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International Space Station as a Testbed for Exploration Environmental Control and Life Support Systems – 2023 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.

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 will be 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 will be 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), or a ground-up redesign 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. 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.

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 intermodule ventilation (IMV) as well as the potable and waste water 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. This effort will not be discussed in detail 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.

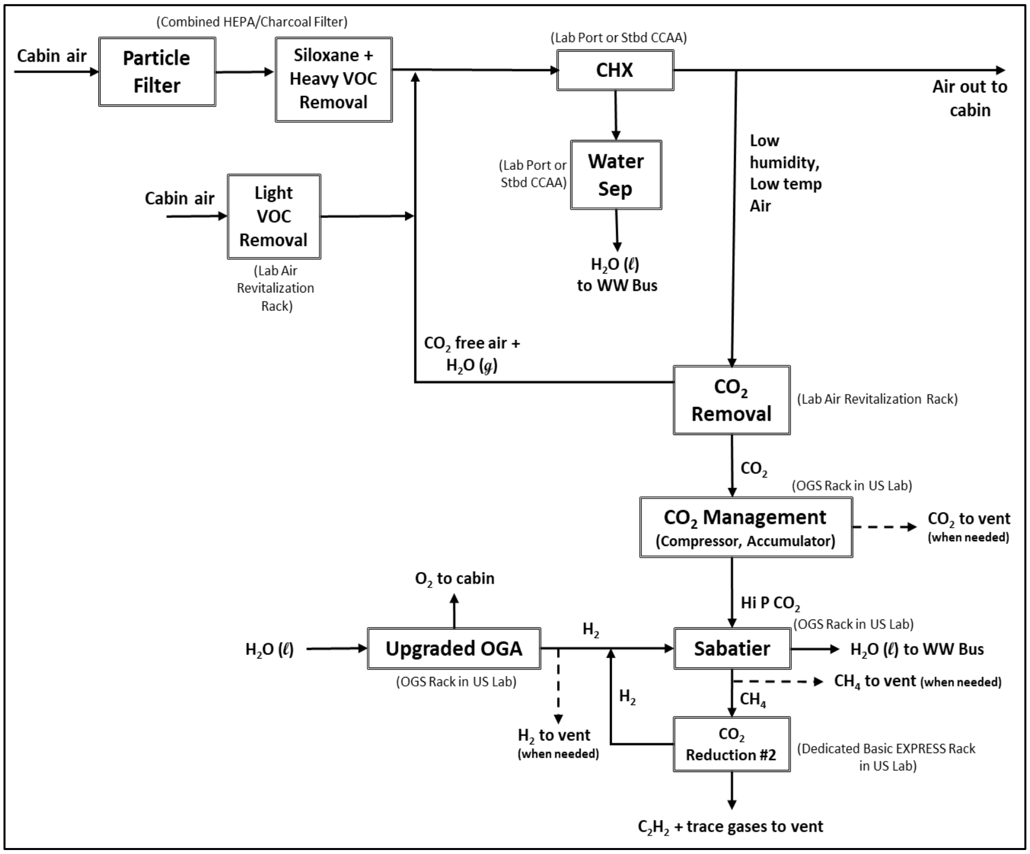

Figure 1. Air String Schematic

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 heat exchanger core samples to ensure proper material strength and quality. An earlier attempt to change the design was unsuccessful, and the design will now contain improved slurper bars similar to the legacy CHX. A design Technical Interchange Meeting (TIM) is planned for September 2023, and anticipated delivery of an integrated legacy Common Cabin Air Assembly (CCAA) containing the new CHX is mid-2025.

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. 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 as has always been present in the USOS[4]. This filter combination continues to operate in all intramodule ventilation air inlets in the US modules, with the first set approaching end of their useful lifetime. Some of the filters will be returned in mid to 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).

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. After the evaluation/demonstration period, NASA will select at least one candidate that will join the Air String as the CO_2 Removal System (as shown in Figure 1) for long duration integrated testing with the upgraded Sabatier Reactor Assembly (SRA). The first candidate, Thermal Amine Scrubber (TAS), began operation on ISS in May 2019 with performance and reliability characterization on-going[5,6,7]. It achieved a year of run time in Oct 2021, and has accumulated over 660 days of cumulative on-orbit run time. At the time of this paper, TAS is non-functional on-orbit due to a failure in the controller in Oct 2022. The unit was returned to ground for refurbishment (via replacement of controller card(s) and electrical components) and is planned for return to ISS in fall 2023. NASA is gathering information to understand the cost/schedule for a TAS re-build that would enable a move to the US Lab Atmosphere Revitalization (AR) Rack as well as upgrade TAS to a 2.0 configuration (new, more capable desiccant wheel humidity removal, blower upgrade, modifications for component maintainability, etc). The second candidate, Four Bed CO_2 ($FBCO_2$) Scrubber[8,9], launched to ISS in mid-2021, and has been successfully operating on ISS since that time, accumulating over 490 days of cumulative on-orbit run time as of this writing (reference Figure 2 below). Both $FBCO_2$ and TAS will have upgraded blowers that are currently on-orbit with the goal of improving robustness and performance. The $FBCO_2$ Calnetix blower 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. The $FBCO_2$ system is now operational with the new blower – future work includes performance characterization and a decision on the need for an additional blower upgrade. A full complement of on-orbit spares for both $FBCO_2$ and TAS will deliver by late 2023. 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.

5. CO_2 Reduction System

The SRA 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]. 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 development project has initiated, and due to some early delays, will now deliver in mid-2025. NASA may also develop an additional technology that could join the Air String as the CO_2 Reduction #2 system in Figure 1. There are two main technologies being developed, but both would take the methane created as a product of the Sabatier reaction and decompose it into hydrogen that can be fed back to Sabatier to react additional carbon dioxide and generate additional water. The waste products, mainly acetylene, would be vented overboard.

Figure 2. Four Bed CO_2 Scrubber Flight Hardware

6. Oxygen Generation System

The Oxygen Generation Assembly (OGA) that is currently on the ISS will be upgraded based on the operational experience gained since its activation[12,13]. The OGA upgrades will 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 enable replacement of the components contained each of the now 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 has slipped into 2025, primarily due to procurement delays, the longer lead time of certain key components of the cell stack, and delay in Critical Design Review (CDR) product readiness. Some key technical challenges remain as the project team works toward a delta CDR sometime in summer 2023, including the acceptance of new absolute pressure sensors and reconciliation of early leak test results. The Hydrogen Sensor Technology (H2ST) technology demonstration (tech demo) has been operational on ISS since April 2022. In Sept 2022 it was relocated to the front of the Oxygen Generation System (OGS) rack after rack relocation to the US Lab, and it is now monitoring the oxygen output from OGA. It is shown in Figure 3 below. One of the four sensors was declared failed after 3 months, and the remainder are being trended for drift. A very small trend upward by all three (3) of the remaining sensors continues to be monitored but is 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.

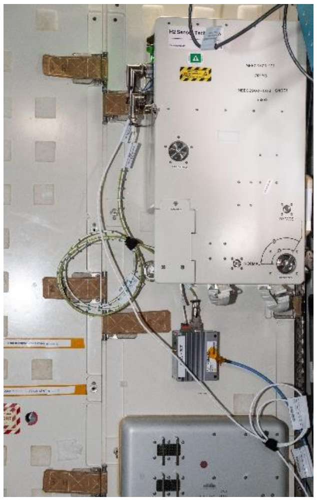

Figure 3. H2ST Installed on OGS Rack Front

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

New, commercially available sensors (CO_2, O_2 and H_2O) were flown and installed in both the US Lab and Node 3. The CO_2 sensor has already been certified and installed in TAS to monitor performance. The sensors will be used for atmosphere trending when the Major Constituent Analyzer (MCA) is unavailable. An additional set of sensors will be deployed in Node 2 in Summer 2023.

Airflow sensors are being evaluated and prepared for flight. 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 optimize processing. A set of air flow sensors is also being flown in Summer 2023 for point-of-use measurement. The advantage of these sensors over the current ISS Velocicalc 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 Velocicalc 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.

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 selected CO_2 Removal System candidate will be integrated into the Air String as the CO_2 Removal system depicted in Figure 1. Candidate selection will determine the specific routing of CO_2 to the CO_2 Reduction system. The candidate that is rated as the second best in the NASA selection will continue to operate in the overboard venting configuration to gather additional operations experience and to assist with ISS CO_2 removal needs. The current goal is to enable either system to run in an integrated configuration, both in order to delay the selection of a winner as long as possible and also to mitigate risks of a longer-term shutdown in the future in the event of a failure.
- 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 9 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.

Power availability is similarly a limited resource that must be distributed judiciously to enable support of the Air String and simultaneously continue operation of science payloads. While ISS power will be supplemented in the near future with solar array enhancements, it is likely the future ISS power demand will increase as the vehicle is modified to support commercialization of low Earth orbit, other critical exploration demonstrations, etc. Power availability for the CO_2 Reduction #2 system is of particular concern since this is an addition to the ECLSS and may require significant power to operate. This aspect will need to be addressed as the integration plans for this system demonstration mature.

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 is scheduled for delivery to ISS in Fall 2023. 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-2025. $FBCO_2$, H2ST, and TAS are installed on-orbit as of April 2022. At this point, only the TAS rebuild and the $FBCO_2$ closed-loop build are not yet on contract with known schedule. 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 4. 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 4, either as an upgraded ISS system or as a new technology[14]. The following are the systems that will fulfill the Water String functions.

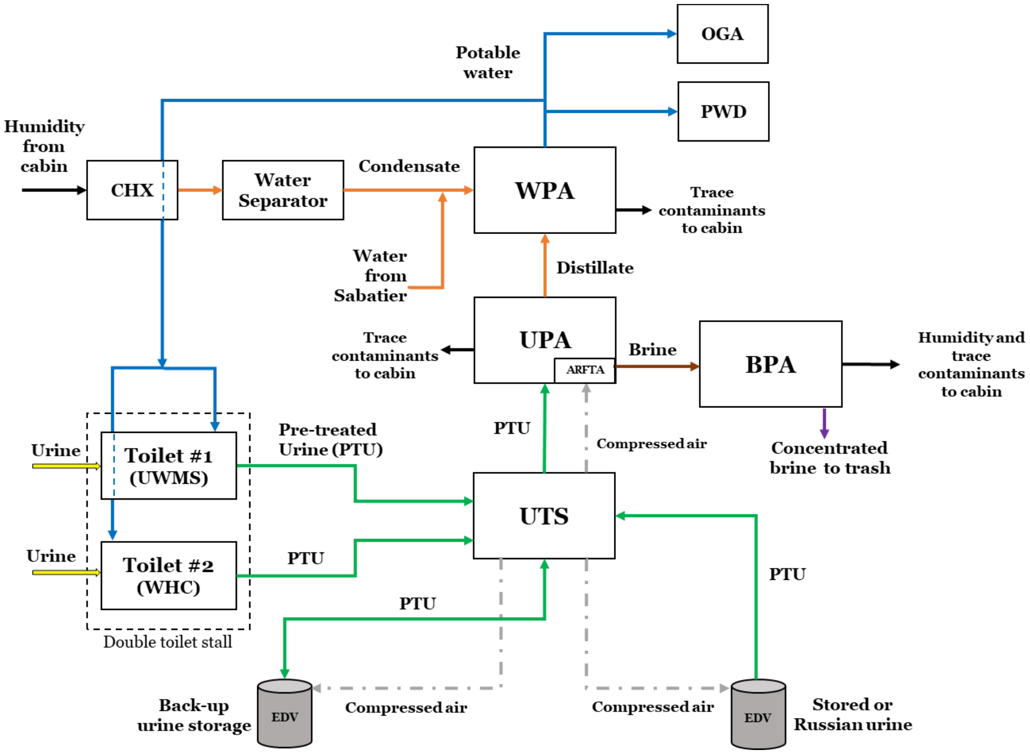

Figure 4. Water String Schematic

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 4. The UWMS was delivered to ISS in late 2020 and is awaiting completion of installation following resolution of problems with the conductivity sensor as well as high acoustics levels, which both require re-design. In early 2023, while attempting a 14-day, 4-crew demo to support NASA objectives for Artemis-II, the dose pump also failed. The dose pump was removed and returned to ground for a failure investigation; at this time the team believes a check valve failure caused the issues. The goal is to complete that failure investigation and fly a new dose pump, along with a COTS conductivity sensor that NASA developed as a stop-gap until the UWMS sensor redesign is completed, in the fall of 2023.

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 (see Figure 5) 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 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. The purge pump was delivered in fall of 2022 and will be installed in the summer of 2023 (delays have been the result of limited crew time available on-orbit) and is shown in Figure 5.

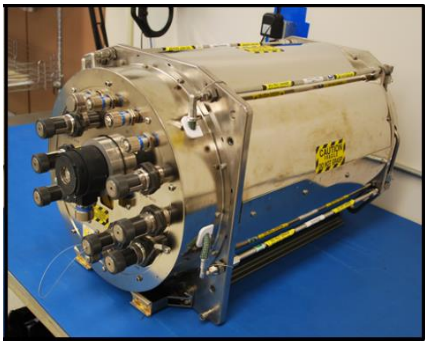

Figure 5. Upgraded UPA DA

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 unit that was launched in fall 2022 as an interim solution for the failed UWMS conductivity sensor. Unfortunately, bubbles within the manifold have prevented the sensor from providing accurate data. MSFC is working on a redesign as the vendor works to fix the UWMS internal conductivity sensor in parallel. Eventually, the sensor on-orbit, if functional, can 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 develop the algorithm necessary to translate position to quantity for ground test.

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 is developing a ground demonstration unit for integration into the UPA testbed – at this time a flight demo has not been approved.

7. Water Processing System

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. Also, the Multi-filtration Bed has been redesigned to contain an improved sorbent material to improve its performance and extend the operational lifetime. An upgraded Catalytic Reactor, shown in Figure 6, 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. It was returned to ground for re-assessment, repaired (following a design change to correct for the previous failure), and will be re-flown to ISS for installation and operation in summer of 2023. The third area of focus is in improving the reliability of the Microbial Check Valve via a redesign that is specific to its operating environment. At this point the check valve has been designed and is going through acceptance testing now; it will be incorporated into the flight ORU for launch in 2024.

7. Brine Processing System

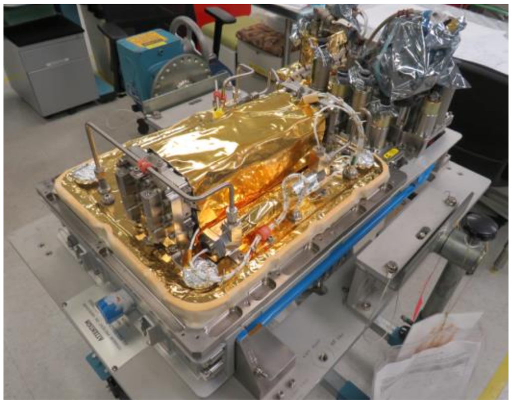

Figure 6 Upgraded WPA Catalytic Reactor

The Brine Processor Assembly (BPA)[17] as shown in Figure 7 and 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. Final data analysis is pending to confirm whether the system helps achieve the overall 98% water recovery technology gap. BPA has been successfully dewatering brine since installation with no significant hardware issues/failures. Initial odor issues were partially resolved with an updated exhaust filter, and better sealing of the outlet duct via tape on-orbit (reference Figure 8). However, the crew does still report nuisance levels of odor when in Node 3 and when performing BPA maintenance. MSFC is developing an updated exhaust duct and a new adapter which are constructed of better odor-reducing materials. The adapter will contain 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. Additionally, NASA is developing improved brine bladder containers which will actually contain odor during long-term storage as well as enable modular configuration for launch/return and stowage. NASA continues to manifest bladders in order to characterize dewatering performance and recover valuable water on ISS.

Figure 7. Brine Processor Assembly Installed on ISS.

Figure 8. Brine Processor Assembly with BPA Exhaust Filter Attached.

8. Potable Water Dispensing System

An upgraded Potable Water Dispenser (PWD) will use lessons learned from the operation of the existing PWD on ISS. For example, this Exploration PWD (xPWD) addresses concerns with microbial growth during dormancy by removing all stagnant portions of the system. It will also demonstrate flow-through ultraviolet (UV) disinfection technology at the point-of-use[18] which, if successful, should reduce overall system consumables usage. xPWD has been tested, certified, and delivered for launch on NG-19 in the summer/fall 2023.

9. 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 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, vs. the current TOCA that uses boron-doped diamond coated electrodes for oxidation and nondispersive infrared for detection. MiniTOCA is currently in development and plans to be delivered to ISS in FY25. The team is currently working to address some issues with placement on ISS, in order to effectively manage airflow, stowage and kick loads. This effort will result in the addition of an enclosure to protect MiniTOCA hardware.

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:

- The newly designed UWMS is located next to the WHC, inside a new 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 is being upgraded inside its current 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 will be located in EXPRESS Rack X in the US Lab. It will receive 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. Challenges

Now that numerous tech demo systems are on ISS and operational, the decision of which hardware to transition to an ISS system, and the timing and method of that transition, is a challenge facing the ISS Vehicle Office. While long periods of on-orbit performance is an excellent indicator of a successful design, ISS experience has taught NASA that failure modes or vulnerabilities could be identified potentially years after initial activation.

Another challenge related to the water string is the fact that brine is generated by the UPA faster than the BPA can process it. The Russian Segment does have a urine processor, but it has yet to be fully functional, so most all of the urine generated by both the Russian and USOS crew is processed on the USOS by the UPA. BPA is sized for 4-crew (the planned Mars Transit mission crew complement), and therefore it cannot keep up with the brine generation rate. It would be advantageous for NASA to fly a second BPA, but finding a location to put the rather large system, that can also be plumbed to receive brine directly from the UPA, is a challenge. The determination to build and fly a second BPA is forward work.

D. Schedule

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

IV. General Integration

The effort to integrate the ECLSS demonstrations on ISS is a high priority within the ISS Program and NASA. The ISS was created not only to perform science but also to advance technologies that will be needed for future human space exploration. As such, ISS Program resources and processes on the ground and on-orbit are being put to bear to enable this effort. The priority to implement this work is categorized very highly amongst the total allocated crew time put towards science/payloads on ISS. The layout of upgraded hardware is shown below in Figure 9.

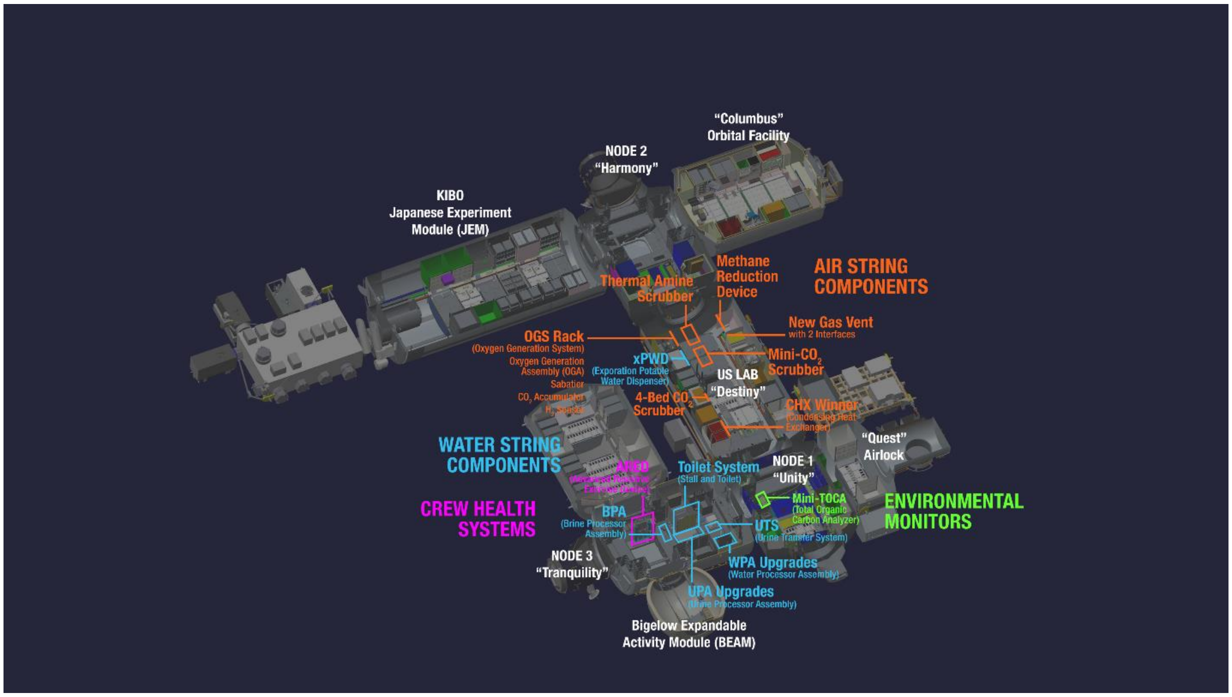

Figure 9. Exploration ECLSS Hardware Layout on ISS.

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) are 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, known as Arcturus, 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. This system is operating on ISS and its use is expected to continue to grow over time.

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.

NASA is also assessing means of improving the autonomy of the ECLS system for future spacecraft. Due to the increased communications delay between the spacecraft and Earth-based systems during missions away from Earth, the need for the spacecraft software to perform the majority of systems operations becomes much more critical than it has been on the ISS. Small incremental improvements to this approach are planned, though these will be ground-based for the foreseeable future. As mentioned in section E, the projects that have been initiated to date mainly center around the Urine Processing Assembly. It provides a good test case given its history of difficult-to-identify failure mechanisms. The Exploration ECLSS teams at JSC and MSFC are working with a group from ARC to develop automation concepts that can be applied in a ground test setting with eventual application on an Exploration Mission.

C. Transition from Tech Demo to ISS System

A challenge that is being approached in 2023 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 a system can be operated similarly to other core ECLSS. 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. With this transition comes a natural decision on reducing 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. It is likely that BPA will be the first system to make this transition sometime in 2023, because the water reclaimed has a significant benefit to ISS logistics beyond the need to verify dewatering performance. However, others such as $FBCO_2$ and COTS air monitoring sensors, will follow soon.

V. 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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