NASA Environmental Control and Life Support Technology Development and Maturation for Exploration: 2017 to 2018 Overview

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Over the last year, the National Aeronautics and Space Administration (NASA) has made steps towards defining a path for extending human presence beyond low Earth orbit. The environmental control and life support (ECLS) technology gap identification and prioritization has remained fairly consistent throughout the past year during which the ECLS community has continued to refine and execute the plan for advancing key technologies and capabilities that enable future exploration missions. The development teams have completed key milestones, moving toward prototypes for ground and on-orbit demonstration. Detailed planning for integrated system demonstrations on ISS has continued. Studies to refine deep space exploration requirements, design and integration considerations were performed. Of particular concern for the emerging deep space exploration architecture was consideration of long-duration intermittent dormancy. This paper provides an overview of the refined ECLS strategic planning and overall roadmap updates as well as a synopsis of key technology and maturation project tasks that occurred in 2017 and early 2018 to support the strategic needs. Plans for the remainder of 2018 and subsequent years are also described.

Nomenclature

AGA	=	Anomaly Gas Analyzer
AES	=	Advanced Exploration Systems
AR	=	atmosphere revitalization
AQM	=	Air Quality Monitor
BAA	=	broad area announcement

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BPA = brine processing assembly
BWP = biological water processor
CapiBRIC = Capillary Brine Residual In-Containment
CCSEM = Computer-controlled Scanning Electron Microscopy
CDM = carbon dioxide monitor
CFR = carbon formation reactor
CMS = Chip Monitoring System
COTS = commercial, off-the-shelf
CPM = Combustion Product Monitor
DA = Distillation Assembly
DMS = differential mobility spectrometry
ECLS = environmental control and life support
EDX = Energy-dispersive X-ray Spectroscopy
ETV = electrothermal vaporization
EVA = extravehicular activity
FCPA = Fluids Control and Pump Assembly
FGM = Formaldehyde Gas Monitor
FY = fiscal year
GCD = Game Changing Development
GC/MS = gas chromatograph/mass spectrometer
GRC = Glenn Research Center
HMC = Heat Melt Compactor
ISM = in-space manufacturing
ISS = International Space Station
IWP = Ionomer-Membrane Water Processor
JPL = Jet Propulsion Laboratory
JSC = Johnson Space Center
JSL = Joint Station LAN
LR = Logistics Reduction
LSS = life support systems
JAXA = Japan Aerospace Exploration Agency
LEO = low Earth orbit
MCA = Major Constituent Analyzer
MCTB = multi-purpose cargo transfer bag
MGM = Multi-Gas Monitor
MPAM = Multi-Platform Air Monitor
MPCV = Multi-purpose Crew Vehicle
MSFC = Marshall Space Flight Center
NASA = National Aeronautics and Space Administration
NRA = NASA research announcement
NextSTEP = Next Space Technologies for Exploration Partnerships
OGA = oxygen generation assembly
ORU = on-orbit replaceable unit
PCPA = Pressure Control and Pump Assembly
PCR = polymerase chain reaction
POM = portable oxygen monitor
PPA = plasma pyrolysis assembly
SAM = Spacecraft Atmosphere Monitor
SBIR = Small Business Innovation Research
SCOR = Spacecraft Oxygen Recovery
SOA = state-of-the-art
TDLS = tunable diode laser system
TEM = transmission electron microscope
TOC = total organic carbon
TRL = technology readiness level

UPA	=	Urine Processor Assembly
UTAS	=	United Technologies Aerospace Systems
UWMS	=	Universal Waste Management Compartment
VOC	=	volatile organic compound
WHC	=	Waste Handling Compartment
WRS	=	water recovery subsystem
C	=	Celsius
F	=	Fahrenheit
ppb	=	parts per billion
ppm	=	parts per million
psia	=	pounds per square inch absolute
kg	=	kilogram
L	=	liter
mm Hg	=	millimeters of mercury
mL	=	milliliter
MPa	=	megapascal
nm	=	nanometer
V	=	volt
μg	=	microgram
μ-g	=	microgravity
μm	=	micrometer

I. Introduction

NASA has evolved its Exploration strategy over the past year consistent with U.S. policy guidance. This Exploration strategy and campaign is depicted in Fig. 1. Beginning in low Earth orbit (LEO), NASA will continue to utilize the International Space Station (ISS) as a testbed to demonstrate key exploration technologies and augment ground-based development activities, including environmental control and life support (ECLS) systems. New commercial platforms in LEO will offer the opportunity for continued testing of ECLS systems beyond the horizon of the ISS. Missions beyond LEO will return humans to the Moon for long-term exploration and utilization, followed by human missions to Mars and other destinations. Throughout this campaign, NASA will engage with partners through nontraditional partnerships, commercial service purchases, and expanded international cooperative agreements.

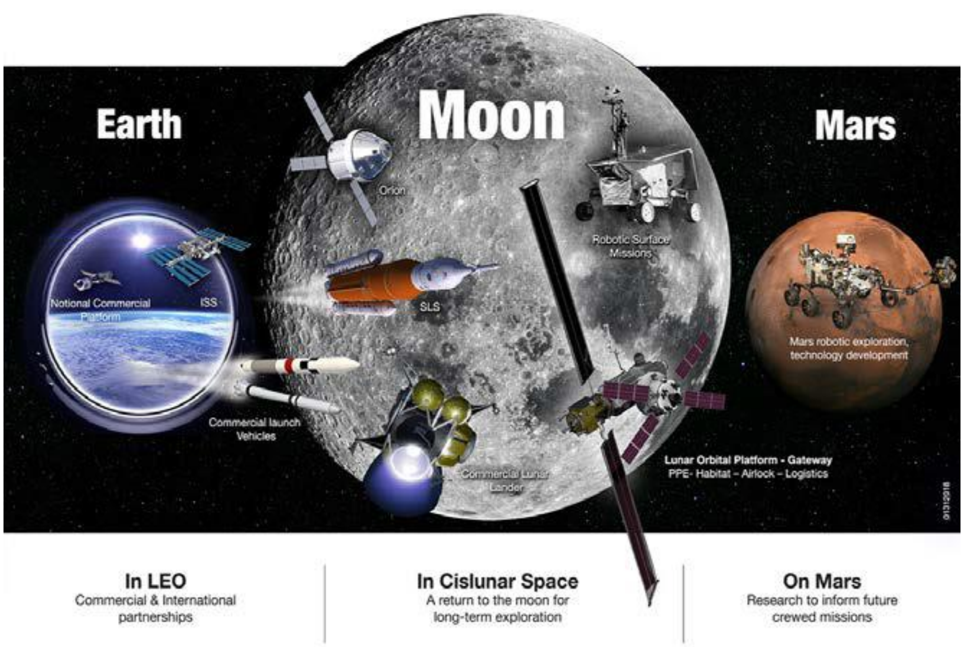

Figure 1. NASA's Exploration Campaign.

Although the revised Exploration Campaign strategy has increased focus on returning to the lunar surface before embarking on missions to Mars, the overall ECLS system capability evolution objectives remain largely unchanged; namely, to evolve the state-of-the-art (SOA) ECLS system into a more reliable, more closed-loop system for long-duration missions beyond LEO with no resupply from Earth. The overall strategy utilizing the ISS to evolve and test the Exploration ECLS system also remains unchanged; however, where these systems are ultimately deployed in the specific lunar and Mars architecture elements may be slightly different. With the potential for human lunar surface missions occurring prior to Mars transit missions, there may be specific ECLSS functional gaps that will require revision and/or acceleration, such as surface dust filtration and partial-gravity water systems.

Table 1 includes a revised summary of ECLS and environmental monitoring capability gaps by function and mission type—short duration (<90 days) microgravity, long duration microgravity (>90 days), and long duration planetary surface with at least partial gravity. Changes in these gaps over the past year are summarized here and discussed in more detail in subsequent sections. System sparing analyses have shown that designing and packaging subassemblies to allow intermediate-level (I-level) maintenance of components versus the ISS approach of on-orbit replaceable unit (ORU) level of maintenance results in significant improvements in sparing and reliability posture for the same overall system mass. Although this is important to consider for all ECLS assemblies, the greatest impact results from the ability to replace components within the current Oxygen Generation Assembly (OGA), particularly within the Hydrogen ORU that is currently enveloped by a pressure dome. Because of this, a more maintainable OGA has been added as a specific capability focus. Another highlighted change is related to disinfection and microbial control, which has evolved over the past year to include not only a proposed change to silver biocide (already being implemented by Orion) but possibly other technologies and operational techniques to maintain cleanliness of all wetted systems, and survive dormant uncrewed periods.

Figure 2 depicts a top-level summary roadmap of activities and ISS flight demonstrations addressing these capability gaps. The period covering 2017-2018 saw great progress which will be highlighted throughout this paper, including initiation of three candidate CO_2 removal flight demonstration projects, and continued progress on condensing heat exchanger technology development, urine and water processor design upgrades, water and microbial monitoring requirements development, and new Brine Processing Assembly (BPA), Universal Waste Management System (UWMS), Spacecraft Atmosphere Monitor (SAM), and particulate monitor flight demonstrations planned for flight in the next year.

A. Next Space Technologies for Exploration Partnerships

The activities under the Next Space Technologies for Exploration Partnerships (NextSTEP) Habitation Broad Agency Announcement (BAA) activities began Phase II efforts to further develop conceptual exploration habitat design studies in late calendar year 2018. These studies build upon the Phase I work which was completed at the end of government fiscal year 2015. The Phase II effort will construct exploration habitat prototypes suitable for assessing the efficacy of the Phase I concepts. As part of Phase II, a focused ECLS system development effort is being led by United Technologies Aerospace Systems (UTAS) to advance the fit and form of an evolvable exploration ECLS functional capability that was developed during Phase I.[1, 2] This effort also seeks to define functional interfaces, to develop a control architecture that incorporates machine learning features, and to incorporate design features to allow for accessibility that is necessary for in-flight maintenance and repair. The Phase II work matures the concept developed by UTAS during Phase I. The intent is for NASA to use results and products produced during Phase II as the foundation for evaluating the feasibility of a universal, evolvable ECLS system that can be used across exploration habitat platforms.[3]

B. Uncrewed Mission Phases

Long duration intermittent uncrewed operational phases present challenges to the ECLS system that have not been experienced in previous crewed spacecraft programs. The ECLS system is considered to be dormant during uncrewed phases since the primary function of life support is not required. However, the dormant ECLS system must still be capable of maintaining the vehicle environment during uncrewed phases in order to sustain remaining vehicle systems and payloads. Additionally, a habitable environment must be reclaimed prior to the return of crew, and system health must be maintained to ensure reliable operation through the next crewed phase.[4]

Technologies being developed for exploration missions must consider the long during intermittent dormant operational modes. Sufficient automation must be present to support system maintenance, vehicle contingencies such as a fire event, and fault detection, isolation, and recovery. Further evaluation and testing must be performed on both new and heritage technologies to understand the impacts of long term dormancy on these systems, and to demonstrate the effectiveness of modifications and operations employed to support intermittent dormancy.

Table 1. ECLS and environmental monitoring capability gaps.

Subsystem Functional Grouping	Function	Capability Gaps	Orion Short Duration μ-g	Long Duration μ-g	Long Duration Planetary Surface
Atmosphere Revitalization	CO_2 Removal	Improved reliability; ppCO_2 <2 mm Hg (2600 ppm) (goal)		X	X
	Trace Contaminant Control	Replace obsolete sorbents with higher capacity; siloxane removal	X	X	X
	Particulate Filtration	Surface dust prefilter			X
	Condensing Heat Exchanger	Durable, chemically-inert water condensation and collection with antimicrobial properties		X	X
	O_2 recovery from CO_2	Recover >75% O_2 from CO_2		X	X
	O_2 generation	Reduced size and complexity, more maintainable		X	X
	High pressure O_2	Replenish 24.8 MPa O_2 for EVA; provide contingency medical O_2		X	X
Water Recovery and Management	Disinfection/ Microbial Control	Disinfection techniques and technologies for microbial control of water systems, dormancy survival	X	X	X
	Wastewater processing	Increased water recovery from urine (>85%), reliability, reduced expendables		X	X
	Urine brine processing	Water recovery from urine brine >90%		X	X
Waste Management	Metabolic solid waste	Low mass, universal waste management system	X	X	X
	Non-metabolic solid waste	Volume reduction, stabilization, resource recovery		X	X
Environmental Monitoring	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 and quantification of species in water		X	X
	Microbial monitoring	Non-culture based in-flight monitor with species identification and Quantification		X	X
	Particulate monitoring	Onboard measurement of particulate hazards		X	X
	Acoustic monitoring	Onboard acoustic monitor		X	X

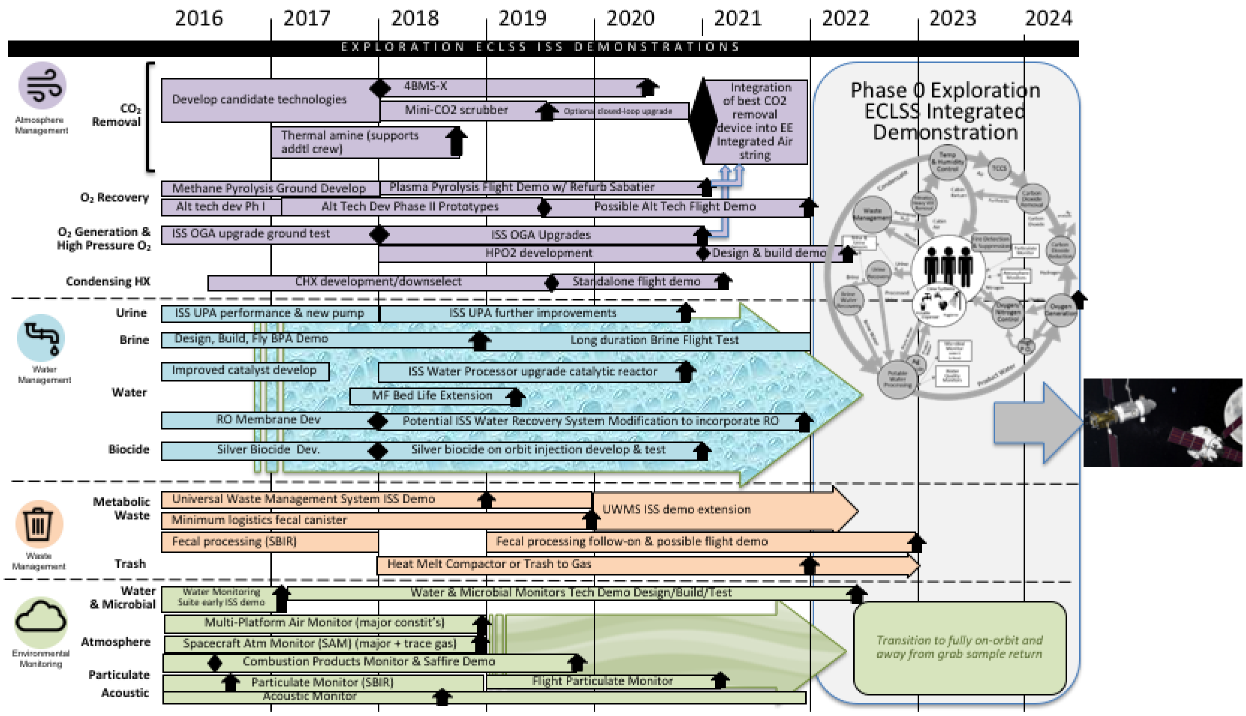

Figure 2. Exploration ECLS system technology development roadmap.

II. Atmosphere Revitalization

During the period between January 2017 and March 2018 technical tasks to advance the atmosphere revitalization (AR) functional area have continued to progress toward exploration mission performance goals. Accomplishments have been realized in the subsystem architecture, oxygen generation and recovery, carbon dioxide removal, and trace contaminant and particulate matter control technical areas. The following summarizes the work accomplished in these technical areas.

A. Subsystem Architecture

Developing the next generation AR functional architecture has centered upon implementing and refining concepts developed by NASA via the Advanced Exploration Systems (AES) Life Support Systems (LSS) Project as the apply to the NextSTEP Habitation, Deep Space Gateway/Transit, Mars Study Capability, and other relevant design analysis cycles related to future exploration mission definition and development. The NextSTEP Habitation ECLS development described earlier includes a specific activity to produce a functional AR subsystem suitable for evaluating functional interfaces with habitat platform concepts. This work is supported by efforts to develop and tailor standards for exploration missions, analyses relating to managing the ECLS system during uncrewed periods, and identifying opportunities for improving energy efficiency via exergy analysis. As well, ECLS component information sized to accommodate four crewmembers has been provided to support developing master equipment lists that are consistent with an evolvable exploration ECLS system functional architecture that supports NASA's exploration mission operational concepts.

B. Oxygen Generation and Recovery

The developmental efforts for oxygen generation and recovery produced significant results relating to Bosch, post-processing Sabatier-produced methane, low maturity technology maturation, and oxygen production and management.

1. Bosch Process Developments

The Bosch process provides the highest theoretical oxygen recovery percentage from carbon dioxide. As such, developing Bosch-based process technologies that are suitable for spaceflight is necessary for realizing the objective to recover >90% of oxygen from carbon dioxide. Significant developments for Bosch-based technologies include a successful closed loop integrated test of a NASA-developed batch carbon formation reactor (CFR) and testing a similar reactor developed by pH Matter (Columbus, OH). The CFR is a component of the series Bosch concept which employs two reactors in series rather than a single reactor. In this testing series, the carbon monoxide conversion of the NASA-developed reactor was better than the reactor developed by pH Matter. Further improvement of the series Bosch process will continue in 2018.[5]

Since trade analyses show Bosch-based processes to be better suited for surface exploration missions, taking advantage of the iron-rich Martian soil as a resource is an area of investigation. In this work, the catalyst used for the CFR stage of a series Bosch unit is regenerated via electrolytic processes. The iron-based catalyst used for CFR reactors was successfully electroplated on a substrate and subjected to multiple regeneration cycles. Areas for improvement have been identified.[6]

2. Sabatier-Produced Methane Post-Processing Developments

Extracting hydrogen from methane produced by Sabatier-based processes allows such a process to reach theoretical oxygen recovery from carbon dioxide levels that can approach that of a Bosch process. The methane plasma pyrolysis assembly (PPA) produces a hydrogen-rich product via creating a microwave-induced plasma. The hydrogen is separated and recycled to allow a higher percentage of carbon dioxide to be processed leading to a higher oxygen recovery percentage. Recent developments have focused on PPA components that provide carbon management, microwave generation, and hydrogen purification. Carbon trap concepts have been tested, including sintered metal (Hastelloy) filter and scroll filter concepts. Tuning the microwave generation source is important to obtaining optimal efficiency from the PPA process. To reach efficiency goals, a solid state microwave generator built by MKS Instruments (Andover, MA) was evaluated. Two hydrogen purification techniques were evaluated—a physical adsorption based process developed by UMPQUA Research Corp. (Myrtle Creek, OR) and an electrolytic-based process developed by Sustainable Innovations, Inc. (East Hartford, CT). The electrolytic-based process was selected for integrated testing with the PPA. Process characterization was also accomplished for the PPA to characterize the thermal load at a 4 crewmember processing rate. This testing at this rate found that ~400 W is rejected to the active cooling system. During 2018 the PPA with carbon management and hydrogen purification components will be tested while integrated to a Sabatier-based carbon dioxide reduction unit and a water electrolyzer unit.

3. Low Maturity Oxygen Recovery Technology Developments

The Spacecraft Oxygen Recovery (SCOR) initiative managed by the Game Changing Development (GCD) program within NASA's Space Technology Mission Directorate has been developing low maturity process technology candidates to recover oxygen from carbon dioxide. In August 2017, two Phase II projects were awarded. These projects are seeking to achieve technical maturity level 5 within two years. UMPQUA Research Corp. is leading the first project, titled "Continuous Bosch Reactor" to develop a Bosch-based reactor technology.[7] This effort is a continuation of the Phase I project and a preliminary design review is planned by May 2018 and a critical design review is planned for September 2018. The second project titled, "Methane Pyrolysis System for High-Yield Soot-Free Recovery of Oxygen from Carbon Dioxide", is being conducted by Honeywell Aerospace (Phoenix, AZ). This effort adapts chemical vapor deposition (CVD) techniques used in aircraft brake manufacturing to manage carbon deposition in CFRs. A preliminary design review was conducted in January 2018 and the critical design review is planned for December 2018.

4. Oxygen Production and Management

The developmental work for oxygen production and management was conducted via Small Business Innovative Research (SBIR) projects. A Phase I project was completed by Sustainable Innovations for a solid state oxygen concentrator and compressor capable of providing high pressure, high purity oxygen. A proposal was submitted to pursue Phase II development. The Phase II award announcements are planned for March 2018. A Phase II project was completed by Proton OnSite (Wallingford, CT). The latter project produced a high pressure, 12-cell electrolysis stack that was independently tested for up to 170 hours by UTAS before the unit shut down due to cell instability.

C. Carbon Dioxide Removal

The carbon dioxide removal development efforts produced significant results in understanding structured sorbents, developing flight demonstration concepts, and low maturity technology development.

1. Structured Sorbent Developments

Structured sorbent media have advantages of being structurally robust and thermally conductive compared to packed beds making them an attractive alternative. Market research on structured sorbents spanning ~100 articles and patents has led to developing a technical framework toward incorporating structured sorbent media into future carbon dioxide removal equipment. A leading structured sorbent technology is an adsorbent-coated metal foil media developed by Catacel (Ravenna, OH), a subsidiary of Johnson Matthey Process Technologies. The efficacy of the Catacel adsorbent media was evaluated and found to be suitable for direct drop-in for packed bed components. A process model, the Dynamic Adsorption Process Simulator (University of South Carolina), was validated for temperature-swing adsorption processes employing structured sorbent media. Process scale-up for the Catacel-developed media is the focus for 2018.

2. Flight Demonstration Opportunities

In 2017, a focus area on carbon dioxide removal was added to the NASA Research Announcement (NRA), Research Opportunities for International Space Station Utilization.[8] This NRA was originally released in 2012 and sponsors periodic proposal cycles. Two flight demonstration projects were selected in 2017 to demonstrate competing carbon dioxide removal technologies suitable for closed-loop ECLS applications.

The Four Bed Carbon Dioxide (4BCO2) removal concept is derived from ISS heritage process technology yet addresses lessons learned regarding sorbent characteristics, bed design, and bed heating to achieve a more robust, durable process.[9-11] The resulting design reduces the incidence of adsorbent media attrition and improved power management. Hardware design and fabrication based on thermal analysis and heater design work conducted in 2017 is in progress. A complete assembly consisting of water saving and carbon dioxide removal stages is being designed and fabricated for demonstration aboard ISS by no later than late calendar year 2020.

The preliminary design, performance, and packaging of a prototype solid amine-based process capable of thermal regeneration and that incorporates a water recovery stage was reported in 2017. During 2018 this prototype design is advancing toward a flight demonstration unit to be delivered in 2019 for demonstration aboard ISS.

3. Low Maturity Carbon Dioxide Removal Technology Developments

Carbon dioxide removal for surface exploration stages may benefit from direct liquid contacting processes. One process developed independently by Honeywell Aerospace Defense and Space (Glendale, AZ) has been of interest and warrants further consideration.[12] A second process employing direct liquid contacting is under development by NASA. During the previous year, process development and flight demonstration of flow phenomena were accomplished. The process employs an aqueous diglycol amine (DGA) solution (65% DGA/35% water) to reduce the amine oxidative loss rate from 10% in ~24 hours to ~3000 hours. Research is indicating that incorporating carbonic anhydrase into the fluid may enhance absorption kinetics for this process. Work continues in 2018 to refine and scale up the process.

D. Trace Contaminant and Particulate Matter Control

The development efforts for trace contaminant and particulate matter control produced significant results in characterizing trace contaminant removal media, particle filtration concepts, suspended particulate matter load characterization, and particulate matter monitoring.

1. Media Market Research and Characterization

Heritage adsorbent media and catalysts used aboard ISS for trace contaminant control are commercially obsolete. For this reason, suitable replacements must be identified and characterized. During the past year, a rice husk-based activated carbon developed by the Japan Aerospace Exploration Agency (JAXA) was evaluated for volatile organic compound (VOC) saturation capacity and ammonia chemisorption capacity. In addition, commercially available high velocity, low aspect ratio gas phase ion exchange media and activated carbon panels available from Camfil USA, a subsidiary of Camfil AB (Stockholm, Sweden), were evaluated for their ammonia and formaldehyde capacities. Additional ammonia and VOC adsorbent media candidates from Molecular Products (Harlow Essex, UK), Calgon Carbon Corp. (Moon Township, PA), Cabot Norit (Boston, MA), and Serionix (Champaign, IL) are under evaluation. Adsorbent characterization and final candidate selection will be accomplished during 2018. Adsorbent bed component preliminary designs and sizing are being developed during 2018 based on the early characterization data. Detailed characterization of the final candidates will be accomplished in 2019 which will allow for the adsorbent bed component refinement.

During AR subsystem integrated testing in 2014 the leading Microlith® catalytic oxidation technology invented by Precision Combustion, Inc. (North Haven, CT) unexpectedly exhibited degraded performance after inadvertent operation without process air flow through the reactor. Further degradation was observed after suspected exposure to organosilicon compounds during a subsequent testing phase.[13] Catalyst sintering and silica masking were suspected root causes for the reduced performance. During 2017 a failure mode investigation by the original equipment manufacturer was accomplished which confirmed catalyst sintering and silica masking. The unit is being refurbished in 2018.

Market research conducted during the past year on commercially available adsorbent media and acid gas scrubbing media did not identify additional candidates beyond those presently under consideration.

2. Filtration Technology Developments

Particulate filtration development has focused on the designing a scroll filter design suitable for demonstration aboard the ISS. The design is sized to fit within the volume envelope of a single ISS cabin filter element. The scroll filter concept was also tested in early calendar year 2018 during the Mars Desert Research Station (Utah) operations. Data from this practical application of the technology have been received and are under evaluation.

3. Particulate Matter Characterization

Understanding the suspended particulate matter concentration and size distribution in the cabin atmosphere is a key component, along with generation rates, to designing a cabin filtration system that meets human health specifications for suspended particulate matter. During late 2016 and early 2017, the Aerosol Sampling Experiment was accomplished aboard the ISS.[14] Samples were returned to the ground and analyzed to aid in refining the particulate matter load model. The work was conducted by NASA's Glenn Research Center (GRC) and the RJ Lee Group (Pittsburgh, PA) with collaboration with Researchers at Ohio State University and Carnegie Mellon University. A second round of work is planned as the Real-time Aerosol Characterization Experiment (RACE) via an SBIR Phase II-X contract with Aerosol Dynamics, Inc. (Berkeley, CA) and BioServe Space Technologies (Boulder, CO) to collect particulate matter and debris samples for return to the ground. A second effort called Divert Unwanted Space Trash (DUST) will return vacuum cleaner bags to the ground for particulate matter and debris studies.

4. Particulate Matter Monitoring Developments

Near real-time particulate matter monitoring will be an important capability for exploration missions. Adapting monitoring technologies to the rigors of space exploration is the focus of the Earth and Space Air Prize which is being sponsored in cooperation with the Robert Wood Johnson Foundation (Princeton, NJ). The prize was established for a 1-year development leading to a winner for a miniaturized aerosol measurement instruments. Twenty proposals were received in January 2018 with selections scheduled for March 2018.

III. Water Recovery and Management

Although an integrated ECLS system is made up of a variety of subsystems, a major driver in sizing an ECLS system is the Water Recovery Subsystem (WRS). As mission durations increase, recycling water becomes critical. Stored water is inadequate, and wastewater sources must be recycled into potable water. The SOA WRS used on the ISS relies on a high rate of consumable use (0.032 kg expendables consumed per kg of potable water produced). The urine processor experienced failures due to precipitation caused by the combination of calcium in the urine and sulfuric acid in the urine pretreatment, and the recovery rate from urine was reduced to approximately 77%. Now that a new pretreatment formulation using phosphoric acid has been introduced, water recovery can meet or exceed the original 85% design goal. Combined with the percentage of water recovered from humidity condensate, the current overall ISS water recovery rate was 85% but can now reach 93%. For exploration systems the goal established by the Human Health, Life Support, and Habitation Systems Roadmap[15] is to reach 98% water loop closure with reduced expendables.

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 SOA 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 2017-2018 NASA has invested in several water recovery areas including upgrades and improvements to ISS systems and technology development under the AES, ISS, and SBIR programs.

A. Water Recovery Architecture

Focal areas for water recovery include upgrades to SOA processes and improvements to address emerging water contaminant challenges.

1. Catalytic Reactor Upgrade

Testing of the UTAS and UMPQUA catalysts was completed and demonstrated these catalysts will increase performance of the Volatile Removal Assembly (VRA) catalytic reactor. A third catalyst developed by ELS Technologies through the NASA SBIR program was delivered in May 2017 for testing at Marshall Space Flight Center (MSFC). Upon evaluation of the data the UTAS catalyst was chosen to be incorporated into the catalytic reactor upgrade.

2. Multifiltration Bed Upgrade

The ISS multifiltration beds are a disposable component of the system, and NASA is interested in ways of reducing the logistics resupply requirements for missions. One of the options is to include a membrane system either upstream of or in replacement of the existing beds. There are concerns that membrane processes will be less efficient in micro-gravity. To address these risks, Aquaporin membranes were flown as a flight payload experiment and showed promise as a viable microgravity technology. This technology may also help with the reducing the concentration of dimethylsilanediol fed to the Catalytic Reactor. Testing was completed in March 2017.

Results of the Aquaporin testing demonstrated that there was a significant amount of brine produced in the process to achieve the water recovery required. Because of the amount of brine produced, this technology is not a viable replacement for the multifiltration beds. Another membrane was tested as well did not trade as a viable replacement for the multifiltration beds. Therefore, further development of this technology has ceased.

3. Siloxane Removal Study

A study was initiated in fiscal year 2016 (FY16) to develop technologies to remove siloxanes that have been identified in the spacecraft atmosphere and have migrated to the water system. Technologies include ultraviolet light and filtration. These technologies were studied through FY17 but determined to not be a viable option.

B. Urine Processing

Developmental efforts in urine recovery have addressed upgrades to the SOA urine processing system, development of alternative urine processing techniques, and recovering water from the concentrated byproduct produced by urine recovery processes.

1. Urine Processor Assembly

Upgrades to the Urine Processor Assembly (UPA) have continued to progress. The Fluids Control and Pump Assembly (FCPA) SN004 installed in the UPA and has approximately 3200 hours of operation as of February 2017 with no anomalies. A Pressure Control and Pump Assembly (PCPA) with a planetary gear assembly has been delivered to the ISS. A new upgrade to the PCPA is to replace the peristaltic pump with a scroll pump as well as integrating the function of the Separator Plumbing Assembly into the PCPA. Various upgrades to the Distillation Assembly (DA) to increase reliability and performance are in work as well. These upgrades to continue through FY18 and FY19.

2. Brine Dewatering

Brine Dewatering seeks to address the goal of 98% water recovery established by Ref. 15. Ninety-eight percent 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 substance 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 FY16 Paragon was awarded a contract to develop their Ionomer-Membrane Water Processor (IWP) into a technology demonstration for flight on the ISS in 2019. Paragon has completed as Critical Design Review in early March. Manufacturing of the flight demonstration unit has started.

Development continued on the Capillary Brine Residual In-Containment (CapiBRIC) technology. A CaprBRIC test unit was developed; however, it was decided to delay testing of the unit. Testing the technology will in FY18 is under consideration.

3. 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.

Collaboration with Texas Tech University continued on the rectangular cross-flow reactor design, build, and test. Texas Tech completed the initial three year grant that included hibernation and establishing steady state operations after hibernation; reactor performance for waste water cases that include ISS waste water, deep space transit waste water, and surface waste water; and simultaneous nitrification and denitrification. A new grant has been awarded for continued research and developing a plan for a flight technology demonstration.

C. 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.

The goals of silver biocide technology development tasks are to identify methods for adding biocidal silver to water in-flight during both operational use and dormancy, as well as methods to maintain the concentration in stored water over long periods of time. Silver biocide offers a potential advantage over iodine, the current SOA in U.S. spacecraft disinfection technology, because 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 maintain potability. 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.

The latest testing includes evaluation of silver dosing systems, silver monitoring, and mitigation of silver deposition onto the system tubing and manifolds. A technology being tested to mitigate silver deposition is to coat the inner diameter of stainless steel tubing with Teflon. Initial results demonstrate that this method keeps the silver in solution. Testing of this technology continues.

IV. Waste Management

Several areas of waste development have made progress over the past year to improve the state of the art. The state of the art in waste management is storage for short periods in flexible soft goods bags for disposal in visiting cargo vehicles. No drying or active odor control occurs. Trash storage even for short periods of time in a spacecraft is undesirable and can result in unacceptable aesthetics (odor) or unhygienic conditions (trash escapes, gas evolution, and microbial releases). Fecal waste is collected in rigid metal containers that are stored prior to disposal. Urine is collected, pretreated and delivered for water recovery. Aboard ISS, the Permanent Multipurpose Module and unused node radial ports are used to temporarily store trash. These volumes are relatively low use habitable volumes so that odors are less noticeable by the crew. During disposal the trash must be manually moved by crew to the departing visiting vehicles through the main habitable volumes. Hence current manually stowed trash methods use valuable habitable volume and crew time as well as contribute to odor and trace contaminant loads. NASA has begun to develop improved metabolic waste collection, trash stowage, and processing technologies. The goal is to test several of these technologies on ISS so that they are ready to support Phase 1 and 2 exploration missions.

A. Waste Reduction

Reducing or avoiding waste production is the most effective form of waste management. The AES Logistics Reduction (LR) Project is developing and collaborating on several technologies that reduce logistics and that translates into a reduction in the amount of trash that needs to be collected, stored, or processed.

The AES LR Project developed a cargo bag that can be disassembled without tools and used for habitat outfitting. This prevents the cargo bag from becoming trash and avoids flying separate outfitting items. Four multi-purpose cargo transfer bags (MCTB) tailored to be acoustic absorbers, were deployed aboard ISS in September 2016. The MCTBs reduce the sound energy from the crew treadmill in Node 3 by ~37%. The MCTB experiment is next to the ISS Waste Handling Compartment (WHC) cabin and combined with the treadmill exercise this is a high moisture and potential soiling environment. The MCTBs are periodically sampled for microbial surface monitoring and aesthetic assessments are performed. Results from this ISS experiment will inform exploration missions on the acceptability of treated fabrics in high soiling environments and the practical application of cargo bags designed for disassembly as part of a near zero waste cargo solutions. As of the time of this paper, there has been an increase in microbial counts on the surface of the MCTBs. However, the microbial levels are still acceptable for continued use.

The AES LR project has collaborated with the AES In-Space Manufacturing (ISM) project in a novel waste avoidance strategy. As part of metabolic waste collection, a funnel used for urine collection is replaced with a new funnel approximately every 30 days. The possibility of recycling used funnels to produce feedstock to then additively manufacture new funnels was being investigated by ISM's SBIR-developed technology of additive manufacturing (Made-In-Space[16]) because it within the manufacturing volume's dimensions. Another ISM SBIR (Tethers Unlimited[17]) conducted a systematic approach to varying the process parameters (temperature, layer height, speed, material) to determine the effect on funnel transparency, surface finish, and cleanability. The initial results were promising but additional development will be required.

B. Trash Management

NASA has continued development, at low level, of Heat Melt Compactor (HMC) technology for processing of non-hazardous trash. The HMC provides a 7:1 reduction in trash volume via compression and application of heat to produce microbially stable, dry trash tiles. This increases habitable volume and improves long term vehicle hygiene. The trash plastic content softens during heating to hold the non-plastic trash in a compressed state when it cools. HMC tiles can be the final disposal form, used as part of a solar storm radiation shelter[18], or a compact form for jettison. Prior versions of HMC cleaned process air and returned it to the cabin atmosphere. However the process air stream can contain over 80 compounds and removal significantly complicates the design. Currently, the HMC ground unit is being simplified to an initial configuration for an ISS technology demonstration of the compaction and heating portions. The process air would be dried and then the gases vented to space using the ISS vacuum system.[19, 20] NASA is preparing to do testing in FY18 to define required processing conditions of the venting configuration to determine if it is possible to recover the majority of the water while allowing the majority of contaminants to be vented. HMC work is augmented by a phase II SBIR (Materials Modification, Inc.[21]) with the development of a gas permeable antimicrobial bag. The bag could be used in the HMC to prevent processing chamber fouling and provide more hygienic tiles for storage/deployment. Both the internal NASA testing and the SBIR results will inform future HMC development and acquisition decisions over the next year.

Depending on the duration, type (transit mission, or Lagrange point), and mission requirements different trash disposal architectures may be beneficial. Trash can be simply stored if the odors/gases/microbial aspect are controlled; but this ties up habitable volume. Trash can be processed in a HMC to increase habitable volume and provide dense material for radiation shielding. Both untreated trash storage and HMC do not change the vehicle mass. Trash can also be jettisoned during a mission to reduce vehicle mass, increase habitable volume, and reduce propulsion requirements—but then it is not available for radiation shielding. Trash can be jettisoned as untreated trash bags, HMC tiles, or gasified (Trash-to-Gas) and vented. The AES LR Project, NASA Langley Research Center's Space Analysis Branch, and the AES Radiation Sensors project performed a joint trade study to determine the combined benefits of the range of proposed trash management solutions for a deep space gateway and Mars transit mission.[22, 23] The analysis indicated that Trash-to-Gas is the minimal mass solution and residual/contingency logistics can still marginally provide the minimal shielding. However Trash-to-Gas technology assumptions are based on very low level technology assumptions. The NASA Space Technology Mission Directorate is funding an Early Career Initiative project (Orbital Syngas Commodity Augmentation Reactor) to investigate the kinetics of trash combustion using a series of 5-second duration drop tower tests at NASA GRC in early 2019 and a suborbital flight with Blue Origin in late 2019. These tests will help improve reactor sizing and performance predictions and may lead to a longer experiment aboard the ISS.

C. Human Metabolic Waste Management

Feces and urine are collected, treated, and stored separately and differently than regular trash aboard the ISS. Both are biologically active materials and compounds within them readily break down from microbial activity and release undesirable gases and odors. For the majority of a deep space mission the crew is in a shirt sleeve environment and a microgravity compatible toilet is used to collect metabolic waste. Feces and urine are collected separately using airflow for capture and transport. Providing adequate airflow and accommodating crew interfaces that enable accurate alignment and comfort are essential for effective capture. Ineffective capture results in urine and fecal material inadvertently escaping requiring increased crew time for cleanup and a gradual deterioration of hygiene in the toilet area.

The AES LR Project in collaboration with the ISS and Multi-Purpose Crew Vehicle (MPCV) programs have been developing a new compact toilet for exploration missions called the Universal Waste Management System (UWMS). The UWMS achieves its compact size via a dual fan/rotary separator[24] and integrated concentric odor bacteria filter. UWMS development also includes a precision urine pretreat pump, high accuracy pretreat quality sensor, and improved crew urine funnel and seat geometries. The UWMS was designed for MPCV's compact crew cabin volume and with low logistics and maintenance requirements for deep space long duration habitats. The UWMS will be demonstrated aboard the ISS over two 30-day periods separated by a 90-day quiescent period as a risk reduction for MPCV Exploration Mission 2 (EM-2) flight. After the initial ISS demonstration, the UWMS will begin a three year test period to meet the needs of planned ISS increase crew size and establish long term component reliability experience. The existing ISS Waste and Hygiene Compartment will be replaced with new UWMS integration hardware to allow both ISS U.S. Segment toilets (the UWMS and the existing Waste and Hygiene Compartment toilet) to be used simultaneously and still meet the UPA inflow requirements. The integration hardware consists of a dual stall structure that mounts to the front of the existing toilet rack and adjacent vehicle surfaces to provide two separate private areas for the toilets. Additionally power, data, and fluid adapters are being developed to support integration. The Boeing

Company is designing an automated Urine Transfer System to sense when the two toilets are operating and direct fluid to the single Urine Processor Tank, or a separate tank if both systems are operating simultaneously or the Urine Processor is not accepting urine.

The core UWMS technology is being developed by UTAS and the design has progressed through the critical design and safety reviews. Significant design challenges have included achieving high accuracy pretreat dosing, mixing, and measurement; accommodating peak urination rates of 50 ml/sec, maintaining minimum free gas inclusion in output pretreated urine, and acoustics. Requirement changes from the ISS and MPCV programs are resulting in some design modifications and will require a delta critical design review in April 2018. The hardware will be delivered to ISS in April 201. Nearly concurrently, a second UWMS will delivered to begin integration into MPCV EM-2 vehicle. Early lessons learned on the ISS may result in modest modifications (in particular final crew interfaces or consumable modifications) to the UWMS unit for EM-2 or subsequent MPCV missions.

The MPCV vehicle has to plan for a contingency where the vehicle pressure shell sustains a leak and is unable to maintain a shirt sleeve ambient environment. In such a scenario, the crew would enter their launch and entry space suits until the vehicle can return to earth. The crew may have to be inside their suit for up to 144 hours. The crew will continue to consume food and water to maintain health and consequently will need to urinate and defecate while inside their suit. Skin exposed to urine and feces for more than a few hours begins to degrade skin integrity and can rapidly develop local infections that lead to potentially life threating infections. The Launch and Entry Suit project team is using a combination of in house investigation of modified standard adult diapers and an automatic active urine and waste collecting garment being developed by Omni Measurement Systems, Inc. via an SBIR Phase II award.[25] The Omni device is derived from a gravity dependent system used in military aircraft and consists of deformable collection device, membrane, and pump. The combination of features enables very low residual urine next to the skin after urination and has been tested successfully for over 72 hours of wear. The launch and entry suit team will be testing various concepts prior to determining the technology and hardware throughout 2018.

In addition to planning for UWMS and vehicle contingencies in metabolic waste collection, NASA is also looking at recovering water from feces and providing long term stabilization of deep space and planetary missions. Advanced Fuel Research, Inc, is researching torrefaction of feces under an SBIR Phase II award. Torrefaction would recover water and microbially sterilize the feces, while minimizing hydrocarbon gas production.[26] Approximately 35 kg of water per crew-year can be recovered from feces. For long term missions this water may be significant enough to warrant processing to improve the overall water recovery efficiency. The technology is being developed around use of the UWMS fecal canister so that the waste would not need to be removed from the canister for processing. The inert residual would may be beneficial in supporting Mars planetary protection goals.

V. Environmental Monitoring

Environmental monitoring focuses on four elements of the environment in habitable volumes of manned vehicles that have direct impacts on the health and performance of the crew: air quality, water quality, microbial presence, and the acoustic surroundings.

Cabin air quality involves monitoring trace VOCs, airborne particles, major constituents, and target gases. Impacting cabin air quality are trace VOCs generated from material offgassing, human metabolic processes, chronic leaks from systems and/or payloads, as well as visiting vehicles.

Major constituents include oxygen, nitrogen, carbon dioxide, water vapor, hydrogen, methane, and argon. Monitoring trace VOCs require a broader dynamic mass with high sensitivity due to the wide variety of VOCs observed, typically in the sub-parts per million concentration range. Major constituents monitoring requires a relatively narrow dynamic mass range but a broad concentration range from a few parts per million to percentages.

Target gases are a subgroup of VOCs that typically require portability to be able to measure in different locations within the manned vehicle. Pockets of higher-than-normal concentrations of a target gas can form due to the lack of convection in microgravity coupled with non-ideal air circulation. This situation arises during maintenance behind a rack or when circulation is disrupted due to temporary stowage of hardware and/or supplies in open areas.

Water quality involves the determination of water potability and simultaneously serves as a useful monitor of the system health of water processing hardware. This capability involves the ability to identify and quantify aqueous species which is currently performed on the ground with return samples: an impractical solution for long duration, Exploration-class missions. Aqueous species in the water come from several sources including any wetted material associated with the water processing system as well as water-soluble VOCs in the cabin air. Pertinent to water monitoring is the monitoring of biocide levels to ensure appropriate levels are maintained for the health of the crew.

Microbial monitoring identifies and quantifies the microbial presence aboard manned vehicles. Similar to water quality, effort focuses on addressing the lack of return samples and ground analysis. Consequently, work focuses on technology that can identify microbial presence and potentially quantify as well.

Real-time acoustic monitoring ensures the noise levels in the cabin are below the limits set forth by the NASA Acoustics Office. The resulting acoustic environment in an enclosed volume arises from the sum of all the noise sources. As such the acoustic levels will vary according to what is operating. As the cabin environment approaches the acoustic limits for long-term auditory health, crossing that limit can be difficult to discern. Crew may be exposed to greater acoustic levels than perceived for a significant amount of time without any indication. This can impact not only long-term auditory health, but it may also impact communication as well.

A. Environmental Monitoring Gaps and Needs

Several elements make up environmental monitoring, with each element having different hardware needs.[27] Despite the different technologies required to ensure environmental health, all must address identified the physical limitations imposed by mission constraints and vehicles demands. 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 NASA's recent activities to address the gaps and needs.

In additional to addressing hardware gaps, ongoing assessments of environmental requirements for Exploration-class mission profiles are required. Similar to hardware, the required monitoring data will be affected by mission constraints and vehicle demands. The ECLSS-TOX List of Target Volatile Compounds for Real-time Monitoring in the cabin atmosphere provides guidance as to which VOCs need to be monitored and at what concentration range. This list are VOCs of concern to the health of the human system and to the health of vehicle systems. The list is to provide guidance based on current knowledge and past experiences. As such, the analytical target list should not be considered "all or nothing", and a particular instruments' inability to monitor a few compounds should be evaluated in the broader context of other system considerations (e.g. reliability, cost, and mass). Technology downselection decisions must consider these important factors at an early stage, even if cost and mass allocations are not yet firm.

Ongoing assessment of water monitoring requirements continues. Water quality parameters still of great interest are conductivity, microbial identification and enumeration, pH, total organic carbon (TOC), and select inorganic and organic species. Although modifications to accommodate mission and vehicle constraints are required, technology for in-flight conductivity, TOC, and pH measurements, and microbial enumeration are at a relatively high technical maturity in terms of available ground technology. Currently technology associated with the in-flight identification and quantification of inorganic and organic species are still considered to be at a low or low/medium technical maturity. Recent discussion has focused on a notional water system architecture and how monitoring fits within such architecture, and a draft list of organics and inorganics to be monitored is in development.

B. Air Quality – Major Constituents

United Technologies Aerospace Systems, through Boeing, is developing an approach to produce a qualified air monitor for oxygen, carbon dioxide, nitrogen, humidity, hydrogen, and methane. This unit is named the Multi-Platform Air Monitor (MPAM) and would be used for the Orion spacecraft and also serve as an upgrade to the ISS Major Constituent Analyzer (MCA).[28] Work continues on the MPAM. A critical design review (CDR) was completed in July 2017 with a delta CDR scheduled in February 2018. The Phase 0/I/II Safety Review was scheduled for March 2018.

C. Air Quality – Major Constituents and Trace VOC Monitoring

The Spacecraft Atmosphere Monitor (SAM) is a technology demonstration development sponsored by the AES LSS Project. This effort, led by the Jet Propulsion Laboratory (JPL) in partnership with Johnson Space Center (JSC) and MSFC, aims at developing an instrument that responds to major shortfalls of the current instruments (such as reliance on return sample and ground analysis, requiring too much crew time, constraints on size, mass, and power, lack of portability, insufficient calibration life, limited capability to measure unknowns which may be present in future exploration vehicles, operations after period of dormancy). To accomplish this goal, we intend to reduce the size of all the subsystems including the mass spectrometer. However, significant effort has been devoted to a major size and power reduction of an autonomous flight gas chromatograph/mass spectrometer (GC/MS), without loss of analytical capability.[29] In order to demonstrate longevity of this instrument, the only component that is microgravity dependent, the ion pump, has been replaced. Instead of a commercial-off-the-shelf (COTS) design, it now is a flight proven ion pump from UTAS.

The system design review was conducted in April 2016. The first development model (DM) that is similar in form and function to the flight unit was demonstrated on April 2017. The second DM is anticipated to be completed and delivered to MSFC for testing in ECLS testing chambers in April 2018. Due to ion pump change, the delivery has been delayed by a few months. Currently, it is anticipated that the flight demonstration unit will be delivered by January 2019 and manifested on SpaceX-18 scheduled for April 2019. Subsequent to the system design review a panel of experts was created to develop the instrument verification and validation testing plan. Test readiness review is scheduled for September 2018.

D. Air Quality – Airborne Particulate Matter

As part of the AES LSS effort, the experiment, known as Aerosol Samplers, was launched in September 2016 to collect data on the quantity and size distribution of particles in the ISS ambient cabin atmosphere.[30] Of concern to human health are smaller particles, particularly in the inhalable size range. Particles were 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 COTS thermophoretic sampler (TPS100) developed by researchers at RJ Lee Group and Colorado State University. It uses thermophoretic force on particles passing through a large thermal gradient, driving them to a cold surface where a transmission electron microscope (TEM) grid is placed. The Passive Aerosol Sampler is a one-piece device containing multiple substrates with sticky carbon tape for particle collection. Passive Samplers were mounted by crew with Velcro at various ISS locations and substrates were exposed for different durations. The goal was to obtain at least one sample with optimal particle coverage for microscopy. Analysis of these samples will provide long-term average particle number concentrations, particle morphology and chemical composition. Computer-controlled scanning electron microscopy (CCSEM) will provide particle size distributions and energy-dispersive X-ray spectroscopy (EDX) will provide chemical information. Particle morphology will help identify particle emission sources. The samples returned on SpaceX-10 in March 2017. Preliminary results of the samples indicates the presence of a wide variety of particles in the ISS atmosphere.[31] Of the seven locations with Passive Samplers, the highest concentrations of particles were in Node 3 (where crew exercise and hygiene take place), followed by Node 1 (where the crew eats). The lowest concentration of particles was in the Permanent Multipurpose Module (PMM), which, at the time of sampling, was used only for storage with relatively little human traffic. Analysis of all samples revealed a large proportion of complex, multicomponent particles which exhibit the unique morphology of a carbon matrix with metal particles embedded within. Over twenty-seven different metals were identified with EDX, mostly combined with carbon, and the average diameter of these embedded metal particles ranged from 4.2 micrometers to 7.3 micrometers.

As part of an SBIR Phase II project, Aerosol Dynamics Inc. (Berkeley, CA) developed an aerosol monitoring instrument suitable for low gravity use based on a tippable, self-sustaining, water-based condensation particle counter. This instrument is capable of measuring particles as small as 10 nm. The instrument, called MAGIC, for moderated aerosol growth with internal water cycling, can be shaken, rotated or operated in any orientation making it suitable for microgravity applications unlike other COTS condensation particle counters.[32] This instrument has no toxic or hazardous fluids, no fluid reservoirs, and is potentially hand-held. Calibration tests with monodisperse particles in upright, inverted and sideways orientations showed that particle detection above 6 nm is comparable to the 5-nm cutpoint of commercial instruments, and is independent of orientation. Further evaluation of diffusion screens suggests information is possible on particle size distribution between 5 nm and 100 nm. Combining this instrument with a commercial optical particle counter to provide sizing for larger particles would provide particle number concentration and approximate sizing for particles from 10 nm to above 20 μm. The capability of MAGIC has generated a high level of interest for a technology demonstration and negotiations are currently underway for a Phase II-X project in which the hardware will be further developed into flight units for a flight experiment on ISS. With the resulting technology readiness level (TRL), it will be a strong candidate for a long-term particulate monitor for extended missions.

E. Air Quality – Monitoring Target Gases

Developments in targeted gas monitoring have been focused on target compounds associated with emergency conditions. Such conditions include hazardous gas accumulation and combustion products.

1. Combustion Product Monitor

Driven by Orion's stringent mass and volume constraints, the development of the next-generation combustion products monitor, the Anomaly Gas Analyzer (AGA), started shortly after the completion of a Combustion Product Monitor (CPM) downselection activity in November 2016. The AGA will be developed jointly by the ISS and Orion Programs. The AGA is a based on a combination of tunable diode-laser spectroscopy (TDLS) using an integrating sphere as a multi-pass optical cell and a photo-acoustic spectroscopy (PAS). TDLS is a relatively mature technology, used in operational flight hardware such as the Portable Oxygen Monitor (POM) and in the successfully demonstrated Multi-Gas Monitor (MGM).[33] Photo-acoustic spectroscopy, on the other hand, is of relatively lower TRL. Whereas TDLS relies on a change in the intensity of incident light of a certain wavelength caused by the absorption of that light by the target species within a defined pathlength, PAS relies on the measurement of pressure fluctuations generated in a medium (humidified air) by the absorption of light of a certain wavelength absorbed by the target species. Pressure fluctuations are usually measured with high-sensitivity, low-power microphones in a vibrationally and thermally isolated cell. The integrating sphere will measure CO_2 (carbon dioxide), O_2 (oxygen), HCl (hydrochloric acid), HF (hydrofluoric acid), and NH_3 (ammonia), whereas the photo-acoustic cell will measure HCN (hydrogen cyanide), CO (carbon monoxide), and N_2H_4 (hydrazine). In addition to these target gases, the AGA will also provide temperature, concentration of water vapor, and total pressure. Using a combination of integrating sphere and photo-acoustic cell allows for a single unit to measure all the target gases.

The AGA will serve as the combustion products monitor, ammonia/hydrazine monitor, and portable carbon dioxide and oxygen monitor for ISS and Orion vehicles. For ISS the AGA will replace the CSA-CP (Compound Specific Analyzer-Combustion Products), the Draeger-based Ammonia Monitor Kit (comprised of ammonia Draeger tubes and the Draeger Chip Measurement System (CMS), and the Carbon Dioxide Monitors (CDMs). The POMs will remain operational aboard ISS for EVA prebreathe activity and for spot checks in areas when oxygen concentration may have decreased due to poor circulation. Maintaining POM will help minimize cost and schedule impacts to its delivery by simplifying testing and certification of the oxygen measuring capability of AGA For the Orion vehicle, ammonia and hydrazine are required for off-nominal post-landing operations in which post-landing ventilation is needed and/or reentry occurs with a depressurized vehicle. In either off-nominal situation, a risk exists of either leaked hydrazine or ammonia entering the cabin prior to hatch opening. The AGA will provide crew a means to measure the cabin atmosphere to determine whether further crew action is required. The AGA Phase 0 Safety Review was completed in June 2017, followed by a System Requirements Review (SRR) in September 2017.

The AGA will have two operational modes: (1) On-orbit Mode, and (2) Post-landing Mode. In Post-landing mode, the AGA will display the concentrations of CO_2, NH_3, N_2H_4, and water vapor, temperature, and pressure. In On-orbit Mode, the AGA will display the concentrations of CO, HCl, HF, HCN, CO_2, O_2, NH_3, water vapor, temperature, and pressure. The required measurement ranges and accuracies for each mode are listed in Tables 2 and 3.

Table 2. AGA measurement range and accuracies in the On-orbit Mode.

Parameter	Measurement Range	Accuracy
Pressure	9.5 – 15.5 psia	± 0.1 psia at ≥9.5 psia
Water Vapor	1.9 - 15 mm Hg	± 0.1 mm Hg at ≥1.9 mm Hg
Temperature	36 - 121 °F	± 0.1 °F at ≥36 °F
CO	5 - 1000 ppm[2]	± 10% at ≥55 ppm[1] ± 5 ppm at <55 ppm
HCN	2 - 50 ppm	± 25% at ≥5 ppm[2] ± 1 ppm at <5 ppm
HF	2 - 50 ppm	± 25% at ≥5 ppm[2] ± 1 ppm at <5 ppm
HCl	2 - 50 ppm	± 25% at ≥5 ppm[2] ± 1 ppm at <5 ppm
CO_2	0.3 - 21 mm Hg (395 - 27600 ppm @ 760)	± 10% ≥ 0.8 mm Hg (1053 ppm) ± 0.2 mm Hg < 0.8 mm Hg
O_2	14 - 50%	± 1% (absolute) at ≤26% ± 2% (absolute) at >26%
NH_3	10 - 30,000 ppm	± 25% at >150 ppm ± 10% at 20 - 150 ppm ± 20% at < 20 ppm

Table 3. AGA measurement range and accuracies in the Post-landing Mode.

Parameter	Measurement Range	Accuracy
Pressure	9.5 – 15.5 psia	±0.1 psia at ≥9.5 psia
Water Vapor	1.9 - 15 mm Hg	±0.1 mm Hg at ≥1.9 mm Hg
Temperature	36 - 121 °F	± 0.1 °F at ≥36 °F
CO_2	0.3 - 21 mm Hg (395 - 27600 ppm @ 760)	±10% at ≥0.8 mm Hg (1053 ppm) ±0.2 mm Hg at <0.8 mm Hg
NH_3	10 - 30,000 ppm	±25% at >150 ppm ±10% at 20 - 150 ppm ±20% at <20 ppm
N_2H_4	2 - 10 ppm	±2 ppm

In addition to the hardware development, the AGA concept of operations (ConOps) for Orion is being refined. Since AGA will be replacing several, individual devices aboard ISS—the Compound Specific Analyzer-Combustion Products (CSA-CP), Ammonia Monitoring Kit (AMK), and CDMs—two of which address emergencies situations aboard ISS (CSA-CPs and the AMKs), the impacts of AGA to the ISS emergency response strategy is also being reviewed. Also in consideration are the safety aspects of relying on a single device to address multiple emergency scenario, and what needs to be done to ensure that the performance of the hardware is sufficient to use in another emergency scenario after it was used in a prior emergency scenario. Bounding the impacts on the hardware of each emergency scenario will help assess the possible limitations of one device used in multiple emergency situations.

2. Real-Time Formaldehyde Monitor

The development of a flight technology demonstration unit of the Southwest Sciences optical Formaldehyde Gas Monitor (FGM) continued through 2017.[34] Similar to AGA, the FGM is based on tunable diode laser spectroscopy, using a multi-pass optical cell for formaldehyde measurements. This technology demonstration is a collaborative effort with NanoRacks LLC (Webster, TX). NanoRacks will provide certification and integration of the FGM for use aboard ISS. In addition, NanoRacks will also provide an updated enclosure with enhanced cooling for the Southwest Sciences-designed formaldehyde monitor, and Wi-Fi capability to connect to the ISS server via the Joint Station Local Area Network (JSL). Once the data is transferred to the ISS server it can then be downlinked directly to NASA ground servers for evaluation by NASA toxicologists and cabin atmosphere quality subject matter experts. The FGM is designed to operate autonomously when activated, measuring ISS formaldehyde levels at user-settable intervals, storing the time and date-stamped data internally, and periodically transferring the data to the ISS server. Although the monitor primarily will be stationary in the ISS U.S. Segment (most likely in the U.S. Lab) connected to a 120-V utility outlet panel or 120-V power strip, hand-held operation is possible using internal batteries for spot checks throughout the ISS U.S. Segment. Auto-switching between battery power and 120-V ISS utility outlet 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.

Testing of the engineering development unit delivered by Southwest Sciences, has shown a lower detection limit of approximately 8 ppb, with a sampling time of 30 seconds, with the ability to measure ≥500 ppb. Formaldehyde is a persistent VOC aboard ISS with a long-term spacecraft maximum allowable concentration (SMAC) of 100 ppb. Currently used passive badges that require return and ground analysis are deployed once every 45 days. The FGM will allow levels to be measured nominally four times per day or continuously for spot checks or off-nominal situations.

F. Water Quality

Developments in water quality monitoring have focused on the analysis of aqueous organic species. However, other parameters indicative of water quality are still of great interest. These include conductivity, microbial identification and enumeration, pH, total organic carbon (TOC), and select inorganic species. Despite the fact that ground-based technology to determine these parameters is quite mature, adapting the ground-based solution to meet the constraints of an Exploration-class mission and vehicle will require considerable attention.

1. Microfluidic-Based Chemical Laptop

JPL, under sponsorship of the NASA Science Mission Directorate as well internal JPL funds, is developing a microfluidic-based chemical laptop that is targeted for signs of life detection on planetary surfaces. This approached has demonstrated that it can detect and quantify ions, inorganic compounds, microbial elements in addition to conductivity and pH. In order to identify and quantify the organic compounds, JPL intends to connect this chemical laptop to a mass spectrometer such as the SAM. Modification and tailoring of the chemical laptop to meet the human exploration requirements will start in FY19.

2. Electrothermal Vaporization of Water Samples

The electrothermal vaporization of water samples provides the ability to volatilize water samples in the liquid phase into the gas phase. Once in the gas phase the water sample can then be analyzed for chemical species in the same manner as any other gas-phase sample such as cabin air. A cabin-air monitor, such as the Air Quality Monitor (AQM), which is a GC coupled with differential mobility spectrometry (DMS) already aboard ISS, can be used to analyze VOCs in air and water. Although work currently uses the AQM as the analyzer platform, any gas phase analyzer with the means to separate, quantify, and identify the components of a gas mixtures can use the electrothermal vaporization process for water analysis. Previous work led to development of water sampling system using simple electro-thermal vaporization (ETV) interfaced to mass spectrometer.[35] Translating the laboratory proof-of-concept version of the ETV into a self-contained, micro-gravity-compatible unit that can be attached to and controlled by the AQM was developed into a senior project by a team of engineering students at Rice University Department of Engineering. The project team developed a micro-gravity compatible sampling system that has been shown to reproducibly vaporize a water sample for analysis by an AQM. Power is delivered by a USB port on the AQM. The Rice University-designed ETV employs capillary action to draw a water sample, introduced by syringe, into the vaporization area inside a coil of kanthal wire. Introducing a current to the coil, supplied by the USB port, vaporizes the water sample. Shortly after vaporization, an AQM run is started and the vaporized sample it drawn into the preconcentrator of the AQM. The vaporized water sample is then analyzed in the same manner as a cabin air sample. Work is currently underway to refine the ConOps of the ETV and the Rice University design. In additional modifications to the existing AQM software to add the use of the ETV for water analysis as an operating mode is being examined.

G. Microbial Monitoring – Identify and Enumerate Air, Water, and Surface Samples

A COTS polymerase chain reaction (PCR) system developed by Biofire Diagnostics, Inc. known as RAZOR® recently completed on-orbit testing, expending all consumables flown with the original payload. 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 validated the PCR chemistry and the performance of the COTS unit, as compared to ground controls. The science objectives for this technology demonstration were the following: 1) determine if PCR testing works in a spaceflight environment to detect known bacterial species in potable water, and 2) determine how well the results from the in-flight PCR testing agree with the controlled experiments on the ground. All science objectives were successfully completed. The RAZOR team reported no in-flight hardware issues, but is awaiting for a software update to allow the on-orbit units to communicate with the recently delivered laptops. Additional test pouches are planned for the summer of 2018 to testing microbial loads in the water system of ISS. Other planned work includes a possible collaborative effort between the RAZOR team and JPL to test a concentrator that may be able to interface with RAZOR, and ConOps development to analyze surface, air, and food. The number of assays continues to increase as microorganisms, bacterial and fungal, are added to the targeted organism list. Assays for E. coli, salmonella, and total microbial count are completed.[36]

Also advancing in-flight microbial monitoring is the MinION Biomolecular Sequencer. The MinION Biomolecular Sequencer, built by Oxford Nanopore Technologies, sequences the DNA of all the microbes in the sample and determines identity by comparison to libraries of sequenced DNA samples. Bacterial and fungal DNA can be sequenced, although kits to analyze fungal DNA is still in development. The device is approximately the size of a USB thumb-drive, weighs less than 120 grams, and is powered by a USB connection. All nine sessions planned for the technology demonstration aboard ISS have been completed, with the results from the initial four sessions aboard ISS published in the following reference.[37] The science objective for the MinION is to validate the DNA sequencing process for spaceflight. This project has shown that the same flow cell can be reused in-flight is are stable for at least six months on orbit. No difference in data quality between the in-flight and ground runs was observed and actually found a substantial increase in the amount of data generated in microgravity versus 1-g, strongly suggesting that the sequencing process was enhanced in the microgravity of space.[38] Recently in-flight experiments successfully used the miniPCR to prepare genetic material that was then sequenced by the MinION. Samples in this experiment used actual samples from the ISS environment taken during nominal microbial sampling sessions which were returned to ground for analysis. The results from the miniPCR/MinION process compared quite well to the results of ground analysis on the same sample clearly showing, for the first time in the history of the spaceflight program.[37]

H. Acoustics Monitoring – Real-Time Acoustic Monitoring

The next-generation acoustic monitor that will serve both Orion and ISS vehicles as acoustic dosimeters and sound level meters, the Svantek 102, was recently flown to ISS (OA-8, November 12, 2017, launch).[39, 28] These units will not only reduce logistics mass requirements but also reduce crew time. The units are battery powered, using nominally stocked AA batteries, and have a two year calibration life. Three units will be maintained aboard ISS. The acoustic monitors were successfully used in the crew-worn and static-deployed sessions in January of 2018. Data has been downloaded and is currently being evaluated by NASA. A software update to the on-orbit units is being planned for March of 2018. The update will allow the crew to use the high resolution recording feature of the acoustic monitor before and after maintenance on the ISS treadmill, T2. The the recording can then be analyzed by ground personnel to determine frequency signatures that may indicate premature wear on the treadmill.[40]

VI. Conclusions

Various agency efforts have endeavored to define and refine concepts for human exploration beyond LEO. Throughout this, the ECLSS capability development efforts have remained relevant and continue to make steady progress. Additional considerations associated with architectural evolution, and intermittent dormancy are being taken into consideration in the various technology efforts.

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