NASA Advanced Explorations Systems: 2017 Advancements in Life Support Systems

Walter F. Schneider[1]
NASA, Marshall Space Flight Center, Huntsville, AL

Sarah A. Shull[2]
NASA, Johnson Space Center, Houston, TX

The NASA Advanced Exploration Systems (AES) Life Support Systems (LSS) project strives to develop reliable, energy-efficient, and low-mass spacecraft systems to provide environmental control and life support systems (ECLSS) critical to enabling long duration human missions beyond low Earth orbit (LEO). Highly reliable, closed-loop life support systems are among the capabilities required for the longer duration human space exploration missions planned in the mid-2020s and beyond. The LSS Project is focused on four areas—architecture and systems engineering for life support systems, environmental monitoring, air revitalization, and wastewater processing and water management. Starting with the International Space Station (ISS) LSS systems as a point of departure where applicable, the three-fold mission of the LSS Project is to address discrete LSS technology gaps, to improve the reliability of LSS systems, and to advance LSS systems toward integrated testing aboard the ISS. This paper is a follow on to the AES LSS development status reported in 2016 and provides additional details on the progress made since that paper was published with specific attention to the status of the Aerosol Sampler ISS Flight Experiment, the Spacecraft Atmosphere Monitor (SAM) Flight Experiment, the Brine Processor Assembly (BPA) Flight Experiment, the CO_2 removal technology development tasks, and the work investigating the impacts of dormancy on LSS systems.

Nomenclature

AES = Advanced Exploration Systems
BPA = Brine Processor Assembly
CDRA = Carbon Dioxide Removal Assembly
CRCS = CO_2 Removal and Compression System
DGA = diglycolamine
ECLSS = environmental control and life support systems
EM = environmental monitoring
ESM = equivalent system mass
EVA = extra-vehicular activity
EXPRESS = Expediting the Processing of Experiments to the Space Station
GC/MS = gas chromatograph/mass spectrometer
HEPA = high-efficiency particulate air
ISS = International Space Station
IWP = Ionomer-membrane Water Processor
LEO = low Earth orbit
LSS = life support systems
NASA = National Aeronautics and Space Administration
RO = reverse osmosis
RWGS = reverse water gas shift
SAM = Spacecraft Atmosphere Monitor

[1]Project Manager AES LSS, NASA MSFC, HP30, walter.f.schneider@nasa.gov
[2]Deputy Project Manager, NASA JSC, XM11, AIAA Associate Fellow, sarah.a.shull@nasa.gov

SBIR	=	Small Business Innovative Research
SCOR	=	Spacecraft Oxygen Recovery
SMT	=	System Maturation Team
STMD	=	Space Technology Mission Directorate
TC-TSAC	=	Thermally Controlled-Thermal Swing and Compression
VOC	=	volatile organic compound
CH_4	=	methane
CO_2	=	carbon dioxide
C_2H_2	=	acetylene
H_2	=	hydrogen
Hg	=	mercury
O_2	=	oxygen
cm	=	centimeter
kg	=	kilogram
m	=	meter
mg	=	milligram
mm	=	millimeter
MPa	=	megapascal
$ppCO_2$	=	CO_2 partial pressure
ppm	=	parts per million
psi	=	pounds per square inch

I. Introduction

THE Advanced Exploration Systems (AES) Life Support Systems (LSS) Project is focused on four areas: architecture and systems engineering for life support systems, environmental monitoring, air revitalization, and wastewater processing and water management. Starting with the International Space Station (ISS) life support systems as a point of departure (where applicable), the mission of the LSS Project is three-fold:

1) Address discrete LSS technology gaps (see Table 1)
2) Improve the reliability of LSS systems
3) Advance LSS systems towards integrated testing on the ISS (see
4) Figure 2)

This paper summarizes the work performed in fiscal year 2017 under the LSS Project to meet these objectives. Details will be given on the following focus areas: atmosphere revitalization, wastewater processing and water management, environmental monitoring, and systems engineering and architecture. Together these four areas represent the entire LSS architecture for human spaceflight as is depicted in Figure 1. Also provided are references to numerous other papers that go into greater technical detail on the technologies under development by the LSS Project.

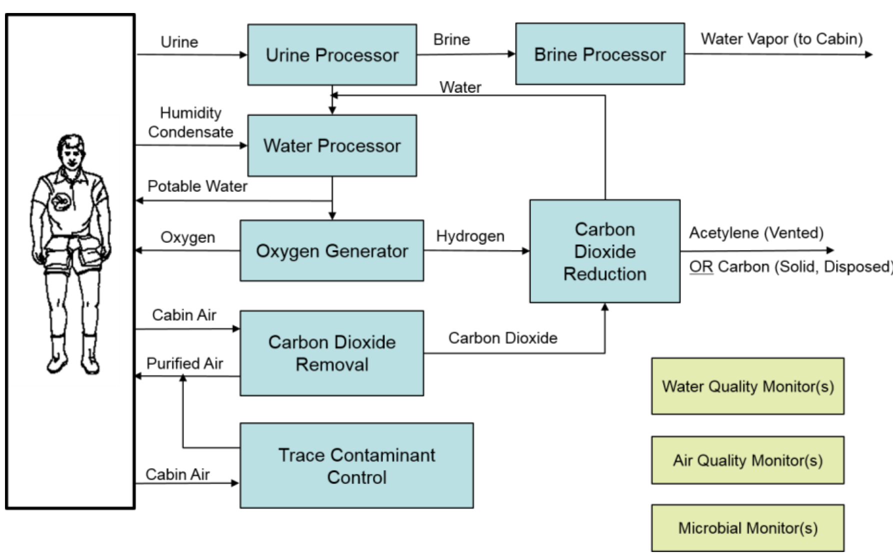

Figure 1. Simplified LSS Schematic.

Over the past three years, the NASA Environmental Control and Life Support Systems (ECLSS) and Environmental Monitoring (EM) System Maturation Team (SMT) has identified the ECLSS-EM capability gaps, summarized in Table 1, for long duration human missions in

Table 1. ECLSS and Environmental Monitoring System Maturation Team Identified Capability Gaps.[2]

Function	Capability Gaps	Long Duration µg Hab	Planetary Surface
CO_2 Removal	Bed and valve reliability; ppCO_2 <4800 mg/m^3 (<2 mm Hg)	X	X
Trace Contaminant Control	Replace obsolete sorbents w/ higher capacity; siloxane removal	X	X
Particulate Filtration	Surface dust pre-filter		X
Condensing Heat Exchanger	Durable, chemically-inert hydrophilic surfaces with antimicrobial properties	X	X
O_2 recovery from CO_2	Recover >75% O_2 from CO_2	X	X
O_2 generation	Smaller, reduced complexity	X	X
High pressure O_2	Replenish 3000 psi O_2 for EVA; provide medical O_2	X	X
Water microbial control	Common silver biocide with on-orbit re-dosing	X	X
Wastewater processing	Increased water recovery from urine (>85%), reliability, reduced expendables, dormancy survival	X	X
Urine brine processing	Water recovery from urine brine >90%	X	X
Atmosphere monitoring	Smaller, more reliable major constituent analyzer, in-flight trace gas monitor (no ground samples), targeted gas (event) monitor	X	X
Water monitoring	In-flight identification & quantification of species in water	X	X
Microbial monitoring	Non-culture based in-flight monitor with species identification and quantification	X	X
Particulate monitoring	On-board measurement of particulate hazards	X	X

both the microgravity environment beyond low Earth orbit (LEO) and the partial gravity environment on a planetary surface. The SMT then developed roadmaps laying out the plan to close these critical gaps between now and the ISS's end of life—presently slated for 2024.[1] International Space Station end of life was chosen as many gap closures culminate with a demonstration of the relevant technology (or technology improvement) aboard the ISS. The LSS Project is working to close many of the capability gaps listed, as will be detailed in the remainder of this paper.

II. Atmosphere Revitalization

The LSS Project's air revitalization task is comprised of work in carbon dioxide (CO_2) removal, oxygen (O_2) generation and recovery, and trace contamination and particulate control. Current state-of-the-art performance for these systems provides for CO_2 removal at a partial pressure (ppCO_2) <4 mm Hg,[3] approximately 51% O_2 recovery from CO_2, and a combination of active and passive methods for trace contamination and particulate matter control[4]. As was stated in Table 1, the capability gaps identified for atmosphere revitalization for human missions beyond LEO are the following:

- Improve CO_2 removal bed design, valve reliability, and provide the capability to control; ppCO_2 <4800 mg/m^3 (<2 mm Hg)
- Identify suitable replacements for obsolete trace contaminant control sorbents and address volatile methyl siloxane control
- Provide means for surface dust filtration
- Recover >75% of the O_2 from CO_2
- Reduce the complexity and size of the O_2 generation hardware
- Provide the capability to replenish 20.7 MPa (3000 psi) O_2 tanks for EVA and provide for contingency medical O_2

The LSS Project is doing work in many of these areas.

A. Carbon Dioxide Removal

Flight crew have reported that higher levels of CO_2 have an effect on their ability to perform tasks.[5] Reducing the ppCO_2 to less than 4800 mg/m^3 (<2 mm Hg) is therefore a high priority. The LSS Project is investigating multiple technology paths to close this capability gap.

At the end of fiscal year 2016 a gate review was held to decide on the CO_2 Removal efforts that would continue into fiscal year 2017. A four-bed molecular sieve technology-based system that incorporates the lessons learned from the ISS Carbon Dioxide Removal Assembly (CDRA) was approved to continue. It was also decided to infuse this work into the ISS Program to continue the maturation progress made under the LSS Project as this technology is a candidate to support the increase in crew size members aboard the ISS.

A decision was made to discontinue work on the CO_2 Removal and Compression System (CRCS). The CRCS project was re-vectored to focus on the compression part of the technology. The past year the CRCS testbed has been re-configured to test the Thermally Controlled-Thermal Swing and Compression (TC-TSAC) system. Initial tests were conducted and design improvements are being incorporated based on test results. Testing will resume towards the end of this fiscal year.

Structured sorbents were approved for further investigation. The structured sorbent technology coats the zeolite directly onto corrugated metal. This will eliminate the dusting issues experienced on the ISS CDRA. During fiscal year 2017 a literature search has been completed and testing of the zeolite coated cores began. Initial breakthrough tests show considerable CO_2 capacity of this technology. Liquid amines were approved for further study. Amine-based processes offer the potential of being low power and low mass systems. Diglycolamine (DGA) was selected as the liquid amine to study for CO_2 Removal. Testing during fiscal year 2017 included characterizing effects from trace contaminants in the spacecraft cabin atmosphere on DGA's chemistry, DGA stability and life testing, and performance testing in the proposed flight configuration. Initial results are promising for this technology. Capillary Structures for Exploration Life Support, a technology demonstration to understand the behavior of liquid amines, was delivered to the ISS. Initial experiment runs successfully demonstrated the capillary flow design used in the proposed flight configuration.

B. O_2 Generation/Carbon Dioxide Reduction

Oxygen generation on the ISS is performed by using water electrolysis to separate the hydrogen and oxygen atoms to yield molecular O_2 and hydrogen (H_2). The O_2 is released to the cabin atmosphere while the H_2 is vented overboard. This technology works very well to generate the O_2 necessary to sustain the crew and maintain cabin pressure. Furthermore, technologies to pressurize oxygen to fill extra-vehicular activity (EVA) tanks to 3000 psi on the spacecraft are being studied.

To achieve the higher ECLSS mass closure the H_2 produced by the oxygen generation process can be used to reduce CO_2 removed from the cabin atmosphere, Two technologies are under investigation by the LSS Project to increase the oxygen recovery rate to meet the stated goal to recover >75% of the O_2 from CO_2. The first technology is based on the Bosch reaction. The Bosch-based technology is theoretically capable of recovering 100% of the O_2 from metabolic CO_2.[6] This technology catalytically reacts the CO_2 removed from the cabin atmosphere and combines it with the H_2 by-product from oxygen generation to produce solid carbon and water. The water is purified and recycled to produce additional O_2. One challenge for Bosch-based processes is determining what to do with the solid carbon by-product. Testing of the series-Bosch Batch Carbon Formation Reactor developed by NASA was completed. A modified reactor geometry demonstrated improved reaction conditions and CO_2 conversion.[7] During fiscal year 2017, the pH Matter Carbon Formation Reactor developed under the Space Technology Mission Directorate (STMD)-sponsored Spacecraft Oxygen Recovery (SCOR) project was tested and evaluating the NASA-developed Reverse Water Gas Shift (RWGS) began. A second test will be conducted pairing the UMPQUA Research Co.-developed Carbon Formation Reactor, also developed under the SCOR project, and the NASA-developed RWGS. The purpose of the testing is to show if system performance is improved by combining components that were independently developed under different programs. Testing of other delivered components will continue into fiscal year 2018.

The second technology is based on the Sabatier reaction with subsequent methane (CH_4) byproduct processing. The Sabatier reaction combines CO_2 with H_2 to produce methane (CH_4) and water. The CH_4 byproduct is typically vented overboard; however, it can be partially pyrolyzed in a plasma reactor to form H_2 and acetylene (C_2H_2). Upon separation from the C_2H_2, the H_2 is recycled to the Sabatier reactor to reduce more CO_2 and produce additional water which can be electrolyzed to yield O_2. The C_2H_2 gas is vented overboard. The total theoretical oxygen recovery from metabolic CO_2 using the Sabatier reaction and CH_4 post-processing is approximately 90% with a realistic recovery of approximately 85%.[8] Testing of the CH_4 plasma pyrolysis to characterize and increase understanding of the system continued in fiscal year 2017.[9] Testing also included designs of carbon filter traps to arrive at a design for a flight system. Several filter prototypes incorporating micro-glass fibers and sintered porous metal media were developed and are being evaluated in integrated tests with the plasma pyrolysis assembly. An H_2 separation system was received for evaluation from a Small Business Innovative Research (SBIR) during fiscal year 2017. The test bed is being re-configured to run integrated tests that include a Sabatier reactor, the plasma pyrolyzer, and the H_2 separator. Planning is underway to develop a flight technology demonstration of this system.

C. Trace Contamination and Particulate Control

Trace contamination control is necessary to remove contaminates from the cabin environment that may be harmful to the astronauts. The state-of-the-art contamination control equipment has performed as expected aboard the ISS, however, the activated charcoal and catalyst used in the system is commercially obsolete. The ISS Program has plenty of this material for the life of the ISS but a new material will be needed for missions beyond ISS. The LSS Project is characterizing candidate materials to use in place of the obsolete activated charcoal. In fiscal year 2017 the LSS Project has been performing an evaluation of nine volatile organic compound (VOC) removal adsorbent candidates and two ion-exchange-based media for gas phase ammonia removal. At the end of the fiscal year the final candidates will be chosen for additional evaluation for exploration.

The LSS Project is also investigating new configuration and packaging ideas for a trace contaminant control system to develop a smaller unit that also is easy to maintain. Testing of an advanced Microlith®-based catalytic oxidizer showed the thermal performance, startup transient duration, and contaminant oxidation performance were found to be comparable or better than heritage designs.[10] Testing of a high flow/low aspect ratio adsorbent bed comparing a flat bed versus cylindrical bed configuration showed both configurations performed similarly; however, the cylindrical bed may be able to be packaged in a smaller volume.[11] The current plan is to complete testing of materials and development hardware testing and finalize the design approach for a technology demonstration on the ISS in fiscal year 2022.

Particulate control is necessary to ensure astronauts do not inhale particulates in the cabin air. Aboard the ISS High-Efficiency Particulate Air (HEPA) filters are used to remove particulate matter from the cabin atmosphere. The LSS Project is working to understand the suspended particulate environment aboard the ISS and investigating filter designs to reduce logistics and crew maintenance time.[4, 12] To understand the particulate environment the LSS Project has flown an experiment to collect particles at ISS HEPA filter locations (see Section IV.B).[13] The results of this experiment will inform the design for filtration system designs.

The HEPA filters used aboard the ISS for particulate filtration are replaced periodically, and between replacements the filters are cleaned with a vacuum cleaner. To reduce logistics and crew maintenance time, the LSS Project is developing a filter that scrolls the filter media across the intake duct. This design allows for the filter media to automatically scroll to provide clean filter media without the need to vacuum. Additionally the packaging of the filter media reduces logistics as it allows for more equivalent filter media to be packaged in this design when compared to the current HEPA filters used on the ISS.[12] A recent trade study showed that this filter concept can provide significant reductions in Equivalent System Mass (ESM) over heritage HEPA filters for deep space exploration missions.[12] Prototype testing of the scroll filter drove out the need for design changes which were incorporated and retested.[14] The scroll filter performed as desired. A new filter design that fits into the ISS HEPA filter volume was developed. Testing of this design is in process. Mars surface dust is a concern with astronauts returning from surface EVAs and dust being brought into the surface habitat from the EVA suits. The LSS Project is participating in the Martian Dust Workshop to address with the community challenges with Mars surface dust.

III. Wastewater Processing and Water Management

A major goal of the LSS Project is developing water recovery systems to support long duration human exploration beyond LEO. Current ISS wastewater processing and water management systems distill urine and wastewater to recover water from urine and humidity condensate in the spacecraft at a ~90% recovery rate.[15] As was stated in Table 1, the capability gaps identified for wastewater processing and water management for human missions beyond LEO are the following:

- Provide a common silver biocide with on-orbit re-dosing
- Increase water recovery from urine (>85%), improve reliability, reduce expendables, and ensure dormancy survival
- Provide for water recovery from urine brine >90% [enables 98% total water loop recovery]

The LSS Project is working on all three of these gaps.

A. Silver Biocide

The current state-of-the-art in biocides aboard the ISS utilizes both silver-based (Russian Segment) and iodine-based (U.S. Segment) water disinfection systems. The iodine system requires removing part or all of the iodine before consumption. Because of this as well as the added need for on-orbit dosing and the desire to have only one biocide for exploration missions, the LSS Project is developing a common silver biocide system. The task is focused around three primary objectives: (1) developing a silver-based biocide dosing system, (2) investigating materials and processing techniques to mitigate silver losses, and (3) understanding the system-, architectural-, and mission-level implications of moving to all silver-based disinfection system.

The current work to date has been focused on developing an electrolytically-generated silver ion dosing system. Specifically, the design and maturation of the three sub-elements of the silver dosing system are being pursued. These sub-elements include, the dosing electrode, a closed-loop feedback controller and a silver ion sensor. To date, a number of sub-element prototypes have been designed and integrated in a ground-based potable water test system. Coupled with this work has been an ongoing review and study into silver material compatibility. The intent of these investigations are to evaluate the rate and effect of silver deposition onto common spacecraft potable water system wetted materials of construction with the goal to identify techniques to mitigate these effects. Initial prototype testing in an analogue potable water system design has validated the early concept feasibility of an electrolytic silver dosing system.[16] However, this testing has also highlighted some potential issues associated with the proposed approach, e.g.: silver particle generation, silver losses through deposition, and sensor drift/limited lifetime. Concept development testing is continuing to better understand these issues. Based on these studies, future design and development testing will be proposed. In addition to these studies, alternative dosing system designs and material processing techniques are also being pursued. Discussions are in work with several vendors and hardware developers regarding alternate silver dosing electrodes, advanced sensors, controllers, non-traditional material processing techniques, and non-electrolytic means for dosing silver. Following completion of these early test and technology trades, a flight-forward design will be completed, built and tested. In parallel, systems analysis will continue to be performed to ensure the technology being developed can be used across all system, vehicle and mission platforms. In order to support the overall exploration milestones, including the potential need to test a silver biocide dosing system on station, early feasibility testing and analysis will continue under the LSS Project through the 2020 timeframe.

B. Urine Processing

The current state of the art in urine processing on the ISS utilizes vapor compression distillation followed by multi-filtration and catalytic oxidation. This process produces potable water at a ~90% total recovery rate. For human exploration missions beyond LEO, the goal is to increased water recovery from urine (>85%), improve reliability, reduced expendables, and enable dormancy survival.[17] To achieve this, the LSS Project is doing work in several areas.

In fiscal year 2017 the LSS Project performed development work on the use of reverse osmosis (RO) membranes in the water processor assembly. The goal of this task is to reduce the expendables associated with the multi-filtration beds in this system. Presently the beds need to be changed out every few months which is a significant driver of consumable mass. The RO membrane work shows promise for cutting this consumable mass in half or better. Because it was recognized that there would be direct benefit to the ISS Program of this technology by helping to remediate dimethylsilanediol on the ISS as well as reducing logistics cost, further development of the RO technology was transitioned to the ISS program from the LSS Project.

C. Brine Processing

Recovery of potable water from wastewater is essential to the success of long-duration human spaceflight. For human missions to Mars, the technology maturation objective is to recover >98% of the water from wastewater sources (urine, humidity condensate, etc.). To reach these goals and satisfy the capability gap to recover >90% of the water contained in urine brine, the development of a brine processor is required. Building upon the work done under NASA's SBIR Program, the LSS Project is working with Paragon Space Development Corp. to develop the Ionomer-membrane Water Processor (IWP) brine processor for flight demonstration on the ISS.

The IWP utilizes forced convection of dry, heated, spacecraft cabin air coupled with membrane distillation to purify and recover water from urine brine.[18] The water vapor generated is released from the IWP into the cabin environment where it is collected and condensed by the existing spacecraft condensing heat exchanger(s). This water is then further processed by the existing Water Processor Assembly to potable standards. To meet the >90% water recovery from urine goal stated above, the IWP is required to recover at least 40% of the water from the urine brine. In fiscal year 2017 the Brine Processor Assembly (BPA) completed a preliminary design review and the Phase I ISS safety review. The critical design review is planned for September 2017. Also during this fiscal year a method to leak test bladders was developed, bladder materials compatibility testing began, and a ground prototype was completed.

IV. Environmental Monitoring

In an enclosed spacecraft that is constantly operating complex machinery for its own basic functionality as well as science experiments and technology demonstrations, it is possible for the environment to become compromised. While current environmental monitors aboard the ISS will alert crew members and mission control if there is an emergency, long-duration environmental monitoring cannot be done in-orbit as current methodologies rely partially on taking grab samples and sending these environmental samples back to Earth. As was stated in Table 1, the capability gaps identified for environmental monitoring for human missions beyond LEO are the following:

- Provide a smaller, more reliable major constituent analyzer, in-flight trace gas monitor (no ground samples), and targeted gas (event) monitor
- Provide in-flight identification and quantification of organic contaminant species in water
- Provide a non-culture based in-flight microbial monitor with species identification and quantification
- Provide for the on-board measurement of particulate matter hazards

The LSS Project is doing work in many of these areas.

A. Major Constituent Analyzer/Trace Gas Monitor

The current state-of-the-art in cabin atmosphere monitoring is the Major Constituent Analyzer and the Air Quality Monitor. Together these monitors are heavy and bulky. For exploration missions, the goal is to develop 'smaller, more reliable' monitors with in-flight analysis capability. The LSS Project is working on the Spacecraft Atmosphere Monitor (SAM), a miniature gas chromatograph/mass spectrometer (GC/MS) system capable of real time measurement of major constituents and trace volatile organic compounds in the cabin atmosphere. The development of a miniature GC/MS for use in SAM allows for a small size (22.2 cm × 24.1 cm × 19.1 cm), low mass (9.5 kg, including consumables), and low power (34 watts) monitor. The SAM is designed to provide data via Ethernet or wireless.[19]

The SAM is planned to fly as a technology demonstration aboard the ISS in fiscal year 2018. S.A.M. is planned to be mounted in an Expediting the Processing of Experiments to the Space Station (EXPRESS) Rack in a single locker volume. The SAM can be removed from the locker and located anywhere in the ISS to take location specific measurements. The SAM a Phase II delta safety review. The test bed was completed and testing with the testbed demonstrated that the SAM is properly detecting gases. The development model is currently being built. Two flights units will be built.

B. Measurement of Particulate Matter Hazards

Aboard the ISS, smoke does not rise to the ceiling and crumbs do not fall to the floor, which demonstrates the unique characteristics of aerosol behavior in low gravity. Dust and suspended particulate matter have been a recurring complaint of the ISS crew as they have experienced nose and eye irritation as well as allergies. This is an indication of high concentrations of inhalable particles, defined as ≤10 micrometer in diameter. To quantify the particulate load in the cabin atmosphere aboard the ISS and satisfy the 'On-board measurement of particulate hazards' gap previously identified, the LSS Project has developed an Aerosol Sampler flight experiment to provide data on quantity, size, and composition of particles in ISS cabin atmosphere. A battery-powered Active Sampler which is a modified off-the-shelf thermophoretic sampler and customized Passive Samplers, all manufactured by RJ Lee Group (Monroeville, PA), were flown to the ISS and returned to Earth this fiscal year.[20] Particles collected by these samplers are undergoing analysis by powerful transmission electron microscopes. An initial report is expected at the end of the fiscal year. Sample analysis may continue into next year due to the volume of data collected. A reflight of these samplers is being considered by the LSS Project. Additionally planning is progressing on the development of the Stage II ISS aerosol experiment, whose objective is to provide real time monitoring.

V. Systems Engineering and Architecture

With so many complex systems supporting life in space, it is important to understand the overall system requirements to define life support system architectures for different space mission classes, ensure that all the components integrate well together and verify that testing is as representative of destination environments as possible. The LSS Project's main focus for systems engineering and architecture is to define the reference LSS architecture for exploration missions[21], identify applicable requirements and standards[22], manage interfaces and integration[23], assist in evaluations/down selects of competing technologies, and provide direction for testing of technologies.

During fiscal year 2017 the LSS Project started an effort to address dormancy. Dormancy periods and hardware requirements to address dormancy are being developed. Future plans are to develop dormancy strategies and then understand if there are any impacts to technology development efforts or heritage hardware designs that need to be considered.

VI. Conclusion

As humans seek to venture beyond LEO, the criticality of having a reliable LSS increases. The LSS Project under NASAs AES Program is actively working on addressing community identified LSS capability gaps in preparation for said missions. Starting with ISS systems as a point of departure, where applicable, the project is evolving these systems and developing new systems to be smaller, lighter and more reliable and to further close the water and air loops to reduce the consumable mass needed. As part of this effort, a series of LSS technology demonstrations on the ISS are planned between now and ISS end of life. These demos are summarized in

Figure 2.

Figure 2. LSS Planned Flight Demonstrations.

	FY17	FY18	FY19	FY20	FY21	FY22	Flight Demo Goal
Spacecraft Atmosphere Monitor (S.A.M.)		▲					Continuous measurement of major constituents, on-demand measurement of trace VOCs.
Brine Processor Assembly (BPA)		▲					One year demonstration of >40% water recovery from urine brine.
Aerosol Sampler Stage I re-Flight		▲					Obtain quantitative data on airborne particles in multiple ISS locations by sample return and ground analysis.
Aerosol Sampler Stage II				▲			Real time monitoring of aerosol particulates.
CO2 Reduction					▲		>75% reduction of CO2 demonstrating the plasma pyrolysis and hydrogen separation technologies.

Shaded Bar = Flight Demo Design/Build ▲ = Flight Demo Launch

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