction. The ISS configuration is continually changing because of additional elements being added and vehicles arriving, becoming part of the configuration, and then departing. Once installed, physical access to components is sometimes restricted or not available and on-orbit troubleshooting, if necessary, can prove difficult. The ISS is the first major human space system that was designed to be assembled, integrated and operated in space by people, and only in space.

Maybe some of this needs to go up into the international significance

Might also talk about research being done even during assembly

For the design of such a complex system, of paramount importance was to have complete understanding of the operations requirements throughout the life of the Program. Often, this phase is "short changed" because of schedule and resource pressure or lack of experience on the part of the designer. For the ISS Program, experienced engineers were allowed sufficient time and effort to analyze and understand the performance that would be required during the life of the Program. Potential candidates were investigated and the merits of each debated at length, and in some cases preliminary analysis performed, before a design was selected. The importance of this effort cannot be overly emphasized.

The ISS design concept changed several times during the definition phase of the Program. Together with the extended period of assembly and the complexities and inevitable problems that could occur over the assembly period, it was recognized that the ISS would need to be able to accommodate unforeseen changes.

The design required that control and operation of various systems and subsystems were distributed throughout the ISS. The system has several tiers of modularity, at the component level, at the rack level, and at the module or element level. The US Segment of the ISS benefited from the establishment and adherence to this fundamental architectural principle. This most fundamental principle addressed hardware change-out and maintainability but required a system that was assemble-able.

As configurations and launch sequence planning have changed over the years, the modularity of the ISS architecture in the US elements has proven critical. Modular racks with standard interfaces to the modules have allowed flexibility in manifesting and on-orbit outfitting. Racks were offloaded from the US Laboratory when the Program changed the ISS to a higher inclination in order to accommodate the Russian launches. The modular architecture designed nearly two decades earlier allowed these changes in configurations and launch parameters with no impact to the hardware design. Although the modularity of the Station has been instrumental it has also resulted at times in the elimination or delay of elements. (not sure I agree with this para)

The ISS is the first vehicle ever designed with rigid requirements for maintainability and re-configurability and, simultaneously, for planned for a truly extended on-orbit lifetime. Each Apollo mission flew for only a matter of days and was used only once. Shuttles fly for a couple of weeks before they undergo major ground servicing and periodic major modifications. Skylab missions lasted for less than a year. Even Mir was designed for a five year life, although it lasted for somewhat longer (15 years) through the addition of new modules.

The ISS was the first spacecraft ever to be physically assembled using extensive EVA and robotics in orbit. (not really, Russian modules weren't) The (Shuttle-based) assembly operations and missions are complex; almost every assembly mission is different. Earth orbit has become a construction site where conditions alternate between freezing cold and searing heat. The construction workers are extravehicular astronauts; the cranes are a new generation of space robotics; and the tools are designed to different laws of physics.

Because of the complexity of ISS assembly, detailed assembly planning is crucial. As on an earth construction site, certain activities must precede others, so the integrated assembly sequence must consider all such dependencies. The ISS Program plans and tracks the exact configuration of the ISS after each assembly stage, and ensures compatibility of the new elements into the existing on-orbit configuration. As new elements are brought on line, ISS documentation, software, procedures, operating plans, interfaces, and support tools are updated.

The best analog to future long-duration human exploration missions currently available is the ISS. Onboard systems and hardware are highly representative in design, complexity, and reliability to what will be required for a trip to the Moon or Mars. Many of the operational constraints are similar to those that will be experienced in the assembly of a Moon base or on a Mars mission. Only testbed we've got to check out systems and ops for exploration another of thos important points

4. *Robotics*

Efficiency, speed and preciseness of in-space assembly required that much of the assembly work be done robotically. ISS robotic systems are operated at the large-scale (e.g., cranes), mid-scale (e.g., anthropomorphic robots), and small-scale (dexterous and/or micro manipulators). Other reliable, remotely operated, self-deploying and self-assembling systems were developed for use in Earth-orbit, but are adaptable for use on the Moon, and beyond. Intelligent and robust docking mechanisms, as well as autonomous rendezvous and docking technologies and the test beds used to develop them are key Exploration mechanisms.

ISS operations make use of an integrated suite of imaging sensors and manipulators for in-space assembly, inspection and operation. The capability to perform a wide variety of local inspection and control operations will be important to the long-term, robust operation of diverse systems in deep space and on other worlds.

Canada, which built the Space Shuttle remote manipulator in the 1970s, also developed the station's primary mechanical arm. Called the Space Station Remote Manipulator System (SSRMS), the 55-foot-long arm has the capability to move around the station's exterior either like an inchworm, locking its free end on one of many special fixtures, called Power and Data Grapple Fixtures (PDGF), placed strategically around the station, and then detaching its other end and pivoting forward, or riding on a Mobile Servicing System (MSS) platform that will move on tracks along the length of the station's 350-foot truss, putting much of the station within grasp of the arm. Canada also is providing a new robotic arm and hand for the station, called Dextre, or the Special Purpose Dexterous Manipulator (SPDM). It consists of two small robotic arms that can be attached to the end of the main station arm to conduct more intricate maintenance tasks.

Two other robotic arms will eventually be installed on the ISS. A European Robotic Arm (ERA), built by the European Space Agency, will be used for maintenance on the Russian segment of the station and the Japanese laboratory module will include a Japanese robotic arm that will tend research equipment mounted externally on a "back porch" of the lab.

These robotic systems introduced new techniques of human and machine interface. For example, training for the robotic operations is routinely performed with virtual trainers and actual on-orbit operation is performed remotely by the crew using computer and television screens and assisted by an automated vision system.

The ISS required the development of an extensive operations support infrastructure. Although it is anticipated that future missions will be more self-sufficient and rely less on real-time support from Earth-based personnel, there will certainly be a similar support infrastructure required to develop the information that must be available to the spaceflight crews to enable their autonomy and to train them. (redundant to previous)

IV. ISS as an Operations Test bed for Exploration

The ISS affords a unique opportunity to serve as an operations test bed for the Exploration tasks. Because it is a large, complex spacecraft operating continuously in space and maintained by the onboard crew, the ISS is an ideal platform to test protocols and procedures that will enable greater crew autonomy and reduce dependence on the ground support team. Training tools, crew and robotic operations, time delayed or intermittent ground communications, and on orbit repair and maintenance can be demonstrated and validated in space. ISS can support demonstrations of new capabilities and tools required for sustaining spacecraft operations, including remote vehicle management, logistics management, in-space assembly and inspections, and flight demonstrations of new crew and cargo transportation vehicles.

Similar to spacecraft that will support future missions beyond low-Earth orbit, ISS does not return to the ground for servicing, and provisioning of spares is severely constrained by transportation limits, especially upon Shuttle retirement. The six-month ISS mission increments can be used as temporal and operational analogs for Mars transit. (won't always be 6-months, check crew rotation plans). The ISS is a viable, and the only, test bed available in the near term for increasing technology readiness levels and/or validating concepts and technologies for human space flight in the microgravity, thermal, radiation, and contamination environments of space. It is the only space-based operational laboratory available for critical Exploration spacecraft systems such as closed loop life support, EVA suit components and assemblies, advanced batteries and energy storage, and automated rendezvous and docking.

Table xxxxx describes some potential operations-related roles for the ISS as a test bed for operational experience and technology validation.

Mission Objective	Capabilities needed For Moon	Capabilities needed For Mars	ISS Role
Crew Operations			
Crew Operations and Training	• Integrated International crews • Evolved operations tools and processes • Skills based IVA and EVA training; evolved on-board training tools	• Integrated International crews • Streamlined operations tools and processes • Computer based IVA and EVA training	• Develop and demonstrate protocols and procedures with international crews • Develop and demonstrate skills-based and on-board training tools
Extra Vehicular Activity (EVA)	• Improved EVA suit materials and on orbit maintainability • Enhanced suit mobility /flexibility; self don/doff	• Highly reliable, maintainable suits; resilient to Mars dust • Reduced crew prep times for EVAs	• Prototype new EVA suit materials, components and sub-assemblies • Verify procedures for on orbit repair and maintenance, self donning/doffing, and airlock management
Spacecraft Systems Operations			

Advanced Habitation and Life Support Operations	• Closed loop life support • Evolved medical care and countermeasures	• Long duration crew accommodations • Long distance crew provisioning and resupply • Advanced environmental control and life support • Long distance medical care and long duration countermeasures	• Evolve crew accommodations and planning systems for provisioning, food and clothing • Characterize operating conditions for next generation closed loop life support • Validate advanced health care and countermeasures
Communications Operations Protocols	• Remote systems management • Systems monitoring tools for reduced ground support	• Remote systems management • Radiation-hardened hardware • Autonomous crew operations • Autonomous systems monitoring tools	• Develop operations procedures for remote vehicle management and intermittent communications • Characterize operating conditions for radiation-hardened hardware and networks • Validate autonomous crew operations and reduce ground support
Crew-System Interface Operations			
Automation, Robotics and Human-Machine Interface	• Combined crew and robotic operations • Robotic exploration aids and EVA support • Ground controlled robotic operations	• Autonomous crew and robotic operations with time delayed communications • Combined airlock and robotic operations	• Validate robotic designs, concepts, tools and operational scenarios for long distance assembly and maintenance tasks
Assembly Operations	• Reliable in-space assembly operations	• Autonomous in space assembly operations	• Demonstrate procedures for in-space assembly systems; self-deploying systems; inspection and control
Systems Maintenance; Repair; Logistics Resupply and Sparing	• Component commonality to support field repair without logistics resupply • Reduced resupply requirements and trash generation • Evolved logistics and inventory management	• Maximum component commonality to support on orbit maintenance and repair • Reduced in route and on-site resupply requirements • Autonomous logistics and inventory management tools	• Demonstrate test, repair and maintenance operations on orbit • Evolve logistics management, maintenance and sparing concepts

NASA is using the ISS as a laboratory for research with direct applications to Exploration requirements in human health and countermeasures, as well as applied physical science for fire prevention, detection and suppression, multi-phase flow for propellant, life support, and thermal control applications. At the completion of assembly, the ISS will support research and technology development programs that meet the Agency's needs for crew health and safety, technology advancement, and validated operational experience essential for long duration missions beyond low Earth orbit. With the transition to VSE, NASA's plans for research and utilization of the ISS have undergone significant changes. The resulting research and utilization approach is still evolving to focus available resources on risk reduction associated with the NASA exploration architecture. However, NASA is well positioned to take maximum advantage of the window of opportunity provided by the ISS.

V. Conclusions

The operation of the International Space Station was dependent at its outset very directly on the knowledge that was gained during earlier operations of Russian and US space systems. The ISS, as we operate it in space today, is an evolution of space systems technologies that were developed by many countries with widely differing design philosophies.

Knowledge gained in operating the ISS, especially during the recent Shuttle hiatus, has the potential for direct application to future Exploration systems. Many of the operations, processes, functions and systems in use on the ISS today provide the same or similar capabilities that will be needed for future Exploration operations. Processes in use today for ISS will serve as a basis for future space systems. Many of the hardware and software systems developed for ISS may even be adapted for direct use on future systems. The personnel and knowledge base in operations, as well as development and integration, should be fully utilized.

In the future, the knowledge achieved through our work with the International Space Station can be applied to the vehicles that will explore the Moon and Mars. These are no longer dreams, they are achievable goals. We are learning about the assembly and maintenance operations required to build and sustain a large space infrastructure over multiple generations. The ISS Program is gaining knowledge of the kinds of new problems that we will face. We have the test bed in place today to learn what does and does not work. We are training the engineers today who will take us to the planets.

VI. Acknowledgments

VII. References

????????? Start of a list - to add other known papers. Needs ordering and formatting to AIAA standards

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