47th International Conference on Environmental Systems
16-20 July 2017, Charleston, South Carolina

ICES-2017-027

ISS as a Test Bed for Exploration ECLS Technology Development and Demonstration

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This paper will discuss opportunities for advancing the Environmental Control and Life Support (ECLS) requirements and technologies needed for space exploration beyond low earth orbit, including some lessons learned, items already planned for use on the International Space Station (ISS), along with what should be/might be added. Also discussed will be possible crew training deltas (e.g. time delays) to demonstrate and experience anticipated operational differences (e.g. deep i-level repairs, crew managed local ppO2, ppCO$_2$ and water management).

Nomenclature

ACS = *Atmosphere Control & Supply*
AR = *Atmosphere Revitalization*
CCAA = *Common Cabin Air Assembly*
CDRA = *Carbon Dioxide Removal Assembly*
CHX = *Condensing Heat Exchanger*
DMSD = *DiMethylSilaneDiol*
ECLSS = *Environmental Control and Life Support Systems*
EVA = *Extravehicular Activity*
FDS = *Fire Detection and Suppression*
IMV = *Inter-Module Ventilation*
ISS = *International Space Station*
MCA = *Major Constituent Analyzer*
OGA = *Oxygen Generation Assembly*
PCM = *Phase Change Material*
PDMS = *Polydimethylsiloxane*
PFE = *Portable Fire Extinguisher*
SMAC = *Spacecraft Allowable Maximum Concentration*
THC = *Temperature & Humidity Control*
TOC = *Total Organic Carbon*
TRL = *Technology Readiness Level*
UPA = *Urine Processing Assembly*
USOS = *United States Operational Segment*
UWMS = *Universal Waste Management System*
WM = *Waste Management*
WPA = *Water Processing Assembly*
WRM = *Water Recovery & Management*

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I. Introduction

THE International Space Station (ISS), a joint project among five space agencies, is the most sophisticated and useful space laboratory ever built. The ISS has orbited Earth for nineteen years and hosted payload experiments in a full range of scientific investigations, ranging from Earth observation to biology to materials to astronomy.

The ISS is well suited for the testing of deep space spacecraft systems and operations for the eventual human exploration of the moon and Mars and provides much closer conditions to the deep space environment than can be simulated on the surface of the Earth, including weightlessness, radiation and other factors unique to space. Candidate exploration systems can be tested in a highly relevant environment before trusting human lives to them. With long duration crew onboard the ISS, opportunities are available to study long term human factors affected by physical and emotional separation. Operations at a distance also allow the opportunity to practice mission operations to refine potential deep space techniques. In the relative safety of low Earth orbit, the ISS is the prime location for testing new exploration systems, providing mission confidence, and assuring mission success.

Life support systems particularly benefit from the full range of testing possibilities offered by ISS as they are absolutely vital to human life and offer significant opportunities for human interaction in operation, maintenance and repair. Trusted and highly reliable life support systems are a prerequisite for committing humans to long durations space missions with limited or no abort opportunities. Having operated for many years, the ISS already provides many lessons learned on the long term operation of life support hardware, from requirements development to failure history to maintenance and logistics. New life support technologies can also be tested at ISS in ways that both demonstrate the technology and benefit ISS. In those situations, the assurance required can be gained from long duration testing to gain months and years of operation confidence. At ISS, crews can also be taught new maintenance and repair procedures to simulate the unanticipated situations that can arise during long missions. The simulations will provide valuable knowledge and experience on minimum training sets and methods for teaching new procedures. Testing of deep repair procedures (i-level) at ISS will also provide valuable insight on how hardware can be repaired rather than replaced.

In this paper, the operational history of the Environmental Control and Life Support Systems (ECLSS) will be discussed, including some lessons learned from requirement development versus implementation, anomalies and anomaly resolution, logistics, maintenance and the simultaneous operation of both Russian and US systems. Next, the viability and usefulness of ISS as a testbed for demonstration of future life support technologies and the status of current evaluations will be examined. Finally, the value of crew interactions and testing will be described, such as testing crew self-sufficiency for repair procedures, determining how detailed crew repairs could be and evaluating effectiveness of teaching techniques that involve limited direct interaction.

For life support equipment, testing at ISS of nominal operations, maintenance and repair will provide the systems confidence required for deep space exploration. The ISS is a vital and unparalleled testbed to advance the life support systems needed for exploration beyond low Earth orbit.

II. Status and overview of ISS USOS ECLS & Regen ECLS Systems

Original ISS system requirements were based on a variety of historical and anticipated values. With most of human space flight history being measured in hours, days or weeks, and with almost no regenerative systems experience, designers blazed a trail to what they thought was required by the hardware. Table 1 lists key ISS system requirements[2].

Those requirements have evolved, in some cases dramatically, based on several factors, primarily extensive experience from hardware operation, logistics support and failures over years of service, along with feedback from many increment crews on ISS. Some of the biggest changes going forward will be: 1) reduced carbon dioxide partial pressure limits (very challenging for hardware to meet); 2) addition of Polydimethylsiloxane (PDMS) to the set of atmosphere contaminants that must be controlled[1]; 3) use of a common potable water biocide; 4) significant increase in on-board analytical capabilities. Potential requirements changes are also shown in Table 1.

While all the items in Table 1 are good examples of lessons learned operating ISS, it underscores the potential to miss the mark when designing equipment to operate in new environments. The desire to design lunar/Mars ECLS correctly drives the need to get some test time on ISS. While it will not be exactly the same environment it will no doubt teach exploration vehicle system designers something important.

Table 1: **Key Systems Requirements vs Current Requirements**

Function	Original ISS requirements	Potential new requirements	Comments
CO_2 removal	5.3 mm avg 7.6 peak 10 mm peak w/crew change	3.0 mm ceiling < 2 mm preferred < 1 mm goal[2]	3.0 mm limit in force today & being driven down by flight docs and increment crew comments; they would prefer < 2 mm Hg
Total pressure control	760 mm nom (14.7 psia)	760 mm in-flight 413-517 mm surface (14.7 psia in-flight) (8-10 psia surface)	ISS typical ~ 14.5 psia; varies mostly driven by ppO2 management drivers Surface Habitats will be lower to support more frequent EVAs
Temperature control	18.3C-26.6C (65F-80F)	18.3C-26.6C (65F-80F)	Crews *rarely* select beyond 22.2 +/-.5 C (72F +/- 1F)
Humidity control	25-75% RH	25-75% RH	No change expected
Particulate control	0.05 mg/m3 (100K p/ft3)	0.05 mg/m3 (100K p/ft3)	No change expected
Trace contaminant control	ISS SMACs[3]	Same list of ISS SMACs + PDMS	PDMS & DMSD are a new challenge. Added charcoal filters to ISS scrubbing Redesign of WPA being investigated
FDS	CO_2 PFE	WM PFE	WM PFE now on ISS & slated for Orion
Water processing	13 L/day (28.6 lbs./day)	9 L/day (19.8 lbs./day)	Original WPA design included shower & laundry throughput. Waste water constituent list recently updated to reflect actual ISS waste water constituents
Potable Water biocide	US: Iodine RS: Silver	All: Silver	All water processing systems need to be compatible and use a common biocide
Urine processing	9 L/day (19.8 lbs./day)	6 L/day (13.2 lbs./day)	Calcium precipitation problems drove down recovery % and change from sulfuric acid based pre-treat to phosphoric acid pre-treat
Water vent	5.3 L/day (11.6 lbs./day)	Zero	Exploration missions cannot afford to throw away water
CO_2 reduction	N/A	~ 1 kg/day H_2O (2.2 lbs./day H_2O)	Added in 2009, developed some issues for Sabatier by adjacent subsystems
Atmosphere monitoring	O_2, N_2 CO_2, H_2O, CH_4, H_2	Improved accuracy over ISS baseline plus additional monitoring systems	Water analysis, trace contaminant monitoring, particulate counts, bacterial & fungal speciation, etc. expected in-flight

Significant and sometimes repetitive failures of ISS ECLS hardware over the ever-increasing operating history have pointed directly to areas that needed attention. In many cases redesign was done and next-generation hardware has either demonstrated the efficacy of the change(s) or is still being evaluated. Table 2 lists current ISS and expected future requirements.

The most notable items are:

1) The OGA cell stack failure[4] where the cell stack failed after 250 days. It is interesting to note that, had this been a Mars mission, this would be about the time the crew would be arriving at Mars. This experience underscores the old adage "Test as you fly and fly as you test".
2) High Total Organic Carbon (TOC) in the Water Processing Assembly (WPA) where the TOC increase in the potable water took over a year to show itself then went exponential as it broke through the beds, causing a dramatic increase in the multi-filtration bed consumption rate.[2]

Table 2: **Notable Failure History**

Function	Failure Item	Comments
ACS	Non-Propulsive Vent	1st failure – impingement on US Lab module resulting in station roll; 2nd failure – Vent isolation valve mechanical failure
ACS	U.S. Lab Window leak	Program response was different than plan
ACS	OGA cell stack failure	Recirculation loop contamination with HF
THC	CCAA CHX hydrophilic coating contamination	Siloxanes, thalate-esters, fatty acids
THC	IMV circuit contamination/ req'd cleaning	Major dust bunnies!
FDS	Smoke Detector contamination	Excessive air velocity, shield required
AR	CDRA containment, then high ΔP issues, etc.	Multiple re-design cycles, up to -5 Beds
AR	CDRA ASV failures	Redesign to -2 ASV
AR	MCA mass spec life & filament failures	Ground processing change required
AR	TCCS sorbent bed deliquescence	(extended) life limiting feature
WRM	WPA cat reactor seal leaks	Extended time and high temp and pressure
WRM	WPA MF bed life (DMSD & high TOC)	Completely unexpected phenomenon
WRM	WPA wastewater tank plumbing & valve biofouling	No biocide and too small clearances
WRM	UPA harmonic drive issues (FCPA)	Redesign required
WRM	UPA DA bearing failures	Redesign required
WRM	UPA calcium precipitation	Difference between flight & ground urine

As a result of the two topics above (evolving requirements and hardware failures), a compelling and ever-growing list of lessons learned is being created to help current and future space vehicle and habitat designers try to outsmart mother nature, the laws of physics and basic (and advanced) chemistry. These lessons, as shown in Table 3, range from the philosophical to the specific. ISS may be somewhat unique in the way it was built and operated during assembly, particularly with how modules can be moved around and with a wide variety of visiting vehicles coming and going, but many of these lessons will apply directly to lunar/Mars vehicles and surface habitats.

As an example, the realization that some systems will operate differently in microgravity than during testing on Earth and that those differences can be significant to the operation of the vehicle in flight will drive consideration of how to test exploration technologies effectively before the intended missions.

For systems where ground testing is actually useful (not microgravity dependent), it is tempting to assume that only a minimum of testing is required before hardware delivery. Unfortunately, this results in the flight system becoming the fleet leader in run time, resulting in possible unexpected failures during the mission. The unanticipated in-flight failures might have been avoidable, or at least predictable, if the fleet leader hardware were on the ground running ahead of the flight hardware.

Table 3: **Lessons Learned**

Topic	Example
Variation between "Spec" and actual conditions	Hardware can be over-designed or not adequate
As-used vs. as-designed (and envisioned) equipment issues	Flight Rule envelope expansion, long term dormant periods, calibration, i-level maintenance
Microgravity impacts on system performance	Unanticipated &, once understood, untestable on the ground (how to test next-gen hardware: ISS)
Limited ground test time vs. in-flight experience (e.g.: Protoflight)	Flight hardware quickly becomes "Fleet-leader" in operational experience; problems show up on-orbit first and it is difficult to evaluate problems or fixes without qualification hardware
System performance trending effort	1000's of telemetry data items take 100's of hours to continually analyze & report, (even after extensive automation)
In-flight failure investigation & system recovery	Design approach quickly gives way to program needs and requires creative maintenance solutions, unusual operational modes & rapid software changes

Topic	Example
Fluid systems need more built-in recovery capability	Ability to flush, purge, fill, drain, sample, dry, microbial shock, sterilize, & leak check after in-flight maintenance
Crew execution of procedures	Generic vs. specific training skills, complex tasks, discipline to follow procedures as-written
Limited crew time to perform maintenance & troubleshooting	Overwhelming list of tasks drive low-priority items out months, even years (curse of redundancy)
Rapid & unexpected performance degradation	Drives concern over “common technology redundancy” & “parallel ops”
Integration issues due to multiple hardware providers	Complicates crew training, spares & maintenance
Hardware damage due to overly complicated/difficult task	Blind-mate connections, high-torque assembly, inadequate visual queues
Unanticipated particulate loading	Use of screens vs. depth filters, lack of crew access for easy cleaning
Accumulated cabin aisle way stowage	Adverse effects on ventilation; Impedes crew maintenance access & Emergency Response
Evolving launch environments	Continually drive efforts to update and approve spares launch configurations (e.g. foam)
It’s the little things	QDs, adaptors, caps, plugs, vents, standard vs. metric, thermal expansion of trapped liquid volumes, “shop-air”, borrowing from non-common fluid systems
Sealed vs. un-sealed bearings	Power & acoustics requirements created long term storage issues & debris sensitivity
Valve manual overrides (both S/W command & physical override)	Extremely valuable, don’t build a bulkhead penetration without one
Sensor drift	Has not been as big a problem as anticipated; most systems going on 10 years w/o issue
Microbial & fungal growth in system tanks, plumbing, valves & sensors	Becoming more of a concern as time goes on
Software Controls	Make ***everything possible*** a variable changeable in software (system control points in particular)
Take long term storage & redundant systems ops into account when designing subsystem hardware	Seals and valve seats don’t work; bearing grease escapes, etc.

In addition to requirements evolution and hardware issues, the sheer magnitude of consumables and spares needed to support humans in space is immense. Examining the amount of up-mass per year by system (WPA, OGA, etc.) that has been required to support 3-6 crew on ISS over the last several years provides some insight into the problem when one considers the increased difficulty of supplying an outpost in lunar orbit, on the lunar surface and on the Martian surface. Table 4 shows ECLSS up-masses. Large ECLSS support requirements becomes the target of mass and volume reduction efforts and drives thoughts on how to capitalize on In-Situ Resource Utilization (ISRU) to provide water and oxygen for metabolic use.

Table 4 - ISS USOS ECLSS Hardware Launched to the ISS since 2012 by mass

Year	Total Pressurized Hardware Launched (kg)	Total ECLSS Launched (kg)	% ECLSS
2012	**2943.21**	**364.05**	**12%**
2013	**4453.62**	**850.47**	**19%**
2014	**8771.51**	**976.51**	**11%**
2015	**12860.23**	**1860.62**	**14.5%**
2016	**6557.7**	**1213.76**	**18.5%**
2017*	**7787.21**	**1201.94**	**15%**

* Includes flights flown as of April 2017 + hardware currently manifested for remaining 2017 cargo flights to the ISS.

With 19 years of joint operation, an interesting comparison of American and Russian operating philosophies can be made, and the best of each should be taken forward as we explore outside LEO. Table 5 highlights some differences in approach. While returning hardware for failure investigations and funding redesigns to improve hardware reliability is expensive, the efforts the U.S. have gone through over the years have helped ISS operations and should bear fruit for exploration missions.

Table 5 - Russian versus USOS system ops, maintenance and repair plans

Topic	Example
$ppCO_2$ target	US Flight docs and astronauts want much lower than spec
Biocide of choice	RS: Silver; US: Iodine (when combined they precipitate out)
Response to hardware failures	Russians fly more spares; US conducts in depth failure investigation and initiates a redesign of the hardware

III. Status of ECLS tech demos currently on or planned for ISS

Sabatier: The Sabatier program broke new ground as the first “commercial type” contract at HSSSI for NASA space flight hardware. The contract had limited requirements for documentation and payment to HSSSI was based on delivery and the on-orbit performance.

The Sabatier Assembly takes in waste hydrogen, which is a by-product of the Oxygen Generator Assembly, and waste Carbon Dioxide from the ISS Carbon Dioxide Removal Assembly (CDRA) and reacts them to form water and methane, as shown in Figure 1. The reactor products are cooled in a heat exchanger where the water product condenses to a liquid. The liquid water and methane gas are then separated in a rotary phase separator, with the water being delivered the ISS Water Bus and the methane being vented to space vacuum. By recycling these waste gases, the Sabatier can produce up to 2000 pounds of water per year, reducing the need to launch that same amount. The Sabatier Assembly was installed and successfully activated on the ISS in October of 2010.

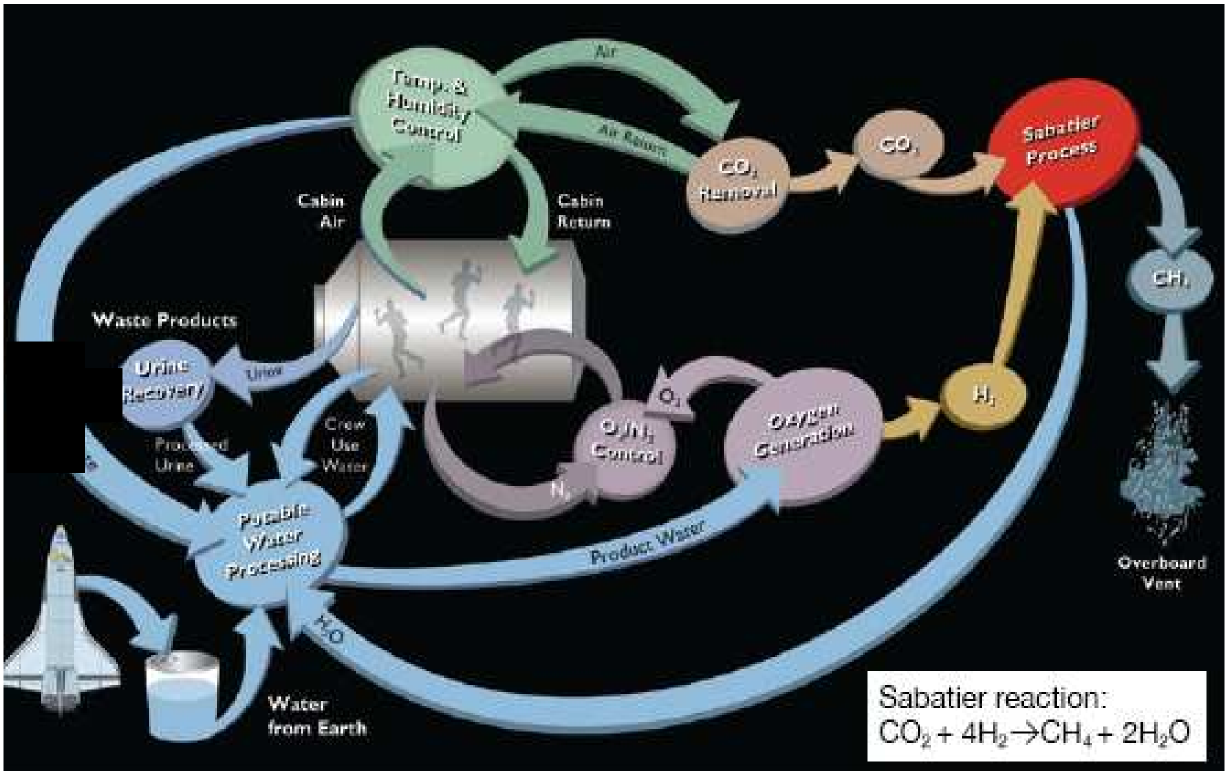
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Figure 1 – Sabatier Reaction as Part of a Closed Loop System

The Sabatier system integration had several challenges from ground assembly/performance testing, to launch, and to final assembly/on-orbit integration. A flexible, modular design was implemented as the system had three different configurations. The launch weight and size were limits imposed to the Sabatier team. It had to fit in standard cargo bags that NASA uses to launch equipment. It also had to be designed for multiple launch vehicles in case the Shuttle was not available. These restrictions forced the team to launch the system in pieces that were then assembled on-orbit. Consideration had to be taken for ease of assembly by an astronaut in zero gravity (in fact, the system was designed so that any component could be replaced on-orbit). Finally, it had to fit in a fixed volume reserved for the Sabatier within the Oxygen Generation System rack. There was no dry-fitting opportunity as the rack awaiting the Sabatier was already on-orbit. The team had to consider possible distortions in the rack physical dimensions and also make sure that fluid and electrical interfaces keying was implemented correctly. There was only one opportunity to install the Sabatier on-orbit and it needed to be correct the first time.

One of the biggest challenges for the team was designing a safe two fault tolerant system that would meet the existing interfaces already on orbit. Although the Sabatier technology has been in development at HSSSI for more than 30 years, the laboratory and test hardware was never designed to meet the stringent NASA safety requirements. To meet these requirements, the Sabatier Assembly was designed to operate at below ambient pressures at all times. This condition minimizes leakage of flammable gases into the rack aboard the ISS. When the Sabatier design was presented to the NASA Safety Review Panel, the chairman of the board stated that the Sabatier design standards should be the benchmark for all future systems that contain combustible gases used on orbit.

Looking forward, the Sabatier Assembly and the knowledge gained from its design, deployment and operation will be significant in the development of systems needed for deep space missions. Resupply of expendable life support equipment and consumables will not be problematic if not impossible for mission far away from Earth. Regenerative life support equipment like the Sabatier Assembly can be used continuously to generate and recycle the life sustaining elements required by human travelers for long duration trips into space.

Amine Swingbed: HSSSI is currently under contract with NASA to deliver an Amine Swingbed (Figure 2) that will be tested on the ISS in early 2018. HSSSI has been developing the amine-based, CO_2 removal system as an alternate to the ISS zeolite-based carbon dioxide removal assembly (CDRA). The system is based on proven sorbent technology, including a passive water save element, and a thermal regeneration process for the CO_2 sorbent beds.

HSSSI has drawn on over 30 years of experience with solid amine-based CO_2 removal systems to develop a thermally desorbed system for the collection and concentration of CO_2. Our approach for an exploration configuration of this system incorporates a passive means of water vapor recovery, using desiccant materials in thermally linked sorbent beds upstream of the solid amine CO_2 sorbent beds, to achieve an approximate 90% nominal water vapor recovery with minimal power input. This design allows the CO_2 to be captured and stored for eventual processing in a CO_2 reduction system such as Sabatier, and as such, has applications as a replacement for CDRA on the ISS or for multiple exploration applications.

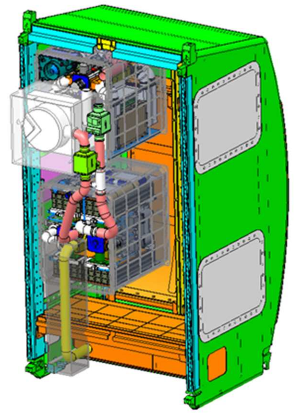

Figure 2 – Amine Swing Bed

Universal Waste Management System (UWMS): HSSSI is currently under contract with NASA to demonstrate the UWMS as a new waste collection system designed to advance the state of life support for both space exploration and Low Earth Orbit (LEO) operations. The project will validate improved functionality in the areas of urine capture, fecal collection and air handling in micro-gravity. Enhanced capability is complimented with a system approach aimed at greatly reducing weight and volume of prior flight systems. The demonstration will utilize the International Space Station (ISS) as a test-bed to prove out technologies that will enable space exploration. Figure 3 shows the UWMS.

Figure 3 – UWMS

The standalone UWMS platform accepts and stores waste, representing self-contained functionality currently not available. Past waste management systems and current applications rely on costly provisions for storage such as tanks or venting capabilities. Providing for a range of solutions associated with the ability to store, transfer, reclaim, or discard waste; the HSSSI UWMS approach includes provisions for continuous solid waste collection based on replaceable canisters and liquid waste management with localized containment or direct vehicle systems integration. The new universal design provides commonality for multiple platforms, eliminating complex integration and the need to develop a unique design for each specific vehicle or space mission application.

The demonstration test will serve two major objectives related to waste management past performance and future applicability: (1) Ensure past and current performance issues associated with waste systems are addressed with the UWMS; and (2) representative utilization of the UWMS will prove feasibility and uncover any unanticipated performance issues with the new design approach only emergent in micro-gravity. With successful demonstration, the progression of waste management technology is directly applicable to both near-term and NASA exploration life support initiatives.

Phase Change Material (PCM) Heat Exchanger: HSSSI has developed solid-liquid PCM heat sinks to reduce the overall system mass for spacecraft thermal control systems. Space vehicles often have to accommodate heat loads and environmental conditions that vary over time. Temporarily storing the energy on-board using PCM heat sinks and rejecting it during times when there is excess heat rejection capacity can save mass and volume because the balance of the system can be designed to typical rather than worst-case conditions. However, PCM heat sink technology has had shortcomings that stem from density changes that occur during the phase change. For example, when a sealed container of wax is solidified from one surface, the void space that occurs due to contraction is located at the opposite end of the container from the cold surface. When the cold surface is then heated, the wax begins to melt from that point, but is hydraulically locked. Locally high pressures and structural failure have occurred in previous PCM heat sinks due to this phenomenon, including one on the US Space Lab. HSSSI has a new technology that can eliminate this issue by melting wax in select locations before hydraulic lock develops. However, prove-out in microgravity is necessary for the upcoming Orion Multipurpose Crew Vehicle, as it includes a PCM heat sink in its thermal control system.

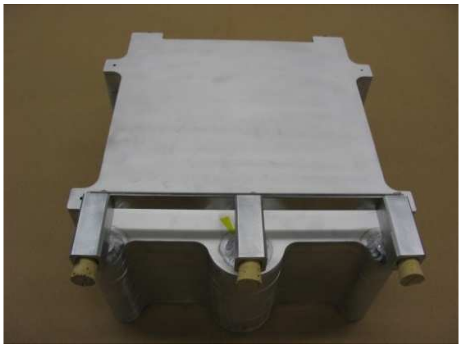
Figure 4 – PCM Heat Exchanger

In order prove out the technology, the HSSSI PCM heat sink was incorporated into an experiment rack created by NASA Johnson Space Center for use on the International Space Station. The experiment was launched on July 18, 2016 and was installed on the station in September 2016. The item has been under test for the past several months to characterize the PCM heat sink before its returned to Earth in 2017 for post-use evaluation. If the experiment is successful, it will pave the way for the technology's inclusion in the next generation of exploration spacecraft.

IV. On-Orbit Maintenance and Repair Demo

I-Level Maintenance with Time Delays

In the nineteen years of ISS operations, crews and ground teams have made repairs to hardware that was never intended to be repaired on-orbit. Recall that the initial operational concept for the ISS was predicated on the Space Shuttle being able to return hardware on a regular basis for repair and refurbishment. With the more limited operations of the Shuttle than originally envisioned and its retirement in 2011, NASA and its contractor teams have had to devise ways to keep the ISS systems operating without the ability to return large amounts of cargo and payloads.

From the Sabatier system and Water Processor Assembly to the Extravehicular Mobility Units, ISS crews have successfully performed repairs that would previously have been performed by ground personnel in a lab facility on Earth. Figure 5 shows Astronauts Scott Kelly & Terry Virts changing out the EMU Fan/Pump/Separator during Expedition 26.

As discussed in the previous sections, the lessons learned from these on-orbit failures of the ISS ECLS system will help guide the requirements and designs of future ECLS systems for deep-space exploration missions. However, the ISS has one advantage as a test-bed for maintenance and repair of hardware, its close proximity to the Earth.

In responding to failures on-board the ISS, and their subsequent repair or replacement, both the ground teams and the crewmembers have the luxury of near-instantaneous, and continuous, voice and data links between the ISS and the Mission Control Centers. As the crews work through procedures, this zero time lag allows for direct and timely interaction. It allows the ground to follow along with the crew in real-time, and to provide commanding to the systems when necessary. It also allows for multiple sets of eyes, both on the ground and on-orbit, to watch the system as it is recovered, thereby providing an additional level of safety.

Figure 5 – Astronauts Scott Kelly & Terry Virts changing out the EMU Fan/Pump/Separator during Expedition 26.

But what if there was a significant time delay between the ground teams and the flight crews? Experience during the Apollo Lunar Missions, where the time delay was 1.3 seconds, showed that this short delay did not seriously affect the interaction between the ground teams the flight crews. Also, the systems on-board the Apollo spacecraft where not designed to be repaired on-orbit, since sufficient redundancy was built into the spacecraft for critical systems and the missions were on the order of days (Apollo 17, the longest of the Apollo missions was only 12 days). But for missions beyond the Earth-Moon system, one-way time delays of up to 20 minutes will be common and will have to be accounted for by mission planners.

In preparation for these deep-space missions, specific and carefully planned I-Level Maintenance demonstrations of repair tasks, with simulated one-way time delays ranging from 5-20 minutes, could be undertaken on-board the ISS. Initial demonstrations would be limited to non-critical systems, but could later be expanded to more complex critical systems in order to increase the realism of the demonstration. These demonstrations would help astronauts and flight controllers learn the impacts of communications delays and how to accommodate them. The lessons learned would help determine the most efficient methods for repair operations in deep space and would help inform future mission planning.

For example, the Sabatier Reactor is nearing the end of its on-orbit life. Currently NASA and HSSSI are considering upgrading a ground unit to a Class 1 Flight Unit in order to replace it. The Sabatier Reactor was not designed to be changed out on-orbit. It was a successful technology demonstrator that has subsequently been utilized as an integral part of the ISS consumables plan in producing water on-orbit. Replacing the reactor will be a challenge, but since the Sabatier is still considered a payload and therefore not a Criticality 1 system, there is a certain amount of latitude available in returning it to service. As such, it would an excellent candidate to demonstrate a major on-orbit repair with a time delay.

Crew Autonomous Maintenance

Currently on-board the ISS, nominal maintenance and repairs are scheduled by the ground team with subsystem experts following along with the crew as the tasks are being conducted. With deep-space exploration missions, consideration should be given to allowing the crew more autonomy in scheduling the tasks. This would allow the crew greater flexibility in determining the best time to perform the maintenance and repair tasks,

As with the I-level maintenance demonstration discussed above, the ISS offers an analog testbed in the space environment for more automatous crew activity, thereby simulating a deep-space mission under the most realistic conditions possible today. By allowing the crew more flexibility to perform I-level maintenance tasks, and not having the control center on-console answering questions real-time, valuable lessons could be learned that could be applied to future deep-space missions.

Of course, the advantage of using the ISS as a test-bed for these capabilities, is that in the event a situation occurs that is deemed safety-critical, the demonstration can be ended and direct near-instantaneous communications can be re-established between the control centers and the crew.

Crew Autonomous Gas & Water Management

Currently for ISS, substantial effort is put into management of ppO_2, $ppCO_2$ and water by ground teams & subsystem experts. With deep-space exploration missions, consideration should be given to allowing the crew more autonomy in managing these resources. For oxygen management, the crew could decide when to add oxygen from a logistics vehicle or adjust the rate of the oxygen generator up or down. Likewise, with carbon dioxide management, the crew could be in charge of CDRA and Vozdukh modes to achieve the desired level of cabin $ppCO_2$. While these are relatively burdensome tasks (hence why ground teams do it for the crew) even for a short term demonstration it would be interesting to see how crew reacts to the responsibility and what deep space mission planners may learn the experience and crew feedback. As this would take some dedicated time from a crew member each day it would have to be considered "payload" or "science" work to justify the hours required.

Water management may be the most daunting of the three listed demonstrations. It takes a team of people on the ground constantly working to decide when to run a UPA process cycle, when to run a WPA process cycle, manage water "on and off" the bus, and deal with subsystem failures and the subsequent step-increase in manual crew water movements in parallel with effecting repair of the ailing subsystem(s). Crews today already monitor water quality with weekly TOCA sample analysis to make sure the potable water is within consumable specification, so that wouldn't change, but to take on the entire responsibility for water management would be in interesting demonstration. It may in fact not be credible to expect crews to manage all these functions without ground help but learning that now would also be advantageous for deep space mission planners.

Again, the advantage of using the ISS as a test-bed for these capabilities, is that in the event a situation occurs that is deemed safety-critical, the demonstration can be ended and direct near-instantaneous communications can be re-established between the control centers and the crew.

V. Conclusion

Using the ISS as a testbed for deep space systems that will be used in the exploration of the moon and Mars provides significant advantages over a testing program that only includes terrestrial opportunities. While the ISS is not a perfect analog for deep space, it is much closer than the environment on the surface of the Earth and will provide invaluable operational experience.

The life support systems already in use onboard ISS today provide many valuable lessons, both positive and negative, on the design and operation of space life support systems. Techniques on maximizing reliability and minimizing crew interaction and logistical burden learned from the many years of successful ISS operations will provide valuable input to evolving life support systems designs. These lessons must be incorporated into future designs continuously.

A life support technology development and testing program that makes maximum use of ISS has clear advantages. ISS testing will help better define and characterize major regenerative systems such as water and urine processing and oxygen generation that are vital in long duration missions. Technologies such as lower partial pressure CO_2 removal, regenerative TCCS, trace contaminant monitoring, microbial stabilization, trash compaction, brine water recovery, and system dormancy can be tested in a relevant environment at ISS prior to designing deep space vehicles. Use of ISS as a testbed will allow the confident deployment of tested life support systems.

Crew operation and maintenance of life support systems will become increasingly important on deep space missions as the longer distances from Earth decrease the effectiveness of ground controllers in understanding critical situations and offering input on mitigation. Using ISS to demonstrate and test crew autonomy in problem identification and mitigation, viability of detailed repair of life support hardware, and impacts of operations at long distance from Earth (through simulation of communication lags) will all provide important information for both the design and operation of future deep space life support systems.

Technology demonstration at ISS is an important component of deep space exploration and should continue. Work on deep space ECLS systems with technology validated at ISS should start within the next few years to allow hardware to be available in the early 2020s. These efforts will allow deployment of vehicles and habitats with deep space life support systems in the mid-2020s. Testing at ISS is beneficial for all life support systems and provides valuable operational experience, while reducing risk and improving performance. Testing at the ISS provides significant benefits in reliability, cost and efficiency no matter where our deep space exploration takes us.

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