

NASA Environmental Control and Life Support Technology Development and Maturation for Exploration: 2015 to 2016 Overview

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Over the last year, the National Aeronautics and Space Administration (NASA) has continued to refine the understanding and prioritization of technology gaps that must be closed in order to achieve Evolvable Mars Campaign objectives and near term objectives in the cislunar proving ground. These efforts are reflected in updates to the technical area roadmaps released by NASA in 2015 and have guided technology development and maturation tasks that have been sponsored by various programs. This paper provides an overview of the refined Environmental Control and Life Support (ECLS) strategic planning, as well as a synopsis of key technology and maturation project tasks that occurred in 2014 and early 2015 to support the strategic needs. Plans for the remainder of 2015 and subsequent years are also described.

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Nomenclature

ABO	= Aviator's Breathing Oxygen	HMC	= Heat Melt Compactor
ACS	= Advanced Clothing System	ISS	= International Space Station
Ag	= Silver	IWP	= Ionomer-Membrane Water Processor
AES	= Advanced Exploration Systems	JEM	= Japanese Experiment Module
AR	= Atmosphere Revitalization	kg	= kilogram
ARREM	= Atmosphere Resource Recovery and Environmental Monitoring	LDST	= long duration sorbent test
ATP	= Authorization to Proceed	LEO	= Low-Earth Orbit
AWP	= Alternate Water Processor	LF-HAR	= low flow, high aspect ratio
BEB	= Brine Evaporation Bag	lpm	= Liters per Minute
BRIC	= Brine Residual In-Containment	LR	= Logistics Reduction
BWP	= Biological Water Processor	LSS	= Life Support Systems
CC&DH	= Command, Control and Data Handling	MCA	= Major Constituent Analyzer
Cd	= Cadmium	M-COA	= Microlith [®] Catalytic Oxidizer Assembly
CDRA	= Carbon Dioxide Removal Assembly	MCTB	= Multipurpose Cargo Transfer Bag
CDS	= Cascade Distillation System	MDM	= Multiplexer/Demultiplexer
CFR	= carbon formation reactor	MEMS	= Micro Electro Mechanical System
CH ₄	= Methane	MGM	= Multi-Gas Monitor
C ₂ H ₄	= Ethylene	Mn	= Manganese
CM	= Crew Members	MPa	= mega-pascal
COTS	= Commercial Off-the-Shelf	MPAM	= Multi-Platform Air Monitor
CP	= Combustion Products	MPCV	= Multi-Purpose Crew Vehicle
CPM	= Combustion Products Monitor	NASA	= National Aeronautics and Space Administration
CRA	= Carbon dioxide Reduction Assembly	Ni	= Nickel
CRCS	= carbon dioxide removal and compression	OGA	= Oxygen Generation Assembly
CTB	= Cargo Transfer Bag	ORU	= Orbital Replacement Unit
Da	= Daltons	OWM	= Organic Water Monitor
DA	= Distillation Assembly	PCPA	= Pressure Control and Pump Assembly
DMSD	= Dimethylsilanediol	PCR	= Polymerase Chain Reaction
ECLS	= Environmental Control and Life Support	PDMS	= Polydimethylsiloxane
ECLSS	= Environmental Control and Life Support System	PLSS	= Portable Life Support System
EM	= Environmental Monitoring	PPA	= Plasma Pyrolysis Assembly
EM2	= Exploration Mission 2	PPS	= Polyphenylene Sulfide
ENose	= Electronic Nose	ppm	= Parts per Million
EVA	= Extravehicular Activity	psia	= pounds per square inch, absolute
FCPA	= Fluids Control and Pump Assembly	QITMS	= Quadrupole Ion-Trap Mass Spectrometer
FOBD	= Forward Osmosis Brine Dryer	R2FD	= Resource Recovery Functional Demonstration
FOST	= Forward Osmosis Secondary Treatment	RASCal	= Rapid Analysis Self-Calibrating Array
FT/IR	= Fourier Transform Infrared	REALM	= RFID Enabled Automated Logistics Management
GC	= Gas Chromatography	RFID	= Radio Frequency Identification
GC/DMS	= Gas Chromatography/Differential Mobility Spectroscopy	RSA	= Rotary Separator Accumulator
GC/IMS	= Gas Chromatograph/Ion Mobility Spectroscopy	SAM	= Spacecraft Atmosphere Monitor
GC/MS	= Gas Chromatography/Mass Spectroscopy	SEOS	= Solid Electrode Oxygen Separator
GCD	= Game Changing Development	SBIR	= Small Business Innovative Research
HCl	= Hydrochloric Acid	SCOR	= Spacecraft Oxygen Recovery
HCN	= Hydrogen Cyanide	SMT	= System Maturation Team
HF	= Hydrofluoric Acid	SOA	= State of the Art
HF-LAR	= high flow, low aspect ratio	STMD	= Space Technology Mission Directorate
Hg	= Mercury	TCC	= Trace Contaminant Control
		TDLS	= Tunable Diode Laser Spectroscopy
		TRL	= Technology Readiness Level

TtG = Trash to Gas
 UPA = Urine Processor Assembly
 UWMS = Universal Waste Management System
 VOCs = Volatile Organic Compound
 VMS = Volatile Methyl Siloxanes
 W = Watt

WPA = Water Processor Assembly
 WRM = Water Recovery and Management
 WRP = Water Recovery Project
 WRS = Water Recovery System
 Zn = Zinc

I. Introduction

IN 2015, the National Aeronautics and Space Administration (NASA) continued to mature the architecture planning to support the strategy published in “NASA’s Journey to Mars, Pioneering Next Steps in Space Exploration”¹. This strategy includes an evolution from the current “Earth Reliant” phase of Low-Earth Orbit (LEO) space exploration to “Proving Ground” missions in cislunar space to finally “Earth Independent” missions to the vicinity of Mars and ultimately the Mars surface. In the past year, more in-depth planning of the near-term transition between the International Space Station (ISS) in LEO and the Proving Ground in cislunar space has been underway at the agency. In a January, 2016 meeting between NASA and its International Space Station partners, a framework for this transition, depicted in Fig. 1, was presented. In this framework, Phase 0 focuses on activities needed to demonstrate technologies and capabilities needed for deep space exploration on the International Space Station. Phase 1 includes initial architecture elements in cislunar space that will augment the capabilities of the Orion and use the Space Launch System to enable longer crew-tended missions in the range of 30-90 days, including the Asteroid Redirect Crewed mission. Finally, Phase 2 expands this capability with a long duration habitation element that would culminate in a one-year crewed Mars validation mission in cislunar space.

Key to each of these phases are the necessary habitation systems, including Environmental Control and Life Support (ECLS), which includes subsystems for Atmosphere Revitalization (AR), Water Recovery and Management (WRM), Waste Management, and Environmental Monitoring (EM). For Phase 0, the current ISS ECLS System (ECLSS) will be evolved to the Exploration ECLSS for a 2-year demonstration on ISS starting in 2022. Components of this system will be launched sooner and have a longer demonstration period. This system will close the capability gaps identified in Table 1 for a long duration microgravity mission, and is expected to be the system implemented in the Phase 2 long duration cislunar habitat. The ECLSS for the Phase 1 short duration habitation augmentation module is expected to be limited to additional consumables to extend the Orion ECLSS mission. However, if volume, mass, and power constraints are not limiting, some closed-loop functionality may still be valuable to reduce required logistics support of consumables to cislunar space.

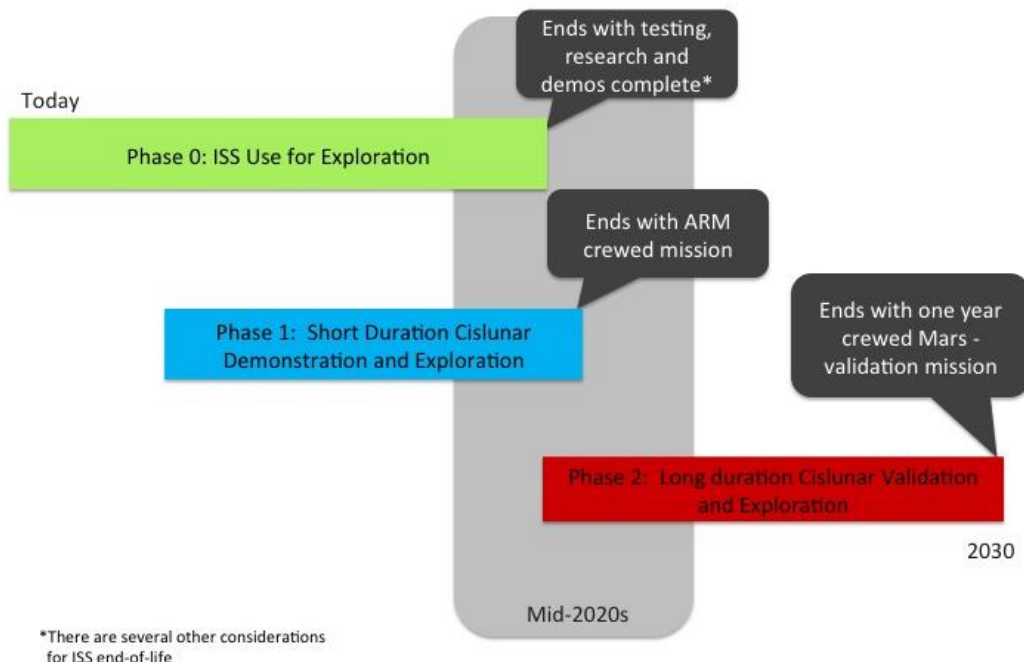


Figure 1. Transition to Cis-Lunar Space Phasing

Table 1. ECLSS and Environmental Monitoring Capability Gaps.

Function	Capability Gaps	Orion	Long Duration ug Hab	Planetary Surface
CO ₂ Removal	Bed and valve reliability; ppCO ₂ <4800 mg/m ³ ² (<2 mmHg)		X	X
Trace Contaminant Control	Replace obsolete sorbents w/ higher capacity; siloxane removal	X	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 contingency medical O ₂		X	X
Water microbial control	Common silver biocide with on-orbit re-dosing		X	X
Urine collection	Backup, no moving parts urine separator	X	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
Metabolic solid waste	Low mass, universal waste management system	X	X	X
Non-metabolic solid waste	Volume reduction, stabilization, resource recovery		X	X
Atmosphere monitoring	Smaller, more reliable major constituent analyzer, in-flight trace gas monitor (no ground samples), targeted gas (event) monitor	X	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 & quantification		X	X
Particulate monitoring	On-board measurement of particulate hazards		X	X

The ECLSS System Maturation Team (SMT) has evolved the roadmaps in each of these capability gap areas to align with an overall strategy to downselect between technology options by 2019 and fly the resulting Exploration ECLSS by 2022 aboard ISS. Development activities conducted by the ISS, Advanced Exploration Systems (AES), Game Changing Development (GCD), and Small Business Innovative Research (SBIR) programs in support of those roadmaps are summarized by this paper.

The current NASA strategy is to employ existing volume on the ISS to support demonstrations of key technologies. NASA considered multiple options, including options from demonstrations of individual units to construction of an entirely new module for demonstrating new technologies. The scope and scale of an exploration class life support system is large enough to be considered a “System of Systems”, and integration of functions across

key interfaces is important. However, the benefits gained by a full simulation in a new module are harder to justify against the cost, especially since a habitat in the cislunar proving ground will provide the full integration before a mission to Mars. These technological investigations are part of the purpose and mission of the ISS, but do require careful consideration of priorities against other research objectives, since space on the ISS is limited and valuable. Also, NASA has not necessarily ruled out the contribution of a module if it meets the goals and needs of an international partner.

The past year has also seen a revitalization of activity in the International System Maturation Team (I-SMT). Multiple nations involved in the ISS partnership are developing life support systems or environmental technologies. New technology demonstrations are planned in the near-term on ISS from Japan, Europe, and Russia. Some technologies seem to be similar between partners, such as a common interest in oxygen generation through electrolysis of water. In some areas dissimilar technologies are proposed to accomplish the same top-level functional goals. A future mission is likely to include contributions from multiple partners, but at this point, it is difficult to say whether, when, or how selections would be made between candidate technologies. Instead, the I-SMT is beginning to come together to discuss shared goals, common challenges in technology development, and common standards or requirements that would help future systems operate together³. The ISS international partners have another key effect on development of life support systems besides the contribution of technologies. While it is not a decision at the level of the ECLSS I-SMT, the retirement date for ISS drives the time available to make decisions and demonstrate key technologies for future applications. Decisions about overall utilization and allocation priorities amongst ISS partners will impact development and demonstration plans for all of the systems.

II. Atmosphere Revitalization

Development and maturation activities within the AR functional area focus on key technical areas that include subsystem architecture, oxygen generation and recovery, carbon dioxide removal, and trace contaminant and particulate removal. The following provides a summary of work in these technical areas.

A. Subsystem Architecture

Work on a notional AR subsystem architecture for exploration missions has built upon the subsystem-level testing efforts in 2012 and 2014 to develop an architectural description. Using this notional architecture, context diagrams are under development to better define functional interfaces between the AR, WRM, and EM subsystems as well as the supporting infrastructure that includes electrical power; command, control, and data handling (CC&DH); thermal control; and structures. Requirements guidance for the architecture's performance are drawn from NASA program documentation and reference publications relating to the Mars Design Reference Mission (DRM). In parallel with these efforts, subsystem modularity is being studied during 2016 under a NASA NextSTEP broad area announcement initiative.

During 2015, the subsystem architecture technical area has fostered collaboration with CC&DH projects to demonstrate system models for autonomous control of selected AR subsystem components in an integrated power and software testing environment in May and September 2015. Autonomous control efforts have been focused within the oxygen recovery technical area and will expand to include other technical areas over the next several years.

B. Oxygen Generation and Recovery

The oxygen generation and recovery technical area includes developmental tasks addressing high pressure-high purity oxygen supply, oxygen recovery, and oxygen generation process simplification and improvement.

1. High Pressure-High Purity Oxygen Supply

The objective for the high pressure-high purity oxygen supply task is to develop the capability to recharge extravehicular activity (EVA) tanks as well as provide on-demand medical oxygen. Competing concepts under development include Solid Electrolyte Oxygen System (SEOS) combined with a mechanical compressor stage and high pressure water electrolysis. Recent and future development has focused on SEOS technology durability and its compatibility with trace contaminants in a typical crewed spacecraft cabin atmosphere. Initial testing during 2015 and extending into 2016 has focused upon Freon 218 compatibility. Freon 218 exists in the ISS cabin atmosphere at significant concentrations and its interaction with the high temperature SEOS process must be characterized and understood. The testing results to date indicate that hydrogen fluoride (HF) and other fluorocarbon compounds are produced. Therefore, a purification stage is likely necessary for a SEOS-based system to be suitable.

The competing process technology for high pressure oxygen supply is water electrolysis at 24.8 MPa (3600 psia). During 2015 two developers investigated this concept. A high pressure cell stack was successfully operated

for three months by Giner, Inc. and a competing high pressure cell stack was developed by Proton under a SBIR project. Work is planned over subsequent years to continue evaluating the merits of the competing high pressure electrolytic cell stack designs.

2. *Oxygen Recovery*

Tasks under oxygen recovery are seeking to more effectively close the oxygen loop and reduce the overall water demand of an exploration-class AR subsystem. Techniques under evaluation in 2015 through 2016 include a methane plasma pyrolysis assembly (PPA), a series-Bosch reactor assembly, and developmental efforts sponsored by the GCD Spacecraft Oxygen Recovery (SCOR) project element. Early conceptual work was also accomplished under NASA Institute for Advanced Concepts sponsorship on a photocatalytic pathway from carbon dioxide to oxygen.

Recent methane plasma pyrolysis developmental work has evaluated a third generation PPA unit at 4 crewmember processing rates under a solo configuration and while integrated with a Sabatier carbon dioxide reduction assembly (CRA). Nominal and off-nominal PPA process characteristics were studied to produce data sets suitable for developing self-diagnosing, autonomous control software. As well, the resulting PPA control model and live data streams were included in two successful multi-system integrated power and software tests (iPAS) conducted in May and September 2015.

Component-level work on the PPA architecture has focused on hydrogen purification. The PPA produces a mixed product gas stream consisting of hydrogen and acetylene (C_2H_2). Techniques to purify the hydrogen so that it may be recycled include metal hydride separations, physical adsorption separations, and electrolytic separations. During 2015 market research was conducted on commercially available metal hydride allows suitable for the PPA hydrogen purification stage. An alloy was selected and procured. Testing is planned in late 2016 or early 2017. In parallel, SBIR projects on electrolytic hydrogen purification (Sustainable Innovations) and microwave-regenerable adsorption purification (UMPQUA Research Co.) were pursued. An electrolytic separator has been tested while integrated with a Microlith[®]-based Sabatier engineering unit and a second generation PPA unit. Testing is planned to continue for the competing hydrogen purification methods in 2016 and continuing through 2017 culminating in a technical selection.

Lower technical maturity concepts are under evaluation with AES and GCD sponsorship. Under AES, a series-Bosch assembly development has completed batch carbon formation reactor (CFR) testing and design. Piece part fabrication of a continuous CFR has also been completed. Assembling the continuous CFR assembly is planned for 2016 with testing planned in 2017. Four technical efforts under the SCOR project element are pursuing their first phase of development with the goal of achieving 75% oxygen recovery from carbon dioxide. Candidate process technologies include a microfluidic electrochemical reactor (University of Texas at Arlington), a high temperature solid oxide co-electrolysis process (Glenn Research Center and PH Matter, LLC), a continuous Bosch-based process design (UMPQUA Research Co.), and a room temperature ion exchange membrane electrolysis unit with an integral CRF (Glenn Research Center and University of Delaware). The first phase will be completed in mid-2016. Two of the candidate process technologies will be selected for a second development phase which will extend through 2018.

3. *Oxygen Generation Process Simplification and Improvement*

Efforts to simplify and improve the water electrolysis-based state-of-the-art (SOA) focused on the ISS Oxygen Generation Assembly (OGA) physical layout. This work continued through 2015 and obtained substantive results indicating that operational and physical layout updates can yield a suitable exploration-class oxygen generator (OGA-X). Key accomplishments in 2015 addressed process safety features. A ventilated cell stack shroud equipped with a hydrogen recombiner was tested successfully. Tests demonstrating the feasibility to eliminate a nitrogen purge and for safely operating without a wastewater interface that rejects water containing dissolved oxygen were also completed. These tests indicate that the oxygen generation equipment mass can be reduced over the SOA by at least 30 kg. An 8-month OGA-X architectural study was completed in late 2016 by United Technologies Aerospace Systems (UTAS). During this time cell stack life testing to evaluate the new chemically-stabilized Nafion[™] membrane material was completed and a multi-cell stack using this material was fabricated and delivered in late 2016 by Giner, Inc. The updated cell stack will be tested in 2016 and the work toward implementing findings from the OGA-X study will be tested in 2017.

C. **Carbon Dioxide Removal**

Tasks under carbon dioxide removal are seeking to enhance performance over the ISS SOA process equipment aboard the ISS, evaluate, and characterize alternative desiccant and carbon dioxide removal sorbents, and develop a combined carbon dioxide removal and compression assembly.

1. Enhancing Performance over the ISS SOA

During 2015 and extending through 2016, enhancing process performance has focused upon understanding nuances in the ISS SOA process equipment behavior. Desiccant beds were tested in 2015 post-flight to understand their working capacity after exposure to the operational environment aboard the ISS. Follow-on testing in 2016 will study the breakthrough characteristics of these beds. Modeling and simulation of the ISS SOA in concert with these testing efforts are seeking to gain the performance necessary to meet carbon dioxide partial pressure guidelines that may approach $<4800 \text{ mg/m}^3$ ($<2 \text{ mmHg}$) for a 4-person crew.

These results serve as lessons learned toward an exploration 4-bed molecular sieve process architecture for exploration (4BMS-X). During 2015 a 4BMS-X test rig was developed and in early 2016 testing began to anchor the testing rig to ISS SOA performance as a basis for comparison. The test rig serves as the proving ground for evaluating and validating promising exploration carbon dioxide removal technologies as well as evaluating functional optimizations such as bed geometry and operational approaches. During 2017 the test rig will evolve to become the ground test engineering unit for inflight exploration carbon dioxide removal technology demonstration.

2. Characterize Alternative Adsorbent Media

Alternative sorbent screening continued in 2015 primarily for ISS SOA sorbents including zeolites RK-38, ASRT 2005, and ASRT 1995. Early low maturity work on thermally regenerable amine- and ionic liquid-based concepts was also conducted. The latter concept, sponsored by the NASA Institute for Advanced Concepts, seeks a direct contact method between the cabin atmosphere and an ionic liquid to remove CO_2 from a habitable environment.

Screening efforts to evaluate structured sorbents were accomplished relating to the ISS SOA sorbents. The screening work employed structural tests for pellet and bulk crush strength, pellet size attrition, pellet hydrothermal stability, and sorbent sensitivity to airborne trace contaminants commonly found in crewed cabin atmospheres. Polymer-bound structured sorbents from Honeywell International and Grace were evaluated as well as a clay-bound monolith manufactured by Grace. The polymer-bound monolithic media exhibited sensitivities to moisture that require high temperature regeneration. The clay-bound monolith showed promising results that warrant further investigation in 2016 through 2017. A long duration sorbent test (LDST) flight experiment to expose promising desiccant and carbon dioxide sorbent media to an in-flight cabin environment, particularly the trace contaminant load, was developed in late 2015 with delivery to the ISS planned in 2016. Data evaluation will be ongoing in 2017.

3. Develop a Combined Carbon Dioxide Removal and Compression Assembly

The combined carbon dioxide removal and compression subassembly (CRCS) completed initial single-unit testing during 2015. The testing results indicated good bed flow distribution between the carbon dioxide removal and compression stages; however, the bed heating performance was sub-optimal. A second subassembly is being assembled to allow for two-assembly functional testing in 2016. Improvements to the CRCS concept are planned for 2017 which will incorporate lessons learned during the 2015 single assembly and 2016 dual assembly testing efforts.

D. Trace Contaminant and Particulate Removal

The trace contaminant and particulate removal functional areas include characterizing adsorbents, catalysts, and processes for volatile organic compound (VOC), ammonia (NH_3), carbon monoxide, and formaldehyde control; testing components for an exploration trace contaminant control (TCC) architecture; and developing requirements and a technical solution for a particulate filtration architecture.

1. Characterizing Trace Contaminant Control Adsorbents, Catalysts, and Processes

Market research was conducted in 2015 on untreated activated carbons to specifically target low concentration VOCs. Three activated carbon products were identified and procured—two from Calgon (207C and OVC) and one from Cabot Norit (RB2). Aboard the ISS another Cabot Norit activated carbon, GCA 48, is being used for volatile methyl siloxane control. Therefore, the GCA 48 was added to the characterization task for 2016. Through early 2016, the Calgon and Cabot Norit activated carbons have been found to exhibit similar equilibrium loading capacities with the GCA 48 being slightly better.

During 2015, additional VOC equilibrium loading capacities were evaluated for Chemsorb 1000 and Chemsorb 3800 (Molecular Products) and Barnabey Sutcliffe Type 3032. The latter activated carbon is the commercially obsolete SOA adsorbent used aboard the ISS. In general the VOC sorbents from Calgon and Cabot Norit have been found to provide performance similar to the SOA activated carbon.

Ammonia removal was evaluated for the range of 0.7 mg/m^3 to 35 mg/m^3 during 2015 for Ammonasorb II (Calgon) and Chemsorb 1425 (Molecular Products) compared to Barnabey Sutcliffe Type 3032. At 0.7 mg/m^3 , the Ammonasorb II and Chemsorb 1425 were both found to provide $\sim 20 \text{ mg}$ ammonia/gram carbon loading which is 68% higher than the loading of Barnabey Sutcliffe Type 3032. The distinguishing characteristic for Ammonasorb II and Chemsorb 1425 will be their VOC equilibrium capacities.

In addition to ammonia adsorbent media, work continued in 2015 on a catalytic ammonia removal reactor. Testing is being conducted in 2016 on competing reactor designs. This testing will guide additional development in 2017.

Ambient temperature carbon monoxide catalysts were tested during 2015 for their ability to remove formaldehyde. A custom catalyst prepared by UTAS and Carulite (Carus Corp.) were found to perform well. A catalyst that has shown promise for carbon monoxide control, Sofnocat 425 (Molecular Products) was found to exhibit no formaldehyde removal activity.

2. Testing Components for an Exploration Trace Contaminant Control Architecture

As part of the TCC architectural efforts, results from integrated testing conducted in 2014 were evaluated and an updated architecture consisting of high flow, low aspect ratio (HF-LAR) and low flow, high aspect ratio (LF-HAR) components supplemented by a low flow thermal catalytic oxidation unit resulted. Two competing, commercially available concepts for the HF-LAR components were identified in 2015. The HF-LAR components will be procured and evaluated during 2016.

An advanced Microlith[®]-based catalytic oxidizer assembly (M-COA) was fabricated, acceptance tested, and delivered to NASA in 2015. In late 2015 through early 2016 this advanced M-COA was tested under exploration trace contaminant control flow rates and trace contaminant loads to evaluate methane oxidation efficiency and thermal efficiency. Performance observed through the first quarter of 2016 indicate performance consistent with testing conducted on a developmental unit in 2005.

In late 2016 through early 2017, a testing series that incorporates HF-LAR, LF-HAR, and the advanced M-COA in an exploration mission architecture will be evaluated. The best performing adsorbents according to the characterization work will be used in the testing.

3. Requirement and Technical Solution Development for Particulate Removal

During 2015, an aerosol sampler flight experiment to characterize the cabin suspended particulate matter load was developed. The flight experiment effort is progressing toward delivery to the ISS by July 2016. Results from the flight experiment will be instrumental in developing an evidence-based particulate load model for designing exploration particulate control equipment.

Filtration concepts based on HEPA media and ceramic-elements for removing carbon dust from the PPA effluent gases have been developed and tested in 2015. Additional development and follow-on testing is planned for 2016 and beyond.

A multi-stage, cabin particulate filtration concept that has been under development since 2014, entered the prototype design stage during 2015. The design was completed and fabrication and testing is planned for 2016.

III. Water Recovery and Management

Although an integrated life support system is made up of a variety of systems, a major driver in sizing a life support system is the Water Recovery System (WRS). As mission durations increase, recycling water becomes critical. Stored water is inadequate, and wastewater sources must be recycled into potable water. The state-of-the-art (SOA) WRS used on-board the ISS relies on a high rate of consumable use (0.032 kg expendables consumed per kg of potable water produced) and has known issues with fouling by particles thereby limiting the recovery rate from urine to approximately 74%. Combined with the percentage of water recovered from humidity condensate, the current overall ISS water recovery rate is 88%. For exploration systems the goal established by the Human Health, Life Support, and Habitation Systems Roadmap⁴ is to reach 98% water loop closure with reduced expendables, so there are significant gains to be made.

Of the various consumables required to sustain human life in space, water accounts for the greatest percentage of material by mass. Spacecraft crews need between 3.5 and 23.4 kg of water per person for each mission day depending on mission requirements. Conversely, spacecraft crews produce between 3.9 and 23.7 kg of wastewater per person per day depending on mission requirements. The levels of wastewater produced can be higher than water requirements because of contributions from water content of food and metabolically produced water. The state-of-the-art water recovery system on ISS is limited to treating only urine and condensate, which is only about 20% of the potential waste stream on long duration exploration missions, which may include hygiene water, laundry water, and water recovered from brines and solid wastes.

In 2014-15 NASA has invested in several water recovery areas including upgrades and improvements to ISS systems and technology development under the AES, GCD, and SBIR programs.

1. ISS Upgrades

The ISS program is investing in developing upgrades to the elements of the WRS that are intended to benefit ISS operations in the near term and human exploration in the long term.

1. *Urine Processor Assembly*

Upgrades to the Urine Processor Assembly (UPA) have continued to progress. The Fluids Control and Pump Assembly (FCPA) SN004 is the first unit delivered to the ISS with both the planetary gear redesign and the manifold redesign. FPCA SN004 is installed in the UPA and has 705 hours of operation as of May 2016 with no anomalies. There is a longer life expectancy so the unit will be continued to be monitored. The flight equivalent FCPA in the UPA test bed at MSFC has been operated for over 3000 hours. The test bed will be continued to be operated to determine the number of hours before failure.

Higher than expected free gas from the urine delivered from the Waste and Hygiene Compartment has been observed in the UPA. To address the higher free gas a design solution is to add the capability to operate the Pressure Control and Pump Assembly (PCPA) at variable speeds. To achieve this the planetary gear ratio selection for the PCPA required testing. Tests were performed in the UPA test bed at the Marshall Space Flight Center (MSFC) with different gear ratios to collect data for the best selection. Testing has been completed and the PCPAs are being retrofitted with planetary gears. The first retrofitted PCPA is planned to be completed in FY16. Additionally an update to the flight software will be needed to operate the PCPA at variable speeds.

Work continues developing and testing bearings using Nitinol. Nitinol bearings for the compressor have been installed in the UPA Test Bed Distillation Assembly (DA). The bearings have been operating nominally since installation. New centrifuge bearings with Hafnium added to prevent the bearing crack experienced last year are planned to be installed in the UPA Test Bed DA early summer of 2016. Gear materials studied included polyphenylene sulfide (PPS) and Nitinol. As reported in last year's paper PPS is not suitable in this application. The Nitinol gears design solution did not work either. In order to keep the Nitinol gears lubricated a coating was applied to the gear teeth. During testing in the UPA test bed the coating wore off substantially sooner than the vendor predicted. There will be no further work on the Nitinol gears as the current gear design in the DA performed as expected.

2. *Water Processor Assembly*

A test has been completed to determine to what extent the operational life of Water Processor Assembly (WPA) multifiltration beds can be extended by taking better advantage of the contaminant breakthrough profile that has been observed in actual operation. Currently, WPA multifiltration bed changeouts are based on initial breakthrough of ionic contaminants from the first (of two) installed beds. However, data suggests that initial breakthrough contaminants (bicarbonate, acetate, and possibly ammonia) may be safely and effectively allowed to pass into the downstream catalytic reactor for oxidation, thereby allowing the installed multifiltration beds to remain in position longer prior to changeout. Ground tests have shown the WPA Catalytic Reactor is effective at oxidizing these additional breakthrough contaminants along with the nominal volatile load to the reactor. Furthermore, a test of a development Multifiltration Bed with an ersatz of the ISS waste water has shown a fairly distinct breakthrough curve for bicarbonate and acetate. A more thorough assessment of this data is provided elsewhere⁵.

Residual organics present in the effluent of multifiltration beds are oxidized in a catalytic reactor operated at elevated temperature. Undesirable consequences of elevated temperature include the need to maintain system pressure above the flash point of water. Additionally, long duration exposure to elevated temperature stresses the integrity of internal polymeric seals required for leak prevention. In order to alleviate these consequences, and to take advantage of advancements made in the field of heterogeneous catalysis over the last two decades, NASA will be supporting the development and comparative testing of one or more candidate catalyst formulations with the potential to provide the required level of oxidation potential and life under ambient temperature conditions. In 2014 United Technologies Aerospace Systems and UPMQUA were awarded contracts to develop new catalysts. The catalysts are expected to be delivered in the spring of 2016. MSFC will test the catalysts to determine the best candidate.

3. *Urine Pre-treat Formulation Change*

Calcium precipitant formation was discovered in the UPA Distillation Assembly in 2009. To address this, phosphoric acid was recommended to replace sulfuric acid in the urine pretreat solution. Testing demonstrated using phosphoric acid would not result in calcium precipitation at recovery levels up to 90%. Urine pretreat with phosphoric acid was approved for use on ISS and has been delivered to the ISS. With the new urine pretreat formulation the urine recovery will be increased from 75% to a minimum of 85% initially, with the goal of eventually achieving 90% recovery on ISS.

B. AES Water Recovery

Under the AES Life Support Systems (LSS) project, the wastewater processing and water management task seeks to develop advanced water recovery systems to enable NASA human exploration missions beyond LEO. The primary objective of this task is to develop water recovery technologies critical to near term missions beyond LEO. The secondary objective is to continue to advance mid-readiness level technologies to support future NASA missions. In 2015-16 the AES LSS Project Water Task is focused on maturation and testing of the Cascade Distillation System, advancements in water chemistry, and brine treatment technologies.

1. Cascade Distillation

The Cascade Distillation System (CDS) represents a rotary distillation system design with potential for greater reliability and lower energy costs than existing distillation systems. The AES LSS project continues to advance the technology through targeted improvements based upon the results of the 2009 comparison test and recommendations of the expert panel. Further information on the CDS can be found in Ref. ⁶.

FY15 accomplishments included successful completion of a critical design review (CDR) for both the second generation cascade distiller and the full CDS 2.0 system. CDS 2.0 is the next generation ground test unit with a flight forward Express Rack configuration. In parallel to CDS 2.0 design work, additional testing was also performed on the first generation CDS. This testing sought to inform the CDS 2.0 design and to better quantify the performance of CDS.

2. Water Chemistry Objectives

Wastewater stabilization is an essential component of the spacecraft water cycle. There is typically a gap between wastewater generation events (showers, urination, etc.) and processing of the wastewater as well as between processing of wastewater and consumption of potable water. In these time intervals, the water must be stored.

Wastewater Stabilization - The goal of the wastewater stabilization method task is to identify and evaluate low-toxicity wastewater stabilization alternatives to the current SOA while maintaining the stabilization functions of preventing urea hydrolysis and microbial growth. First, stabilization prevents the breakdown of urea (urea hydrolysis) into ammonia, a toxic gas at high concentrations. Second, it prevents the growth of microorganisms, thereby mitigating hardware, and water quality issues due to biofilms and planktonic growth. Current stabilization techniques involve oxidizers and strong acids (pH=2), such as chromic and sulfuric acid, which are highly toxic and pose a risk to crew health. The purpose of this task is to explore less toxic stabilization techniques.

In FY15, a urine pretreatment formulation was finalized that produced no solids at 85% water recovery. This formulation consists of permanganate (KMnO₄) with phosphoric acid (H₃PO₄). The dosage of this formulation was then optimized and re-demonstrated at 85% recovery. Following successful demonstration, the optimized dosage was placed into a six month dormancy study to evaluate stabilization in storage. Samples were taken weekly and analyzed for changes in chemistry and biological growth. The six month study completed in February, 2016 and demonstrated no significant increase in total organic carbon or microbial growth. A toxicity assessment was also performed on the formulation and indicated that the pretreatment chemical is Toxicity 2 while the pretreated urine is Toxicity 1. The goal was for both toxicities to decrease to 1 so the forward plan is under development.

Silver Biocide - The purpose of the silver biocide task is to identify methods for adding silver biocide to water on-orbit during both operational use and dormancy, as well as methods to maintain silver concentration in stored water. Silver biocide offers a potential advantage over iodine, the current SOA in US spacecraft disinfection technology, in that silver can be safely consumed by the crew. Low concentrations of silver (<500 µg/l) have been shown to kill bacteria in water systems and keep it potable. Silver does not require hardware to remove it from a water system prior to consumption, and therefore can provide a simpler means for disinfecting water that requires fewer consumables than the ISS SOA.

In FY15, work completed on characterizing the conditions conducive to silver particle vs. ionic species formation. Work also began on testing the compatibility of electrolytically generated silver at potable concentrations with spacecraft water system materials at various surface area to volume ratios. In parallel, an SBIR Phase II contract to develop a silver biocide delivery system was awarded and is progressing.

3. Brine Dewatering

Brine Dewatering seeks to address the goal of 98% water recovery established by the Human Health, Life Support, and Habitation Systems roadmap, 98% water recovery cannot be achieved without recovery of water from brine. It is a challenging problem. When wastewater brines are dried, the residual is inevitably a viscous goo, laden with particles of precipitated solids. This brine residual causes several problems for traditional recovery systems, such as clogging pitot tubes, causing bearings to seize, and fouling heat transfer surfaces.

In FY15, the LSS project continued development of the NASA developed brine dewatering technologies (Brine Residual In-Containment (BRIC)⁷, a Brine Evaporation Bag (BEB)⁸, and a Forward Osmosis Brine Dryer (FOBD)

and explored mitigation of common roadblocks associated with brine dewatering in a microgravity environment, including reliable operations, and safe handling and disposal of the remaining brine solids. At the conclusion of this work, the three NASA Developed technologies and Paragon's Ionomer-Membrane Water Processor (IWP)⁹ were compared and a down select was made to choose the best technology to be demonstrated on the ISS. IWP was the winner of this down select and is progressing towards flight demonstration on ISS. BRIC was not selected for full flight demonstration at this time but did show enough promise to continue low level development.

4. *Biological Water Processor*

A biological water processor (BWP) is intended to aid in closed-loop life support systems development aimed at high water recovery rates by performing water remediation by encouraging urea hydrolysis and the speciation of ammonium. The BWP utilizes the natural metabolic processes of bacteria, rather than limiting their growth, to nitrify bacteria and oxidize ammonium in aerobic environments. The aim of the BWP is to leverage the benefits of biological wastewater treatment, which include eliminating pretreatment consumables and power intensive distillation processes, while utilizing a passive system to encourage the natural metabolic process of microbes.

In FY15 the LSS project continued their collaboration with Texas Tech University on the rectangular cross-flow reactor design, build, and test. Texas Tech determined the optimum geometry of the BWP to accommodate demonstration on-orbit, to minimize overall volume and to maximize operational performance. They then designed and built a reactor in this configuration. Operation of the rectangular reactor will occur in FY16. In parallel, Texas Tech also began evaluating the feasibility of an extremely low pH bioreactor for treatment of urine and production of flush water.

C. **Water Recovery SBIRs**

In 2014, NASA is also sponsoring several SBIR Phase I and II projects related to water recovery, these include:

- Silver Ion Biocide Delivery System for Water Disinfection (Reactive Innovations, LLC)¹⁰
- Miniaturized, High Flow, Low Dead Volume Preconcentrator for Trace Contaminants in Water under Microgravity Conditions (Thorleaf Research, Inc.)¹¹
- Water Recovery for Regenerative Life Support Systems (Creare, Inc)¹²
- Advanced Electrochemical Oxidation Cell for Purification of Water (Vesitech, Inc)¹³
- Ionomer-membrane Water Processor System Design and EDU Demonstration (Paragon Space Development Corp)¹⁴.

IV. **Waste Management**

Waste management is increasingly being recognized as an area requiring technology development by exploration mission studies¹⁵ and NASA Roadmaps⁴. Exploration vehicles will be smaller than the ISS and there will be long periods between when the crew starts to use logistical items, which become waste, and when they would be jettisoned in departing vehicle elements. For Mars surface missions, consideration of planetary protection measures must also be taken into account. In addition to the ECLSS domain, waste management crosses several domains including habitation and logistics. Waste management within ECLSS primarily addresses solid waste but it also has liquid waste components, i.e. urine, in common with the Water Recovery area. Solid waste management is divided generally into waste reduction, trash management, and human metabolic waste management. An overview of these three waste management areas and NASA's current and planned research are described below. Completed or previous waste development work is described in earlier papers^{16,17}. The AES Logistics Reduction Project (LR) and other NASA programs are developing technology in each of these areas. The AES LR technology projects are filling gaps identified in the NASA technology roadmaps⁴. AES LR trash modeling for a 6-person one year mission predicts a total of 8,060 kg of crew-related logistics is required. These logistics contribute the majority of an estimated 3,840 kg of waste. The contents of the AES LR logistics and trash model were defined previously and the latest estimates represent a Mars transit mission that specifically analyzed the potential volume savings of several technologies¹⁷.

A. **Waste Reduction**

Reducing the original logistics consumables is a very beneficial form of waste reduction. It not only directly helps with lower launch weight, it also reduces in space propellant to move the mass after it is used and becomes waste. AES LR is researching three logistics minimization technologies that can reduce the solid trash burden: advanced clothing, reusable cargo bags, and automated logistics tracking.

After hygiene items, clothing is the largest crew consumable waste product¹⁷. Crew clothing is primarily cotton based on the ISS and requires significant consumable up mass, approximately 75 kg/crew-year. There is no laundry

capability on ISS. AES LR Advanced Clothing Systems (ACS) has completed an ISS investigation of a variety of wool, modacrylic, and polyester clothing articles for both aerobic exercise and routine wear. The ISS technology demonstration called the 'Intravehicular Activity (IVA) Clothing Study' on increments 39/40 was conducted with 3 US and 3 Russian crew members. This study was the first human science collaboration with Roscosmos under the restructured Scientific and Technical Advisory Council. The details of the clothing study have been previously published^{16,18} but the results are summarized here. For the exercise clothing component, wool exhibited the longest length of wear for exercise shirts but polyester was viewed more favorably. If wool replaced the current X-static shirts being flown, a mass savings of nine kilograms for a crew member-year can be realized. For the routine wear component, modacrylic was the longest length wear in routine shirts and viewed more favorably than wool. If modacrylic replaced the cotton shirts being flown, a mass savings of six kilograms for a crew member-year can be realized. The ACS project has made recommendations to ISS for incorporation into future crew provisioning decisions in addition to the items tested.

Most logistics are launched in cargo transfer bags (CTBs) which are a suitcase like size shape. CTBs are available in a range of set sizes, for example, a 'single sized CTB' has approximate dimensions of 50-cm long x 42 cm wide x 25 cm high. The majority of CTBs become trash themselves after the logistics are consumed. AES LR is developing Multipurpose cargo transfer bags (MCTBs) to allow logistics bags to be unfolded on-orbit to a flat configuration and used to outfit the crew cabin for sleep compartments, acoustic blankets, or contingency water processing. This would reduce the number of used CTBs that become trash. In 2015, AES LR initiated and completed development of a MCTB specifically designed to reduce acoustic emissions from the ISS crew exercise treadmill by 2-3 dBA¹⁶. Four acoustic MCTBs were launched in December 2015 on Orbital-ATK flight 4. The MCTBs were used to protect cargo during launch to ISS, like any standard CTB, but then unfolded and applied to two ISS rack surfaces. This ISS demonstration showed a zero trash residual approach rather than flying dedicated acoustic blankets that would have required two CTBs to package them. This one application of MCTBs saved ~8 kg of mass. The crew will take acoustic measurements to verify results and the results will be published at the ISS Research Conference mid-2016.

For ISS, filler foam is used between CTBs and cargo items to fill the voids around the grouped items. To minimize crew time, similar cargo items are all packed together rather than mixing cargo items of different sizes and shapes to maximize packaging efficiency. Filler foam can represent 15% of the total cargo volume and all the filler foam becomes waste. If the crew could readily find items in densely packed CTBs that are optimized for volume, then filler foam could be substantially reduced and the number of CTBs reduced which would reduce trash volume. AES LR is developing Radio Frequency Identification (RFID) technology to allow 3D localization of crew items with RFID Enabled Automated Logistics Management (REALM)^{19,20}. In 2015, the initial REALM hardware for monitoring ISS cargo movement through the Node 1, US Lab, and Node 3 hatches was prototyped and tested. This initial hardware is called REALM-1. In 2016, the REALM-1 flight hardware was fabricated and the hardware is tentatively scheduled to launch in September 2016 for a one year ISS technology demonstration. AES LR is also developing a mobile RFID reader (REALM-2) that will be a primary payload on STMD's next generation freeflyer called Astrobe²¹. This will provide coverage in modules where REALM-1 is not deployed and investigate how the combination of mobile and fixed readers can be optimized for exploration needs. Eventually dense zone drawers and bag readers will augment REALM-1 and REALM-2 sparse zone reader capabilities.

Finally, REALM technology will establish a low power and communication network that will enable future broad use of RFID-enabled wireless sensors that will benefit ECLSS and other technology areas. NASA has funded SBIR phase II development of an advanced 6-degree-of-freedom hybrid RFID-infrared inventory tag system with Advanced Systems & Technologies, Inc²². The hybrid tag will utilize the REALM-1 technology demonstration and allow 3D localization accuracy to the 2-3 centimeter resolution, which is an order of magnitude better resolution than RFID alone which will benefit logistics, robotic applications, and wireless sensors.

B. Trash Management

Trash processing ranges from simple trash drying, to moderate heating and compaction, to high temperature thermo-chemical decomposition of the trash ('Trash-to-Gas'-TtG). In 2015, AES LR completed assembly of a second generation (Gen2) Heat Melt Compactor (HMC) for ground testing. HMC is the mid-range of trash processing. The HMC provides a 7:1 reduction in trash volume via compression and application of heat to produce microbially stable, dry trash tiles. The plastic content of space trash softens during heating to hold the non-plastic trash in a compressed state when it cools. HMC tiles can be the final disposal form, interim storage until more fully processed, or a compact form for jettison. The HMC will be able to process approximately 1 kg of mixed trash and recover approximately 200 mL of water per batch. The major design challenges of the HMC technology are designing the compaction chamber and its steam vents and seals to be tolerant of the softened plastic and

caramelization of food residuals²³. The major process design challenges include ensuring adequate heating of the low conductivity trash to inactivate microorganisms and sufficiently dry the trash. An additional challenge was discovered during Gen2 checkout testing in 2015. The HMC compaction force was too low and several other issues needed to be resolved. Repair options are being investigated and some implemented so that testing can hopefully resume mid-2016²⁴.

Complementary activities are two Phase I SBIRs to develop a microgravity compatible condensers^{25,26} for the based water recovery system that could eventually be integrated to an ISS flight experiment of HMC technology. Water recovery challenges from HMC include: unsteady steam generation rates from trash, tolerance of a wide range of organic volatiles from trash, and low relative humidity of the non-condensable gas effluent to allow compatibility with downstream HMC source contaminant control systems.

HMC technology can be complimentary to other trash management technologies, such as, trash-to-gas (TtG) previously investigated by AES LR²⁷. Jettison of trash either by periodically ejecting HMC tiles or venting of TtG can save vehicle propellant because the overall vehicle mass is reduced during thrust operations. If the mission benefits of trash jettison by the NASA Evolvable Mars Campaign team appear viable HMC or TtG development may be suitable for further development.

C. Human Metabolic Waste Management

Metabolic waste collection in space (space toilet) uses cabin atmosphere to capture feces and urine. The hardware has typically required a substantial installed and consumable mass. If microgravity collection is ineffective it can rapidly create unhygienic conditions in a spacecraft. Escaped material can spoil the toilet hardware, the crew cabin, and the crewmember. This can result in considerable crew time to wipe down and clean surfaces and a considerable wipe mass over the mission. Additionally, the urine must be pretreated to protect the toilet hardware and allow high water recovery in the downstream urine processing or venting systems. In 2015, AES LR worked with ISS and MPCV to initiate development of a Universal Waste Management System (UWMS) that is very compact and compatible with Orion and future exploration mission vehicles²⁸. The UWMS is being developed by United Technologies Corporation Aerospace Systems (UTAS) and consists of a dual fan/rotary separator, shorten fecal transport tube, integrated odor/bacteria filter, urine pretreat dose pump, and pretreat quality indication device. The hardware will be delivered to ISS in 2018 with an ISS technology demonstration of nominal operation and recovery from a quiescent period. A second UWMS will provide the toilet functions for the Multi-Purpose Crew Vehicle (MPCV) EM-2 mission.

Fecal processing by torrefaction is being investigated for recovering water from feces, microbially sterilizing it, while minimizing hydrocarbon gas production (Advanced Fuel Research, Inc.)²⁹. This technology produces an inert material that would help meet Mars planetary protection goals. The technology is not part of the UWMS but it will be tested with UWMS compatible fecal canisters to evaluate future integration options.

In addition to primary vehicle level metabolic waste collection, NASA is also investigating launch and entry suit contingency waste collection. The crew must wear a waste collection garment inside the space suit to collect urine and feces. For ISS, this is a commercial adult diaper. MPCV has a loss of module contingency where crew would have to be in their suits up to 144 hours. The crew must continue to consume food and water to maintain health and performance. Long term waste management systems are needed to prevent in-suit urination and defecation from creating serious health issues. The phase I and phase II work (Omni Measurement Systems, Inc.) is developing active collection techniques that can effectively collect the waste inside the suit using a deformable collection device, membrane, and pump³⁰.

V. Environmental Monitoring (EM)

Environmental Monitoring is comprised of four disciplines and are aligned with the Environmental Health System on board ISS and for Orion. The functional aspects of each discipline are the following:

- Cabin Atmosphere Quality
 - Monitor trace volatile organic compounds (VOCs)
 - Monitor airborne particles
 - Monitor major constituents (typically O₂, N₂, CO₂, H₂O, H₂, and CH₄.)
 - Monitoring target gases (formaldehyde, CO₂, O₂, system chemicals, etc.)
- Water Quality
 - Identify and quantify aqueous species
 - Monitor biocide levels
- Microbial Monitoring

- Identify and enumerate microbial presence in the cabin atmosphere, water, and surface
Monitor for the presence of coliform in water
- Acoustic Environment
 - Real-time acoustic monitoring

1. Environmental Monitoring Gaps and Needs

Technologies required to address established risks to crew health during Exploration-class missions were identified³¹. Starting with current, operational hardware onboard ISS as the “state of the art”, limitations to the “state of the art” were identified in each discipline as they apply to Exploration-class missions. Limitations found common to current ISS hardware for missions beyond LEO include:

- Reliance on return sample and ground analysis
- Require too much crew time
- Constraints on size, mass, and power
- Lack of portability
- Obsolescence
- Insufficient battery life
- Insufficient calibration life
- Limited capability to measure unknowns which may be present in future exploration vehicles
- Operations after period of dormancy
- Need for consumables
- Insufficient shelf life

An effort is underway to address these gaps, determine the most promising solutions, and mature those solutions to flight technical demonstration and ultimately to baseline flight system hardware. The following provides a summary of the activities in 2015-2016 within the Agency to address the gaps and needs.

A. Cabin Atmosphere Quality – Major Constituents

Multi-Platform Air Monitor (MPAM) - United Technologies Aerospace Systems, through Boeing, is developing a magnetic sector mass spectrometer approach to produce a qualified air monitor for oxygen, carbon dioxide, nitrogen, humidity, hydrogen, and methane, that would be used for the Orion spacecraft and also serve as an upgrade to the ISS Major Constituent Analyzer (MCA)³².

B. Cabin Atmosphere Quality – Major Constituents and Trace VOC Monitoring

Spacecraft Atmosphere Monitor (SAM) – SAM is an AES LSS sponsored technology demonstration development led by JPL, and in partnership with JSC, aiming to achieve a major size reduction of an autonomous flight GC/MS, without loss of analytical capability³³. The SAM instrument will monitor both the major constituents and minor constituents. It had its system requirement review in July 2015. The system design review was held on 7-8 of April 2016.

C. Cabin Atmosphere Quality – Airborne Particles

The Advanced Exploration Systems (AES) Life Support Systems (LSS) project is funding an aerosol sampling experiment on ISS to obtain data on ambient airborne particles. Dust and particle-laden cabin atmosphere has been a recurring complaint of the 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 ≤ 100 micrometer in diameter. However, research shows that many negative health effects are correlated to fine and ultrafine particles (≤ 2.5 micrometers and ≤ 100 nanometers, respectively). The Aerosol Samplers experiment will provide data on quantity and sizes of particles in ISS ambient cabin atmosphere, particularly in the larger inhalable size range. Particles will be collected with two types of samplers manufactured and supplied by the company RJ Lee Group (Monroeville, PA) and returned to Earth for subsequent analysis.

The Active Sampler is a battery-powered commercial, off-the-shelf (COTS) thermophoretic sampler (TPS100) which was developed by researchers at RJ Lee Group and Colorado State University.³⁴ The collection method uses the thermophoretic force on particles passing through a large thermal gradient, which drives them to the cold surface. The collection substrate which is on the cold side of the gradient is a Transmission Electron Microscope (TEM) grid, which is 3 mm in diameter, and is used to directly view particles in a variety of electron microscopes. The Passive Aerosol Sampler is a one-piece device that passively collects particles. The outer aluminum case (108 mm x 45 mm x 25 mm) contains five individual sampling substrates covered by sticky carbon tape for particle

collection. Crew will mount the Passive Samplers with Velcro at various ISS locations, near filters to take advantage of the ‘dirty’ incoming process atmosphere flow. The collection substrates will be exposed for different durations (eg. 2 days, 4 days, 8 days, 16 days, and 32 days) in order to obtain at least one sample with optimal particle coverage for microscopy. Data obtained from analysis of these samples will include long-term average particle number concentrations, particle morphology and chemical composition. Computer-controlled Scanning Electron Microscopy (CCSEM) will be used to create particle size distributions by measuring individual particle sizes for hundreds to thousands of collected particles from one sample. Chemical analysis will be performed by Energy-dispersive X-ray Spectroscopy (EDX) and particle morphology will enable identification of particle emission sources.

The Aerosol Dynamics Inc. in Berkeley, California as part of a SBIR, is developing an aerosol instrument suitable for low gravity use. The innovation is based on the development of a tippable, self-sustaining, water-based condensation particle counter, capable of measuring particles as small as 10nm. Particles carried in a laminar flow are enlarged through water condensation and counted individually by optical scattering, but in contrast to commercial instruments, all of the liquid water is within the wicked walls of the condensational growth chamber. The water vapor used for condensation is recaptured by this wick, and transported internally via capillary action, without a fluid reservoir. The instrument, called MAGIC, for moderated aerosol growth with internal water cycling, can be shaken, rotated, or operated in any orientation, unlike other commercial-off-the-shelf condensation particle counters, and water is replenished by the relative humidity of the surrounding ambient air³⁵. This instrument can be combined with ultrafine particle pre-cut and repackaged with a commercial optical particle counter to provide sizing for larger particles as well. Thus, the combined instrument system would provide particle number concentration and approximate sizing for particles from 10 nm to above 20 μm . There is a high level of interest for a technology demonstration with this instrument, should it be funded for a Phase II SBIR, and it would also be a candidate for a long-term particulate monitor for extended missions.

D. Cabin Atmosphere Quality – Monitoring Target Gases

1. Multi-Gas Monitor

The Multi-Gas Monitor (MGM) is an ISS-sponsored optical target gas monitor technology demonstration based on tunable diode laser spectroscopy (TDLS) using an integrating sphere optical platform. MGM was developed by Vista Photonics, Inc.³⁶ and launched on 37Soyuz in November 2013. It was installed and activated on February 03, 2014, in NanoRacks mounted in Express Rack 5 of the Japanese Experiment Module (JEM). MGM monitors oxygen, carbon dioxide, ammonia, and water vapor, collecting data every 30 seconds. With an integrated battery, MGM is also designed for remote operations throughout the ISS. MGM continues to operate on board ISS and is the subject of another paper at the 2016 ICES. The core technology behind MGM – tunable diode laser spectroscopy – is currently being evaluated for combustion products monitoring and for real-time monitoring of ammonia on-board ISS. MGM has clearly demonstrated the efficacy of tunable diode laser spectroscopy in meeting the needs imposed by manned spaceflight and Exploration-class mission onto target-gas monitors.

2. Combustion Product Monitor (CPM)

Under the sponsorship of the AES LSS project, JPL has developed low-power, solid-state lasers emitting at the wavelengths required to monitor combustion products³⁷. Laser spectroscopy techniques will produce instruments that will have a multi-year lifetime without the need for consumables, re-calibration, or maintenance. Using these lasers, JPL with support of Port City Instruments has constructed a 5 channel (CO, CO₂, HCN, HF, and HCL) optical combustion products monitor. This instrument successfully passed its calibration, validation, and characterization at Glenn Research Center (GRC). As a follow up, JPL has developed a new version that addresses all the lessons learned, small and battery operated that meet all the Orion requirements. This version is currently being considered as a technology demonstration on SAFFIRE IV-VI experiments. A functional and environmental test of the instrument is expected to start toward the end of summer 2016.

A hand-held, battery operated combustion products monitor developed under SBIR Phase I and II contracts was delivered to Glenn Research Center for testing.³⁸ The device is based on tunable diode laser spectroscopy and capable of monitoring, in real-time, concentrations of carbon monoxide, carbon dioxide, hydrogen cyanide, and hydrogen chloride with a 1-second response time. Unfortunately, issues with one of the components has delayed testing of the unit. It is anticipated that testing will resume in mid-2016.

The development of next-generation target gas monitors such as the next combustion products monitor (CPM), real-time formaldehyde monitor, and MGM appears to be centering on a route that utilizes laser-based spectroscopy. Primary drivers for this can be attributed to known characteristics of optical systems such as long calibration life, little to no consumables, and the ability to survive vacuum. In addition, there is a great deal of flexibility in the design of optical systems, providing an opportunity to consolidate the ability to monitor many target gases in a

single device, e.g., the Tricorder. In addition, adopting a strategy to develop hardware to meet the needs of several programs will help defray the certification and build costs. Certification costs can be quite significant for hardware like the CPM because of the requirements imposed by its criticality. Using the same basic, core technology, and laser-based spectroscopy can be easily adapted to meet the needs of differing manned vehicles, despite having considerably differing concepts of operations. For ISS the configuration of next-gen target gas monitors should have minimal impacts to well-developed and mature procedures and responses³⁹. For the Orion vehicles procedures and responses are different and the configuration of the target-gas monitors will reflect that difference.

3. *Carbon monoxide and carbon dioxide monitoring*

As part of risk reduction for future space suit, JPL is developing a compact CO₂ sensor that fit into the Portable Life Support System (PLSS). A prototype of this instrument was delivered to JSC PLSS team that verified the instrument's functional performance under different extreme conditions. The instrument is being retrofitted to include CO sensor as well. Hence with the same form factor, one can measure CO and/or CO₂. The CO monitoring is done using JPL developed small package, low power laser. This small instrument can be used for fire and post fire clean up monitoring. Given the small size of the optical head, it is ideal for a distributed sensor monitoring of a large volume such as ISS. This instrument is currently being evaluated for use in conjunction with CO₂ removal from habitable environment.

4. *Real-Time Formaldehyde Monitor*

Under a NASA SBIR Phase I contract⁴⁰, Southwest Sciences, Inc., Santa Fe, NM, conducted an initial development assessment of an optical monitor for the continuous, real-time monitoring of formaldehyde at levels nominally found in the ISS cabin atmosphere and in the presence of potentially interfering volatile organic compounds at comparable or even at higher concentrations. Detection of formaldehyde was accomplished down to 30 parts-per-billion with good signal-to-noise, with the possibility of reaching a 10-ppb lower limit with longer integration times in the presence of other aldehydes in the ISS atmosphere. As with MGM, the optical formaldehyde monitor is based on tunable diode laser spectroscopy. With matching funds from the ISS Program, Southwest Sciences was awarded an SBIR Phase IIe contract, to develop a flight technology demonstration unit of the optical formaldehyde monitor. This technology demonstration will be in collaboration with NanoRacks LLC, Webster, TX, and NASA JSC. Anoraks will provide certification and integration of the flight formaldehyde monitor for use on-board ISS. The formaldehyde monitor will operate autonomously when activated. Sampling and analysis will occur at user-settable intervals and the data will be stored internally. Similar to the Air Quality Monitors (AQM) used to monitor VOCs in the ISS atmosphere, data will be transferred via Wi-Fi over the Joint Station LAN (JSL) to the ISS Server, where it can then be downlinked directly to JSC Toxicology servers for evaluation by JSC Toxicologists and cabin atmosphere quality SMEs. Although the monitor is meant to be stationary in a single location (most likely in the US LAB) plugged into a 120V UOP (utility outlet panel) or 120V power strip, hand-help operations running on internal batteries will be possible. Auto-switching between battery power and 120V ISS UOP power greatly simplifies the transition from a stationary unit to a hand-held unit able to measure, in real-time, formaldehyde levels if crew members become symptomatic. The flight unit will be ready for flight by the end of September 2016.

E. Water Quality – Identify and Quantify Aqueous Species

1. Organic Water Monitor (OWM)

The ISS Program started an effort to simplify the effort by which experiments and technology are processed for flight to ISS. This effort, known as Revolutionize ISS for Science and Exploration (RISE), created a more efficient process to use ISS as a test-bed to benefit science and to mature technology required for Exploration. As part of an effort to challenge the science and engineering communities, projects were solicited by the ISS Program and eventually several were chosen to “test” the RISE process, developing and certifying for flight in approximately a 12 month time period after authorization to proceed (ATP) was given. One of the projects chosen for this was the Water Monitoring System.

The Organic Water Monitor, which is an element of the water monitoring system, is a device being developed by the JPL for the AES program to expand existing gas GC/MS capabilities to address water analysis. This instrument was selected as part of the water-monitoring suite (include microbial and silica monitoring) by ISS for a fast track flight technical demonstration. It is anticipated that this suite of instruments be delivered by March 2016. The flight demonstration of the instrument onboard ISS is scheduled for the summer of 2016.

F. Microbial Monitoring – Identify and Enumerate Cabin Atmosphere, Water, and Surface Samples

The Water monitoring System, mentioned above, also include, as part of the demonstration, a COTS polymerase chain reaction (PCR) system developed by Biofire Diagnostics, Inc. Simply put, PCR is a process in which genetic material is amplified by a series of denaturation, annealing, and extension steps. Amplification of genetic material

allows for identification and quantification of microbes. This technology demonstration will validate the PCR chemistry and the performance of the COTS unit, as compared to ground controls. A second project chosen to go through the new RISE process also advances in-flight microbial monitoring, the Biomolecular Sequencer. Unlike PCR which specifically targets microbes of interest with pre-loaded primers, the Biomolecular Sequencer, built by Oxford Nanopore Technologies, sequences the DNA of all the microbes in the sample, and determines identity by comparison to massive libraries of sequenced DNA samples. Bacterial and fungal DNA can be sequenced. The device is approximately about the size of a USB thumb-drive, weighs less than 120 grams, and is powered by a USB connection. This technology demonstration is manifested on SpaceX-9 and will validate the DNA sequencing process for spaceflight.

Part of the Water Monitoring System is the Organic Water Monitor (OWM) developed by JPL. In this iteration, OWM will identify and quantify organic species in water samples using gas chromatography mated to a miniaturized thermal conductivity detector. Although the water monitoring effort was envisioned to include inorganics as well as minerals, due to limited resources it was directed to focus on organics only.

In order to effectively monitor microbial burden, sample concentration is a must since crewed vehicle's air, water, and surface are kept clean and are extremely low in biomass. The existing or any proposed microbial burden estimation system, like RAZOR, requires a sample concentration module. To this effect, under SBIR phase II funding, Innova Prep, is developing a system to concentrate a large volume of water sample (e.g., one liter). The prototype developed in phase I is promising and its feasibility to work in the microgravity conditions was investigated. This concentrator is a pencil size cylinder filled hollow fiber membrane filter. As the water passes through the concentrator, the microbes are captured within the lumen of the fiber. Following capture, the microbes are eluted using a wet foam elution process and delivered to a detection system.

G. Acoustics Monitoring – Real-Time Acoustic Monitoring

Under NASA SBIR Phase I and Phase II contracts⁴¹⁴², three capabilities were developed, tested, and validated: (1) the design of a data collection subsystem that integrates measurement microphones and the feasibility of using a MEMS microphone, (2) the development of accurate and computationally efficient signal processing algorithms for acoustic frequency (octave, 1/3-octave, and narrowband) analysis and sound level measurement, and (3) the construction of a ZigBee-based wireless sensor network for continuous noise monitoring and data communication. Although this system has a great potential to provide real-time acoustic monitoring and considerably reduce crew-time, powering the sensor network requires more development. Options currently under consideration include advanced battery systems and/or implementing operational techniques (e.g., powering off transmitters/receivers when not in use). As development continues with the wireless sensor option, The Acoustics Office has been evaluating COTS hardware as a potential stop-gap. The 3M Personal Safety Division offers the Noise Indicator which can provide visual indication of noise levels above or below 85dBA hazard limit. This is an effective way to meet the current ISS flight rule (B13-152) that requires crew be alerted of hazardous noise levels ($\geq 85\text{dBA}$). In addition to this COTS noise indicator, a combination sound level meter and acoustic dosimeter by Svantek SP. This device can be powered by USB (if needed), capable of unattended monitoring, and can record wave files for more detailed post analysis. Planning for the evaluation of the noise indicator and the combo device is currently underway with the goal of using the RISE initiative to test these systems on board ISS.

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