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How Do Lessons Learned on the International Space Station (ISS) Help Plan Life Support for Mars?

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How can our experience in developing and operating the International Space Station (ISS) guide the design, development, and operation of life support for the journey to Mars? The Mars deep space Environmental Control and Life Support System (ECLSS) must incorporate the knowledge and experience gained in developing ECLSS for low Earth orbit, but it must also meet the challenging new requirements of operation in deep space where there is no possibility of emergency resupply or quick crew return. The understanding gained by developing ISS flight hardware and successfully supporting a crew in orbit for many years is uniquely instructive. Different requirements for Mars life support suggest that different decisions may be made in design, testing, and operations planning, but the lessons learned developing the ECLSS for ISS provide valuable guidance.

Nomenclature

ARS = Atmosphere Revitalization System
CDRA = Carbon Dioxide Removal Assembly
CM = Corrective Maintenance
ECLSS = Environmental Control and Life Support System
ISS = International Space Station
LCC = Life Cycle Cost
LEO = Low Earth Orbit
LLRU = Lower Level Replaceable Unit
LRU = Line Replaceable Unit
MCA = Major Constituent Analyzer
MOLA = Mars Orbiter Laser Altimeter
OGS = Oxygen Generating System
ORU = Orbital Replacement Unit
PM = Preventative Maintenance
R&R = Remove and Replace
RSA = Russian Space Agency
SEI = Space Exploration Initiative

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SSF	=	Space Station Freedom
TCCS	=	Trace Contaminant Control Subassembly
UPA	=	Urine Processor Assembly
WPA	=	Water Processor Assembly
WRS	=	Water Recovery System

I. Introduction

THE space station program is described and compared to a Mars mission. The development of the space station and its life support system is discussed. A long table lists the International Space Station (ISS) lessons learned that have been published. The table is organized in the areas of approach, design, commonality, complexity, reliability, diverse redundancy, testing, test on orbit, operations, maintenance, and lower level repair. Some major lessons learned and important problems are further discussed.

How, taking account of the ISS lessons learned, can we best develop life support for deep space and the journey to Mars?

II. Space station life support and the Journey to Mars

NASA's "Journey to Mars" report explains the agency's approach to human exploration and developing space technology. (NASA, Oct. 15, 2015) Dava Newman gave an overview of the NASA Journey to Mars,

> "(W)e're on the space station in low Earth orbit now. We have to get to cislunar space before getting to Mars. Mars is the horizon goal. With Mars as a horizon goal, we're trying to be clear and concise about what we're learning on space station about buying down risk for human health and our technology investments. The end goal is Mars, and if you have your end goal as Mars, then I think we can work backwards so that our Mars requirements really inform what we're doing in deep space. … We have nine more years [on space station] to keep buying down human health risk and technology risk. In deep space, it's about technology investments, and these technologies are completely tied into the mission to Mars. … So we have to have a really good prioritized list of what are the technology investments that we're making, that we can invest in, that will help us get to Mars." (Foust, Nov.16, 2015)

Using the space station for developing technology for Mars is a major NASA priority for the Journey to Mars, and life support system technology investment is key in buying down risk for human health. The "Journey to Mars" report notes that,

> "NASA will have to learn new ways of operating in space, based on self-reliance and increased system reliability; … and the ability to design, build, or repair systems with common, modular components. … We do this by designing a resilient architecture that focuses on critical capabilities across a range of potential missions, investing in technologies that provide large returns, and maximizing flexibility and adaptability through commonality, modularity, and reusability." (NASA, Oct. 15, 2015)

The report specifically mentions using the space station to advance Environmental Control and Life Support Systems (ECLSS) to enable deep-space, long-duration Mars missions.

> "The ISS is the only microgravity platform for the long-term testing of new life support and crew health systems, advanced habitat modules, and other technologies needed to decrease reliance on Earth. Over the next decade, we will validate many of the capabilities needed to maintain a healthy and productive crew in deep space. Currently manifested or planned experiments and demonstrations include improved long-duration life support for Mars missions." (NASA, Oct. 15, 2015)

In addition to the lessons already learned for Mars on the space station, more research and development and future lessons learned are planned.

III. The space station and the Mars mission

The International Space Station (ISS) is the most complex engineering project in history and the most expensive single item ever built. It is the largest and longest inhabited structure that humans have ever put into space. The cost of the ISS is about $150 billion, including $50 billion for space shuttle launches. It weighs nearly one million pounds and has been continuously occupied since November 2, 2000. (Wikipedia, International Space Station)

The space station is a fabulous human accomplishment. But how does it help us get to Mars? Human space habitats are vaguely similar to those on Earth. Just as automobiles and trucks provide transportation and houses are for permanent residence, crew launch systems are used for transportation and space stations or planetary bases are a place to stay. And both on Earth and in space, there are hybrid systems for transportation and brief residence. A terrestrial recreational vehicle or motor home, like the space shuttle, would typically be lived in for days, weeks, possibly stretching to months, but not for only a few hours or for many years. The space station will be lived in until 2024, a total of 24 years, and has the nature and requirements of a permanent residence. A Mars mission will probably use different transit and surface habitats, and the time spent in each will be between one and two years. This means that Mars life support will have requirements and design solutions influenced by both crew launch systems and the space station. Since the Mars mission duration is between the shuttle and space station mission durations, it may use a combination of shuttle and space station life support methods.

The ISS is in Low Earth Orbit (LEO), at about 248 miles above the Earth's surface. Mars is 140 million miles away at its furthest distance on the far side of the sun. Mars is roughly a million times further away than ISS. The travel time to ISS is a day or two, while the travel time to Mars is about 200 to 250 days, roughly a hundred times longer. No resupply or on-demand return to Earth is possible from Mars.

A major goal for ISS is developing and maturing the enabling science and technology for future human space exploration missions beyond LEO. This should be reflected in aggressive efforts to advance ISS regenerative life support systems and, where appropriate, to explore alternatives.

IV. The development of the space station and long duration life support

The US began the development of Space Station Freedom (SSF) in the 1980's. After the collapse of the Soviet Union, SSF was merged with the on-going and future plans for Mir to become the International Space Station (ISS).

A. Space Station Freedom (SSF) to International Space Station (ISS)

After the Apollo moon landing, NASA proposed developing many programs including a space shuttle, a series of large space stations, more missions to the moon, a lunar base, and an initial mission to Mars in the 1980s. President Nixon wanted to reduce the budget priority of space missions and asked NASA to pick one of the many possible programs. The two most urgent were the space shuttle and space station, but the space shuttle was considered higher priority to be funded first since it would be needed to build the space station. President Nixon approved the development of the space shuttle in January 1972.

The space station had to wait until the space shuttle was flying. President Reagan approved the space station during his 1984 State of the Union address and design efforts began. President Bush endorsed completing Space Station Freedom (SSF) as part of the Space Exploration Initiative (SEI) in 1989, in a speech marking the 20th anniversary of the Apollo 11 landing.

The collapse of the Soviet Union reduced the political support for SSF and increased efforts to cut its capabilities and cost. In 1990 SSF was found to be over budget, over weight, and underpowered. An analysis by Fisher and Price found that on-orbit assembly would require an impossible amount of ExtraVehicular Activity (EVA). A revised 1991 space station design had greatly reduced capabilities.

In June 1993, space station funding was retained in NASA appropriations by a single vote in the House. Later that year, NASA and the Russian Space Agency agreed to combine SSF and the on-going Russian Mir 2 program. President Clinton accepted the proposal and Russia became a full partner in the renamed International Space Station (ISS). (Logsdon, 2008) (Encyclopedia Astronautica, Space Station Freedom) (Encyclopedia Astronautica, International Space Station)

B. Long duration life support

Short duration missions from before Apollo to the space shuttle used open loop life support systems. Carbon dioxide was removed by lithium hydroxide canisters, trace contaminants by activated charcoal, and humidity by a condensing heat exchanger and water separator. Oxygen was supplied by high pressure tanks and water by fuel cells or tanks. (Eckart, 1996) (Wieland, 1994)

Decades before they occurred, it was realized that long missions would consume very large amounts of lithium hydroxide, activated charcoal, oxygen, and water and that closed loop recycling life support would be needed. Initial closed loop ECLSS development and testing began in the 1960's. Three closed chamber manned tests of 30, 60, and 90 days were conducted in 1965, 1968, and 1970 by McDonnell Douglas. The equipment was similar in all three tests but upgraded and redesigned for later tests. The subsystems used were similar to those ultimately flown on ISS, and included a molecular sieve to remove carbon dioxide, a Sabatier reactor to convert carbon dioxide to water, a water electrolysis unit to produce oxygen, humidity concentrate multifiltration, and a urine vacuum distillation system. (Eckart, 1996) (Wieland, 1994)

For the 90-day test, the crew remained in full isolation with no resupply of spares, tools, or expendables. All maintenance and repair were performed by the crew. It was noted that the crew operations, maintenance, and repair were effective and often ingenious. Integrated tests produced results that were not obvious in subsystem studies or component tests. (Pearson and Grana, 1971)

C. ISS and life support launch

Russia's *Zarya* module was the first ISS module, launched on Nov 20, 1998. It was quickly followed by the Node 1 *Unity* U.S. module, and there are now about eighteen pressurized modules and structures, not including visiting vehicles. The station has been continuously occupied since Nov. 2, 2000. The ISS Atmosphere Revitalization System (ARS), mostly housed in the Atmosphere Revitalization (AR) rack, contains a Carbon Dioxide Removal Assembly (CDRA), a Trace Contaminant Control Subassembly (TCCS), and a Major Constituent Analyzer (MCA). They have been operating on board ISS since 2001. The full redundant AR rack was launched on STS-128 in 2009. The Oxygen Generating System (OGS) was delivered in 2006 and began operation in the U.S. Laboratory module *Destiny* in 2007, then moved over to Node 3 *Tranquility* in February 2010 along with the Water Recovery System (WRS) racks. The WRS consists of a Urine Processor Assembly (UPA) and a Water Processor Assembly (WPA). The WRS was initially operated in 2008 in *Destiny* and is now in *Tranquility*. The Sabatier was installed in the OGS rack in *Tranquility* in 2010.

V. Lessons learned from the International Space Station (ISS) Environmental Control and Life Support System (ECLSS)

Many papers describe the history of ISS and some specifically list lessons learned. A consolidated list of lessons learned has been compiled to help explain how the ISS ECLSS experience can help guide life support development for a mission to Mars.

A. Table of lessons learned from ISS ECLSS development and operations

Table 1 lists lessons learned from ISS ECLSS. Each line represents one lesson learned given by a single source, and is a close paraphrase or quotation of the original. It was felt that presenting the original lessons learned without rewriting or combining them gave a more accurate impression of the writer's original intent. The lessons learned have some repetition and overlap, but not as much as could be expected.

The table of ISS ECLSS lessons learned includes 74 items from 15 different sources. It is organized in the areas of approach, design, detailed design, commonality, complexity, reliability, diverse redundancy, testing, test on orbit, operations, maintenance, and lower level repair.

Table 1. Lessons learned from ISS ECLSS.

Area	Lesson learned	Reason	Reference
Approach			
	Additional investments in ECLSS are needed	Current ECLS systems do not meet the requirements of deep space	(Guirgis et al., 2014-233)
	Enabling technology (especially ECLSS) needs to be developed	The ISS ECLSS technology is less than adequate for some planned operational scenarios	(Lengyel and Newman, 2014)
	Reduce size, mass, and power	ISS hardware can be generally characterized as big, heavy and power hungry systems	(Guirgis et al., 2014-233)
	Optimize system loop closure	Cost increases rapidly with degree of system loop closure	(Guirgis et al., 2014-233)

Area	Lesson learned	Reason	Reference
Approach, continued			
	Consider alternate technologies to ISS ECLSS	Alternate technologies could have reduced power, reduced mass, less complexity and greater reliability	(Guirgis et al., 2014-233)
	Design trade-offs must address competing or conflicting higher-level goals and objectives	The Concept of Operations should address all areas including logistics, maintenance, stowage, utilization, habitability, and operations.	(Lengyel and Newman, 2014)
	The U.S. and Russians have different hardware design philosophies	The Russians use heritage hardware, the U.S. hardware has little heritage and is more complex	(Sanchez and Voss, 2005-705)
	Encourage expressing dissenting opinions	Many difficult technical issues will surely arise	(Lengyel and Newman, 2014)
Design			
	Allow sufficient time for flight hardware development	Can underestimate the effort and time needed to take development hardware to flight	(Carrasquillo, 2005-0337)
	Allow time for redesign	Success oriented schedules can neglect potential problems and rework	(Carrasquillo, 2005-0337)
	Allow mass growth for safety and hazard control	Sensors and effectors added to meet safety and hazard requirements may grow a subsystem by 50%	(Carrasquillo, 2005-0337)
	Pay attention to interfaces	ISS ECLSS is an integrated system	(Bazley, 2015)
	Hardware must be modifiable for an unanticipated space environment	The space environment is not fully known until it is experienced	(Sanchez and Voss, 2005-705)
	Attempt to minimize spares	Much mass and volume is required for system spares	(Sanchez and Voss, 2005-705)
	Use miniaturization carefully	Miniaturization can increase complexity and make maintenance difficult	(NRC, 2012)
	Be careful even with small changes	Small design changes can cause big problems	(Carrasquillo, 2005-0337)
	Be careful even with small components	Small, ancillary components can present the greatest challenges	(Carrasquillo, 2005-0337)
Detailed design			
	Provide for storage of excess water	Needed for system failure or water imbalance	(Bazley, 2015)
	Provide universal hose interfaces	Needed for contingency connections	(Bazley, 2015)
	Water types should be compatible and mixable	The many water types on ISS make transfer and storage difficult	(Shkedi, 2008-01-2008)
	Store water outside the vehicle wherever possible	Water storage requires volume and handling	(Shkedi, 2008-01-2008)
	Pay attention to dust production and accumulation	Dust contamination is a common issue in ISS	(Parodi et al, 2013-3414)
Commonality			
	Use commonality	Commonality reduces the number of spares and tools	(NRC, 2012)

Area	Lesson learned	Reason	Reference
Commonality, continued			
	Have robust systems that can be repaired with common parts and tools	Future missions will be even more constrained in logistics and stowage	(Lengyel and Newman, 2014)
	Require commonality in low level parts, connectors, components, and interfaces	Almost no standardization requirements were levied on ISS	(Lengyel and Newman, 2014)
	Maximize commonality for fasteners, batteries, etc.	Commonality reduces storage and increases operational efficiency	(Bertels, 2006-5952)
	Balance diverse redundancy and commonality	Diversity improves reliability but adds maintenance and logistics complexity	(Gentry, 2013)
	Balance diverse redundancy and commonality	Redundancy reduces common cause failures but increase parts counts	(Gatens, 2015)
Complexity			
	Reduce design and interface complexity	Lower complexity improves reliability, maintainability, and operability	(Jordan, 2009-6791)
	Reduce complexity	The more complex a technology, the more prone it will be to failures	(Carrasquillo et al., 2004-01-2385)
Reliability			
	Highly robust systems are needed in deep space	Issues continue with elements of the ISS life Support hardware	(Harding and Bergin, 2015)
	Deep space technology, especially life support, must be ultrareliable and thoroughly tested to determine failure modes and their repair approach	The CDRA has failed often	(Lengyel and Newman, 2014)
	Improve ECLSS to be "as close to 100 percent reliable as possible and/or easily repairable."	"Current ISS experience with both U.S. and Russian ECLSS systems shows significant failure rates that would be unacceptable for an extended human exploration mission."	(NRC, 2012)
	Develop more reliable systems to reduce redundancy	Redundancy requires mass, volume, and logistics	(Carrasquillo et al., 2004-01-2385)
	Increase MTBF accuracy by improving hardware reliability and testing	MTBF is used to determine the needed number of spares	(Bertels, 2006-5952)
	Design systems to have compartmentalized, non-cascading failure modes	Cascading failures can overwhelm emergency response procedures and backup systems	(Lengyel and Newman, 2014)
	Carefully choose between reliability, repair, and replacement	The trade space includes crew training, crew time, ground support, stowage, logistics, and cost.	(Sanchez and Voss, 2005-705)
Diverse redundancy			
	Provide redundancy of critical systems	Redundancy allows continued operation during contingencies	(Bazley, 2015)
	Provide diverse redundant systems	For failures and contingencies	(Bazley, 2015)
	Implement dissimilar redundancy in life support	U.S. and Russian segments of the ISS provide dissimilar redundancy in life support systems.	(Lengyel and Newman, 2014)

Area	Lesson learned	Reason	Reference
Diverse redundancy, continued			
	Use dissimilar redundancy appropriately	Dissimilar redundancy provides additional mission assurance by avoiding common failure modes but adds additional cost, mass and complexity	(Guirgis et al., 2014-233)
	Use unlike redundancy along with demonstrated high reliability for critical systems	Common cause failures defeat similar redundancy.	(Lengyel and Newman, 2014)
Testing			
	Test thoroughly	Discover failure modes and design errors	(Gatens, 2015)
	Perform end-to-end, multi-element, system level testing	Testing identified multiple problems that would have been difficult or impossible to remedy on-orbit.	(Lengyel and Newman, 2014)
	Conduct high fidelity, integrated, system-level, end-to-end testing	Inadequate testing will make the crew rely on potentially flawed spares and risky in-flight repair, potentially endangering the crew	(Lengyel and Newman, 2014)
	The importance of testing must be stressed	Budget issues always end up limiting the scope and duration of test programs	(Lengyel and Newman, 2014)
	Provide budget and schedule for sufficient testing	Testing reduces operational problems and total mission cost	(Gatens, 2015)
	Use the protoflight approach carefully	The protoflight approach can increase schedule and cost risk	(Carrasquillo, 2005-0337)
Test on orbit			
	Mature technology by ground test and in-space operation	The use of protoflight ECLSS on the ISS has resulted in extensive on-orbit repairs	(Hodgson et al., 2012)
	Perform significant testing on the ground and ISS	Testing needed for reliable ECLS systems for multi-year missions	(Guirgis et al., 2014-233)
	Test systems on orbit	Systems on orbit act differently than on the ground	(Parodi et al, 2013-3414)
	Test in operational environment	Many problems seen only in actual environment, e.g., 0 g	(Gatens, 2015)
	Actual on-orbit system use can differ from expected	For example, higher urine calcium levels occurred on-orbit as compared to ground	(Gentry, 2013)
Operations			
	Consider operations in design	Cutting costs up front can make operations more difficult, increase the life cycle costs, and lead to critical safety issues	(Jordan, 2009-6791)
	Be careful changing operational systems	Changes cause “unintended consequences”	(NRC, 2012)
	Be aware of conflict between design and operations	Conflicting needs or concerns naturally exist and require balance	(Jordan, 2009-6791)
	Perform telemetry data trend analysis	Data trends can help predict problems	(Parodi et al., 2013-3414)
Maintenance			
	Provide easy access to ORUs	Easy access needed for crew maintenance	(Jordan, 2009-6791)

Area	Lesson learned	Reason	Reference
Maintenance, continued			
	Provide easy accessibility to ORUs	Substantial amounts of crew time are required for on-orbit maintenance	(Bertels, 2006-5952)
	Provide easy access to filters	Easy access needed for crew maintenance	(Jordan, 2009-6791)
	Be aware of microbial and fungal growth	Biofilm can clog water flow paths and storage vessels.	(Gentry, 2013)
	Hardware must support field diagnosis and repair	Significant crew time is required to maintain hardware that was not designed for on orbit repair	(Sanchez and Voss, 2005-705)
	Hardware should be designed for human operations and maintenance	Crews can effectively deal with hardware problems	(Sanchez and Voss, 2005-705)
	Maintenance in deep space must be performed with equipment on board	There is no possibility of a resupply ship providing additional hardware	(Harding and Bergin, 2015)
	Design for availability	Availability is the product of balanced reliability and maintainability	(Lengyel and Newman, 2014)
	Design for maintenance without extensive ground support	Ground support communications will have variable multi-minute delays	(Lengyel and Newman, 2014)
	Design for maintainability, minimizing the number of individual parts, number of steps, and time-to-repair	The exercise treadmill motor repair required removing and replacing over 100 individual screws.	(Lengyel and Newman, 2014)
	Enable the crew to repair by crew selection and training and by providing tools and parts	Crew repair has been successful and is the last resort	(Lengyel and Newman, 2014)
	Gain operational experience	Operational experience is necessary to understand maintainability	(Carrasquillo et al., 2004-01-2385)
	Design systems to be replaceable or repairable on-orbit	Even the best designs can experience failures	(Shkedi, 2008-01-2008)
	Provide tools, materials, and equipment to respond to unexpected failures	Non-ORU failures occur and require more complex repairs	(Bertels, 2006-5952)
Lower level maintenance			
	Devise ways to perform lower level maintenance	ORUs have high launch mass and repair only one failure	(Shkedi, 2008-01-2008)
	Use lower level replacement parts for deep space	Big and complex ORUs are not suitable for deep space packaging or sparing	(Guirgis et al., 2014-233)
	Develop Intermediate-level (I-level) maintenance capabilities, meaning ORU sub-component repair	I-level maintenance will reduce spares mass and volume but take more time and be more complex	(Bertels, 2006-5952)

B. Discussion of the table of lessons learned from ISS ECLSS development and operations

The table of lessons learned seems to give a reasonable and consistent picture of the development and operation of the ISS ECLSS. The lessons learned fall into a dozen familiar areas, but these simply follow the normal course of space program development from design through operations, maintenance, and repair. The lessons learned are consistent with each other and reflect well-known history.

Typically each particular lesson learned stresses one particular concern. Lessons learned tend to be simple direct statements, “Do this,” or “Don’t do that,” but there are always limits, costs, and complications. Systems engineering tells us that we must balance different and often conflicting goals and values. Trade-offs and compromises must always be made. Some lessons learned do reflect this, using the words, “along with,” “balance,” “trade-offs,” and “optimize.”

VI. Discussion of some lessons learned about ISS ECLSS

Table 1 of ISS ECLSS lessons learned includes twelve areas: approach, design, detailed design, commonality, complexity, reliability, diverse redundancy, testing, test on orbit, operations, maintenance, and lower level repair. Further comments are made on the six more difficult of these areas, which are approach, reliability, diverse redundancy, testing, maintenance, and lower level repair.

A. Approach

Lessons learned listed under “Approach” suggested that ISS ECLSS needs to be improved for Mars, and especially that its mass and volume must be reduced. It was mentioned that the U.S. and Russians have different hardware design philosophies

1. The ISS ECLSS needs improvement

A paper by ISS ECLSS team members written before the ISS regenerative ECLSS was launched suggests that improvements in the ISS ECLSS are needed.

“The baseline environmental control and life support (ECLS) systems currently deployed on board the International Space Station (ISS) and that planned to be launched in Node 3 are based upon technologies selected in the early 1990’s. While they are generally meeting or exceeding requirements for supporting the ISS crew, lessons learned from years of on orbit and ground testing, together with new advances in technology state of the art, and the unique requirements for future manned missions prompt consideration of the next logical step to enhance these systems to increase performance, robustness, and reliability, and reduce on orbit and logistical resource requirements.” (Carrasquillo et al., 2004-01-2385)

The problems cited for the ISS ECLS include high power consumption, difficult maintainability and logistics, sensitivity of several components to particulates and fouling, gravity related problems in multi-phase fluid flow and separations, and the lack of fine particle settling in microgravity. There are potential improvements in robustness, performance efficiency, and expanded capability. These can be obtained by a more integrated design approach and by “a focused, functionally-based systems engineering approach to specifying the ECLS system and developing the process design.” (Carrasquillo et al., 2004-01-2385)

2. ISS ECLSS rack packaging and mass

One lesson was that, “ISS hardware can be generally characterized as big, heavy and power hungry systems.” (Guirgis et al., 2014-233) The major ISS modules were designed to fly on the Space Shuttle and used a modular system of interchangeable racks attached to four utility standoffs. Using ISS racks “imposes unnecessary mass penalties” for use beyond LEO “because of the additional structure required for each rack and the complex distribution of utilities necessary to supply all racks.” (Smitherman et al., 2012)

The purpose of recycling oxygen and water is to save the cost of launching their mass into orbit. Recycling systems are justified on ISS by showing that the mass of the oxygen or water they produce over their ten or fifteen year operational life would be ten or twenty times larger than the mass of the recycling systems themselves. However, Mars transit and long surface stay missions have a much shorter duration than ISS, typically from one to one and a half years. This means that the current ISS recycling systems if used for Mars would produce materials having only one or two times their own mass in oxygen and water. The ISS rack structure is not suitable for Mars. While most subsystems still show a benefit on paper, the mass advantage will be further eroded by added redundancy and sparing needs to ensure crew survival on Mars missions where prompt return or unanticipated resupply are impossible. One must strive to maximize mass benefits by minimizing weight, volume and spares needed for the regenerative systems that would leave LEO.

3. The Russian design heritage approach

It has been noted that, “the Russians do not need to plan as extensively for failures because they do not use as much new technology.” (Patterson, 2001) The Russians use more heritage hardware. (Sanchez and Voss, 2005-705) And, “Americans need to plan extensively for failures because new technology is widespread. … The reliability of many items is unknown and reactions to failures must be heavily preplanned. … the implementation of so much new technology at one time has never before been attempted in space.” (Patterson, 2001) It should also be noted Russian systems historically had no means of being returned for failure investigation and therefore Russian engineers had limited insight into how to improve the existing designs. Simply providing enough spares to cover failures is not really an option outside of LEO and each failure must be understood to improve the reliability of each design. The

ISS's engineers access to failed hardware returned from orbit has had immense value in helping to understand and correct issues. The Russians have had to do without this capability through much of their their manned space program. For both Russian and US systems, on-orbit diagnosis has inherent imitations that impede design evolution to increase maturity and drive out failures. The Russian use of heritage designs would tend to reduce ECLSS failures, but does not appear to achieve the dramatic reductions that might be anticipated under more ideal conditions.

B. Reliability

ISS ECLSS reliability has been much lower than anticipated. Russell and Klaus state "total ECLSS maintenance for 865 days was found to exceed the design estimate by a factor of 22." A contributing factor was the oxygen generation system's greater than expected failure rate. (Russell and Klaus, 2007) Failures continue at different rates for different subsystems. Some have had no dramatic maturity increase or significant reliability growth, others such as the oxygen generation system have had high early failures and then operated well, and several have run almost flawlessly for fifteen years. (Hodgson et al., 2013-3409) (Jones, 2014-075). Improved reliability would be a benefit for ISS and is even more needed for Mars.

C. Diverse redundancy

Using diverse redundancy at the system level is an alternate approach to using Orbital Replacement Units (ORUs) or lower level spare parts, but they can be combined. It may be that different systems and different technologies require different approaches, either repair or redundancy. Common cause failures can defeat redundancy. Common cause failures can disable all of a large set of identical parts or systems. Using diverse redundant systems is an important way to achieve reliable space life support. (Jones, 2015-047) However, it has high overhead. Diverse redundancy requires multiple development projects, different kinds of spares, tailored operating procedures and crew training, and probably unique integration configurations. It opposes the use of commonality to reduce sparing mass penalties and enhance reparability. As systems are operated on ISS, the common cause failure modes are discovered and can be corrected by redesign. Achieving the required reliability for Mars could require a mix or choice between redesign for reliability, similar redundancy, and diverse redundancy. The best approach would depend on when the costs of reducing common cause failures in a single design sufficiently exceed those of implementing two or more diverse designs.

D. Testing

Many of the lessons learned cited above deal with testing for regenerative life support systems. In some cases they reinforce the importance of things that were done in developing the ISS regenerative life support systems. Lengyel and Newman, for example, stress that integrated, end-to-end system level testing is essential and point out that it uncovered significant issues that would have been very difficult to correct on-orbit (and potentially fatal in a Mars mission without a capability for effective ground based hardware support). (Lengyel and Newman, 2014). In others, they suggest the need for more or different testing including reconsideration of the use of protoflight approaches (Carrasquillo, 2005-0337) (Hodgson et al., 2012), or the addition of space-based testing to traditional ground based test programs (Hodgson et al., 2012), (Guirgis et al., 2014-233), (Parodi et al., 2013-3414), (Gatens, 2015), (Gentry, 2013). One can hardly be surprised at these suggestions given the incidence of early failures or degraded performance in many of the regenerative ECLSS subsystems on ISS. While these issues have been successfully addressed on ISS, the ground support and resupply activities that enabled resolution would not have been possible in a Mars mission, and some of the issues that arose would certainly have threatened crew survival. Together ISS experience and these testing lessons learned suggest that improved ECLSS testing is essential if we are to achieve the levels of system reliability and the knowledge of sparing requirements needed for a successful human mission to Mars.

The critical questions that ECLSS testing in support of a Mars mission must answer include all of those traditionally addressed in flight qualification – operational performance, compatibility with mission environments and interfaces, endurance through the anticipated mission lifetime, etc., but also include or significantly expand several others. To support a Mars mission, we will need to know in advance how likely component or subsystem failures are, where they are most likely to occur and what spares and maintenance provisions will be needed to ensure life support availability throughout the mission. The test program must also tell us how long life support systems may be unavailable while under repair and what expendable inventories are required during those intervals and provide the data needed to ensure that the probability of an unrecoverable failure is low enough to support crew survival goals for the mission.

The lessons learned listed above point out that successfully answering these questions requires a rigorous integrated test program pursued over time in appropriate testing environments. As suggested in several lessons learned, a rigorous test program requires integrated testing to ensure that system level effects are properly reflected in the mature design. It also requires thorough understanding of failures and issues that arise from engineering evaluation of failed components to determine failure causes and mechanisms, as a basis for eliminating them where practical and for assessing the potential for common mode failures across redundant items. In order to establish sufficient knowledge of failure rates to assure crew survival goals are met, testing will need to represent many times the operating time on a Mars mission. While this may be achieved by operating multiple parallel units, the duration for each individual unit needs to exceed planned mission operating times to ensure that life related issues (e.g. wear-out, corrosion, biofilm development, etc.) are addressed. ISS experience suggests that appropriate testing environments for ECLSS must include testing in space. Several of the issues with ISS ECLSS subsystems that were not identified in ground test programs were the direct result of differences between the space operating environment and ground test environments. Differences that proved critical include microgravity, differences in atmospheric composition, and differences in crew waste composition. In some of these cases, ground test environments could have been adjusted based on available data given enough engineering insight and imagination and would then have produced test results that identified the failures and allowed their elimination before flight. However, taken as a whole, the ISS ECLSS experience suggests that the interactions between systems as multivariate and complex as those in a regenerative ECLSS and an occupied human spacecraft will demand testing in the actual space flight environment before the level of reliability and knowledge of maintenance provisioning needs required for long human missions beyond LEO are achieved.

Another lesson that may be taken from the ISS ECLSS experience is that in a long complex mission like a human flight to Mars, the probability of unanticipated problems will always be high. In addition its obvious design implications – design for maintainability, commonality, etc., to maximize response options – this implies that test programs to support such missions should yield residual operational hardware on Earth or in earth orbit (ideally both) that can be used to support the mission crew in analyzing and responding to ECLSS issues that were not explicitly addressed in crew training, maintenance planning, and spares provisioning.

In addition to providing the lessons learned cited here and driving the regenerative ECLSS maturation already accomplished, ISS can be a crucial enabling platform for the rigorous, integrated, extended, space-based testing .that is needed to get us safely to Mars. With planned operation to 2024 and possible program extensions, ISS provides at least eight more years of space operational experience with regenerative ECLSS technologies and systems. Benefits for Mars can be maximized through a concerted effort to expand what we have learned taking full advantage of the increased down-mass capability afforded by the Dragon capsule. Still more can be learned by flying replacement or parallel ECLSS hardware that incorporates design lessons learned and is as close to Mars mission designs as possible within ISS integration constraints during that time frame.

Further opportunities may avail themselves with NASA's efforts to establish a cis-lunar outpost "proving ground" for next generation or Mars-bound ECLS upgrades or new technologies. Likewise any efforts by U.S. or International partners to return to the lunar surface would also be an excellent opportunity to trial run any Mars surface technologies that vary from ISS designs due to the available and sometimes useful gravity component.

E. Maintenance

The ISS maintenance approach using ORUs been considered a problem for ISS and for future missions.

1. The ISS Orbital Replacement Unit (ORU) approach.

ISS ORUs are removed and replaced on-orbit either in Preventative Maintenance (PM) if they have a limited operational life or for Corrective Maintenance (CM) to replace any that fail. The ISS has more than 5,700 ORUs and hundreds of thousands of spare parts that are supplied by nearly 200 manufacturers. (Soldon, 2004)

ISS maintenance uses ORUs, but the usual term in the military is Line Replaceable Unit (LRU). LRUs are modular and interchangeable. They improve system availability because they can be stocked and replaced quickly on site. In some cases Lower Level Replaceable Units (LLRUs) are provided to quickly repair an LRU. LRUs must be specifically designed and are often supported by tools, test procedures, and training. Parts, boards, assemblies, and components may be used to repair LRUs but are not considered LRUs. (Wikipedia, Line replaceable unit)

The definition and design of the LRUs and the selection of the appropriate level of repair are difficult systems design issues. The most obvious factor to consider is the cost or, for space, the launch mass required to achieve the reliability needed. But other non-economic issues can be controlling, such as down time, manpower, ability to test and diagnose, difficulty of repair, risk of damage, transportation and storage, and the tools and test equipment required. (Parada Puiga and Bastena, 2014) (MSFC-HDBK-3074) (Patterson, 2001)

2. The Russian maintenance design approach

The Russian Space Agency (RSA) has had a different approach to maintenance. The RSA approach for MIR and ISS is to replace a failed ORU by a spare ORU provided by a Progress re-supply flight. The RSA has had limited down-mass, preventing sending ORUs to Earth for repair. Little mass can be returned on Soyuz and Progress burns up in re-entry. The space shuttle allowed ground servicing of US ORUs. It has been noted that, “the Russians do not need to plan as extensively for failures because they do not use as much new technology.” (Patterson, 2001) The Russians use more heritage hardware. (Sanchez and Voss, 2005-705) And, “Americans need to plan extensively for failures because new technology is widespread. … The reliability of many items is unknown and reactions to failures must be heavily preplanned. … the implementation of so much new technology at one time has never before been attempted in space.” (Patterson, 2001) The U.S. process of returning and repairing ORUs has provided information about their designs and where improvements are needed to increase reliability.

F. Lower level repair

There are usually three levels of maintenance; organizational, intermediate, and depot. Organizational maintenance usually consists of actions to remove and replace (R&R) LRUs. Intermediate repair facilities can use test equipment and spare parts stocks to handle simple common failures. Furthest back from operations, at repair depots or even manufacturers’ sites, maintenance can include complex repairs, overhauls, and design modifications. (Wikipedia, Level of repair analysis)

The ISS uses standard three level maintenance. Organizational maintenance is corrective maintenance by on-orbit ORU removal and replacement or preventative maintenance through scheduled change out of ORUs. Intermediate maintenance is corrective maintenance to disassemble and repair ORUs. It has been done successfully several times on ISS, although obtaining scarce crew time is difficult. Depot maintenance is corrective maintenance at a NASA depot or manufacturer’s facility to repair broken ORUs or spare parts that cannot be fixed at the other maintenance levels. (Soldon, 2004) (Patterson, 2001)

The ISS ORU repair approach is not thought to be feasible beyond LEO. (Bertels, 2006-5952) Lower level repair should be considered. “Alternate concepts of operation must be explored in which required spare parts, materials, and tools are made available to make repairs; the locations of the failures are accessible; and the information needed to conduct repairs is available to the crew.” (Cirillo et al., 2011-7231)

VII. Conclusion

Developing and operating the International Space Station (ISS) and the ISS Environmental Control and Life Support System (ECLSS) has been a fantastic endeavor. The lessons learned with the ISS ECLSS so far are a critical step on our journey to Mars that will influence our approach to ECLSS design, reliability, redundancy, testing and maintenance for that mission. They make it clear that we have a sound technology foundation for the ECLSS we will require and also unmistakably show how much remains to be accomplished. ISS has clearly demonstrated the need to make regenerative ECLSS smaller, lighter, and more robust and reliable than we have achieved in the ISS systems. Experience on board has demonstrated both the value and the costs of diverse redundancy in regenerative life support and provides important guidance for design trade-offs for future Mars missions. ISS experience in introducing many new regenerative life support systems into operational use in space has shown some of the limitations in the ground based test programs used to develop and certify them and reinforced prior lessons learned about the crucial importance of integrated testing and truly representative test environments. These strongly indicate that Mars mission ECLSS should be subjected to extended operational tests in space to ensure the crew's safe return to Earth. ISS experience has also reinforced the importance and value of engineering evaluation of failed hardware to enable increases in reliability and robustness and the urgent need for a robust down-mass capability to allow engineering evaluation without the time and resource constraints placed on flight crew. Invaluable experience in ECLSS maintenance has been gained and will guide improved designs for maintainability and enhanced maintenance operations planning for the Mars mission ECLSS.

ISS contributions to the development of a Mars mission ECLSS are far from complete. With eight more years of planned crewed operations, more essential experience in regenerative life support in the unique spacecraft environment is inevitable. It is of crucial importance that we make the effort to maximize the value of this opportunity by seizing every opportunity to learn from the continued operation of current systems and, where possible, to add experience with updated and upgraded systems that are closer to those that will take us to Mars. Likewise when a cis-lunar facility is created and humans return to the lunar surface, foremost in the engineer’s minds during the design and deployment of the ECLS systems should be the intention to prove out the technologies for Mars in the closest possible analog environments before the commitment to the "all in" Trans-Mars-Injection thruster burn!

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