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Life Support for Deep Space and Mars

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How should life support for deep space be developed? The International Space Station (ISS) life support system is the operational result of many decades of research and development. Long duration deep space missions such as Mars have been expected to use matured and upgraded versions of ISS life support. Deep space life support must use the knowledge base incorporated in ISS but it must also meet much more difficult requirements. The primary new requirement is that life support in deep space must be considerably more reliable than on ISS or anywhere in the Earth-Moon system, where emergency resupply and a quick return are possible. Due to the great distance from Earth and the long duration of deep space missions, if life support systems fail, the traditional approaches for emergency supply of oxygen and water, emergency supply of parts, and crew return to Earth or escape to a safe haven are likely infeasible. The Orbital Replacement Unit (ORU) maintenance approach used by ISS is unsuitable for deep space with ORU's as large and complex as those originally provided in ISS designs because it minimizes opportunities for commonality of spares, requires replacement of many functional parts with each failure, and results in substantial launch mass and volume penalties. It has become impractical even for ISS after the shuttle era, resulting in the need for ad hoc repair activity at lower assembly levels with consequent crew time penalties and extended repair timelines. Less complex, more robust technical approaches may be needed to meet the difficult deep space requirements for reliability, maintainability, and reparability. Developing an entirely new life support system would neglect what has been achieved. The suggested approach is use the ISS life support technologies as a platform to build on and to continue to improve ISS subsystems while also developing new subsystems where needed to meet deep space requirements.

Nomenclature

4BMS = Four Bed Molecular Sieve
ARS = Atmosphere Revitalization System
CDRA = Carbon Dioxide Removal Assembly
DSLS = Deep Space Life Support
ECLSS = Environmental Control and Life Support System
EVA = Extravehicular Activity
GER = Global Exploration Roadmap
ISS = International Space Station
LCC = Life Cycle Cost
LEO = Low Earth Orbit
LOC = Loss of Crew

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MPCV	=	MultiPurpose Crew Vehicle (formerly Orion)
NASA	=	National Aeronautics and Space Administration
OGA	=	Oxygen Generation Assembly
OGS	=	Oxygen Generation System
ORU	=	Orbital Replacement Unit
Pr(LOC)	=	Probability of Loss of Crew
RO	=	Reverse Osmosis
SFWE	=	Static Feed Water Electrolysis
SPWE	=	Solid Polymer Water Electrolysis
SSF	=	Space Station Freedom
TIMES	=	Thermoelectric Integrated Membrane Evaporation System
TRL	=	Technology Readiness Level
UPA	=	Urine Processor Assembly
VCD	=	Vapor Compression Distillation
WPA	=	Water Processor Assembly
WRS	=	Water Recovery System

I. Introduction

THIS paper considers life support for deep space missions and Mars. What life support system is needed and how should it be developed?

NASA has the goal of sending humans to Mars, but it does not have a specific Mars mission. However NASA is currently developing two major capabilities needed for the Mars mission, a heavy lift launch rocket and a reentry capsule. There are no current programs to develop other capabilities needed for Mars such as a deep space transit habitat, a Mars lander and ascent vehicle, or a Mars surface habitat. Both the transit and surface habitat must support the crew for a year or more using resources sent with the crew or previously put in place. The crew's dependency on the transit and surface habitats' Deep Space Life Support (DSLS) systems is a major risk to the crew, probably exceeding the risk of launch or reentry (Jones, 2013b).

The DSLS for Mars is usually assumed to be a recycling life support system similar to the ISS system. It should be based on ISS life support but must meet unique deep space mission requirements. The DSLS must have much higher reliability, reparability, and availability, since consumables resupply, unplanned parts delivery, or emergency crew return are much more difficult than on ISS or anywhere in the Earth-Moon system. A matured and upgraded ISS life support system is unlikely to meet DSLS needs. A specifically dedicated effort is needed to develop DSLS.

The ISS life support architecture and the on-board system itself should be used as the starting point and supporting platform for DSLS development. The suggested approach is to redesign or replace critical subsystems as needed, one by one, to achieve the needed high reliability. A long test time is needed to verify low failure rates and to gather data needed to plan for spare parts and maintenance.

It seems inevitable that in time we will accomplish all our hoped for space missions. We will return to the Moon and establish bases. We will establish space stations beyond Low Earth Orbit (LEO) in the Earth-Moon system. We will visit Mars and establish bases there. Expeditions will be made to the asteroid belt and the Jovian moons. The exploration of space will lead to a major human expansion, the human settlement of near-Earth space, the Moon and Mars, and the use of resources from the asteroids and moons of Jupiter. Affordable, reliable life support will be needed for the first long lonely trips in deep space, to Mars and the asteroids, with no safe havens and few abort options.

Any anticipated human path into space could be wrong, but the solar system is a given. When we travel beyond the Earth-Moon system into deep space, to Mars, we will need highly reliable long duration DSLS. We should start now to develop the most difficult life support system, a high reliability microgravity transit system. It is needed for our first step beyond the Earth-Moon system.

Do we need a Mars mission before we develop the DSLS? The Apollo program showed that a NASA mission with urgency, focus, and coordination can produce magnificent results. But NASA also develops capabilities step by step, as in building the shuttle and using it to build space station. We are now developing a launch system and crew capsule without a defined mission. The Constellation Program, going to the Moon, Mars, and beyond, showed that having a mission does not ensure all planned elements are developed. Limited funding put first things first. The Apollo-style launch system and crew capsule were well begun but little effort was spent on reaching the Moon and none on Mars. And the Moon preparations ignored the Mars requirement for high reliability life support (Green and Watson, 2008; Nejad et al., 2009; Jones, 2010) and cancelled the methane rocket intended for Mars ascent (NASA, 2006, Jones, 2013a; Wooster, 2007). An ambitious mission with incremental funding became a first step mission, an unappealing long delayed return to the Moon. If reaching deep space and Mars is our goal, developing DSLS is the means, before and after the mission is defined.

A DSLS using stored oxygen and water and carbon dioxide removal material would be highly reliable, but would have very high mass and be difficult to launch. A recycling DSLS requires will require long and costly development and test to ensure its reliability. If a Mars mission is initiated on a short schedule and reliable recycling DSLS has not been developed, mission planners may be forced to use high capacity propulsion systems with complex multi-rendezvous schemes (Jones, 2013c; Jones, 2012; Jones, 2014b).

II. Space station and deep space life support

Plans for a Mars mission usually assume that the life support system will be similar to the International Space Station (ISS) Environmental Control and Life Support System (ECLSS) (Connolly, 2000; Drake, 2009). The ISS ECLSS is largely an operational oxygen and water recycling life support system. Its systems architecture was designed and its subsystem technologies selected based on decades of research and development.

The ISS is the only current long-term human occupied microgravity platform, and provides a unique test bed for identifying microgravity problems and testing improvements. The ISS ECLSS is a landmark achievement that demonstrates the fundamental systems architecture of long duration partial recycling life support. The development of DSLS must be based on this store of knowledge.

A. Developing DSLS by maturing ISS ECLSS

The current approach to developing the DSLS is through ISS ECLSS maturation and upgrades.

> "Living in space for long durations with little or no resupply of water and oxygen is a fundamental capability that is being matured through day-to-day operations on the only platform capable of the task – the ISS. This is because the technologies dealing with gases and liquids are highly dependent on the gravity environment. The ISS Programme is using routine upgrades of the current life support systems to increase operational availability and reduce system mass, consumables, and power needs beyond the current technology." (ISECG, 2013, p. 27)
>
> "The ECLSS technical community has developed a general roadmap framework summarized herein to pursue short-duration operations through development of the MPCV ECLSS and long-duration operations by utilizing ISS-derived ECLSS capabilities. … In the current NASA environment, completing the MPCV ECLSS hardware development, performing targeted ISS demonstrations to address existing reliability issues and add capabilities, and pursuing a rigorous ground testing program will drive us to effective solutions for the next steps of human exploration beyond low earth orbit." (Metcalf, et al., 2012)

Space habitat designers support the current consensus that the way to develop DSLS is to improve the ISS ECLSS. But the limitation has been noted that "ISS does have two key differences from the actual exploration environment that will be experienced beyond LEO," space radiation and spacecraft atmosphere (Hodgson et al., 2013). A third important difference is in operations, since the frequent crew changes, resupply, and waste removal on ISS will not occur in deep space.

B. The ISS ECLS

The ISS ECLSS is shown in Figure 1.

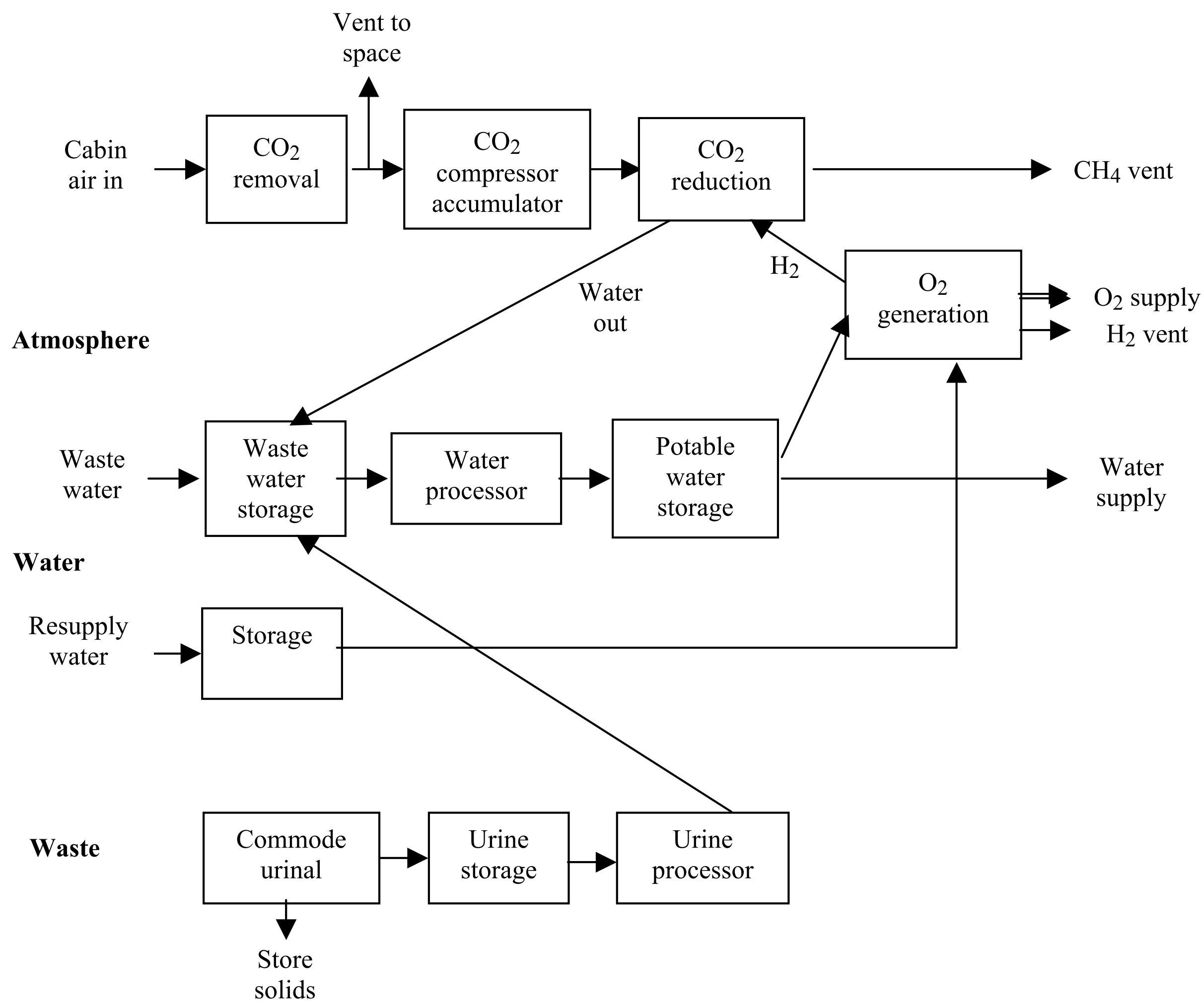

Figure 1. The ISS life support system.

As shown in Figure 1, the ISS life support system contains atmosphere, water, and waste recycling processors. The four bed molecular sieve (4BMS) carbon dioxide removal system is designed to allow the carbon dioxide to be vented to space or to be delivered to the Sabatier carbon dioxide reduction system. The electrolysis oxygen generator provides oxygen directly to the cabin atmosphere. The hydrogen can be vented overboard or used for carbon dioxide reduction.

Waste hygiene water and cabin condensate is stored and routed through the potable water processor to a potable storage tank. Resupply water delivered by Progress or other resupply vehicles is usually run through the water processor before potable use. Urine is pumped from the urinal to the urine processor and the distillate is combined with other wastewater. The commode bags and compacts feces. Solid wastes and feces are usually loaded into Progress and burned up during Earth reentry. (Diamant and Humphries, 1990; Carrasquillo and Bertotto, 1999; Bagdigian and Ogle, 2001)

Major ISS ECLSS technologies are listed in Table 1.

Table 1. ISS ECLSS technologies.

ISS assembly	ISS technology
Atmosphere Revitalization System (ARS)	
Carbon Dioxide Removal Assembly (CDRA)	Four Bed Molecular Sieve (4BMS)
Sabatier Reactor Subassembly (SRS)	Sabatier
Oxygen Generation System (OGS)	
Oxygen Generation Assembly (OGA)	Solid Polymer Water Electrolysis (SPWE)
Water Recovery System (WRS)	
Water Processor Assembly (WPA)	Multifiltration
Urine Processor Assembly (UPA)	Vapor Compression Distillation (VCD)

C. The ISS ECLSS technology selection process

The space station technology selection process was reported in a 1992 NASA Technical Memorandum. (Carrasquillo, Carter, et al., 1992) This technology selection effort was originally for Space Station Freedom (SSF). The selected SSF ECLSS technologies and alternates are given in Table 2.

Table 2. The selected SSF technologies and the earlier baseline and alternates.

Function	SSF selected	earlier SSF baseline	earlier SSF alternate
Carbon dioxide removal	4BMS	4BMS	
Carbon dioxide reduction	Sabatier	Bosch	Sabatier
Oxygen generation	SFWE	SFWE	SPWE
Potable water processing	Multifiltration	Multifiltration	RO
Hygiene water processing	Multifiltration	RO	Multifiltration
Urine processing	VCD	TIMES	VCD

(Technology acronyms not identified in Table 1 are Static Feed Water Electrolysis(SFWE), Reverse Osmosis (RO), and Thermoelectric Integrated Membrane Evaporation System (TIMES).)

The SSF technology selection process can be summarized as follows.

1. Candidate SSF technologies were identified.
2. Technologies of low technical maturity were eliminated.
3. Trade studies considering safety, resource requirements, performance, reliability, maintenance, and complexity were used to select baseline and alternate candidates for each SSF technology. (Table 2)
4. The baseline and alternate SSF candidates had prototypes developed and were compared using quantitative and qualitative criteria. One baseline technology, 4BMS, had no alternate. One choice, Sabatier over Bosch, was made quantitatively, based on lower launch mass and resupply savings. The other four choices were based on qualitative justifications. In two of these cases the baseline was chosen, in the other two the alternate. (Table 2)

The ISS technology selection was based on the SSF selection, but one SSF chosen baseline technology (SFWE) was later replaced by its SSF alternate (SPWE). The three SSF baseline technologies not selected (SFWE, RO, TIMES) appeared almost as good as those selected (SPWE, Multifiltration, VCD). High technical maturity was the most important selection factor.

The ISS ECLSS design process raises several interesting issues. The first technology screening eliminated low technical maturity technologies. The baseline and alternate subsystem bench testing began in 1986. Although schedule pressure seems a poor justification given the more than twenty years that elapsed before flight, selecting for high technical maturity reduces development cost and risk as well as schedule. Should high technical maturity be the most important selection factor?

The ISS ECLSS was not designed using alternate system architectures that were traded-off at the system level. The component technologies were traded head-to-head within the standard recycling system architecture. Could an alternate ECLSS architecture, for example using carbon dioxide electrolysis, be considered?

Not all the ISS ECLSS technology selections were clearly better than their alternates. The candidate technology pairs were compared qualitatively and in detail based on prototype testing, but no overall single figure of merit was developed. The Equivalent System Mass was not computed but later became the standard metric in ECLSS design. The three technologies chosen for oxygen generation, water purification, urine purification were selected based more on qualitative than quantitative justifications. All three changed between SSF baseline identification and ISS selection. Would different requirements produce different selections?

The stated issues have important implications. Since only high technical maturity technology is considered for flight, any new technologies for deep space must be flight proven. The fundamental recycling architecture of ISS has remained unchanged for decades and a different one is practically unthinkable. But alternate technologies that fit within the ISS architecture are of great interest.

D. The ISS ECLSS needs improvement

A paper by ISS ECLSS team members written before the ISS Node 3 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, Bagdigian, et al., 2004)

Problems cited 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, Bagdigian, et al., 2004)

(Carrasquillo, Bagdigian, et al., 2004) also make clear the absolute necessity of on-orbit operational experience, especially over the long term. The transport and accumulation of fine particles in microgravity caused problems with ventilation fans, smoke detector, 4BMS, and the water processor Volatile Removal Assembly. ISS ECLS systems could not have been exposed to such debris loads during development testing or flight hardware ground testing. In addition to discovering operational failure modes, it is necessary to acquire operational experience with ECLS equipment to fully understand maintainability needs. See also (Carrasquillo, Wieland, et al., 1996) for a similar discussion.

E. Is maturing ISS ECLSS the right path to DSLS?

The ISS ECLSS is a landmark achievement on the path to space. All future space ECLSS will be descended from the ISS ECLSS. The DSLS used on early deep space missions is expected to be similar to the ISS ECLSS in architecture and basic technologies. However, the optimum DSLS would not be the best system for ISS, since it would not use the rapid resupply and repair options available in LEO. Conversely, a matured and upgraded ISS ECLSS may not be the optimum DSLS for Mars, since it could lack the high reliability needed, fail to incorporate capabilities required to support EVA intensive surface missions, and incur relatively high expendables and consumable resupply mass penalties while still meeting ISS needs effectively. Still, the ISS ECLSS is the obvious foundation for developing the DSLS. The DSLS would benefit by reversing the recent trend toward "greater emphasis on hardware that benefit ISS" (Hodgson et al., 2013) to instead focus on utility for deep space missions.

The basic architecture and candidate subsystems for recycling life support have long been well known. An innovative independent DSLS test bed to fly on ISS or in a spacecraft in the Earth's vicinity has been proposed. ECLSS will in time move beyond ISS in many areas and may adopt fundamentally different architectures and incorporate technologies not anticipated today. There is now a broad community consensus behind the current approach. The need for a very high level of maturity and confidence creates a formidable barrier to introducing novel solutions for our first missions into deep space. Nonetheless, it might be useful to deliberately develop possible alternate architectures and investigate innovative technologies as part of the planning for the DSLS.

Upgrading ISS ECLSS and developing DSLS both start here and now with ISS ECLSS. They will share common elements but evolve in diverging directions. The relationship between improving the ISS and developing the DSLS depends on the commonality and the differences between ISS ECLSS and DSLS requirements.

III. Life support requirements for ISS and deep space

What are the life support requirements for future space missions, for deep space beyond the Earth-Moon system, for Mars? How do they differ from the life support requirements for the space station in LEO? The crew's basic daily requirements for life support are determined by fundamental human physiology and are similar everywhere. Gravity environment, workload, and EVA can increase peak and average metabolic loads during planetary surface missions, but these are quantitative rather than qualitative changes. In contrast, the operational requirements for the life support system - including power and thermal interfaces, safety, reliability, maintainability, and reparability - are fundamentally mission dependent. The required performance of the life support system changes somewhat, but the implementation of the system can be significantly different.

Ideally, a life support system should be designed "top-down," from mission requirements, to the systems architecture, and then the subsystem technologies. However schedule and budget realities and the critical importance of operational experience in developing robust and reliable systems may drive a more evolutionary approach. We already have a standard architecture using the well understood technologies of the ISS ECLSS. The current task is to see how well the ISS ECLSS fits the requirements and design considerations for deep space.

A. Mission segment based life support requirements for ISS and Mars

We consider life support system requirements for three mission segments, for ISS ECLSS for LEO, a Mars transit DSLS, and a Mars surface DSLS. An overview the parameters of these mission segments with their associated system benefits and costs is shown in Table 3.

Table 3. ISS and Mars mission segment parameters and life support system benefits and costs.

Category	**Item**	**#**	**ISS**	**Mars transit**	**Mars surface**
Mission segment parameters	Propulsion cost	1	1	10	10
	Travel time	2	hours	~ 6 months	~ 6 months
	Duration	3	10 years	~ 1 year	~ 1.5 years
	Quiescent waiting	4	none	~ 1.5 years	limited[1]
	Environment	5	LEO	deep space	Mars surface
	EVA time	6	limited	very little[2]	much
	Sun light cycle	7	92 minutes	full sun	24 hours, 37 minutes
	Gravity	8	~ 0 g	~ 0 g	~ 1/3 g
	Radiation	9	Earth shielded	maximum	Mars shielded
	Planetary material	10	none	none	atmosphere, regolith
	Total risk	11	low	high	very high
System benefits	Life support performance	12	standard	reduced	reduced
	Reliability of performance	13	low	high	high
System costs	Radiation protection	14	some	high	some/regolith?
	Life Cycle Cost	15	high	much higher	much higher
	Crew time	16	high	much higher	much higher
	Pr(Loss of Crew)	17	low	high	high

[1] Operational verification of pre-emplaced surface systems prior to crew departure is included in some scenarios.

[2] There are possible EVA's for contingency responses for external systems and crew supported deep space experiments.

The mission segment affects the life support requirements and system design through four key mission parameters, the propulsion cost, the travel time, the mission duration, and the space or planetary environment. The environment in turn determines the Extravehicular Activity (EVA) time, sun light cycle, gravity, radiation, available material, and expected risk. The life support system benefits are its performance, the quantity and quality of materials and functions, and the reliability of its performance. The system costs include the necessary radiation protection, the system's Life Cycle Cost, (LCC) the crew time needed to operate and maintain the system, and the Probability of Loss of Crew [Pr(LOC)].

System design requires making trade-offs between conflicting benefits and costs. No one design can optimize all the mission objectives. Often one or two key mission objectives control the major design decisions. Avoiding the worst problems may determine the final design choice (Rechtin, 1991; Aslaksen, 1992). Planetary protection requirements for Mars should influence the DSLS design.

The largest potential problem, the greatest risk for life support is that the system will fail and the crew will be lost. In LEO, probably only a loss of atmosphere could be fatal. On the Moon or anywhere in the Earth-Moon system, loss of carbon dioxide removal capability could be fatal in a few hours or days. In deep space, on a Mars mission, lack of water or even food would also cause a loss of the crew. For most life support failures within the Earth-Moon system, supplied parts or materials or a crew return can be provided in a few days.

Clearly, since a life support failure in deep space creates a much larger risk to the crew, deep space life support reliability is much more critical than it is for the ISS ECLSS. However, ultra-reliability is difficult and expensive to achieve and there are many other important considerations, such as launch mass and crew time for operation. High reliability was desired for ISS but it must have higher priority in allocating resources and programmatic decisions for a deep space mission since the consequences of failure are much more severe. A balanced systems engineering approach including all considerations is necessary to achieve the correctly balanced design.

B. Overview of similarities and differences in mission requirements for ISS and Mars

This section gives an overview comparison of the requirements for life support systems in LEO or deep space based on Table 3. A detailed analysis of all seventeen items in Table 3 is given in an Appendix.

The ISS mission parameters are somewhat similar to those of Mars transit, considering vacuum, little or no EVA, microgravity, and no planetary material, items number 5, 6, 8, and 10. Therefore, ISS is a good test bed for a Mars transit DSLS. However the DSLS will experience higher radiation.

The Mars transit and Mars surface mission parameters and life support systems are very similar. They have similar propulsion cost, travel time, operational duration, and risk, and they require similar performance, reliability, cost, and Probability of Loss of Crew [Pr(LOC)]. Mars transit and surface are similar in 8 of the 17 items, numbers 1, 2, 3, 11, 12, 13, 15, and 17. They differ in deep space or planetary environment and their effects, the 7 items 5, 6, 7, 8, 9, 10, and 14. These are Environment, EVA time, Sun light cycle, Gravity, Radiation, Planetary material, and Radiation protection. Items 4 and 16 are unclear. Quiescent waiting is required for the transit system during the surface visit, but not necessarily for the surface system. If the surface system is pre-emplaced and checked out before crew departure, a six months quiescent waiting time is required. Crew time is more readily available during transit, but the surface system may be more complicated due to the use of atmosphere resources.

Would we design the same DSLS for Mars surface and Mars transit? Possibly, but probably not. The transit system could work on the surface, but the optimum transit system would probably need more radiation protection and use more crew time than the optimum surface system. And a transit system could not take advantage of the gravity and resources available on the surface.

The differences between ISS and the Mars missions are much greater. It was noted that ISS is similar to Mars transit in vacuum, little or no EVA, microgravity, and no planetary material, items 5, 6, 8, and 10. Two ISS mission parameters are somewhat similar to those of Mars surface, both having a sun light cycle and planetary radiation shielding, items 7 and 9. Overall, ISS is different from either Mars transit or Mars surface or both in all 17 mission parameters and life support system benefits and costs. One ISS difference would tend to make ISS life support systems more suitable for deep space. The ten-year duration of ISS, item 3, would justify highly efficient and reliable systems that would be very suitable for deep space.

Would we design the same life support for ISS and Mars transit? It seems not. Could we use a matured and upgraded, designed and paid for, flight qualified ISS ECLSS for Mars transit? It would be a poor fit. Should we use ISS ECLSS as starting point and guide for the DSLS? Definitely yes. We must consider the changes to ISS ECLSS that would be beneficial for Mars transit.

C. Modifications to ISS ECLSS for Mars transit

What are the further improvements we would make to a matured and upgraded ISS ECLSS for Mars transit? The above discussion and the differences between ISS and Mars requirements described in the Appendix suggest the following:

1. Higher closure and lower system mass, but only if cost-effective.
2. Higher reliability, maintainability, and reparability.
3. Design for quiescent waiting.
4. Hardening for deep space radiation.
5. A changed quantity of life support materials, especially water, to reflect changed costs and needs.
6. Higher development cost for mass reduction, autonomy, higher reliability, and radiation hardening.

7. Higher planned crew time for a lower level maintenance and repair approach and significant design for repair to limit the severity of this impact.

The first item includes two indirect goals, closure and lower mass. The last three items are the expected costs and penalties, probably changed quantity of life support, higher development cost, and higher crew time. There are only three actual performance requirements for Mars transit that an ideal matured ISS ECLSS would not provide. These are first, higher reliability, maintainability, and reparability, second, quiescent waiting, and third, design for deep space radiation. Obtaining these is the fundamental reason that deep space life support must go beyond ISS ECLSS.

D. ISS issues

ISS ECLSS is successfully operational, with an architecture and subsystem technologies derived from decades of research and planning. However, operations over several years have revealed unanticipated problems that have forced redesigns and compensating procedures. Questions have arisen about some of the design decisions and even some of the development processes used. The ISS ECLSS problem areas of interest in planning for DSLS include reliability, maintenance, sizing, and testing.

1. 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; Jones and Ewert, 2010). Failures continue with no dramatic maturity increase or significant reliability growth (Hodgson, et al., 2013; Jones, 2014a). The ISS ECLSS does not use built-in redundancy. The ISS Water Recovery system (WRS) does not have redundant systems to increase reliability. "The WRS will be designed to be zero fault tolerant for functionality." (MSFC-SPEC-2841, 2004; Jones, 2008) Operations are more secure due to the presence of the diverse redundant Russian ECLSS systems. Improved reliability would be a benefit for ISS and is even more needed for DSLS.

2. Maintenance and repair

If a failure occurs in the ISS ECLSS, the failed system must be repaired. The ISS maintenance concept depends on Orbital Replacement Units, (ORU's), which are subsystems that can be readily replaced when the operating unit either passes its design life or fails. Use of ORU's saves crew time but requires the transportation and stocking of more units than are likely to be used, since achieving high reliability means ORU's must be available to repair even unlikely failures. Transportation of the relatively large ORU's is now much more difficult after the retirement of the Shuttle. Using lower level repair will reduce the mass and volume of spare parts, but will require numerically more spares, tools, test equipment, training, and crew time.

In a detailed review of ISS WRS failures and the lessons learned, it was stated that it would be much better to be able to replace small failed components rather than large ORU's, presumably because of the difficulty of maintaining stocks of ORU's and the delay in providing them when unexpectedly needed (Carter, 2010; Jones, 2010) Systems design should segregate the failure causes in the smallest, most easily replaceable parts. The ISS failure database should be used to identify failure causes that should be reduced in the DSLS and to help design the best possible repair or replacement scenarios for the remaining anticipated failures. Spare parts require inventory management and increased launch mass and volume. Maintenance and repair may cause secondary failure, e.g.. leaking or failed mechanical joints and seals.

3. Protoflight

The ISS ECLSS components were developed as "protoflight" hardware. The expense of a conventional flight qualification program was considered unaffordable. System and integration testing was limited, Studies of spacecraft testing show that subsystem tests do not discover all the subsystem errors and that system level testing finds many subsystem as well as system level problems. Space station designers argued that the ability to repair problems on board allowed them to accept, or rather transfer, more risk (Jones, 2007).

Testing is to engineering as experiment is to science, the assessment of reality. With insufficient testing, reasonable expectations may be disappointed. "The use of partially matured, proto-flight ECLSS on the ISS has resulted in extensive on-orbit repairs and modifications and has relied on extensive resupply and support from Earth." (Hodgson et al., 2012) Conditions limited investment in test and integration that might have made the ISS ESLSS more robust.

4. Sizing

The amount of water provided for the crew for hygiene on ISS was greatly reduced from the amount planned for SSF. The designed capacity of the ISS WRS seems to exceed ISS requirements. (Jones, Appendix A, 2008-01-2193) Experience on ISS has allowed the estimated required amount of water to be significantly further reduced (Jones, 2008). "This reduction dramatically affects ECLSS equipment sizing, expendables requirements and system design trades." (Hodgson et al., 2012)

5. Summary

The ISS ECLSS is less reliable than desired, has a now unworkable maintenance and repair concept, and has a water processor oversized for changing requirements. The ISS ECLSS designers have identified many other needed enhancements, as indicated previously. ISS ECLSS requires considerable improvement. Any improvements would be useful for DSLS, but DSLS requires further and different advancements than ISS ECLSS.

IV. ISS ECLSS platform based development of DSLS

The current approach to developing the DSLS is through ISS ECLSS maturation and upgrades, but DSLS must achieve performance beyond current requirements for ISS ECLSS. However, the ISS ECLSS architecture, technical knowledge, and the operational on-board system itself should be used as the starting point and foundational platform for DSLS development. Changes, whether to improve performance or to achieve new and difficult requirements, will be easier to accomplish by replacing one subsystem and one function at a time on ISS. The ISS ECLSS provides a unique test bed for identifying microgravity problems and integrating and testing new systems.

A. Platform based approach

The DSLS should adopt the ISS ECLSS system architecture and subsystem function definitions. These have been understood and accepted for more than forty years. The recommended approach to DSLS is a separately funded program to develop and test life support technologies on the ground, in independent test space flight, on the ISS integrated into an evolving ISS ECLSS, and then as a new DSLS in a new human space habitat beyond LEO for radiation exposure but within the Earth-Moon system for crew safety. Independent program funding is needed because the priorities and objectives of DSLS differ from ISS or advanced research. Ground test is required to establish reliability, flight test to identify microgravity issues, integration with or on ISS to solve integration problems, and test beyond ISS in LEO to experience deep space radiation and demonstrate autonomy, without being too far for quick resupply or return.

The ISS is necessary. “(T)he ISS has provided both the complex, in-space, long duration manned test environment that has exposed system weaknesses and the robust, forgiving, near-Earth operational environment that allows safe, iterative improvement and maturation of those technologies.” (Hodgson, et al., 2012) Using ISS to develop DSLS will be a consummate fulfillment of the purpose of the space station. The ISS will benefit from improved life support reliability and operability.

B. Research and development approaches

The suggested development path for DSLS is based on the unique resource of ISS. The usual NASA research and development program is a progression from basic research at low TRL’s thorough proof of concept, prototypes, and flight qualification at higher TRL’s. It is difficult to obtain funding for a flight system and to persuade the intended user to adopt the technology. This approach is followed in life support development but has not yet replaced any of the 1980’s era space station hardware technologies.

Industrial R&D is classified as either incremental short term improvements to a current product, with low risk and low payoff, or innovative new product development, with possible high payoff in the future but high risk of no payoff. Because of the different risks and payoffs, new product projects cannot directly compete with incremental projects for funding. Immediate safe opportunities are usually preferred to risky investment in the future, so a separate allocation of funding is needed for innovative work to be pursued. NASA has recently increased its emphasis on innovation by separately organizing and funding advanced technology. Deep space life support similarly requires separate funding to prevent diversion to ISS ECLSS problems or other urgent needs.

Platform based evolution is usual in computer system families, which have well defined architectures and subsystems. Any of the keyboard, display, processor, memory, and operating system can be upgraded independently within the systems architecture. Recycling life support is similarly suitable for platform based upgrades. The original ISS ECLSS subsystems were selected by comparing two different technologies head-to-head for each function. (Carrasquillo, Carter, et al., 1992) Familiar or innovative subsystem technologies can be developed as replacements.

C. Development and ground test

The space station subsystems should be redesigned to meet the higher reliability and other requirements for deep space, to take advantage of the lessons learned on space station, and to use the many advances in design engineering over the last thirty years. The ultimate goal of DSLS subsystem development is to achieve verified satisfactory reliability, maintainability, and reparability. This can be done only by designing for high reliability and ease of maintenance. To experimentally measure a failure rate, testing must be done until some failures are produced.

Usually new complex space systems cannot have low failure rates verified by test, because of the high cost of multiple unit, multiple year testing. Since long multiple unit testing is costly, requirements for high reliability are usually verified by analysis. High reliability can be verified by analysis only if the system is designed for high reliability, using components with tested high reliability and following good design principles, such as derating and parallel redundancy. Unfortunately, specification and design errors may introduce unanticipated failure modes that are not detected by routine paper analysis. Life support experience has shown that failure rates are higher, usually much higher, than indicated by analysis. (Likens, 1992)

Achieving high reliability for long life systems requires repeated cycles of redesign, test, operation, failure, failure analysis, and redesign. Initial systems testing often reveals major problems that require redesign. When these are solved, many smaller problems usually appear. Cutting the failure rate in half can take as much time and effort as the original system development (Rechtin, 1991; Jones and Kliss, 2006).

"A plan should be established to achieve the needed reliability. The required system reliability should be analyzed and allocated to subsystems and components. Technologies, materials, and components should be selected to improve reliability. Planning must include life testing of components to confirm their reliability and maintainability and spares requirements must be defined. The design should isolate the predominant failure modes in small, low mass, easily replaceable components. Analysis and test data must confirm that the system is capable of the required ultra reliability. The subsystems and integrated systems should be tested sufficiently to discover design errors that may cause failures." (Jones and Ewert, 2010)

If the DSLS subsystems do not have sufficient reliability, it may be necessary to provide multiple redundant subsystems. To avoid common cause failures, the redundant subsystems should be technically diverse but using different technologies for redundant subsystems would greatly increase the development and launch cost of the DSLS and reduce opportunities for common spares and maturation.

"For ECLSS that require long lead times for technology maturation, systems development must start in the very near future in order to deploy usable and reliable systems in the intermediate (5- 10 year) future." (Hodgson et al., 2013) It is later than we think. Compensating for lost time will require a greatly increased budget. We will need all of the time we have.

D. Flight tests

"ECLS technology maturation must include extended in-space operation. ECLSS experience on ISS includes numerous examples of issues that were not and could not reasonably be predicted, simulated and corrected solely in ground based test and analysis efforts. Despite great advances in our understanding of microgravity effects, fluid physics, human biology, and chemistry, the complex interactions of multiple effects in a functioning manned spacecraft over a long duration continues to stretch the boundaries of our imagination and challenge ECLSS designs in unexpected ways." (Hodgson, et al., 2012)

1. Independent flight test

DSLS subsystems should be tested in space as soon as possible. Microgravity failure mechanisms can be identified and repair procedures demonstrated. The ISS is the obvious place for flight tests, but initial testing in an independent spacecraft would reduce the impact on ISS.

2. Integrated test on ISS

DSLS subsystems should be tested on the ISS as integrated components in an evolving ISS ECLSS. They should be operated as part of the ISS ECLSS to acquire long in-space test time.

3. Test beyond LEO

"The need to "test as you fly" to fully mature long duration ECLS systems will ultimately limit the use of ISS as a testbed for exploration ECLS technologies. By design, the ISS operates in low-Earth orbit, protected from deep space radiation by the Earth's magnetic field. It is also designed for operation at an atmosphere equivalent to sea level on Earth. These two factors drive the need for a separate platform for ECLSS maturation through exposure to deep space radiation environment and exploration atmospheres. This need can be met by an ISS-derived exploration platform at an Earth-moon libration point." (Hodgson et al., 2012)

V. Conclusion

Future human space exploration will include the first trip in deep space to Mars, with no resupply, no rescue, and no escape if life support fails. A highly reliable deep space life support system should be developed as soon as possible, since it will require a long time to develop and test. The suggested approach is to use the space station life support system as a development platform, adopting its systems architecture and replacing as necessary its subsystems one-by-one with high reliability technologies suitable for the deep space voyage to Mars.

Experience suggests that maturation in as close to actual mission environments and operations as possible is essential and will need to encompass multiple replications and mission durations to establish confidence in robustness and definition of sparing requirements that will support initial deep space exploration missions. To commit to those missions we will need high confidence that the ECLSS design will support safe return for the crew with a consumable inventory and equipment complement that will not impose unsupportable launch mass penalties. To accomplish this we will need to operate exploration relevant ECLSS on ISS and on an anticipated future node in the lunar neighborhood as well in ground integration test facilities and we will need all of the time we have. This demands that the space life support community must overcome budgetary pressure (that we have already seen and can be sure will continue) to scale back ECLS systems and operations in near or on-lunar missions to the bare minimum. Recent suggestions for simple applications of largely non-regenerative technologies in near term missions beyond LEO because they meet specific mission needs and can reduce mission costs make this issue clear. If that path is pursued, operational data for advanced closed loop ECLSS in relevant environments will be insufficient to support LOC goals and mission provisioning decisions. Prudent program managers for exploration missions will see no viable ECLS options except flying essentially what we have on ISS today (or even simpler and less advanced technologies) to minimize risk and cost with significant resulting mission limitations and risks to the crew.

Appendix: Item by item differences between ISS and Mars requirements

The items of Table 3 are examined one by one to determine the detailed differences between ISS and Mars requirements.

Mission parameters. The mission affects life support requirements through cost, time, and environment.

1. Propulsion cost. Using conventional propulsion, providing the Mars transit and return rocket and fuel requires 10.2 times the mass of the payload in LEO. Similarly, providing the Mars transit and descent rockets and their fuel requires 9.6 times the mass of the payload in LEO (Price et al., 2009, Jones, 2013c). The launch and emplacement cost for life support hardware, materials, and spares will be about ten times higher in deep space than in LEO. The savings in propulsion cost achieved by increasing closure and reducing total system mass are ten times higher in deep space than in LEO. This suggests that deep space systems should be designed for higher closure and lower mass than LEO systems. However, increasing closure is not justified if the total system mass increases. And decreasing total system mass is not justified if the total Life Cycle Cost (LCC) increases. Propulsion cost is only one element of LCC, and it is usually lower than the system development cost (Jones, 2013c). Advanced propulsion may significantly reduce future costs.

2. Travel time. The trip to Mars requires about six months, while LEO can be reached in a few hours. The travel time effectively prohibits providing systems, parts, or materials in response to a failure, or bringing back the crew in an emergency. The long travel time to Mars requires life support with higher reliability, maintainability, and reparability, achieved autonomously by design, spares, and redundancy.

3. Duration. The long duration of the ISS and Mars missions requires long life, high reliability life support. However, the possibilities of prompt resupply or return from LEO make the penalty for failure much more affordable in LEO. A failure that is an inconvenience in LEO can cause Loss of Crew in deep space. The mass of oxygen, water, and food consumed by the crew increases directly with duration. This suggests that long duration systems should be designed for higher closure, if that is cost-effective.

4. Quiescent waiting. The Mars transit system, expected to remain in Mars orbit for 1.5 years, requires a long term quiescent waiting ability, while ISS does not. Although there would be no crew consumption of water and oxygen, and the system will usually be quiescent, microbial contamination and corrosion are possible.

5. Environment. LEO, deep space, and the Mars surface have different EVA time, sun light cycle, gravity, radiation, available material, and expected risk.

6. EVA time. ISS requires limited EVA, and a deep space transit vehicle probably will need little or none, but exploration of the surface of Mars will require extensive EVA. EVA can have a significant impact on the life support system. The physical effort of EVA requires additional life support consumables and the suit cooling water and exhaled carbon dioxide will probably be lost. Provision for airlock operations can also have a significant impact and may dominate mission requirements for atmosphere diluent gas and introduce new contaminants and air and water treatment needs.

7. Sun light cycle. The rapid orbit of ISS, the deep space location of Mars transit, and the rotation of Mars produce different solar illumination. If solar power is used, the requirement for battery storage at night will make its cost highest on the Mars surface. Mars has about half the solar illumination of Earth. Mars surface could reduce the effectiveness of solar power on Mars.

8. Gravity. Microgravity has caused problems for ISS ECLSS. Proven operation in microgravity would be necessary for a Mars transit DSLS system.

9. Radiation. The ISS is shielded by Earth's mass and magnetic field, and a Mars surface base is shielded by Mars' mass and atmosphere. A deep space transit vehicle is exposed to more solar and cosmic radiation. This may require life support designed for deep space radiation or at least tested in deep space and may significantly influence design trades by altering mission benefits and penalties associated with increasing consumable materials mass that could add to radiation shielding for the crew and mission equipment.

10. Planetary material. The atmosphere and regolith of the Mars surface could provide important life support materials.

11. Risk. The long travel time to Mars greatly increases mission risk by preventing aiding or bringing back the crew in an emergency. The Mars surface mission has the additional risk factors of descent, exploration EVA, and ascent.

System benefits. The life support system must provide sufficient quantity and quality of materials, such as oxygen and water, and functions, such as carbon dioxide removal, with the needed reliability of performance.

12. Life support performance. The quantity of material required, particularly water, for ISS was significantly reduced from the original requirements for SSF. The crew daily allowance of water was further reduced during the Constellation Program. The cost and difficulty of providing life support in deep space could suggest providing a lower quantity of water than provided by ISS, or the water allowance could increase to allow crew showers and perhaps provide radiation shielding in transit or laundry and cleaning to help mitigate Mars dust (Jones, 2008).

13. Reliability of performance. The long travel time to Mars, by preventing the quick supply of spare parts or crew return, directly forces higher mission reliability (including possible repairs with preplanned logistics) while the long operating time of ISS does not. Extremely high reliability would be desirable for ISS but clearly is not absolutely necessary because emergency support from Earth or emergency return on short notice are available options.

System costs. The system costs include any provided radiation protection, LCC, crew time, and the Pr(LOC).

14. Radiation protection. The maximum solar and cosmic radiation received by a deep space transit vehicle may require the cost of design for deep space radiation and testing in deep space.

15. Life Cycle Cost. LCC includes the system development cost, the launch or propulsion cost, and the operating cost. The operating cost is typically about ten percent of the system development cost per year (Jones, 2013c). The propulsion cost is about ten times higher for Mars than for LEO. The system development cost will be higher for deep space than for LEO, due to the needs for mass reduction, autonomy, higher reliability, and possibly radiation hardening.

16. Crew time. The ISS crew spends about half its time on operation, maintenance, and repair, and the ISS ECLSS has required more time than anticipated. However, the current ISS maintenance approach is considered unsatisfactory, and a lower level, more crew time intensive approach has been suggested (Carter, 2010; Jones, 2010). Given the need for higher mission reliability with limited mass and volume for spares, much higher crew time use to support the DSLS can be expected, and significant design effort to improve maintainability and limit MTTR may be required to avoid adverse impact on mission objectives.

17. Probability of Loss of Crew. Pr(LOC) due to a life support failure is low for a crew on ISS, because of good system performance, ground support and resupply in response to system failures, and also especially because of the option of an emergency return to Earth. The Pr(LOC) in deep space may be higher because of the lack of an emergency return capability, and also because it may not be possible to achieve a sufficiently high system reliability without any Earth based contingency resupply capability.

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