# International Space Station
# Lessons Learned for Space Exploration

September 2014

Human Exploration & Operations

Mission Directorate (HEOMD)

Editors

David M. Lengyel, NASA HEOMD (Retired)

Dr. J Steven Newman, ARES Corporation

# Foreword / Approval

This report has been developed by the National Aeronautics and Space Administration (NASA) Human Exploration and Operations Mission Directorate (HEOMD) Risk and Knowledge Management team in close coordination with the HEOMD ISS International Space Station Division in support of ongoing and future NASA deep space and commercial space exploration activities.

This document provides a point-in-time, cumulative, summary of key lessons learned derived from the design, fabrication, integration, test, assembly, and operations of the International Space Station (ISS). Lessons learned invariably address challenges and risks and the way in which these areas have been addressed. Accordingly the risk management thread is woven throughout the document.

This report is accompanied by a companion NASA web-site containing video interviews, related documents, related videos, related links and ISS knowledge-based risks (or KBRs).

Signed ______________________

Sam Scimemi, HEOMD, ISS Division Director

# Executive Summary

On January 9, 2014, the director of the White House Office of Science and Technology Policy (OSTP), announced President Obama's decision to extend International Space Station (ISS) operations until at least 2024 during a speech at the International Space Exploration Forum (ISEF) in Washington D.C. NASA Administrator Bolden added, "NASA is committed to the space station as a long-term platform to enable the utilization of space for global research and development. We're committed to implementing a unified strategy of deep space exploration, with robotic and human missions to destinations that include near-Earth asteroids, the moon and Mars."

This compendium and the associated web-based resources are intended to assist in the early discussions for future space exploration missions, to stimulate thinking and raise questions that need to be addressed and in concept development, formulation, and planning phases. Each lesson learned is accompanied by a corresponding application to future exploration programs.

Lessons were acquired through audio and video interviews with current and former ISS managers, designers, operators, flight controllers, astronauts, and various technical functional discipline leads. The compendium also incorporates selected lessons learned from the 2009 ISS Multilateral Coordination Board (MCB) report.

Results are organized in the following categories:

**Policy and Partnerships**
- Policy
- International Partners
- Commercial Partners

**Engineering and Management**
- Systems Engineering
- Budget / Schedule
- Risk Management
- Internal Communication
- External Communications

**Design, Development, Test & Evaluation (DDT&E)**
- Mission Architecture
- Engineering Design
- Technology, Materials, Commercial Off-the Shelf (COTS)
- Interfaces, Integration & Test

**Operations**
- Logistics, Maintenance, Operations & Utilization
- Crew Operations
- Crew Medical
- Science Utilization

## Contents

# Part I. Introduction

## Objective / NASA Looking Ahead:

The objective of this document is to provide insights from the International Space Station design, development, assembly, and operations relevant for ongoing and future NASA deep space and commercial space exploration activities.

Primary references provide a longitudinal perspective (2005, 2009, and 2013) on key experiences, issues, approaches, strategies, do's, don'ts, and cautionary tales that will be relevant to the formulation and implementation of future space exploration initiatives.

2013 Sources

- Appendix A provides a list of audio and video interview participants.

2009 Sources

- International Space Station Lessons Learned As Applied to Exploration, Kennedy Space Center, July 22, 2009, "International Space Station Multilateral Coordination Board, Benoit Marcotte, CSA, Yoshiyuki Hasegawa, JAXA, William Gerstenmeier, NASA, Simonetta Di Pipp, ESA, Alexey Krasnov, Roscsomos.

  *Note: Selected Lessons Learned from this report are incorporated with an asterisk and number format (e.g. *24 – Lesson).

2005 Sources

- From ISS to the Moon, Mars, and Beyond – Applying Lessons Learned, MJ. Sanchez, JS Voss, 43rd AIAA Aerospace Sciences Meeting & Exhibit, January 10-13, 2005, Reno Nevada.

## Themes and Framework:

Interview Themes:

Telephone interviews were tailored for each individual interviewee and conducted using a flexible format that included an interviewee-appropriate subset, or all, of the following:

- Management and Communications
- Planning and Preparation for ISS DDT&E and Real-Time Operations
- Benchmarking / Lessons Learned by ISS from Other Programs (e.g. Phase 1, Shuttle)
- Startup Transients from ISS (Things That Didn't Work at First)
- Things We Didn't Know But Discovered Along the Way
- Impact of Budget Limitations / Restrictions on ISS
- Impact of Human Capital / Critical Skills (NASA Civil Service and Contractors)
- Benefits from International Partner Participation
- Top Risks Encountered (Strategic, Operational, Tactical)
- Critical Processes Utilized (Documented?) – Were They Effective
- Impact of Major Program Changes (e.g. Redesign, Directed Re-baseline, Columbia Mishap)

- Top Three Takeaways Useful for Deep Space Exploration

<u>Framework for Analysis:</u>

Lessons are organized using the following categories:

**Policy and Partnerships**
- Policy
- International Partners
- Commercial Partners

**Engineering and Management**
- Systems Engineering
- Budget / Schedule
- Risk Management
- Internal Communication
- External Communications

**DDT&E**
- Mission Architecture
- Engineering Design
- Technology, Materials, COTS
- Interfaces, Integration & Test

**Operations**
- Logistics, Maintenance, Operations & Utilization
- Crew Capability & Training
- Crew Operations
- Crew Medical
- Science Utilization

## Additional Resources:

<u>ISS Lessons Learned Module:</u>

This report has a companion website implemented on multiple NASA public access servers that contains supporting videos and public domain documentation. The module includes this report along with video interviews and 116 related documents from both internal NASA and external sources. In addition, the website provides 15 ISS related risk problem/risk solution videos (referred to as Knowledge-Based Risks or KBRs) along with associated document bundles. The KBRs topics are listed in Appendix A of this report.

# Part II. Lessons Learned

## Policy & Partnerships

## Policy

**Lesson: Assembling Political Support for Future Deep Space Missions**

One interviewee opined the need for three elements: 1) An underlying, sustainable, geopolitical rationale, 2) NASA Institutional Interest (Congressional support), and 3) the renewal of a more robust development culture at NASA. There is no "magic bullet" of advocacy that will emerge to support deep space missions, such as Sputnik or the fall of the Berlin Wall.

*Application to Exploration:* Realistic, practical, grounded, policy architecture must be developed in order to garner public monies and political support for deep space missions.

**Lesson: NASA, Office of Management and Budget (OMB) and Congressional Collaborative Partnership Critical**

The 2010 relationship between NASA, OMB, and Congress was not representative of the "partnership concept" necessary to garner support for future deep space exploration initiatives. The 1993 "House - one vote" survival of the ISS was also identified as a time of difficulty in collaboration and communication between the executive and legislative branches of the government.

*Application to Exploration*: Trust and collaborative partnership are required between NASA, OMB, and Congress as an underpinning for moving forward with any future deep space exploration initiative.

**Lesson: Communication and Performance Underpins NASA-Congressional Relationship**

Ongoing communication between Congressional staff and NASA personnel is important to help inform and shape Congressional understanding of programmatic performance issues as well as for relationship building. Communication efforts should serve as an ongoing mentoring and educational process, especially for new members. Communication of performance metrics in a timely and transparent manner was identified as important – in particular cost, schedule, and programmatic milestone status.

*Application to Exploration*: NASA must continue to proactively strive to communicate and inform Congress at all levels: personal staff, committee staff, and members as a basis for the necessary collaborative relationship.

**Lesson: Collaboration and Partnership to Achieve a Sound Space Policy**

Space policy should be established through a collaborative effort between the Executive and Legislative Branches of government. The way the government is set up is such that the President proposes and the Congress disposes. NASA should be sensitive to Congress because they created NASA through an authorizing act (The Space Act of 1957); every authorization bill since is an amendment to that core text.

*Application to Exploration:* Communicate and collaborate with Congress and the Executive Branch – it is not a "them versus us" situation. Both branches of government have a role. Openness, honesty, and frankness are essential.

**Lesson: Effective Communications between NASA, Congressional Oversight, Appropriations Committees, and the Public**

After the redesign in 1993, the Space Station narrowly escaped cancellation in the House Appropriations Subcommittee. This resulted in NASA rethinking their communications strategy with Congress and internal preparations for future potential issues related to Space Station.

The Space Station Information Center, also known as the "War Room," was established as a focused effort in 1994 and again in 1995 and 1996 for six week periods "to prepare informational materials that could be made available to Members of Congress in response to issues raised about the space station prior to and during the debate". This effort was continued until 1998 when it was felt that the communication and collaboration activities had been inculcated into the day-to-day behavior of the participants. ISS support had gone from a one vote margin in 1993 to roughly an overall three-to-one margin by 1998. Organized under the combined authority of the Administrator's Office and the Office of Legislative Affairs, the War Room included representation from other Headquarters offices, namely, the Office of Space Flight, the Office of Public Affairs, the Office of External Affairs (International), and the Office of Life and Microgravity Sciences. Representation of these offices was generally provided by a Deputy Associate Administrator from those organizations or another senior staff

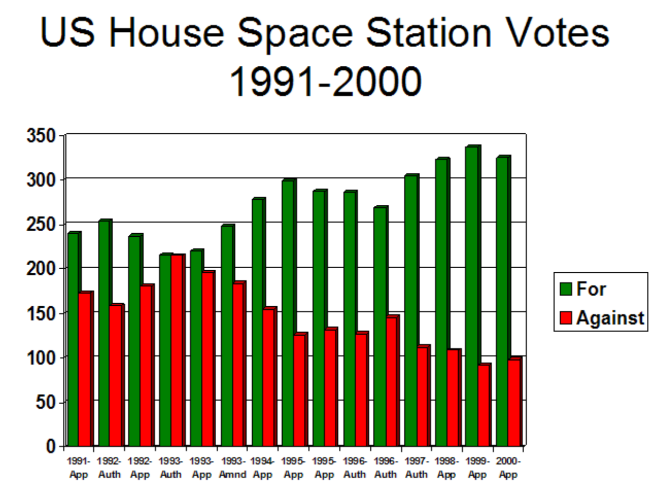


*Figure 1. Chart reflecting comparative levels of support for and opposition to the space station as demonstrated by total votes cast in the US House of Representatives during floor debate on proposed amendments to authorization or appropriations legislation to terminate the space station program from 1991 to 2000. Primary source: Congressional Record. – Jeff Bingham White Paper.*

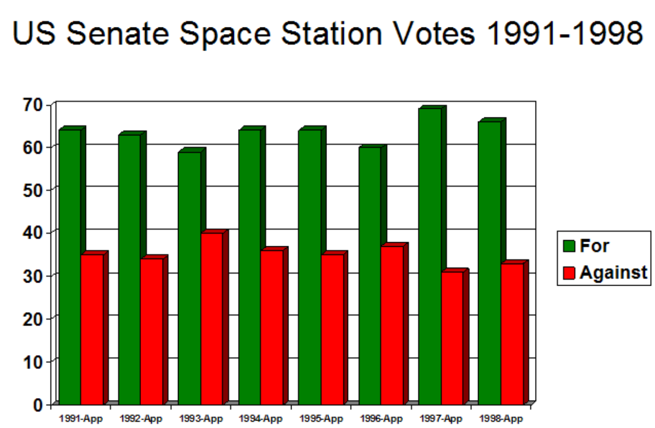


*Figure 2. Chart reflecting comparative levels of support for and opposition to the space station as demonstrated by total votes cast in the US Senate during floor debate on proposed amendments to authorization or appropriations legislation to terminate the space station program from 1991 to 1998. Primary source: Congressional Record. – Jeff Bingham White Paper*

designee."

*Application to Exploration:* Large, complex programs with long development timeframes are often vulnerable to changing administrations, Congresses, public perceptions and funding decisions. At certain times, effective communications may require a more focused and deliberative effort between NASA organizations to maintain support through the inevitable periods of waning interest and resource constrained environments.

**Lesson: ISS Extension Will Be Based on Utilization Productivity Over Next Ten Years… The Clock Is Ticking**

On January 8, 2014, the White House announced the extension of ISS operations until at least 2024. ISS is now at a point in its life-cycle in which it needs to deliver on science utilization. In order to maintain stable funding and continue to extend the planned life, the ISS must deliver on the promise of micro-gravity research.

*Application to Exploration*: It is important to continue to recognize that "delivering on the promise" is essential to maintaining political and financial support for exploration missions.

**Lesson: "Technical Truth & Credibility" is Essential in Maintaining Relationships with the Hill**

One interviewee defined NASA's accepted and appropriate role in space policy battles as providing "technical truth & credibility." The 2010 NASA authorization debate was attributed to lost credibility between NASA and Congress. The abrupt change in policy reflected in the President's 2010 budget was considered by many as lacking a sound technical rationale. The perception of inadequate technical rigor and logic translates to political vulnerability.

*Application to Exploration:* NASA must recognize that a sound technical basis must be established as an underpinning for space policy development and the nurturing of effective relationships with Congress.

## International Partners

**Lesson: Adaptability Is a Key Element of Success for International Programs**

"The development of ISS changed over time – it changed because of financial constraints, it changed because of technical issues, it changed because of political policy changes. One of the amazing things about ISS as a program was our collective ability, as the lead and through our partnership, to adapt to all of those things in one way or another. Examples included changes in operational utilization approaches, changes in crew transportation scenarios, and changes in the approach to cargo resupply."

*Application to Exploration*: It is important to have a good framework for the program that allows for adaptation. The original ISS agreements provided a framework that was not so precise and detailed to be limiting when things started to change, but it had to be clear enough that everyone had common understanding and was working towards the same goals.

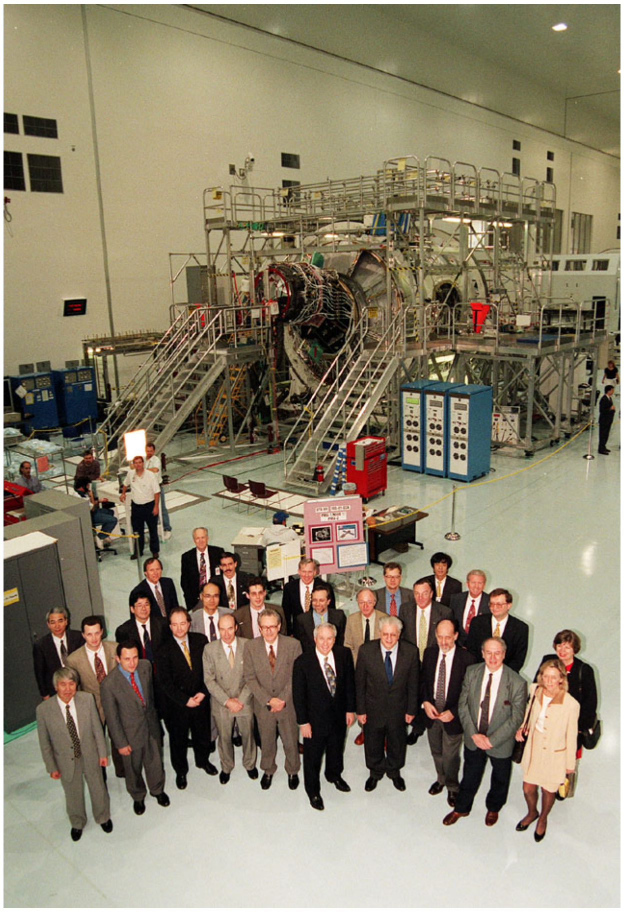

*Figure 3. ISS Partners at Space Station Processing Facility at KSC in 1998 (NASA).*

**Lesson: Adding the Russians – Have a Well-Defined Mechanism for Bringing In New Partners**

Because NASA had multilateral obligations and legally binding agreements already in place with the original ISS international partners, the invitation for the Russians to join in 1993-1994 needed to come from all the member nations of the partnership. The partners expressed a very strong desire to protect what we had already put into place in terms of the management structure, the decision processes for operations, and the methodology that we had for negotiating the rights and obligations of the partners. The initial position for negotiating partnership with the Russians was nicknamed the *minimalist approach.* That lasted for about a nanosecond at the first meeting with the Russians. Because they are a sovereign nation with a long history in human space flight, they had very strong ideas on how things should be done. To add the word *Russia* everywhere appropriate in the existing agreements was not in their best interest. Thus began the four year negotiation process to bring Russia in as an ISS partner.

*Application to Exploration:* Adding new partners into any international program can be a time consuming process, particularly if existing partners use this opening to renegotiate existing terms and conditions of the agreement. The ISS experience clearly points out the need to have a well-defined mechanism for bringing in new partners.

**Lesson: "Determining Contribution and Maintaining Affordability"**

At the Memorandum of Understanding (MOU)-level, the hardest topic to deal with was how to share resources during operations and utilizations. Who would have what allocation at the outset? So with the original partners there was a formula, a percentage developed to share was based on what was considered to be the rough value of the on-orbit assets that that partner provided (for example, the value of the robotic arm or a laboratory). But every time we got together for a negotiation with the Russians the list of elements they were going to provide seemed to change. We finally ended up with a concept we called "keep what you bring." The original concepts involved in shared, or common, operations and utilization costs were not applied in regards to our Russian partner. The concept of "keep what you bring" and segmented operations was ultimately utilized and this had a domino effect across many domains including operations, science, crew training, and so on.

*Application to Exploration:* The exploration programs of the future should study the ramifications of this concept on ISS for long-term sustainability of their agreements in the future. Thorough advance planning and discussions are required to consider alternative models for managing and measuring partner contributions for future joint international exploration endeavors. Further, once contribution agreements have been established, all participants will need to look at affordability initiatives for common operating costs, finding ways for reducing operations and maintenance costs to maintain balance across contribution agreements and sustain political support for the program.

**Lesson: Treating the Partners like A Contractor and Expecting Them to Act like a Partner**

In 1993, a $400M letter contract was signed with the Russian Space Agency for Phase 1 (Shuttle-Mir Program), long duration missions, and ISS docking mechanisms, among other products and services. At the same time, NASA contracted with Khrunichev through Boeing to build the Functional Cargo Block (FGB), the first module to be launched in the ISS assembly sequence. A former NASA employee stated, "I think one of the biggest mistakes in the program from my perspective was treating the Russians as a contractor and expecting them to act like a partner – and we kept blurring the lines between those two things."

*Application to Exploration:* The lesson learned for exploration is that it is easy for a partner to walk away if you treat them like a contractor – they build something, they deliver it then what is the incentive for them to stay engaged in the program? That is why ISS was designed with the requirement for partners' sustaining engineering function as well as sharing the common systems operations costs. These activities ensure that partners had a long term continuous role in the program and a vested interest in how it operated.

**Lesson: Partnerships for Exploration Must Address Partner Political and Financial Risks**

The top strategic risks for ISS tend to be driven by political and fiscal realities across the partnership. In the U.S., we want long term programs but the financial system and the political system do not support sustaining those long term commitments without a continuous fight to do so. Financial issues and a new administration in the U.S. drove a redesign effort in 1993. NASA sold Russian participation as driving down costs in the long-term by bringing their Mir space station experience to bear as well as redundancy in transportation systems. Canada at one point ran into fiscal problems and they actually came with a formal letter of withdrawal from the program and we convinced them not to deliver the letter and work out some alternatives to help them with their financial problems. During the second round of bi-lateral MOU agreements (1994-1998), the Europeans really wanted a rationale for using Ariane V with the program and so the Automated Transfer Vehicle (ATV) concept came about. No government likes to give money to another country when they can spend it domestically. The ISS program figured out what the partners needed most and what we needed together to be the most complementary and valuable assets to add to the program.

*Application to Exploration:* Partner political and financial considerations tend to be the top strategic risks for partners. Exploration should consider turning these risks into opportunities for the benefit of the partnership.

**Lesson: Periodic Agency Leadership Face-to-Face Meetings Essential**

Over time, each of the ISS partners has had their share of domestic issues. This makes it important for the partners to understand one another's environments. Many of these issues are discussed at the multilateral coordination board (MCB) – which is the board at HEOMD directorate-level – and with the NASA administrator and his counterparts at the heads of agency level (HoA). Topics discussed at the MCB and HoA forums include the political environment, space policy, a change in administration, and economic issues that are coming up.

*Application to Exploration*: Open communications between the partners is a key element in maintaining strong partnerships. The forums developed for ISS, the MCB and HoA, may be extensible to the exploration effort and should be considered for incorporation in future programs to "weather the storm" of the inevitable partner domestic challenges.

***6-Lesson: Ensure All Mission Objectives Are Well-Integrated**

A clear definition of different roles, responsibilities and scope of activities should be established at a top level. The mission objectives should be supported by an integrated architecture including end-to-end system requirements and plans for the safety of the crew. Standardization of technical interfaces and interoperability aspects are critical to success. Clear functional objectives for each specific element to be developed should be defined in the context of the overall mission.

*Application to Exploration:* Roles and responsibilities of each Partner, and clear functional objectives for the elements developed must be carefully integrated in the overall exploration architecture with close attention to technical interfaces and aspects of interoperability and crew safety.

***1-Lesson: Accommodate Partner's Own Objectives**

The most significant outcome of the station mission has been the sustainment and growth of each Partner/nation's aspirations for human spaceflight. This occurred because from the onset all Partners shared a common objective to build, operate and utilize a crewed multi-discipline laboratory in low earth orbit as an international partnership. The partnership was also flexible enough to foster collaboration with other non-Partner nations.

*Application to Exploration:* Develop a long-term shared vision for space exploration that transcends domestic policies and fosters a shared destiny among the Partners. The mission objective should be a succinct, inspiring statement that enables Partners to participate based on their objectives and priorities to the greatest extent possible while ensuring the provision of all critical path items. Each phase of space exploration should also be defined by clear goals. Plans should also allow for unforeseen events, or withdrawal of participants, without jeopardizing the overall mission objective.

**Lesson: Dealing with International Partners – It's Not Going to Be Simple – Learn From ISS**

The ISS Program taught NASA a lot about how to negotiate with international partners (IP) when there are multiple complex considerations and constraints. "The ISS IP experience was extremely useful in developing the framework for the Orion Service Module with ESA. Understanding our partner's limitations and constraints, including the bureaucracy that they need to work through, helped NASA develop this arrangement and to be able to more effectively communicate the risks to upper management. ISS is an incredible example of the practical aspects of working with IPs."

*Application to Exploration:* Dealing with international partners will invariably not be clean and simple and you can expect to have the same kinds of constraints as those imposed upon the ISS. The ISS Program provides a wealth of examples on how to manage international partnerships that should be understood for future agreements.

***11-Lesson: Plan for an Evolving Public Policy**

Along with the mission objectives, the station architecture accommodated each Partner's sensitivities and priorities in human space flight. The station architecture allowed each Partner to develop the technical capabilities and functions that met their goals and did not over extend their political and budgetary constraints. The ISS partnership also allowed for different public affairs policies and strategies.

*Application to Exploration*: Align international Partner technical responsibilities with their programmatic and political needs. Be sensitive to each Partner's domestic policy process, including media relations and public advocacy. Structure the exploration architecture to reduce issues involving any future changes in Partner policies.

***29-Lesson: Carefully Balance Specificity and Flexibility in Program Agreements**

Multilateral and bilateral partnership agreements need to be explicit while still allowing some flexibility for each agency to contribute to the resolution of unforeseen circumstances. The ISS Intergovernmental Agreement (IGA) and MOU documents spell out roles, duties, commitments and responsibilities for the partnership, and provide an overarching framework tested over time with a track record of experiences for the partnership.

*Application to Exploration:* Future international programs agreements need to be specific from the onset to deal with ownership, commitments, roles, Partner responsibilities and technical interchanges or transfers.

***30-Lesson: Manage Working Groups Judiciously**

The ISS management framework demonstrated the utility of working groups. However, some revision remains necessary: (1) the activity of working groups must be deeper integrated in the system to include all participants; (2) scope and authority of actions set by groups must be strictly determined; (3) number of groups should be limited; and, (4) the process of establishing and dismissing groups should be closely regulated.

*Application to Exploration:* Exploration programs should use working groups when necessary, but not indiscriminately. The groups should consist of all participants in the subject domain, and operate under specific terms of engagement.

***33-Lesson: Use Consensus Approach to Decision Making**

The practice of governance by consensus within the ISS partnership provides assurance that Partners have a voice in decisions, management and other issues. The partnership benefitted from consensus building by identifying Major Partners' interests, including constructive changes. A provision in which one Partner has the ability to make a decision in those rare cases in which consensus could not be reached is essential to ensuring that the program continues.

*Application to Exploration:* Governance by consensus is beneficial in major international projects. Agreements should encourage consensus decisions while allowing for a means of resolution in extreme cases.

***34-Lesson: Use a Formal Framework for International Cooperation**

The ISS Program had a Governmental-level commitment from all the Partners called the IGA (Intergovernmental Agreement). This greatly contributed toward maintaining support for the ISS program from each participating government and to the program's stability despite its complexity and long duration.

*Application to Exploration:* A Governmental-level international commitment would be effective for exploration programs, since a withdrawal or delay of the program due to a cooperating agency's circumstances could prove critical. Even if the architecture is a "program of programs" (integrated series of disparate programs), it would be effective to construct such an international framework for cooperation, so that each participating country could view their contribution toward achieving common global goals.

***35-Lesson: Use a Dedicated Group to Develop the International Framework**

The ISS approach of tasking a dedicated group to develop initial proposals which can be subsequently reviewed, amended and further developed in a full multilateral environment, representing all envisaged Partners, is an effective and workable approach to developing a formal framework for international cooperation.

*Application to Exploration*: In the human exploration management process, many key parameters must be identified and assessed. Due to the increased complexity and arrival of new Partners, the decision making process needs to reach the right balance of each Partner's investments. An experienced dedicated group should be assembled for these purposes.

***31-Lesson: Establish Inter-Partner Technical Liaison Offices**

In the ISS program, Partners agreed to establish technical liaison offices with other key Partners with whom there was major interaction. There are significant benefits in terms of easy access to program personnel and data, as well as the ability to expedite a variety of development and operational issues.

*Application to Exploration:* Establish technical liaison offices with key Partners in order to facilitate communication.

***32-Lesson: Obtain Early Agreement on Common Technical Communications**

The ISS international agreements provided, to the maximum extent possible, common technical communications for language, units of measurement, distributed system and element nomenclature, and interface standards (human and robotic).

*Application to Exploration:* All exploration Partners should agree on common technical communications at the beginning of the program.

## Commercial Partners

**Lesson: Establish Shared Ground-Rules for Commercial Activities and Commercial Contributions**

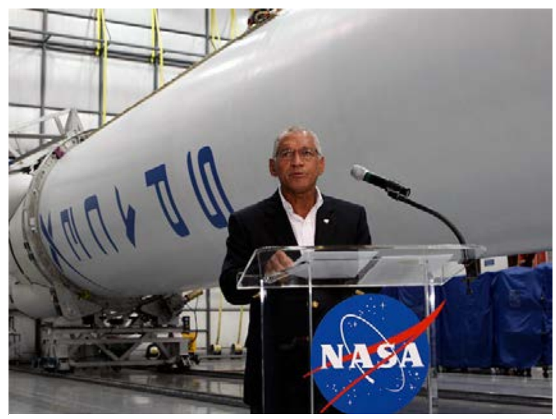

*Figure 4. NASA Administrator hailed the conclusion of the agency's Commercial Orbital Transportation Services (COTS) program in a news conference at NASA's headquarters in Washington D.C. Photo Credit: SpaceX.*

Early on there were different ideas about what commercialization on ISS meant. For the NASA team, the experience base was on things like the electrophoresis experiment on the Spacelab – it would be companies who wanted to use the Shuttle for commercial activities. Conversely, the Russian idea of commercialization was more like filming and commercial advertisements on-board ISS using the astronauts and their cosmonauts. This was contrary to NASA’s culture but was perfectly reasonable to the Russians. Another difference was that Russian commercialization included flying millionaires up to the station. Mixed messages early on during ISS development and assembly concerning differing commercial frameworks and lack of a coherent plan served to delay opening doors for commercial participants.

*Application to Exploration:* Exploration should establish shared ground-rules for commercial activities, contributions, and partnerships in future architectures up front and early on.

**Lesson: Commercial and University Research: Two Risk Thresholds**

Commercial research is more risk adverse than university-funded research. Whether it is a startup or a big company, commercial entities want to be sure that they get a return on investment and they need that return to be shown in a quarterly basis. A university gets a grant and they might have three years before their progress is checked on. Whatever they discover is good whereas in commercial research, the discoveries must be turned into something that pays off relatively quickly. A means of discouraging commercial research or partnerships with other agencies is to come in and try to start charging them for services (transportation up mass, crew time, user fees, etc.) that make ISS research cost more than doing it here on Earth. The cost-benefit for them is high risk versus high return so any charges levied on them are too much.

*Application to Exploration:* A user pay model was anticipated for commercial research early on for ISS. This turned out not to satisfy the calculus involved in the commercial business case. If commercial research is anticipated for Exploration, this should be taken into consideration.

***55-Lesson: Considering Commercial Engagements Early in the Process and Determine the Best Stage to Pursue**

Partners should determine how to deal with commercial engagements early in the Partnership and then each Partner can determine when is the best time to pursue commercial engagements depending on their program.

In the ISS Program, each Partner has taken a unique approach to commercial engagement. A variety of engagements have contributed toward decreasing program costs and stimulating the space industry. These activities were conducted amid international harmony and within the responsibility and rights of each participating agency. Attention was necessary to clarifying the responsibility of each participating agency for safety.

One Partner believes that commercial engagement brings almost nothing during the early stage – just minor additional financial support. In the later stage, when technology spin-offs became more and more visible, business also gets interested. Even later, business starts investing in large commercial projects (e.g., communication, navigation, Earth remote sensing), appreciably supporting and helping in development of space infrastructure.

Another Partner thinks we should consider the ISS an extension of life on earth and, thus, there is no need to invent a particular arrangement for ISS commercial development as business will develop as soon as necessary conditions appear. Nonetheless, it is important to offer and ensure the opportunity for business involvement at the earliest stage of the program. Business will find the right time and way by itself.

*Application to exploration:* It is important to consider the possibility of commercial engagement from an early phase of the space exploration study. However, attention should be given to effects on safety, Partner responsibilities and rights. Opportunities for business to participate in exploration programs should be carefully and appropriately timed.

***56-Lesson: Establish Framework and Await Clear Markets for Commercial Engagement**

Commercial engagement can provide beneficial effects; however, it can also lead to conflicts of interest and endangerment of operations with risks that are difficult to quantify. In the ISS program, the overall strategy and legal framework was not always clear, and it was difficult for a commercial Partner to find a profitable role.

*Application to exploration:* The definition of a clear market that would allow industries to invest and obtain a return, plus a legal framework that allows industry to own what they would achieve, is the best means to assess and prepare for commercial engagement. A common approach among the partners should be sought.

# Engineering Management

## Systems Engineering

**Lesson: Systems Engineering – Clarity in Requirements Management**

Clarity needs to be established between architectural functional requirements, performance requirements, design requirements, and contract specifications and their respective management levels (Levels 1 through 4). Level 1 (Headquarters) imposition of design and contract specifications leads to confusion and preempts the design tradeoff analysis process, and ultimately leads to cost and schedule impact.

For future complex space system design activities it is recommended that Level-1 stick to architecture, Level-2 manages programmatic and technical issues on a daily basis (daily control boards as necessary), and Level-3 focuses on the project execution, developing the design and "micromanaging the interfaces."

*Application to Exploration:* Rigorous systems engineering discipline is encouraged to ensure success in future deep space missions.

**Lesson: NASA Needs to Re-establish Institutional Capabilities in DDT&E for Human Spaceflight**

The interviewee outlined concerns regarding the long gap between Space Shuttle and ISS design/development/test efforts and the present time. At the same time, NASA's excellence in mission operations is evident and continues to develop with the 365/24 operation of ISS. Assuming that good flight operations personnel are the right people to lead DDT&E efforts is a mistake. DDT&E is uniquely difficult and requires a different engineering skill-set than operations.

*Application to Exploration:* As a matter of policy, NASA must develop a new cadre of engineers through more hands-on, real-world developmental flight test programs such as X-38 or ARES I-X to re-establish the broad base of experience necessary for future space exploration.

**Lesson: Strengthening Systems Engineering & Integration (SE&I) and Integrated Logistics & Support (ILS) Roles in Design**

Interviewees described the difficulties ILS managers faced in influencing design decisions. The ILS function owned no requirements and lacked authority beyond advocating ILS best practices. This issue was in-part a result of not being located within the engineering design organization. The challenge is to achieve a better balance of input from SE&I and operational organizations in the design process.

*Application to Exploration:* Past engineering management and SE&I approaches may necessarily warrant examination to bolster the authority and role of SE&I to incorporate integrated system-level requirements ownership – going beyond management of interfaces, configuration management and verification and validation system level requirements.

**Lesson: Rigorous Development and Management of Interface Control Documents (ICDs)**

ISS Command and Data Handling (C&DH) interface control documents were developed within the ISS program and were managed with great rigor. C&DH verification testing was also managed within the program, also with great thoroughness. C&DH benefited by a formal ICD process and integration into a program-level board structure.

*Application to Exploration:* The basic blocking and tackling of systems engineering must be part of a solid and authoritative SE&I function for future exploration activities.

## Budget / Schedule

**Lesson: Rigorously Manage Schedule and Cost, and Requirements Baselines**

It is imperative to maintain accurate and up-to-date, schedule, cost and requirements baselines. Senior program management must not become too involved in addressing complex technical issues at the expense of focus on the programmatic baseline.

*Application to Exploration:* Future long duration space missions will be multi-year endeavors and will be continuously scrutinized by Government Accounting Office (GAO), Congressional committees, OMB, OSTP, and other stakeholders.

***36-Lesson: Accommodate Partner Budget Cycles**

Each Partner agency in the ISS program must be aware of the evolution of policies of the other Partners and the ways in which each Partner's budget operates. These differences are crucial in planning program milestones, in order to best build global political support.

*Application to Exploration*: Each Partner must be aware of the budget cycles of other Partners and be willing to accommodate to the greatest degree possible. Maintaining a high level of situational awareness is beneficial in improving cooperation on both a political and a technical level, tactically and strategically.

**Lesson: Systems Engineering –"Where Can This Thing Stall, Where is the Critical Path?"**

The program manager focus on the critical path is of paramount importance where a small failure can "cascade and slow down a complex system." End-to-end, multi-element, system level testing was identified as "an absolute Saving Grace" for the ISS, identifying multiple problems and issues that would have been difficult or impossible to remedy on-orbit.

*Application to Exploration:* Focused critical path management informed by multi-element integrated testing is an area that needs emphasis in future exploration mission DDT&E implementation.

**Lesson: Wakeup Call: Driving Cost and Schedule Control**

The White House directed Tom Young review and report (International Space Station (ISS) Management and Cost Evaluation - 2001) was a wakeup call to ISS program management and forced NASA to look at cutting ISS costs in order to survive.

"…. Tom scrubbed us again on the technical but more importantly on how we were managing the budget, how we were organized, and then there was an output. Part of that was, you know at that time we were facing potentially cancellation right, to not finish the space station if we couldn't show a plan that closed and made sense. So that really I think showed a priority for the team that we had to cut costs and we had to look at what was fundamentally required in order to achieve the space station in full assembly complete. Could we do things, you know faster and simpler and save money. So that whole, I would say crisis, helped drive that emphasis. …"

External forces were used to help drive innovation and affordability initiatives challenging the status quo and re-orienting management and the workforce to seek greater efficiencies.

*Application to Exploration:* The cancellation of Orion in 2010 caused the program to redefine itself including adding a flight test for a lower cost. Without that impetus, the program might not have been able of accomplish this within the timeframe and budget allocated. The program is more efficient and leaner now. In the future NASA should look to get benefits from potentially negative events.

## Risk Management

**Lesson: "Prepare for the Unexpected" - Prepare for both Technical and Operational as well as Programmatic Unexpected Events**

It is essential to plan for unexpected, disruptive events that will test the program's flexibility and architectural, design, and operational margins. Examples include a diverse host of issues, such as: the loss of Columbia and impact on ISS operations, budget cuts, near cancellation, loss of political support, sequestration, and partner issues. "Keep your requirements up to date, don't overstate or understate financial risk, maintain stable requirements, and understand your budget. Be prepared for the unexpected. Be hypersensitive and aware that challenges will emerge."

*Application to Exploration:* Future long duration space missions will be multi-year, multi-partner endeavors and will always be vulnerable to political, budget, technical, and operational risks. Margins need to be robust and carefully managed; alternatives (plan B and C) must be built in to architecture.

**Lesson: "Managing Through Uncertainties and Unknowns"**

The Columbia tragedy presented ISS managers with a host of challenges: maintaining the ISS in an operational configuration, disagreements and negotiations with partners (maintaining crew on board), crew size, ensuring safe return capability, consumables (water supply), and many more issues. Meanwhile the timeline for Space Shuttle return to flight kept "sliding to the right," – first six months, then one year, and eventually two years. Throughout this period of "rolling timelines" ISS management evolved an approach for managing through the uncertainties and unknowns.

First, decisions were made when they needed to be made – not before. The program capability framework was employed as a ready-resource prepared to respond to the real-time decision. The concept was "be prepared but not overly prepared." Contingency planning scenarios (potentially an endless resource drain) were limited to understanding critical risks and identifying the first three steps necessary to stabilize a situation, buy time, re-plan, and move forward.

*Application to Exploration:* The ISS management/risk management experience after loss of Columbia provides a template for consideration in operational planning for future space exploration missions.

**Lesson: "Decision Making Without a Net"**

Another result of the Columbia tragedy was an overwhelming NASA senior management focus on Shuttle return-to-flight with (relatively) diminished oversight over ISS operations and management. While implicitly conveying confidence in the ISS management team the independent "second set of eyes" was no longer deeply involved in vetting critical decisions. Accordingly the ISS management team was extremely cautious and thorough in approaching critical decisions.

*Application to Exploration:* The lesson conveys/recognizes the importance and value in peer review by informed independent management or functional managers when making key decisions.

**Lesson: Risk Issues with Dissenting Opinions**

A former ISS manager noted that the decision authority has the responsibility to create an environment that is conducive to individuals' expressing dissenting opinions while project participants are responsible for speaking up and taking a position on any issue where they have informed concerns. Discussions can lead to consideration and acceptance of the minority opinion, an "agree to disagree" scenario or the dissenting opinion being appealed to a higher level of management. The manager noted that disagreements often involve technically complex issues with strongly held, well-articulated arguments for and against the management position. While embracing and encouraging dissenting opinions the ISS experience has shown that resolution of various issues has been difficult and cumbersome. Accordingly it was recommended that the Agency establish a more effective process for resolving important controversial technical issues.

*Application to Exploration:* Many difficult technical issues will surely arise in the development of future space exploration systems. NASA program managers and technical authorities (Engineering and Safety & Mission Assurance) may wish to consider the effectiveness of current processes (or lack of process) in addressing appeals to program decisions.

**Lesson: Stay Hungry & Inquisitive: Spacesuit Water Leak Close Call**

"When routine problems are occurring you are in a rhythm of solving problems - when everything is going well you drop your guard – that's when you are most vulnerable." This circumstance was realized on July 16, 2013, when water started leaking into the space suit helmet of Italian astronaut Luca Parmitano during Extravehicular Activity (EVA) maintenance activities. The loss of inquisitiveness and a questioning posture was cited as an issue in not following up on previous water-related anomalies. The team became "comfortable" with water in the spacesuit, a subtle shift in the traditional diligence regarding spacesuits. Clearly, failure modes existed that were not understood. Recognize that close calls are "gifts," a blessing, and a reminder to maintain vigilance. When everything is (or seems) smooth go re-examine what you think you know about critical systems. It is important to continuously challenge the team, challenge the data, go back and relook at what you think you understand, re-examine hazard mitigations – make sure they will work in a zero-g environment.

*Application to Exploration:* The cautionary comments are relevant now and in the future for all high risk space exploration activities.

***37-Lesson: Anticipate Budget Fluctuation**

During the course of ISS development, each Partner's space station budget changed to varying degrees from the ideal profile due to national policies. The budget strategies for each Partner's program did not always take these funding disruptions into account and was a significant factor in the delay of ISS assembly completion.

*Application to Exploration:* Programs should take into account the probability of periodic budget discontinuities and disruptions among the Partners. Interim milestones which show technical achievements throughout the schedule are critical.

**Lesson: Program Management – "Externalities Happen"** (5)

"Reasonable budget reserves and schedule slack" are critical to guard against the "inevitable externalities" beyond the control of the Program Manager. Congressional action or inaction (continuing resolutions), or re-direction from OSTP may at any time upset carefully planned budgets and schedules.

*Application to Exploration:* Plan for the inevitable - develop and maintain margin for cost and schedule.

**Lesson: DDT&E Startup Transients Can Be Chaotic – Get Used To It and Don't Panic**

ISS provides a recent reminder of how chaotic DDT&E can be (from both the government and contractor perspective) and the tools and processes necessary to manage the chaos, the churn, and uncertainty which are a natural state of a program in this phase of the lifecycle. Even with an experienced contractor like Lockheed-Martin for the Orion Program, NASA experienced many of the same natural startup transients as ISS – e.g., the potential process overload when you go from 20 drawings to 600 a month. The Orion employees that were previously part of the ISS Program during the early Node 1 and U.S. Lab DDT&E timeframe knew what that was like and what strategies worked during DDT&E implementation, which was of benefit to the Orion Program. ISS DDT&E was impacted by a major redesign, the addition of a new partner, and a major program cost overrun. These scars and bruises are useful memories for managers and engineers who are involved in future programs because they can use the lessons to minimize the "churn" in future programs. They can dampen out these issues by communicating with the workforce, providing stability, and providing the capability to predict risks based on lesson learned.

*Application to Exploration:* Having personnel accustomed to the ISS DDT&E experience is a benefit for new programs and projects because they can apply lessons learned from their previous experiences to reduce the risk of natural "startup transients."

## Internal Communication

**Lesson: Cultural Changes in Different Phases of Program and the Impact on Research**

Early in program development there is a "design culture" through the processes of developing requirements and proceeding through a set of technical reviews (Systems Requirements Review (SRR), Preliminary Design Review (PDR), Critical Design Review (CDR), etc.). For ISS, we then got to the assembly phase, or "assembly culture," which was quite long. During this phase everything is very hard – life is at risk during assembly missions. This requires an incredibly high-performing engineering and operations team and the main concerns are loss of mission or loss of crew. On ISS, the teams became so used to this and the culture of the organization in this phase was not focused on research. As we came close to assembly complete, the Program Manager, in consultation with the teams, had to perform a reorganization to shake the teams out of the entrenched assembly mentality and culture and start people thinking about the research mission of the vehicle. It is important for all participants to align around the research-focused mission – this includes logistics, planning, mission operations, and so on.

*Application to Exploration:* The organization should be prepared to actively manage the cultural changes between program phases, recognizing that the changes from design to assembly happens more naturally, but from assembly to research there may be significant start transients if not effectively managed.

**Lesson: Importance of Technical Interchange Conferences with International Partners**

The ISS Environmental Control and Life Support System (ECLSS) team highlighted the importance of maintaining active interchange between international partner technical communities. Every interviewee emphasized the importance of developing personal relationships and trust with international partners. Open exchanges will also stimulate thought on design options and alternatives while promoting conversation across often stove-piped technical disciplines.

*Application to Exploration:* Exploration will inevitably involve international participation. Interchange at the technical level will be as important as the development of MOUs and agreements at the diplomatic and Agency levels.

***25-Lesson: Establish Export Control Practices Early**

Frequently, program-related information needs to be exchanged that is likely to involve trade secrets or intellectual property. The imposition of International Traffic in Arms Control (ITAR) created difficulty for all ISS Partners in getting ITAR-classified data from NASA contractors. The added costs and delays needs to be averted to the maximum extent possible by avoiding inclusion of broad-brush classifications or by being more specific on those elements that really need to be export control protected.

*Application to Exploration:* Ensure workable provisions for export control are established early in exploration programs.

***26-Lesson: Improve Technology Transfer Procedures for Common Interfaces**

There were numerous obstacles in transferring technical information regarding the common interfaces.

*Application to Exploration:* Improve the procedure for technical information transfer related to common interfaces.

***27-Lesson: Improve Data Sharing Practices**

In the ISS program, a number of hardware components were procured from foreign countries. Export controls of some countries often constrained technical information transfer and led to delays in schedule and increases in development cost.

*Application to Exploration:* Common hardware will continue to be procured overseas in the exploration program. A comprehensive framework for technical information transfers is needed, in order to simplify procedures, reduce cost, and accelerate program implementation.

## External Communications

### Lesson: "Relentlessly Communicate Intangible and Especially Tangible Benefits"

The interviewee stressed the importance of continually communicating the benefits of any future exploration mission to the Congress and White House. While NASA has traditionally done well in communicating intangible advantages, it was observed that tangible benefits have not been communicated very effectively. Of particular utility will be emphasizing the tangible benefits related to: Guidance, Navigation & Control (GNC) systems, data management systems, communication systems, robotics, energy efficiency and thermal control, and environmental control and life support systems.

*Application to Exploration*: Future exploration missions should certainly highlight tangible contributions to the areas discussed above as well as the easier set of intangibles (e.g., inspiration, discovery).

### Lesson: Fly as Fast as You Can

The Functional Cargo Block (FGB) and U.S. Node 1 were launched almost two years before the Russian Service Module. Many junior employees thought this was an unwise decision at first. However, it was really important that ISS got the flight phase started as early as possible. From an operational standpoint, the U.S. and Russian mission control centers were able to fly this rather uncomplicated vehicle in an X-nadir spin mode, but more importantly they were able to interact for 18 months or so in an operational setting which exercised real-time operations, planning, engineering, and management communication paths and forums. Perhaps more importantly, it demonstrated to stakeholders that the program was now coming out of the DDT&E phase into an assembly phase in space. To reinforce the notion that we were on a path to a habitable space station, the STS-88 flight crew timeline included entering the Node and FGB during the first assembly mission.

*Application to Exploration:* It is important to visibly demonstrate progress early on in a long-duration exploration program. Stakeholders, including Congress and the American public, need positive reinforcement that their tax dollars are actually achieving the desired objectives.

### *38-Lesson: Recognize the Criticality of Strategic Communications

Active management of strategic communications concerning the ISS is critical. Current conditions require a formal commitment by management to manage all facets of the programs' communications. To avoid crisis, or to respond expertly and in a timely manner, to unplanned events requires a dedicated, proactive team with expertise in all areas.

*Application to Exploration:* In addition to a highly structured array of boards and reviews for technical aspects of system development and operations, thought needs to be paid to developing an effective mechanism for coordinated strategic communications on exploration programs.

***39-Lesson: Support Public Relations**

Public relations (PR) activity is particularly important in large and expensive programs like the ISS. Smart and well thought-out PR activity is a useful way to minimize the non-profitable character of human space flight by offering intangible benefits.

*Application to Exploration*: Many people are ready to accept and support the idea of exploration if it is attractively offered. Joint efforts of all Partners should be thoroughly communicated.

***40-Lesson: Include Flight Crew in Public Relations**

In the ISS Program, public relations are playing an important role to gain the understanding and support of the general public. In particular, having the flight crew talk to citizens around the world from the ISS has a great impact through inspiration.

*Application to exploration:* In the space exploration program, enabling flight crew interaction with the public at an early stage of the program would be highly effective. There is also a need to inform the outcomes of the space exploration program to the general public in each participating country efficiently and widely.

***41-Lesson: Include Educational Projects in Public Relations**

Activities involving education have been very important to the ISS program and play a significant role in contributing to a scientifically literate society. ISS outreach and education programs have directly involved teachers and students in a variety of contexts (e.g., contests, classroom lessons, publications, educational kits, etc.).

*Application to exploration:* Educational activities performed on the ISS can be linked to the exploration beyond earth orbit. This requires a joint effort by all Partners and necessitates starting promotion and outreaching activities from the very early stages.

***42-Lesson: Include Tangible Benefits with Early Visibility to the Public**

Public support and understanding of the ISS program declined because it took 20 years from the start of investments in 1987 to the deployment on orbit of international Partner elements.

*Application to exploration:* For the future exploration program, it is desirable to establish a program whereby the outcomes from contributions and investments by international Partners can be obtained and become visible to the public as early as possible.

***43-Lesson: Plan Early Achievements to Sustain Political Support**

The ISS program was ambitious and developed over a significant time period. Much of the emphasis was on the final goal to complete assembly. As a result, political support tended to weaken at times.

*Application to exploration*:  Future exploration programs should include major milestones in segments with clear objectives to be achieved in the short, medium and long term.  All Partners should coordinate this in a joint communication plan.

## DDT&E

## Mission Architecture

**Lesson: "Stage Your Objectives"**

Avoid a big reach, "all or nothing approach." Rather, develop an architecture that will ensure achievable capability plateaus along the way toward a greater objective. This incremental approach will increase the likelihood that early success milestones are achieved. Further, establish success criteria that will be reasonably achievable – under-promise and over-deliver.

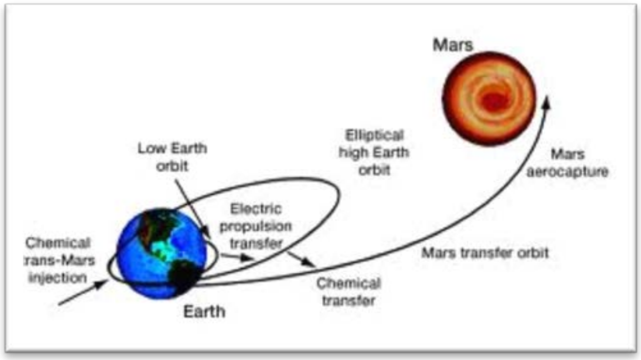


*Figure 5. Notional Mars Mission (NASA)*

*Application to Exploration:* A step-wise strategy will assist in establishing early political and public support and mitigate toward full funding for successive objectives.

**Lesson: Mission Requirements Database (MRDB)**

Develop, evolve, and formally baseline a MRDB to use in conducting design studies for key factors including power, crew time, thermal, data and communication, as well as spacecraft volume. Requirements creep can be managed by demanding traceability of all requirements back to the MRDB.

*Application to Exploration:* With volume and mass limitations it is critical to maintain rigorous control of the functional requirements baseline. The MRDB will be used often to vet and control introduction of new requirements.

***2-Lesson: Establish Realistic Expectations**

The purpose of the mission should be defined as thoroughly and clearly as possible with planned achievements that are commensurate with planned spending. It is particularly important not to overestimate the mission objectives and scientific outputs.

*Application to Exploration:* The goal for each space exploration program must be realistic and well- articulated to include the global problems that the mission will help to resolve. For example, if the goal of the mission is scientific research, integration of the Partner research programs can help in meeting this requirement.

***3-Lesson: Employ Reference Missions to Define Requirements**

Reference missions developed in cooperation with all Partners were useful in identifying unique and common requirements. These requirements needed to be defined, in order to develop an architecture that met the needs of all Partners.

*Application to Exploration:* Reference missions and requirements need to be defined in cooperation with all Partners, in order to accelerate and materialize the on-going joint study of the architecture for international human exploration. Reference missions that reflect the stated goals and maximize accomplishments of common Partner objectives should be defined in cooperation with all Partners. They should demonstrate how international cooperation advances accomplishment of goals and objectives.

***4-Lesson: Use Clear Mission Objectives to Drive Support**

Properly formulated mission objectives (i.e., they are ambitious, attractive and achievable) will ensure stable political and social support. Stages of mission accomplishment must be timely with achievements reported promptly and comprehensively. Continuous progress toward achievement of mission objectives must be observed.

*Application to Exploration:* Exploration programs should establish clear intermediate objectives in time-phased stages that show consistent progress toward overall mission objectives.

***5-Lesson: Allow Mission Objectives to Evolve Gracefully**

As mission objectives evolve over time, the impact of changes to the mission objectives of the other Partners need to be considered since individual Partners have differing objectives. Mission objectives should be flexible enough to make maximum use of spacecraft elements as the program evolves with better understanding of capabilities and resources.

*Application to Exploration:* Periodic review of the mission objectives is needed and Partners should re-affirm or re-align as needed.

***7-Lesson: Establish Appropriate Interdependencies**

Interdependencies are beneficial when they leverage a Partner's investment to accomplish a more robust mission than the Partner could have achieved had they remained independent. For example, interdependency in Mission Control Centers and flight crew brought new achievements for the program. However, it is very important that interdependencies be appropriately established with respect to the Partner contributions. Over-dependence on a single Partner for a critical element does not promote program stability and changes in key areas such as engineering interfaces, element readiness dates, and flight schedules can add unplanned cost and delays.

*Application to Exploration:* Partners should seek interdependencies where they are essential or beneficial to the exploration mission; however, critical elements must be ensured in each Partners contribution and single sourcing of critical elements should be avoided whenever financially practical. The trade between Partner autonomy and mission effectiveness is especially critical in human exploration due to the large investment.

***8-Lesson: Avoid Elements on the Critical Path that Cause Interdependency**

Interdependency may entail Partners depending on each other's contributions to achieve mission success but having a single Partner contribution on the critical path should be avoided. Interdependencies are best if balanced (equal Partners), long-term oriented (based on clear predicted needs), and flexible (allow for contingencies) with changes quickly communicated (allows time for reaction to minimize impacts). An international framework of joint strategy and contributions is key to program stability.

*Application to Exploration:* A better mix in the contribution between system and utilization infrastructure would be more suitable. Duplication of capabilities between at least two Partners in key strategic areas, corresponding to their financial and technological capabilities, would be preferred.

***9-Lesson: Redundant Transportation Commitments**

The ISS program clearly demonstrated how transportation resources affect all Partners. Constricted transportation has long-term implications that may limit the capability to operate, maintain and utilize the ISS. Transportation should have been treated as a core system that was a fundamental commitment to the partnership rather than a unique program. Dissimilar redundancy in transportation has been critical to the preservation of the ISS.

*Application to Exploration:* Future exploration programs must be structured with alternative transport vehicles, so there is no particular system that becomes a single-point-of-failure.

**Lesson: Deep Space Mission Design: "Plan on Bringing the Tools"**

Thinking far into the future one interviewee discussed the concept of exploring the "space frontier environment" with a concept of operations based on bringing tools, critical raw materials, and hard to manufacture items (such as computers), minimizing on board supplies and spare parts, with plans to use native resources at the destination for habitat construction and other needs.

*Application to Exploration:* The exploring the frontier concept will logically flow from architectural considerations into design tradeoff analyses concerning reliability, spares, consumables, mass, and volume as well as crew capability, training, and operations concepts.

## Engineering Design

**Lesson: We Have to Have Robust Vehicles**

"We have to have robust vehicles that the crew can figure out and fix with the parts and tools they have with them."

*Application to Exploration:* Relative to the ISS, future space exploration missions will be even more constrained with respect to logistics and stowage, so it will be extremely important to have robust systems that can be repaired with common parts and tools.

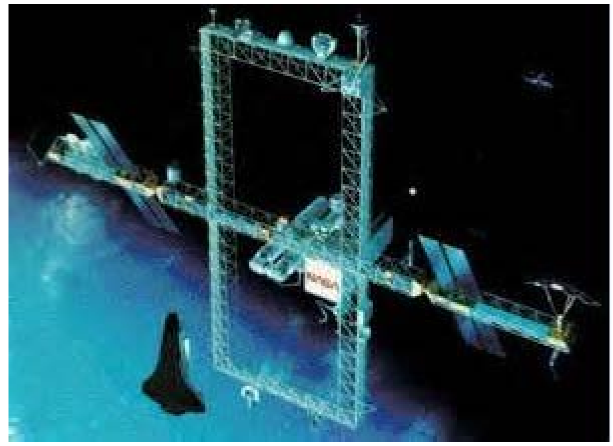

*Figure 6. Early Design of the International Space Station*

***12-Lesson: Employ a Robust Design**

The modularity of station elements provided the needed configuration flexibility when the program faced budgetary and political challenges. This architecture provided long-term operability and reliability robustness for critical systems. However, the station architecture also relied on critical path elements for which there were no alternatives. The delay in delivery of those also delayed achievement of mission objectives.

*Application to Exploration:* In order to meet the mission objectives, the architecture should be robust and flexible enough to take into account the potential loss of a key function (e.g., transportation) for many months, or the loss of any single deployable element. The architecture should include redundant and dissimilar critical functions.

**Lesson: Design for Autonomy**

"The whole concept of ISS is for it to be controlled from the ground. For a deep space mission, I don't think you want that - there will need to be a different approach. Fundamentally, the vehicle will need to be designed using a concept wherein the crew is largely autonomous with only limited support from the ground."

*Application to Exploration:* Design of deep space mission hardware, software, and CDH protocol must be architected and designed for largely autonomous operation.

**Lesson: Temper complexity – Keep it Simple on Front End**

It is essential to get off on the right foot and achieve an initial "win." Overly complex program architecture and design can render a program vulnerable to cancellation. Program complexity may include requirements uncertainty, requirements creep, and requirements complexity. Lack of an initial win along with baseline "flail" makes any program vulnerable and can lead to loss of political support.

*Application to Exploration:* Planning for future exploration missions must introduce a "keep it simple" philosophy as an element in tradeoff analyses. Once well established and successful, the program can expand and extend in terms of capability and complexity.

**Lesson: Start Simple, Build from There; Employ a "Smart Lego" Strategy**

Consistent with the notion of "keep it simple," strive to develop space systems that are: 1) simple robust designs; 2) capable of autonomous station keeping; 3) modular; and 4) expandable.

*Application to Exploration:* Exploration missions will inevitably require multiple elements assembled and integrated in low earth orbit, or in the case of a lunar outpost, multiple elements assembled on the surface of the moon. The notion of modularity and common international interfaces for both docking and distributed systems is an important consideration.

**Lesson: Concepts of Operations (CONOPS) Needs to Feed the Design**

Every interviewee identified the need for a design that better incorporates operational scenarios – Concepts of Operations (CONOPS) - and the need for near autonomous operations and in-flight repair capability. The CONOPS should address all areas including flight operations, logistics, maintenance, stowage, utilization, habitability, and medical operations. All these areas are impacted if the operational scenarios are not factored into the design in the beginning.

*Application to Exploration:* The design requirements definition process must be as long as necessary to conduct trade-off analyses that render a practical design baseline that addresses often competing or conflicting higher-level goals and objectives.

**Lesson: Software Design Must Be Flexible**

"You're going to have problems and the software needs to be flexible enough that you can update changes and you can react to different parts of the program and failures that you have. If you have a good designer, there is the capability to go in and alter the way that the systems work if the software is flexible enough. So there needs to be a lot of attention paid to – 'how am I going to react when I start having problems?' because there's nothing you can really do when you're that far away."

*Application to Exploration:* The software architecture of future deep space exploration systems must be flexible enough to allow crew response to unanticipated problems and designated crew members must possess the programming skills.

**Lesson: Ensure that Design Enables Failure Response**

Ensure that systems are designed, to the extent possible, to have compartmentalized, non-cascading failure modes that "buy time" to implement "simple, dumb, stupid" emergency response (manual) procedures and backup systems.

*Application to Exploration:* The implementation of Failure Modes, Effects and Criticality Analysis (FMECA) will necessarily play a key role in design trade-off considerations.

**Lesson: Design for Storage and Trash in the Operational Context**

Interviewees noted that stored items radically expand in volume once opened and if not re-compacted as trash for disposal will occupy a greater volume. Expanded material then will pose an active storage problem, potentially blocking ventilation systems and impacting life support functionality. Once again, the need to carefully consider CONOPS in the early design phase is underscored.

*Application to Exploration:* As noted above, realistic operational scenarios that represent the day-to-day operational environment must be incorporated into vehicle design and layout.

**Lesson: Maintain an Availability Mindset in Architecture and Design**

Availability is the product of Reliability & Maintainability Analysis. It is essential to examine the tradeoff between reliability and maintainability with the goal of arriving at the highest level of availability. This is particularly important for distributed systems such as data management, thermal, electrical power, and guidance navigation and control.

*Application to Exploration:* Deep space mission architecture will unavoidably need to "design for availability," which in turn will convey the need for crews trained in repair procedures and linked to spare and storage design as well as in-flight manufacturing capabilities.

**Lessons: Vehicle Design – Maintenance**

"The ISS design required huge support from ground." The design should not require 27 people in a control room monitoring telemetry for relatively simple repair or maintenance tasks. The need exists to move toward a paradigm where ground control is conducting strategic analysis and monitoring while the crew is performing tactical functions without extensive supervision.

*Application to Exploration:* The concept of Design for Maintainability is an essential element in architecting an efficiently operable deep space crewed vehicle.

**Lesson: Vehicle Design – Logistics**

ISS was not system optimized from a logistics standpoint. For example, there were way too many types of fans. ISS needed one fan – not necessarily optimized for each function – but rather good enough for multiple applications. This same concept needs to extend to fasteners – commonality needs more prominence in system-level design planning. ISS design decisions have led to the need for micromanagement of both operations and logistics. Future space exploration systems will require a much greater degree of computer automation to support maintenance and logistics.

*Application to Exploration:* Operational logistics considerations must be fully integrated into design decisions.

**Lesson: High-Reliability, Autonomy and Reliance on the Ground – The Carbon Dioxide Removal Assembly Case Study**

Having high-reliability system capabilities, especially environmental control and life support systems, as well as having enough information onboard such that the crew is as autonomous as they can be will be critical for future mission success. Early on in ISS operations, the ISS flight control team thought they understood how the Carbon Dioxide Removal Assembly (CDRA) system would work. A set of nominal procedures, a set of malfunction procedures, and a set of in-flight maintenance procedures were developed and the crew was trained heavily on this system. Unfortunately, the CDRA has not failed the same way twice which tends to perplex the crew and flight control team. This requires the team to call in the design engineers and specialists and have extended conversations on the ground to determine what failed.

*Application to Exploration:* The technology selected for deep space missions must be ultra-reliable. It also must be thoroughly tested such that we understand each of the failure modes and their repair viability. Accompanying the hardware should be an information/data package that may be stored on-orbit along with training materials and procedures for the crew.

**Lesson: Logistics Supportability Analysis (LSA)**

LSA is a body of activity aimed at identifying resources needed in order to support the hardware as well as identifying crew operator tasks, parts, and tools (unique and common). In addition the LSA identifies how much crew time is going to be needed in order to conduct maintenance, not only at an aggregate level, but also at an individual sub-system level. The LSA also considers predicted reliability and informs the design team concerning ways to either improve the reliability or to make systems simpler to maintain.

The LSA also serves to support program management as the program evolves and progresses through its various design milestones (PDR, CDR and so forth). In the typical Department of Defense (DoD) program the LSA Records (LSAR) document evolves into tech manuals. In the case of ISS this did not happen. Instead we took the LSAR body of data, maintained it, enhanced it, and worked with the Mission Operations Directorate flight controllers to build the crew maintenance procedures."…we skipped that entire "build the tech manual" step simply by enhancing the existing data we had. The beauty of it on a program like ours is, as the station continues to get maintained and sustained and gets various design changes and upgrades, those engineering changes then get fed back into the LSAR, which then get reflected in those maintenance procedures. So it greatly reduces any opportunity for error in the maintenance procedures that get handed to the crew.

*Application to Exploration:* LSA will be an important discipline to implement as part of the overall vehicle design and Integrated Logistical Support (ILS) process providing the basis from which to develop excellent crew maintenance procedures. As planning evolves for future space missions one might anticipate LSA evolving into manuals and eventually video modules.

**Lesson: Vehicle Design – Inordinate Amount of Time Environmental Monitoring**

"On ISS we spend a lot of time, way too much time, conducting environmental monitoring," – testing water, testing air, conducting noise exposure dosimetry, monitoring CO2, calibrating oxygen sensors, swabbing surfaces, and/or changing batteries. We need to find a way to automate these activities in a way that is intelligent and efficient.

*Application to Exploration:* Again, system designers need to engage with operators early in the design process to assess how design decisions ripple into operations and impact crew activity timelines. Environmental monitoring should be automated to the extent possible within budget constraints.

**Lesson: Vehicle Design – Habitability**

ISS has proven "functionally, not too bad" in its habitat design with a number of noted exceptions. The circular sleeping layout may need rethinking to afford greater privacy. The locations of the kitchen and exercise treadmill in close proximity to the toilet were not ideal. An additional habitat design issue is lighting – "there is no floor in space" and some of the areas that needed better lighting may have been overlooked because of the gravity based design bias. A final habitability issue of note is the overabundance of trash. "Way too much trash" is sent to orbit in the form of packaging that must then be stored and disposed of.

*Application to Exploration:* Habitation layout and habitability must be thoroughly evaluated with a multi-skilled team of reviewers including operators, behavioral scientists, and system and sub-system designers.

**Lesson: Vehicle Design – Habitat, Privacy and Personal Space**

"…If you are a program manager for a human space flight program you do have to put the human front and center. The food, water, oxygen, habitability, privacy requirements all move forward to accomplish a very successful mission. Talking about exploration 36 months and billions of miles away from our planet, I think you want to put the human in the best possible position to be successful and reduce the stresses that you can control, because there is a lot we are not going to be able to control that they will be challenged with. Privacy and personal space is critical. Habitability is very important in terms of your space, having a small space that you could have and consider your own - decorating with some pictures of your family, some mementos from home to give you that solace and comfort. Noise abatement is also significant, not only to protect your hearing but to enable rest and relaxation…"

*Application to Exploration:* Habitability, layout, and consideration of crew comfort and privacy must be "front and center" in the earliest phases of design for long duration space missions.

**Lesson: Unpredicted Space Operating Environment**

In a 2009 paper by Sanchez and Voss, the authors discussed surprises encountered on ISS regarding unpredicted thermal environments which resulted in changes to ISS operations to create shadow zones. The authors also discussed the radio frequency (RF)-multipath issues associated with the ISS operating environment. Flexibility in operational attitudes and establishment of RF exclusion zones provided mitigation.

*Application to Exploration:* Despite years of space-faring experience and sophisticated thermal design analysis, the ISS encountered problems. Future exploration mission design must anticipate unknowns in the deep space environment and ensure that design margins and operational flexibility offer a way to mitigate or respond to the challenge.

**Lesson: Reliability Verses Redundancy: Common Cause Failures**

"You need to pay a lot of attention to the reliability of the concepts versus the redundancy concepts that you have to achieve the performance that is necessary for a long duration. Let's say you have a triple redundant system degraded by a single radiation burst, it might take all the redundancy out in one stroke. So you need to carefully consider how you manage and the solution for redundancy versus reliability, that's critical."

*Application to Exploration:* Unlike redundancy must be considered as an essential design requirement for critical systems along with demonstrated high reliability.

**Lesson: Design Trade-Space**

In a 2009 paper by Sanchez and Voss, the authors emphasized the importance of design trade-off analyses to carefully evaluate multiple variables including: autonomy, dependency on ground controllers, complexity, automation, reliability, redundancy, availability, repair, crew training, crew time, stowage, spares, logistics, cost, volume, convenience, efficiency, ease of use, and waste. The authors recommended "modular system design with commonality between components" as a goal in seeking optimum solutions.

*Application to Exploration:* Architectural studies will necessarily have to consider the entire set of variable discussed above as well as others.

**Lesson: "100 Screws to Get to the Motor!" – Design for Maintainability**

When the ISS exercise treadmill required repair of a motor it was necessary to remove (and replace) over 100 individual screws. This example underscores the need for implementing a design for maintainability (DFM) philosophy, especially for safety critical and life-support systems and sub-assemblies. Notable interviewee quotes include: –"Drive it Up-Front" (early in the design process) and "Design in the Support or Support the Design," implying the need for DFM or planning for crews to dedicate significant day-to-day efforts performing maintenance – and "ILS must be there on Day-1."

"… You need to think about the worst case of getting below a certain level in an Orbital Replacement Unit (ORU) that you never thought of and that three pound motor took a couple of hours to replace, not just because of the screws, but how it was embedded inside of that treadmill. So the lesson is, if you think it's going to break at a lower level and you're not going to have that operational capability that maybe you thought you would have somehow to fix it with software, access to the lower level is something you need to consider when you design hardware for space. …"

*Application to Exploration:* Many ISS items that were not designed for repair (because of Space Shuttle upmass/downmass capability) eventually ended up being repaired on orbit. With limited logistics for deep space exploration, the design of future space exploration hardware will necessarily need to adopt a robust DFM philosophy throughout design - that minimizes number of individual parts, number of steps, "time-to-repair," and articulates necessary crew skill and training requirements.

**Lesson: ILS Must Influence Design and Tradeoff Analyses – Design for Supportability (Maintainability)**

ISS ILS experts underscored the need to ensure that ILS requirements are afforded a more prominent role in future space system design with ownership of specific "Level-1" maintainability requirements flowed-down to NASA design-Centers, contractors and Government Furnished Equipment (GFE) providers. Interviewees noted that requirements for supportability, maintainability and reliability must start with the highest level program document and flow down to the lowest level specification.

*Application to Exploration:* It is worthwhile to revisit the extent to which the ESD Orion Project (Multi-Purpose Crew Vehicle) has embraced the DFM mindset and the degree to which maintainability and supportability requirements have been included in the design. Specific lessons may be available for the next generation crewed space system.

**Lesson: Hardware Commonality – "Design Requirements from Day Zero!"**

Interviewees noted that "almost no standardization requirements were levied on ISS, as they were considered a constraint on design. Consequently each manufacturer used their "usual" parts and materials, leading to a proliferation of parts and material types, as well as orbital replacement unit (ORU) interfaces. The lack of commonality drove parts cost, as well as costs associated with design documentation, packaging & handling. Specific benefits accrue in terms of operational maintainability, flexibility, and the ability to respond to known-unknown contingencies that may arise. The DoD B-2 Bomber Program was cited as an example of a Government agency successfully imposing top-down commonality requirements over the inevitable protests from individual design centers and their contractors. The NASA culture of strongly autonomous Centers is seen as a barrier to establishing commonality requirements. These same "cultural forces" can be seen as resisting program system-level requirements that go beyond defining interfaces.

*Application to Exploration:* Future exploration endeavors must strive for greater commonality in parts, connectors, components, assemblies, and interfaces. Commonality requirements should be levied on all elements, including crew transport vehicles, cargo vehicles, habitats and laboratories. The value of imposing commonality standards is self-evident, especially for a deep space exploration mission where flexibility and improvisation will be important to crew response in a contingency. Once again, the Agency and the HEOMD organization must support engineering management and SE&I functions in imposing workable commonality standards.

**Lesson: Dissimilar Redundancy in Life Support Systems**

U.S. and Russian segments of the ISS provide dissimilar redundancy in life support systems. When a component in one fails, the other can pick up the burden while repairs are underway. The key is reparability – in the case of the U.S. carbon dioxide scrubber, a Line Replaceable Unit (LRU) (zeolite bed) change-out is required. The Russian system has routine failures but repairs require only simple maintenance. Recommended future system design goals: "simplicity, robustness, and reparability."

*Application to Exploration:* Future exploration missions life support systems need to consider unlike redundancy, but both systems must necessarily be repairable in-flight.

***19-Lesson: Plan for Flexibility in Design Life**

The design life of the ISS began as a design constraint. However, this has been overtaken by the desire of the partnership to extend ISS life. It would have been beneficial to further modularize systems to accommodate an indefinite presence in space. A system design requirement of 15 years does not necessarily dictate the system be retired in that period if it continues to hold value.

*Application to Exploration:* Agreements for long duration international missions should be reached to design for disposal and expansion and to provide the capability to replace aging, or end-of-life systems, with new and improved products for as long as the Partners need to conduct the mission.

***20-Lesson: Use Dissimilar Redundancy in Systems for Program Flexibility and Stability**

Any critical element of the program should have a dissimilar backup. During the on-orbit integration stage, redundancy is especially critical and dissimilar redundancy of functions must be ensured. This improves program flexibility and stability in case of contingencies, accidents, or delays.

*Application to Exploration:* Future long-life exploration systems should be designed as "open systems" based on modular infrastructure with capability for the modules replacement through uniform interfaces

***21-Lesson: Establish Dissimilar Redundancies Early in the Program**

Operation of the ISS stabilized when dissimilar redundancy in systems (e.g., transportation, environmental control and life support, etc.) was achieved. Unfortunately, this occurred relatively late in the program for some systems.

*Application to Exploration:* The necessity for dissimilar redundancies in all critical systems could be much higher as exploration expands outward. To sustain the program in a stable state, these redundancies may be necessary for some critical functions at an early program phase.

***22-Lesson: Apply Dissimilar Redundancy to Critical Systems Comprehensively**

Critical functions for dissimilar redundant systems in the ISS program included crew transportation, life support, power generation, cargo logistics, communication, launch facilities, control centers, data management, countermeasures, and in-situ resource generation.

*Application to Exploration:* In human exploration, both dissimilar redundancy and robustness for the critical functions are necessary because they affect crew safety and mission success. In order to identify the underlying strategic implications, an analysis at the total system level with identification of critical risks, definition of acceptable risk levels, implementation of mitigation concepts, and ultimately trades between robustness and dissimilar redundancy is essential.

## Technology and Materials

**Lesson: Technology Maturity**

"I think with technology readiness and technology maturity we, as an agency, need to do a better job on being more rigorous in asking ourselves how ready technologies are when we get into a flight program. I think there are cases where we underestimated that in Space Station and wound up biting off quite a bit along the way, so as an agency we need to do a much better job critically assessing new technology ideas and rigorously comparing them against what we currently have available to us because once you get into a flight program it's very hard to, in the schedule of time and budget, to be able to overcome basic technology problems."

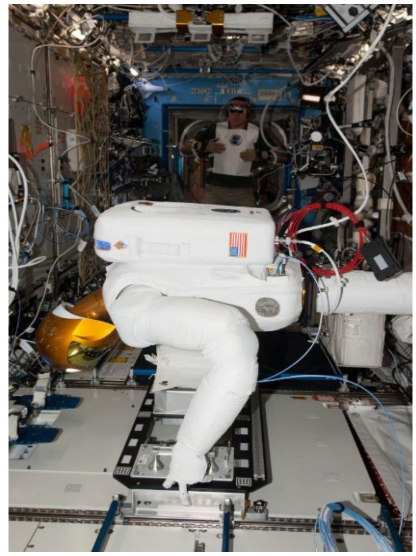

*Figure 7. Chris Cassidy Tests Robonaut 2 ISS036-E-038294 (28 Aug. 2013. In the International Space Station's Destiny laboratory, NASA astronaut Chris Cassidy, Expedition 36 flight engineer, wears tele-operation gear. (NASA)*

*Application to Exploration:* The success of future exploration missions is dependent on adhering to published cost, schedule, and requirements baselines and achieving initial operational capability on time and in budget. Technology risks must be avoided by prudent selection of proven, high reliability components and systems. Technology stretches must be avoided.

**Lesson: High Reliability Components**

"…High reliability parts, especially in the electronics world, EEE parts, used to be there was a great deal of difference between what we called space-rated parts and what we called commercial parts, and we would look down our noses at commercial parts and call it RadioShack parts. Over the past few decades the commercial parts have gotten much more reliable to the point when you look at commercial parts and space-rated parts they often come off the same production line and the only difference is the level of testing and screening. We have gotten comfortable in part because of that in buying COTS hardware such as laptops. Used to be, when we bought laptops, there was some retrofitting done in order to assure that we had the reliability that we expected. We're now buying laptops literally off-the-shelf and going through the material certification and cleaning, packaging them and launching them to orbit. So we've gotten that comfortable with commercially-made parts and the computer systems that they go into that we're able to pure COTS in many instances now."

*Application to Exploration:* Future exploration missions should leverage COTS items such as in laptops to extent practical so limited resources can be for the more challenging design and development activities.

**Lesson: Material Properties**

Environmental Control and Life Support System (ECLSS) interviewees citing pellet transformation to dust particles in a CO2 absorption sub-system noted that material physical and chemical properties need to be more thoroughly characterized for actual operating conditions and environments.

*Application to Exploration:* Again, systems and sub-systems require high fidelity testing to ensure availability of critical systems throughout the mission.

**Lesson: You Can't Schedule Technological Breakthroughs**

You want to minimize reliance on technology breakthroughs and focus higher technology readiness level (TRL) systems to the greatest extent possible. The ISS environmental control and life support systems were identified as problematic where the capability of the technology was evolutionary and less than adequate for some planned operational scenarios (6+ crew for 6 to 12 month missions).

*Application to Exploration:* Enabling technology (especially ECLSS) development needs to be addressed at an Agency level now and on an ongoing basis to ensure critical capabilities for future deep space missions.

***23-Lesson: Use Commercial Off-the-Shelf Products Where Possible**

An effective strategy in the ISS program was to simplify designs by utilizing commercial off-the-shelf (COTS) hardware and software products for non-safety, non-critical applications.

*Application to Exploration*: Use of COTS products should be encouraged whenever practical in exploration programs.

**Lesson: C&DH "Software was a Bear;" Software Architecture Evolves; Stay Flexible; Think COTS**

"One of the biggest ISS mistakes was not getting off Ada." The ISS computer architecture locked into what was quickly becoming an obsolete programming language (Ada) that resulted in the need for dedicated Ada programmers and a lack of flexibility. The world has since moved on to C and C++.

*Application to Exploration*: Design of future space systems must be done in a manner acutely attuned to the current and evolving software programming environment.

**Lesson: Integration of Evolving COTS Technology**

"When we dropped the IBM solution and moved to the Draper Lab solution there was no crew work station." Ames Research Center (ARC) engineers assisted ISS managers in evaluating ISS control using a commercial laptop. This enabled on-orbit crews and ground controllers to begin using similar hardware and software for specific C&DH activities and functions.

*Application to Exploration*: Design of future space systems must plan to leverage developments and evolution in computer technologies, maintaining flexibility to incorporate changes and updates in hardware as well as operating systems.

## Interfaces, Integration, Test & Verification

**Lesson: Fidelity of Integrated End-to-End Testing**

System-level, end-to-end test scenarios must replicate nominal as well as off-nominal operational and environmental conditions, duty cycles, and durations necessary to expose latent defects and verify the hardware/software. Less than adequate test fidelity will lead to on-orbit or in-flight repair and potentially endanger the crew and mission.

*Application to Exploration:* It seems that budget issues always end up limiting the scope and duration of test programs. On the other hand, any deep space mission must arguably have a no-compromise, no-shortcut, high fidelity end-to-end system-level test program. Program managers must demonstrate leadership in bringing all stakeholders to a common understanding of the importance of the activity.

**Lesson: Integrated End-to-End Testing is Essential**

The ISS Multi-Element Integrated Test (MEIT) program was cited by multiple interviewees as an absolutely essential requirement. Many significant problems were identified and corrected during the MEIT activity. Latent defects in design emerged that are not evident in sub-system and component-level testing. Problem solving on-orbit is costly (if even feasible), leads to delays, consumes crew time, and may endanger crew safety.

*Application to Exploration:* Robust end-to-end testing should be a non-negotiable must-do in any exploration mission. The ISS concept of operation has the flexibility to change-out ORUs and troubleshoot problems with real time communications. Exploration missions will have neither benefit. End-to-end testing is the final safeguard; beyond that the crew must rely upon spares (potentially flawed) and the ability to repair.

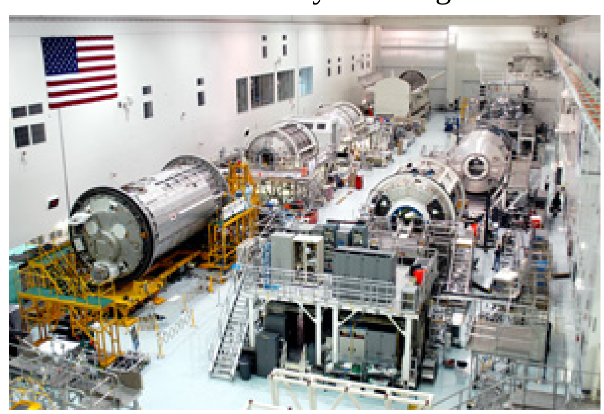
*Figure 8. NASA KSC Space Station Processing Facility (NASA)*

**Lesson: "You Can't Do Too Much Testing"**

"The more you can take all your problems on the ground, you're a lot better off because we didn't think we'd find a lot of software problems at Houston, but we found a lot and prevented a lot of problems." "You need to do the proper verification on the ground and it needs to be a rigorous verification if you're going to go to deep space in that you really try to find all of the ins and outs and make the systems fail."

*Application to Exploration:* Deep space missions will require extensive ground testing and should draw upon ISS test and verification experiences.

***13-Lesson: Apply Common Standards and Tools for Developing Interfaces**

The ISS Partners instituted a robust interface management and change control process that was able to keep track with the design of elements and distributed system across the ground and on-orbit segments of all Partners. The actual design of the station interfaces evolved around industry standards where available, but also unique interfaces were created where needed.

*Application to Exploration*: Apply commonly used standards and tools to implement and manage rigorous interface control. Only when absolutely necessary should Partners develop unique capabilities to meet unique challenges.

***14-Lesson: Apply Existing Interface Designs Where Available**

Full commonality is not necessary as historical and cultural specificity of each Partner will remain individual. However, standardization and unification of appropriate interfaces in basic spheres of interaction (system integration, power, transportation, management, etc.) are critical.

*Application to Exploration:* Interfaces already agreed to and used in practice under the ISS program should be investigated for application to future exploration programs wherever practical.

***15-Lesson: Implement Processes to Establish Common Interfaces with Modular Design**

A multi-Partner advisory team is best qualified to assess, recommend, coordinate and implement areas eligible for interface commonality before phase A, and to apply dissimilar redundancy for critical applications. This process is best addressed in international agreement documents. Also, modular design should be applied to the production process.

*Application to Exploration:* A process to thoroughly address commonality issues and opportunities should be formally established, at the highest level, early in exploration programs and a modular design approach should be encouraged.

***16-Lesson: Establish Core System Interface Documents Early**

Common core system interface documents should be generated at the onset of the program, and should accommodate design options that initially use state-of-the-art technology, but also provides hooks and scars for enhancements as technology advances throughout the life of the program.

Application to Exploration: Common core system interfaces should be specified as early as possible in exploration programs, and should include provisions for later systems upgrades as technology advances.

***17-Lesson: Minimize External Interfaces to End-to-End Systems**

Whenever possible, a single agency should design, develop, test and integrate hardware to a standard core interface as a complete end-to-end system. This minimizes duplication of effort and contractual disputes between system designers and contracting organizations.

*Application to Exploration:* Exploration programs should partition end-to-end systems in order to ensure that a single Partner manages all internal interfaces.

***18-Lesson: Verify Interface Requirements Compliance Early**

Sharing of verification closure material for interface requirements needs to be done early in the development process, in order to minimize rework. Partners should have mutual access to verification closure materials for interface requirements, and Partners should be invited to all design and test reviews.

*Application to Exploration:* Exploration program agreements should be developed to include mutual access to design and verification closure information to ensure interface compliance and suitability.

***24-Lesson: Employ Common Processes, Interfaces, and Standards**

The standardization of technical interfaces and interoperability aspects are critical to success. In the ISS program, commonality of various interfaces made it possible to simplify the interface definition significantly.

The ISS is the longest-duration international space effort to date that is available as a test bed for verification of systems interoperability, as well as international science and space exploration studies. Common partnership interfaces and standards create a common operational environment that leads to on-orbit flexibility and adaptability as situations evolve.

*Application to Exploration:* Agreements to utilize common processes, interfaces and standards are necessary to build-in flexibility and adaptability for future missions. Commonality of interfaces should be achieved as much as possible in the exploration program.

## Operations

## Logistics, Maintenance, Operations & Utilization

**Lesson: Integrated Logistics Support and Analysis**

Detailed recommendations were offered concerning future exploration missions: 1) conduct integrated logistics support analysis as part of earliest design; 2) eliminate dependency on resupply; 3) reduce the spares footprint – rely on repair; 4) be capable of repairing "anything that moves;" 5) strive for modularity, commonality, and standardization; 6) establish supportability metrics including mass, volume, number of spares, and crew time for maintenance; and 7) develop the requirement for common spares across elements.

*Figure 9. Astronaut John L. Phillips, Expedition 11 NASA ISS science officer and flight engineer, is photographed among stowage bags in an airlock on the ISS on May 18th, 2005. (NASA).*

*Application to Exploration:* The design tradeoff analyses for future space exploration missions should carefully consider the guidance outlined above. Sub-optimization may necessarily be traded for system level optimization; at the same, time critical functionalities must not be compromised. Note additional dependencies on system design reliability and similar as well as dis-similar redundancies. This phase of future exploration program architecture and planning must be very thorough.

**Lesson: Stowage and Inventory Management**

Stowage and Inventory Management has been a continuous issue onboard the ISS for many years. Crews often have difficulties finding needed tools and supplies for activities resulting in many hours spent searching for items, delayed activities and frustration. Recent efforts have substantially improved the situation, but it's extremely difficult to keep track of everything and find ample stowage space especially when a new visiting vehicle arrives. Bar coding and radio frequency identification (RFID) projects are underway for use on the ISS, but there are unique challenges due to the "radio frequency" rich environment as well as the number and size of items to be tracked.

*Application to Exploration:* Especially with larger vehicles, stowage and inventory management systems are critical for timely operations. Commercial or custom built systems such as RFID need to be deployed from the beginning to manage the tens of thousands of individual items to reduce the amount of crew and ground time spent on stowage and inventory management.

***10-Lesson: Micromanage Consumables**

Resupply, logistics and onboard stowage have proven to be critical issues for the ISS. Out of necessity, the program carefully reevaluated the usage rates for critical consumables and found innovative ways to reduce resupply requirements. Micromanagement of consumables was found to be essential to ensure adequate supply inventories. Reliability and maintenance strategies are critical.

*Application to Exploration:* Consumables will be even more critical for extended lunar or Mars expeditions because of the more limited resupply opportunities. Micromanagement of consumables and inventory will be critical and should be thoroughly addressed during the systems design phase.

## Crew Capabilities & Training

**Lesson: Crew Selection and Skill Base**

*Figure 10. Expedition 38 Crew Members Emergency Simulation Activity (NASA).*

"Back to crew selection, one thing that I thought was a factor for us and it will definitely be a factor for Deep Space, is you need people that have skills; they can repair their washing machine, they've been under the hood of their car. So there's a very short syllabus in what they call "in flight maintenance" and that sort of stuff but there isn't that much emphasis done. But we even talked a little bit about the possibility of sending people to Airplanes and Power Plant (A&P) school or work at a mechanics shop for a while. People who know their way around a toolbox are very valuable up there. We are not going to have that luxury when we go beyond low earth orbit (LEO)."

*Application to Exploration:* Multiple interviewees have emphasized the importance of ensuring that crews on long duration flights have strong hands-on capabilities and training in mechanical and electrical maintenance and repair.

**Lesson: The Crew Must Know How to Fix Stuff**

The imperative of autonomous, or near autonomous operations, will require emphasis on selecting and training crews capable of repairing failed systems. A mechanical aptitude, in addition to skills training, is necessary for the crew to be autonomous during exploration class missions where the day to day operations and the general extent of the mission is controlled locally with updates and directions coming from mission control.

*Application to Exploration:* Exploration missions design philosophy, space vehicle layout, concept of operations, crew selection, crew training, sparing, in-flight manufacturing, storage, and other considerations must enable the crew repair capability.

**Lesson: Crew Qualification and Training Must Include Software Skills**

"Testing and finding out what the problem is and being able to go in and fix it are essential; yes you need knowledgeable software savvy crew members. That should be one of the requirements for the crew members."

*Application to Exploration:* "Software needs to be written with that in mind – I've got to be able to make changes and react to the real-time situation."

**Lesson:  Segmented Operations**

The original ISS operations concept called for integrated operations across the U.S.  and Russian segments.  However, this lasted only for the first increment crew and after that we went to segmented operations where U.S. crew handled U.S. systems and vice versa.  Having an agreement on that operations concept earlier would have saved thousands of hours of training time in the early operation of the ISS.  There would have been a different training template and mindset going into early operations.  Learning the Russian segment systems from an integration and redundancy perspective with U.S. systems was useful but not in depth knowledge of their systems.

***Application to Exploration:*** It is essential to determine your operational concept as early as possible and then flow changes to the ops concept down through the entire process.  Determine upfront, through both an instructional systems development process as well as international agreements, the required training for crew and controllers.  This is particularly important if partner spacecraft are integrated with NASA spacecraft.

**Lesson:  Hands-On Immersion Training**

"[ISS crews] probably spend 80% of our time doing electrical and mechanical skill repair tasking… we get only 20-25 hours training on these skills, during  the 2 ½ years of training prior to going on a space station mission …"

In the last year, the crew office has been sending astronauts to immersion style training where they work side by side with certified aviation mechanics doing actual hands on work on airplanes.  They spend a week in the avionics shop and a week in the hydraulics and engine shops.  Following that they spend time on the hangar floor doing maintenance on the aircraft.  In these three weeks of training they get more mechanical and electrical training than they would get during years of training for an ISS mission.

*Application to Exploration:* Immersion style training should be consider a powerful tool for practical hands on skills development, not only for mechanical and electrical skills development as noted above, but also for language skills, medical operations, etc.

**Lesson:  Simulator Fidelity**

"For a spacecraft that's as complicated as Space Station, that's always in the process of changing, you can never have high fidelity equipment for every single thing that you might run across.  So, the decisions that need to be made here are to figure out what pieces of equipment need to be high fidelity and the skills you learn from those will be applicable to those pieces of equipment and possibly similar pieces of fittings and connectors that will still be used on other pieces of equipment although in a different configuration.  An example of that has to do with our CO2 scrubber.  Initially we had a low fidelity CO2 scrubber where almost nothing in this mockup was like what it was on orbit and now the Program is providing crews a high fidelity CO2 scrubber.  And this is a piece of equipment that we seem to be fiddling with quite a bit on orbit and by training crews with similar fittings and connectors with all the possible interferences and all the foam coverings needed for the low temperature tubing and all the stuff you have to deal with in this high fidelity mockup, this is an example of putting the resources, the limited resources, we have into a mockup for training so that we can get the skills that crews need.

*Application to Exploration:* Ensure appropriate level of simulator fidelity for exploration missions.

**Lesson: Operator, Specialist, and User Training**

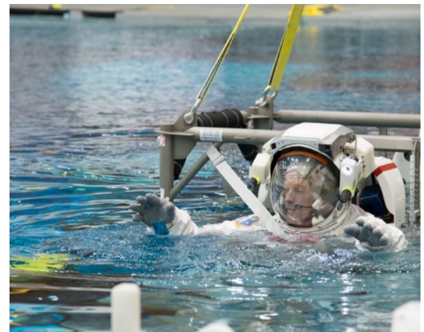

*Figure 11. Expedition 39/40 Pool Topside Training - Astronaut Steve Swanson (NASA).*

The first ISS crews were extensively trained in both U.S. and Russian systems. Early in ISS construction we were able to do this because the station was relatively small at that time. But that resulted in a four-year training flow. Subjecting crews to that long of a flow was hard on the crew from a personal standpoint and would limit their re-flight capability in the future. NASA examined ways to reduce the training flow for crew and flight controllers. The concept that resulted for crew training was that of delineating *operator*, *specialist* and *user*. An *Operator* was responsible for nominal tasks on particular system; a *specialist* would receive additional training for off-nominal tasks; and a user would receive the lowest level of familiarization training. This allowed NASA to reduce the training flow to 24-30 months.

*Application to Exploration:* Crew and controller training were critical to mission success for ISS. Consideration should be given to the length of the training template length for both and employing the ISS concepts of operator, specialist and user training may be a means of rightsizing this training.

**Lesson: Ready for training? Are you sure?**

"For the first ISS crew, the training facilities and crew procedures were not fully ready. As increments 1-4 crews were going through training, we provided information on everything we thought they needed to know based on our best estimate of the operational concepts both for individual systems and the integrated system. It was a painful startup experience."

*Application to Exploration:* Crew and controller training systems and courseware are typically deployed through an instructional systems development process that is driven by the flight hardware and software systems engineering process. It is a perennial problem in all large development programs to have training systems ready for the initial cadre of crew and controllers because of this. Exploration should endeavor to keep this gap between development of the flight system and training system as small as possible.

**Lesson: Payload Training**

"Our payload training process can be optimized a little more to help us be more successful on orbit." An initial area to consider is placing more focus and emphasis on unique and critical aspects (success factors) of the payload experiment and less emphasis on general skill-set aspects of the experiment (e.g. changing batteries).

Secondly, it is important to consider the time lag between the training and the actual use of the training on-orbit. It is not practical to assume that crew members will remember specific detailed procedures 18 months or longer after the training, however they will remember the critical success factors. When setting up the experiment they will seek out the detailed procedures. The detailed guidance may be in the form of: written instructions, pictures, conversation with experimenters on the ground, or from how-to video clips provided by the experimenters.

*Application to Exploration:* Just-in-time training, refresh-training, task-specific video support and task-specific question and answer support may be an effective complement to classroom training for activities to be performed months later.

**Lesson: Have a Good Skill Set and Get Ready For Just-In-Time Training**

Senior ISS crewmembers agree that first and foremost, ISS crews should have a good skill set. For example, you might not know how to use a special microscope but you know how to use a standard microscope. With that, you can take your knowledge and skills and apply it to the new event. You do not need to have a class on how to use the special microscope in order to figure out how to use it, but you do need just-in-time training (JITT) – watch a video or read a background paper after that you can jump right in and use it. With good background skills and JITT you can get it done expertly.

Another, related issue is the long lag time between the training event and the opportunity to use the training: "The training flow for an ISS crewmember is typically around 30 months long. Some of the training conducted early on is not put to use until on-orbit. Compare this to buying a DVD player, learning how to program it, and then not seeing the player for over two years. Will you be able to program it then? Probably not.

*Application to Exploration:* Exploration should learn from this experience and develop it further for deep space missions. Depending on the length of the training templates for deep space exploration missions, the training organization, in conjunction with the crew office, may want to consider a library of just in time training videos for use on-board. Given that communication latencies between the flight control team and the crew may be lengthy, these training products and associated procedures must be very clear and concise and not open to interpretation.

***50-Lesson: Use Available Space Assets to Conduct Training and Maintain Operations Skills**

The ISS Program used the Space Shuttle and Mir Station to conduct training and maintain operations skills**.** Now, the ISS is being effectively utilized to sustain operation skills and conduct flight and ground crew training.

*Application to Exploration*: Exploration programs should use the ISS to conduct training and maintain operations skills relevant to the future of space exploration. For example, the ISS can be used to demonstrate maintenance and repair operations mandatory as the distance from Earth increases.

**Lesson: Keep the Trainers on the Ground as Flight-Like as Possible – Use an Integrated Approach**

We do not currently do a good job of keeping flight simulators on the ground as flight-like as possible. A big part of that is stowage. On the ground, our simulators are pristine whereas on orbit the vehicle is not anything like the simulator. An integrated training simulator that incorporates all of the constraints, particularly with regard to stowage, and the realities of the configuration on-orbit would better serve the crew. This has implications for crew timelines for system maintenance and payload activities. In the beginning, it took crews two to three times as long to complete a task as was budgeted in the timeline. Part of this was due to differences in 1 versus 0 G operation, but many times this was due to the fact that tools, experiments and equipment for an operation were stowed in different locations. Individual instructors on the ground need to be aware of these limitations as well.

*Application to Exploration:* An integrated approach to simulator configuration, which included the stowage constraints, would make training more efficient as well as help crews understand the actual vehicle configuration better and the limitations on performing various operations.

**Lesson: Hiring Local Talent for Training Liaison Positions – Developing Trust**

NASA enjoys excellent liaison support at Gagarin Cosmonaut Training Center (GCTC) in Star City, Russia. This pertains to both administrative and logistics support and also instructor support. NASA ended up hiring two former Russian Training Instructors (former GCTC personnel) to assist our crews in Russia and also NASA training personnel in Houston. Their training and language expertise was invaluable to our success.

*Application to Exploration:* In the event that NASA will incorporate partner training overseas, exploration training management should reflect on the liaison office lessons learned from GCTC especially the prospect of hiring former training instructors in the partner country.

## Crew Operations

**Lesson: Crew Resource Management (CRM)**

*Figure 12. Christopher C. Kraft Space Operations center, NASA JSC (NASA).*

"As of December 2013, NASA has only 35 astronauts. This includes the 8 new astronaut candidates (ASCANs) in the pool. Only seven astronauts of the 35 have flown as commander or pilot on the space shuttle. The remaining crewmembers (minus the ASCANs) have either flown as mission specialists or as flight engineers on Soyuz. By the time we get a flyable U.S. Vehicle, we could very well not have a single astronaut left that has flown in an ascent or entry on a U.S. Vehicle. This could pose crew knowledge and skills issues for exploration missions. Crew Resource Management is the effective use of all available resources for flight crew personnel to assure a safe and efficient operation, reducing error, avoiding stress and increasing efficiency. Today, CRM is applied in U.S. commercial aviation. When you look at the CRM that NASA developed for the cockpit for the space shuttle, it is what some might call "CRM on steroids." Right now, the only kind of CRM is when we fly the T-38, which is one of our most important types of training outside of a simulator. NASA has smart energetic crew members, many with a strong military aviation background and CRM experience. However, by the time we return to crewed missions for exploration, we may not have any astronauts left that have ever flown an ascent and entry in a spacecraft. This could come at a cost – it could be lost missions, close calls or lost vehicle. It will be important to nurture, practice, and maintain the CRM competency within the astronaut corps as a core skill and value.

*Application to Exploration:* It will be important to maintain a focus on crew readiness and CRM as NASA moves towards exploration missions.

**Lesson: Crew Autonomy – More Flexibility Needed For Exploration**

"If you look at how scientists work in Antarctica they have a basic mission, a leader and they figure out what needs to be done. After a short morning briefing you get to work , then you go to lunch, brief again and then go back to work in the afternoon. At the end of the day you discuss the day's activities. On ISS we don't do that. We brief, but our days are orchestrated in a highly regimented way that is not optimum for how humans actually accomplish work. The next frontier when we go away from earth, the moon or mars, we can capitalize on what we have already learned. But we are going to have to become more autonomous and more like a classic British expedition sailing about the world for a couple of years where you had to be able to make your own decision and figure out how to survive given the tools, equipment and knowledge that you set sail with."

*Application to Exploration:* The crews of exploration missions will have more autonomy from mission control. The operational paradigm of detailed planning for every crew activity should be examined in favor of a less orchestrated approach. The ISS has begun transitioning some tasking to a less orchestrated approach. To really flourish in the space frontier we have to have robust vehicles that the crew can figure out and fix with the parts and the tools that they have with them. And you have to have a management structure that allows outside the box thinking.

**Lesson: Be Wary When You Are Not Having Problems**

ISS is currently operating without significant problems. Nonetheless, minor problems, close calls, and mishaps continuously inform the program that "you may not understand as much as you think you know." The program is continuously introducing failure exercises or events to maintain crew and ground controller emphasis on potential failure modes and recovery scenarios.

*Application to Exploration:* Exploration missions will require much greater crew autonomy and will continually test crew flexibility and skill-based knowledge to solve problems. Crew training will have to provide extended anomaly response and resolution training and in-flight operational regime must incorporate continuous anomaly response and resolution exercise.

**Lesson: "You Have to Be Able to Manufacture Piece Parts"**

Reparability is key to the availability design because space and volume for spare parts is limited. The 3-D printing experiment and additive manufacturing currently onboard ISS is a first step toward developing an in-flight manufacturing capability. More needs to be done to develop this technology, especially in moving from plastic to titanium (or other metals) powder production capability.

*Application to Exploration:* 3-D printing is absolutely an enabling technology for deep space missions.

**Lesson: Undocumented Assumptions, Culture and the Impact on Operational Behavior**

"When you have an accident or a malfunction on-orbit, it often has to do with undocumented assumptions – people assume something behaves in a certain way and it doesn't. Often when we go across cultures among the ISS international partners, the likelihood of this increases and there might be fairly subtle differences. It is not just important to understand the technical but also the cultural, operational behavior of your partners. Crew authority versus the ground control team is a prime example from ISS – some crew members have had much less authority to call a stop than we are accustomed to on the NASA side. If you assume, even at a high level, that they are going to behave like we do in the midst of an operation, you can find out that that is not the case. While we did not have an incident, these assumptions can lead to serious mistakes and call for documenting them."

*Application to Exploration:* The planning and preparation for real time operations should accommodate the cultural differences between partners. These differences should be well understand and to the maximum extent possible, documented to minimize and control risk.

**Lesson: You Have to Have a Mindset that You Don't Always Come Home When Scheduled; You Have to Set Expectations with Your Family as Well**

The Columbia accident and other examples were cited concerning the need for crew to have pre-established expectations that any mission may be extended due to unplanned circumstances. "From an ISS learning point, you have to have a mindset that you don't always come home when you are scheduled to and you need to be okay with that. Also you have to be willing to live in a severely rationed supply environment."

Extension of missions will inevitably dictate changes in diet and housekeeping routine. Crew members will be tested in terms of their flexibility, resiliency, and sense of humor. "Missions can be extended at the drop of a hat, like after Columbia and after the Soyuz was damaged during ground processing and your family has expectations that you will be home at a certain time, but that gets extended – you have to be able to set those expectations with your family as well."

*Application to Exploration:* Long duration missions certainly may end up being even longer than planned. Crew must be very carefully vetted and selected, and be prepared to face difficulties, deprivation, and long separation from loved ones.

**Lesson: Development of an operations concept early in the system design—the Portable Computer System (PCS) Story**

After ISS redesign there was a requirement to have command and control of the vehicle via portable laptop computers. The U.S. segment utilizes seven PCS laptops connected to the 1553 bus. On the Russian segment there are seven laptops used to command the Russian elements. Eight laptops are utilized in the Japanese modules and two additional laptops are used in the European modules. By allowing different interpretations of the requirement for PCS control of the ISS, the partners created four different laptops, with four different operating systems, four different graphical interfaces, and four different support structures for updating the software. This also increased the amount of time required to train crew members.

Another takeaway – "…when you're putting together a (user) interface you need to think about actually have a human using it and you need to make sure you have some commonality and everything sort of makes sense. When you sit down and use Microsoft Word or a device from Apple, it's not really an accident that you can sit down and sort of figure it out without a whole lot of training. There's some thought that went in before that and I think a lot of times we don't put that level of thought into what we're doing or we don't have that emphasis in the requirements and so you shift from a development load to do that to an operations load where you've got to train someone to figure out how to do a relatively simple task…"

*Application to Exploration:* With limited logistics for deep space exploration, it will be necessary to get all partners in synch with requirements interpretation. Budgets and physical constraints will potentially drive commonality but it is not a given. Also, the design of common laptop user interfaces and operational functionality must be intuitive and user friendly, requiring only high-level orientation and training, and striving for ease of use comparable to successful COTS software applications.

**Lesson:  Learning to Fly – The Challenges with Software Development Conundrum**

Both the design and operations concept should be well thought out before automation is applied to software command and control (C&C) functions of the spacecraft.  This also applies having the flexibility to patch software as the operations concept is refined.  Complicating software development and deployment, the typical ISS C&C software updates are delivered with known problems which are documented in "special instructions" (SPINS).  This requires the operations team to develop workarounds for each of these issues.  The guidance, navigation and control (GN&C) software for the ISS has been a case in point.  The G&C software is required to keep the ISS level and steady yet we did not understand at first how sensitive it was to the thruster selection.  If the vehicle were to lose attitude control and a series of thruster burns would be needed to reestablish attitude control that was fine for attitude control.  But over time, we have learned things about the structural sensitivity of our solar arrays such that we could be subjecting their structure to a potentially catastrophic failure mode.  This was not identified when the software was developed or tested – it was discovered as we learned more about the vehicle through operating it.

*Application to Exploration*:  It will be important to thoroughly vet and simulate deep space operational concepts and vehicle software as they apply to integrated space craft systems.  While it may be impossible to eliminate SPINS for software in the future, they should be minimized. Rigorous, physics-based simulations may help reduce the "learning curve" for crew and flight controllers.

**Lesson:  Crew operations – Time Management Challenges**

"When I was up, the emphasis was different because we were still in the construction phase.  I generally tell people that I spent one third of my time doing maintenance and operations, one third doing construction, and one third doing science.  And we have to fit in two and a half hours of exercise every day.  We were struggling to get to 35 hours a week of science on the U.S. side with three crewmembers on board.  The time management is challenging up there.  Instead of having 16 half hour activities to do every day, it would be much easier to have two four hour activities each day.  Set up and tear down costs a lot of time.  We had weekly calls to discuss procedures and activities, and I thought it was reasonable."

*Application to Exploration:*  Long duration mission time-line planning must necessarily balance maintenance, training, exercise, and science.  The time allocation strategy must also recognize the advantages of fewer transitions to minimize set-up and tear down inefficiencies.

**Lesson:  Crew Scheduling – Providing Flexibility**

"Early on in ISS crew operations, we were very meticulous and structured with the activities that were placed on the crew timeline – very similar to what we did for the Space Shuttle Program. Over the years we have learned that for crew members on extended duration missions, one of the psychological improvements that we can provide them is some level of control over their day-today activities.  We have worked with the crew office as well as with our planners and their tools to maximize the flexibility for the on-orbit crew.  This has helped with the motivation of the crew and allowed them to find efficiencies in their planning – this has allowed more time than anticipated for payload activities."

*Application to Exploration:* Providing crew members with flexibility for planning their day-to-day schedules would benefit the exploration programs.

**Lesson: Finding Efficiencies in Operations**

The Mission Operations Directorate (MOD) has been proactive in finding efficiencies that allow them to do the same amount of work with a reduced budget. At some point however, you reach a point of no return – budget cut-backs beyond which cut into the core capabilities that MOD provides.

*Application to Exploration:* A going-in budget scenario for Exploration might include finding efficiencies in the first set of missions and applying them to subsequent missions. Making this a continuous process, given the low frequency of flights, may be setting us up for failure.

***28-Lesson: Employ Automation Wherever Practical**

The ability to use automation to operate mission systems without crew intervention has provided significant benefits. International Partners should have the capability and responsibility for direct command from multiple control centers, with their local facility serving as the primary control and monitoring of the end-to-end system.

*Application to Exploration:* Use automation to relieve the crew of routine or hazardous functions wherever practical. Furthermore, optimize the use of automation to provide operational flexibility. Partners should have the capability and responsibility for direct command from multiple control centers in order to improve operations.

***47-Lesson: Integrate the Utilization and Operations Strategy**

The ISS [early on] suffered from an unevenly managed operations and utilization effort. User communities had difficulty defining a responsible organization and advocating benefits of the program. A single organization combining development, operations and utilization would have been much more committed to overall program success.

*Application to Exploration:* Utilization should be developed as part of the long-term mission strategy for the program, with clear technical, policy, and communications goals, and appropriate stakeholder buy-in. Future exploration programs should have scientific elements thoroughly defined and fully integrated with system development and operations.

***48-Lesson: Fully Develop Flight Crew Experience**

The experience flight crew gain working on the ISS has expanded their professional skills, increased their self-reliance in space operations, and lowered the risk of dangerous situations. The ISS can now be considered as a part of our versatile human existence and as a natural transfer of the earthly life to the space platform.

*Application to Exploration*: Exploration flight crew should be afforded as many opportunities as practical to expanding their experience base living and working in space.

***49-Lesson: Use Available Space Assets as Technology Test Beds**

The ISS Program used the Space Shuttle and Mir Station as technology test beds and now the ISS is serving as a unique testing platform for development and qualification of space technologies. It will be further strengthened as experience grows and capability of autonomous existence in space increases.

*Application to Exploration*: Exploration programs should use the ISS to develop, demonstrate and qualify next generation space technologies and operations relevant to the future of space exploration. The ISS partnership can accommodate Non-Partner use of the ISS for development and qualification of space technologies.

***44-Lesson: Decentralize Certain Operations**

Decentralizing certain ISS operations allowed each Partner to develop the necessary skills and capabilities to conduct human space flight domestically, as well as to develop a global human spaceflight culture. Mission preparation and real-time operations have continued to evolve to be more efficient and less travel-intensive with more capable collaboration and training tools.

*Application to Exploration:* Each Partner should be encouraged to develop the human spaceflight skills and capabilities necessary to complement their contribution. A technology roadmap for such collaboration should be developed to augment, and possibly reduce, the amount of human transit time between Partner sites.

***45-Lesson: Include Long Term Planning for Extended Operations**

It was important for each Partner to have a vested interest in the continuing operations, not just the development of the ISS. Termination, or exit criteria, by one Partner are not simple due to obligations to remaining Partners. Decisions about assets upon dissolution and the terms that apply may be problematic.

*Application to Exploration:* Partners providing systems and components need to commit to the total life cycle of the program including any likely extended operations and disposal.

**Lesson: Flying iPads**

NASA on-orbit operations have evolved along with commercially available information technology here on Earth. We have started flying iPads on-orbit which has become a huge resource for the crewmembers. Procedures can be uploaded, a laptop does not have to be carried around, and pictures can be taken of system hardware or payloads and e-mailed to the ground to enhance communications. It ends up being a very portable device that can be used for many tasks.

*Application to Exploration:* It may be hard to predict what information technologies will be available for the crew in 20 years. What is known is that NASA has and should continue to evolve with that technology in the future for exploration.

## Crew Medical

**Lesson: Develop Your Medical CONOPS, Develop Your Hardware and Test it Well**

"When we went from the Shuttle to the ISS, we thought our tool suite for modeling and managing exposure to radiation during flight was sufficient but they were not. We rely a lot on computer systems interfacing with data streams and calculating values based on space weather parameters and vehicle shielding – it is a lot of complicated interactions between IT systems. We did not put these systems through rigorous testing before ISS operations. It took us several years before we could obtain a tool suite that would produce an answer in real-time to provide feedback to flight directors with appropriate accuracy as it evolved."

*Figure 13. ISS Expedition Commander Leroy Chiao performs an ultrasound examination of the eye on Flight Engineer Salizhan Sharipov (NASA)*

*Application to Exploration:* A long lead time for radiation hardware will be required to perform design, develop, test and evaluate and associated tools and IT support that will align with exploration CONOPS.

**Lesson: Drawing a Line between Data Points – The Dangers of Extrapolation**

People would like to be able to say that bone loss in ISS crewmembers is a certain percent per month in human space flight. However, we have only two data points – one pre-mission and one post-mission. You can draw a line between those two data points any way you like. We know it is negative but we do not know if the loss plateaus in three months or four months. Getting time course data is a very smart thing but there are technical limitations during a mission – you have to be creative about how you do it. When you have a six month mission, you have those two data points so you know the growth change. Trying to say that a mission of twice that duration is twice that loss is not a conclusion that you can accurately make. If we had data to say that the loss or gain plateaued at three months then a twelve month mission is no different than six month mission. But in medicine, sometimes things change in steps as the body reaches different thresholds. It can habituate to a certain stimulus and reach some type of homeostasis but if you continue to stress in it a certain way it will reach another threshold and change again.

*Application to Exploration:* The application of using ISS crew medical research data is challenging when trying to apply it to exploration design reference missions. Care must be exercised in trying to extrapolate data.

**Lesson: Crew Selection, Crew Conflict and Cohesion, and Potential for Crew to Ground Conflict**

Many of the first ISS crew members were Space Shuttle-era veterans and not necessarily well adapted to long duration space flight of six months or more. Crew selection became an issue as a result of this. Crew selection for a mission considers personality styles and how people work well together.  The reality is that there were a limited number of people suited to fly long duration missions.  The opportunity for conflict intervention on a deep space mission is limited so compatibility must be assured, to the degree possible, during crew selection process.

*Application to Exploration:*  Crew selection for deep-space missions will only become more critical to mission success.  Flight medicine professionals should be brought in as a partner in the crew selection decisions.

**Lessons Learned:  Crew Medical – Psychology**

It is recommended that individuals be observed within stressful training scenarios where their interactions and behaviors with fellow teammates can be evaluated – an approach potentially more effective than one-on-one evaluation meetings once a month.

*Application to Exploration:*  Medical evaluation of individual crew member stress and compatibility will continue to be important.  It may be worthwhile to consider the effectiveness of current practices.

**Lesson:  Crew Compatibility**

"The way it worked was each country or each agency would present their candidate to the group for a flight and really it was just a question of seeing how their candidate met the criteria.  If there was a criteria that was not met all the time it was the language thing. So what I was trying to say is I think the technical criteria were pretty well satisfied all the time.  What we did not look at, in depth was crew chemistry. The Russians pay a lot of attention to the soft aspects of crew health and behavioral health, and their psychologist who was assigned to us just had great reviews about how we interacted."

"NOLS is the National Outdoor Leadership School, so they offer one to two week team-building courses and we would typically send people on those.  That was considered within NASA a prerequisite to being assigned to a long duration flight, to have had at least one of those training courses.  There was actually a whole syllabus where you would start out with some two or three-day workshop in-house at NASA and then NOLS was kind of like the entry level course and then the graduate level course was something like Aquarius, this habitat down off of Key Largo (an underwater habitat).  Ideally you would take a candidate crew and you would put them through something like that together.  Then you would have professionals sort of evaluate if the mix was good or not.  But you just don't have the time to do that; it's a great idea but it's just not realistic."

*Application to Exploration:*  The NOLS and Aquarius facilities and programs provide the kind of team building and development activities necessary for thorough compatibility evaluations appropriate for long duration missions.

**Lessons Learned:  Crew in Transit**

"On the journey to the destination the crew needs something useful to do – they must be constructively occupied during transit."  It is recommended that a mission-related training program (perhaps modular) be devised to provide focused and useful crew engagement on a daily basis. In addition a daily exercise regime is deemed essential to promote mental as well as physical well-being.

*Application to Exploration:* Deep space missions will be long, lonely, and mentally stressful. Mission architecture and planning must consider crew mental health management and incorporate structured activities, such as training as part of the strategy.

**Lessons Learned: Crew Medical – Eye Safety**

"There is always stuff floating around in space." The human eye is one of the most vulnerable parts of the body and eye damage scenarios are extremely hard to address in space. "It is super critical to avoid getting stuff in your eyes." One example is drilling out a stripped fastener where metal shavings may be created – even with a vacuum suction, gels, and eye protection, potential hazards may remain.

*Application to Exploration:* System safety hazards analyses must carefully consider human health hazards as well as the traditional hazards such as fire, explosion, electrocution, depressurization, and sharp edges. Mitigation measures and personnel protective equipment must be identified to mitigate risks to crew vision.

**Lesson: Behavioral Support and the Risk of Significant Behavioral Decrement on a Mission**

Feedback from active astronauts returning from their missions, unanimously agree that the behavioral support program offered has provided substantial buoyancy in terms of their morale while on orbit. Family connectedness (IP phone), telecons, and leisure activities have been very helpful techniques in this effort. The goal is to prevent eventual sliding to the right on a bell-curve toward significant behavioral decrement.

*Application to Exploration:* Crew behavioral support has been a successful effort for ISS crew members and should be continued in the future. There will be significant change, or paradigm shift, for exploration because there will be more crew autonomy and less real-time control from the ground instructing the crew what to do. This will require different training scenarios for the crew as well as for the ground controllers. There will be a necessity for meaningful work and crew activities, especially on the outbound and inbound journeys for a Mars mission. Significant boredom caused by idle time will work against the crew members in terms of their psychological fitness and readiness. These are issues that need to be further explored. Finally, because the crew will be more autonomous, the crew medical officer, the crew commander and, as well as the entire crew will need to be much better trained with regard to early detection of psychological detriment during a mission using a variety of methods which may include advanced behavioral assessment technology.

**Lesson: The Occupational Surveillance Element of ISS as an Analog for Deep Space Exploration and the Role of Microgravity**

Terrestrial analogs such as Antarctica are useful for understanding confined, long duration missions. However, ISS is the one that helps us understand the role of microgravity. From the perspective of the visual impairment and inter-cranial pressure project where we now see something that we did not expect to see, how can we be better able to foresee medical issues in the future that we had not anticipated? This drives flight medicine research to determine the key analysis tools on-orbit.

*Application to Exploration:* Occupational surveillance of crew members during deep space missions will be informed by ISS as an analog, particularly for microgravity-induced conditions. Care must be exercised however going forward in evaluating this data to determine the key susceptibilities or early markers. Deep space missions will have their own unique challenges with the radiation perhaps playing a more dominant role.

**Lesson: Use Care in Analyzing Lessons Learned From ISS Telemedicine**

In the area of flight medicine research, we have had to learn to be careful about how we analyze the data from various analogs and how this information is applied for future exploration missions. We have learned a lot about real-time medical training of the ISS crew using telemedicine. Factors include: how the crewmember learns, how they process data, and how they use the instrumentation.

*Application to Exploration:* Given the communications issues with deep space exploration, the real-time operations telemedicine paradigm used for ISS may be less efficient due to communication delays. We need to carefully understand the right things to take away from the ISS experience to apply to exploration missions.

**Lesson: Educating and Communicating Radiation Exposure Risk Acceptance**

We never approached exceeding our radiation standard during space shuttle missions. Early in the ISS program it was the same thing – single six month missions that were within those same standards. Only recently and as the result of examining the one-year ISS mission, have we started to challenge what the documented limits are. Both the crew and ISS program management started to take notice of what the standard meant, how it evolved, the tools used to model and calculate radiation versus the standard. The Institute of Medicine is examining the NASA radiation standard and this activity is helping to educate management, ISS crew members and physicians.

*Application to Exploration:* The radiation standard, which may continue to evolve over time, must be thoroughly understood by all stakeholders. This requires an educational process across several domains: medical operations, management, and crew.

**Lesson: The Need for Private Sleep Quarters**

Private sleep quarters are relied upon to have some personal time. Significant positive feedback has been received from the crew. This tiny cubby hole of a world is important to the crew – to be able to decorate it, put up family photos, and obtain some privacy.

*Application to Exploration:* Although smaller vehicles with less habitable space are anticipated for deep space missions, future spacecraft designs should incorporate some form of individual private sleep quarters. The challenge will be how to do similar things with less space than ISS provides.

**Lesson: Developing a Close Working Relationship between the Crew and the Flight Surgeon**

The flight surgeon, the behavioral health team, and ISS crews have evolved a trusting relationship. The medical personnel have developed this trust and have become an advocate for the crew (e.g. crew rest cycles).

*Application to Exploration:* The relationship developed between the crew and medical personnel during the Shuttle and ISS Programs should serve as a model for deep space exploration.

**Lesson: Developing Confidence in Crew Members to Be the Crew Medical Officer (CMO)**

Many crew members, with the exception of those with medical experience as EMTs or paramedics, have little medical training, knowledge or experience. Practical medical training for crew members has developed a level of confidence. This allows a level of autonomy on their part and an ability to use tools such as ultrasound to diagnose issues.

*Application to Exploration*: The medical training provided to ISS CMOs should serve as a model for deep space exploration.

**Lesson: Clinical Research and Operational Medicine Synergies**

Currently there is an effort in ISS to ensure that the operational and clinic research sides collaborate and understand long-duration medical issues. For example, during ISS operations, three new EVA pre-breath protocols were developed – this was a great marriage of the research teams sitting down with the operational side to discuss what we knew. This drove down the potential for years of research and focused resources more effectively.

*Application to Exploration:* The collaboration between the medical operations and research teams created synergies for the ISS Program and should serve as a model for deep space exploration.

**Lesson: Do Not Underestimate the Importance of Crew Exercise**

Crew exercise is not only important physiologically but also psychologically for ISS crew members and should not be underestimated. During one increment, the resistive exercise device broke and was rendered inoperative for a period of time. When the device was eventually repaired the crew's appreciation was overwhelming and their general mood improved.

*Application to Exploration:* The experienced gained during ISS points to the importance of crew exercise both physiologically and psychologically and should serve as a model for deep space exploration.

**Lesson: Collaboration between NASA and International Partners Medical Teams – Sharing Information to Improve Overall Crew Performance**

There was a big learning curve in collaborating with IP medical teams to determine how to dovetail medical operations together. A space medical operations team meets every Thursday to review the week on ISS. The crew flight surgeons report on their activities as well as crew medical issues. NASA is getting better at documenting issues which allows for reflection on their data and lead to observations such as headaches that might be related to CO2 or other issues. Making sure that the IP medical teams know what NASA is observing and sharing this information between IPs, as well as how we approach these issues, is important. This then provides them information in the event that a similar medical anomaly comes up with one of their crew members.

*Application to Exploration:* The collaboration between the NASA medical team and the International Partners should serve as a model for deep space exploration.

**Lesson: ISS Crew Latent Medical Anomalies – What's Next?**

Latent engineering design defects are similar to latent medical anomalies in some sense. They manifest themselves only after the system is fielded and can cause anomalies and/or failures. The male crewmember inter-ocular issues that were discovered over the last few years are perhaps a harbinger of other medical issues that may arise over longer-duration missions in the future. The medical community believes that this particular issue has occurred in past flights, perhaps even on the Russian Mir Space Station but we are only seeing it now because of the fidelity in being able to take the ocular imagery and crew members have not complained of the issue. The fact is that the inter-ocular pressure issue has been happening all along. Different people manifest the issue differently and in different degrees but did not show overt symptoms for a long time. Even people who were asymptomatic showed anatomical changes without the functional impact. This is based on things that we can currently see; we still do not know what is potentially happening in watershed areas of the brain.

The point is that we are going to have other medical issues related to long-duration flight that will come up. Today there are some physiological issues surfacing due to the dust environment on ISS that are causing some changes that can be observed in the nasal passageways. The question is how new undiscovered medical anomalies will play out in the future.

*Application to Exploration:* Latent medical anomalies pose risks for future crewmembers engaged in deep space exploration. ISS medical issues should be fully documented and explored for NASA to develop proper mitigation steps in the future. We should perhaps expect future unknown-unknown risks, or enigmas, in the medical field.

## Science Utilization

**Lesson:  Exploring Frontiers – "A Whole new Series of Questions"**

"For exploration, it is about going into a frontier and for me a frontier is a place where your normal intuition no longer applies and the answers are no longer in the back of the book – you have to think of, and create, your own answers to the questions and I think this is what draws us to frontiers in the first place.  Here is the irony – you go into a frontier with a set of questions, you figure the answers out and after you look at the answers you say "we asked the wrong questions" and so now you formulate a whole new series of questions and again you go through another iteration and this is what is so inviting about frontiers … I think all of humanity benefits from the fruits of exploring frontiers and ISS is just the prime example of exploring a frontier in this time."

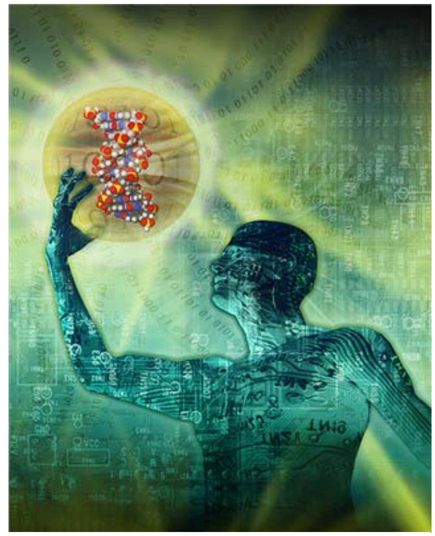

*Figure 14.  2013 ISS Medical Research Conference Poster (ISS-CASIS.org)*

*Application to Exploration:*  The human role in exploration is eloquently underscored in the quotation above – future mission science utilization planners must maintain a flexible array of options to assist in responding to discoveries and reformulating their questions.

**Lesson:  Scientific Knowledge Gained**

"People are very quick to point out that the Apollo era was a heyday of NASA and a lot of people underestimated the value of what we are doing now with ISS.  But here is a line of thought – if you look at Apollo, think of the technology benefits using two general categories:  1) the technology that it took to push the lunar mission, and 2) the knowledge gained because we went to the moon and we learned a lot about how the moon formed and the process is going on in our solar system.  Now you look at ISS, we have the technology associated with building ISS and then we have the knowledge gained because we have ISS and so I look at these four different categories from these two separate programs and I'm willing to say that the technology advanced in the Apollo program is basically a wash with the technology that we have developed to build ISS.  So let's say that the benefits of doing these two programs from a technology point of view are equal and look at the knowledge advance from these two programs – with Apollo we learned a lot about the moon, which in turn taught us a lot about earth and our solar system.  In terms of how that effect the daily life of everyone on the planet, it's really small – it does however enrich our imagination and tickle our minds to understand more about how our solar system works with planet earth being a member of our solar system .  I don't want to undermine the value of that knowledge itself but in terms of impact of daily lives of humans I argue it's pretty small.  Now you look at what ISS is doing and then end result is scientific research whose most applications directly apply to humans on earth, we are using space as in environment where we can tweak the gravity knob and the space environment knob and use it as a lab to investigate phenomena like combustion and human physiology and surface tension phenomenon technology and all these things in a manner that is impossible to investigate on earth because of the role of gravity or the vacuum of space.  The fundamental knowledge gained from what we are going on ISS is directly applicable to how we organize and operate our human civilizations on earth. What I predict is those 20 years in the future when historians are talking about what we gained from doing ISS I think they are going to write that ISS had a huge impact on the daily lives and quality of life of humanity living on earth.

*Application to Exploration:* Debate and discussion of "the value of space exploration" will always be part of the political process necessary to garner support and funding for deep space missions. The return on investment to society should be articulated in both "knowledge gained" to conduct the mission and potential "knowledge gained" in conducting the mission.

**Lesson: Don't Have the Science Organization Peak Too Soon**

NASA rallied a large science organization with a peak budget of nearly $800M. A large portfolio of ground research had been established to later feed ISS research on-orbit. The development delays of ISS had dramatic impact on scientific interest, the ability to sustain funding and the whole view of the ISS as a science tool. As many as three-quarters of the Principal Investigators (PIs) had to be cancelled after the Columbia mishap when NASA re-scoped the science funding. The ISS configuration was not mature enough to do the research that the PIs were funded to do. That asynchrony was damaging for science in human space flight as a whole.

*Application to Exploration:* The exploration architecture will undoubtedly have platforms available for science customers (universities, the Science Mission Directorate, commercial customers, etc.). Attention must be given to the phasing of funding to these communities to guard against peaking too soon.

**Lesson: Don't Baseline Complicated Science Requirements Upfront – Plan for Upgrades**

Given the long development cycle of some science hardware, requirements which are both complicated and baselined too early may lead to unanticipated hardware upgrades. Exercise equipment (treadmills, resistive exercise devices, etc.) and life support equipment will probably go through three generations of hardware/software. The original rack interface controllers are going straight to a laptop versus a bus. At the time that the research racks were designed, it was almost unthinkable to go that way. Communications bandwidth for payloads will also go through three iterations. To keep the laboratory facilities relevant you naturally have to go through a series of upgrades.

*Application to Exploration:* This lesson is applicable to almost any scientifically-oriented exploration mission. Research instruments and facilities will need to undergo a natural series of upgrades during the mission(s) therefore we should build this into our planning processes.

**Lesson: Learning to work with the Science Mission Directorate (SMD)**

SMD is used to flying their own dedicated instruments on their own dedicated satellites. We had a number of locations for them to attach instruments. However, SMD was worried early in the program about getting to final assembly. During budget planning activities for the design phase there was tension between the program and SMD over who should fund the DDT&E for the external payload attach work. This budget tension, combined with the risk of investing in the

ISS with some likelihood that it would not get fully assembled, resulted in SMD losing interest in building instruments for these sites. However, once the assembly was complete, these barriers came down quickly and now SMD opens many proposals with science for ISS and IPs are proposing dozens of instruments. There was a lag in confidence in working with human space flight.

*Application to Exploration:* This lesson points to the exploration program not charging users for sunk costs – transportation or infrastructure – because this will destroy scientific interest in using the platform. Realize that the schedule risk in human space flight has been historically so high that users may come in late because they have other options to fly. Deep space missions may have astrophysics scientific studies that might be done in transit that might not be done any other way which will require careful collaboration with SMD. Consideration should be given to how the program is designed such that inputs from SMD are considered without committing them to early resource decisions and therefore cost and schedule risks.

**Lesson: Keep It Simple and Modular – How to Succeed at Science**

We made some pretty big promises to the research community that we could not afford to keep due to budget dislocations when we actually got there. For example, once upon a time the materials science research facility was three racks all connected together with piping. Even the human research racks started full of hardware which has been almost completely replaced with modular, hand-held units which are mostly COTS hardware. Being able to swap out hardware, especially when there were development delays, really helped ISS science.

*Application to Exploration:* This lesson points to developing research capabilities that are incremental and modular. Consideration should also be given to using COTS hardware for research.

**Lesson: ISS Science – Requires Integrated Support to Succeed**

The ISS science hardware concept of operations involves ISS providing (hosting) large, refrigerator size payload racks with payload developers building inserts, sub-racks containing science experiments. Experience has shown that this turn-key concept works best (and is dependent upon) broad NASA ISS operational ownership (software, safety, mission integration, mission operations) in supporting the science mission/experimental objectives.

*Application to Exploration:* This lesson points to the importance of integrated support to the science missions. One concept to consider is providing a program-based "payload integration manager," to address administrative, logistics and process requirements allowing the scientists to focus on the science. This lesson provides thought for future exploration mission planners as they seek to develop a more collaborative, integrated, and effective way to work with the scientific community.

***46-Lesson: Reduce Payload Processing and Launch Schedules**

Because it takes a long time in the ISS Program to manifest a [complex] payload, there is a risk of loss of science community involvement (e.g., particularly when lead times are longer than a post- graduate program).

*Application to Exploration:* Manifest lead times need to be shortened and payload processes need to be simplified to ensure greater science community involvement in exploration programs. An optimized operations architecture should be foreseen.

***51-Lesson: Use Available Space Assets to Pursue Science and Applications**

The ISS Program used the Mir Station, Space Shuttle, Spacelab and Spacehab to conduct precursor science and applications research in preparation for the ISS era. Now, the ISS has proven to be the most capable platform ever produced to conduct science and applications development in a microgravity environment.

*Application to Exploration:* Exploration programs should use the ISS to pursue science and applications relevant to the future of space exploration. The ISS should be used to develop in-situ research capabilities.

***52-Lesson: Consult with End-Users Early in the Program**

The ISS benefited from consulting with scientists early, in order to ensure the ISS would be useful and productive. The mission performance requirements were established at the 1993 critical design review (CDR) milestone, and the "as-built" configuration meets all requirements (except logistics due to unanticipated termination of the Space Shuttle program).

*Application to Exploration:* Engage end-users early to ensure program design will meet the needs of all parties.

***53-Lesson: End-Users Should Coordinate Internationally**

International science working groups were formed early in the ISS partnership to coordinate utilization activities at the agency science level. These groups reduced unnecessary redundancy, introduced efficiencies in the planning and selection of payloads, and enabled international technical and scientific collaborations.

*Application to Exploration:* Coordination of end-users from all Partners can bring benefits with respect to the ultimate productivity of the utilization program.

***54-Lesson: Recognize Value of Prior Exploration Programs**

The ISS leveraged considerably from the value of previous human and robotic space exploration efforts, and has now proven to be an extremely valuable platform for exploring long-duration human stays in space. In addition, the ISS allows us to perform many complex hypothesis-driven studies requiring human intervention or monitoring.

*Application to Exploration*: Exploration science and technology should take advantage of the human presence, the life-friendly environment and the possibility of long-duration free-fall study with the possibility of direct intervention that is only available on ISS.

# Appendix A: Interviews

Telephone Interviews: Telephone interviews with selected individuals who were involved in the management, planning, implementation, and operation of the ISS program took place between October and November 2013. The following outlines each specific individual.

- NASA/Dr. Gary Kitmacher – 18 Oct
- FAA/Tom Martin – 22 Oct
- NASA (retired)/Michael Lopez-Alegria – 22 Oct
- NASA (Retired)/Jerry Clubb – 23 Oct
- NASA (Retired)/Mark Uhran – 23 Oct
- NASA (Retired)/Tommy Holloway – 24 Oct
- NASA/Retired/Lynn Cline – 24 Oct
- NASA/Robyn Gatens – 28 Oct
- NASA/Dave Williams – 28 Oct
- NASA/Robert Bagdigian – 28 Oct
- Boeing/Greg Gentry – 28 Oct
- NASA/Jason Dake – 28 Oct
- NASA/Kevin Watson – 28 Oct
- NASA/Bill Gerstenmaier – 29 Oct
- NASA/Sam Scimemi – 30 Oct
- NASA/Tony Butina – 31 Oct
- NASA/Bill Robbins – 31 Oct
- NASA/John McBrine – 1 Nov
- NASA (Retired)/Lynn Wigbels – 4 Nov
- NASA/Ginger Kerrick – 5 Nov
- NASA (Retired)/Jeff Bingham – 6 Nov
- NASA/Dan Jacobs – 6 Nov
- NASA (Retired)/Dr. Scott Pace – 7 Nov
- NASA/Dr. Joe Dervay – 7 Nov
- NASA/Dr. Gary Bevin – 7 Nov
- NASA/Dr. Jennifer Fogarty – 7 Nov
- NASA/Dr. Eddie Semones – 7 Nov
- NASA/Dr. Steve Hart – 7 Nov
- NASA/Dr. Walt Sipes – 7 Nov
- NASA/Dr. Rick Senter – 7 Nov
- NASA (Retired)/Sandy Magnus – 8 Nov
- NASA/Mark Geyer – 13 Nov
- NASA/Dr. Julie Robinson – 15 Nov
- NASA/Dr. Don Pettit – 19 Nov

Video Interviews

- Lynn Cline,12/18/13, HQ
- Robyn Gatens,12/18-19, HQ
- Julie Robinson, 01/15/14, ARES Houston

- Ginger Kerrick, 01/10/14, ARES Houston
- Mike Lammers, 01/10/14, ARES Houston
- Mark Geyer, 01/10/14, ARES Houston
- Scott Pace, 12/11/13, HQ
- Don Pettit, 01/17/14, ARES Houston
- Jennifer Fogarty, 01/09/14, ARES Houston
- Tony Butina, 01/09/14, ARES Houston
- Bill Robbins, 01/09/14, ARES Houston
- Joseph Dervay, 01/09/14, ARES Houston
- Al Holland, 01/09/14, ARES Houston
- William Gerstenmaier – 01/28/14 HQ
- Sandy Magnus 01/29/14 ARES Houston

# Appendix B: Knowledge Based Risks (KBRs)

- KBR 10087 - Micrometeoroid and Orbital Debris (MMOD): Unclear and Present Danger
- KBR 10440 - ISS: Multi-Element Integration Testing (MEIT)
- KBR 11936 - ISS: P6 On-Orbit Solar Array Repair
- KBR 2649 - Insufficient Stowage Volume Within Crew Habitable Areas
- KBR 2650 - Failures of On–Orbit Mated Interfaces
- KBR 2651 - Exceeding Acoustic Levels Inside Spacecraft
- KBR 7084 - Composite Overwrap Pressure Vessel Safety Hazards
- KBR 6890 - EVA Glove Punctures
- KBR 4713 - Integrating Redundancy into Highly Reliable Systems
- KBR 2676 - Fasteners Seizing Or Binding On–Orbit
- KBR 11825 - SARJ Vibrations Pose Risk to ISS Power and Operations
- KBR 11937 - Mission Management Team Changes Post Columbia
- KBR 2664 - Risk of ISS Flight Elements Not Mating and Functioning In–Orbit
- KBR 2663 - Improper Application And Verification of Bolted Fasteners
- KBR 2705 - Metal Whisker