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National Aeronautics and Space Administration (NASA) Environmental Control and Life Support (ECLS) Technology Development and Maturation for Exploration: 2013 to 2014 Overview

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The National Aeronautics and Space Administration (NASA) Strategic Space Technology Investment Plan (SSTIP) was released in December 2012. This plan, crafted from a series of draft Space Technology Roadmaps that were reviewed and critiqued by the National Research Council with input from public and key stakeholders, provides guidance for NASA's space technology investment over the next four years to support a 20-year space exploration horizon. Environmental Control and Life Support (ECLS) is among the eight (8) core technology investment areas that the SSTIP specifically identifies as indispensable for NASA's present and planned future missions. Improving reliability, reducing logistics burdens, and increasing loop closure are identified as key challenges to lowering overall mission life cycle costs and enabling a wider range of mission opportunities. To meet these challenges, the NASA ECLS community identified key technology gaps that need to be filled in order to enable and enhance representative classes of exploration missions. Over the last year, the effort to identify and prioritize technology gaps has evolved to include implementation planning through the efforts of newly-established NASA System Maturation Teams. An important component of this planning has been to assist senior agency leaders and program managers to understand ECLS investment needs and to organize a coherent, integrated investment strategy that leverages contributions across multiple directorates and

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programs. The integrated strategy also served as a guide for project and task managers as they worked to tailor individual technology development and maturation projects and task plans for 2013-14 to better and more cost-effectively meet the agency's strategic needs. This paper provides an overview of the refined ECLS strategic planning, as well as a synopsis of key technology and maturation project tasks that occurred in 2013 and early 2014 to support the strategic needs. Plans for the remainder of 2014 and subsequent years are also described.

Nomenclature

ACS = Advanced Clothing System
Ag = Silver
AES = Advanced Exploration Systems
ALM = Automated Logistics Management
amu = atomic mass unit
AQM = Air Quality Monitor
AWP = Alternate Water Processor
BWP = Biological Water Processor
CAMRAS = CO_2 and Moisture Removal Assembly
Cd = Cadmium
CDRA = Carbon Dioxide Removal Assembly
CDS = Cascade Distillation System
CH_4 = Methane
cm = centimeter
CO = Carbon Monoxide
CO_2 = Carbon Dioxide
COTS = Commerical Off-the-Shelf
CP = Combustion Products
CTB = Cargo Transfer Bag
ECLS = Environmental Control and Life Support
ECLSS = Environmental Control and Life Support System
EH = Environmental Health
DA = Distillation Assembly
DMSD = Dimethylsilanediol
DRM = Design Reference Mission
DSH = Deep Space Habitat
DTO = Detailed Test Objective
EM = Environmental Monitoring
FCPA = Fluids Control and Pump Assembly
FO = Forward Osmosis
FOST = Forward Osmosis Secondary Treatment
FTIR = Fourier Transform Infra Red
GC = Gas Chromatography
GC/DMS = Gas Chromatography/Differential Mobility Spectroscopy
GC/FID = Gas Chromatography/Flame Ionization Detector
GC/IMS = Gas Chromatograph/Ion Mobility Spectroscopy
GC/MS = Gas Chromatography/Mass Spectroscopy
GCD = Game Changing Development
GFE = Government Furnished Equipment
HHP = Human Health and Performance
HMC = Heat Melt Compactor
HRP = Human Research Program
H_2 = Hydrogen
H_2O = Water
ISS = International Space Station
JEM = Japanese Experiment Module
JPL = Jet Propulsion Laboratory
kg = kilogram
LEO = Low Earth Orbit
LRR = Logistics Reduction and Repurposing
LSAH = Lifetime Survey of Astronaut Health
MC = Microcolumn
MCA = Major Constituent Analyzer
MCTB = Multipurpose Cargo Transfer Bag
MDM = Multiplexer/Demultiplexer
MEMS = Micro Electro Mechanical System
mGM = Micro-Gas Monitor
MGM = Multi-Gas Monitor
Mn = Manganese
MOT = Mission Operations Test
MPAM = Multi-Program Air Monitor
NEA = Near Earth Asteroid
NH_4^+ = Ammonium
Ni = Nickel
NO_x = Nitrogen Oxide
O_2 = Oxygen
ORU = Orbital Replacement Unit
PC = Pre-concentrator
PCPA = Pressure Control and Pump Assembly
PCR = Polymerase Chain Reaction
ppmv = parts per million by volume
psia = pounds per square inch absolute
PLSS = Portable Life Support System
QCL = Quantum Cascade Laser
RASCal = Rapid Analysis Self-Calibrating Array
RFID = Radio Frequency Identification
RMMD = Rapid Multiplex Microbial Detector
RNA = Ribonucleic Acid
RO = Reverse Osmosis
SBIR = Small Business Innovative Research
SMT = System Maturation Team
SOA = State of the Art
SSTIP = Strategic Space Technology Investment Plan
STS = Space Transportation System

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 Compounds
W = Watt
WPA = Water Processor Assembly
WRP = Water Recovery Project
WRS = Water Recovery System
Zn = Zinc
µg/l = micrograms per liter

I. Strategic Planning

The National Aeronautics and Space Administration (NASA) Strategic Space Technology Investment Plan (SSTIP) was released in December 2012. This plan, crafted from a series of draft Space Technology Roadmaps that were reviewed and critiqued by the National Research Council with input from public and key stakeholders, provides guidance for NASA’s space technology investment to support a 20-year space exploration horizon. Environmental Control and Life Support (ECLS) is among the eight (8) core technology investment areas that the SSTIP specifically identifies as indispensable for NASA’s present and planned future missions. Improving reliability, reducing logistics burdens, and increasing loop closure are identified as key challenges to lowering overall mission life cycle costs and enabling a wider range of mission opportunities.

In January 2014, NASA received authorization to extend the life of the International Space Station (ISS) to 2024. The unique environment of the ISS makes it the ideal test platform for many of the key systems and technologies needed for future human missions beyond LEO, and this life extension allows NASA to more fully utilize the ISS for evolving technologies and capabilities. NASA has examined technology, human health, and operational gap areas for future missions and identified which of these areas could and should be validated on the ISS.

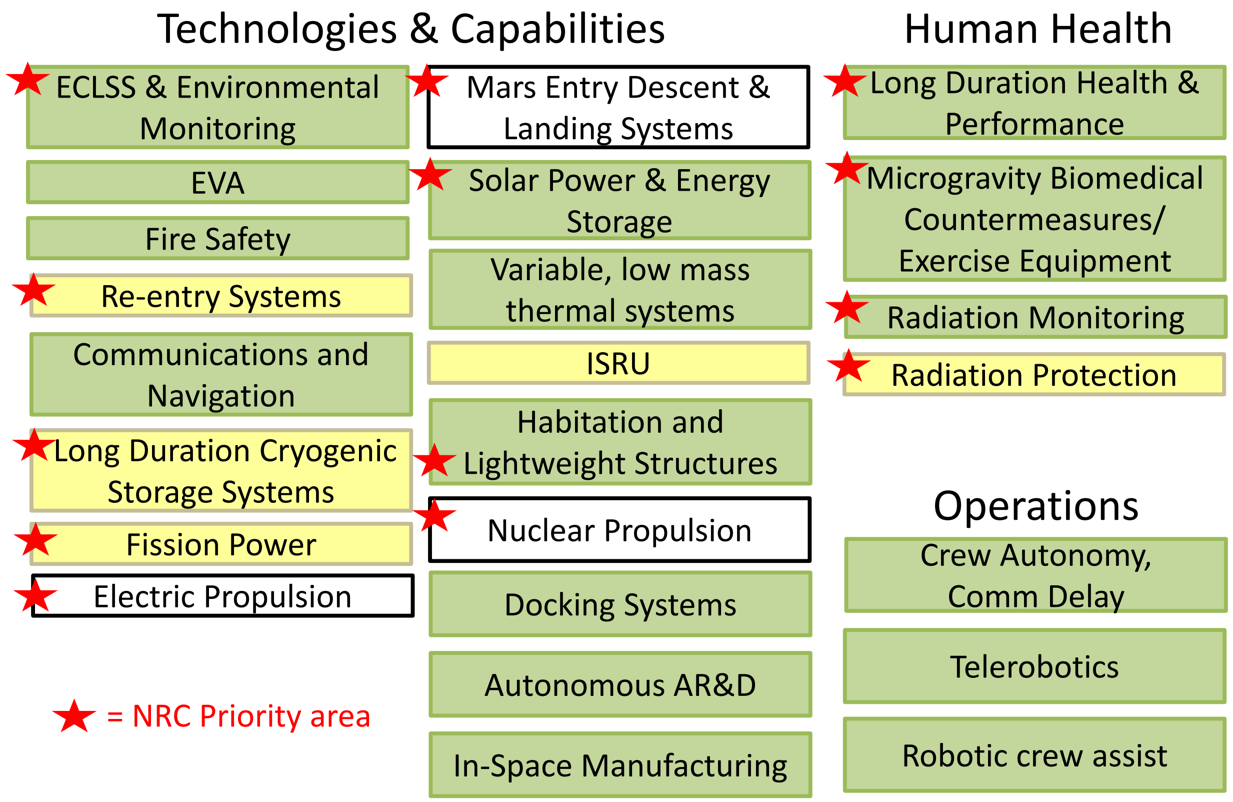

Figure 1. Exploration Technologies and Capabilities That can be Validated Using the ISS.

The items highlighted in green in Figure 1 can be validated using the ISS or ISS assets (such as commercial cargo vehicles), while the items in yellow can be partially validated using the ISS. Along with the human health area, ECLSS (including Environmental Monitoring) is arguably the most critical technology area for which ISS can and should be utilized to prepare us for future exploration missions. The ISS technology demonstration program's goal is to utilize the ISS to the maximum extent possible to validate these technologies and capabilities for future human exploration missions. This program has been working closely within NASA, and with industry and international participants involved in technology development to identify and enable flight demonstration opportunities that align with these priorities.

The current ISS regenerative air and water systems form the basis for these future architectures. Key improvements such as increased reliability and additional loop closure will be needed for future missions and development activities are underway to address those items, with the goal to ultimately validate the Mars ECLSS on ISS for at least two years. In the area of environmental monitoring, some candidate atmosphere and water quality monitors have been flown and are currently in operation on ISS, but additional improvements and capabilities need to be developed in order to satisfy the crew health requirements without the need for return of grab samples and ground analysis. The goal is to fly a suite of monitors that can fully satisfy both engineering and medical requirements through on-orbit analysis.

With these overall goals and the timeline of the ISS in mind, the NASA ECLSS community, led by the ECLSS-EM System Maturation Team (SMT) has identified specific functional gaps and target performance parameters that it believes are essential to enable future human exploration missions. NASA has defined a human exploration capability driven framework which includes "mission classes" that gradually increase our capability to expand beyond low Earth orbit and into deep space, including ultimately human missions to Mars. Those mission classes are defined as:

- Extending reach beyond LEO (present-2021): initial short-duration crewed missions to cis-lunar space and/or lunar orbit

- Into the Solar System (2021-2027): short to medium-duration crewed missions in cis-lunar space, including initial near-earth Asteroid missions

- Exploring Other Worlds (2027-2033): long-duration crewed missions to other NEAs, Phobos/Deimos, with potential for short-duration crewed excursions to lunar surface.

- Planetary Exploration (2033 and beyond): long-duration crewed transit and surface missions including Mars and the Solar System

For all of the mission classes and associated Design Reference Missions (DRMs), the key discriminators for ECLSS are whether the mission is short or long duration, and whether it is conducted in microgravity or on a planetary surface. Utilizing these more generic discriminators allows the ECLSS capability gaps to be easily mapped to DRMs and architectures as they continue to evolve. Also, once a capability is enabled for one set of mission classes, it can be extended to future mission classes.

Table 1 summarizes the results of the functional gap analysis performed by the ECLSS-EM SMT. For each major functional area contained within ECLSS and Environmental Monitoring, the specific capability gaps are noted, with those gaps considered to be enabling needs for future missions highlighted in red (as opposed to needs considered to be "enhancing"). Gaps are mapped to the various mission classes described above, also noting where an upgrade or demonstration of the capability on ISS is warranted, which is the case for the vast majority.

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	✓		✓	✓	✓
Trace Contaminant Control	Replace obsolete sorbents and catalyst w/ higher capacity	✓	✓	✓	✓	✓
Particulate Filtration	Surface dust pre-filter				✓	✓
O_2 recovery from CO_2	Recover >50% O_2 from CO_2	✓			✓	✓
Condensing Heat Exchange	Durable, chemically-inert hydrophilic surfaces with antimicrobial properties	✓		✓	✓	✓
O_2 generation	Reliability, reduced complexity	✓		✓	✓	✓
High pressure O_2	Replenish 3000 psi O_2 for EVA	✓		✓	✓	✓
Water microbial control	Common silver biocide with on-orbit redosing	✓		✓	✓	✓
Urine collection	Backup, no moving parts urine separator	✓	✓	✓	✓	✓
Wastewater processing	Increased water recovery from urine (>85%), reliability, reduced expendables, dormancy survival	✓		✓	✓	✓
Urine brine processing	Water recovery from urine brine >90%	✓			✓	✓
Metabolic solid waste	Universal waste management system	✓	✓	✓	✓	✓
Non-metabolic solid waste	Volume reduction, stabilization, resource recovery	✓			✓	✓
Atmosphere monitoring	Smaller, more reliable major constituent analyzer, in-flight trace gas monitor (no ground samples), targeted gas (event) monitor	✓	✓	✓	✓	✓
Water monitoring	In-flight identification & quantification of species in water	✓		✓	✓	✓
Microbial monitoring	Non-culture based in-flight monitor with species identification & quantification	✓		✓	✓	✓
Particulate monitoring	On-board measurement of particulate hazards	✓		✓	✓	✓
Acoustic monitoring	On-board acoustic monitor	✓			✓	✓

From this gap analysis, NASA is currently developing detailed roadmap plans for closing the gaps within the timeframes required to support ISS and future mission needs. Draft roadmaps of gap-closing activities were initially developed by the ECLSS-EM SMT, and more detailed, technology-specific roadmaps are in work by NASA's Space Technology roadmap teams with a targeted completion by the end of 2014. The roadmaps will identify current near-term funded work as well as necessary future work including ground testing and flight demonstrations. It is important to maintain these roadmaps as a central mechanism for tracking progress toward objectives, since individual budgets and portfolios from funding organizations tend to change from year to year.

II. NASA Investments: Air Revitalization

NASA's taxonomy of the air revitalization capability includes atmosphere conditioning (including open- and closed-loop carbon dioxide removal, trace contaminant control, particulate and microbial control, carbon dioxide reduction, circulation, temperature control, and humidity control) and pressure management (nitrogen and oxygen delivery, nitrogen and oxygen supply, cabin pressure relief/venting/equalization, and high pressure oxygen supply). An overview of these air revitalization areas and NASA current and planned research are described below.

A. Atmosphere Conditioning

Carbon Dioxide Removal – Among the highest ECLSS priorities is the need to reduce the crew time that has been expended maintaining closed-loop CO_2 removal capability, as represented by today's Carbon Dioxide Removal Assembly (CDRA) on the ISS. The CDRA 5A zeolite sorbent's tendency to release fines under operational conditions have led to rising pressure drop within adsorbent beds and the fouling of seals within downstream selector valve assemblies[1]. Mitigation strategies that have been adopted by the ISS include changing the type of 5A zeolite utilized (from the original UOP ASRT to UOP RK-38) and modifying the sorbent bed assemblies and packaging to facilitate easier crew access for periodic cleaning of internal screens and filters. Unfortunately, flight data since the change have indicated accelerated pressure drop increases as well as indications of water entering the sorbent beds and the Sabatier CO_2 reduction assembly located downstream of the CDRA; at the time of this paper, root cause(s) for these observations had not been determined.

One of NASA's technology development focus areas has been to develop sorbent screening and characterization procedures that can provide a fuller understanding of a candidate sorbent material's performance potential and durability[2,3]. In light of the most recent CDRA on-orbit data, comparative thermal cycle testing of 5A ASRT and RK-38 with traces of humidity has been introduced into the suite of characterization tests to assess to what extent, if any, water vapor contributes to the breakdown of the materials, and to determine which of the two is the most durable in the presence of water vapor.

A separate area of concern that may have implications on carbon dioxide removal performance required in the future relates to the potential for elevated carbon dioxide levels in crew cabin atmospheres to contribute, at least partly, to crew health effects such as headaches and increased cranial and ocular pressure[4]. While the potential contribution of elevated carbon dioxide to ocular pressure still remains to be determined, controlling partial pressure of carbon dioxide to 2 mmHg or less (compared to 3-4 mmHg that has been common on ISS) is now being tracked as a potential capability need requiring investment. Performance mapping of a CDRA ground test unit in 2013 included test points at 2, 3, 3.5, and 5 mmHg carbon dioxide partial pressure to aid in assessing the ability of the state-of-the-art to support varying levels of carbon dioxide.

Finally, an enhancement desired for exploration is to reduce the power associated with preserving water (aka, "water save") that might otherwise be lost from a spacecraft cabin atmosphere in the process of removing carbon dioxide. A trade study completed in 2013 compared a number of candidate bulk and residual drying technologies and combinations, and concluded that the ISS CDRA's desiccant bed (composed of silica gel and 13X zeolite) remained as the most mass and volume efficient solution[3]. On-board the ISS, a flight demonstration of the CO_2 and Moisture Removal Assembly (CAMRAS) included a moisture-save cartridge[5].

Trace Contaminant Control – NASA's highest priority need in the area of trace contaminant control is to acquire and certify sorbent and catalyst materials to replace those used on ISS that are now no longer in production. The capacities of a number of commercially available sorbents for ammonia and high-priority volatile organic compounds (VOCs) of interest to spacecraft cabin air quality control have been evaluated[6]. Catalysts suitable for low temperature ammonia removal[7] and employing photo-catalytic materials[8] have also been evaluated.

In addition to control of contaminant build-up within spacecraft bulk cabin atmospheres, the vent gas from a heat melt compactor used for solid waste reduction and resource recovery has been characterized [9] as a requisite step towards designing a suitable point-source contaminant control system or device. Also, although not a direct hazard to crewmembers, various types of siloxanes have been found in the ISS cabin atmosphere. These siloxanes are believed to be the precursors, via mechanisms that haven't yet been fully understood, to various silicone-containing diols which have been isolated from ISS humidity condensate and from potable water samples.[10,11] Since the solubility and refractory nature of these compounds make them difficult to remove from water, alternative means to remove them from process air upstream of cabin condensing heat exchangers are being sought.

Particulate and Microbial Control – Onboard the ISS, a substantial amount of crew-time is expended accessing and cleaning filter media distributed throughout cabins, ductwork, and system and payload racks. An indexing media filter concept has been developed with the goal of reducing the crew-time burden associated with filter cleaning[12]. Recent efforts in the area of particulate control have focused on refining cabin load models and filtration media test protocols. Debris collected from ISS cabin air filters was collected and characterized.[13] This data was used to update particulate load models used for cabin atmosphere modelling[14]. Test protocols were also developed to aid in extending the shelf life of ISS particulate filters.[15]

O_2 Recovery from CO_2 – The U.S. segment of the ISS includes a Sabatier CO_2 reduction assembly to generate recoverable water from CO_2 using H_2 produced via electrolysis in the Oxygen Generation System. Due to the stoichiometry involved, this method is limited to recovering no more than 50% of the oxygen available in crewmember's metabolically-produced CO_2. For long duration missions beyond low earth orbit, reliable higher oxygen recovery efficiencies are needed. Although promising technologies exist, the key challenge is to enable greater recovery of O_2 without the need for prohibitive amounts of complex equipment or expendables to accomplish the job.

A number of different approaches are being investigated. One would increase oxygen recovery by preserving H_2 reactant that is otherwise lost as part of the Sabatier's methane by-product. A plasma pyrolysis process targeting the decomposition of methane into H_2 and acetylene is being tested.[16] Recycling the recovered H_2 back to the Sabatier in this fashion could increase O_2 recovery to as much as 83%. Another approach being investigated would replace a

Sabatier and methane post-processor with a Bosch process designed specifically for complete conversion of CO_2 to carbon[17]. A bio-electrochemical alternative to a physicochemical Sabatier was also investigated through a Small Business Innovative Research (SBIR) Phase I award.[18] NASA recently published a solicitation for advanced oxygen recovery technologies under its Space Technology Game Changing Program, in an effort to focus additional resources in this area.

Challenge tests to demonstrate the robustness of the Sabatier catalyst to volatile organic compounds that could possibly be passed to it with the carbon dioxide delivered from the CDRA were conducted and shown to have no measurable effect on conversion efficiencies.[19]

Temperature and Humidity Control – Airside passages in ISS condensing heat exchangers are coated with hydrophilic material to promote uniform wetting. Although the coating formulation included silver to retard microbial growth in the moist environment, the heat exchangers need to be periodically dried out on-orbit to prevent microbial fouling. The durability of the coating and its long-term hydrophilic effectiveness are areas of concern. Additionally, recent data suggests that the coating may catalyze the conversion of polydimethlylsiloxanes, which are prevalent in the ISS cabin atmosphere, into dimethylsilanediol (DMSD) in humidity condensate. Once in the condensate, DMSD is known to pass through ISS Water Processor Assembly in sufficient concentrations to cause detectable increases in reclaimed potable water.[20] Durable, chemically-inert, hydrophilic surface materials which exhibit long term, effective antimicrobial properties without crew intervention are required for future exploration missions.

B. Pressure Management

Nitrogen and Oxygen Supply and Delivery – Aboard the ISS, oxygen is generated in a liquid cathode feed water electrolysis system referred to as the Oxygen Generation System; ambient pressure oxygen is vented directly to the ISS cabin atmosphere and by-product hydrogen is either vented overboard or combined with CO_2 in the Sabatier CO_2 Reduction Assembly to produce methane (which is vented overboard) and water. Although the OGS has generated over 6,600 lb of oxygen, operational experience with it has suggested opportunities to improve its reliability and operational robustness through targeted simplification of its integrated design. Collaborative investments by NASA's ISS and Advanced Exploration Systems (AES) programs have been aimed at simplifying the design and operation while preserving the heritage on-orbit experience that has been accumulated with the technology over its six-year operational life. Among the options being examined are the feasibility of using an alternate means of detecting hydrogen in the product oxygen outlet for hazard control purposes, the feasibility of operating the system without purging the anode side of the cell stack with nitrogen before startups and shutdowns, and demonstrating whether conditions within the rotary separator accumulator could in fact support a potentially hazardous detonation event as had been assumed throughout development. If the risk of hazards due to detonation can be demonstrated to be less than assumed, system size and complexity might be reducible and operational flexibility could be enhanced. Finally, the suitability of a new formulation of commercially-available Nafion® 117 for long term use in a liquid cathode feed electrolyzer is being assessed through single cell testing.

High Pressure Oxygen Supply – Future human space exploration missions are expected to require the capability to recharge oxygen storage tanks in EVA Portable Life Support Systems (PLSS), short duration space excursion vehicles, and surface rovers. A target pressure of 3600 psia has been used to guide planning and technology development. A number of different architectural paths, each requiring different technology solutions, are being explored through trade studies and testing, as are potential commonality opportunities with capabilities needed for emergency crew health maintenance, energy storage, and in-situ resource utilization. From an ECLSS perspective, there are three basic architectural paths: delivering oxygen directly from an ambient pressure water electrolysis assembly to a post-processor for drying and compression, delivering oxygen at ambient pressure to the cabin atmosphere from which it is then separated as needed and dried and compressed, or generating oxygen at storage pressure from a water electrolysis system operating at 3600 psia. Concepts for separating oxygen from cabin atmosphere by means of pressure swing adsorption[21] or electrochemical separation across a ceramic membrane[22] have been evaluated. Opportunities are being explored to leverage investments by NASA's Human Research Program (HRP) in similar technologies for use in portable oxygen concentrators for emergency medical use[23]. An ambient pressure liquid cathode feed electrolyzer capable of producing oxygen up to 3600 psia was developed under NASA SBIR funding[24]; elevated concentrations of oxygen in the by-product hydrogen are currently being investigated. NASA investments in advanced fuel cells and regenerative fuel cell systems (that combine fuel cells with water electrolysis cells and solar arrays in integrated energy generation and storage systems)[25] provide cross-cutting benefit to enabling high pressure oxygen generation to meet ECLSS needs.

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 (0.07 lb expendables consumed per lb 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[26] 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 2013-14 NASA has several areas of investment in water recovery including upgrades/improvement to ISS systems and technology development under the AES, Game Changing Development (GCD), and SBIR programs.

A. ISS Upgrades

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

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.

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 planned to be conducted in 2014 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. A competitive solicitation is planned to be released in the spring of 2014.

B. AES Water Recovery

The mission of the AES Water Recovery Project (WRP) is to develop advanced water recovery systems to enable NASA human exploration missions beyond LEO. The primary objective of the AES WRP 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 2013-14 the AES Water Recovery Project is focused on maturation and testing of the Cascade Distillation System, advancements in water chemistry, and brine treatment technologies.

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 WRP will advance the technology through targeted improvements based upon the results of the 2009 comparison test and recommendations of the expert panel. System reliability will be enhanced through redesign of bearing assemblies and improved rotor dynamics. Additionally, CDS power efficiency will be improved by optimizing the thermoelectric heat pump and heat exchanger design. The project also aims to advance the technology readiness level (TRL) of the CDS by testing its performance with flight-like waste streams, and designing a medium fidelity system prototype to demonstrate performance in relevant operational environments, including future operation as part of an integrated ECLS system, operation at reduced pressure, and microgravity operation. Recent accomplishments included testing of a prototype thermoelectric heat pump and preparing for integrated testing of it with a CDS distiller and alternate urine pretreat formulation discussed below. Design of a second generation prototype distiller is ongoing. Further information on the CDS can be found in Ref. 27.

1. *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 "rotovap" 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[28].

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.

Dormancy - The AES WRP is investigating dormancy as a critical issue for future microgravity missions, specifically missions including long periods of uncrewed operation. These types of missions may have requirements for life support systems to support crew activity, followed by a dormant period of up to one year, and subsequently for the life support systems to come back online for additional, periodic crewed missions. As such, it is critical that the future exploration water systems be designed to accommodate dormant periods. The purpose of the dormancy assessment is to identify a viable approach for configuring ISS-derived water systems to survive a 1-year dormancy period. This task will develop the system architecture and an operational concept for an exploration water system that addresses dormancy issues, and perform tests to assess microbial stability of pretreated urine during dormancy periods. In March, 2014 one-year stability tests of a suite of urine and brine solutions representing a range of pretreatment and concentration conditions were completed, with evidence of microbial growth detected in only two of the twenty-four solutions tested.

Brine Dewatering - Brine Dewatering seeks to address the goal of 98% water recovery established by the Human Health, Life Support, and Habitation Systems roadmap[26]; 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. This task is evaluating three NASA developed and three SBIR Phase II brine dewatering technologies for applicability to an exploration mission architecture. The technologies currently being evaluated include a Brine Residual In-Containment (BRIC)[29], a Brine Evaporation Bag (BEB)[30], a Forward Osmosis Brine Dryer (FOBD), an Ionomer-Membrane Water Processor (IWP)[31],a nanomaterials spray dryer[32], and an Ultrasonic Brine Dewatering System (UBDS)[33]. Additionally, the project will 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.

Alternative Water Processor –NASA's GCD Program is sponsoring the development of an Alternative Water Processor (AWP) system capable of recycling wastewater from sources expected in future exploration missions, including hygiene and laundry water, using a "disruptive" technology based on natural biological processes. The AWP will be capable of recycling more than 95% of exploration wastewater, increasing closure compared to the state of the art. In addition to improving the water recovery rate, "greener", less toxic pretreatment methods will be required for its operation. The performance of the AWP system will be quantified through systems-level testing, with delivery to the AES Water Recovery Project when work is completed.

In this project task, an alternative water processor is being investigated with the goal of replacing the UPA and reducing or eliminating the need for the multi-filtration beds of the WPA. At its center are two unique game changing technologies: 1) a biological water processor (BWP) to mineralize organic forms of carbon and nitrogen and 2) an advanced membrane processor (Forward Osmosis Secondary Treatment) for removal of solids and inorganic ions. In addition, "greener" and less toxic methods for wastewater stabilization will be utilized. Biological processing will require fewer resources while providing excellent system performance: >90% removal of wastewater organics including surfactants, pH stabilization, oxidation of NH_4^+ to NO_x^- (up to 80%), and improved properties of concentrated brines. The Forward Osmosis Secondary Treatment (FOST) system is a membrane processor that uses both forward osmosis (FO) and reverse osmosis (RO) and can easily tolerate wastewaters high in non-volatile organic content and solids associated with shower and/or hand washing. These contaminants have good rejection performance but high membrane fouling potential using conventional pressure-driven membrane techniques. The FOST approach addresses this issue through incorporation of FO pretreatment which allows conventional RO to be used to reject these contaminants effectively without premature fouling due to micellar surfactant aggregates.

C. SBIR

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)[28]
- Miniaturized, High Flow, Low Dead Volume Preconcentrator for Trace Contaminants in Water under Microgravity Conditions (Thorleaf Research, Inc.) [34]
- Water Recovery for Regenerative Life Support Systems (Creare, Inc)[35]
- Advanced Electrochemical Oxidation Cell for Purification of Water (Vesitech, Inc)[36]
- Ionomer-membrane Water Processor System Design and EDU Demoonstration (Paragon Space Development Corp)[68]

IV. NASA Investments: Waste Management

The NASA ECLSS roadmap includes solid waste management and several waste areas are common with NASA Habitation and Logistic needs. Waste Management within ECLSS primarily addresses solid waste but 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. The AES Logistics

Reduction and Repurposing Project (LRR) and other NASA programs are developing technology in each of these areas.

A. Waste Reduction

Waste minimization of trash includes consideration of the original consumables that are used and become trash. Crew clothing is primarily cotton based on the ISS and requires significant consumable up mass, ~75 kg/crew-year[37]. There is no laundry capability on ISS. There are three areas of clothing development. First, AES LRR Advanced Clothing Systems (ACS) is investigating 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 ~80 participants under ISS aerobic exercise conditions with a range of clothing materials[38]. This testing allowed selection of a variety of wool, modacrylic, and polyester for an ISS technology demonstration on increments 39/40 in the summer of 2014.

NASA funded a SBIR phase II with UMPQUA Research Corporation to develop an 'Advanced Microgravity Compatible, Integrated Laundry System.' The contract funds development of a scaled prototype that uses a flexible bag for clothing and evacuates the air prior to introducing water. The system uses pulsed water jets for agitation and can fill and drain the flexible bag to aid in cleaning. Water is squeezed out by applying pressure across the flexible bag. Pulsed jet air tumbling and microwave drying are being tested. The project is investigating several process parameters to reduce water (<8 kg water/kg clothing) and power requirements[39].

AES LRR is performing a trade study of several clothes cleaning technologies including water based and non-water freshening systems such as ozone or ultraviolet light compared against existing ISS cotton clothing and from initial AES LRR ACS results. The trade study is in work and future results will provide guidance regarding for which missions the laundering of clothing is advantageous to reduce up mass as well as trash generation.

In addition to clothing minimization, AES LRR is also researching two other logistics minimization technologies that can reduce the solid trash burden[33]. Multipurpose cargo transfer bags (MCTBs) allow logistics bags to be unfolded 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 (can't be unfolded) that become trash. Radio Frequency Identification (RFID) technology is also being investigated to allow 3D localization of crew items and automated logistics management (ALM). Without 3D localization, crew logistics must be packaged in defined groupings to prevent excessive crew time for localization on-orbit. This defined grouping has required foam to take-up ~30% of cargo volume of recent ISS resupply missions. ALM can prevent excessive crew time for localization and allow dense volumetric packaging of CTBs for launch. This ALM function can result in a 15% increase in mission cargo volume.

B. Trash Management

Trash processing is an area of substantial research by the AES LRR and SBIR programs. AES LRR is performing research and design of a heat melt compactor (HMC) for exploration. LRR analysis indicates HMC technology has the potential to recover about 10 m^3 of habitable volume, produce over 900 kg of radiation shielding tiles, and recover 230-720 kg of water for a one year of four mission[37].

The AES LRR HMC is developing the fundamental temperature, gas pressure, and mechanical compaction pressure parameters to sterilize trash, recover water, and minimize off-gassing. Current design is focused on a 9-in square processing chamber, which is mechanically driven, near atmospheric pressure, and double locker compact design[40]. The goal is to minimize squeezed out water to reduce the contaminants in the waste water and completely treat off gassing compounds prior to delivery to other ECLSS systems. In addition to waste, the AES LRR HMC is being tested with packaging foam to understand potential mission benefits[41]. A second generation flight like ground unit will be manufactured and tested by the end of 2014. Under a Phase II SBIR, Orbitec is investigating a variant of HMC technology that is pneumatically driven, sub-atmospheric pressure, and a larger four-locker configuration that could process larger exploration trash volumes and produce 16-in tiles[42]. The large scale trash processing poses additional thermal management challenges. Both waste processing technologies will be tested in late 2014 to determine the processing technology most applicable to exploration needs.

An advanced waste processing technology being investigated by AES LRR is Trash to Gas (TtG). TtG technologies process a wide range of trash (including human feces and ECLSS urine brines) using relatively high temperatures and pressures to decompose the organic constituents and recombine them into useable gases. Most recent research is focused on the production of methane to augment propellant for exploration's use in small landers or vehicle station keeping. Other gases are also feasible, e.g. oxygen, carbon dioxide, and water, depending on the selected technology. AES LRR TtG performed comparative testing between seven technologies[43]. Steam reforming technology had the highest waste to methane conversion efficiency and was selected for further study. The steam reformer hardware was delivered by Pioneer Astronautics, Inc under Phase II SBIR 'Lunar Organic Waste Reformer'[44]. Limited testing is planned in 2014 to support a conceptual micro-gravity design.

C. Human Metabolic Waste Management

Managing human metabolic waste represents a special case of waste, due to its biological nature and objectionable odors that can rapidly create unhygienic conditions in a spacecraft. The effective collection of metabolic waste is a significant challenge in microgravity. Past shuttle and current ISS toilets are not completely effective at collecting waste from crew members resulting in escapes of material. The 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 LRR 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[45]. There is a notional ISS technology demonstration planned for UWMS in the 2017 timeframe. The UWMS uses air flow for urine and fecal collection like previous flight toilets. Extensive crew member evaluations of seat geometry, air flow, and simultaneous funnel positioning are being performed to significantly reduce the potential for urine and fecal escapes. The UWMS will utilize fecal compaction in removable canisters to reduce stowed waste volume by ~60%. A key aspect of the UWMS that enables a compact installation is the dual fan separator technology[46].

In addition to improvements in metabolic waste collection, NASA is also funding a SBIR with Advanced Fuel Research on the 'Torrefaction Processing of Human Fecal Waste"[47]. The research is investigating the use of microwave, radiant, and conductions to dry and stabilize the waste while minimizing off gassing of undesirable compounds.

V. NASA Investments: Environmental Monitoring

A. Environmental Monitoring (EM) Gaps and Needs

Human Health and Performance (HHP) scientists and ECLS engineers consider environmental monitoring a key component to the overall management strategy to ensure environmental health. Environmental monitoring data help ECLS engineering manage the performance of ECLS systems. HHP clinical and scientific personnel use the same data to manage risks to crew health associated with the cabin environment such as acute crew health problems associated with contamination events, assessments of crew-reported symptoms and potential links to contaminant exposure and/or cabin environment observations, guide crew actions during off-nominal environmental problems, and eventually contribute exposure data to the Lifetime Survey of Astronaut Health (LSAH) to aid in post-flight monitoring of crew health.

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 listed below.

- 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 risk-based, gap analysis of environmental health (EH) was performed by Agency-wide EH-subject matter experts in 2012.[48] Capabilities required to address these risks were determined and technology gaps were ascertained from the state of current ISS operational hardware, considered in the analysis as the current state-of-the-art. It is important to note that operational considerations were considered in the gap analysis. Operation concepts drive logistics, which, in turn, drive several of the gaps that need to be addressed. Although specific limitations of the current hardware within each discipline were identified, the following limitations were found to apply to all the current ISS SOA hardware for any missions beyond low-Earth orbit (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 and 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 hardware. Manned 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 electrochemical cells for target gases such as carbon dioxide, combustion products, and system chemicals. The following provides a short summary of the projects in 2013-2014 within the Agency that attempt to address the gaps and needs. The projects are sorted by the needed capabilities identified above.

B. Air Quality – Trace VOC Monitoring

Air Quality Monitor - The Air Quality Monitor (AQM) is a GC/DMS instrument for trace VOC monitoring of the ISS cabin atmosphere.[49] After applying lessons learned derived from an ISS detailed test objective (DTO), the government-furnished equipment version (AQM - GFE) was delivered to ISS in March, 2013, underwent in-flight validation from May to October, and was subsequently declared operational in January, 2014. Two units are deployed, each having a different type of GC column to maximize separation of the different types of VOCs observed in the ISS cabin atmosphere. Each unit has a total mass of 7 kg and a total volume of 9.8 L (mass and volume includes the external power supply), and operate in a completely autonomous manner, wirelessly interfacing to ISS systems. The external power supply provides the capability to move the AQM to any module, and can also operate on batteries to facilitate remote operations. The AQM will serve as the ISS cabin air monitor to 2024 and can continue to serve until 2028 based on the number of units in the fleet and the lifetime of each unit. Future work on the AQM-GFE includes upgrading the GC column in each unit, enhance the software to include self-monitoring capabilities, and power supply improvements.

COTS FT-IR - A commercially available, portable FT/IR instrument, the Gasmet DX-4040, was tested in four modules (Core lab, Vegetable plant atrium, Hygiene module, and Xhab loft) of the Deep Space Habitat (DSH) during the Mission Operations Test (MOT) conducted at the Johnson Space Center.[50] The Gasmet DX-4040 followed the concentrations of several VOCs in the ppm concentration range, and the changes could be correlated to the activities that occurred in each module.

Micro-Gas Monitor – Micro-Gas Monitor (mGM) is an AES-sponsored development being led by JPL aiming to achieve a major size reduction to GC/MS, without loss of capability.[51] This next generation GC/MS will couple a microelectromechanical system-based GC (MEMS-based GC), developed by Cbana, Inc. under SBIR sponsorship[52], to a redesigned ion-trap mass spectrometer. The mass range of the mGM is reported to be 1-2000 atomic mass units (amu), and the entire unit will feature miniaturized vacuum chamber and pumps, reducing its mass to approximately 2.5 kg, consuming 20W of power. The mGM is designed to monitor major constituents as well as trace VOCs.

Micro GC's for Contaminant Monitoring in Spacecraft Air - Leveraging accomplishments under NASA SBIR Phase I and II contracts[52], the AES program is funding continued development of a micro gas chromatograph (GC) by JPL and Cbana, Inc. Based on work using a 1 m coated microcolumn in Phase I, Cbana, Inc. developed a new micro-GC system to separate and detect of all contaminants listed in NASAs Spacecraft Maximum Allowable Concentrations for Airborne Contaminants (SMACs) using cabin air as the carrier gas. To achieve this, three sets of preconcentrators, columns, and detectors are used in parallel, each with the appropriate selectivity for a given class of gases. The prototype micro-gas chromatograph/flame ionization detector (GC/FID) will be comprised of pre-concentrators with fast injection valves, micro-columns to separate different gas analytes, an air sampling pump, a water-hydrolysis hydrogen generator to provide enough oxygen and hydrogen for a micro-flame ionization detector, thermal management, controls and circuit board to drive the system. This project ended Aug 2013. Based on Cbana's report, the technical accomplishments in the Phase 2 work were a pre-concentrator (PC) that could be heated up to 300°C within one second, a microcolumn (MC) able to separate more than 33 SMAC compounds, micro-FID and micro-thermoconductivity detectors (TCD) that separated 17 SMAC compounds with a MC or a capillary column, and the development of a micro-GC-TCD "lunch box", which was 20 x 25 x 13 cm3 with a mass of 4kg equipped with the micro-GC as well as a sampler module, which made it serve as a standalone, portable GC.

C. Air Quality – Monitoring 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).[53] 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 ISS Program made an agreement with the Orion Program for ISS to fund the development of and qualification of an air monitor that will be common between ISS and Orion. The Systems Requirements Review is complete and initial design work is starting.

D. Air Quality – Airborne Particles

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

E. Air Quality – Monitoring Target Gases

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.[54] 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 is a technology demonstration designed to be operated on board ISS for a least a year.

Tunable Environmental Laser Spectroscopy (TELS) - Under the sponsorship of the AES program, JPL and Port City Instruments are developing low-power, solid-state lasers emitting at the wavelengths required to monitor combustion products.[55] In this collaborative effort, Port City Instruments will integrate the JPL-developed lasers into their own system to construct an optical combustion products monitor. Low-power, solid-state lasers for other target gases of interest will also be developed.

Rapid Analysis Self-Calibrating (RASCal) Array - RASCal is an AES-funded project being performed by JPL to develop advanced array analysis and hardware to dramatically improve response time and calibration time.[56] This technology is the logical progression of the ENose event monitor, also developed by JPL, which flew on STS-95 in 1998, and was an ISS technology demonstration in 2009. RASCal incorporates newly developed hybrid sensor arrays to significantly improve response time and provide the capability of self-correcting the array to account for drifts.

Improved Combustion Products Monitor for the ISS – Development of a laser-based combustion products (CP) monitor using wavelength modulation spectroscopy was sponsored under NASA SBIR Phase I and II contracts[57]. The device will monitor, in real-time, the concentrations of carbon monoxide, carbon dioxide, hydrogen cyanide, and hydrogen fluoride at concentration levels relevant to pre-combustion events and with a 1 second response time. The device will be hand-held, battery operated, and have a potential multi-year lifetime without the need for consumables, re-calibration, or maintenance. This project is funded to Dec 2014.

Real-Time Formaldehyde Monitor for the ISS - Under a NASA SBIR Phase 1 contract[58], 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. The major accomplishment of this project was the development of a sensor for formaldehyde using a newly available laser and fully autonomous analyzer. This monitor uses wavelength modulation absorption spectroscopy with a diode laser and a multiple pass absorption cell to achieve the required detection sensitivity. The development involved demonstrating sufficient detection sensitivity and ascertaining that none of the other gases in the ISS would interfere with these spectral measurements. 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 preliminary plan for a stand-alone, compact Phase 2 prototype was developed. This project ended in November 2013, and a proposal for Phase 2 was submitted.

Quantum Cascade Laser-Based CO Sensor for Fire Warning - NASA SBIR Phase I and II contracts[59] funded Maxion Technologies, Inc. to develop a carbon monoxide (CO) sensor for post fire cleanup. The sensor is intended to have the dynamic range required to detect and monitor CO from approximately 1 to 500 ppmv with a resolution to 1 ppmv. The sensor is based on a quantum cascade laser (QCL) that emits at the wavelength ideal for CO. The project technical objectives were to: a) Develop a low-power-dissipation QCL, b) fabricate a QCL-based prototype CO sensor, c) demonstrate the required dynamic range and sensitivity to CO, and d) field test the prototype sensor at a NASA facility for performance under controlled burns. The single frequency laser developed by Maxion required less than 2.88 W of electrical power to provide the necessary optical signals to allow the sensor to monitor the R6 line of CO at 2169.50 cm-1 (4.6100 microns). The QCL-based CO sensor had a precision of 0.1-0.2 ppm for 10 sec averaging. This project ended in August 2013.

F. Water Quality – Identify and Quantify Aqueous Species

Vehicle Environmental Monitor – The Vehicle Environmental Monitor (VEM) is device being developed by the JPL for the AES program to expand existing gas chromatography/mass spectrometry (GC/MS) technology to address water analysis in addition to performing trace VOC analysis. VEM has the potential for a combined trace VOC, major air constituents, and water analyzer system for future manned spaceflight[60].

Portable Sensor for Rapid in Situ Measurement of Trace Toxic Metals in Water - Under NASA SBIR Phase I and II contracts[61], 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. This project is funded to April 2014.

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.[62] The design combines high water sampling flow rates with low dead volume in the device, which should enhance pre-concentration and avoid cavitation effects, and can be utilized with any trace VOC sensor technology. Based on analysis, the developer (Thorleaf Research) projected a miniaturized water pre-concentrator module with a mass on the order of 0.5 kg and an average power consumption of <1 watt, depending on configuration. 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 major accomplishment of the Phase 1 work was the demonstration of the feasibility of a miniaturized high flow, low dead-volume pre-concentrator.

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

Microbiological Monitors Formulation (water/air) - This is a multi-center effort to evaluate commercially available quantitative or semi-quantitative molecular-based methodologies such as polymerase chain reaction (PCR).[63] This effort initially identified commercial platforms that require minimal modifications for operations in microgravity followed with proof-of-concept testing of the top candidates. Current work sponsored by AES is focusing on front end sample collection and concentration to integrate with the PCR sensor.

A Miniaturized Sensor for Microbial Monitoring of Spacecraft Water Environment - NASA SBIR Phase I and II contracts[64] sponsored the development and demonstration of an automated, milli-/micro-fluidics-based sensor cartridge for sample preparation and detection of microbes in water. In Phase 1, the key technology elements were reported as demonstrated: (1) a computational virtual-prototyping approach followed by state-of-the-art micro-fabrication and engineering were used to design the major components of the sensor cartridge; and (2) experiments with microbial samples commonly found in space water environment were performed to demonstrate component functionality and to establish proof-of-concept of the proposed technology. This project is funded to February 2014. A Phase 2 proposal focuses on component design optimization with fabrication enhancements, extended testing, and characterization, and the development of an integrated microfluidic cartridge and instrumentation capable of automated operation. Operation of the prototype instrument will be demonstrated in both terrestrial and hypo-gravity environments (in collaboration with NASA researchers/facilities).

Rapid Multiplex Microbial Detector - A NASA SBIR Phase I contract[65] sponsored initial development of a rapid nucleic acid-based detector for spaceflight water systems for the quantification of multiple waterborne pathogens with minimal consumables and crew time. The Rapid Multiplex Microbial Detector (RMMD) amplifies genetic material for near real-time identification of specific genetic sequences of predetermined bacteria and fungi. This device uses a patented polymerase enzyme for rapid RNA amplification with reagents having long-term shelf life and thermal stability. This project ended in Nov 2013, and plans for an engineering development unit that consists of an amplification/detection process controller, sample cartridges, and reagents, that can be tested in space are proposed for Phase 2. The major accomplishments of Phase 1 include the evaluation of the microbes that should be detected for the Phase 1 development and for the final spaceflight application, the development and testing of lyophilized formulations of isothermal genetic amplification chemistry, the development and testing of detection chemistries for four different bacterial strains, and a preliminary design of a bench-top prototype amplification cartridge and process controller. Employing RNA amplification allows not only for the determination of microbial identify, but also of microbial viability.[66]

H. Acoustics Monitoring – Real-Time Acoustic Monitoring

A Zigbee-Based Wireless Sensor Network for Continuous Sound and Noise Monitoring on the ISS - 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 contract [67], 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 microphones, (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 network for data communication. The Phase II project focuses on system integration and optimization, software implementation, and graphical user interface development. An in-situ calibration plan will be suggested and a demonstrable system will be delivered to NASA for testing in a ground facility at the completion of the Phase II contract. The expected Technology Readiness Level (TRL) then is expected to reach 6.

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References

[1] http://www.nasaspaceflight.com/2013/10/iss-hardware-providing-lessons-learned-deep-space-missions/

[2] Knox, J., Gauto, H., Gostowski, R., Watson, D., Thomas, J., Miller L., and Coker, R., “Development of Carbon Dioxide Removal Systems for Advanced Exploration Systems, 2013-2014,” AIAA, submitted for publication.

[3] Knox, J., Gauto, H., Trinh, D., Wingard, D., Gostowski, R., Watson, D., Kitttredge, K., King, E., Thomas, J., and Miller L., “Development of Carbon Dioxide Removal Systems for Advanced Exploration Systems, 2012-2013,” AIAA, 2013.

[4] Fogarty, J.A., Otto, C., Kerstman, E., Oubre, C., and Wu, J., “The Visual Impairment Intracranial Pressure Summit Report,” NASA/TP-2011-216160, October, 2011.

[5] Sweterlitsch, J., and Button, A., “Amine Swingbed Payload Testing on ISS,” AIAA, submitted for publication.

[6] Monje, O., Surma, J., Johnsey, M., Melendez, O., “Evaluating the Adsorptive Capacities for Chemsorb 1000 and Chemsorb 1425,” AAIA, 2014

[7] Monje, O., Melendez, O., “Low Temperature Catalyst for NH3 Removal,” AAIA 2013-3423, 2013.

[8] Levine, L., Coutts, J., Richards, J., Hintze, P., and Clausen, C., “Review of Transforming TiO_2 into a Visible-Light-Responsive Catalyst for Water and Air Purification,” AAIA 2012-3629, 2012.

[9] Delzeit, L., Fisher, J., Alba, R., Wignarajah, K., and Harris, L., “Chemical Characterization of the Heat Melt Compactor Effluent Gas,” AIAA 2013-3395, 2013.

[10] Carter, D.L., Tobias, B., and Orozco, N., “Investigation of DMSD Trend in the ISS Water Processor Assembly,” AIAA 2013-3510, 2013.

[11] Rector, T., Metselaar, C., Peyton, B., Steele, J., Michalek, W., Bowman, E., Wilson, M., and Carter, L., “An Evaluation of Technology to Remove Problematic Organic Compounds from the International Space Station Potable Water,” AIAA, submitted for publication.

[12] Agui, J., and Vijayakumar, R., “Development of an Indexing Media Filtration System for Long Duration Space Missions,” AIAA 2013-3486, 2013.

[13] Perry, J., and Coston, J., “Analysis of Particulate and Fiber Debris Samples Returned from the International Space Station,” AIAA, submitted for publication.

[14] Meyer, M., Green, R., and Agui, J., “Revised Particulate Matter Load Sources for ISS Ambient Air Quality Monitoring,” AIAA, submitted for publication.

[15] Green, R., Vijayakumar, R., and Agui, J., “Development of Test Protocols for International Space Station Particulate Filters,” AIAA, submitted for publication.

[16] Abney, M., Greenwood, Z., Miller, L., Alvarez, G., Iannantuono, M., and Jones, K., “Methane Post-Processor Development to Increase Oxygen Recovery beyond State-of-the-Art Carbon Dioxide Reduction Technology,” AIAA 2013-3513. 2013.

[17] Abney, M., Mansell, J., Stanley, C.,Edmunson, J., Alleman, J., Chen, K., and Dumez, S., “Series-Bosch Technology for Oxygen Recovery During Lunar or Martian Surface Missions,” AIAA, submitted for publication

[18] http://sbir.gsfc.nasa.gov/SBIR/abstracts/11/sbir/phase1/SBIR-11-1-X3.01-8150.html

[19] Nalette, T., Yu, P., Perry, J., and Abney, M., “Investigation of the Potential Impact of Trace Contaminants on the Performance of the Sabatier Catalyst,” AIAA 2013-3528, 2013.

[20] Carter, L., Bowman, B., Rector, T., Gentry, G., and Wilson, M., “Investigation of DMSD Trend in the ISS Water Processor Assembly,” AIAA 1563699, 2013.

[21] Graf, J., “A Cabin Air Separator for EVA Oxygen,” AIAA 2011-5225, 2011.

[22] Graf, J., Taylor, D., and Martinez, J., “Determining the Source of Water Vapor in Cerium Oxide Electrochemical Oxygen Separator to Achieve Aviator Grade Oxygen,” Microscopy and Microanalysis, 2014, submitted for publication

[23] Olsen, S., Hussey, S., and Calaway, K., “Development of an Oxygen Concentrator for Future Exploration Missions,” NASA Human Research Program Investigator’s Workshop, 2014

[24] http://sbir.gsfc.nasa.gov/SBIR/abstracts/09/sbir/phase2/SBIR-09-2-X2.01-9873.html

[25] Mercer, C., Jankowsky, A., Reid, C., Miller, T., and Hoberecht, M., “Energy Storage Technology Development for Space Exploration,” AIAA 2010-8709, 2010.

[26] “Human Health, Life Support, and Habitation Systems: Technology Area 06”, April 2012. http://www.nasa.gov/offices/oct/home/roadmaps/index.html

[27] Callahan, M.R., Patel, V., and Pickering, K.D., “Cascade Distillation Subsystem Development: Early Results from the Exploration Life Support Distillation Technology Comparison Test,” 40th International Conference on Environmental Systems, AIAA 2010-6149, 2010.

[28] http://sbir.gsfc.nasa.gov/SBIR/abstracts/12/sbir/phase1/SBIR-12-1-H3.03-8904.html

[29] Callahan, M., Pensinger, S., and Pickering, K., “Preliminary Feasibility Testing of the Brine Residual In-Containment (BRIC) Concept,” 42nd International Conference on Environmental Systems, AIAA 2012-3526, 2012.

[30] Delzeit, L., Fisher, J.W., Pace, G., and Shaw, H., “Brine Evaporation Bag Design Concept and Initial Test Results,” 42nd International Conference on Environmental Systems, AIAA 2012-3525, 2012.

[31] Kelsey, L.K., Straus, J., and MacCallum, T., “Employing Ionomer-Based Membrane Technology to Extract Water from Brine,”, 42nd International Conference on Environmental Systems, AIAA 2012-3527, 2012.

[32] Coppa, N., Milani, A., and Fardiq, D., “Reduction of Brine to Dry Solids Using Nanopowder Drying Agents,” 41st International Conference on Environmental Systems, AIAA 2011-5173, 2011.

[33] Akse, J., Wheeler, R., Holtsnider, J., and Fisher, J., "Brine Dewatering Using Ultrasonic Nebulization," 41st International Conference on Environmental Systems, AIAA 2011-5170. 2011.

[34] http://sbir.gsfc.nasa.gov/SBIR/abstracts/12/sbir/phase1/SBIR-12-1-H3.02-9850.html

[35] http://sbir.gsfc.nasa.gov/SBIR/abstracts/11/sbir/phase2/SBIR-11-2-X3.04-9372.html

[36] http://sbir.gsfc.nasa.gov/SBIR/abstracts/12/sbir/phase1/SBIR-12-1-H3.03-8812.html

[37] Ewert, M. K., Broyan, J. L. "Mission Benefits Analysis of Logistics Reduction Technologies", 43rd International Conference of Environmental Systems, AIAA-2013-3383.

[38] Broyan, J. L., Chu, A., Ewert, M. K., "Logistics Reduction and Repurposing Technology for Long-Duration Space Missions", 43th International Conference of Environmental Systems, AIAA-2013-3383.

[39] http://www.sbir.gov/sbirsearch/detail/411579

[40] Turner, M.F., Fisher, J.W., Broyan, J.L., Pace, G., "Generation 2 Heat Melt Compactor Development", 44th International Conference of Environmental Systems, AIAA, submitted for publication.

[41] Harris, L., Alba, R., Wignarajah, K., Fisher, J. Monje, O., Maryatt, B., Broyan, J., Pace, G., "Processing of Packing Foams Using Heat Melt Compaction ",44th International Conference of Environmental Systems , AIAA, submitted for publication

[42] Jeff R. Johnson1 and Adam M. Marten2 "Testing of a High Efficiency, High Output Plastic Melt Waste Compactor," AIAA 2013-3372

[43] Anthony, S.M., Hintze, P.E., Allada, R, "Trash-to-Gas: Determining the Ideal Technology for Converting Space Trash into Useful Products," 44th International Conference on Environmental Systems, AIAA, submitted for publication.

[44] http://www.sbir.gov/sbirsearch/detail/369405

[45] Stapleton, T. J., Baccus, S., Broyan, J. L., "Universal Waste Management System Development Review," AIAA 2013-3400, 43rd International Conference on Environmental Systems, Vail, CO.

[46] Stapleton, T. J., Converse, D., Broyan, J. L., "The Dual Fan Separator Review of the Combination of Waste Management System Rotary Equipment into a Single Component," , 44th International Conference on Environmental Systems, AIAA, submitted for publication

[47] http://sbir.gsfc.nasa.gov/SBIR/abstracts/12/sbir/phase1/SBIR-12-1-H3.03-9380.html

[48] Macatangay, A. V. "An Assessment of Environmental Health Needs," International Conference on Environmental Systems, AIAA 2013-3465, Vail, CO, 2013.

[49] Limero, T., Trowbridge, J., Wallace, W. "Preparation of the Operational Air Quality Monitors for Deployment on the International Space Station," 43rd International Conference on Environmental Systems, American Institute of Aeronautics and Astronautics (AIAA), Vail, CO, July 2013.

[50] Monje, O., Rojdev, K., "Dynamic Sampling of Cabin VOCs during the Mission Operations Test of the Deep Space Habitat," 43rd International Conference on Environmental Systems, American Institute of Aeronautics and Astronautics (AIAA), Vail, CO, July 2013.

[51] Madzunkov, S. M., MacAskill, J. A., Simcic, J., Kidd, R. D., Darrach, M. "Recent Developments in Gas Chromatographs and Mass Spectrometers for Crewed and Robotic Space Missions," 43rd International Conference on Environmental Systems, American Institute of Aeronautics and Astronautics (AIAA), Vail, CO, July 2013.

[52] http://sbir.gsfc.nasa.gov/SBIR/abstracts/09/sbir/phase2/SBIR-09-2-X2.03-8721.html

[53] Lewis, J.F., Barido, R. A., Boehm, P., Cross, C.D. "Orion Multi-Purpose Crew Vehicle Active Thermal Control and Environmental Life Support Development Status," 43rd International Conference on Environmental Systems, American Institute of Aeronautics and Astronautics (AIAA), Vail, CO, July 2013.

[54] http://www.nasa.gov/mission_pages/station/research/experiments/1187.html.

[55] Briggs, R. M., Frez, C., Forouhar, S., May, R. D., Ruff, G. A. "Portable 4.6μm Laser Absorption Spectrometer for Carbon Monoxide Monitoring and Fire Detection," 43rd International Conference on Environmental Systems, American Institute of Aeronautics and Astronautics (AIAA), Vail, CO, July 2013.

[56] Homer, M. L., Shevade, A. V., Fonollosa, J., Huerta, R. "Faster Array Training and Rapid Analysis for a Sensor Array Intended for an Event Monitor in Air," 43rd International Conference on Environmental Systems, American Institute of Aeronautics and Astronautics (AIAA), Vail, CO, July 2013.

[57] http://sbir.gsfc.nasa.gov/SBIR/abstracts/11/sbir/phase2/SBIR-11-2-X3.03-9754.html

[58] http://sbir.gsfc.nasa.gov/SBIR/abstracts/12/sbir/phase1/SBIR-12-1-H3.02-9747.html

[59] http://sbir.gsfc.nasa.gov/SBIR/abstracts/09/sbir/phase2/SBIR-09-2-X2.04-8356.html

[60] Jan, D.L., and Newton, R., "Environmental Monitoring as part of Life Support: Deep Space Exploration", 42nd International Conference on Environmental Systems, AIAA 2012-3433, 2012.

[61] http://sbir.gsfc.nasa.gov/SBIR/abstracts/10/sbir/phase2/SBIR-10-2-X3.03-9702.html

[62] http://sbir.gsfc.nasa.gov/SBIR/abstracts/12/sbir/phase1/SBIR-12-1-H3.02-9850.html

[63] Oubre, C. M., Birmele, M. N., Castro, V. A., Venkateswaran, K. J., Vaishampayan, P. A., Jones, K. U., Singhal, A., Johnston, A. S., Roman, M. C., Ozbolt, T. A., Jett, D. X., Roberts, M. S., Ott, C. M. "Microbial Monitoring of Common Opportunistic Pathogens by Comparing Multiple Real-Time PCR Platforms for Potential Space Application," 43rd International Conference on Environmental Systems, American Institute of Aeronautics and Astronautics (AIAA), Vail, CO, July 2013.

[64] http://sbir.gsfc.nasa.gov/SBIR/abstracts/09/sbir/phase2/SBIR-09-2-X2.03-9435.html

[65] http://sbir.gsfc.nasa.gov/SBIR/abstracts/12/sbir/phase1/SBIR-12-1-E1.03-8342.html

[66] http://sbir.gsfc.nasa.gov/SBIR/abstracts/10/sbir/phase2/SBIR-10-2-O3.06-9150.html

[67] Ott, C. M., Personal Communication.

68 Kelsey, L., Straus, J., and MacCallum, T., "Employing Ionomer-Based Membrane Pair Technology to Extract Water from Brine", 42nd International Conference on Environmental Systems, AIAA, 2012-3527, 2012