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International Space Station as a Testbed for Exploration Environmental Control and Life Support Systems – 2024 Status

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Human exploration missions beyond low Earth orbit, such as NASA's Artemis Program, present significant challenges to spacecraft system design and supportability. A particularly challenging area is the Environmental Control and Life Support System (ECLSS) that maintains a habitable and life-sustaining environment for crewmembers. NASA is utilizing the experience gained from its current and prior spaceflight programs to mature life support technologies for exploration missions to deep space. The intent is to establish a portfolio of life support system capabilities with proven performance and reliability to enable human exploration missions and reduce risk to success of those missions. As a fully operational human-occupied platform in microgravity, the International Space Station (ISS) presents a unique opportunity to act as a testbed for exploration-class ECLSS, such that these systems may be tested, proven, and refined for eventual deployment on deep space human exploration missions. This paper will provide an updated status on the testbed development, including hardware and ISS vehicle integration progress to date, as well as future plans for efforts to design, select, build, test, and fly Exploration ECLSS on the ISS.

Nomenclature

AOGA = Advanced Oxygen Generation Assembly
AR = Air Revitalization
ARC = Ames Research Center
ARFTA = Advanced Recycle Filter Tank Assembly
BPA = Brine Processor Assembly
CCAA = Common Cabin Air Assembly
CDRA = Carbon Dioxide Removal Assembly
CH_4 = methane
CHP = Crew Health and Performance
CHX = Condensing Heat Exchanger
CO_2 = carbon dioxide
COTS = Commercial Off the Shelf
DA = Distillation Assembly
ECLS = environmental control and life support
ECLSS = environmental control and life support system
EDV = Russian-built water tank
EMI = electromagnetic interference
EVA = extravehicular activity

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EXPRESS = Expedite the Processing of Experiments to ISS
FCPA = Fluids Control and Pump Assembly
(g) = gas phase
H_2 = hydrogen
H_2O = water
HEPA = high efficiency particulate air
IMV = intermodule ventilation
ISS = International Space Station
JSC = Johnson Space Center
LSR = Life Support Rack
(l) = liquid phase
MCC-H = Mission Control Center - Houston
MER = Mission Evaluation Room
MSFC = Marshall Space Flight Center
NASA = National Aeronautics and Space Administration
OGA = Oxygen Generation Assembly
OGS = Oxygen Generation System
PPSA = Purge Pump and Separator Assembly
PTU = Pre-treated Urine
PWD = Potable Water Dispenser
SRA = Sabatier Reactor Assembly
TIM = Technical Interchange Meeting
TOCA = Total Organic Carbon Analyzer
TCCS = Trace Contaminant Control System
US Lab = United States Laboratory Module
USOS = United States On-orbit Segment
UWMS = Universal Waste Management System
UPA = Urine Processor Assembly
UTS = Urine Transfer System
UV = ultraviolet
VOC = volatile organic compound
WHC = Waste and Hygiene Compartment
WPA = Water Processor Assembly
WRS = Water Recovery System
WW = Waste Water

I. Introduction

HUMAN exploration missions beyond low Earth orbit, such as NASA's Artemis Program, will require effective and reliable Environmental Control and Life Support Systems (ECLSS) to support human life during these long duration excursions far from the protection of Earth. The National Aeronautics and Space Administration (NASA) is executing an effort to demonstrate an exploration-class ECLSS on the International Space Station (ISS) that can be used on Artemis and Mars transit missions. The purpose is to allow characterization of system performance, system reliability, and integration challenges in the relevant environment of ISS. Additionally, where practicable, an increase in automation, parts commonality, and subcomponent repairability are being introduced as part of system upgrades. ISS is unique in that it not only hosts a microgravity environment, which is essential for testing two or three-phase systems such as ECLSS, but also hosts a closed atmosphere with crewmembers providing waste products while experiencing microgravity. This creates highly relevant conditions which properly challenge an ECLSS in a very similar manner as it would be challenged during long-duration microgravity-based human exploration missions beyond low Earth orbit.

The ISS demonstration of this exploration-class ECLSS is most relevant to the portion of future missions that occur in microgravity environments, such as a Mars transit mission. The portions of missions that occur in partial gravity, such as lunar or Martian surface stays, may have slightly altered requirements that the microgravity-based ECLSS may not satisfy. If it is determined that changes to the microgravity-compatible systems are needed or are beneficial for partial gravity, it is likely these will be tested on Earth instead of on ISS. Additionally, the operational pressures will likely be different for surface missions, which impacts operations and design to some extent. These design modifications will need to be addressed outside of this demonstration given the ISS operating environment.

The ECLSS hardware being demonstrated on ISS is a combination of upgraded existing vehicle systems as well as new technologies that will further close the mass balance loop and improve system reliability. The upgrades to existing vehicle systems utilize the vast experience gained during ISS operations to date to update areas within the ECLSS that have shown the potential for performance and reliability improvements[1]. The new technologies have been matured through ground-based laboratory testing and shown to perform well enough to necessitate an on-orbit demonstration to fully prove their viability for inclusion in a future exploration vehicle's ECLSS.

The demonstration on ISS is being configured to create a system that is as similar to a future vehicle's ECLSS as much as possible. This means that subsystems that directly integrate together to exchange process fluids are physically co-located and integrated together via hoses and cables. Subsystems that will exhaust into or ingest the vehicle's cabin air will do so in the ISS configuration. The ISS demonstration configuration will not repackage the ECLSS subsystems to mimic a future vehicle's physical layout or secondary structure (e.g. rack or pallet), nor will a ground-up redesign be performed to maximize common parts and subcomponent repairability. This is because the future vehicle's exact configuration is not known at this time and the ISS structure and layout limit significant reconfiguration. That being said, where modifications to enable component-level maintenance are possible, they will be prioritized with the goal of demonstrating this type of activity on-orbit in a critical system. The ECLSS firmware controllers will also not be redesigned to address mechanical and electrical parts obsolescence challenges, since these same challenges would present themselves again when performing the detailed design for a future vehicle's ECLSS. Further, future exploration vehicle cabins may be operated at different pressures than on ISS. This change in environment will not be able to be mimicked on ISS (priority for this effort will be in a ground test bed).

The ECLSS demonstration on ISS has been partitioned into "strings" in order to group portions of the system together for ease of integration. The Air String and Water String are each described in subsequent sections of this paper. The Air String will be located in the United States Laboratory (US Lab) module of the ISS. The Water String will be located in the Node 3 module of the ISS. The two strings are integrated together via the common atmosphere that circulates throughout the ISS via intermodular ventilation (IMV) as well as the potable and wastewater busses that are routed throughout most of the United States On-Orbit Segment (USOS).

The environmental monitors to be demonstrated on ISS will be deployed as dictated by installation volume, vehicle utilities (e.g. power, cooling, data), and their particular function. For example, a device that monitors potable water quality will be located directly inline within the potable water distribution system to enable direct analysis and demonstrate joint operations. As an additional example, a device that monitors major atmospheric constituents can be placed in one module of particular interest and potentially moved to a different module if deemed necessary.

A more recent, significant addition to the ISS on-orbit demonstration, is a plan to build Ground Test Beds at Marshall Space Flight Center (MSFC) that will match as much as possible the integrated systems and effectively double the data set used for Exploration mission architecture design. The ground test bed will also enable future technology demonstration and the potential demonstration of competing components/further design evolution as NASA transitions from ISS operations and prepares for Exploration missions. The same team manages this large effort, but it will not be discussed in this paper.

The objective of this paper is to refine the description from the prior year's papers[2] with the most up-to-date scope of the Exploration ECLSS demonstration campaign on ISS, the approach for integration into the ISS Vehicle, and the progress achieved in executing the campaign. The authors intend to provide an update to this paper in subsequent years as ISS demonstration continues and further progress is made.

II. Air String

The Air String comprises the systems that revitalize the atmosphere and recover waste products from the atmosphere into usable products. The Air String to be demonstrated on ISS is depicted schematically in Figure 1.

A. Air String Hardware Complement

The Air String consists of the following functions:

- The condensing heat exchanger (CHX) and water separator that control humidity and temperature of the vehicle's atmosphere and collect the condensate for subsequent processing.
- The trace contaminant control system (TCCS) that removes chemical contaminants from the vehicle's atmosphere that are generated by crew, vehicle systems and surfaces, payloads, cargo, visiting vehicles, etc.

- The carbon dioxide (CO_2) removal system that scrubs crew metabolic CO_2, spacesuit CO_2 scrubbing canister regeneration products, and payload-produced CO_2 from the atmosphere.
- The oxygen generation system that ingests and electrolyzes potable water, generating separated streams of gaseous oxygen for crew breathing and gaseous hydrogen for use in the CO_2 reduction system.
- The CO_2 reduction system that recovers oxygen from CO_2 through reaction with hydrogen to produce water and byproducts.

Each of the functions listed above will be tested in the Air String, either as an upgraded ISS system or as a new technology. The following are the expected systems that will fulfill the Air String functions. Areas where there are multiple potential candidates are described as such.

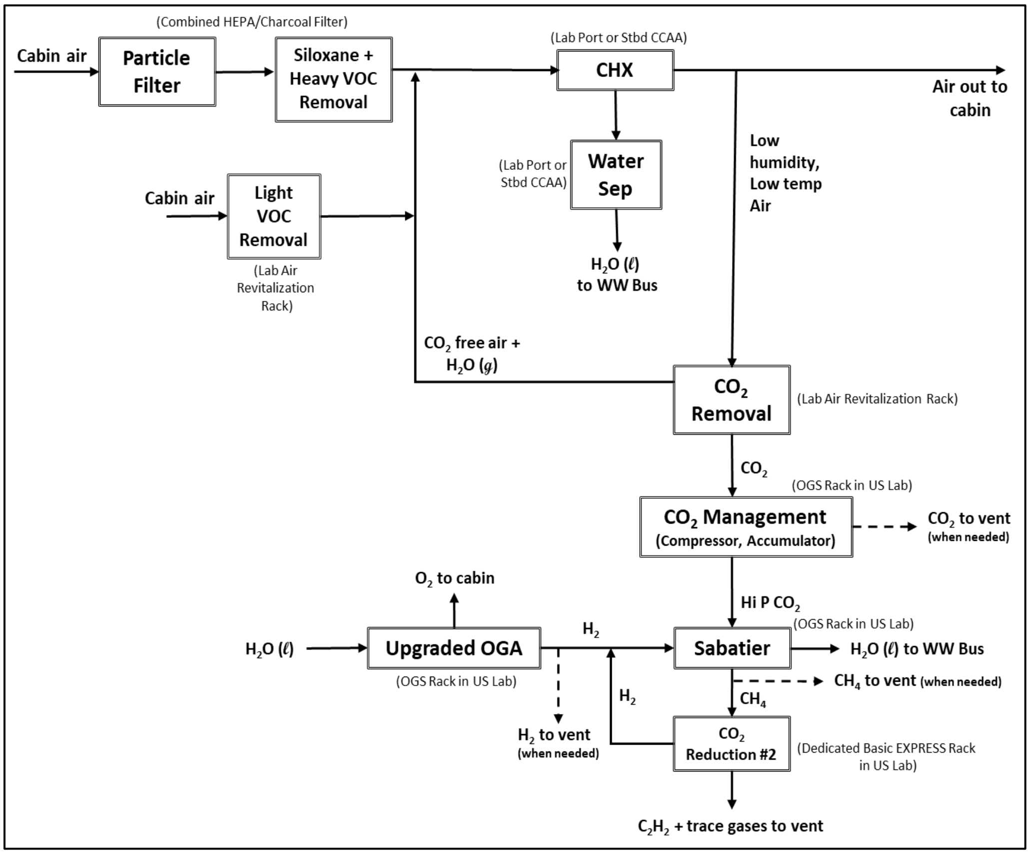

Figure 1. Air String Schematic

1. CHX

The ISS legacy CHX[3] will be upgraded to incorporate a modified hydrophilic coating with improved properties for microbial control, siloxane resistance, and overall lifetime. It is hoped that this upgraded coating will enable longer periods between CHX dry outs or eliminate the need for these dry outs altogether. To field a CHX containing this coating, NASA has initiated the build of the heat exchanger core using additively manufactured processes. This approach is expected to reduce the time, complexity, and cost to build the heat exchanger cores in the future. Initial problems encountered in 2022 with cracking during additive manufacturing were resolved. At this time, the project team is working through evaluation of sub-scale engineering units for build quality and performance. A design Technical Interchange Meeting (TIM) is planned for July 2024, and anticipated delivery of an integrated legacy Common Cabin Air Assembly (CCAA) containing the new CHX is mid-2026.

2. Water Separator post-CHX

The Water Separator technology will remain with the current state-of-the-art rotary separator that pairs well with the selected hydrophilic CHX. The on-orbit ISS Water Separators have shown accumulation of foreign object debris (FOD) where the liquid condensate is separated from air. Current theory is that this accumulation is a result of precipitation from heat exchanger coating washing off the heat exchanger and build up from dried condensate. This accumulation causes issues with hardware including fouling of check valves and simply filling the volume where condensate separated. The Water Separator becomes ineffective when filled with FOD so operational changes have been implemented with the management of the system. The Heat Exchanges are regularly dried so as to control and minimize microbial growth. The frequency of dry-outs has been reduced from every month to every 90 days in order to reduce the accumulation of precipitate that forms when the Water Separator is dried. The system will be monitored for changes in performance with the goal of extending dry0outs to every 6 months. A passive water separator device that pairs with a hydrophobic CHX has been demonstrated on the ground to prove that it can effectively separate a large volume and high velocity gas/liquid air stream. This separation method may be considered for planetary surface missions with partial gravity fields.

3. TCCS: Additional filtering has been added to the ISS at the inlet of the CHXs to remove volatile siloxanes from the cabin atmosphere. These siloxanes have been shown to enter the condensate and negatively impact the life of components within the Water Processor Assembly (WPA). The upgraded filter design includes a portion for carbon, intended to remove siloxanes and heavy volatile organic compounds (VOCs) and a portion for high efficiency particulate air (HEPA) filtration. HEPA filtration as has always been present in the USOS[4]. This filter combination continues to operate in all intramodular ventilation air inlets in the US modules, with the first set approaching end of their useful lifetime. Some of the filters were returned in late 2023 for analysis and testing in order to evaluate their effectivity and inform future installed life estimates. Replacements are being provided to continue to support sufficient filtering and protection of the downstream systems. On-orbit monitoring data and return of condensate samples to the ground continue to show an overall reduction in atmospheric and condensate-based siloxane levels since the filters were installed. No other upgrades to the ISS TCCS are planned (although catalyst obsolescence is being addressed via ground testing). A coolant leak external to ISS presented a risk to the ISS Life Support System. Several Extravehiclular Activities (EVA) were scheduled shortly after the leak. The coolant was a siloxane that can damage the Condensing Heat Exchanger hydrophilic properties and challenge the Water Processor's ability to maintain low TOC water. A cleaning and scrubbing plan was developed to deal with the potential contamination. This plan included isolation of the suits and deployment of extra charcoal filters affixed to the intake of the primary condensing heat exchanger at the time. This trace contaminate scenario is an example of how a system may have to be modified to adapt to a situation outside of the design expectations. Such a scenario could present itself in different mission phases such as Mars transit or vehicle aggregation at Gateway.

4. CO_2 Removal System:

NASA has pursued two primary candidate CO_2 Removal technologies. Both of these systems have been built to support demonstration on ISS for a minimum of one year with full-scale (4 crew equivalent) CO_2 removal performance. These units are located in Expedite the Processing of Experiments to ISS (EXPRESS) Racks or Basic EXPRESS Racks. The first candidate, Thermal Amine Scrubber (TAS), began operation on ISS in May 2019 with performance and reliability characterization on-going[5,6,7,20]. It achieved a year of run time in Oct 2021, and has accumulated over 720 days of cumulative on-orbit run time. TAS was inoperable for just over a year, from Oct 2022 to Jan 2024, due to a controller card failure. A software update which will reduce the risk of damaging the CO_2 valve by preventing it from reaching hard stop under certain failure conditions, as well as eliminate some nuisance software issues that require ground operators to clear will be uplinked in June 2024. The second candidate, Four Bed CO_2 ($FBCO_2$) Scrubber[8,9,21], launched to ISS in mid-2021, and has been successfully operating on ISS since that time, accumulating over 490 710 days of cumulative on-orbit run time as of this writing (reference Figure 2 below). The $FBCO_2$ Calnetix blower[22] was installed in Feb 2023, along with a controller and an acoustic cover for the front of the rack to mitigate acoustic impacts of the new hardware. An updated software release whch will enable maximum Calnetix blower speed, as well as eliminate some nuisance software issues that require ground operators to clear, will be uplinked in spring 2024. A full complement of on-orbit spares for both $FBCO_2$ and TAS is available on-orbit. In 2023 NASA (both ISS Program and Mars Campaign Office) agreed that based on both performance/reliability data as well as the known cost for required upgrades, a down-select decision could be made. $FBCO_2$ was chosen to be integrated with Sabatier in its existing location. Hardware and software for air string integration is in development, and is referred to as a closed-loop build. Additionally upgrades to the Calnetix blower are under assessment; the goal is to optimize performance and reliability. TAS will continue to be operated on ISS as long as possible within existing resources and spare component availability. Aside from the NASA systems, the Japanese Space Exploration Agency, JAXA, is also planning to fly a technology demonstration of their CO_2 removal system in preparation for future use on Gateway. This demo is planned for the end of 2024.

5. CO_2 Reduction System

The Sabatier that was operating on ISS until October 2017 is currently being upgraded and will return to the ISS for continued operation. The system redesign focuses on improving system performance, robustness to external contamination, and reliability[10,11] through the addition of a getter (filter) upstream of the reactor. In addition, two (2) new humidity sensors will detect moisture in the CO2 feed and safe the system. Additionally, the updated design will be maintainable at a lower level (enabling reactor changeout, for example). The location of this unit in the Air String is shown in Figure 1. The Sabatier 2.0 project will enter Critical Design Review (CDR) in summer 2024, and delivery is planned for early 2026. NASA may also develop an additional technology that could join the Air String as the CO_2 Reduction #2 system in Figure 1. In 2024, NASA made a down-select decision, and now one technology is in development for potential demonstration on ISS (previously there were two competing options). The system in development will take the methane created as a product of the Sabatier reaction and decompose it into hydrogen. That hydrogen can be fed back to Sabatier to react additional carbon dioxide and generate additional water. The waste product is solid carbon which could be utilized or disposed of. The ISS is scarred to support such as system if it matures sufficiently.

6. Oxygen Generation System

The Oxygen Generation Assembly (OGA) that is currently on the ISS is being upgraded based on the operational experience gained since its activation[12,13,23]. The OGA upgrades consist of improvements to correct design weaknesses noted during operation, redesign that will enable a replacement at the component level (individual valves, etc.), as well as improvements to reduce spares usage rates and potentially reduce overall vehicle risk. For example, the cell stack that contains the electrolyzing membranes is currently, along with other components, within a sealed dome that cannot be opened in-flight. To replace any one failed component within this dome, the entire dome must be replaced. The upgraded OGA, also known as Advanced OGA (AOGA), will replace components contained within two smaller domes (one containing the cell stack, the other the Rotary Separator Accumulator). This approach will greatly reduce the mass and volume of the total OGA spares complement. Additionally, the upgraded system will be capable of a purge/flush procedure which will clear the recirculation loop of contaminants that could affect downstream systems such as Sabatier as well as enable dormancy periods. Advanced OGA delivery is currently planned for late 2025.In 2023 the project team worked through numerous technical challenges, and at this time the design and test plan are finalized. The pressure sensors are in testing to verify structural integrity and the cell stack components are in production. Critical path for AOGA lies in procurement of long-lead parts (baseplate, connectors, sensors & valves, etc.) as well as some key machining/manufacturing work that has historically required an iterative process to achieve successful results. The Hydrogen Sensor Technology (H2ST)[23] technology demonstration (tech demo) has been operational on ISS since April 2022. One of the four sensors was declared failed after 3 months, and the remainder are being trended for drift. NASA continues to monitor a very small trend upward by all three (3) of the remaining sensors but the rate increase is still much slower than the legacy sensors in OGA. This new sensor could be incorporated into the AOGA design in the future if the demonstration on ISS is successful.

7. *Commercial Off the Shelf (COTS) Air Monitoring Sensors*

New, commercially available sensors (Vaisala CO_2, Spectrecology O_2 and Vaisala H_2O) were flown and installed in the US Lab, Node 3, and most recently Node 2. The CO_2 sensor was previously certified and installed in TAS to monitor performance. The sensors are being used for atmosphere trending when the Major Constituent Analyzer (MCA) is unavailable. To date the sensors have generally stayed within the accuracy bands of MCA for each given constituent (the oldest having been in use since Dec 2020). There is some noticeable interference between an RFID antennae and the ppCO2 sensor, but the 1-hour average data remains accurate. One issue did occur when the data cable was inadvertently disconnected from the sensor; a replacement cable is being manifested for replacement.

Airflow sensors have also been evaluated and approved for use on ISS. The portable airflow sensor is intended to be incorporated into the exhaust flow of the Brine Processor to gain insight to performance and hopefully eventually

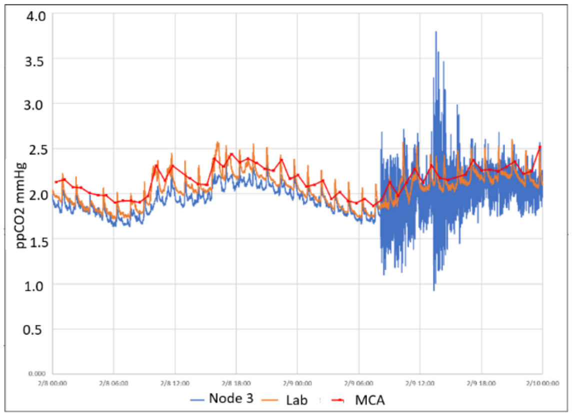

Figure 2. MCA and ppCO2 sensor comparison

optimize processing. The sensor and exhaust duct were flown in January 2024 and will be installed once the software is finalized and tested. A set of air flow sensors was also flown in Summer 2023 for point-of-use measurement. The advantage of these sensors over the current ISS legacy airflow meter is that the data can be sent directly to ground over a longer period of time to trend performance rather than a spot check that the existing system provides. Additional uses for the hardware include intermodule ventilation monitoring, visiting vehicle air exchange, and critical system air cooling monitoring (for example OGA). This could eventually reduce crew time by allowing ground teams to target housekeeping based on trend data rather than conservative time intervals. At this time the ground team is working on a modification to the way the sensor is attached to the front of the OGS rack in order to improve the consistency of measurements going into the OGA.

B. ISS Integration Approach

The subsystems within the Air String must be integrated together in order to perform their functions. Products from one system flow directly into another system to enable further processing as depicted in Figure 1. Some of these products, such as gaseous hydrogen from the OGA, are hazardous and must be carefully managed to reduce overall ISS vehicle risk. It is also important to reduce the number of components or length of hoses containing these hazardous materials that are exposed to the ISS cabin and the ISS crew in the event that a leak occurs.

To enable the required degree of subsystem integration and reduce vehicle risk as much as possible, the components of the Air String will be co-located in the US Laboratory module. This module contains twenty-four rack locations within six full rack bays. It is the location of the majority of the US payloads, and its large size and reconfigurability affords the opportunity to outfit the module to accommodate the Air String. In the summer of 2022, the OGS Rack was moved into the US Lab; this relocation made an integrated Air String possible. The H2ST tech demo is now installed on the front of the OGS Rack and is gathering data using the OGA oxygen outlet stream.

The Air String subsystems described in the section above will be located as follows:

- Upgraded CHX will replace a legacy CHX in one of the two Common Cabin Air Assembly (CCAA) racks located in the US Lab.
- TCCS combined siloxane and HEPA filters are now installed in the locations of the prior HEPA filters throughout the US modules.
- TCCS will remain in the US Lab AR Rack.
- The 4 Bed CO2 Removal System will be integrated into the Air String as the CO2 Removal system depicted in Figure 1. Specific routing of CO2 to the CO2 Reduction system is yet to be determined. The Thermal Amine Scrubber will continue to operate in the overboard venting configuration to gather additional operations experience and to assist with ISS CO2 removal needs..
- Sabatier will be installed in its prior location inside the OGS Rack which is now in the US Lab. CO_2 Reduction #2 (methane reduction device) will be allocated a portion or entirety of a Basic EXPRESS Rack in a rack bay, near the OGS Rack, so as to reduce the hose length needed to route hazardous gases such as hydrogen and methane between the racks. A CO_2 Management System, currently planned to consist of the Sabatier compressor and a new accumulator assembly, will be integrated into the OGS Rack to compress and accumulate the CO_2 that is provided from the CO_2 Removal System to the Sabatier The improvements to Sabatier and new accumulator assembly will require the OGS Rack front to be extended into the US Lab aisle area.

- OGA upgrades will be incorporated into the OGS Rack. This rack is now located in the US Lab.

C. Challenges

Outfitting the US Lab to accommodate the Air String has numerous challenges to overcome. Currently, the US Lab contains a rack in each rack bay. In order to execute the Air String as shown in Figure 1, described in the section above, and depicted in the ISS topology layout of Figure 6 towards the end of this paper, existing racks will have to be relocated to other modules or positions within the US Lab. Some of these have already occurred; for example, the European Space Agency Life Support Rack (LSR) was relocated to Node 3 so that the OGS Rack could be installed in the US Lab P1 location. The effort took multiple years to plan and execute, and involved new hardware, vehicle power balancing, new power and water line routing for the LSR, additional software, and two full days of crew time. In the end both OGA and LSR were successfully activated in their new locations. While the rack swap was largely very successful, there were a few lessons learned related to a pinched cable and some duplicative discussions/actions that occurred as new personnel took on the work from previous points of contact closer to execution. This type of effort will also be required to move payload racks to accommodate the CO_2 Reduction #2 rack in LAB1S1 near the OGS Rack in the US Lab, should it fly.

Additionally, the utilities required to support the Air String in the US Lab are a major aspect of the integration process into ISS due to the significant usage of liquid cooling and power by these systems. The active liquid cooling (moderate temperature and low temperature) is a limited resource in the US Lab because numerous systems and payloads use these resources on a continuous or intermittent basis. Detailed assessments of the US Lab Internal Thermal Control System have been completed and additional system capabilities are available to enable operation of the Air String in the US Lab while simultaneously continuing to support science payload operations.

Overboard venting in the US Lab is the third resource that is limited, and this utility significantly drives the location of the subsystems described above. The LAB1P1 location contains an overboard vent that was converted from a water to a gas vent (specifically hydrogen and methane) in 2006 in order to operate the OGS Rack in that location prior to the arrival of Node 3. CO_2 Reduction #2 also requires an overboard vent that is capable of venting its waste products at appropriate pressures and rates to accommodate efficient and safe system operation. Due to this need, this system cannot share the LAB1P1 vent with the OGS Rack. Consequently, to support CO_2 Reduction System #2 on ISS and co-locate it with the Air String to enable operation, an effort is in-work to modify the LAB1S1 water vent to a gas vent similar to the LAB1P1 vent, capable of supporting two users. This effort requires design and build of new hardware as well as two Extravehicular Activities (EVAs) for installation. The vent conversion and vacuum jumper hardware has been delivered on the ground awaiting the decision to fly and install. Once installed, this vent will be available for use by the two CO_2 Removal candidates. Finally, when CO_2 Reduction #2 system is onboard, one of the CO2 tech demos can share this vent.

D. Schedule

The target date to establish the full Air String in the US Lab is now predicted to be mid-2026. $FBCO_2$, H2ST, and TAS are installed on-orbit as of April 2022. At this point, all planned components are on contract with known schedules (with the exception of a CO2 Reduction #2 system). The integrated Air String development and integration schedule will be finalized when the scope of the entire effort has been defined and the associated project schedules are baselined.

III. Water String

The Water String comprises the systems that collect human waste and the systems that process the liquid waste and other waste waters to potable water for crew consumption and hygiene, oxygen generation, spacesuit cooling, and payload use. The Water String that will be demonstrated on ISS is depicted schematically in Figure 3. It should be noted that the CHX and Water Separator as well as OGA and Sabatier are shown on both the Air String and Water String schematics. These indicate key areas where the two strings interact via the potable and waste water buses that are routed throughout most of the USOS.

A. Water String Hardware Complement

The Water String consists of the following functions:

- The human metabolic waste collection system that will collect human solid waste for disposal and will collect and stabilize the liquid human waste (urine and flush water) for processing.
- The urine processing system that recovers usable water from liquid human waste.

- The water processing system that processes and polishes waste water including processed urine, condensate, and CO_2 Reduction System-produced water into potable water of the quality necessary for crew consumption and hygiene as well as oxygen generation, spacesuit cooling, and payload use.
- The brine processing system that recovers usable water from the brine generated by the urine processing system.
- The potable water dispensing system that meters and distributes potable water from the potable water bus to the crew for food/drink consumption and filling of hygiene water bags.

Each of the functions listed above will be represented in the Water String in Figure 3, either as an upgraded ISS system or as a new technology[14]. The following are the systems that will fulfill the Water String functions.

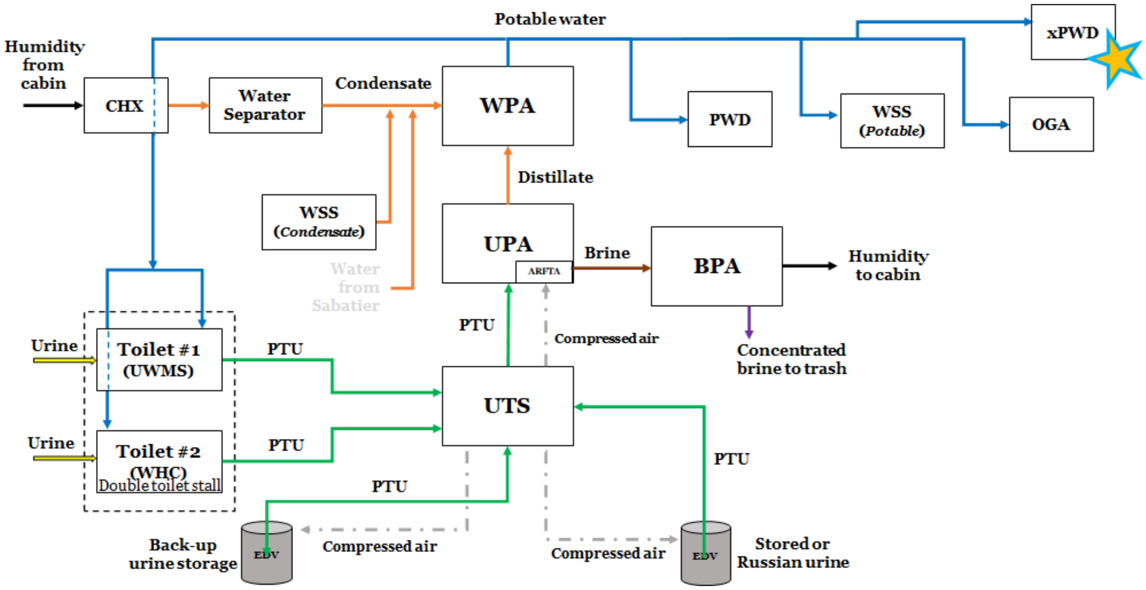

Figure 3. Water String Schematic

1. Human Metabolic Waste Collection (Toilet)

A micro-gravity compatible toilet has been developed that is intended to reduce mass and volume as well as consumable usage rates as compared to the existing ISS toilet state-of-the-art. It was also designed to better accommodate female crewmembers. This toilet, also known as the Universal Waste Management System (UWMS)[15], has joined the USOS toilet complement along with the existing Waste and Hygiene Compartment (WHC) toilet; both are currently located within Node 3. Both toilets will feed their collected urine directly to the Urine Processor Assembly once UWMS has a functional conductivity monitor to ensure proper pre-treat dosing. The newly designed toilet is intended to become the primary toilet in the USOS so that it can be demonstrated for an extended duration with multiple crew complements. UWMS is depicted as Toilet #1 in Figure 3. The UWMS was delivered to ISS in late 2020 and is awaiting completion of the initial tech demo following resolution of problems with the conductivity sensor as well as high acoustics levels, which both require re-designs that are in-work currently. In early 2023, while attempting a 14-day, 4-crew demo to support NASA objectives for Artemis-II, the dose pump failed to dispense pretreat . It was determined that the PEEK material in the check valve is not compatible with pre-treat over an 'indeterminant' amount of time. Redesign of the check valve to an improved material is in work. While the new check valve is in development, a spare Dose Pump of the legacy design was prepared and will fly in March 2024 with the hopes of enabling the Artemis-II demo and additional run time (more data gathering) for UWMS. More details can be found in the UWMS ICES paper for 2024. NASA also developed an independent conductivity monitor that utilizes a COTS toroidal sensor for use on-orbit as a stop-gap measure until the UWMS sensor is redesigned. The initial attempt to use this monitor was unsuccessful due to the presence of bubbles in the line which impacted sensor readings. MSFC performed a redesign, which included reducing the amount of space around the sensor head where bubbles can collect as well as incorporating an innovative bubble diverter upstream which should redirect any bubbles around the sensor. The bubble diverter was built in collaboration with Dr. Mark Weislogel from Portland State University. The new COTS Conductivity Monitor is scheduled to launch in March 2024, along with the spare legacy Dose Pump.

2. Urine Processing System

The Urine Processor Assembly (UPA) that is currently on the ISS will be upgraded[16] to correct design weaknesses identified by the operational experience gained since its activation. An upgrade to the Distillation Assembly (DA) was installed into the ISS UPA in 2020 and is exhibiting improved performance as expected. The upgraded unit includes enhancements which eliminate several failure modes that have reduced the lifetime of previous units. This upgraded DA now has significantly more runtime on-orbit than any previous non-upgraded unit. A ground study was performed to identify areas within UPA that would benefit from additional failure insight. A team was formed between MSFC, Johnson Space Center (JSC) and Ames Research Center (ARC) technical experts to establish a plan for how to implement the recommendations from the study in an upgraded fluids pump test unit. Some of these recommended concepts from the study include a new conductivity sensor in the brine loop, a quantity sensor on the Advanced Recycle Filter Tank Assembly, which collects brine during a concentration cycle, and automating the valve currently manipulated by crew to direct urine/brine flow in the system. An upgraded, single-channel fluids pump whose design focuses on maintainability is in development for ground demonstration.

3. Purge Pump and Separator Assembly

One such redesign incorporates an alternate purge pump type that is smaller, more efficient, and potentially more reliable than the current pump. The new pump design also enables replacement of lower-level components which reduces the required mass and volume of spares overall. PPSA was installed in Aug 2023, but unfortunately failed in Oct when vacuum could no longer be maintained in the DA, even after a valve changeout. A failure investigation is underway at MSFC with the goal of being completed by summer 2024.

4. Brine Conductivity

The brine loop inside the UPA accumulates concentrated brine over the concentration cycle. The current upper limit for brine concentration is based on the volume of urine processed and the estimated precipitation limit. Once urine is concentrated, precipitates can form and will clog the UPA. The concentration of brine may be monitored by a conductivity sensor. An effort to gain insight to brine concentration was initiated to provide a direct measurement for brine conductivity and thus provide insight to the brine concentration. The concept for this sensor was used as the basis for a COTS Conductivity Monitor referenced in section A.1. Eventually, the sensor that was flown to aid in UWMS operation on-orbit, if functional, could potentially be relocated (with the use of adapters) into the brine loop within UPA.

5. Advanced Recycle Filter Tank Assembly (ARFTA) Quantity Insight

The UPA's brine tank, called the ARFTA, periodically needs to be drained when the concentration of brine risks forming precipitates in the UPA. This process involves using compressed air from the Urine Transfer System (UTS) and pushing the brine into an external container or the Brine processor. The only way to confirm the tank is emptied is for crew to use an inspection mirror to look at a physical tank quantity indicator. This indicator is a ball bearing that follows a track and is moved by magnets in the bellows inside the ARFTA. This fill indication is also periodically used to leak check the ARFTA's bellows. A clever idea of sensing tank position using the same magnets in the tank was proposed by the team at MSFC: an array of Hall Effect sensors along the ball bearing track could infer the position of the bellows as it is filled and drained. That information could be processed and downlinked to Flight Controllers, thus reducing crew interaction. This capability is an enabler to further automate the processing of urine for ISS and future exploration missions. The team has completed a prototype and will begin ground testing of the valve and algorithm for control in summer 2024.

6. Fluids Control and Pump Assembly (FCPA)

The UPA has two pumps, one for gas purging and one for liquid transport. The upgrades to the gas pump were mentioned above. The FCPA is actually a 3 channel pump. One channel moves urine from the storage to the Distillation Assembly. A second channel removes concentrated Brine from the distillation Assembly. A third channel moves distilled water from the Distillation Assembly to the water processing system for further processing. These three pumps are combined into a complex ORU driven by a single motor. A proposed update, called the Single Channel Fluids Pump, separates the three channels to three independent pumps. More efficient and similar pumps enable finer control of fluid movement as they can be controlled independently. That control would be advantageous for dormancy operations. They will be designed to be easily replaceable / repairable to minimize the number of spares needed for long term operation. The project team at MSFC has developed a ground demonstration unit for integration into the UPA testbed – the fourth iteration of this design is anticipated to be complete in spring 2024. A flight demonstration is not planned.

7. Water Processing System

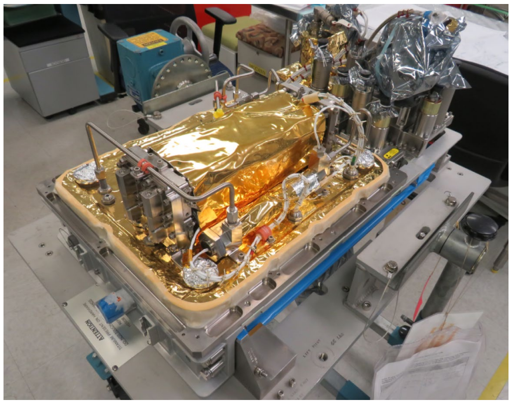

Figure 4. Upgraded WPA Catalytic Reactor

The Water Processor Assembly (WPA) that is currently on the ISS is being upgraded based on the operational experience gained since its activation. The WPA upgrades consist of improvements to reduce water leak potential and sensor drifts that have been observed during operations, demonstration of a reduced size packed bed that more closely matches an exploration mission's needs, and redesign or operational changes that better control biofilm growth in the waste water side of the system. Several of the upgrades have been executed on ISS and are under operational demonstration. For example, the configuration of the Multi-filtration Beds was reduced from two beds to one in order to improve the WPA's ability to withstand siloxanes in the incoming condensate and will better posture the system for future dormancy needs. The two bed configuration was allowing more siloxanes to accumulate before stronger ionic compounds built up in the system. A roll-off effect would occur when stronger ionic compounds load the beds and the release siloxanes would overwhelm the reactor. Also, the Multi-filtration Bed was redesigned to contain an improved sorbent material to improve its performance and extend the operational lifetime. Two ORUs with the upgraded material have been installed to-date. An upgraded Catalytic Reactor, shown in Figure 4, containing an upgraded catalyst material and more robust fluid fitting seals was installed on ISS Spring of 2021, but suffered fitting leakage early in its operational life. A failure investigation determined that the gland was too small for the new metal seals. The Catalytic Reactor was reworked and flown again in the summer of 2023; it is currently awaiting installation when the installed ORU fails. An effort to redesign the check valve within the Microbial Check Valve ORU proved unsuccessful; at this time the community agrees that a solenoid valve (in conjunction with resin) would be better suited to the operating environment of that location. A study is ongoing to determine if hardware and existing software could enable a non-interference demonstration on ISS.

8. Brine Processing System

The Brine Processor Assembly (BPA)[17] as depicted in the Figure 3 schematic, has been operating on ISS since March 2021 and has proven capable of dewatering UPA-produced brine so that more of the total system water can be recovered for crew/system use. The water that is liberated passes through a semi-permeable membrane that is optimized to contain urine-borne VOCs. The liberated water vapor is passed into the cabin air and collected by the CHX for processing by the WPA. BPA has been successfully dewatering brine since installation with no significant hardware issues/failures. Additional details on performance can be found in Paragon's Brine Processor Assembly ICES paper also planned for 2024. Initial odor issues were partially resolved with an updated exhaust filter, and better sealing of the outlet duct via tape on-orbit. However, the crew does still report nuisance levels of odor when in Node 3 and when performing BPA maintenance. Crew has been provided charcoal masks as additional odor protection during bladder R&R activities. MSFC has designed and delivered an updated exhaust duct and a new adapter which is constructed of better odor-reducing materials (ex. Tygon tubing), and better sealing surface to the exhaust. The adapter contains the new COTS humidity and airflow sensors (the same sensors as being certified and flown for other applications on ISS), which will aid in BPA performance characterization. The adapter flew to ISS in January 2024 and is awaiting the completion of final software testing and install date is still to be determined. Additionally, NASA is developing improved brine bladder odor bags which will improve odor control during long-term storage as well as continuing to enable modular configuration for launch/return and stowage. These new odor bags are anticipated to be available by mid-2024. NASA continues to manifest and procure addition bladders in order to recover valuable water on ISS. In 2023, after data review, NASA was able to announce that, with the addition of BPA, we have the capability to recover 98% of the water on ISS. This achievement represents the closing of a key technology gap for a Mars Transit mission.

9. Potable Water Dispensing System

An upgraded Potable Water Dispenser (PWD) was developed based on lessons learned through years of operating the existing PWD on ISS. For example, the Exploration PWD (xPWD) addresses concerns with microbial growth during dormancy by removing all stagnant portions of the system. It also demonstrates the use of flow-through ultraviolet (UV) disinfection technology at the point-of-use[18] which is expected to reduce overall system consumables usage. xPWD was installed in the Lab and activated in Aug 2023, and after successful on-orbit water quality and microbial sample analysis it was cleared for crew use in September 2023. A few nuisance software responses have been identified, however a planned software update in early 2024 will resolve them. Initial indications are that temperature control is improved from the legacy PWD system.

Figure 5. xPWD Installed on ISS

10. Mini Total Organic Carbon Analyzer (MiniTOCA)

An upgraded Total Organic Carbon Analyzer (TOCA) will use a different technology to assess the quality of water on ISS and reduce the current size/mass (over 40% volume reduction) of the current TOCA, which is more suitable for long duration human space exploration[19]. MiniTOCA uses UV for oxidation and a tunable laser spectroscopy for detection, versus the current TOCA that uses boron-doped diamond coated electrodes for oxidation and nondispersive infrared for detection. MiniTOCA is currently in development and will be delivered to ISS in FY25. The MiniTOCA Support Hardware project experienced some delays while addressing a few comments that arose during delta CDR, but hardware delivery is still with the MiniTOCA system.

B. ISS Integration Approach

The Water String has been established in the Node 3 module where the Water Recovery System (WRS), containing the WPA and UPA, and the WHC currently reside. Similar to the Air String, the subsystems of the Water String are co-located and physically integrated to enable process fluids to pass between them as depicted in Figure 4. The exception is the xPWD, as described below.

The Water String subsystems described in the section above will be located as follows:

- UWMS is located next to the WHC, inside a double toilet stall that was created to provide a private space for crew use for both the UWMS and the WHC independently. The Toilet Stall has been delivered and deployed on ISS. The UWMS and WHC are physically plumbed to deliver their collected urine directly to the UPA via the UTS that is described in section G.
- The UPA is being upgraded inside its current WRS#2 Rack.
- The WPA upgrades reside inside the existing WRS#1 and WRS#2 Racks.
- The BPA is mounted in the Node 3 Overhead Midbay, with an interfacing hose allowing direct transfer of brine from the UPA to the BPA. The water liberated by the BPA enters Node 3 cabin and is removed by the USOS humidity control system. The concentrated brine generated is put into the trash for disposal.
- The xPWD is located in EXPRESS Rack 7 in the US Lab. It receives potable water from the Water String via the USOS potable water bus that distributes potable water from Node 3 to the US Lab.

The physical layout of the Water String in the Node 3 module is shown in Figure 4.

C. Schedule

Much of the upgraded hardware is already on ISS being tested and evaluated. The largest pieces remaining are AOGA (2025), Sabatier 2.0 (2026), CHX (2025), and final integration of an air string (which relies on either an upgraded TAS or hardware to support integration of $FBCO_2$).

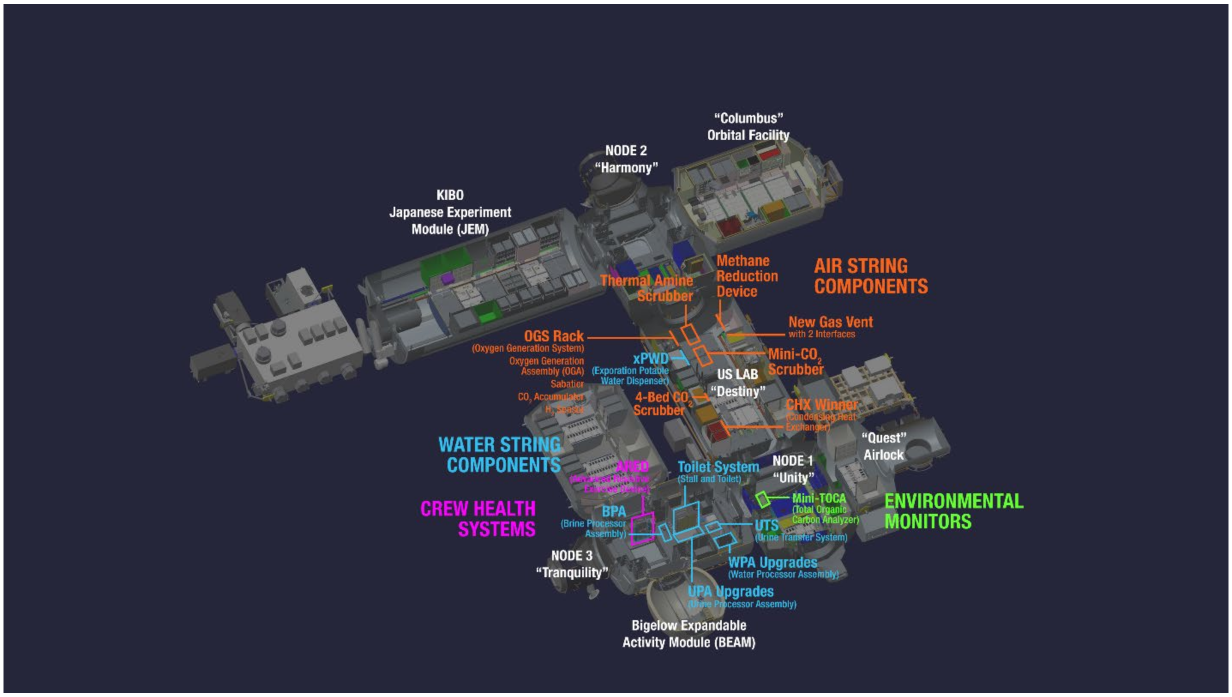

Figure 6. Exploration ECLSS Hardware Layout on ISS.

A. Operations and Certification Approach

The standalone demonstrations such as the CO_2 Removal candidates, the BPA, UWMS, xPWD, and Mini-TOCA are being developed as non-critical system tech demos that will be certified with little to no reliability requirements to facilitate quicker and less costly certification efforts. The intent, however, is that these systems perform the intended functions, and all are required to operate safely. The system upgrades will be installed inside of, and operated as part of, the existing critical vehicle system; however, most of the subassemblies that are upgraded will be considered as demonstration units and not certified as part of the critical system configuration until they have been proven to function. As such, the ISS Program will continue to maintain the nominal spares fleet for the critical vehicle systems to ensure uninterrupted operations of these systems on ISS.

Another objective of demonstrating an upgraded ECLSS on ISS is to operate the entire system in an integrated fashion in the same manner as the ISS ECLSS is operated. This allows the characterization of the real-time operational aspects of the system upgrades and new technologies. These systems are outfitted with internal sensors to ensure operational efficiency can be determined during the on-orbit demonstrations. To facilitate the integrated operational approach, the ISS ECLS System Team is the responsible engineering organization for supporting real-time operations and hardware sustaining efforts. Mission Control Center – Houston (MCC-H) is responsible for installing, operating, and monitoring, as well as training the crew for installation and maintenance, for each of the demonstrations. Also, as with the ISS vehicle systems nominally, MCC-H flight controllers and the Mission Evaluation Room (MER) will develop and execute strategies for troubleshooting any noted issues for each of the demonstrations.

B. Command and Telemetry Approach

The demonstration of ECLSS on ISS necessitated a new system for command and telemetry that enables an effective yet straightforward approach to real-time telemetry downlink, archive of this telemetry data, and commanding via MCC-H. This capability uses the onboard Ethernet Joint Station Local Area Network (JSL) system to allow regular monitoring of system performance and analysis of performance trends over an extended duration. It also facilitates quicker turnaround of demonstration software updates (as opposed to the legacy ISS MIL-STD-1553 protocol system and its standard/annual update schedule) in the event optimization or improvements are deemed warranted. Commanding via MCC-H enables the system-like operations approach that was described in the section above. NASA is currently evaluating options to expand the number of connection points in order to enable more individual sensors and systems. Additionally, the growing use of the COTS Air Monitoring Sensors has driven a desire to use them during the preparation for Extra Vehicular Activities, which means certifying the sensors as well as the data/power equipment for the lower pressure and elevated oxygen environment needed during pre-breathe and suit donning.

Systems that are being upgraded in their existing racks will continue to be operated and monitored via their current command and telemetry pathway. This approach minimizes the overall changes needed and ensure continued operation of the critical ECLS systems.

C. Transition from Tech Demo to ISS System

A challenge that is being approached currently is the establishment of criteria that will be used to transition hardware, from an ISS perspective, from a tech demo to a system. In general, ECLSS tech demo hardware underwent limited performance/functional testing on the ground and may in some cases contain COTS parts that would not traditionally be used in space-flight hardware. Thus risk acceptance by the ISS Program is required. While it is in the interests of NASA for exploration missions to continue to operate tech demos for as long as possible in order to continue to refine reliability data, as well as potentially identify design flaws that do not manifest for many years (something ISS Program has experienced with numerous ECLS systems), there will come a point where the technology itself has been demonstrated, and the minimum objectives have been achieved. The process of determining where that threshold of capability is will vary for each system and is not something that NASA has worked through before. Continued use of the tech demo must provide a benefit to the ISS Program independently at this point, and there will be an understandable drive to reduce the level of legacy ECLSS sparing in an effort to reduce cost and maximize the demonstration of Exploration-class ECLSS before the end of the ISS Program. These decisions represent a new paradigm for NASA.

BPA will reach 3 years of on-orbit operation in June 2024, so sparing needs are being assessed as well as options to potentially optimize water recovery given that nominally urine is processed for all 7 ISS crew. FBCO2 will also reach 3 years of ISS demonstration toward the end of 2024, and so similar sparing and operational support changes are in work. $FBCO_2$ will continue to be the prime CO_2 removal device on ISS, in conjunction with TAS while it remains operational given the existing sparing posture. Both the Lab and Node 3 CDRAs will remain operational and spared in order to retain redundancy and enable short periods of high crew loading. Even though ECLSS tech demos will start to be considered systems on ISS, the data gathered continues to be invaluable for Exploration mission development and risk reduction.

IV. Conclusion

The opportunity afforded by the presence of the ISS as a testbed for ECLSS advancements is being utilized to the fullest extent. A fully integrated and upgraded ECLSS is in development, incorporating improvements to existing hardware with newly added subsystems and capabilities. It will be tested on the ISS for an extended duration to characterize the system's performance and reliability. There are challenges to overcome in outfitting such a complex system in the existing ISS vehicle, but many of these challenges have already been addressed. The effort will be on-going for many years, and the progress of this effort will be the subject of future papers.

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