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National Aeronautics and Space Administration Environmental Control and Life Support Technology Development and Maturation for Exploration: 2014 to 2015 Overview

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

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Nomenclature

ABO = Aviator’s Breathing Oxygen
ACS = Advanced Clothing System
Ag = Silver
AES = Advanced Exploration Systems
AR = Air Revitalization
ARREM = Atmosphere Resource Recovery and Environmental Monitoring
ATP = Adenosine Triphosphate
AWP = Alternate Water Processor
BEB = Brine Evaporation Bag
BRIC = Brine Residual In-Containment
BWP = Biological Water Processor
C&DH = Command and Data Handling
Cd = Cadmium
CDRA = Carbon Dioxide Removal Assembly
CDS = Cascade Distillation System
CH_4 = Methane
C_2H_4 = Ethylene
CM = Crew Members
COTS = Commercial Off-the-Shelf
CP = Combustion Products
CPM = Combustion Products Monitor
CRA = Carbon dioxide Reduction Assembly
CTB = Cargo Transfer Bag
Da = Daltons
DA = Distillation Assembly
DMSD = Dimethylsilanediol
ECLS = Environmental Control and Life Support
ECLSS = Environmental Control and Life Support System
EM = Environmental Monitoring
EM2 = Exploration Mission 2
ENose = Electronic Nose
EVA = Extravehicular Activity
FCPA = Fluids Control and Pump Assembly
FOBD = Forward Osmosis Brine Dryer
FOST = Forward Osmosis Secondary Treatment
FT/IR = Fourier Transform Infrared
GC = Gas Chromatography
GC/DMS = Gas Chromatography/Differential Mobility Spectroscopy
GC/IMS = Gas Chromatograph/Ion Mobility Spectroscopy
GC/MS = Gas Chromatography/Mass Spectroscopy
GCD = Game Changing Development
HCL = Hydrochloric Acid
HCN = Hydrogen Cyanide
HF = Hydrofluoric Acid
Hg = Mercury
HMC = Heat Melt Compactor
ISS = International Space Station
IWP = Ionomer-Membrane Water Processor
JEM = Japanese Experiment Module
kg = kilogram
LEO = Low Earth Orbit
lpm = Liters per Minute
LR = Logistics Reduction
LSS = Life Support Systems
MCA = Major Constituent Analyzer
M-COA = Microlith® Catalytic Oxidizer Assembly
MCTB = Multipurpose Cargo Transfer Bag
MDM = Multiplexer/Demultiplexer
MEMS = Micro Electro Mechanical System
MGM = Multi-Gas Monitor
Mn = Manganese
MPAM = Multi-Program Air Monitor
MPCV = Multi-Purpose Crew Vehicle
Ni = Nickel
OGA = Oxygen Generation Assembly
ORU = Orbital Replacement Unit
OWM = Organic Water Monitor
PCPA = Pressure Control and Pump Assembly
PCR = Polymerase Chain Reaction
PDMS = Polydimethylsiloxane
PLSS = Portable Life Support System
PPA = Plasma Pyrolysis Assembly
PPS = Polyphenylene Sulfide
ppm = Parts per Million
QITMS = Quadrupole Ion-Trap Mass Spectrometer
R2FD = Resource Recovery Functional Demonstration
RASCal = Rapid Analysis Self-Calibrating Array
REALM = RFID Enabled Automated Logistics Management
RFID = Radio Frequency Identification
RSA = Rotary Separator Accumulator
SAM = Spacecraft Atmosphere Monitor
SEOS = Solid Electrode Oxygen Separator
SBIR = Small Business Innovative Research
SMT = System Maturation Team
SOA = State of the Art
STMD = Space Technology Mission Directorate
TCC = Trace Contaminant Control
TDLS = Tunable Diode Laser Spectroscopy
TRL = Technology Readiness Level
TtG = Trash to Gas
UPA = Urine Processor Assembly
UWMS = Universal Waste Management System
VOCs = Volatile Organic Compound
VMS = Volatile Methyl Siloxanes
W = Watt
WPA = Water Processor Assembly
WRP = Water Recovery Project
WRS = Water Recovery System
Zn = Zinc

I. Strategic Planning Updates

IN 2014, the National Aeronautics and Space Administration (NASA) released its "Pioneering Space" strategy, including the "Pathway to Mars". This strategy includes an evolution from the current "Earth Reliant" phase of Low Earth Orbit space exploration to "Proving Ground" missions in cis-lunar space to finally "Mars Ready" missions to the vicinity of Mars and ultimately the Mars surface. As part of this planning, NASA has been developing an Evolvable Mars Campaign strategy depicted by Fig. 1 with candidate scenarios and architectures that could satisfy objectives of Mars missions with achievable building block elements and technologies. Even as NASA refines its future mission planning, the importance of a reliable, long-duration Environmental Control and Life Support (ECLS) system remains a consistent need for all of these scenarios and architectures.

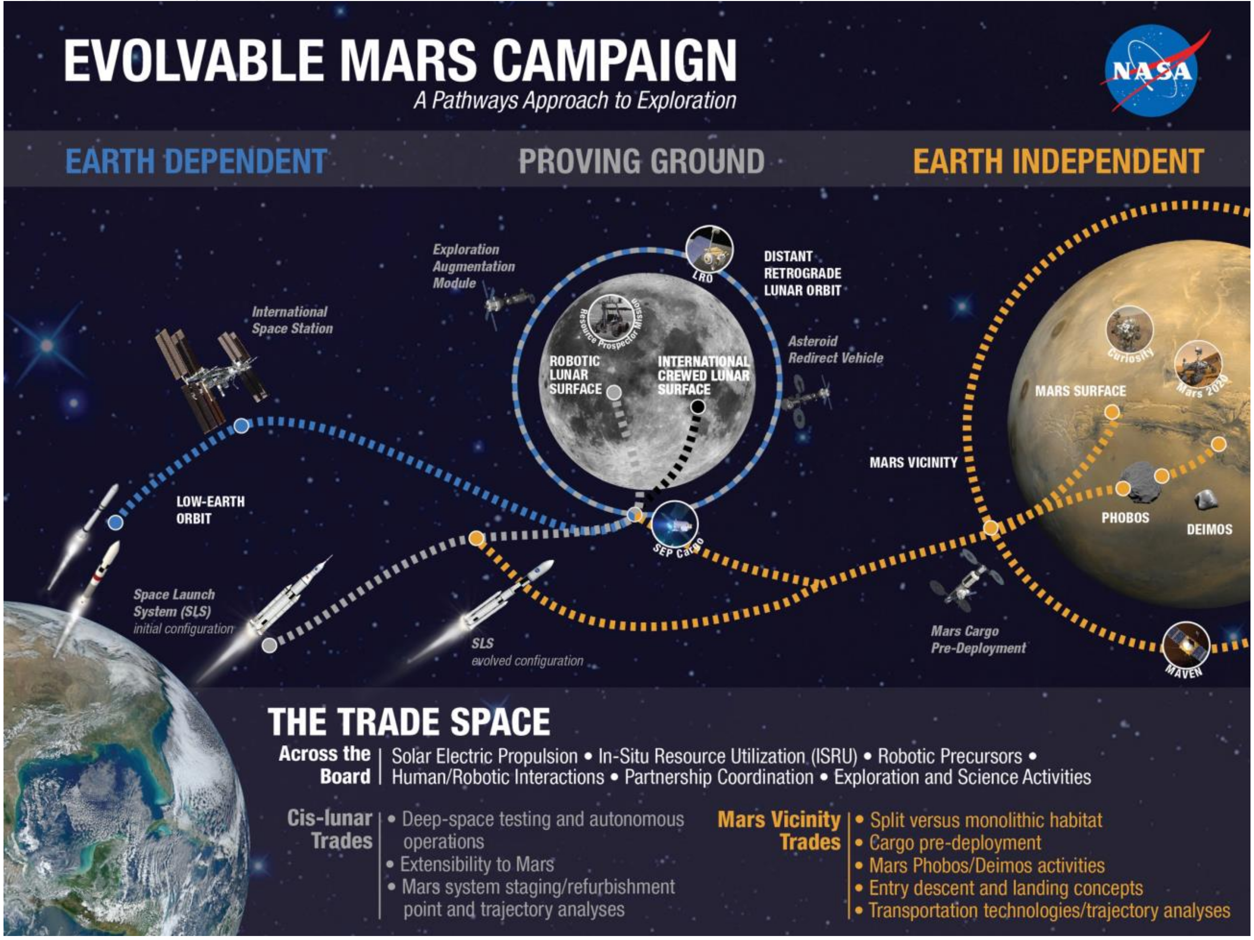

Figure 1. The Evolvable Mars Campaign

Another activity that was completed by the agency this past year was the revision of the Space Technology Roadmaps to be released in 2015. Environmental Control and Life Support Systems (ECLSS) interests are described in "Technology Area 6: Human Health, Life Support, and Habitation Systems" (TA-06 Roadmap). The long term technology development goals have not dramatically changed. The newer versions of the roadmap will include specific performance parameter goals for the highlighted technologies. In air revitalization systems, the roadmap includes carbon dioxide (CO_2) removal for closed-loop systems, CO_2 reduction to generate oxygen, trace contaminant control, particulate and microbial control, temperature and humidity control, oxygen supply, and high pressure oxygen supply. Water recovery technology areas highlighted include wastewater collection and processing, as well as microbial control for potable water to be used by the crew. Waste management technologies in need of development include solid metabolic wastes, contingency urine collection, treatment of trash compaction and stabilization, and conversion of trash or waste to useful gases. While technologies for spacesuits are listed separately, there are several cross-cutting interests. Technologies of interest for Portable Life Support Systems (PLSSs) include several related to CO_2 removal, as well as sensors for pressure and CO_2 levels.

Table 1. Capability Gaps Mapped to Mission Classes (Red = Enabling, Black = Enhancing)

Function	Capability Gaps	ISS Upgrade/ Demo	Extending Reach Beyond LEO	Into the Solar System	Exploring Other Worlds	Planetary Exploration
CO_2 Removal	Bed and valve reliability; $ppCO_2$ <2 mmHg	**X**		X	**X**	**X**
Trace Contaminant Control	Replace obsolete sorbents w/ higher capacity; siloxane removal	**X**	**X**	**X**	**X**	**X**
Particulate Filtration	Surface dust pre-filter				**X**	**X**
Condensing Heat Exchanger	Durable, chemically-inert hydrophilic surfaces with antimicrobial properties	**X**		**X**	**X**	**X**
O_2 recovery from CO_2	Recover >50% O_2 from CO_2	**X**			**X**	**X**
O_2 generation	Smaller, reduced complexity	**X**		X	**X**	**X**
High pressure O_2	Replenish 3000 psi O_2 for EVA	**X**		**X**	**X**	**X**
Water microbial control	Common silver biocide with on-orbit re-dosing	X		**X**	**X**	**X**
Urine collection	Backup, no moving parts urine separator	**X**	**X**	**X**	**X**	**X**
Wastewater processing	Increased water recovery from urine (>85%), reliability, reduced expendables, dormancy survival	**X**		X	**X**	**X**
Urine brine processing	Water recovery from urine brine >90%	**X**			**X**	**X**
Metabolic solid waste	Universal waste management system	**X**	**X**	**X**	**X**	**X**
Non-metabolic solid waste	Volume reduction, stabilization, resource recovery	**X**			**X**	**X**
Atmosphere monitoring	Smaller, more reliable major constituent analyzer, in-flight trace gas monitor (no ground samples), targeted gas (event) monitor	**X**	**X**	**X**	**X**	**X**
Water monitoring	In-flight identification & quantification of species in water	**X**		X	**X**	**X**
Microbial monitoring	Non-culture based in-flight monitor with species identification & quantification	**X**		X	**X**	**X**
Particulate monitoring	On-board measurement of particulate hazards	**X**		**X**	**X**	**X**
Acoustic monitoring	On-board acoustic monitor	**X**			**X**	**X**

The TA-06 Roadmap was consistent with the gaps defined by the NASA ECLSS Systems Maturation Team (SMT) and summarized in Ref. 1. Table 1 provides the most recent summary of functional gaps from the ECLSS SMT. Changes in the capability gaps since 2014 include the following:

1) The addition of siloxane removal to the trace contaminant control functional gaps. Recent on orbit issues with siloxane compounds causing premature breakthrough of the water processor multifiltration beds, and being potentially responsible for degradation of air revitalization equipment have resulted in efforts to understand and mitigate the effects of these types of compounds.

2) The Condensing Heat Exchanger function was added with the need for durable, chemically-inert hydrophilic surfaces with antimicrobial properties. The ISS State of the Art heat exchanger coatings have been subject to degradation affecting downstream components, and require periodic dry-out cycles in order to protect against microbial growth.
3) The O_2 generation gap description was modified from "Reliable, reduced complexity" to "Smaller, reduced complexity". This change was made after analysis of on orbit failures and maintenance related to the Oxygen Generation Assembly (OGA) indicated that the required reliability for future missions could be met by the existing design, and that emphasis should be placed on reducing the complexity and size of the current system for future missions (which will also have a positive impact on reliability).

The ECLSS SMT continues to track progress of development efforts against these gaps using individual roadmaps for each functional area, and to advocate for sponsorship of next steps in accordance with these roadmap plans. Although there are currently funded development efforts ongoing for almost all of the identified gaps (with some exceptions), the challenge will be to bring them to flight demonstration on the International Space Station (ISS), the ultimate testbed and proving ground for the next generation ECLSS that will be used for deep space missions. Efforts to make the flight demonstration process more schedule and cost efficient are being implemented within the ISS Program that will help enable the ECLSS upgrades to be flown when they are ready.

II. NASA Investments: Atmosphere Revitalization

The atmosphere revitalization function includes core capabilities to condition the cabin atmosphere by removing CO_2, trace contaminants, and particulate matter as well as maintaining a pleasant temperature and humidity condition while supplying an adequate supply of oxygen and maintaining the cabin pressure. These core capabilities are necessary regardless of the mission duration, yet, for reaching deep space exploration objectives the process technologies selected should ideally be equally effective for open-loop and closed-loop subsystem architectures. As such, supplementing the core capabilities with methods and equipment to recover and recycle vital resources such as oxygen from carbon dioxide as well as developing autonomous control methods are necessary to achieve sustainable in-space logistics that minimizes total mission resource requirements.

Research and technology development efforts through calendar year 2013 are summarized by Ref. 1. As of the conclusion of calendar year 2014, key accomplishments of NASA's Advanced Exploration Systems (AES) research and technology efforts in the atmosphere revitalization are the following:[2]

1) Developed and tested integrated subsystem architectures and compared performance versus the ISS Air Revitalization (AR) architecture establishing the feasibility of ISS-derived AR for deep space missions.
2) Developed and implemented methods for screening and characterizing mechanical strength and capacity performance adsorbent media used for bulk and residual drying, CO_2 removal, and trace contaminant control.
3) Assessed bulk and residual drying functional trade space options that found that the ISS Carbon Dioxide Removal Assembly (CDRA) desiccant bed to be the most mass and volume efficient solution as well as indicating that the desiccant bed size can potentially be reduced for exploration class missions to save mass and volume.
4) Advanced technical maturity of methane Plasma Pyrolysis Assembly (PPA) to enhance oxygen recovery through 3rd generation and demonstrated integrated operational performance with Sabatier carbon dioxide reduction development unit.
5) Tested trace contaminant control (TCC) component configurations as well as evaluated commercial adsorbent and catalyst product candidates leading to subsystem mass and volume reduction.
6) Improved insight of trace contaminant propagation through the integrated AR subsystem architecture that provided confidence that there is minimal risk associated with volatile organic compound (VOC) poisoning of CO_2 reduction catalysts.
7) Gained improved insight on CO_2 and bulk/residual drying sorbent mechanical properties and adsorption capacities as well as matured analytical predictive techniques.
8) Demonstrated operational simplifications for the ISS OGA that may reduce future mass and volume and address limited life Hydrogen (H_2) sensor issues to reduce logistics demand.

Reference 2 contains an extensive bibliography to guide the reader to details on these and other accomplishments in the technical areas contained within the atmosphere revitalization function. The following discussion summarizes NASA's more recent accomplishments as well as present and planned research and technology development investments in process technologies and candidate subsystem architecture testing that contribute to realizing exploration goals.

A. Core Functional Capabilities

Core capabilities are those required for any crewed space mission regardless of the mission's duration. Among the core capabilities are carbon dioxide removal, trace contaminant control, particulate removal, and temperature and humidity control. The following discussion summarizes accomplishments and future plans for these core functional areas.

1. Carbon Dioxide Removal

Developmental efforts in carbon dioxide removal have focused on screening and selecting adsorbent media that is functionally and structurally more robust than the State of the Art (SOA) media used in the ISS CDRA, evaluating CDRA process conditions that support maintaining a CO_2 partial pressure <2 mm Hg to address concerns related to crew health and performance at higher partial pressures, and gaining greater insight on in-flight observations from the ISS. Improved, more durable CO_2 sorbents are considered vital to improving CO_2 removal process reliability relative to the ISS CDRA. Energy-efficient structured sorbents and other alternative sorbents that may prove more durable than SOA adsorbent media have been identified and evaluated. As well, hydrothermal stability of SOA media have also been investigated to better understand the contribution that cyclic process conditions such as temperature and moisture loading have on adsorbent media mechanical strength properties. The best performing options are being considered for incorporating into an exploration CO_2 removal process architecture. More recently, post-flight evaluation of CDRA bed materials has indicated that high molecular weight trace contaminants may contribute to drying stage working capacity degradation and subsequent water migration through the AR architecture. More work is necessary to better understand the phenomena and identify root causes that may provide insight for future CO_2 removal equipment design.

Testing a CDRA engineering unit configured to a high functional and configuration fidelity to the ISS CDRA-4 through standard CO_2 concentration challenge points as well as at conditions to investigate the capability to handle large crew metabolic loads up to 9 crewmembers (CM) and to provide <2 mm Hg partial pressure control for exploration missions. The CDRA engineering unit's CO_2 sorbent and desiccant beds were configured according to the ISS CDRA-4 beds. The CO_2 removal and desiccant media used in the beds were flight-like. The testing found that increasing the flow by 22.5% combined with reducing the cycle time to 90 minutes allowed the unit to control the CO_2 partial pressure to <2 mm Hg under a 4-CM load. This performance does come at a cost as average heater power increased by 200 Watts compared to the standard configuration. Additional power increases are likely as the blower power can also be expected to increase. More work is necessary to determine how an ISS CDRA-derived process can be operated to meet lower CO_2 concentrations while minimizing the increased power demand.

Ongoing and planned future work within the CO_2 removal technical area includes the following:

1) Evaluate the sensitivity of adsorbent media to high molecular weight trace contaminants commonly observed in crewed spacecraft cabin atmospheres.
2) Evaluate the mechanical strength characteristics of adsorbent media, including pellet crush strength, bulk crush strength, attrition rate, and cyclic hydrothermal stability.
3) Evaluate process performance for candidate sorbents under temperature/vacuum swing adsorption process conditions.

2. Trace Contaminant and Particulate Removal

The trace contaminant and particulate removal functional area has focused on selecting and characterizing the best performing adsorbent media, catalysts, and particulate filtration media and techniques to improve performance to the equipment used aboard the ISS as well as address commercial obsolescence issues associated with adsorbents and catalysts used aboard the ISS. In addition, evaluations and tests have been conducted to better understand design considerations for future exploration missions and evaluate options for integrating TCC and particulate matter control equipment within a vehicle's atmosphere revitalization and cabin ventilation architectures. Specific areas of emphasis for the TCC and particulate removal technical area were the following:

1) Trace contaminant control design, requirements, and integration concept development and evaluation
2) Microlith® thermal catalytic oxidation assembly development
3) Commercial adsorbent and catalyst characterization
4) Catalytic ammonia removal process development
5) Indexing media filter system development
6) Particulate load characterization to support filtration equipment design specification

The overall trace contaminant control requirements were developed and minimum flow rate and power targets were established based on the project's technical requirements and the figures of merit. The integration concepts evaluated TCC components integrated with the CO_2 removal and cabin ventilation equipment. These concepts were functionally demonstrated and found to contribute to mass and volume reductions of approximately 12 kg and 15 liters relative to the ISS SOA.

A Microlith®-based thermal catalytic oxidizer assembly (M-COA) was demonstrated in two configurations closely integrated with the CO_2 equipment. These configurations were found to provide effective removal flow margins ranging from 5% to 138% relative to the minimum 1.4 m^3/h (0.84 $ft^3/minute$) flow required to support a 4-CM exploration mission design. Additional work is necessary to address meeting the more challenging exploration mission flow requirement. Key to this objective is reducing the unit's pressure drop. An advanced M-COA was designed and built by Precision Combustion, Inc. under Small Business Innovative Research (SBIR) Phase III contracts.[3] This unit possesses a more simple recuperative heat exchanger design that may yield a lower overall assembly pressure drop to allow for achieving higher flow rates. Testing this advanced M-COA unit is the subject of future component-level and integrated tests.

Two primary TCC adsorbent bed configurations were evaluated. The first employed a low flow, high aspect ratio bed similar to that used aboard the ISS. Flow through the bed was set at 10 m^3/h (6 $ft^3/minute$) which is the minimum for a 4-CM exploration mission. This bed was integrated directly with the cabin ventilation duct downstream of the main cabin fan. The objective was to use the motive force from the cabin fan to provide flow through the bed. Testing found that a small booster fan was necessary to achieve the necessary flow. As a result, a second concept that placed a high flow, low aspect ratio activated carbon cartridge concept (Barnebey Sutcliffe Division of Calgon Corporation) in the cabin ventilation duct immediately upstream of the cabin fan was tested. This concept performed much better than expected with respect to contaminant breakthrough, particularly for high molecular weight compounds such as volatile methyl siloxanes (VMS) that are suspected of being associated with both CO_2 removal, humidity control, and water processing equipment performance degradation aboard ISS. Further evaluation of this high flow, low aspect ratio adsorbent cartridge concept will be pursued in the future.

Market research was conducted to select candidate commercially-available adsorbents for removing ammonia and VOCs. Similar market research was conducted on ambient temperature carbon monoxide catalysts. A best-performing ammonia removal adsorbent (Ammonasorb II, Calgon Carbons) and carbon monoxide catalyst (Sofnocat 423, Molecular Products) were determined. Further work to characterize the ammonia adsorbent at low ammonia concentrations as well as evaluate co-removal of VOCs must be completed to optimize the TCC equipment architecture. Additional market research to identify additional candidate activated carbons targeting dilute VOC concentration loads must be completed and selected candidates characterized. Carbon monoxide catalyst long-term stability must also be evaluated.

Additional work was conducted on developing a selective ammonia catalytic reduction reactor for spacecraft TCC applications. Efforts on the ammonia catalytic reduction reactor completed a subscale concept demonstration and evaluated commercially available and custom catalyst formulations. Reactor performance at full scale is the focus of future work.

Particulate matter removal tasks focused on evaluating advanced filtration media, developing a scroll-type filter design to minimize crew time and involvement with filter element maintenance, developing methods for assessing filter service life and integrity, and updating the particulate generation source model used for design specifications. Advanced filtration media produced under SBIR contacts by Giner, Inc. and Seldon Technologies were evaluated to add to the performance database of commercial filtration media. Design modifications and improvements for the scroll-type media filter concept were identified and designs were generated to implement the improvements. The filtration literature was surveyed and filter leak testing standards were procured. Based on these standards, filter testing protocols and apparatus were developed and used to demonstrate filter integrity testing methods. These methods may be amenable to checking filter element integrity in-flight. A literature survey was conducted to update the particulate generation source model used for ISS cabin filtration system and component design.[4] The updated model was documented in a conference publication.[5] Future work is planned to develop a flight experiment to characterize the particulate load aboard the ISS to gain deeper insight.

Planned developmental work in the trace contaminant and particulate removal technical area is the following:

1) Test and characterize high flow, low aspect ratio adsorbent cartridges for their service life characteristics
2) Test, characterize, and evaluate the Advanced M-COA unit
3) Characterize the performance of candidate commercially-available ammonia and VOC adsorbent media as well as ambient temperature carbon monoxide oxidation catalysts across wider ranges of concentration and cabin temperature and relative humidity conditions.
4) Design, fabricate, and test a high fidelity prototype scroll filter concept in a cabin ventilation system functional mockup
5) Demonstrate ammonia catalytic reduction process efficacy at the scale necessary for exploration missions.
6) Develop and execute a flight experiment to gain insight on cabin particulate matter loading.

3. *Temperature and Humidity Control*

Developmental work has been limited in the temperature and humidity control functional area. More recent work has been conducted to gain insight on phenomena and mechanisms associated with condensing heat exchanger hydrophilic coating performance degradation and polydimethylsiloxane (PDMS) hydrolysis to dimethylsilanediol (DMSD). Continuing efforts are planned to better understand these technical challenges and identify solutions.

B. Oxygen Supply and Recovery Capabilities

The oxygen supply and recovery technical area has addressed several aspects of providing oxygen for the crew's use including improvements to the ISS OGA, means to provide high pressure, high purity oxygen for recharge extravehicular activity (EVA) tanks, and methods to recover more oxygen via CO_2 reduction processes.

1. *Oxygen Supply*

The ISS OGA has been reliably producing breathing oxygen aboard the ISS for over seven years. Lessons learned from operating the ISS OGA have led to proposing incremental improvements to advance the baseline design for use in a future long duration mission. These improvements promise to reduce system weight, crew maintenance time and resupply mass from Earth while increasing reliability. For future long duration missions, high pressure oxygen generation is also required to support EVA operations. Areas for investigation to advance SOA ambient pressure oxygen generation and extend its application to high pressure oxygen generation technology were the following:[6]

1) Replace hydrogen sensor—Hydrogen sensors require frequent maintenance and calibration. Recombiner technology was successfully demonstrated as a replacement with over 100 hours of safe operation.
2) Delete wastewater interface—Simplify future system design. The purpose of this interface is to reject feed water with an excessive amount of oxygen gas bubbles. Bench testing of Rotary Separator Accumulator (RSA) is required to verify no adverse effects from feed water containing entrained oxygen bubbles. A developmental RSA was designed and manufactured and is being prepared for future testing.
3) Delete nitrogen purging equipment—Simplify future system design. This will allow savings of 22.7 kg (50 lb) of mass and simplification of the system design. In the baseline design, oxygen is purged from the anode cavity upon shutdowns to create an inert unpowered condition. Using the OGA Test Bed, safe operation was demonstrated with nitrogen purging disabled. Testing consisted of three 1-week runs consisting of a baseline run with both purges, a run with the startup purge disabled, and a run with both the startup and shutdown purges disabled. Each of the N_2 purge deletion tests were conducted twice for repeatability which was observed. The overall conclusion is that disabling N_2 purging does not appear to introduce new safety risks to operating the OGA.
4) Replace cell membranes—Current membrane material is obsolete. The baseline ISS cell stack design contains obsolete membrane material (non-chemically stabilized Nafion 117). Giner, Inc was contracted to investigate the performance of single cells that are of the same design as the ISS OGA, but with new modern membrane material and catalyst. Giner built three single cells and tested them over a 10 month period. Excellent performance was demonstrated, with minimal voltage degradation over the entire test period.
5) Replace vacuum dome—The dome encases the cell stack, RSA and other components preventing access by the crew for maintenance. The dome's purpose is to detect leakage of hydrogen out of the cell stack or RSA via a pressure rise in the dome. Work began to replace the vacuum dome with an ambient pressure shroud which included adding a blower, recombiner a flow meter and other equipment to force air over the cell stack and RSA and detect hydrogen leakage via the recombiner. Future work includes demonstrating safe operation of the OGA Test Bed without a vacuum dome.
6) Redesign cell stack power supply—The 45.4 kg (100 lb) power supply is designed to support oxygen production for a crew of 11. It is likely that future missions will have a crew size of 4. The power supply can be redesigned to reduce mass by 30% or 13.6 kg (30 lb). Work is necessary beyond the study phase to accurately quantify the potential mass and volume savings.
7) Design, build, and test a high pressure cell stack—A subscale development high pressure cell stack was designed, built and tested on the ground via SBIR projects. Evaluation of this technique for providing oxygen at high pressure is continuing.

Beyond providing oxygen via electrolyzing water, alternative means to produce high pressure, high purity oxygen using gas phase electrolysis and mechanical compression was evaluated. The Solid Electrode Oxygen Separator (SEOS), a ceramic stack that dissociates diatomic oxygen at high temperature and transports monatomic oxygen across the membrane where molecular oxygen reforms, was demonstrated by measuring the oxygen product purity, flow and pressure. SEOS development accomplished the following:

1) Demonstrated the capability of producing high purity, high pressure oxygen that meets ISS high pressure oxygen needs for EVA and/or medical purposes.
2) Identified a moisture contamination source and technical solution. The glass within the SEOS unit was allowing water vapor into the flow stream at the high operating temperature. Low pressure and high pressure desiccant beds have been added and it is anticipated that the SEOS device should be capable of delivering Aviator's Breathing Oxygen (ABO) grade oxygen, even if the process air contains >5% CO_2, >100 ppm methane, or any other contaminant that may be been found in a crewed spacecraft atmosphere at levels >10 ppm. This capability must be further demonstrated via testing with helium and other trace contaminants.
3) Demonstrated a nominal delivery rate of 2 liters/minute (lpm). With modifications that increase the weight of the system by less than 10%, the modified device can potentially deliver emergency medical oxygen at 5-15 lpm and up to 100 psig delivery pressure, if the system is not operated for more than 250 hours.

2. *Oxygen Recovery*

The goal for the oxygen recovery technical area is to first increase the percentage of oxygen recovered from CO_2 above what has been attained aboard ISS and second enhance the recovery to a goal of >90%. Using the ISS Sabatier-based CO_2 reduction process as a starting point, emphasis has been placed on recovering hydrogen from the methane product gas. The recovered hydrogen is then recycled as a Sabatier process reactant feed. Methane processing has focused on developing the PPA through step-wise scaling from ½-CM methane processing rate to a full-scale 4-CM methane processing rate. Additionally, various Sabatier-based oxygen recovery architectures were explored to maximize performance while minimizing complexity. Finally, methane and hydrogen purification technologies were explored and advanced.

The results of testing the 1-CM system were used to scale the design to a 4-CM capability.[7] The 4-CM PPA employs a new reactor design to accommodate the larger gas flows. Initial testing has demonstrated significant improvement in overall performance.

In addition to PPA development, various Sabatier-based oxygen recovery architectures have been explored.[8] The most promising architecture involves a modification to Sabatier reactor operation whereby the reactor operates hydrogen-rich to eliminate CO_2 in the methane product stream. The methane exiting the Sabatier reactor is processed by a PPA. Downstream of the PPA a single gas separation step recovers hydrogen from the PPA effluent that is recirculated to the Sabatier reactor feed.

Gas separations technologies are central to the oxygen recovery technical area. Several methane and hydrogen purification technologies were explored to provide the necessary functions in the oxygen recovery architecture. Unfortunately, none of the approaches explored to date have proven successful and the search for suitable gas separations techniques and technologies continues.[9] Two potential gas separation approaches are under evaluation via the 2014 SBIR program.

Oxygen recovery techniques and process technologies that are not Sabatier-based, such as Bosch technology and electrolytic approaches to CO_2 reduction have been under development a low resource levels. In addition to NASA's efforts to develop a unique reactor series to carry out the Bosch reaction steps four projects are being pursued in 2015 to develop other alternative approaches to oxygen recovery. These approaches will continue to be developed to provide alternatives to the ISS-derived approach that is presently the focus of the most attention.

In 2014, NASA conducted a competition for alternate methods to recovery useful resources from carbon dioxide. The target was to recover at least 75% of the oxygen in the CO_2 as a product in the form of O_2 or H_2O. The Sabatier reactor in use on ISS is estimated to only be able to react 42% of the CO_2 produced by crewmembers due to a shortage of H_2 in the system. This is based on combining a theoretical maximum of 50% closure with non-ideal behavior such as start-up, shut-down, and separations processes. The H_2 is generated by water electrolysis as a byproduct of generating oxygen, and the amount of H_2 available not a separately controlled variable in the process. Thus, the technologies need to be able to improve how much CO_2 reacts without requiring additional hydrogen.

The selected technologies makeup a new Game Changing Development (GCD) project starting in 2015. The technologies selected represent a diverse set of techniques. The first project will convert CO_2 into O_2 and CO, and use a reactor to deposit carbon and convert the CO back to CO_2 to be recycled back to the beginning of the process. A second technique allows CO_2 and H_2O to enter the reactor together, creating product O_2 and syngas (H_2 and CO) which is reacted to deposit carbon and recycle CO_2 and H_2O back to the beginning of the process. The third project is an approach to using the Bosch process, combining CO_2 with H_2 from water electrolysis to deposit carbon and generate H_2O. All three of these have the potential to recovery significantly more than 75% of the oxygen present. The fourth process selected uses CO_2 and H_2O as input, and generates product O_2 and ethylene (C_2H_4). The C_2H_4 product vents less hydrogen per carbon molecule consumed than Sabatier, but would never achieve beyond 75% recovery. The technologies selected also explore other system benefits, such as safer operating points (lower temperatures and pressures) or minimal crew intervention.

C. Autonomous Control Capabilities

As future crewed space exploration missions extend beyond low Earth orbit (LEO), the ECLS system must become more tightly integrated with respect to core functionality, control, and equipment health monitoring. The role of the Earth-based mission control team will change to focus on slow changes and long-term trending of baseline performance. However, under circumstances that produce changes in performance that are more rapid than the communication turnaround time with the mission control team, ECLS control will require the crew to interact with the ECLS system equipment and advanced autonomous control software. The control system must either be self-adaptable or enable the crewmembers to adapt the ECLS system to rapidly changing situations, to solve system problems, and to efficiently anticipate and schedule maintenance.[10]

Ideally, an autonomous control system must manage the ECLS system in response to failures, functional trends, configuration changes, and environmental conditions that occur over periods in the range of tens of minutes. The control system must enable the ECLS system to operating seamlessly with no ground-based intervention under such circumstances while providing an appropriate level of automation that minimizes crew interaction as well as maintains safety-critical operations and procedures. When crew interaction is necessary, the control system must be intuitive and "crew-centered". Beyond providing functional autonomy and an appropriate automation level, additional aspects of autonomous control and process health monitoring include command and data handling (C&DH), software development and testing to achieve maturity comparable to core ECLS system process technologies, hardware-software complexity, and crew interfaces.[11] Work to achieve these objectives and reach a maturity comparable to core ECLS system process technologies requires the following:

1. Defining autonomous control of ECLS
2. Dividing autonomous ECLS roles between software and crew
3. Evaluating hardware-software complexity
4. Implementing ECLS process health monitoring
5. Defining command and data handling (C&DH) for software
6. Ensuring crew control over the level of automation
7. Ensuring resulting software runs on flight hardware
8. Developing and testing software
9. Defining crew interfaces

ECLS system technology development has centered upon core process technologies over software. Therefore, work remains to achieve software maturity comparable to many of the core process technologies under consideration for crewed space exploration missions beyond LEO.

A specific developmental opportunity exists for the PPA. The PPA is an excellent candidate for control and process health monitoring software because both the equipment and software are at comparable technical maturity levels. Focused development to build and demonstrate an autonomous software product for the PPA is the focus of present work with early products scheduled for delivery by the end of calendar year 2015.

D. Subsystem Architecture Integrated Testing

Evolving the ISS AR subsystem equipment architecture has been a leading strategy for enabling future crewed deep space exploration missions.[12-13] The ISS AR subsystem architecture was assessed according to functional trade spaces to establish a basis for comparison.[14] These trade spaces served to define the project work breakdown structure and integrated testing architecture for the AES Life Support System charged with developing atmosphere revitalization capabilities for exploration. Integrated functional architectures were tested in a sealed chamber in a progression beginning with the ISS AR subsystem and followed by two successive alternative architectures that retained a strong ISS-derived process technology core.[15] The testing series began with the Resource Recovery Functional Demonstration (R2FD) test to establish the basis for comparison. The R2FD test used ISS AR subsystem flight-like developmental hardware configured according to the ISS AR subsystem architecture. The Atmosphere Resource Recovery and Environmental Monitoring (ARREM) Project's Cycle 1 and Cycle 2 tests used many of the same test articles as the R2FD test but were configured differently to realize targeted functional improvements, subsystem complexity reductions, and mass savings.

The Cycle 1 testing series demonstrated that an ISS-derived architecture is feasible for exploration mission applications.[16] The Cycle 1 architecture was found to provide equivalent or improved performance relative to the ISS SOA. The simple TCC component reconfiguration is projected to reduce AR subsystem mass by at least 12 kg and volume by 15 liters. Potential exists for using smaller CO_2 removal beds and other components for exploration mission applications because the ISS equipment is designed for greater metabolic loads compared to the 4-CM exploration metabolic load. The degree of loop closure provided by the CRA was adequate yet a higher degree of loop closure must be demonstrated to reach exploration figure of merit goals.

The Cycle 2 testing series built on Cycle 2 and included upgrades to the CO_2 removal equipment and additional changes to the architecture by incorporating the trace contaminant control components at different locations in the subsystem and test chamber ventilation configurations.[17] Similar to Cycle 1, a series of static metabolic challenge loads was used to challenge the architecture. The Cycle 2 test series added an additional phase that subjected the architecture to a dynamic 4-CM metabolic load. As was observed during the Cycle 1 testing series, the ISS-derived architecture was capable of handling the static loads. The Cycle 2 architecture also performed well under the 4-CM dynamic load. The oxygen generation unit operated successfully and safely without a nitrogen purge allowing an additional 22.7 kg (50 lb) mass reduction over the ISS AR subsystem. Including this mass savings as well as the potential for 30% mass reduction of the power supply module, the projected mass savings for an ISS-derived core AR subsystem is at least 48.3 kg (106.5 lb) without considering additional redesign of the CO_2 removal equipment. It is recognized that achieving additional oxygen recovery may offset these mass savings. Overall, the Cycle 2 testing series demonstrated that a second generation ISS-derived AR subsystem architecture is capable of handling the dynamic metabolic load representative of an exploration mission without anomaly or excursion outside habitable limits.

III. NASA Investments: Water Recovery and Management

Although an integrated life support system is made up of a variety of systems, a major driver in the sizing of a life support system is the Water Recovery System (WRS). As mission durations increase, recycling of water becomes critical. Stored water is inadequate, and wastewater sources must be recycled into potable water. The state-of-the-art (SOA) WRS used on-board the ISS relies on a high rate of consumable use (0.032 kg expendables consumed per kg of potable water produced) and has known issues with fouling by particles thereby limiting the recovery rate from urine to approximately 74%. Combined with the percentage of water recovered from humidity condensate, the current overall ISS water recovery rate is 88%. For exploration systems the goal established by the Human Health, Life Support, and Habitation Systems Roadmap[18] is to reach 98% water loop closure with reduced expendables, so there are significant gains to be made.

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

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

A. ISS Upgrades

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

1. Urine Processor Assembly

Upgrades to the Urine Processor Assembly (UPA) include improving the mechanical robustness of pump drives used in both the Fluids Control and Pump Assembly (FCPA) and Pressure Control and Pump Assembly (PCPA) and of a manifold-mounted valve body assembly used in the FCPA. Alternate materials that combine required corrosion resistance with greater mechanical strength are being developed for use in the Distillation Assembly's (DA) centrifuge and compressor bearings. Alternate materials are also being evaluated for possible use in DA compressor gears. The existing O-ring belt that drives centrifuge rotation and which is prone to slippage is being evaluated for possible replacement with an alternate configuration. And the internal liquid level, which is intended to detect off-nominal fluid accumulation within the DA's evaporator, is being redesigned to reduce false positive indications. Looking ahead to exploration, parametric modeling and ground testing is being conducted to determine to what extent the existing UPA technology could be downsized and optimized to better improve resource utilization (size and power) while preserving the operational heritage being accumulated through ISS operations.

Over the past year on-orbit failures of the FCPA have dictated a change in strategy for the upgrades to the FCPA, PCPA, and DA. To ensure a robust sparing posture, rebuilding of the failed FCPAs was deemed a priority over completing the upgrade designs. As a result completing the upgrades to the PCPA and DA were phased into FY16. The upgrades to the FCPA are planned to be included in near term builds. Based on successful ground testing, the

FCPA manifold-mounted valve body assembly has been incorporated into the rebuild of FCPA SN002 and was delivered to the ISS on the SpaceX-6 flight. The pump drive upgrade is planned to be incorporated into the FCPA SN004 rebuild planned to start towards the end of FY15. The decision will be finalized based on achieving approximately 2000 hours of run time in the UPA test bed. The pump drive upgrades were installed in both the FCPA and PCPA test bed units in January 2015.

Alternative designs to the O-ring drive belt in the DA was completed. The alternate designs included a Gates belt drive and a V-belt drive. Both designs are promising alternatives. Unfortunately, the extensive amount of redesign to incorporate either design will not allow for incorporation into the current DA design. However, the designs will be considered if a new DA design is pursued pending results of the parametric modeling and ground testing effort. Work continues developing and testing bearings using Nitinol. Nitinol bearings for the centrifuge and compressor have been manufactured. Centrifuge bearings were delivered and incorporated into the DA test bed unit late last year. The bearing experienced a failure. As a result the material formulation to strengthen the bearing and the bearing heat treat process was changed. New bearings were manufactured and delivered. The bearings will be incorporated into the DA upon completion of the run time needed for the FCPA pump drive upgrade. Gear materials studied included polyphenylene sulfide (PPS) and Nitinol. PPS was selected since it would not absorb as much water as Vespel that is the current gear design material. During assembly yielding of the PPS material showed the mechanical properties of the PPS were not suitable in this application. Manufacturing of Nitinol gears continue.

2. *Water Processor Assembly*

Tests are being planned to determine to what extent the operational life of Water Processor Assembly (WPA) multifiltration beds can be extended by taking better advantage of the contaminant breakthrough profile that has been observed in actual operation. Currently, WPA multifiltration bed changeouts are based on initial breakthrough of ionic contaminants from the second (of two) installed beds. However, data suggests that initial breakthrough contaminants (bicarbonate, acetate, and possibly ammonia) may be safely and effectively allowed to pass into the downstream catalytic reactor for oxidation, thereby allowing the installed multifiltration beds to remain in position longer prior to changeout. Ground tests are being conducted to validate this approach.

Residual organics present in the effluent of multifiltration beds are oxidized in a catalytic reactor operated at elevated temperature. Undesirable consequences of elevated temperature include the need to maintain system pressure above the flash point of water. Additionally, long duration exposure to elevated temperature stresses the integrity of internal polymeric seals required for leak prevention. In order to alleviate these consequences, and to take advantage of advancements made in the field of heterogeneous catalysis over the last two decades, NASA will be supporting the development and comparative testing of one or more candidate catalyst formulations with the potential to provide the required level of oxidation potential and life under ambient temperature conditions. In 2014 United Technologies Aerospace Systems and UPMQUA were awarded contracts to develop new catalysts. The studies are planned to be completed in 2015.

B. AES Water Recovery

Under the AES Life Support Systems (LSS) project, the wastewater processing and water management task seeks to develop advanced water recovery systems to enable NASA human exploration missions beyond LEO. The primary objective of this task is to develop water recovery technologies critical to near term missions beyond LEO. The secondary objective is to continue to advance mid-readiness level technologies to support future NASA missions. In 2014-15 the AES LSS Project Water Task is focused on maturation and testing of the Cascade Distillation System, advancements in water chemistry, and brine treatment technologies.

1. *Cascade Distillation*

The Cascade Distillation System (CDS) represents a rotary distillation system design with potential for greater reliability and lower energy costs than existing distillation systems. The AES LSS project continues to advance the technology through targeted improvements based upon the results of the 2009 comparison test and recommendations of the expert panel. Further information on the CDS can be found in Ref. 19.

FY14 accomplishments included fabrication and testing of a prototype thermoelectric heat pump, performance testing with flight-like waste streams and design of a second generation prototype distiller and system. Results of the FY14 CDS testing are summarized in

Table 2.

Table 2. CDS Performance Testing Summary

Test Name	Objective	Results
CDS Benchmark Test	• Compare CDS performance with performance in 2009. • Validate performance of the new CDS bearings and other CDS and test stand upgrades.	• 12 Runs Completed • > 38-L Processed • Specific power ~85 W-hr/Kg
ISS Analog Performance	Evaluate CDS performance with current ISS urine pretreatment.	• 3 Runs Completed • >17-L Processed Wastewater • Specific power ~96 W-hr/Kg
ISS Alt-Pretreat Performance	Evaluate CDS performance with new ISS urine pretreatment.	• 3 Runs Completed • ~ 30-L Processed • Specific power ~ 105 W-hr/Kg

In FY15, a preliminary design review for the CDS as well as design reviews for the Cascade Distiller and the ground test bed system were conducted. Detailed discussions and documented comments are being addressed leading to a CDS 2.0 CDR to be conducted at the end of FY15.

2. *Water Chemistry Objectives*

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

Wastewater Stabilization - The goal of the wastewater stabilization method task is to identify and evaluate low-toxicity wastewater stabilization alternatives to the current SOA while maintaining the stabilization functions of preventing urea hydrolysis and microbial growth. First, stabilization prevents the breakdown of urea (urea hydrolysis) into ammonia, a toxic gas at high concentrations. Second, it prevents the growth of microorganisms, thereby mitigating hardware and water quality issues due to biofilms and planktonic growth. Current stabilization techniques involve oxidizers and strong acids (pH=2), such as chromic and sulfuric acid, which are highly toxic and pose a risk to crew health. The purpose of this task is to explore less toxic stabilization techniques. Benchtop rotary evaporator testing of a candidate Bronopol formulation was recently completed; changes to the formulation are being assessed in an effort to mitigate precipitant formation that was observed.

Silver Biocide - The purpose of the silver biocide task is to identify methods for adding silver biocide to water on-orbit during both operational use and dormancy, as well as methods to maintain silver concentration in stored water. Silver biocide offers a potential advantage over iodine, the current SOA in US spacecraft disinfection technology, in that silver can be safely consumed by the crew. Low concentrations of silver (<500 µg/l) have been shown to kill bacteria in water systems and keep it potable. Silver does not require hardware to remove it from a water system prior to consumption, and therefore can provide a simpler means for disinfecting water that requires fewer consumables than the ISS SOA. The Russian segment of the ISS has utilized an electrochemically generated silver solution, which is colloidal in nature. Reliably providing a silver biocide to drinking water by electrochemical means would reduce mass required for removing another biocide such as iodine from the water. This could also eliminate the need for crew time to replace iodine removal cartridges. Conditions conducive to silver particle vs. ionic species formation are being characterized. An SBIR Phase II contract to develop a silver biocide delivery system is pending[20].

Future long term missions would benefit from electrochemically produced silver as the biocide could be produced on demand and requires only a small concentration to be effective. It has been hypothesized that silver colloids provide a reservoir for the dissolution of ionic silver, the biocidal form of silver.

3. *Brine Dewatering*

Brine Dewatering seeks to address the goal of 98% water recovery established by the Human Health, Life Support, and Habitation Systems roadmap[18], 98% water recovery cannot be achieved without recovery of water from brine. It is a challenging problem. When wastewater brines are dried, the residual is inevitably a viscous goo, laden with particles of precipitated solids. This brine residual causes several problems for traditional recovery systems, such as clogging pitot tubes, causing bearings to seize, and fouling heat transfer surfaces.

In FY14, an evaluation was completed of three NASA developed and three SBIR Phase II brine dewatering technologies for applicability to an exploration mission architecture. The technologies evaluated include a Brine Residual In-Containment (BRIC) [21], a Brine Evaporation Bag (BEB) [22], a Forward Osmosis Brine Dryer (FOBD), and an Ionomer-Membrane Water Processor (IWP) [23]. A nanomaterials spray dryer[24], and an Ultrasonic Brine Dewatering System (UBDS) [25] were also slated to be tested but upon initial operation both units were found to be non-functional so they were eliminated from the evaluation.

In FY15, the LSS project will continue development of the NASA developed brine dewatering technologies and explore mitigation of common roadblocks associated with brine dewatering in a microgravity environment, including reliable operations, and safe handling and disposal of the remaining brine solids. The plan is to further develop the brine dewatering technologies and then down select to the best technologies at the end of FY15. The down selected technologies will be candidates for testing on the ISS.

4. *Alternative Water Processor*

In FY14, the Next Generation Life Support element within the Space Technology Mission Directorate (STMD) Game Changing Development project completed work on the Alternative Water Processor (AWP) task. By the end of the project, the integrated system of a Biological Water Processor (BWP) and the Forward Osmosis Secondary Treatment (FOST) system were able to recover 91% of the input wastewater. It's estimated that the new systems could save 29% of the consumables mass than state of the art technologies would require to perform the same functions in future exploration missions. However, the BWP was unable to meet the goals for removing ammonium (55% instead of the 75% goal) and total organic carbon (83% instead of the 90% goal). Analysis of the results show that this is not a failure of the system design, but an inherent limitation of the nutrient ratios in the feed wastewater. Simulations of each component were also developed and used to examine system architecture or optimal ways to achieve performance. For example, simulations suggest that use of highly concentrated phosphoric acid to acidify the wastewater fed to the FOST would result in overall savings in consumable resources by improving product quality and reducing downstream polishing requirements.

In FY15 the LSSP is continuing the AWP work by collaborating with Texas Tech University on a rectangular cross-flow reactor design, build and test. This reactor aims to significantly reduce the mass and volume of the BWP.

In 2015 a new GCD project was initiated to explore a possible synthetic biology technique for use in a life support system. The AWP project had explored the use of lipid membranes for water separation processes in the FOST. The biomembrane task will examine what other organic materials would perform well as water separation membranes, as well as what organisms could be engineered to produce those molecules. The project will also explore structures or other tools necessary to make any product molecules align into a useful separations membrane. The long-term goal of the technology development is to create a highly robust and reliable system because the membrane would be continuously healed and regenerated as organisms in the system produce the target compound.

C. Water Recovery SBIRs

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

- Silver Ion Biocide Delivery System for Water Disinfection (Reactive Innovations, LLC)[20]
- Miniaturized, High Flow, Low Dead Volume Preconcentrator for Trace Contaminants in Water under Microgravity Conditions (Thorleaf Research, Inc.) [26]
- Water Recovery for Regenerative Life Support Systems (Creare, Inc)[27]
- Advanced Electrochemical Oxidation Cell for Purification of Water (Vesitech, Inc)[28]
- Ionomer-membrane Water Processor System Design and EDU Demonstration (Paragon Space Development Corp)[29]

IV. NASA Investments: Waste Management

Waste management inside a fixed volume human spacecraft has unique integration issues and the NASA ECLSS roadmap defines the major challenges. In addition to the ECLSS domain, waste management crosses several domains including habitation and logistics. Waste management within ECLSS primarily addresses solid waste but has it also has liquid waste components, i.e. urine, in common with the Water Recovery area. Solid waste management is divided generally into waste reduction, trash management, and human metabolic waste management. An overview of these three waste management areas and NASA current and planned research are described below. Completed or previous waste development work is described in earlier papers[30, 31]. The AES Logistics Reduction Project (LR) and other NASA programs are developing technology in each of these areas. AES LR trash modeling for a 6-person one year mission predicts a total of 8,060 kg of crew-related logistics is required. These logistics contribute the majority of an estimated 3840 kg of waste. The contents of the AES LR logistics and trash model were defined previously[32] and the latest estimates represent a Mars transit mission that specifically analyzed the potential volume savings of several technologies[32].

A. Waste Reduction

Waste minimization of trash includes consideration of the original consumables that are used and become trash. After hygiene items, clothing is the largest crew consumable waste product[32]. Crew clothing is primarily cotton based on the ISS and requires significant consumable up mass, approximately 75 kg/crew-year. There is no laundry capability on ISS. AES LR Advanced Clothing Systems (ACS) investigated a limited number of commercial off-the-shelf exercise and routine wear clothing articles, including some with anti-microbial treatments. In 2013, ACS performed ground tests with approximately 100 participants under ISS aerobic exercise conditions with a range of clothing materials[31]. Initial results indicated that some of the fabrics (in particular certain types of wool) could extend wear time. This testing allowed selection of a variety of wool, modacrylic, and polyester clothing articles for an ISS technology demonstration on increments 39/40 in the summer of 2014 with 3 US and 3 Russian crew members. The crew completed baseline ground testing evaluations in January 2015. The data is currently being analyzed and will be published later in 2015. If the on-orbit experiment validates the ground test results, longer wear and lighter weight fabrics could reduce mass and volume for exploration missions. Additionally, in 2015, ACS is performing microbial proliferation and lint generation characteristics of the proposed fabrics. The AES program will make recommendations to ISS for incorporation into future crew provisioning decisions.

AES LR completed a trade study of several clothes cleaning technologies including water based laundry and non-water freshening systems such as ozone or ultraviolet light. The study used an equivalent system mass analysis technique to compare the benefits of laundry for both existing ISS cotton clothing and initial AES LR ACS recommendations. Although laundry reduces the logistical mass of clothing, the laundry system utilizes vehicle resources (power, water, pressurized volume, etc.). When the vehicle resource penalties are accounted for, simplified laundry systems breakeven for missions of approximately 10-14 months compared to disposable clothing[32]. This result has a significant implementation impact to exploration architectures. If Mars transit is typically 6 months, the lowest mass and most reliable approach is disposable clothing. Development of a laundry system can be delayed until Mars surface missions (approximately 17 months) where the duration is long enough and the Mars partial gravity will greatly simplify any required liquid/gas/solid separations in a laundry system. The other conclusion is further development of advanced long wear clothing, towels, and washcloths is the best way to reduce mass for the early phases of exploration, including Multi-Purpose Crew Vehicle (MPCV). In addition to clothing minimization, AES LR is also researching two other logistics minimization technologies that can reduce the solid trash burden.

First, a large percentage of logistics are launched in cargo transfer bags (CTBs). Some CTBs are reused for storing dry trash, but many CTBs become trash themselves after the logistics are consumed. AES LR is developing Multipurpose cargo transfer bags (MCTBs) to allow logistics bags to be unfolded on-orbit to a flat configuration and used to outfit the crew cabin for sleep compartments, acoustic blankets, or contingency water processing. This would reduce the number of used CTBs that become trash. In 2015, AES LR is developing a MCTB specifically designed to reduce acoustic emissions from the ISS crew exercise treadmill. Four acoustic MCTBs will be used to protect cargo during launch to ISS, like any standard CTB, but then unfolded and applied to two ISS rack surfaces. This ISS demonstration will demonstrate a zero trash residual approach rather than flying dedicated acoustic blankets that would have required two CTBs to package them. These two CTBs would become trash residual.

Second, ISS cargo is packaged to minimize crew time which results in logistics being grouped in a manner that is not volumetrically ideal. Currently filler foam is used between CTBs and cargo to fill the voids around the grouped items. Filler foam can represent 15% of the total cargo volume and all the filler foam becomes waste. If the crew could readily find items in densely packed CTBs that are optimized for volume, then filler foam could be substantially reduced which would reduce trash volume. AES LR is developing Radio Frequency Identification (RFID) technology to allow 3D localization of crew items with RFID Enabled Automated Logistics Management (REALM) [33, 34]. In 2015 the initial REALM-1 hardware for monitoring ISS cargo movement though the Node 1 and Node 3 hatches will be prototyped. The REALM-1 hardware will fly in 2016 and eventually be augmented with mobile (REALM-2) and dense RFID (REALM-3) readers. In 2015, the ISS program is implementing an initiative to rapidly increase RFID tagging of cargo to take advantage of this technology to support the initial REALM-1 one year experiment on ISS.

NASA has funded SBIR phase I development of an advanced hybrid RFID-infrared inventory tag system with Advanced Systems & Technologies, Inc.[35]. The hybrid tag should utilize the planned REALM-I technology demonstration and allow 3D localization accuracy to the 2-3 centimeter resolution, which is an order of magnitude better resolution than RFID alone.

NASA has also funded SBIR phase I development of a multifunctional superomniphobic (water and oil repellant) and antimicrobial coating that could be applied to both fabric and metallic surfaces[36]. The coatings could substantially reduce the number of wipes required for cleaning cabin surfaces. Currently ISS utilizes approximately 230kg of wipes per year for both crew hygiene and cleaning cabin surfaces.

B. Trash Management

AES LR is performing research and design of a heat melt compactor (HMC) for exploration trash processing. HMC technology can be complimentary to other trash managements, such as, trash to gas (TtG) previously investigated by AES LR[31]. In 2015 AES LR has continued HMC fabrication and assembly of a high-fidelity HMC second-generation unit (Gen2) for ground testing. The HMC provides a 7:1 reduction in trash volume via compression and application of heat to produce microbially stable, dry trash tiles. The plastic content of space trash softens during heating to hold the non-plastic trash in a compressed state when it cools. HMC tiles can be the final disposal form or an interim storage until more fully processed by TtG technologies. The HMC will be able to process approximately 1 kg of mixed trash and recover approximately 200 mL of water per batch. The major design challenges of the HMC technology are designing the compaction chamber and its steam vents and seals to be tolerant of the softened plastic and caramelization of food residuals.[38] The major process design challenges include ensuring adequate heating of the low conductivity trash to inactivate microorganisms and sufficiently dry the trash. The Gen2 HMC should be completed in May 2015 and initial check out testing will be performed to determine the performance characteristics.

A complementary activity is a Phase I SBIR with Orbital Technologies Corporation to develop a microgravity compatible membrane based water recovery system that could eventually be integrated to an ISS flight experiment of HMC technology[39]. Water recovery challenges from HMC include: unsteady steam generation rates from trash, tolerance of a wide range of organic volatiles from trash, and low relative humidity of the non-condensable gas effluent to allow compatibility with downstream HMC source contaminant control systems.

C. Human Metabolic Waste Management

The effective collection of metabolic waste is a significant challenge in microgravity, due to its biological nature and objectionable odors that can rapidly create unhygienic conditions in a spacecraft. Escaped material can soil the toilet hardware, the crew cabin, and the crewmember. This can result in considerable crew time to wipe down and clean surfaces and a considerable wipe mass over the mission. AES LR is working with ISS to develop a Universal Waste Management System (UWMS) that is very compact and compatible with Orion and future exploration mission vehicles[40]. In 2014, NASA developed the detailed performance and program requirements for the UWMS to support both an ISS technology demonstration in 2018 and the Exploration Mission (EM2) MPCV mission in 2020 timeframe. In 2015, NASA is evaluating proposed work and plans to make a selection of the future path for UWMS development. To improve the UWMS capture efficiency, compared to previous shuttle and existing ISS toilets, extensive crew member evaluations of seat geometry, air flow, and funnel positioning are being performed to significantly reduce the potential for urine and fecal escapes are being conducted by AES LR in 2015.

In addition to a primary waste collection system, NASA is also interested in low mass contingency urine collection systems. NASA has funded SBIR phase I development of a capillary fluid system using superhydrophillic coatings for contingency urine collection with Innosence, LLC[41]. The use of a capillary system provides a robust unlike redundancy option for MPCV rather than a manifesting a spare rotary urine separator.

NASA is also using the SBIR Select program to request addition development in solid and liquid waste management for human space craft, specifically for 'human solid waste management' and 'water recovery from brine'[42]. Selections from this solicitation will occur in the summer of 2015 and will be described in future papers.

D. An Integrated Solid Waste Management Approach

Combining trash processing with logistics minimization and logistics reuse can significantly reduce waste volume and provide increased habitable volume. Figure W1 represents existing ISS trash flow and a possible combination of waste management strategies (green boxes on left figure)[34]. RFID tagged logistics that are monitored by the REALM technology are indicated by a REALM box in W1. As indicated previously, the ability accurate logistics tracking allows volumetrically denser tracking which reduces packaging foam. LR analysis indicates combining technologies has the potential to recover about 21 m^3 of habitable volume. The details of using of trash as a source of propellant, TtG in Fig. 2, relative to the penalties of trash jettison was analyzed by AES LR in 2014[43].

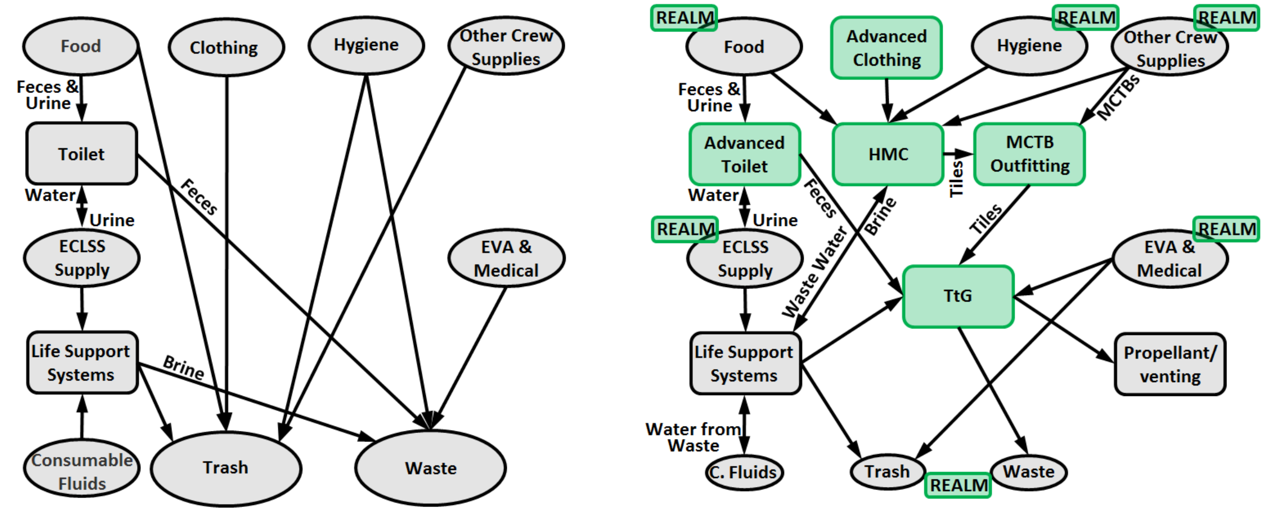

Figure 2. Logistics to trash flow schematic for the ISS (left) and implementing all LR technologies (right).

V. NASA Investments: Environmental Monitoring

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

- Air Quality
  - Trace Volatile Organic Compounds (VOCs)
  - Airborne particles
  - Major Constituents (typically O_2, N_2, CO_2, H_2O, H_2, and CH_4)
  - Monitoring target gases (formaldehyde, CO_2, O_2, system chemicals, etc.)
- Water Quality
  - Identify and quantify aqueous species
  - Biocide levels
- Microbial Monitoring
  - Identify and enumerate air, water, and surface samples
  - Presence of coliform in water
- Acoustic Environment
  - Real-time acoustic monitoring

A. Environmental Monitoring Gaps and Needs

These functional needs, i.e., gaps that are required to address identified risks to crew health during Exploration-class missions have been identified. Current, operational hardware onboard ISS served as the logical starting point to meeting the functional needs. Specific limitations were identified with the current ISS hardware used in each discipline as they apply to Exploration missions. However, the following limitations were found common to all the current ISS hardware for any missions beyond LEO.

- Reliance on return sample and ground analysis
- Require too much crew time
- Constraints on size, mass, and power
- Lack of portability
- Obsolescence
- Insufficient battery life
- Insufficient calibration life

- Limited capability to measure unknowns which may be present in future exploration vehicles
- Operations after period of dormancy
- Need for consumables
- Insufficient shelf life

A concerted 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. Crewed spaceflight has employed a wide variety of analytical instruments from powerful, broadly applicable analytical platforms such as gas chromatography-ion mobility spectrometry (GC/IMS), gas chromatography/differential mobility spectrometry (GC/DMS), gas chromatography/mass spectrometry (GC/MS), and Fourier Transform/Infrared Spectrometry (FT/IR), to fairly simple, very specific sensors such as electrochemical cells for target gases such as carbon dioxide, combustion products, and system chemicals. The following provides a short summary of the activities in 2014-2015 within the Agency to address the gaps and needs.

B. Air Quality – Major Constituents

Multi-Purpose Air Monitor (MPAM) - 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, that would be used for the Orion spacecraft and also serve as an upgrade to the ISS Major Constituent Analyzer (MCA).[44] The MPAM is a magnetic-sector mass spectrometer similar to the current MCA on board ISS, but is designed to replace five of the seven orbital replacement units (ORUs) used by the current MCA. As a “drop-in” replacement, the MPAM will have the ability to interface to the existing sample distribution system and INTSYS Multiplexer/Demultiplexers (MDMs). The development of MPAM continued through 2014-2015.

C. Air Quality – Major Constituents and Trace VOC Monitoring

Spacecraft Atmosphere Monitor (SAM) – SAM is an AES LSS sponsored technology demonstration development led by JPL, and in partnership with JSC, aiming to achieve a major size reduction of an autonomous flight GC/MS, without loss of analytical capability.[45] The SAM instrument will monitor both the major constituents (CH_4, H_2O, N_2, O_2, CO_2, and argon) and trace volatile organic compounds. To achieve this capability SAM’s next generation GC/MS couples a microelectromechanical system (MEMS) based Gas Chromatograph (GC), jointly developed by JPL and Cbana, Inc. under SBIR sponsorship[46], to a JPL designed Quadrupole Ion-Trap Mass Spectrometer (QITMS). The SAM QITMS mass range is 10 to 500 daltons (Da) with better than unit mass resolution over the entire mass range. Through employment of the MEMS GC, SAM will need a much reduced carrier gas load (up to 100 times less), enabling the use of a miniature and robust ion/getter pump, instead of the conventional turbomolecular vacuum pump. These developments will yield an instrument volume of approximately 25.4 cm x 22.9 cm x 20.3 cm (10 in x 9 in x 8 in), that weighs less than 9.0 kg, and consumes about 40W of power during nominal operations that are similar to the MPAM requirements.

D. Air Quality – Airborne Particles

There is currently no active work in this area of Air Quality.

E. Air Quality – Monitoring Target Gases

1. *Multi-Gas Monitor*

The Multi-Gas Monitor (MGM) is an ISS-sponsored optical target gas monitor technology demonstration based on tunable diode laser spectroscopy (TDLS) using an integrating sphere optical platform. Developed by Vista Photonics, Inc.[47] and launched on 37Soyuz in late 2013 and installed in February 2014, the MGM is designed to monitor oxygen, carbon dioxide, ammonia, and water vapor, and is nominally located in the NanoLabs rack in the Japanese Experiment Module (JEM), collecting data every 30 seconds. With its integrated battery, MGM is also designed for remote operations throughout the ISS. MGM continues to be operated on board ISS for a year and an update of its performance during 2014-2015 is the subject of another paper at the 2015 ICES.

2. *Combustion Product Monitor (CPM)*

Under the sponsorship of the AES LSS project, JPL has developed low-power, solid-state lasers emitting at the wavelengths required to monitor combustion products.[48] Using these lasers, JPL with support of Port City Instruments has constructed a 5 channel (CO, CO_2, HCN, HF and HCL) optical combustion products monitor. This proof of principal instrument currently is under calibration, validation and characterization at Glenn Research Center (GRC). Results of these tests are presented in a separate paper[49] Next version of this CPM will include the lessons learned from the development and testing of the instrument and will be built to the mass, volume and power specifications that are being developed by the Orion program. Laser spectroscopy techniques will produce instruments that will have a multi-year lifetime without the need for consumables, re-calibration, or maintenance.

As part of post landing contingency monitor that can distinguish between ammonia and hydrazine, the AES LSS project has sponsored a seedling effort at JPL with the goal of demonstrating that tunable laser spectroscopy is capable of performing the task. To this end, a prototype instrument was constructed from Commercial Off-the-Shelf (COTS) parts, including the laser. This instrument has demonstrated unambiguous hydrazine measurement in the presence excess ammonia. The next phase is to develop low-power, semiconductor lasers that will be incorporated into the Engineering unit with the mass, volume and power specification being developed by Orion program.

3. *Rapid Analysis Self-Calibrating (RASCal) Array*

RASCal is an AES LSS funded project being performed by JPL to develop advanced array analysis and hardware to dramatically improve response time and calibration time.[51] This technology is the logical progression of the Electronic Nose (ENose) event monitor, also developed by JPL, which flew on STS-95 in 1998[52], and was an ISS technology demonstration in 2009[53,54]. RASCal uses support vector machines, in the data analysis, to shorten the time to identify an event. The ability to incorporate time-dependent information in the data analysis has also decreased the time for array training which leads to decreased integrated sensor exposure to analytes, which will also help extend sensor lifetime. Drift correction is used to both improve results and to extend the lifetime of the array calibration. FY 15 effort is focused on applying this technology to monitor safety of onboard batteries in collaboration with JSC.

4. *Real-Time Formaldehyde Monitor for the ISS*

Under a NASA SBIR Phase 1 contract[53], Southwest Sciences conducted initial development of a sensor for the continuous, real-time monitoring of formaldehyde at levels nominally found in the ISS cabin atmosphere and in the presence of potentially interfering volatile organic compounds at comparable or even at higher concentrations. Detection of formaldehyde was accomplished down to 30 parts-per-billion with good signal-to-noise. Extensive spectroscopic evaluations found that none of the other known gases in the ISS will interfere with these measurements. A 10 ppb detection limit is possible with longer integration times (approximately 100 seconds) in the presence of other aldehydes in the ISS atmosphere, such as acetaldehyde. A preliminary plan for a stand-alone, compact Phase 2 prototype was developed. Although a proposal for Phase 2 was submitted, it was not funded. This is currently a candidate for technology demonstration through the ISS Program using NanoLabs integration.

5. *SBIR Projects*

Development of a laser-based combustion products (CP) monitor using wavelength modulation spectroscopy was sponsored under NASA SBIR Phase I and II contracts[50]. The device will monitor, in real-time, the concentrations of carbon monoxide, carbon dioxide, hydrogen cyanide, and carbon dioxide at concentration levels relevant to pre-combustion events and with a 1 second response time. The device is a hand-held, battery operated unit. Development of the SBIR Phase II prototype continues and is scheduled for testing at Glenn Research Center in the spring of 2015. Testing will include calibration, single gas testing, testing for potential interferences, and under combustion conditions of actual ISS conformally-coated power boards.

F. Water Quality – Identify and Quantify Aqueous Species

1. *Organic Water Monitor (OWM)*

The Organic Water Monitor is a device being developed by the JPL for the AES program to expand existing gas GC/MS capabilities to address water analysis. Integration of the OWM with SAM has the potential for a combined trace VOC, major air constituents, and water analyzer system for future crewed spaceflight[55]. Although the water monitoring effort was envisioned to include inorganics as well as minerals, due to limited resources it was directed to focus on organics only. This instrument was selected as part of the water monitoring suite (include microbial and silica monitoring) by ISS for a fast track flight technical demonstration. It is anticipated that this suite of instruments be delivered by December 2015.

2. *Portable Sensor for Rapid in Situ Measurement of Trace Toxic Metals in Water*

Under NASA SBIR Phase I and II contracts[56], Giner, Inc. conducted initial development of a sensor to detect select trace toxic heavy metals (Ag, Cd, Mn, Ni, and Zn) in water. Using an automatic side-stream sampling technique which can be integrated with the Water Recovery System, the electrochemical sensor will only require small volumes of water to detect metals in the low parts-per-billion range. The sensor is projected to show long-term repeatability and reliability, require minimal maintenance or user calibration time, and provide near real-time data. Giner has partnered with Johnson Space Center for testing of the sensor and determine the appropriate concentrations. The Phase II contract ends July 2015.

3. Miniaturized, High Flow, Low Dead Volume Pre-Concentrator for Trace Contaminants in Water under Microgravity Conditions

Initial development of a miniaturized high flow, low dead-volume pre-concentrator for monitoring trace levels of contaminants in water under microgravity conditions was conducted under a NASA SBIR Phase I contract.[57] The goal was to demonstrate feasibility for such a system and to develop a detailed design for fabricating and demonstrating prototypes in Phase II. Phase I of this project ended in November 2013 and a concept design has been developed for Phase II submission. The Phase II plan involves the development of the preconcentrator design into a miniaturized water preconcentrator module. Usually, this preconcentrator is a small cylinder shape with 1/8 of an inch in diameter and 1 inch in height filled with a VOC adsorbent (e.g, Carboxen).

The 2014 SBIR call for proposals in environmental monitoring was restricted to “monitoring systems for mineral species in water and wastewater”.

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

Two proposals were submitted to the JSC Payloads Office for consideration. The first proposal called for a demonstration feasibility study be performed onboard ISS using a COTS adendosine triposhphate (ATP)-based system. This system employs a COTS-based unit coupled to ATP chemistry adapted for application to ISS, with the goal of having an analysis performed in approximately 1- minute. Unfortunately, the unit is unable to distinguish between viable and non-viable microbes. What is reported by this unit is total microbial burden (both bacterial and fungal). ISS microbial kits report results in colony forming units per area, and some correlation between the two data sets will need to be developed. This proposal is under review.

A microbiological monitoring formulation activity for water and air monitoring has been established. This is a multi-center effort to evaluate commercially available quantitative or semi-quantitative molecular-based methodologies such as polymerase chain reaction (PCR).[58] This effort initially identified commercial platforms that require minimal modifications for operations in microgravity followed with proof-of-concept testing of the top candidates. The second proposal involves the use of molecular-based technologies to identify and quantify microbes in ISS. This proposal calls for the demonstration of a COTS Polymerase Chain Reaction (PCR) system developed by Biofire Diagnostics, Inc for military field use. Simply put, PCR is a process in which genetic material is amplified by a series of denaturation, annealing, and extension steps. Amplification of genetic material allows for identification and quantification of microbes. This technology demonstration will validate the PCR chemistry and the performance of the COTS unit, as compared to ground controls. This proposal is under review.

In order to effectively monitor microbial burden, sample concentration is a must since crewed vehicle’s air, water, and surface are kept clean and are extremely low in biomass. The existing or any proposed microbial burden estimation system, like RAZOR, requires a sample concentration module. To this effect, JPL under AES LSS project funding as well as internal JPL program funded a pilot study to verify the use of the Mars Program Office validated COTS system to concentrate large volume of water sample. The prototype developed in FY’14 is promising and its feasibility to work in the microgravity conditions should be explored. This concentrator is a pencil size cylinder filled hollow fiber membrane filter. AS the water passes through the concentrator, the microbes are captured within the lumen of the fiber. Following capture, the microbes are eluted using a wet foam elution process and delivered to a detection system. In addition, after the feasibility study, the concentrated samples should be integrated with microbial detection system. A collaborative work with multi-center effort is underway in utilizing this “smart sample concentrator” with the ISS program funded WetLab 2 or the above mentioned iATP or recently selected for flight technical demonstration RAZOR system.

H. Acoustics Monitoring – Real-Time Acoustic Monitoring

Acoustic surveys are now performed once every two months using hand-held devices at 60 locations on the ISS requiring a significant amount of crew time. In addition, the sporadic monitoring program is not adequate and there is a need for an automated, continuous acoustic monitoring system that is efficient in power consumption (long battery life), accurate, highly integrated, wireless connected, scalable, small and lightweight. Under a NASA SBIR Phase I and Phase II contracts[59], three capabilities were developed, tested, and validated: (1) the design of a data collection subsystem that integrates measurement microphones and the feasibility of using a MEMS microphone, (2) the development of accurate and computationally efficient signal processing algorithms for acoustic frequency (octave, 1/3-octave, and narrowband) analysis and sound level measurement, and (3) the construction of a ZigBee-based wireless sensor network for continuous noise monitoring and data communication. These systems are currently under review by the ISS Program to potentially replace the currently used COTS sound-level meters.

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