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NASA Environmental Control and Life Support Technology Development and Maturation for Exploration: 2018 to 2019 Overview

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During 2018 and 2019, NASA's Environmental Control and Life Support (ECLS) technology development projects have taken vital steps toward establishing readiness for the next generation of human space exploration missions. Technology demonstration systems were delivered for evaluation aboard the International Space Station (ISS). Key reviews have been completed and planning is underway for the complex challenges of integrating the multiple technology demonstrations with upgraded ISS systems on orbit. In parallel, planning is beginning for ground testing to be conducted that strategically complements the on-orbit demonstrations. Analyses of reliability and supportability are being considered for their impact on subsystem and system design as well. Outside of the technology development projects, the Gateway program has also defined more detailed plans and schedules which aid the ECLS community in developing more detailed functional and performance requirements toward strategies for deploying an early open-loop functional capability that can evolve to provide improved capabilities or greater loop closure. As these plans mature, NASA is also considering where disruptive technologies may provide value, and determining what new gaps or new details may emerge for future missions. 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 2018 and early 2019 to support the strategic needs. Plans for the remainder of 2019 and subsequent years are also described.

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Nomenclature

AES	=	Advanced Exploration Systems
AGA	=	Anomaly Gas Analyzer
AR	=	atmosphere revitalization
AQM	=	Air Quality Monitor
BAA	=	Broad Agency Announcement
BEST	=	Biomolecular Extraction and Sequencing Technology
BWP	=	biological water processor
CASIS	=	Center for Advancement of Science in Space
CDR	=	critical design review
CMS	=	Chip Measurement System
COTS	=	commercial-off-the-shelf
CRUD	=	Collaborative Research on Undesirable Debris
CSA-CP	=	Compound Specific Analyzer-Combustion Products
DGA	=	diglycol amine
DUST	=	Divert Unwanted Space Trash
ECLS	=	environmental control and life support
EM	=	environmental monitoring
EM2	=	Exploration Mission 2
ESAP	=	Earth and Space Air Prize
ETV	=	electro-thermal vaporizer
FGM	=	formaldehyde gas monitor
FY	=	fiscal year
GRC	=	Glenn Research Center
HMC	=	Heat Melt Compactor
ISS	=	International Space Station
JPL	=	Jet Propulsion Laboratory
JSC	=	Johnson Space Center
JSL	=	Joint Station Local Area Network
LEO	=	low-Earth orbit
LSS	=	life support system
MARS	=	Mobile Aerosol Reference Sensor
MEMS	=	micro electro-mechanical systems
MFB	=	multifiltration bed
MOF	=	metal organic framework
MSFC	=	Marshall Space Flight Center
NASA	=	National Aeronautics and Space Administration
NextSTEP	=	Next Space Technologies for Exploration Partnerships
PAS	=	photo-acoustic spectroscopy
PCPA	=	Pressure Control Pump Assembly
PDR	=	preliminary design review
PPA	=	plasma pyrolysis assembly
RACE	=	Real-Time Aerosol Characterization Experiment
RFP	=	request for proposals
RWGS	=	reverse water gas shift
SAM	=	Spacecraft Atmosphere Monitor
SBIR	=	Small Business Innovative Research
SCOR	=	Spacecraft Oxygen Recovery
SNC	=	Sierra Nevada Corp.
SOA	=	state-of-the-art
STMD	=	Space Technology Mission Directorate
TCPS	=	Trash Compaction and Processing System
TDLS	=	tunable diode-laser spectroscopy
TIC	=	total inorganic carbon

TOC	=	total organic carbon
TOCA	=	total organic carbon analyzer
TSA	=	temperature swing adsorption
UPA	=	Urine Processor Assembly
UTAS	=	United Technologies Aerospace Systems
UWMS	=	Universal Waste Management System
VES	=	Vacuum Exhaust System
VOC	=	volatile organic compound
WHC	=	Waste and Hygiene Compartment
WRS	=	Water Recovery System

I. Introduction

NASA plans to advance human spaceflight through a continued presence in low-Earth orbit (LEO), human missions to cis-lunar space and the Lunar surface, and missions that continue to Mars. The Environmental Control and Life Support (ECLS) system and technology development efforts in 2018 and 2019 support each of the exploration mission elements depicted by Fig. 1. Technology investments have been selected to enable the ultimate goal of long-duration missions beyond Earth. While NASA's goals for sustainable missions may eventually include bioregenerative aspects, the initial architectures evolve from the physico-chemical systems utilized on the International Space Station (ISS) and lessons learned from many years of experience. Experience and analysis has revealed components in need of critical upgrades, and additional functions that could increase Earth independence by reducing logistics needs. Because many of the systems evolve from ISS systems, upgrades in place are possible to get system level demonstration while only replacing some components. Other demonstrations of new technologies, such as brine water processing, benefit from the high fidelity testing using real interfaces. The Gateway spacecraft does not need all of the functions required for a Mars mission. Key technologies like CO_2 removal, will be proven on ISS before use on Gateway, and Gateway development and experience will help prepare for lunar surface and Mars missions.

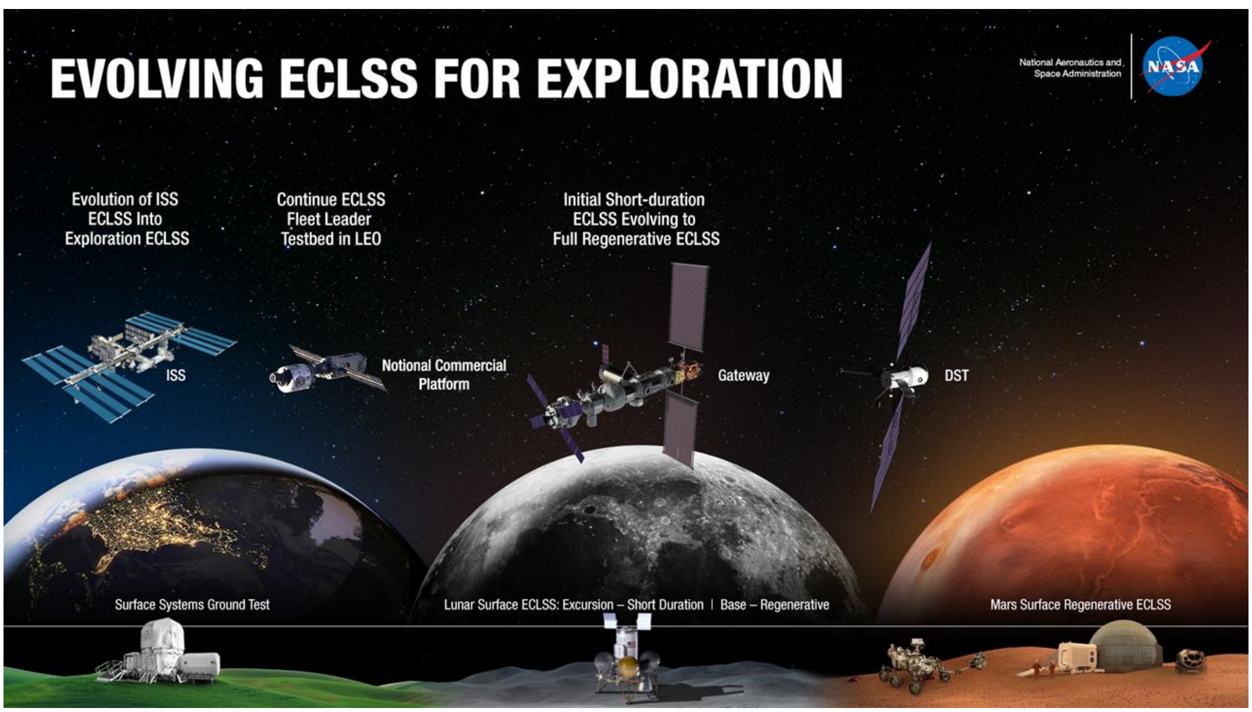

Figure 1. Exploration ECLSS strategies support multiple vehicles, with ground and microgravity development activities and demonstrations.

II. Technology Gaps and Roadmaps

Initial technology gaps were developed for ECLSS technologies based on lessons learned from ISS and architecture trade studies conducted based on estimates of technology performance. Gaps are refined over time as future missions are better understood, and as trade studies are updated with more mature technology size and performance data.

A. Technology Gaps

Table 1 includes a revised summary of ECLS and EM 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. Gateway missions are likely to require the short duration microgravity functions, but may evolve to longer duration stays and longer duration microgravity capabilities, which would also be used for Mars transit missions.

Detailed analysis of lunar surface missions has not yet occurred. Initial missions are likely to be short, with capabilities similar to the Orion short-duration missions, with additional particulate control concerns due to lunar dust and regolith. But if NASA missions go to the lunar surface to stay permanently, technologies applicable to Long Duration Planetary Surface" gaps will be applicable.

B. Roadmaps

The technology area roadmaps, for which Fig. 2 provides an illustrative example, document the forward development path for each key functional gap, including technologies in work, major decision points, and future insertions to flight systems. During 2018 and 2019, much more focus was given to deliveries of technology for use on the Gateway. Additionally, lunar surface elements are also being announced, and new technology gaps or customer needs for existing functions may appear. Thus, the individual technology roadmaps are being updated to demonstrate the intended delivery of each function.

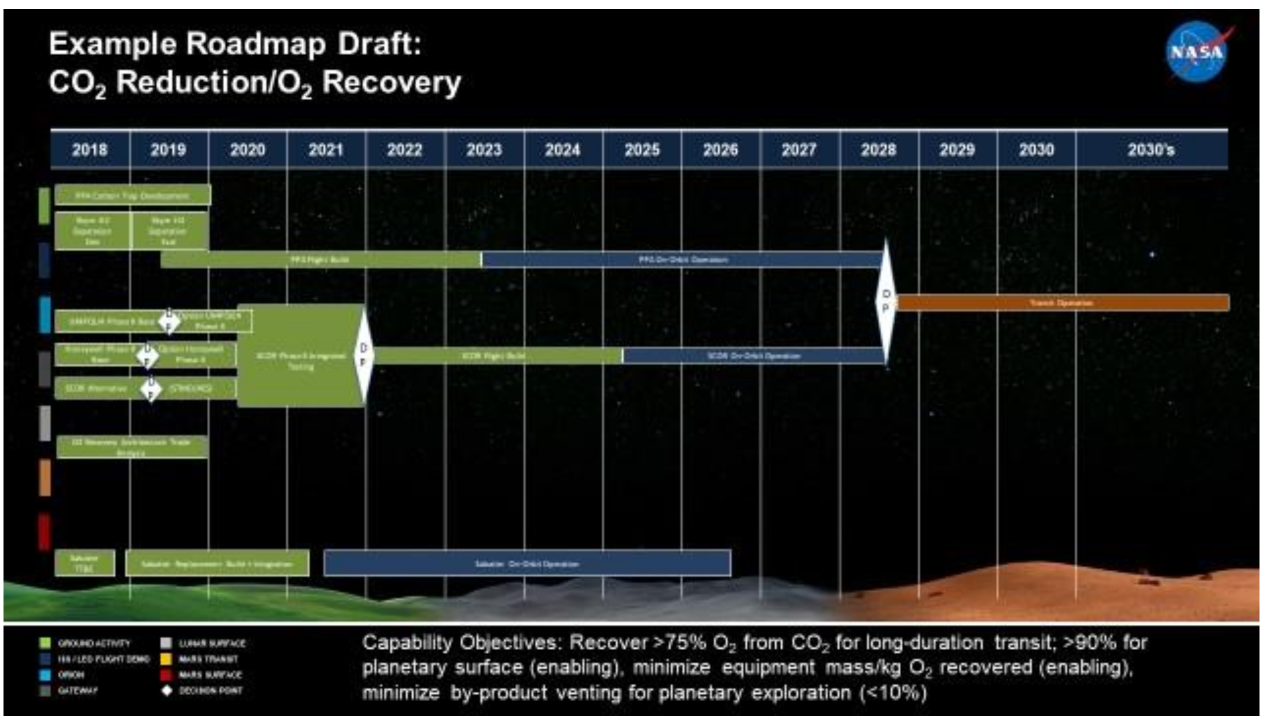

Figure 2. Example updated roadmap showing ground activities, ISS activities and intended delivery to Mars capabilities.

Table 1. ECLS and EM 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 pre-filter			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	On-board measurement of particulate hazards		X	X
	Acoustic monitoring	On-board acoustic monitor		X	X

III. Atmosphere Revitalization

During the period between January 2018 and March 2019 technical tasks to advance the atmosphere revitalization (AR) functional area have made accomplishments toward exploration mission performance goals. Significant 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 significant accomplishments in the subsystem architecture, oxygen generation and recovery, carbon dioxide removal, and trace contaminant and particulate matter control technical areas.

A. Oxygen Generation and Recovery

Work continued for the period between January 2018 and March 2019 to develop techniques and process equipment for high pressure oxygen generation and methane post-processing. Phase II SBIR work was completed, including 140 hours of operation, by ProtonOnsite (Wallingford, CT) on a high pressure water electrolysis unit. Test stand development and technical reviews were completed to conduct additional performance characterization testing at NASA's White Sands Test Facility in 2019. Planning was completed during 2018 to test and evaluate a commercially available gas purifier that employs a metal oxide sorbent to remove moisture from high pressure gas streams. This device will be tested during 2019 to determine the unit's capacity for one month of operation.

Work also continued on evaluating techniques for supplemental oxygen generation and supplying oxygen for medical uses. The primary supplemental oxygen generation technique evaluated is based on solid state ceramic oxygen compression. The technical maturity of this approach is low. During the work period a framework to produce a suitable test article was developed. Also, a thermal management method was explored with the objective to reduce the power required for solid oxide electrolysis systems. More detailed designs will be pursued during 2019. Two portable medical oxygen concentration technologies were subjected to early performance evaluation during the work period. The objective of the evaluation was to prepare for parametric tests planned for 2019 to study the synergistic performance of oxygen concentrators integrated with a ventilator under various flow rate, temperature, and ventilation conditions. A Phase II Small Business Innovative Research (SBIR) project was awarded to Skyre, Inc. to continue work on an oxygen concentrator and compressor unit. This two-year effort will be completed in 2020.

Tasks conducted to advance oxygen recovery from carbon dioxide centered on components of the methane Plasma Pyrolysis Assembly (PPA). Specific tasks involved developing a solid state microwave generator (Richardson Electronics), characterizing performance of a carbon trap, and developing a hydrogen-acetylene separator, and demonstrating integrated operations with oxygen generation and carbon dioxide reduction processes. The carbon trap is being developed by NASA's Glenn Research center and completed several rounds of testing. Electrolytic hydrogen-acetylene separation unit were developed by Skyre, Inc. (East Hartford, CT) and tested in NASA facilities. The results indicated poor performance and a new design is being pursued during fiscal year 2019. A test article was built by Umpqua Research Co. (Myrtle Creek, OR) for evaluating the characteristics of microwave-generated plasma in free fall conditions. The parabolic flight testing was completed in November 2018.

Alternative technology development toward alternatives to Sabatier-based carbon dioxide reduction continued under the Spacecraft Oxygen Recovery (SCOR) project that is sponsored by NASA's Space Technology Mission Directorate (STMD). The focus during the work period was on a Bosch-based process technology that employs a reverse water gas shift (RWGS) reactor arranged in series with a carbon formation reactor. A NASA-developed RWGS reactor was integrated with a carbon formation reactor designed by Umpqua Research Co. The test objective was to evaluate performance of a series-Bosch (S-Bosch) "mix and match" process architecture that employs reactor components produced independently by different suppliers. Design work for an S-Bosch brassboard unit was also completed. The S-Bosch brassboard unit fabrication is planned for 2019. Work continued on two technology development efforts by Umpqua Research Co. and Honeywell Aerospace (Phoenix, AZ) under the SCOR project as part of a game-changing development solicitation.

Studies to use ionic liquids as a means to regenerate Bosch catalysts in situ continued during the work period. This study complements the Bosch carbon formation reactor development to address the challenge that results from catalyst fouling with carbon. A reactor design has been completed that optimizes the original design developed in 2017. The optimized reactor will be fabricated in 2019 and tested at a two crewmember equivalent scale. The testing will serve as the basis for the next generation reactor design and will include all of the catalyst regeneration and in-process functional stages.

B. Carbon Dioxide Removal and Management

Technical progress relating to carbon dioxide removal pertained to evaluating structured sorbent media performance and the efficacy of liquid amine processes. Thermal and electrical conductivity properties of Catacel structured sorbent media were evaluated by test and computational fluid dynamics analysis. These evaluations determined that the thermal conductivity is close to that of zeolite pellets and indicates that a structed media may have similar heating and cooling dynamics as a packed bed. Dynamic temperature and pressure swing process performance was observed to achieve the minimum 68.5% removal efficiency necessary for exploration missions, indicating structured sorbents may be viable replacements for packed beds. Evaluation continues to test these observations and, in particular, understand sorbent density adjustments that may be needed for operational robustness. Data obtained from structured zeolite 13X media indicate bed density may need to be increased by approximately 20% to 30% to confidently provide >4 kg/day carbon dioxide removal.

Alternative sorbent development work is planned for 2019 to evaluate metal organic frameworks (MOF) for carbon dioxide removal. This work builds on recent reports by TDA Research (Wheat Ridge, CO) on several MOFs that may be promising for carbon dioxide removal. Carbon dioxide and water isotherms will be investigated during 2019 and a study will be conducted to evaluate MOF application to carbon dioxide removal.

Liquid amine-based processes were further developed. The work focused on an aqueous diglycol amine (DGA) working fluid. To enhance the performance, incorporating carbonic anhydrase was studied. The interaction of aqueous DGA with chemical contaminants commonly found in a crewed spacecraft cabin atmosphere were also evaluated. This amine-based process continues to be under evaluation at sub-scale.

An ionic liquid-based process for carbon dioxide removal has been under development by Honeywell under sponsorship provided by the Center for the Advancement of Science in Space (CASIS). This effort is working toward a prototype demonstration aboard the ISS in 2020. Work planned in 2019 is focused on characterizing the characteristics of the selected ionic liquid including chemical and thermal stability; vapor pressure; and carbon dioxide capture in the presence of moisture, nitrogen, oxygen, and trace chemical contaminants.

Capillary sorbent fluidics in microgravity that are inherent in liquid-based contacting processes. Flight experiment science objectives will be completed in 2019 to add to the results from primary objectives that were completd in 2017.

Carbon dioxide management via temperature swing adsorption (TSA) was pursued during the work period. A TSA-based compression system was evaluatd under different heating schemes to provide a basis for power optimization. This carbon dioxide management concept was compared to mechanical compression. Ongoing work is characterizing candidate sorbent media and optimizing the adsorbent bed design.

C. Trace Contaminant and Particulate Matter Control

The leading adsorbent media candidates from commercial suppliers continued to be evaluated for their low concentration ammonia capacity and mixed volatile organic compound saturation capacities. Adsorbent media from Camfil, Molecular Products, Serionix, and Calgon are under evaluation. Characterization is scheduled to be completed in 2019. Early adsorbent media characterization data were used to aid in sizing an adsorbent bed for a 1100-day mission. A bed was assembled from commercially available parts and provided to United Technologies Collins Aerospace for use in their Next Space Technologies for Exploration Partnerships (NextSTEP) ECLS modularity study work. As well, a radial flow, high velocity, low aspect ratio bed design was adapted from a commercial product and components were acquired in preparation for an integrated test of the exploration trace contaminant control functional architecture. This integrated test is scheduled for mid-2019. Preparation for endurance testing the leading thermal catalytic oxidation technology began in late 2018 with a scheduled test start in 2019. The test seeks to evaluate the catalytic oxidation technology performance over a least two years of continuous operation. Insulation needs for the catalytic oxidizer test article were also investigated and specifications developed.

Particulate matter control advancements were made in refining the scroll filter concept to better seal the filter media edges and demonstrate the filtration concept in the Mars Desert Research Station. The demonstration in the research station was completed in February 2018.

In support of particulate matter filtratration technology development, efforts continued to provide improved insight on the characteristics of the suspended particulate matter load in crewed spacecraft cabins. These efforts involve several initiatives. Aerosol sampling and characterization aboard the ISS is being led by NASA's Glenn Research Center (GRC) teamed with RJ Lee Group (Monroeville, PA) and six universities. The aerosol sampling work is augmented by the Divert Unwanted Space Trash (DUST) and Collaborative Research on Undesirable Debris (CRUD) experiments which have returned vacuum cleaner bags filled with debris that has been shared with Ohio State University (microbiome RNA extraction and sequencing), Clarkson University (particle size distribution), University of Birmingham-UK (identify organic flame retardants), University of Toronto (volumetric size distribution and mass concentration), Washington University in St. Louis (organic and inorganic species identification), and Carnegie Mellon University (single particle analysis techniques). Two rounds of aerosol sampling have been accomplished by GRC and RJ Lee Group which have yielded insight on particle shapes and chemical makeup. Two additional aerosol characterization technology demonstration efforts aboard ISS are being conducted during fiscal year 2019. Data from these efforts will be combined with data acquired during the previous aerosol samping and analysis efforts. In addition to these efforts, the Real-Time Aerosol Characterization Experiment (RACE) is being administered as an SBIR Phase II-X project and was awarded in late 2018. Work on RACE is progressing during 2019 toward the goal of a flight demonstration aboard ISS in 2020.

Additional work is being conducted to improve aerosol monitoring via the Earth and Space Air Prize (ESAP) which is a crowd sourcing initiative sponsored by the Robert Wood Johnson Foundation. The ESAP received 20 proposals in November 2017. These proposals were reviewed and three finalists were selected in April 2018. The finalists were the following:

1) Aerodyne Microsystems Inc. for a micro electro-mechanical systems (MEMS)-based sensor that gravimetrically measures aerosol mass from 0.08 to 5 µm in size.
2) Applied Particle Technology for a miniaturized multi-wavelength optical particle counter with in-situ refractive index measurement for accurate size distribution measurement and optical speciation.
3) Colorado State University, Prof. John Volckens Group for a Mobile Aerosol Reference Sensor (MARS) that features a quiet ultrasonic pump, a cyclone inlet, and a low-cost nephelometer.

The instrument proposed by Applied Particle Technology was selected as the Grand Prize winner in December 2018.

II. 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 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 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[1] 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 2018-2019 NASA has invested in several water recovery areas including upgrades and improvements to ISS systems and technology development under the Advanced Exploration Systems (AES), ISS, and SBIR programs.

A. Water Recovery

Focal areas for water recovery include upgrades to state-of-the-art (SOA) processes and improvements to address emerging water contaminant challenges.

1. Catalytic Reactor Upgrade

Boeing and Collins Aerospace are scheduled to deliver the upgraded Catalytic Reactor that implements the new catalyst previously developed by Collins Aerospace, as well as metal seals to replace the rubber seals that have previously limited life to approximately two years. This new hardware is scheduled to be delivered to ISS in late 2020.

2. Multifiltration Bed Upgrade

The ISS Multifiltration Beds (MFBs) are a disposable component of the system, and NASA is interested in ways of reducing the logistics resupply requirements for missions. To increase life of the MFBs the bed materials and packing were redesigned. Boeing and Collins Aerospace are expected to deliver the new MFB in FY19. This design is a candidate for an exploration system. The new MFB design will implement the Ambersob 4652 adsorbent as well as replaceing the weak base amine exchange resin with the mixed ion exchange resing already used in the remaining cylinders (Rohm & Haas IRN-150).

3. *Siloxane Removal Study*

to remove siloxanes on the ISS that have been identified in the spacecraft atmosphere and have migrated to the water system two mitigation strategies have been employed. New siloxane free wipes and hygene products have identified and delivered to the ISS for crew use. A new siloxance filter design is planned to be installed the summer of 2019, installing them when heat exchagers are replaced. The plan is over the course of the next year to replace current HEPA filters with siloxance filters.

B. Urine Recovery

Developmental efforts in urine recovery have addressed upgrades to the SOA urine processing system, development of alternative urine processing techniques, and recovering Spacewater 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 Pump Assembly with a planetry gear ran for 4150 hours. The team is working with the gear supplier to increase life. The Pressure Contol Pump Assembly (PCPA) with a plantary gear is currently installed in the ISS Water Recovery System Rack 2. The improved planetary gear will be incorporated into future PCPA builds. Ground testing of a scroll pump to replace the PCPA peristalitic pump showed improvemnt with pumping capacity. Efforts are underway to get a flight scroll pump to replace the peristaltic leading to a planned flight demonstrion of the new PCPA incorporating the Separator Plumbing Assembly function in 2020. The Distillation Assembly has been redesigned to incorporate a Gates belt in place of the o-ring belt to elimate o-ring belt slipping. A unit with this redesign is planned for 2020.

2. *Brine Dewatering*

Brine Dewatering seeks to address the goal of 98% water recovery established by the Human Health, Life Support, and Habitation Systems roadmap.[1] 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 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.

Paragon has completed manufacturing of the Brine Water Processor and has started testing of the unit. The unit is planned to be delivered in December 2019 for flight demonstration on the ISS.

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 on the rectangular cross-flow reactor design, build, and test. Texas Tech continues research on their reactor. Tasks include developing a method for long-term storage on incolum, develop a plan for a flight technology demonstration, and incorporating a flush/urine separator assembly with pretreat into their existing reactor.

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.

1. *Silver Biocide*

The goals of silver biocide technology development tasks are to identify methods for adding biocidal silver to water on-orbit 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 evalution of silver dosing systems, silver monitoring, and mitigation of silver deposition onto the system tubing and manifolds. Test articles for testing surface treatments have been manufactured and testing has started. Testing electrode designs for depositing silver in the water has started. Upon completion of these tests an integrated systems test will start.

IV. Waste

NASA missions must manage both human metabolic waste, and dry and wet trash generated by crew activities.

A. Metabolic Waste

Collection, stowage, and recycling of human metabolic waste is an important part of human spaceflight. Advances in this area continue to build on the systems used in previous programs. Currently, an exploration toilet is under contract to develop the next generation technology to provide for the collection of waste during space missions. Tested on the ISS (Figure 3), the toilet will provide a much-needed additional toilet for increased crew sizes starting in 2019.[2] A second unit will be provided for the Orion Exploration Mission 2 (EM2) crewed mission. The development challenges have compressed the original schedule. The Orion unit witll be installed in the EM2 vehicle prior to completion of the initial testing on ISS. Minor changes to the Orion unit may be possible but not significant ones. This is a risk is acknowledged by the programs.

The core unit is the same for both units. The primary difference is the urine pretreatment system. For ISS, alternate pre-treat (a hexavalent chromium-phosphoric acid solution) will be used to treat the urine before recycling. On the Orion program, a string of solid Oxone tablets will be used for this purpose. The urine collected on the Orion program is not recycled for these short missions. The urine is temporarily collected in a bellows tank before being vented from the vehicle. In both cases, the pretreat solutions are used to inhibit growth and precipitates in the urine solutions.

The project will provide both the ISS and Orion toilets units in September 2019. The design is complete and component deliveries are the focus for the first part of 2019. Assembly and testing are scheduled for later in the year. A delta critical design review (d-CDR) was completed in May 2018 to incorporate additional requirements added by request for proposal number 2 (RFP#2).

Major component designs that were completed include Dose Timing, Odor Bacterial Filter materials and placement, gearbox design, electrical draw and thermal loading. The decision was made to use additive manufacturing for the Dual Fan Separator Housing because traditional methods like machining and casting were not suitable for the complex shapes of the housing and vendors were unwilling to bid the work.

United Technologies Aerospace Systems (UTAS)—now United Technologies Collins Aerospace—worked with NASA to define specifications and acceptance criteria for this new method of manufacture of a fracture critical part. The flight housings (one for ISS and one for Orion) were completed along with two pre-production articles used for testing and two units for spares. Testing of the units showed some anomalies resulting in additional test coupons to validate the expected results.

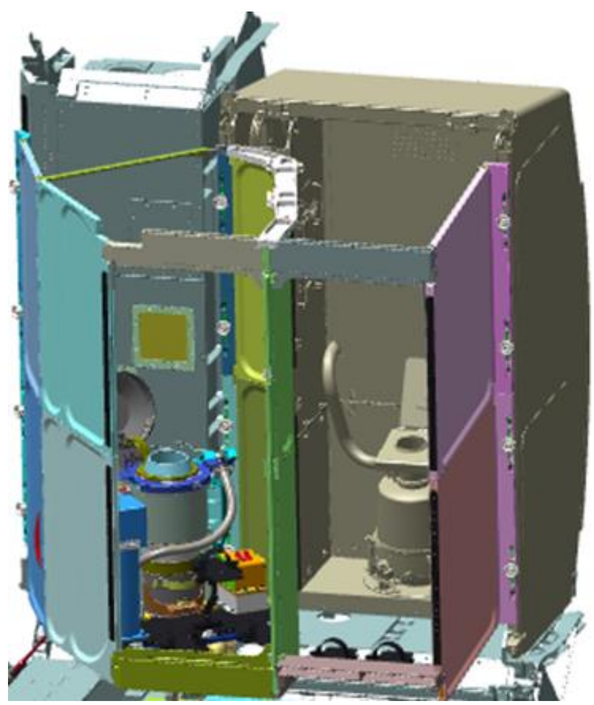

Figure 3. Model of UWMS Hardware Stall with UWMS and ISS Waste Collection System.

Figure 5. Toilet Trainer.

Figure 4. UWMS Integration Hardware Stall on ISS.

A toilet Trainer unit (Figure 5) was assembled with printed parts, flight-like components and commercial off-the-shelf (COTS) items. The Trainer was used for preliminary fit checks with the mounting adapter and stall integration hardware and in the Hygiene Bay mockup of the Orion unit.

The Universal Waste Management System (UWMS) Integration Hardware Stall was delivered for launch on NG-10 in advance of the UWMS and other Integration Hardware. The stall replaces the Waste and Hygiene Compartment (WHC) Kabin previously used with the Russian ASU. The new stall arrangement allows for entry into the WHC on the starboard side and a location for the new toilet (to fly in late 2019, early 2020.) The stall was installed in February, 2019 with no issues. The stall includes seat track for handrail installations, bi-fold doors with fold into the stall volume and modular construction for flexibility in installation and removal (Fig. 5). Shown below in the view of Node 3, ISS, the stall is the white structure. The bifold doors are on the front (two sets), the mesh screen is at the top of the stall structure and a Multipurpose Cargo Transfer Bag was relocated onto the side (in orange) of the stall from the WHC structure.

New funnels (Figure 6) were launched on NG-10 and the crew of Expedition 56 evaluated the three designs. Additional funnel evaluations are on the schedule by the crews of Expedition 57 and 58 (two female crew members will be available for this evaluation.) The funnel designs build on the previously used shuttle funnels, the current Russian "yellow" funnel and hope to improve the collection efficiency for female crew members during simultaneous operations.

Additionally an Integrated Flow test for the ISS system with the UWMS controller, the Urine Transfer System development hardware, simulated hoses and fittings and mockups for the ISS systems at MSFC has been planned.

In FY19, the main focus will be the delivery of UWMS Unit 1 (ISS) and Unit 2 (Orion) along with the remaining Integration Hardware items. To attain these deliveries, component schedules are being closely monitored.

Figure 6. New Funnel Design.

B. Trash Management

NASA has continued development 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 shelter18, or a compact form for jettison. The HMC task develops a reliable technology primarily for reducing trash volume and stabilizing trash for long-term storage. HMC also recovers water from waste materials and produce microbiologically-stable, low-volume tiles that could be potentially used to augment radiation protection, storage, or disposal. For a one-year mission of four-crew, it is estimated that HMC could recover ~8 cubic meters of habitable volume, produce over 900 kg of radiation shielding tiles, and recover 230kg of water from ~1,300 kg of trash.

A full-scale, second-generation (Gen2) HMC has been developed. This unit is being used to finalize process parameters using ground tests. These results will be used to inform development of a unit for an ISS technology demonstration. Multiple NASA Centers will participate in the development and test activities. Phase I SBIR efforts were conducted by two different companies on microgravity-compatible condensing heat exchanger designs that could be applied to the HMC. A third SBIR company is developing bags for processing trash in the HMC with the desired properties of water vapor permeability, solids confinement, and microbiological growth inhibition.

In FY18 the NextSTEP-2 BAA Appendix F call for a Trash Compaction and Processing System (TCPS) was released. This is a trash management system which is not limited to previous HMC technology and progresses the HMC work. The procurement is phased over multiple years with Phase A (FY19-FY20) to develop and validate a flight concept with prototype demonstrations and a Phase B (FY20-23) build of a flight unit for an ISS Tech Demo. An industry day was held to inform interested companies in July. Two companies, UTAS and Sierra Nevada Corp (SNC), were selected for Phase A in September. Phase A consists of development to a PDR maturity with a demonstration of high risk and key hardware areas with a ground prototype.

NASA risk reduction activities continued in FY18 in three areas: modifying HMC Gen 2 to be used as a facility to test and validate TCPS design concepts; development of a dew point measuring system for HMC processed off-gas/water vapor mixtures as related to ISS Vacuum Exhaust System (VES) venting requirements; and preliminary validation of an Adsorption Water Recovery System to collect water during TCPS processing in zero g.

In FY19 the TCPS procurement was finalized by NASA Headquarters. The HMC team will continue risk reduction that will include tests using the HMC Gen2 with operational scenarios to inform TCPS contracts to develop their designs and prototypes. The Gen2 HMC will be operated as close to the SNC and UTAS chamber operating conditions as is practical to obtain tile, gas, and water test results. Additionally, the Gen2 HMC will be used to test a previously provided MSFC catalytic oxidizer and an adsorption water recovery system operating with Gen 2 will be examined. If time and resources allow, SBIR chamber liner bags will be tested for their ability to reduce gas and water contaminants. Finally, tests will be conducted with a dew point detection system to understand ISS VES compatibility requirements with HMC trash processing operations to inform phase B TCPS procurement requirements. The team will also continue to engage ISS, crew operations, and human factors experts to increase the probability of success for the planned phase B flight demonstration.

Pending the successful results from Material Modifications, Inc's Phase II SBIR development, award of a future phase IIX SBIR award is possible for further assessment of the material for flight and to support the TCPS contracts.

V. Environmental Monitoring

Progress has been accomplished for developing microbial monitoring, atmosphere composition monitoring, and water quality monitoring.

A. Microbial Monitoring

Further in-flight testing of the the MinION Biomolecular Sequencer was the focus of the Biomolecule Extraction and Sequencing Technology (BEST) payload. 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 about 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 on-board ISS have been completed, with the results from the initial four sessions on board ISS published in the following reference.[37, 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] Work currently focuses on improving the consumable required for miniPCR and for MinIon. Refrigeration is required and shelf life for MinIon cells is currently limited to approximately 6-months.

A shift from a culture-based microbial monitoring scheme to a non-culture-based microbial monitoring scheme has also started. Non-culture based schemes hope to bypass the culturing step in media and the requisite 5-day incubation period currently required by culture-based systems. The goal would be to sample with a swab and performed the analysis directly from the swab.

B. 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

The Anomaly Gas Analyzer (AGA) is the next-generation combustion-products monitor 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). 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. The required measurement ranges and accuracies for each mode are listed in Tables 2 and 3.

The AGA will serve as the combustion products monitor, ammonia/hydrazine monitor, and portable carbon dioxide monitor and oxygen monitor for the 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 on-board ISS for EVA prebreathe activity and for spot-checks in areas when oxygen concentration may have decreased due to poor circulation. For the Orion vehicle, ammonia and hydrazine are required for off-nominal post-landing operations in which post-landing ventilation is needed and/or re-entry 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 1 Safety Review was completed in February, 2018, and the Preliminary Design Review

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 ≥ 9.5 psia
Water Vapor	1.9 - 15 mmHg	± 0.1 mmHg ≥ 1.9 mmHg
Temperature	36 - 121 °F	± 0.1 °F ≥ 36 °F
CO	5 - 1000 ppm[2]	± 10% ≥ 55 ppm[1] ± 5 ppm < 55 ppm
HCN	2 - 50 ppm	± 25% ≥ 5 ppm[2] ± 1 ppm < 5 ppm
HF	2 - 50 ppm	± 25% ≥ 5 ppm[2] ± 1 ppm < 5 ppm
HCl	2 - 50 ppm	± 25% ≥ 5 ppm[2] ± 1 ppm < 5 ppm
CO_2	0.3 - 21 mmHg (395 - 27600 ppm @ 760)	± 10% ≥ 0.8 mmHg (1053 ppm) ± 0.2 mmHg < 0.8 mmHg
O_2	14 - 50%	± 1% (absolute) ≤ 26% ± 2% (absolute) > 26%
NH_3	10 - 30,000 ppm	± 25% > 150 ppm ± 10% 20 - 150 ppm ± 20% < 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 ≥ 9.5 psia
Water Vapor	1.9 - 15 mmHg	± 0.1 mmHg ≥ 1.9 mmHg
Temperature	36 - 121 °F	± 0.1 °F ≥ 36 °F
CO_2	0.3 - 21 mmHg (395 - 27600 ppm @ 760)	± 10% ≥ 0.8 mmHg (1053 ppm) ± 0.2 mmHg < 0.8 mmHg
NH_3	10 - 30,000 ppm	± 25% > 150 ppm ± 10% 20 - 150 ppm ± 20% < 20 ppm
N_2H_4	2 - 10 ppm	± 2 ppm

(PDR) was completed in June, 2018. Three development units were delivered to the Johnson Space Center (JSC) in August, 2018, starting a comprehensive battery of testing. In addition, the AGA End-Item-Specification document, the Operations Concept Baseline document, the Software Requirements Specifications, Interface Control Document for the AGA to the Orion vehicle, and the AGA Project Technical Requirements document were all baselined.

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.

Bounding the impacts on the hardware of each emergency scenario will help assess the possible limitations of one device used in multiple emergency situations. To this end, testing the capabilities of the unit after exposure to one emergency has been one of the goals in 2018. Performance was assessed in environments that mimic laptop battery fires that may occur in the open cabin. This scenario served as a worst-case combustion event scenario performed at WSTF.

2. Real-Time Formaldehyde Monitor

The development of a flight technology demonstration unit of the Southwest Sciences optical Formaldehyde Gas Monitor (FGM) continued through 2018. 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 between NanoRacks LLC (Webster, TX) and Southwest Sciences, Inc. (Santa Fe, NM). NanoRacks will provide certification and integration of the FGM for use on-board ISS. Thermal analysis revealed elevated temperatures on the electronics board of the unit. This led to the redesign of the enclosure to add an additional fan, and to separate the electronic boards from the optical components (optical cell, laser, and detector). Each side has its own cooling fan, significantly reducing surface temperatures on the electronic side and isolating the optical side in its own thermal environment. In additiona the reliability of the data-logging and Wi-Fi capabilities were considerably improved by employing a Raspberry Pi-based communications board. Wi-Fi capability allows the FGM to connect to the ISS server via the Joint Station Local Area Network (JSL) for autonomous data transfer to the ISS server and subsequent downlink directly to NASA ground servers for evaluation by NASA toxicologists. 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-help 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 $\geq$500 ppb. Formaldehyde is a persistent VOC on board 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. Currently, the FGM is scheduled for delivery to ISS on SpaceX-18.

C. Water Monitoring

Water quality monitoring have focused on two areas, (1) the analysis of aqueous organic species, and (2) the determination of total organic carbon. Despite this focus parameters such as conductivity, microbial identification and enumeration, pH, and monitoring for select inorganic species are key indicators of water quality. While measuring these parameters on the ground are quite mature, the technology will still require adaptation for Exploration-class missions and vehicle constraints. The Jet Propulsion Laboratory (JPL) under sponsorship of the NASA Science Mission Directorate as well as internal JPL funds have continued work on a microfluidic-based chemical laptop primarily targeted for detecting signs of life on planetary surfaces by detecting and quantifying ions, inorganic compounds, microbial elements in samples as well as measuring conductivity and pH. In order to identify and quantify the organic compounds, JPL intend to connect this chemical laptop to a mass spectrometer such as the Spacecraft Atmosphere Monitor (SAM).

3. Electrothermal Vaporization of Water Samples

Volatilizing water samples into the gas phase and then employing a gas-phase analyzer to identify and quantify the chemical species present has been a very successful strategy in the ground analysis of water samples. This approach could then capitalize on the presence of a cabin-air monitor to monitor VOCs not only in air, but also in water. Previous work led to development of water sampling system using a simple electro-thermal vaporizer (ETV) interfaced to mass spectrometer. The proof-of-concept version of the ETV was then translated into a self-contained, micro-gravity-compatible system that has been shown by ground studies to reproducibly vaporize a water sample for analysis by an ISS-configured Air Quality Monitor (AQM). The Rice University-designed ETV draws a water sample into the vaporization area consisting of a coil of kanthal wire. Energizing the coil by an on-board USB port vaporizes the water sample which is it drawn into the AQM for analysis. Much of the current work has been in the modifications of the existing AQM software to add ETV functionality for water analysis as an operating mode. The current concept of operations will have crew load the sample onto an inert matrix that can be heated inducing vaporization. The Expert® software that operates the AQM will have a mode for water analysis. After the sample is loaded via syringe, the crew would initiate a water analysis with a single button. From here on, the analysis would be automated, with the AQM providing a final report. In additional to automation, simpler designs of the vaporization cell are being tested.

2. Total Organic Carbon Analyzer

Total organic carbon (TOC) is a fundamental water quality indicator providing insight into toxicity as well as the performance of the water processing system. The ISS Total Organic Carbon Analyzer (TOCA) provides TOC as well as total inorganic carbon (TIC) directly from the USOS water processor assembly through a hose, on a weekly basis, and from a bag filled from the potable water dispenser, on a monthly basis. TOCA has been instrumental in the maintenance of the ISS water processing assembly since it became operational in 2008 by informing crew when TOC limits were reached. Combining chemical analysis with TOC has proven to be invaluable in the management of water processing on-board ISS. Confirmation that increasing TOC can be attributed to organic species of low toxicity allows engineers to run filtration beds longer, potentially decreasing the number of spares required on-orbit or during a long-during, Exploration-class missions. Fewer spares can be a significant savings in mass and volume.

Considerations made in the development of TOCA for Exploration-class missions was the subject of a 2018 ICES paper[3]. In this paper are requirements for analytical performance, interface and environment, safety, and device life. Experience with the current ISS TOCA is considered. It is generally accepted that the Exploration TOCA is expected to be smaller in mass and volume than the ISS TOCA. As with any flight hardware, mass and volume is typically mandated by the technology employed. Crew-time was also considered with the goal of increasing autonomous operations. While several technologies are presented, future development appears to focus on uv oxidation, membrane conductometric detection of CO_2 (product of complete oxidation of organic species, along with water), and acidification and separation of inorganic carbon species. Refinement of requirements as well as potential breadboard-level investigations is the logical next step with an ultimate goal of demonstrating the performance of the Exploration TOCA on-board ISS.

VI. Ground Testing Strategies

A robust ground testing campaign has been identified as a necessary component for developing the exploration ECLS technologies and capabilities for the future deep space exploration programs. This testing campaign builds on 20 years of ISS flight experience to with a range of ECLS technologies relative to system availability and supportability weaknesses with a focus that seeks to address technical gaps and opportunities for improvement. This experience helps identify technology and performance gaps and provides insight relative to technology durability, system availability, and microgravity sensitivities. The testing campaign will be designed to complement planned ECLS technology demonstration initiatives aboard the International Space Station.

Under the auspices of the AES Life Support Systems (LSS) Project, a robust multi-year approach to ECLS technology ground testing that best utilizes existing NASA and/or vendor facilities to execute a robust ground testing campaign across varying levels of integration and sophistication will be developed and executed. Existing test articles will be used and opportunities for upgrading test article fidelity will be identified. Higher fidelity test articles for the most promising options for each ECLS functional area will be specified and procured. The multi-tiered testing approach will employ methods that include the following:

- Component and assembly testing
- Comparative testing of two or more test articles
- Endurance/life testing
- Early integrated testing for two or more test articles
- Integrated subsystem testing
- Integrated system testing

The testing effort will include studies to aid with planning as needed to address areas of uncertainty that include defining test scope and duration definition, selecting test location, establishing endurance/life testing policy and procedures and the number of test articles required for endurance/life testing, and determining the best role for testing that incorporates human-in-the-loop components. This approach complements technology flight demonstration that is planned aboard the ISS and addresses a range of exploration mission technical challenges relative to supportability and uncertainty associated with component and system reliability.

VII. NextSTEP BAA Progress

The activities under the NextSTEP Habitation Broad Agency Announcement (BAA) activities continued Phase II efforts to further develop conceptual exploration habitat design studies. Exploration habitat module prototypes suitable for assessing the efficacy of the Phase I concepts continued to be designed and constructed for delivery scheduled in late 2019 and early 2020. A focused ECLS system study development effort being led by United Technologies Collins Aerospace (Windsor Locks, CT) has continued to advance the packaging, fit, and form fit of an exploration-class ECLS functional capability.[4,5,6] This primarily seeks to demonstrate modular ECLS functional deployment and hardware accessibility features toward enabling in-flight maintenance at intermediate or lower levels than presently done aboard the International Space Station (ISS). NextSTEP Phase II habitat concept developers have continued to evaluate the modular ECLS functional grouping approach relative to compatibility with their habitat design and efficacy for addressing exploration mission logistics constraints. The products from the NextSTEP ECLS development work will be delivered in 2019 for NASA to evaluate the concept's feasibility.[7] Follow-on work is being considered to incorporate technical feedback provided by the NextSTEP habitat concept developers.

VIII. Conclusion

Significant progress has been realized toward addressing the technological gaps for executing and sustaining future space exploration missions. As NASA continues to team with commercial and international partners, academia, and other government agencies, the successes are multiplying and the pace is quickening toward an outpost in cis-lunar space that will be the first step on the journey. Lessons learned from the ECLS systems aboard the ISS as well as technology upgrades and demonstrations will provide the necessary confidence for a sustained human presence beyond low-Earth orbit.

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