NASA Environmental Control and Life Support Technology Development for Exploration: 2022-2023 Status

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NASA is pursing Environmental Control and Life Support System (ECLSS) technology development and hardware upgrades to support Gateway, lunar surface, Mars transit, and Mars surface missions. This paper will highlight 2022-2023 progress of the technologies and how they are maturing on paths to ground testing and demonstration in microgravity. Technologies NASA is trading, new developments, and particular challenging issues will be highlighted. Technologies addressed in this paper are in the areas of atmosphere revitalization, water recovery and management, waste management, and environmental monitoring.

I. Introduction

NASA remains focused on developing new technologies for future missions and platforms that may offer advantages over the state of the art as well as improving existing systems based on lessons learned from operations on the International Space Station (ISS). This work is focused on closing the capability gaps identified by the NASA Environmental Control and Life Support (ECLS) community and is documented in NASA's gap repository and in the Environmental Control and Life Support Systems-Crew Health and Performance System Capability Leadership Team roadmaps. The roadmaps provide a high-level status, track when these systems are planned to mature to technology demonstrations and track their planned on-orbit test periods. This paper identifies the technologies in the NASA portfolio with a brief description of the technology and status highlights. Additional details on individual technologies can be found in the referenced documents.

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II. Atmosphere Revitalization

Atmosphere Revitalization includes technologies for removing carbon dioxide from the spacecraft atmosphere, recovering oxygen through carbon dioxide reduction, generating oxygen, controlling humidity by removal of atmospheric moisture, removing trace contaminants, and filtering particulates in the atmosphere.

A. Carbon Dioxide Removal

There are two carbon dioxide removal systems currently on the ISS as technology demonstrators, the Four-bed Carbon Dioxide Removal system, and the Thermal Amine System. Three other technologies, Carbon Dioxide Removal by Ionic Liquid System, Liquid Amines, and Carbon Deposition are being investigated. These three technologies offer potential volume, mass, and power savings over the technologies currently on the ISS. Additionally, Rapid Cycle Temperature Swing Adsorption and Multisorbents are subsystem technologies being developed with the potential to replace the zeolite beds in the Four-bed Carbon Dioxide Removal system. An alternate technology to the carbon dioxide compressor and accumulator is Air Cooled Temperature Swing Adsorption Compression.

1. Four-bed Carbon Dioxide Removal

The Four-Bed Carbon Dioxide Scrubber (4BED) is a system that uses a zeolite-based sorbent to continuously remove carbon dioxide from the atmosphere. Since its activation on the ISS in September 2021, it has been performing as expected without any significant failures or issues[1]. In the spring of 2023, 4BED's blower was upgraded to a new magnetic bearing blower to address hardware obsolescence and improve performance. During its demonstration on the ISS, it was observed that 4BED scrubs and concentrates trace contaminates, specifically Octafluoropropane (freon), which poses a potential risk to downstream systems. To further understand this phenomena, future plans include characterizing its ability to scrub selected trace contaminates using the ground 4BED Engineering Development Unit (EDU) and integrated ground testing with downstream hardware such as a Sabatier carbon dioxide reduction system.

2. Thermal Amine Scrubber

The Thermal Amine Scrubber (TAS) is a CO_2 removal technology based on thermally regenerated solid amine with passive water save capability. It was designed and built by Collins Aerospace and flew to ISS for demonstration in 2019[2]. TAS uses two Express Rack double lockers and an International Subrack Interface Standard drawer and is located in the US Lab. Currently TAS is not operating due to a failure in its controller. The controller has been returned and refurbished and is planned to be reflown the summer of 2023.

3. Carbon Dioxide Removal by Ionic Liquid System

Carbon Dioxide Removal by Ionic Liquid System (CDRILS) is a carbon dioxide removal technology being developed by Honeywell Aerospace. Honeywell has recently been doing testing on a prototype unit at their Glendale, Arizona facility. Aging tests and tests on effects of trace contaminants on their system have been performed.[3] Future plans are to fly a technology demonstration on the ISS. Honeywell has performed preliminary packaging studies and has started to compile requirements for a flight demonstration.

4. Liquid Amines

Carbon dioxide removal with liquid amines is a technology in development by NASA. Recently, the team has been working on optimizing contactor tray design from additively manufactured materials with analysis and prototyping, as well as an evaluation of different amine-based sorbent formulations. CapillarySorbent (CapiSorb) is a flight experiment to understand the behavior of a liquid in a capillary channel when exposed to thermal gradients in microgravity. By exploiting recent advances in our understanding of the fluid physics of capillary surfaces, it may be possible to manage thin films of liquid sorbents without the need for containment within membranes that restrict diffusion, reducing performance. The experiment was completed in April 2023 and the results demonstrated the technology works in microgravity.[4,5]

5. Carbon Dioxide Deposition

Carbon Dioxide Deposition uses cryogenic cooling to collect Carbon Dioxide. The unique characteristic is phase change freezing rather than sorbents as the removal mechanism. A trade study of materials for testing on the Materials International Space Station Experiment (MISSE) experiment platform was completed. Testing continues to show contaminant uptake does not affect Sabatier reactor performance. Full scale design of the evaporator as well as design and assembly of the cryogenic heat pump test stand were completed. Manufacture and test of subscale contactors and degassers with chosen sorbents are in work. Assembly of a full-scale system is underway. Additional system components such as the CO_2 buffer tank, fabrication of a thermal radiator and testing of variable conductance heat pipes continue.[6,7,8]

6. Rapid Cycle Temperature Swing Adsorption

Clay bound sorbent granules used in the Carbon Dioxide Removal Assembly (CDRA) and the 4BED are predisposed to dust release. The Rapid Cycle Temperature Swing Adsorption is a technology to coat the sorbent directly on a metal substrate. These plates would be drop-in replacements for a packed bed of clay bound sorbents. In addition, this technology allows for faster cycling due to improvements in heat transfer and pressure drop, potentially resulting in smaller beds. This year the coated plates have been fabricated and initial tests were completed. Plates for a subsystem test have been manufactured and coated. CO_2 testing will start spring 2023.

7. Multi-Sorbents

Multi-sorbents work is the development of formulation and process to optimize zeolite paste for 3D printing custom sorbent geometries and integration of thermal control elements. Three zeolite 13X paste formulations were chosen from work done to analyze lattice structures for capacity, permeability, thermal properties, and structural integrity. The plan for this year is to test the 3D printed structures in a bench top test.[9]

8. Air Cooled-Temperature Swing Adsorption Compression

Air Cooled-Temperature Swing Adsorption Compression (AC-TSAC) captures and stores carbon dioxide for delivery to a Sabatier reactor for reduction of CO_2 to methane and water. The AC-TSAC system was rebuilt and upgraded for integrated testing with the ground 4BED CO_2 removal system at MSFC. Testing was completed in early 2023, and work will continue toward a flight design configuration with a higher fidelity to optimize for CO_2 removal and process controls.[10]

B. Trace Contaminant Control

Trace contaminant control is required in a spacecraft to maintain a safe breathing atmosphere. For exploration missions NASA is addressing obsolesce of the activated charcoal currently used on the ISS and developing a catalytic oxidizer using a thermal-catalytic material in lieu of the catalyst design used on the ISS.

1. Exploration Forward Trace Contaminant Control System

An exploration forward Trace Contaminant Control System (TCCS) conceptual design has been completed and test hardware is being manufactured. The system consists of a redesigned adsorption guard bed and a novel high-temperature catalytic oxidizer. Future work will involve redesign of the post-oxidizer scrubber bed once a suitable acid-gas sorbent is identified. Candidate TCCS blower replacements are also under consideration. A second-generation catalytic reactor has exceeded 900 days of life testing with no failures and life testing continues. A third-generation catalytic oxidizer has been delivered to NASA and will be incorporated into the TCCS life test bed with the selected exploration-hardware prorotypes.[11, 12]

2. Sorbent Development

Several types of trace contaminant control sorbents are used in the TCCS to ensure the capacity and breadth of the system's contaminant removal capability. New sorbents are under evaluation because of obsolescence of the state-of-the-art material. In addition, various hydrogen chloride contaminant removal acid-gas sorbents were characterized. Novel materials were synthesized and characterized[13]. Evaluation of additional commercial off the shelf sorbents will be conducted this year.

C. Particulate Filtration

There are no planned upgrades to the system on the ISS. The bacterial scroll filter has incorporated lessons learned from ISS operations, including the understanding that large particles and lint are the predominant driver in maintenance time.

1. Bacterial Scroll Filter

The Bacteria Filter Element scroll filter technology is a filter that scrolls the media, eliminating the need for periodic cleaning by astronauts. During the prior year NASA has started preliminary design work for a flight technology demonstration on the ISS

2. Carbon Particle Separation

The development of several carbon particle separation process technologies for use within oxygen recovery subsystems such as methane pyrolysis and Bosch carbon formation reactors have advanced.[14] In addition, NASA utilized crowd sourcing to seek unique concepts for carbon particle removal through the NASA Tournament Lab and hero[x] ("NASA Particle Partition Challenge").

D. Condensing Heat Exchanger

NASA is working updates to the current ISS heat exchanger design to improve microbial control, siloxane resistance, and life. Additionally, NASA is developing an alternative technology that has the potential for mass, power, and volume savings as well as reliability improvements.

1. ISS Condensing Heat Exchanger Upgrade

NASA is planning to demonstrate an upgraded Condensing Heat Exchanger (CHX) on ISS, which performs cabin air temperature and humidity control as part of the Common Cabin Air Assembly. The CHX is being developed by Collins Aerospace and Boeing and will have an improved hydrophilic coating for better microbial control, siloxane resistance and overall lifetime. The CHX will utilize additive manufacturing with titanium which will reduce its mass. A design technical interchange meeting (TIM) is planned for fall 2023, with a Critical Design Review (CDR) to be held in 2024.

2. Laser Processed Condensing Heat Exchanger

The Laser Processed Condensing Heat Exchanger (LP-CHX) incorporates a novel electroplating process to mitigate microbial growth as well as treat the condensate water collected. Work performed this period demonstrated that the electroplated LP-CHX could be produced at a lower cost and a shorter schedule.

E. Oxygen Recovery from Carbon Dioxide

The Sabatier Carbon Dioxide Reduction Assembly (CRA) on the ISS recovered approximately 47% oxygen from carbon dioxide when it was operational. For a Mars transit mission, the oxygen recovery target is greater than 75%. The CRA’s percent recovery is rather low because the amount of available hydrogen is limited. Several technologies are being developed to close this gap[15], either by adding a methane pyrolysis reactor to recover hydrogen from the methane by-product of the CRA to process additional carbon dioxide, or by replacing the CRA with a more efficient technology. A Bosch system would replace the CRA, theoretically recovering 100% oxygen. However, challenges in handling solid particulate carbon in microgravity may make Bosch more applicable to surface applications.

1. Methane Post Processor Assembly (MPPA)

The MPPA is based on the Plasma Pyrolysis Assembly (PPA), that utilizes a microwave magnetron to generate plasma in which methane is decomposed to hydrogen and acetylene. The hydrogen, if returned to the CRA, theoretically increases the recovery of oxygen to 86%. In the last year, there were several different efforts to address challenges and mature the technology. In a cooperative effort between Umpqua Research Company and NASA, a Regenerable Carbon Filter[14] was developed and tested and integrated into the 3rd Generation PPA test stand[16,17]. Testing of a solid-state microwave generator was conducted. The addition of a cold plate enabled higher output power levels (~650W). Skyre investigated novel membranes for use in its electrochemical hydrogen separator.[18] The 2nd Generation PPA was upgraded in preparation for Phase II testing of Skyre’s three-cell electrochemical cell stack.

2. Hydrogen Recovery by Carbon Vapor Deposition

Honeywell Aerospace’s Hydrogen Recovery by Carbon Vapor Deposition (CVD) technology was developed to recover hydrogen from the Sabatier’s methane product, returning the hydrogen back to the Sabatier to recover additional oxygen[19,20]. Using a high temperature pyrolysis process, it produces a solid carbon product that is safe to handle. Honeywell developed, tested, and shipped a 4-person level brassboard reactor system to NASA[21], where plans include integrated testing with a developmental Sabatier developed by Precision Combustion Inc.[22] NASA is developing analytic models of the technology in support of integrated testing and further maturation of the technology. The CVD technology is under consideration for a flight demonstration. Toward this goal, Honeywell is developing the Flight-Like Advanced Material Reactor[23], which completed its Preliminary Design Review (PDR).

3. Bosch

Umpqua Research Company completed two activities toward development of its Continuous Bosch Reactor. Their contract entitled “Carbon Separation and Storage for Continuous Operation of a Bosch Reactor” was completed, which sought alternative means for management of particulate carbon. Umpqua also performed numerous parametric studies with its subscale reactor in support of NASA’s completion of a kinetic model of the Bosch process, which is being written up for release as a NASA Technical Memorandum.

Series Bosch utilizes two reactors that optimize each of the two main sets of reactions, reverse water gas shift and carbon formation[24]. Recent work focused on demonstrating that the system can be packaged in a form factor to meet size and mass constraints for mission deployment and improving performance of the carbon formation reactor (CFR). pH Matter’s Automated Carbon Formation Reactor is under consideration for use in Series Bosch.[25] Development of a NASA-designed CFR continued.

4. ISS Sabatier Upgrades

The Sabatier combines CO_2 with H_2 to generate water. The Collins Aerospace Sabatier CRA accumulated approximately 2 years of runtime on the ISS before the reactor failed due to contamination. NASA has contracted Collins to deliver an upgraded system (Sabatier 2.0) with the following improvements: a new replaceable getter to protect the reactor from contamination, additional temperature sensors on the reactor to detect degradation, humidity sensors to alert systems to safe the Sabatier to avoid compressor damage or other downstream impacts, and a focus on maintainability (the reactor and the Laminar Flow Element will be replaceable components).[26,27] A preliminary design review of the upgrades has been completed. Currently the Sabatier is projected to be delivered for flight spring of 2025.

F. Oxygen Generation

NASA currently generates oxygen on the ISS via operation of the Oxygen Generation Assembly (OGA). NASA is working upgrades based on lessons learned and maintainability objectives for future space missions. NASA is also developing a Static Vapor Feed Electrolysis technology that does not require some of the sub-systems needed on the OGA.

1. Advanced Oxygen Generation Assembly

The Advanced Oxygen Generation Assembly (AOGA) is an evolutionary upgrade to the ISS OGA with key features focused on exploration: a change from a single hydrogen dome to separate, maintainable domes for the cell stack and rotary separator accumulator, a new cell stack design that incorporates current industry standard materials and improved membrane support structure, and a design that enables a recirculation loop purge and flush for dormancy. The AOGA is being developed by The Boeing Company and Collins Aerospace for demonstration on ISS.[28] AOGA will have a delta critical design review during summer 2023 Delivery is planned in 2025.

2. Static Vapor Feed Electrolysis

Static Vapor Feed Electrolysis (SVFE) is a water electrolysis technology to produce oxygen which simplifies the current state of the art. SVFE does not have a recirculation loop for the water feed nor a hydrogen-water phase separator. NASA is developing a rig to test a forty-cell stack planned to be delivered from Giner in April 2024. The cross-center team, including representatives from MSFC, GRC and JSC, completed a Systems Requirements Review and a PDR for the test rig. The plan is to complete a Critical Design Review in 2023.

G. High Pressure Oxygen

Currently NASA provides high pressure oxygen for Extra Vehicular Activities with Nitrogen/Oxygen Resupply tanks. This approach to manifest the required tanks for exploration missions is mass intensive. NASA is pursuing several alternatives to generate high pressure oxygen *in situ* within spacecraft and surface habitats.

1. High Pressure Oxygen Generation

NASA is investigating generating high pressure oxygen via a high-pressure electrolysis technology. Prior testing demonstrated cycling a cell stack from low pressure to high pressure significantly reduced cell stack life. If this new technology were deployed, high pressure would need to be regulated down for low pressure operations. Giner is designing and testing a 24.8 MPa (3600 psi) cell stack. NASA is designing and developing a test stand to test the feasibility of this approach. Functional testing is planned to start in 2024.

2. Low Pressure Oxygen Compression to High Pressure

NASA is developing a technology to compress low pressure oxygen to high pressure. The systems will have a layered bed to dry the oxygen and then go through two stages of compression. The first stage will compress the oxygen to 103 kPA (15 psi) from ambient to a buffer tank. The second compression stage will use a Cobham compressor to compress the oxygen to 24.8 MPa (3600 psi). The reason for the two-stage process is the Cobham compressor cannot compress from ambient pressures. The test bed has been designed and is being built in preparation for checkout prior to cleaning the system to cleanliness levels required for operation with oxygen. After oxygen cleaning the test stand will be reassembled and prepared for testing.

3. Ceramic Oxygen Generation

The Ceramic Oxygen Generator collects and compresses oxygen at low and high pressure. The team demonstrated low pressure high purity oxygen production with first stage design. A new geometry for the high-pressure ceramic generator was tested to demonstrate ambient pressure oxygen production, thermal management, and pressure integrity. Currently the team is working toward development of a full-scale two-stage system to produce high pressure oxygen.[29]

III. Water Recovery and Management

Potable water is a product of the Water Processor Assembly (WPA). Urine from the ISS toilet is sent to the Urine Processor Assembly (UPA) where water is removed from the urine and sent to the WPA. The WPA also processes atmospheric moisture originating from human respiration, evaporated sweat, evaporated UPA brine from the Brine Processor Assembly (BPA) and other sources via the condensing heat exchanger. The total water recovery from these combined systems is targeted at 98%. NASA is testing biocide alternatives to iodine to control microbial growth in the wastewater system and researching ways to mitigate biofilm growth during dormancy.

A. Distillate/Condensate Processing to Potable Water

NASA is upgrading the hardware of the current ISS Water Processor Assembly (WPA) based on lessons learned from ISS operations. Potable water dispensing options are being investigated for Gateway, Mars transit missions, and surface mission that are unique to those missions. No alternative technologies are currently being sought to replace WPA component subsystems.

1. Water Processor Assembly Upgrades

The WPA on ISS is being upgraded to improve the life of the Catalytic Reactor, a key component for removing volatile organics and sterilizing the water to prevent microbial growth. The demonstration Catalytic Reactor has improved catalyst and metal seals in the hot section (an upgrade from elastomeric which leak and are the life-limiting components of the Catalytic Reactor). The Catalytic Reactor is being built by The Boeing Company and Collins Aerospace and is being launched summer 2023 for installation on-orbit. WPA also has an upgraded multi-filtration bed with synthetic resin that replaced the original charcoal, and NASA plans to fly a new microbial check valve with the intent of improving functionality of the valve in a very low delta pressure environment and extending life of the microbial barrier.[30]

2. Potable Water Dispenser

The Potable Water Dispenser (PWD) on ISS will be augmented by an exploration upgrade of the system. The eXploration PWD enables dormancy through the elimination of dead legs in the water path and utilizes in-situ ultraviolet sterilization of the water as it exits the system rather than a traditional consumable filter.[30] The eXploration PWD has been delivered and will launch on the next available flight for installation on ISS.

B. Wastewater Processing, including Urine, Brine and Hygiene.

NASA is not developing any additional technologies to process urine or urine brine in microgravity, but minor hardware modifications are planned. NASA is upgrading the current urine processor based on lessons learned from ISS operations. On a surface mission the presence of gravity reduces the complexity of wastewater processing systems. NASA is testing several different technologies for urine and wastewater processing for surface missions.

1. Urine Processor Assembly Upgrade

The Urine Processor Assembly (UPA) treats the urine from the toilet prior to delivery to the Water Processor Assembly for final processing to potable water. The UPA has been operated on the ISS since 2008. Learning from the system over time, the UPA has been upgraded to increase reliability and maintainability. The Pressure Pump Separator Assembly (PPSA) is an upgrade that combines the function of the Pressure Control Pump Assembly and the Separator Plumbing Assembly into one unit. The PPSA was launched to the ISS in August of 2022 and is awaiting installation. The currently installed Distillation Assembly (DA) has the latest upgrades incorporated and is performing as expected.[31] NASA is also looking to change the pump design on the Fluids Control and Pump Assembly from a single three channel pump to three individual single channel pumps. This concept allows for easier maintenance and sparing.

2. Brine Processor Operations

The BPA has completed nineteen operations of processing brine from the UPA as of February 2023. It is estimated that 340 liters of water from the UPA brine have been recovered.[32] Data from returned bladders has been evaluated to determine if the goal of 98% total water recovery from the UPA, WPA, and with the addition of the BPA has been met. The results demonstrated that 99% total water recovery from UPA, WPA, and BPA was achieved.

3. Planetary Urine Processor

NASA's MSFC is investigating urine processing by simplified distillation intended for lunar and/or planetary urine recovery applications. There are several potential advantages: local gravity is exploited for more conventional phase separation processes, the system is tolerant to formation of solids, safer pretreatment methods can be utilized (such as hydrogen peroxide) and brine processing could potentially be eliminated. Three Planetary Urine Processor concepts are being pursued with supporting laboratory investigations, bread board testing and data assessments. Concept 1 utilizes a liner bag nested within a distiller tank, which was demonstrated to reach 98% water recovery. After processing, the liner with remaining brine and solids are discarded. Concept 2 was a more complex system with two tanks, a primary distillate tank and a smaller secondary tank with improved heat transfer efficiency that incorporates a liner. This work was limited to initial design. Concept 3 designs are intended to further improve energy efficiency by recovering latent head of condensation to aid in the evaporation process. Designs were completed and fabrication was initiated. A series of urine stabilization studies involving several alternative oxidizers and stabilizers was performed. Studies focusing on microbial control were completed. Hydrogen peroxide was selected as the most viable candidate, given considerations for consumable mass and our ability to generate hydrogen peroxide in real time.[33]

4. Wastewater Processing using Bioreactors

Pancopia and Texas Tech University (TTU) continued work toward development of a Two Stage Biological Wastewater Processor[34]. TTU's rectangular Counter-diffusion Membrane-Aerated Nitrifying-Denitrifying Reactor served as the first stage. It mineralizes organic carbon and converts influent nitrogen into equal parts of ammonium and nitrite, ideal for further degradation by Anammox. Pancopia's AnammoX[335] or Mixed-culture AnammoX reactors serve as the second stage, converting the nitrogen to nitrate and nitrogen gas. The current effort includes characterization of the composition of product gases released. Other work performed by TTU includes evaluation of different water recovery system architectures using integrated biological-physicochemical components for partial gravity applications, including reverse osmosis and membrane filtration, for treatment of urine and grey water separately and in combination[36].

Collaborative work by KSC and the University of South Florida included development and investigations of an Anaerobic Membrane BioReactor (AMBR), a PhotoMembrane BioReactor (PMBR) and a Suspended Aerobic Membrane BioReactor (SAMBR)[37]. Studies included integration of reactors together and with other water recovery processes, including investigations toward use of effluents for crop fertigation. Capacitive Deionization is being investigated for removal of sodium prior to utilization of the product stream as recycled fertilizer.

C. Microbial Control and Dormancy

On the ISS recycled potable water quality is maintained by the WPA using continual dosed iodine. Orion is using silver for the stored potable water system and the current Gateway architecture includes both stored iodine and silver in early mission phases. Orion and Gateway are predosing water storage tanks with silver. For Mars transit and surface missions continual dosing will be needed. Iodine has several disadvantages that are operationally managed. Alternative biocides require additional development before they can be considered for implementation within future water recycling systems. For utilization of silver as a biocide for water recovery systems, silver dosing, silver monitoring, and an understanding of silver loss to materials used within the systems will be needed for system design. Bromine and ultraviolet are also under consideration for microbial control in potable water. NASA is researching biofilm mitigation strategies for wastewater tanks and associated plumbing. Biofilm mitigation will be especially important during periods of dormancy.

1. Silver Dosing

Silver must be continually dosed to maintain sufficient levels for inhibiting microbial growth in potable water systems. Three silver dosing technologies under investigation include Electrolytic Silver, DirectINJECT, and Silver foam. Electrolytic Silver completed testing and produced enough water for one crew year without disruption. Additional testing was conducted to understand the test anomalies and aid in the reactor housing and geometry design.[38] The DirectINJECT capillary delivery system traded better than two pumped systems. The DirectINJECT team will be building up and testing a triplicate capillary dosing system. A one-year test was initiated to evaluate a silver foam flow through system.[39] Initial functional testing of a Microbial Check Valve was completed. The team will continue long duration testing, investigate dormancy, and mitigate issues with product variability.

2. Silver Monitoring

Technologies for monitoring the levels of silver in potable water systems will be needed to verify that dosing systems consistently deliver the required levels of silver to maintain biocidal activity. Innosense successfully completed initial investigations to characterize its nanomaterials-based in-line sensor for measurement of ionic silver. The development of a prototype continues. NASA is testing a capacitively coupled contactless conductivity silver sensor that senses dissolved silver salts.[40] Sensor sensitivity was tested with and without the DirectINJECT silver doser in cold start and continuous flowrate conditions. Intelligent Optical Systems investigated novel fluorescent materials for use in an optical silver ion sensor. While sensitivity and reversibility to silver ions in the range of interest was demonstrated for a specific fluorescent material, additional work will be needed to successfully immobilize it on sensor surfaces without affecting its performance.

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3. Materials Compatibility with Silver

A variety of metallic, polymeric, and coated materials were investigated to assess their compatibility with ionic silver, with the aim to identify materials that prevented or minimized silver loss from potable water. Testing to characterize the loss of silver biocide continued, using legacy tubing, Teflon-lined flex hoses, and coated material coupons. Gas permeation effects from flex hoses were also considered. Coated samples and bellows showed less silver loss than uncoated samples and bellows. The data will be compiled and reviewed by materials and water system subject matter experts to determine forward work.[41, 42]

4. Bromine

In September 2022, Umpqua Research Company (URC) completed its contract entitled "Halogen Binding Resins for Potable Water Disinfection". Utilizing the success of its Microbial Check Valve (MCV) for iodine, other halogens were investigated, including chlorine and bromine. A new resin was developed for use in a simple flow through cartridge that leaves a 0.5 to 4.0 mg/L bromine residual in water, with a throughput capacity near that of the original MCV in use on the ISS.

5. Ultraviolet

Ultraviolet (UV) light is under consideration for use as a non-chemical alternative to microbial control in potable water and for biofilm prevention. H2O Insights successfully completed their contract entitled, "Side-Emitting Optical Fibers (SEOF) for Delivery of UV-C Light to Disinfect Key Bacteria in Space Station Water and Storage and Conveyance Systems". The technology incorporates silica nanoparticles on optical fibers to achieve side-emission of UV-C light along the entire optical fiber length[43]. These fibers can deliver UVC-light in hard-to-reach areas within potable water systems, including tubing and bellows tanks. Incorporation of a UV LED reactor in the Exploration Potable Water Dispenser (see Section 24) was based on prior technology development at NASA that assessed UV LEDs for microbial control.

6. SilverXX

Silver XX (AgXX) is a coating that generates reactive oxygen species (ROS) and is being investigated for disinfection and prevention of biofilm growth. Testing has shown that the material impacts cell viability and is inhibitory to bacterial growth. Tests to assess the effectiveness of AgXX in water and nutrient delivery systems were completed. A final report of plant growth tests was submitted to the Ohalo III crop production system design team prior to food safety assessment.[44]

7. Hydrogen Peroxide

Hydrogen peroxide is under consideration as a safe, alternative agent for urine pretreatment that can be generated in situ. Urine stabilization studies determined that adequate microbial control could be achieved[33]. Further testing will be completed in 2023 to characterize the performance as part of continuous nominal and off-nominal operations, varying concentrations and considering dormancy.

8. Dormancy

Dormancy has been identified as a critical issue for future human exploration missions due to concerns of microbial growth or chemical degradation that would prevent water systems from operating properly once crew returned to the vehicle[45]. Both Lunar and Mars missions will likely involve operational systems that could be placed in an extended untended configuration. This period of dormancy could last for up to one year depending on the specific mission but could be up to three years due to contingencies. NASA is currently researching potential effects of dormancy on spacecraft water management systems and developing strategies to mitigate potential effects.

NASA continues to develop a test stand to perform initial dormancy testing. Subassemblies of ISS water recovery systems are being constructed for evaluation using the test stand. Universal Waste Management System and Water Separator subassembly components have been additively manufactured in titanium in cooperation with the Army's Combat Capabilities Development Command Aviation & Missile Center in Huntsville, AL. Urine filter assembly components were machined, and the condensate check valve began fabrication.

The ISS wastewater tank that collects humidity condensate and urine distillate has had issues with growth of biofilms, and these issues are expected to be exacerbated during periods of dormancy. In the last year, NASA has continued research tasks to identify viable methods for inhibiting growth of biofilms, to develop design solutions for implementing these various methods, to trade candidate methods toward selecting the best solutions, and to evaluate effectiveness of these solutions in ground-based tests. Using a bioreactor test stand designed for these investigations, various treatment tests were performed (e.g., nutrient filter, thermal treatment, and coatings). SANUWAVE investigated use of its shockwave technology to manage biofilms in water tanks. In a cooperative effort with NASA, the Center for Biofilm Engineering at Montana State University studied nutrient effects on biofilm formation.[46,47,48,49,50]

IV. Waste Management

Waste management involves the collection of astronaut urine for recycling and collecting fecal matter for disposal. The Universal Waste Management System was developed for use on Orion and future space missions.

A. Universal Waste Management System

NASA funded the development of the Universal Waste Management System (UWMS) as an exploration toilet for use on long duration missions such as Mars Transit[51]. Two toilets were delivered, one used with urine recycling in a regenerative architecture, which is on the ISS[52,53] and one delivered for the Artemis II mission demonstrating pretreatment used in a short mission where urine is vented or stored. Aside from these differences and minor dimensional changes for vehicle installation, the two units are identical. Currently, the toilet used in a regenerative ECLS architecture is undergoing testing on ISS. Technical challenges are being evaluated and corrected in advance of completion of a technology demonstration designed to mimic a long-duration exploration mission[54]. The unit for a short, crewed mission is installed in the Artemis-2 vehicle for launch in 2024. Minor updates have been made to the unit based on lessons learned from the ISS.[55] This includes inclusion of a smaller seat based on crew preference, installation of an acoustic cover for mitigation of sound in the Hygiene Compartment and manifesting additional fecal canisters for storage of solid waste based on actual usage/storage rates. Evaluation and additional testing will continue on the ISS into 2023.

B. Fecal Can Alternate Design

NASA developed the Alternative Fecal Canister (AFC) as a lower mass and volume alternative to the Hard-sided Fecal Canister (HFC) designed for use with the UWMS.[55,56] Stowed in a collapsed form prior to use, a significant reduction in volume was obtained. The design includes a soft-goods, flexible body, with a rigid top that interfaces with the UWMS during use and with the fecal canister lid used with the UWMS HFC for storage after use. Extensive material testing was done to select a commercially available material. A body bag material was selected. It proved to be impervious to odor migration. Further odor testing showed odor did escape the assembly when capped and future work includes development of a gasket material to replace the current BISCO foam originally used. The AFC units are currently on ISS awaiting a technology demonstration with the UWMS. The investigation will provide information on ease of use by crew, comparison to the HFC in handling, and odor control.

V. Environmental Monitoring

A. Atmosphere Monitoring

Monitoring both major constituents and trace gases in a spacecraft is essential to ensure a safe atmosphere for the crew. NASA is developing instruments that measure only major constituents, only trace gases, and measuring both major constituents and trace gases in a single instrument.

1. *Spacecraft Atmosphere Monitor*

The Spacecraft Atmosphere Monitor (S.A.M.) utilizes gas chromatograph/mass spectrometer technologies to analyze major constituents and trace gases in the spacecraft atmosphere. S.A.M. Technology Demonstration Unit (TDU) Number 2 has been assembled and undergoing testing for a flight to ISS in 2023. S.A.M. TDU1, which was returned from ISS, will be upgraded to include trace gas analysis capabilities, and is planned to be reflown to the ISS in 2024.[57]

2. *Air Quality Monitor*

Air Quality Monitors (AQMs) continue to be used for in-flight trace contaminant monitoring on the ISS, but there are concerns about the availability of spare units to continue operations through 2030. To address the potential gap in support, all current AQMs are being run to failure during flight operations on the ISS. The hardware team is also working with the instrument manufacturer to refurbish several units to increase the number of available spares.

3. *FLIR Griffin Trace Gas Monitor*

The FLIR Griffin G510 is a portable gas chromatograph – mass spectrometer (GC-MS) that is being evaluated for in-flight monitoring of volatile organics in the habitable volume of crewed spacecraft. Although the instrument looked promising during initial testing, several limitations were identified that the manufacturer is working to address. Examples of limitations include carrier gas quantity, calibration stability, and the calibrated mass range on the COTS device. One of the most intriguing aspects of the Griffin G510 is that it uses the same instrument configuration as most ground GC-MSs used for environmental monitoring. The instrument also comes pre-loaded with a version of the NIST mass-spectral library, which should help with identification of non-target contaminants.

4. Portable Tunable Laser Spectrometer

The Portable Tunable Laser Spectrometer (PTLS) is an instrument that uses laser spectrometry to measure CO_2, O_2, and water vapor in the spacecraft atmosphere. PTLS is also designed for wireless communication allowing for the instrument to be easily placed throughout the spacecraft. The lasers used in the instrument have been characterized and tested for flight environments. Southwest Sciences is designing and building six PTLSs for flight on the ISS.[58,59]

5. LAM

The Laser Air Monitor (LAM) utilizes Tunable Laser Diode Adsorption Spectroscopy, which does not contain moving parts. The system has been developed by Dynetics for use in the Orion program. A LAM will fly on Artemis-II for cabin pressure monitoring only, with full capability planned for Artemis-III. LAM measures CO_2, O_2, H_2O and cabin pressure. Currently, NASA does not plan to fly LAM as an ISS technology demonstration.[60]

6. Major Constituents Analyzer

The Major Constituents Analyzer (MCA) continues to be operated intermittently to preserve the life of critical system components. Recently, the ISS program decided to further limit MCA operations to only support EVAs. Previously, MCAs were also operated during crew handovers to help characterize CO_2 generation rates for new crews. Several alternate systems are being developed and evaluated to supplement MCA operation.

7. Anomaly Gas Analyzer

Qualification and acceptance testing of the initial delivery of Anomaly Gas Analyzers (AGAs) is nearly complete. Several minor issues were encountered during environmental acceptance testing, but these did not adversely impact the performance of the monitors. A temperature limitation was also discovered that may limit how closely AGAs can be used near a confirmed combustion event. The ISS AGA units are planned to be delivered in 2024.

B. Water Monitor

To ensure that potable water quality meets requirements and to troubleshoot issues in real-time during flight, water monitors are in development. Water quality is monitored on the ISS by measuring the total organic carbon content. NASA is developing a total organic carbon monitor that has less mass and volume than the instrument on ISS. NASA is also developing a monitor that will identify organics and inorganics in water. This capability will be essential for a Mars transit mission in which returning water samples to Earth for analysis will not be possible.

1. Miniature Total Organic Carbon Analyzer (MiniTOCA)

The Miniature Total Organic Carbon Analyzer uses UV for oxidation of organics and tunable laser spectroscopy for quantification of the resulting carbon dioxide. A PDR was completed in April 2022. An engineering design unit to be completed and tested in 2023.[61]

2. Spacecraft Water Impurity Monitor

Spacecraft Water Impurity Monitor (SWIM) consists of the Organic Water Monitor (OWM) and the inorganics analyzer. Together both will detect and identify the organic and inorganic constituents as well as other measures of water quality. Work has focused on development of an OWM breadboard. Planned activities for the remainder of 2023 include completion of the first development unit of the OWM, a demonstration of the Capillary Electrophoresis (CE) inorganic detection method, and development and testing of a SWIM Inorganics CE system.[62]

C. Microbial Monitoring

In-flight microbial monitoring will be essential to ensure that requirements for environmental quality aboard spacecraft are being met and to verify that cleaning procedures and operations are effective in maintaining a clean and safe cabin. NASA has validated a method to monitor microbial growth on surfaces. This same technology is being applied for microbial monitoring of potable water and spacecraft atmosphere.

1. Biomole/MinION

The Biomolecule Sequencer successfully completed an on-orbit validation for surface monitoring on the ISS[63]. Following the completion of this effort, the hardware was transitioned to operational status and is currently being maintained as part of the Crew Health Care System. Current efforts are focused on certification of MinION 2.0, which will provide enhanced computational capabilities in a stand-alone system. An on-orbit demonstration of methods to monitor water are planned, and methods to test air in the habitable volume of spacecraft are being developed[64]. NASA is working closely with various vendors to develop and test temperature stable reagents that will extend the shelf life of the consumables needed for on-orbit sequencing and eliminate the need for refrigerated storage.

D. Particulate Monitoring

Understanding particulates in the spacecraft atmosphere will be important on surface missions and vehicles that are part of the mission. To avoid false fire alarms the monitor must distinguish between smoke particles and dust particles. Additionally, understanding the morphology of particles generated will inform NASA of techniques to filter particles in the spacecraft atmosphere.

1. Airborne Particulate Monitor

The Airborne Particulate Monitor (APM) measures a range of particle sizes and concentrations. The APM was first deployed on ISS during Increment 64 and over the last year has been deployed six times across ISS Increments 67 and 68 including recording of data on aerosol concentrations during elevated crew numbers. Preliminary analysis of the data suggests that even during handovers when crew numbers increase, particle generation is sufficiently low that the vehicle filtration system is efficient at removing airborne particles. The plan is to continue APM operations on orbit until data from two additional handovers are collected in order to calculate a per person particle emission rate.[65]

2. Exploration Forward Aerosol Particulate Monitor

The Aerosol Monitors Payload will prove the efficacy of several different monitoring technologies for use in crewed spacecraft. This payload contains a gravimetric sensor from Access Sensor Technologies for use as a particle mass reference, the Moderated Aerosol Growth with Internal Cycling (MAGIC) condensation small size particle counter, a Telosair aerosol distinguishing sensor and passive samplers. Requirements are being defined ahead of a Systems Requirements Review, in preparation for a technology demonstration.

E. Spacecraft Acoustics

The Acoustic Monitoring and Control technical area aims to fill technology gaps needed to successfully design and develop vehicle systems that meet strict acoustic requirements[66] (sound levels) in human spacecraft. It is important to control acoustical noise aboard crewed space vehicles and space habitats to provide a satisfactory environment for voice communications, alarm audibility, restful sleep, and to minimize the risk for hearing loss and annoyance.[67]

1. Quiet Fans

Work is being performed to design fans to meet noise requirements, including: development of small fans that produce sound power levels <54 dBA; and development of prime mover (flow rate > 2831 lpm (100 cfm)) and high-pressure rise (e.g., toilet, CO_2 removal) fans that produce duct-borne sound power levels <70 dB without acoustic treatments. The current project has successfully used large-fan design technology to develop a small quiet and efficient fan for a design point of 4248 lpm (150 cfm) at a pressure-rise of 895.8 Pascal (3.6 inches-H_2O).[68,69]

2. Noise Abatement

Beyond controlling noise at the source, the next steps are to mitigate the noise along the propagation path(s), and finally at the receiver, i.e., at crewmembers' ears. Technology gaps and development in the former area includes improvements to sound absorbing and sound blocking devices and spaceflight materials, which must meet other spaceflight criteria such as cleanability, flammability, off gassing, and reduced mass.[70] A recent success has been with development and flight certification of an absorbent foam that is encased within a cleanable Kapton® coating, called Soundfoam HTC® for use in waste and hygiene areas to mitigate high-level toilet noise. Finally, to control noise at the receiver, acoustic monitoring is needed to understand the vehicle's environmental (continuous and intermittent) noise levels, as well as the crews' noise exposure levels.[77] The goal of this autonomous and continuous monitoring is not to provide data to the ground controllers, but to inform the crew when sound levels exceed 85 dBA, i.e., the function of a 'Noise Hazard Level Indicator,' so that they know that hearing protection or a reduction of noise exposure levels is needed.

VI. Conclusion

Over the past year, NASA has made significant investments in the development and maturation of many ECLSS technologies, over a wide range of technical areas, including atmosphere revitalization, water recovery and management, solid waste management, and environmental monitoring. Some technologies are being developed to close capability gaps and to provide functions where viable technology solutions do not exist. Examples include monitoring and control of silver biocide in potable water, in-situ high pressure oxygen generation, and quiet fan technologies. Many of these technologies offer potential advantages over the current ECLSS systems that may reduce hardware and consumable mass, power, and/or volume, including equivalent systems mass. Several investments are being made to mature technologies as upgrades to address known issues or to make necessary improvements. Finally, several novel low TRL technologies are being explored that show promise. References have been provided to direct the reader to more information on many of these technologies. Additionally, readers may contact authors of this paper or referenced papers for additional information.

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