International Space Station as a Testbed for Exploration Environmental Control and Life Support Systems – 2026 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 fly Exploration ECLSS on the ISS.

Acronyms and 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	=	transliterated from ЕДВ; Russian-built water tank
EMI	=	electromagnetic interference
EVA	=	extravehicular activity
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-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 comparable 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 lunar orbit or a Mars transit mission. The portions of missions that occur in partial gravity, such as lunar surface 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 be different for surface missions, which impacts operations and design. 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 modern 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 modern 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 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 currently and the ISS structure and layout limit significant reconfiguration. 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 closed loop ground test bed with humans in the loop).

The ECLSS demonstration on ISS has been partitioned into "strings" 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 in the United States Laboratory (US Lab) module of the ISS. The Water String will be 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 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. Sensors that measure humidity will be located near sources of humidity or near dehumidification systems.

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 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 electrolyzes potable water, generating separated streams of gaseous oxygen for crew breathing and gaseous hydrogen for use in a CO_2 reduction system.
- The CO_2 reduction system recovers oxygen from CO_2 through reaction with hydrogen from electrolysis 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 modern 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.

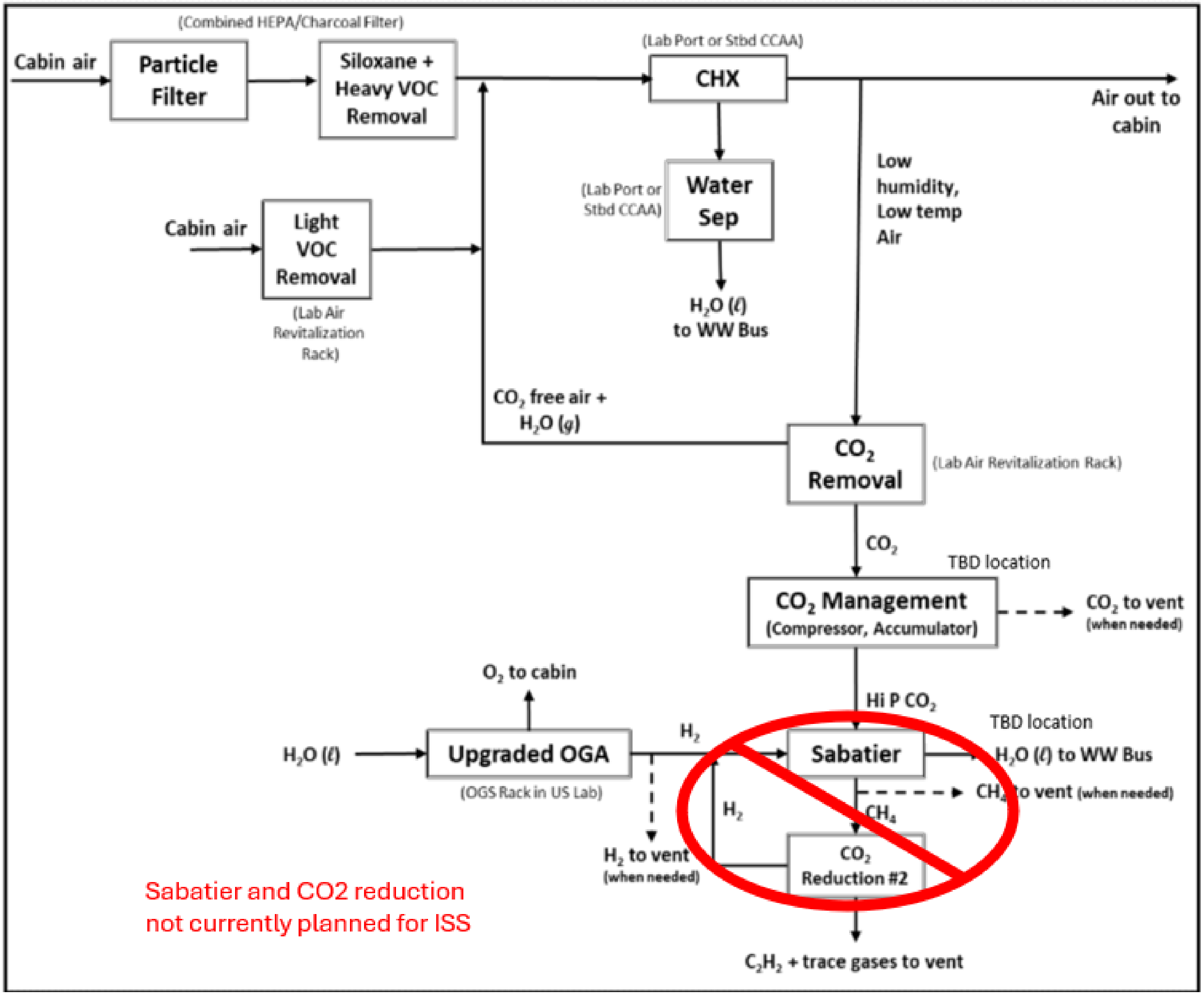


Figure 1. Air String Schematic

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 manufacture a CHX containing this coating, NASA has initiated the build of the heat exchanger core using additive manufacturing 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. Currently, the project team is processing a full-scale build of the heat exchanger weldment. This unit will be a qualification unit and evaluated for build quality and leak tested.

After that, a flight unit will be built and processed to fly to ISS and demonstrate the coating performance for the remainder of the ISS Program. Vendor delays for the weldment may impact the lifetime evaluation on-board the ISS or prevent integration on ISS. The original project goal was >3 years of on-board evaluation with parallel ground testing. Depending on the de-orbit date of ISS, ground testing may not have time to complete the lifetime evaluation of the coating. The ground test unit will be delivered several months after the flight unit, but testing is expected to be concurrent on-orbit and the ground to increase the number of units tested and gain more information about the performance of the coating. The ground tests will attempt to re-create the atmospheric conditions and trace contaminants seen on ISS, but ultimately the best place to test this technology is on ISS. Comparison between the two units' performance will need to acknowledge the different operational environments when making decisions for the future of this technology.

2. Water Separator post-CHX

The Water Separator technology will remain with the current state-of-the-art rotary separator that is required 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. Samples returned and analyzed on the ground have confirmed large quantities of FOD material used to manufacture the hydrophilic coating. Attempts to characterize all other contributors of FOD accumulation were hampered by vendor asserted intellectual property rights concerns to the FOD so a complete understanding of condensed humidity and volatiles or microbial conditions remains somewhat unclear. This accumulation causes issues with hardware including fouling check valves and filling the volume where condensate is separated from air. 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 to control and minimize microbial growth. The frequency of dry-outs has been reduced from every month to every 90 days to reduce the accumulation of precipitates that form when the Water Separator is dried. The system will be monitored for changes in performance with the goal of extending dry-outs 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.

In October of 2025, the ISS Program successfully tested a 2-phase separator on ISS. A brief summary of this activity is presented in the Waste Management section of this paper. Although the intent for this separator was to evaluate suitability for waste management hardware, the same technology could be used with a condensing heat exchanger.

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 sorbent material, intended to remove siloxanes and heavy volatile organic compounds (VOCs) and a portion for high efficiency particulate air (HEPA) filtration. HEPA filtration 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 , analysis indicates that the filters loaded asymmetrically across the vehicle suggesting localized loading near areas of high activity. Analysis of the HEPA filters effectively showed minimal degradation, and an extended life in operations to run to failure with routine cleaning. The Charcoal filters were removed when water data showed they had run to failure, at about 4.25 years run time. On ground assessment showed that the filters could be run to failure, or to the 4 years run time and perform their function. For conservatism, the ISS program accepted a 3-year operational life on the charcoal filters. 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. 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]. TAS had a number of failures since installation which drove the replacement of components (Desiccant Wheel, System Controller, Bulk Water Save Valve), but is expected to reach the goal of three years operational time on ISS in Fall 2026. TAS is no longer being actively sustained with a logistics plan but will continue to operate as long as existing spares last. The second demo, 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, and achieved three years operational runtime in February 2025. The Calnetix blower has been installed since Feb 2023 and has performed well. In June 2024, the Air Save Pump failed, and after some troubleshooting was replaced with an on-orbit spare. However, due to an error in the transference of design data, the spare pump did not contain an internal valve (whereas the original pump did). Without the valve, $FBCO_2$ was unable to maintain vacuum on the adsorbent beds. Operational workarounds were implemented to compensate for the lack of a valve, and an external COTS valve was developed and flown to correct the issue. The new valve assembly was installed on orbit in Feb 2025. A Resistor Bypass Box was installed in Feb 2025 as well, allowing the Calnetix blower to reach maximum speed of 60k RPM, increase air flow through the system, and improve system CO2 removal performance. Aside from the NASA systems, the Japanese Space Exploration Agency, JAXA, flew a technology demonstration of their CO_2 removal system on HTV-X1 in preparation for future use on Gateway, and had begun demonstration testing in February 2026.

Upgrades to the Calnetix Blower and Controller are in discussion. Potential areas for improvement include impeller optimization to match 4 Bed CO2 design and blower design updates to improve reliability.

5. CO_2 Reduction System:

The Sabatier that was operating on ISS until October 2017 was originally being upgraded for re-flight. However, technical and programmatic issues led both NASA and the supplier to decide to cancel the project. Unfortunately, valuable reaction efficiency and water vapor collection questions will remain. Future CO2 and Hydrogen loss efforts will be tested on the ground or potentially future microgravity platforms.

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. The AOGA team evaluated different component packaging approaches to reduce on-orbit spare mass and volume demands. 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 to ISS is currently planned for mid-2027. Critical path for AOGA lies in the completion of three new manifolds which are required to retrofit AOGA with the legacy pressure sensors. The legacy pressure systems were originally not categorized as fracture critical. The team has formulated a plan and presented to the NASA Fracture Control Board, forward work for use of these sensors in a Fracture Critical was identified including NASAGRO analysis and review of the qualification testing regime. Consensus from the NASA Fracture Control Board showed the plan to be adequate for use of the legacy sensors in AOGA. 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 a second sensor failed in Jan 2025. The remaining two sensors are stable. This new sensor could be incorporated into the AOGA design in the future if the demonstration on ISS is successful, and discussions are underway to make use of this data in the life extension of the in-line legacy sensors as well. The OGA team began testing the legacy H2 sensors upon return from use on ISS. The goal of this testing was to identify the drift of the sensors while in use on orbit in order to understand the drift mechanism. The H2 sensors were being held to a 201-day installed life. This was based on qualification testing and the length of time a sensor was operated in an on-orbit operational environment. The test data collected from the testing upon return showed a unique drift rate for each sensor ORU (three sensors are installed in each ORU). In many cases, the “as seen” drift rate could allow for longer installations in OGA on ISS. With approval, the current sensor has been extended to a life of up to 348 days with an R&R in May 2026. During this time, the OGA team agreed to perform bi-weekly review of OGA data, focusing on data that would show the introduction of H2 into the O2 delivery line. Upon return, the sensor will undergo ground testing to verify how the anticipated and “as seen” drift rates correlate thereby providing rationale to continue with the life extension. If this plan is approved going forward, this will reduce on orbit crew time, hardware launched and ground processing.

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

New, commercially available sensors (Vaisala GMP252 CO_2, Pyroscience FDO2 O_2 and Vaisala HMP113 H_2O) were flown and installed in the US Lab, Node 3, Node 2, and most recently in the Airlock. 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 antenna and the $ppCO_2$ sensor, but the 1-hour average data remains accurate. Overall, the COTS air sensors have performed well on ISS, and are now the primary Major Constituent Air Monitor on ISS, replacing the use of the legacy MCA. COTS sensors have also been installed into the ISS Airlock and proven useful during EVA Prebreathe activities (when the Air Lock is at reduced pressure). Starting in January 2026, the ISS program began the transition to making the COTS air sensors the primary sensor used for flight operations, replacing the last required use of the legacy MCA. Once implemented, the COTS air sensors will be the primary air monitor on the ISS. One of the legacy MCAs has been retired and the 2nd will remain in place if ever needed for future activities but is no longer required for ISS operations.

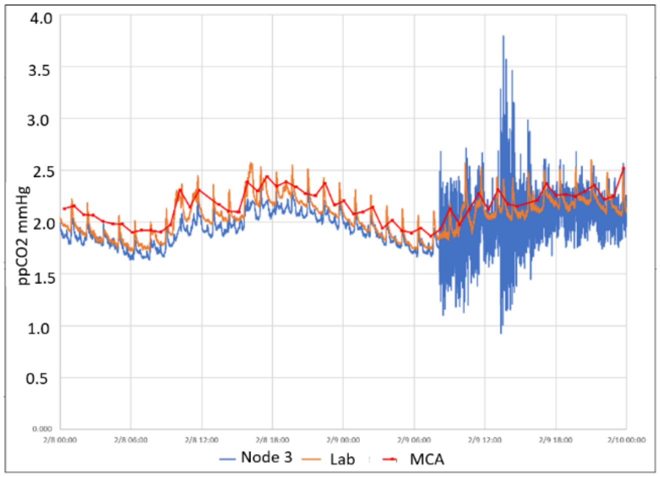


Figure 2. MCA and ppCO2 sensor comparison

Airflow sensors (Degree Controls UAS 1000) have also been evaluated and approved for use on ISS. The portable airflow sensor has been incorporated into the exhaust flow of the Brine Processor to gain insight into performance and hopefully eventually optimize processing. The sensor and exhaust duct were flown in January 2024 and installed in Dec 2024. 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. The air flow sensors have proven accurate when clean, but FOD in the ISS atmosphere tends to cling to the sensor head (triboelectric effect), blocking flow in locations where air passing over the sensor is not filtered. NASA is investigating filters and/or alternate sensor head materials to reduce the need for sensor cleaning. The screen to be used on the OGA inlet air flow sensor will be installed early to mid-2026.

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 Air Revitalization Rack.
- The 4 Bed CO_2 Removal System will be integrated into the Air String as the CO_2 Removal system depicted in Figure 1. Specific routing of CO_2 to the CO_2 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.
- OGA upgrades will be incorporated into the OGS Rack. This rack is now located in the US Lab.

Operating the upgraded ECLSS on ISS while maintaining ISS core systems until the upgraded system has proven performance offers a long duration space platform in an appropriate environment without risk to an exploration mission or crew. Advanced ECLSS operations on ISS as an operational system provides the only means to achieve

TRL9 maturity by incorporating: System performance in the space and spacecraft environment with humans in the loop; Flight and ground crew training and operation procedures; Systems and mission con ops; Logistics requirements as driven by operations in the spacecraft environment; Safety incorporated into operations and design features, and Interoperability in the space systems infrastructure.

ISS systems have also been upgraded to address the conditions that have arisen due to the unique combination of long duration operations in the unique spaceflight environment of a closed system with humans in the loop in microgravity. The conditions addressed were not seen nor predicted in ground tests but were only discovered in operations under the unique operating conditions found in human-in-the-loop space flight on ISS.

Operating these upgraded ECLSS capabilities at the ISS helps to: reduce exploration risks and their associated financial costs to the exploration missions, demonstrate distributed operations with international partners, establish interface standards, and allow for validation of engineering models being used to design future missions and systems. The ISS vehicle systems, operational processes and enhanced logistic practices have matured to become less reliant on resupply from earth through logistics reduction and increased system capabilities and reliability. While benefiting ISS, these improvements in capabilities are effectively a demonstration of an exploration mission, proving less reliant on resupply from earth means ISS operates similar to that of an exploration mission.

C. Schedule

The target date to establish the full Air String in the US Lab is now predicted to be mid-2028. $FBCO_2$, H2ST, and TAS are installed on-orbit as of April 2022. At this point, all planned components are on contract with known schedules (except for AMCHX). 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 is comprised of the systems that collect human waste and the systems that process the liquid waste and other waste waters to provide 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 wastewater 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 wastewater 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, heats per crew settings, 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.

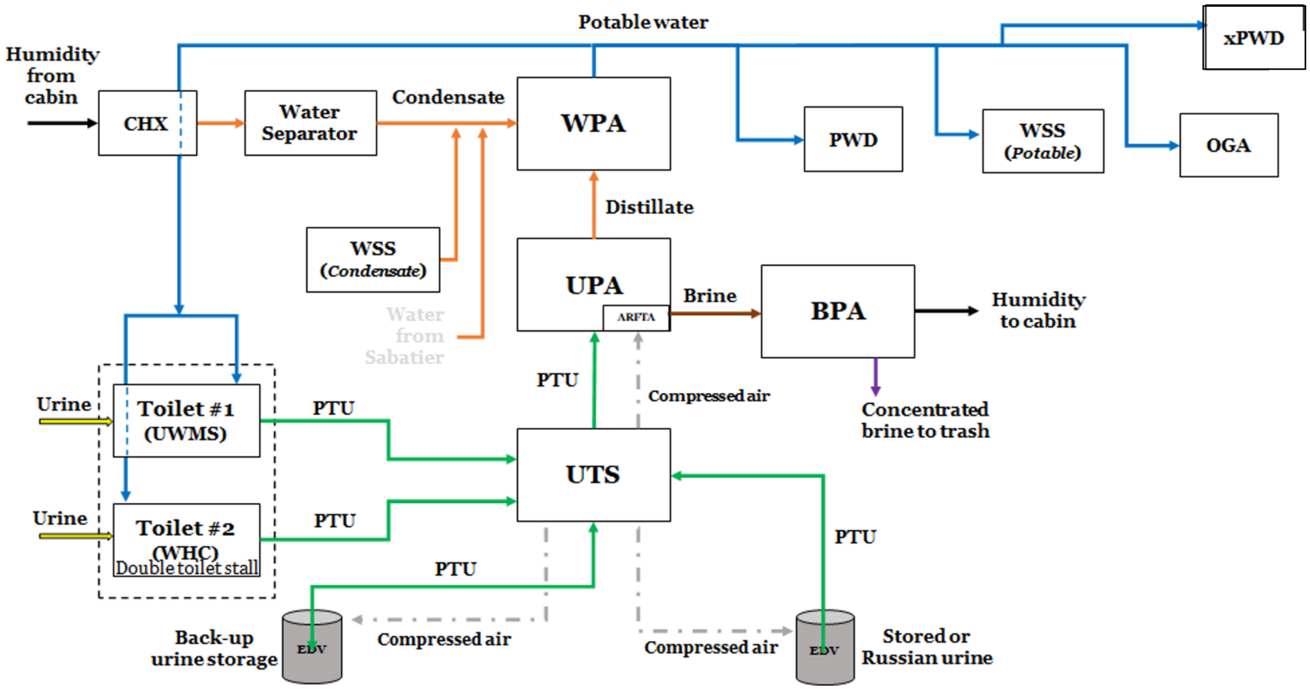


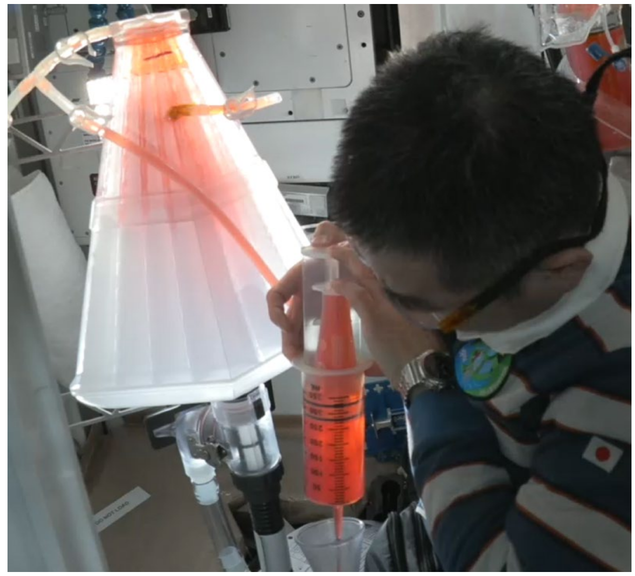
Figure 3. Water String Schematic

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 still in work. While the new check valve is in development, a spare Dose Pump of the legacy design was flown in March 2024 with the hopes of enabling the Artemis-II demonstration and additional run time (more data gathering) for UWMS. However, upon re-activation of UWMS in May 2024, the Dose Pump failed to dispense pretreat again. Furthermore, in July 2024 while attempting to troubleshoot the Dose Pump another failure occurred with the Controller which took the entire UWMS system down preventing any additional troubleshooting. More details can be found in the UWMS ICES paper submittals for 2025. Both the Controller and Dose Pump were returned to ground for TT&E late 2024, and investigations are still on going. The newly delivered MSFC Conductivity Monitor that was delivered with the Dose Pump in Jan 2024 did not get a chance to be fully validated on orbit given the premature failure of UWMS. Next planned attempt for reactivation of UWMS will occur likely occur early/mid 2026.

1.1 Passive Separator

In early 2025, the ISS Program began evaluating technologies that could be used for an air and urine separator. A NASA Research Announcement (NRA# NNJ13ZBG001N, focus area #5) was issued to industry to solicit proposals. Separately, an effort was initiated and a contract was issued with IRPI to test a prototype passive two-phase separator. The effort was paused in April of 2025 due to federal budget concerns. The two-phase separator test was fully funded prior to the budget concerns, so that effort was executed on-board ISS. The team developed the concept from idea to delivery for launch in ~88 days. In October 2025 (5 months after inception) the two-phase separator was tested on ISS (Figure 4). The results surpassed expectations and proved the technology's viability for use as an ECLSS component[25, 26]. Further evaluations for related technologies will continue into 2026. A full description and results of the effort will be presented in future publications.



1.2 Solid Pretreat

Current ISS urine pretreatment systems use concentrated liquid pretreat, which requires a mechanical dosing and conductivity sensing method. A "string of pearls" (woven packaging using a string of solid pellets) pretreat design, using a similar chemical formulation as the US Alternative Pretreat, is being developed as a passive dosing alternative. A short-term (~5 days) ISS Flight Demo is targeted for early 2027 to demonstrate usability with the ISS Toilet and validate proper dissolution of the solid pretreat in microgravity along with integration to the Urine Processor Assembly (UPA). The Orion UWMS also utilizes a "string of pearls" solid pretreat design; however, it contains a different chemical formulation that is not compatible with UPA.

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.

3. Purge Pump and Separator Assembly

The purge pump redesign incorporates an alternate purge pump type that is smaller, and more efficient 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 determined that internal tolerances caused a custom designed valve to seize. The tolerances were adjusted, and the system is currently awaiting launch to ISS. The system will be re-installed on ISS in 2026 after the currently installed legacy PCPA fails.

4. 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 tank 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 into 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, and a dormancy flush was demonstrated. The pumps are easily replaceable / repairable to minimize the number of spares needed for long term operation. The project team has developed a ground demonstration unit for integration into the UPA testbed – the fourth iteration of this design was complete in spring 2024. A flight demonstration is not planned.

5. 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 wastewater 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 to improve the WPA's ability to withstand siloxanes in the incoming condensate and 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 begin to saturate the beds and displace/ release siloxanes will 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 5, 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 was installed on 5/10/2024 and soon began leaking, proving this seal design does not work for this aplication in the flight hardware. The unit was removed and returned to the ground. Any future testing of an upgraded reactor will occur on the ground due to budget and schedule. 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 determined hardware and existing software could enable a non-interference demonstration on ISS. There were discussions on where to place the new valve on either side of the MCV ORU. On the potable side, it would be in WRS1, allowing closer isolation to the Water Storage ORU. On the waste side, it would provide flexibility for remote management of waste tank volume by enabling distillate offload to external storage when the WPA fails. The study focused on installing the valve on the clean side of the MCV, but there was no budget left to assess placing it on the waste side.

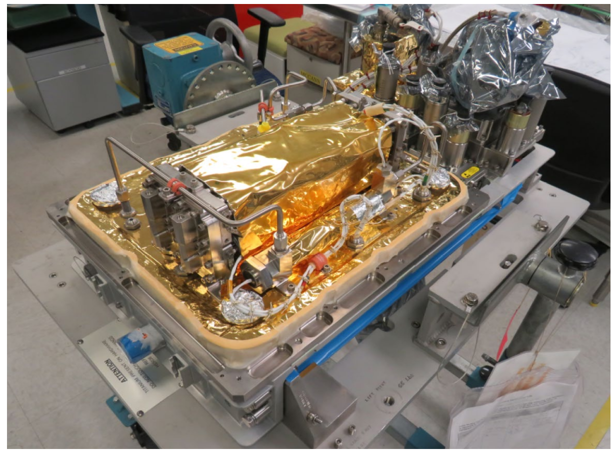


Figure 5. Upgraded WPA Catalytic Reactor

6. 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 is recovered for crew/system use. The liberated water vapor 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 published in 2025[24]. 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 with charcoal masks as additional odor protection during bladder R&R activities. NASA 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, which replaced the existing adapter on ISS BPA in December 2025. 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 was installed on BPA late 2024. Additionally, NASA developed and performed an on-orbit ISS crew odor evaluation of the initial design of the improved brine bladder odor bags which improved odor control during long-term storage as well as continuing to enable modular configuration for launch/return and stowage. The final improved odor bag design was delivered in 2025 and has been verified (per crew on-orbit questionnaire) to have drastically improved odor control of the bladder post dewatering cycle . NASA continues to manifest and procure additional bladders to recover valuable water on ISS. As of December 2025, BPA has recovered roughly 1395L of water over 1079 days of active operation, which averages to 1.3 L/day.

7. Potable Water Dispensing System

Figure 6. xPWD Installed on ISS

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 were identified, however a software update completed in 2024 resolved them. The xPWD filter higher throughput and improved insight due the ultrasonic flowmeter and ability to downlink data has greatly improved daily operations and logistics management.
Initial indications are that temperature control is improved over the legacy PWD system.

With the end of the 3-year technology demonstration run-time approaching in September 2025, planning is in-work to perform an on-orbit dormancy test, which involves launching the spare xPWD as a risk mitigation in case of post-dormancy issues and to be used as a backup to the prime xPWD unit

Additionally, the xPWD team and supporting organizations are evaluating an option to the original post-demonstration plan, which was to relocate the xPWD from its current location to replace the PWD in the ISS Galley rack. The option involves leaving xPWD in its current location so that it can continue to run in parallel to PWD; thus, extending xPWD run time. A programmatic decision will be needed to dedicate the current payload rack to xPWD, rather than the payloads being targeted to use that rack.

8. 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, whereas the current TOCA which uses coated electrodes for oxidation and optical sensing for detection. MiniTOCA is currently in development and will be delivered to ISS in FY26. The MiniTOCA Support Hardware, composed of the hardware and hoses needed to mount MiniTOCA to the ISS Node 1 deck connect it to the ISS nitrogen and potable water system bus and protect it from crew kick loads, is on track to be delivered ahead of the MiniTOCA system. The two Node 1 deck panels and brackets specifically designed to accommodate the MiniTOCA footprint will be launched on the NG-24 Cygnus cargo vehicle and will be installed by the crew prior to the arrival of the MiniTOCA and the remainder of the support hardware and consumables on a later cargo vehicle.

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 3. 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.
- 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 resultant concentrated brine is placed 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 6.

C. Schedule

Much of the upgraded hardware is already on ISS being tested and evaluated. The largest pieces remaining are AOGA (2027), CHX (2028), and final integration of an air string (which relies on either an upgraded TAS or hardware to support integration of $FBCO_2$).

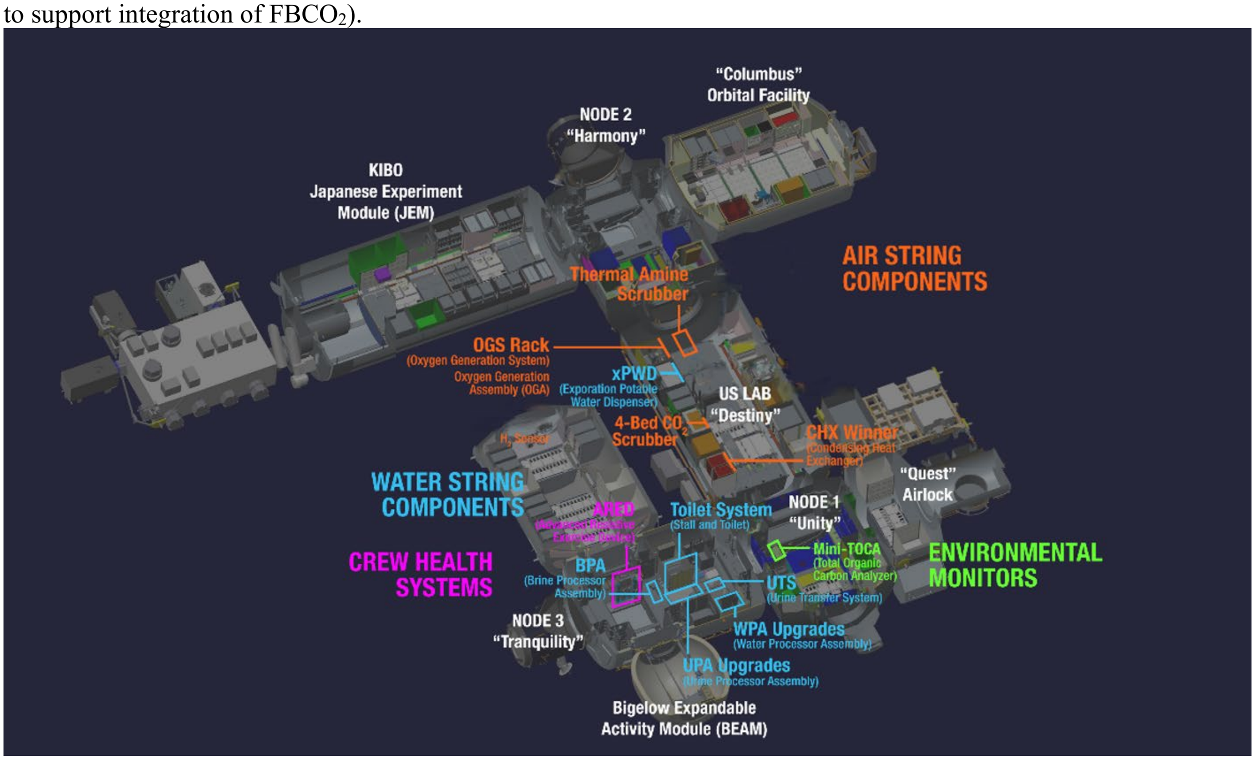


Figure 7. Exploration ECLSS Hardware Layout on ISS.

IV. ISS Integration

A. Operations and Certification Approach

The standalone demonstrations such as the CO_2 Removal candidates, the BPA, UWMS, xPWD, and Mini-TOCA have been 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 proved 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 that the ISS ECLSS is operated. This allows the characterization of the real-time operational aspects of the system upgrades and modern technologies. These systems are outfitted with internal sensors to ensure operational efficiency and performance can be determined during the on-orbit demonstrations. To facilitate the integrated operational approach, the ISS ECLSS Team is the responsible engineering organization for supporting real-time operations and hardware sustaining efforts. For each of the demonstrations, the Mission Control Center – Houston (MCC-H) is responsible for installing, operating, and monitoring, as well as training the crew for installation and maintenance. Also as with the legacy ISS vehicle systems, 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 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 (EVAs).

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 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 beneficial 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 to reduce cost and maximize the demonstration of Exploration-class ECLSS before the end of the ISS Program.

BPA reached its 3 years of on-orbit operation in June 2024, and sparing assessments are ongoing to enable optimal water recovery. FBCO2 reached 3 years of ISS demonstration at the end of 2024, and so similar sparing and operational support changes have been started. 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 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.

V. Conclusion

The opportunity afforded by the presence of the ISS as a testbed for ECLSS advancements is being utilized to the fullest extent with current systems but there is room to do more. A fully integrated and upgraded ECLSS continues to evolve, incorporating improvements to existing hardware with newly added subsystems and capabilities. The upgraded integrated ECLSS 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 4 more years, and the progress of this effort will be the subject of future papers.

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