International Space Station as a Testbed for Exploration Environmental Control and Life Support Systems – 2022 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
CHX = Condensing Heat Exchanger
CO_2 = carbon dioxide
ECLS = environmental control and life support
ECLSS = environmental control and life support system
EDV = Russian-built water tank
EVA = extravehicular activity
EXPRESS = Expedite the Processing of Experiments to ISS
(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
(l) = liquid phase

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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
PTU	=	Pre-treated Urine
PWD	=	Potable Water Dispenser
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 missions. The purpose is to allow characterization of system performance, system reliability, and integration challenges in the relevant environment of ISS. 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 it 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 to be demonstrated on ISS will be 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 will 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[1,2]. The new technologies to be added 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 possible. This means that subsystems that directly integrate together to exchange process fluids will be physically

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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). 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 USOS.

The environmental monitors to be demonstrated on ISS will be deployed as installation volume, vehicle utilities (e.g. power, cooling, data), and their particular functions dictate. For example, a device that monitors potable water quality will be located directly inline within the potable water distribution system in order 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.

The objective of this paper is to refine the description from the prior year's papers[3,4] 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.

A new, 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 effectivey double the data set used for Exploration mission architecture design. This effort will not be discussed in detail in this paper.

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.

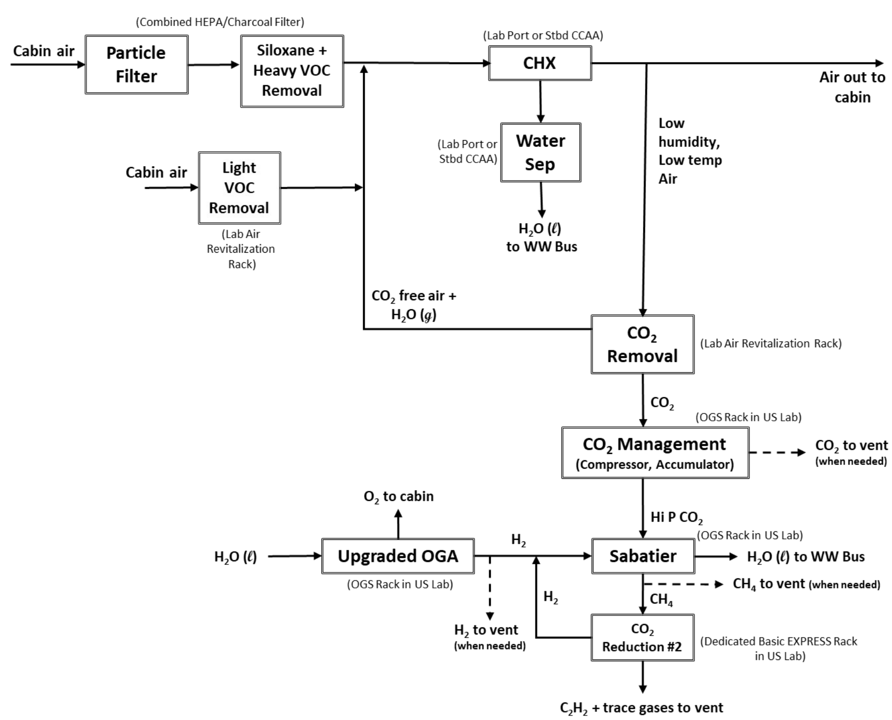


Figure 1. Air String Schematic.

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 CO_2 reduction system that recovers oxygen from CO_2 through reaction with hydrogen to produce water and byproducts.
- 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.

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.

- **CHX:** The ISS legacy CHX 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 dryouts or eliminate the need for these dryouts altogether. To field a CHX containing this coating, NASA is pursuing build of the heat exchanger core using additively manufactured processes. This approach is expected to reduce the time and cost to build the heat exchanger cores in the future.
- **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 may be flown to ISS as a flight experiment to prove if it can effectively and repeatably separate a large volume and high velocity gas/liquid air stream. If this concept is proven successful, it may be considered for planetary surfaces mission with partial gravity fields.
- **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. The upgraded filter design includes a portion for siloxane and heavy volatile organic compound (VOC) removal and a portion for high efficiency particulate air (HEPA) filtration as has always been present in the USOS. 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. Replacements will be 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[5]. No other upgrades to the ISS TCCS are planned.
- **CO_2 Removal System:** NASA is pursuing three candidate CO_2 Removal technologies. Two 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 will be located in Expedite the Processing of Experiments to ISS (EXPRESS) Racks or Basic EXPRESS Racks during this initial demonstration period. After the one year demonstration period, NASA will select one candidate that will join the Air String as the CO_2 Removal System in Figure 1 for long duration integrated testing. The first candidate, Thermal Amine Scrubber, began operation on ISS in May 2019 with performance and reliability characterization on-going[6,7,8]. It achieved a year of run time in Oct 2021. The second candidate, Four Bed CO_2 Scrubber[9], launched to ISS in mid-2021, and has been successfully operating on ISS since that time.Both Four Bed CO_2 and Thermal Amine will have upgraded blowers that will launch in mid-2021 with the goal of improving robustmeess and performance. The third NASA candidate technology, the Mini-CO_2 Scrubber, is continuing to mature and may launch to ISS with subscale CO_2 removal performance for initial testing. NASA is assessing the ability of this technology to meet full scale CO_2 removal performance. A commercial partner is also developing a CO_2 removal technology[10] that is undergoing ground testing. Its forward path towards additional ground testing or demonstration on ISS is under assessment.

Figure 2. Four Bed CO_2 Scrubber Flight Hardware.

- **CO_2 Reduction System:** The Sabatier Reactor Assembly (SRA) that was operating on ISS until October 2017 will be upgraded and returned to the ISS for continued operation. The system redesign will focus on improving system performance, robustness to external contamination, and reliability[11]. The location of this unit in the Air String is shown in Figure 1. The Sabatier 2.0 project has initiated, and will deliver in mid-2024. NASA may also develop an additional technology that could join the Air String as the CO_2 Reduction #2 system in Figure 1. It would ingest the methane created as a product of the Sabatier reaction and decompose it into hydrogen that can be utilized to react additional carbon dioxide to form additional water. The waste products generated will be vented overboard.
- **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 lower level of components to be replaced, 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 within the dome. 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 to enable dormancy periods and to clear the recirculation loop of contaminants that could affect downstream systems such as Sabatier. Advanced OGA will deliver in mid-2024. A separate technology demonstration will evaluate an alternate hydrogen sensor technology with the potential for reduced sensor drift and more tolerance for contact with water. This new sensor could be incorporated into AOGA if the demonstration on ISS is successful.

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. At the present time, the ISS ECLSS contains an air string in Node 3. However, there is insufficient rack space in Node 3 to accommodate the addition of the CO_2 Reduction #2 system, therefore the OGS Rack will be relocated to the US Lab in order to establish the Air String in that module. The OGS Rack is planned to relocate to the Lab in the summer of

2022, which will facilitate the Hydrogen Sensor Tech Demo to begin gathering data on the rack front prior to Advanced OGA arrival.

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 (AR) Rack.
- One of the two CO2 Removal Systems will be installed in the US Lab AR Rack in-place of the US Lab Carbon Dioxide Removal Assembly (CDRA). The US Lab CDRA will be removed and stowed onboard ISS in the event it is needed in the future. The other CO2 Removal System willremain in its EXPRESS Rack throughout its life on ISS. These devices will be physically located in these ares, but the selected candidate will be integrated into the Air String as the CO_2 Removal system depicted in Figure 1. Which candidate is selected 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.
- CO_2 Reduction #1 (the Sabatier Reactor Assembly) will be installed in its prior location inside the Oxygen Generation System (OGS) Rack. CO_2 Reduction #2 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 to route hazardous gases such as hydrogen and methane between the racks. A CO_2 Management System will be installed within the OGS Rack to compress and accumulate the CO_2 that is provided from the CO_2 Removal System to the CO_2 Reduction #1 system. The improvements to Sabatier and a new accumulator assembly will require the OGS Rack front to be extended into the US Lab aisle area.
- OGA upgrades will be located in the OGS Rack. This rack will be relocated from Node 3 to its previous location 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 8 towards the end of this paper, existing racks will have to be relocated to other modules or positions within the US Lab. For example, to place the OGS Rack in its previous location at LAB1P1 which affords it the proper utilities including interfaces for potable water, waste water, adequate power, active liquid cooling, and overboard venting, the European Space Agency's Life Support Rack must vacate this location. This rack will be relocated to the Node 3 module which will require design and build of hoses and cables, performance of detailed system analyses, and revisions to ISS vehicle software. 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.

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. This effort requires design and build of new hardware as well as two Extravehicular Activities (EVAs) for installation. Once it is installed, this vent will be available for use by the CO_2 Removal candidates towards the end of their one year minimum demonstration periods and then whenever it needs to vent its CO_2 overboard, Thermal Amine Scrubber can share this vent with the CO_2 Reduction #2 system.

D. Schedule

The target date to establish the full Air String in the US Lab is now predicted to be late 2024. There are many aspects of the effort that do not yet have solidified project schedules, so it is not possible to predict the actual completion date. The integrated Air String development and integration schedule will be finalized when the scope of the entire effort has been defined and the associated project schedules are baselined.

III. Water String

The Water String comprises the systems that collect human waste and the systems that process the liquid waste and other waste waters to potable water for crew consumption and hygiene, oxygen generation, spacesuit cooling, and payload use. The Water String that will be demonstrated on ISS is depicted schematically in Figure 3. This figure also indicates the relative schedule for arrival on ISS for each of the major subsystems. 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.

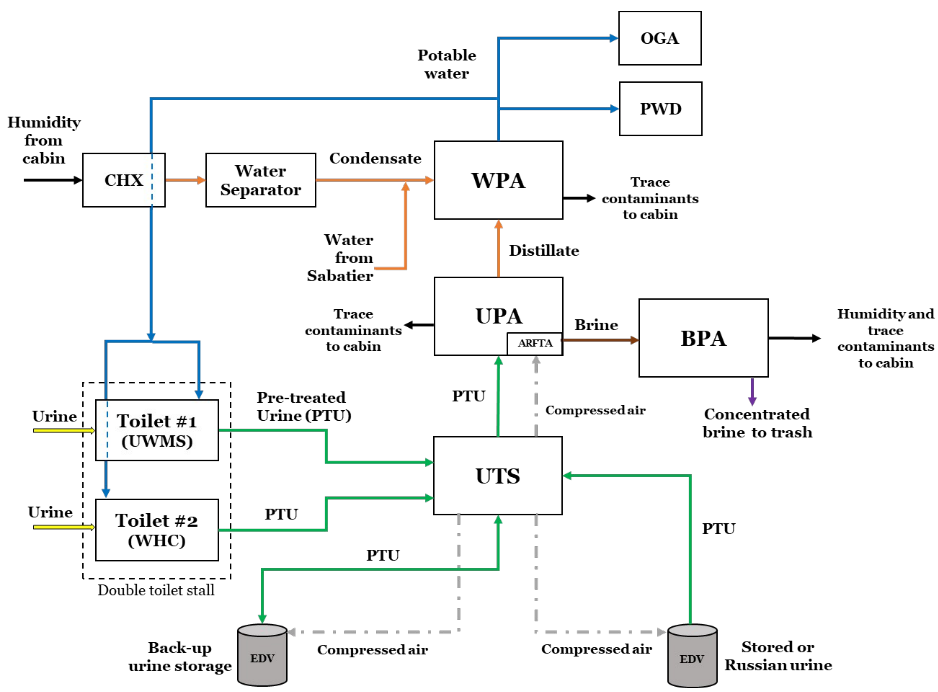


Figure 3. Water String Schematic.

E. 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, either as an upgraded ISS system or as a new technology. The following are the systems that will fulfill the Water String functions.

- **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 accommodate female crewmembers. This toilet, also known as the Universal Waste Management System (UWMS)[14], will join the USOS toilet complement along with the existing Waste and Hygiene Compartment (WHC) toilet that is currently located within Node 3. Both toilets will feed their collected urine to the Urine Processor Assembly. 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. The new toilet is depicted as Toilet #1 in Figure 3. 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. It is anticipated that additional operation on ISS will occur while these changes are made, on a limited basis.
- **Urine Processing System:** The Urine Processor Assembly (UPA) that is currently on the ISS will be upgraded[15,16] to correct design weaknesses identified by the operational experience gained since its activation. 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 will be delivered toward the end of 2022. An upgrade to the Distillation Assembly was installed into the ISS UPA in 2020 (see Figure 4) 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. Also, ground studies and testing are being initiated to identify if there are any additional system modifications that can reduce the complexity of the effort to configure for long term dormancy and to improve the ability to detect failures in UPA components.Some of these concepts 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. Upgrades to the fluids pump are also being pursued, with a focus on maintainability.

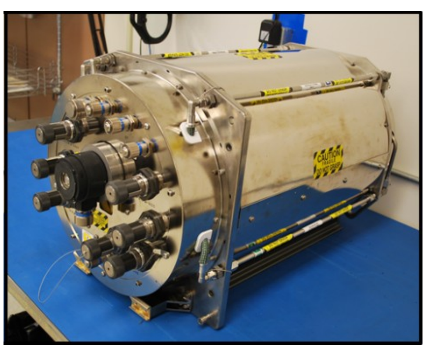
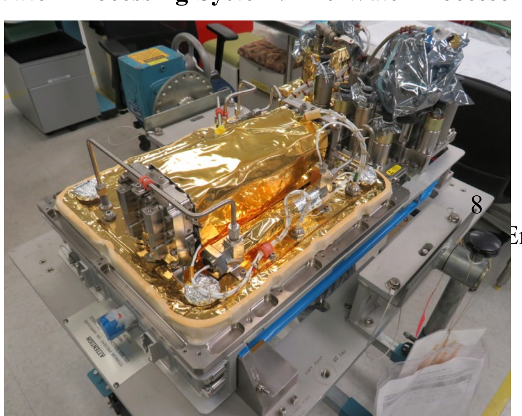


Figure 4. Upgraded UPA Distillation Assembly.

- **Water Processing System:** The Water Processor Assembly (WPA) that is currently on the ISS will be upgraded based on the operational experience gained since its activation. The WPA upgrades will 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 Multifiltration 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 Multifiltration Bed has been redesigned to contain an improved sorbent material to improve its performance and extend the operational lifetime. And 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. It has been returned to ground for re-assessment, repair, and will be reflown to ISS for installation and operation by early 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.

Figure 5. Upgraded WPA Catalytic Reactor (with thermal cover removed).

- **Brine Processing System:** A new technology has been proven in ground-based testing that is 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. The Brine Processor Assembly (BPA)[17,18] has was installed on ISS in March 2021, as shown in Figure 6 and depicted in the Figure 3 schematic.

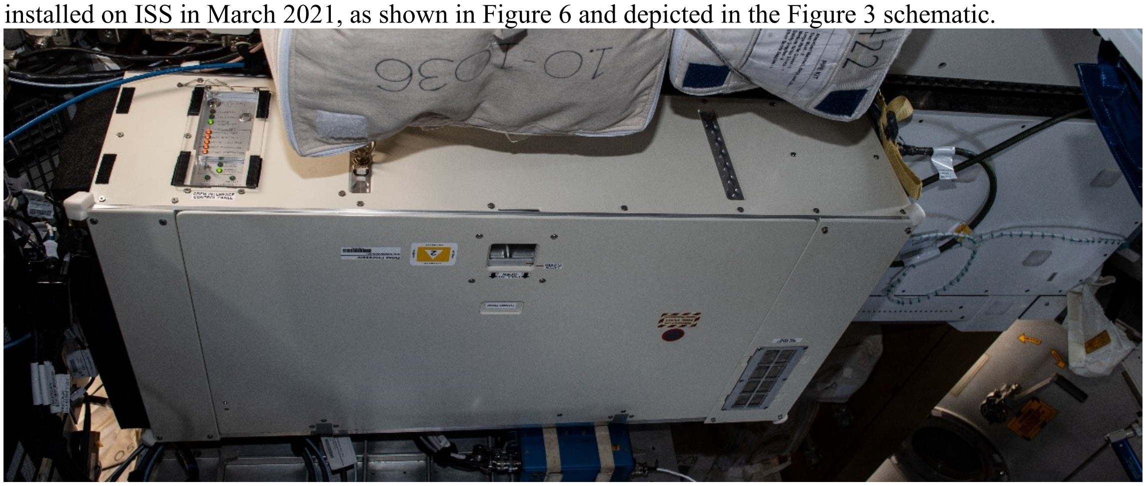


Figure 6. Brine Processor Assembly Installed on ISS.

- BPA has been successfully dewatering brine since installation with no significant hardware issues/failures. However, shortly after activation, crew began to report nuisance odors from the BPA, in particular at the exhaust outlet where the humid air exits. BPA was turned off until ground teams could assess the odors, and develop a mitigation plan. This resulted in a 2 month ground testing campaign at Paragon in Tucson,AZ which completed a dewatering cycle while collecting multiple gas samples for analysis. A set of gas samples went to White Sands Test Facility for qualitative Standardized Odor Testing utlizing human subjects, as well as samples sent to JSC Space and Life Sciences' Labs for traditional trace contaminent chemical gas analysis. Post testing analysis concluded that with an addition of an exhaust filter to the BPA exhaust, the selected filter greatly reduced VOCs coming from BPA that can cause nuisance odors. The new BPA exhaust housing and several filters were delivered on SpX23 (August 2021). BPA was reactivated in November 2021 with a new adapter attached to the BPA exhaust outlet which allowed a silicone duct to connect to the adapter and the new BPA exhaust housing (w/ filter), see Figure 7. Since reactivation, crew has noted the new exhaust filter has significantly reduced the previously noted nuisance odors. BPA has completed seven succesful dewatering cycles as Feb 2022. Bladders are planned for return on future SpX vehicles to validate dewatering performance in microgravity.

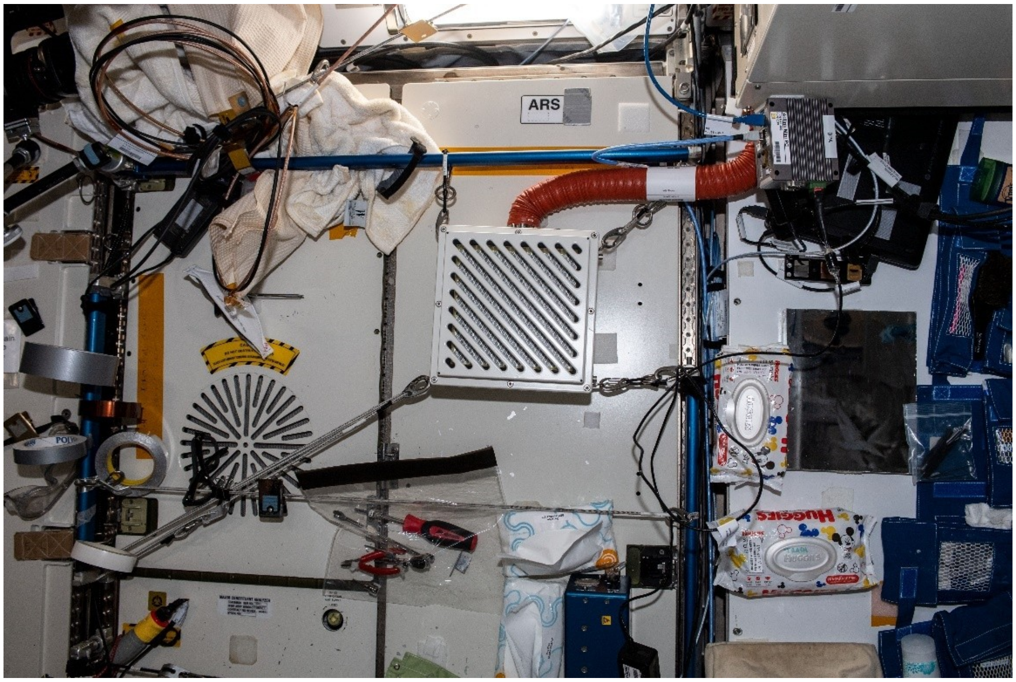


Figure 7. Brine Processor Assembly with BPA Exhaust Filter Attached.

- **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 will address concerns with microbial growth during dormancy by removing all stagnant portions of the system. It will also demonstrate a flow-through ultraviolet (UV) disinfection technology at the point-of-use[19] which should reduce overall system consumables usage if successful.
- **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. MiniTOCA uses UV for oxidation and a tunable laser spectroscopy for detection, vs. the current TOCA that uses boron-doped diamond coasted electrodes for oxidation and nondispersive infrared for detection. MiniTOCA is currently in development and plans to be delivered to ISS in early FY25.

F. ISS Integration Approach

The Water String will be 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 will be co-located and physically integrated to enable process fluids to pass between them as depicted in Figure 3. The exception is the Exploration PWD that is likely to be located in the US Lab in an EXPRESS Rack, 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[20]. The UWMS and WHC are physically plumbed to deliver their collected urine directly to the UPA via the Urine Transfer System that is described below.
- The UPA will be upgraded inside its current WRS#2 Rack.
- The WPA will be 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 will enter the Node 3 cabin and be removed by the USOS humidity control system. The concentrated brine generated will be put into the trash for disposal.
- The Exploration PWD will be located in an EXPRESS Rack 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 8.

G. Challenges

Physical space on ISS is at a premium given the amount of systems, payloads, spares, consumables, etc., that are operating and/or stored on the vehicle. Because of this limitation, determining the best location to house the new toilet and its associated privacy compartment was a significant challenge that has been overcome and is instantiated in the double toilet stall that is installed on ISS.

- Also, the presence of two toilets in the USOS operating simultaneously created a unique challenge of managing the urine flow from both of these systems into the UPA. To overcome this challenge, an automated system was developed to detect urine flow from either toilet and direct only that system's flow to the UPA. If the second toilet is also sending urine at the same moment, its urine will be sent to a backup urine storage tank. The automated system is the Urine Transfer System (UTS) and it, along with the backup urine storage tank, is depicted in Figure 3. Also shown in this figure is the UTS's ability to transfer urine into the UPA from an external tank via a built-in air compressor. This hardware is operational on ISS and is ready to support UWMS and WHC operations. The use of this hardware to date with just the WHC has already reduced the burden on the crew to manually transfer urine and will overall save crew time spent on ISS for system maintenance and operation.

H. Schedule

The majority of the hardware was installed on ISS by late 2021. This includes the UTS, BPA, WPA upgrades, and UPA upgrades that are already installed, as well as the addition of the new toilet. Additional upgrades to UPA and WPA, as well as delivery of the Exploration PWD, will occur in 2022 and beyond.

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.

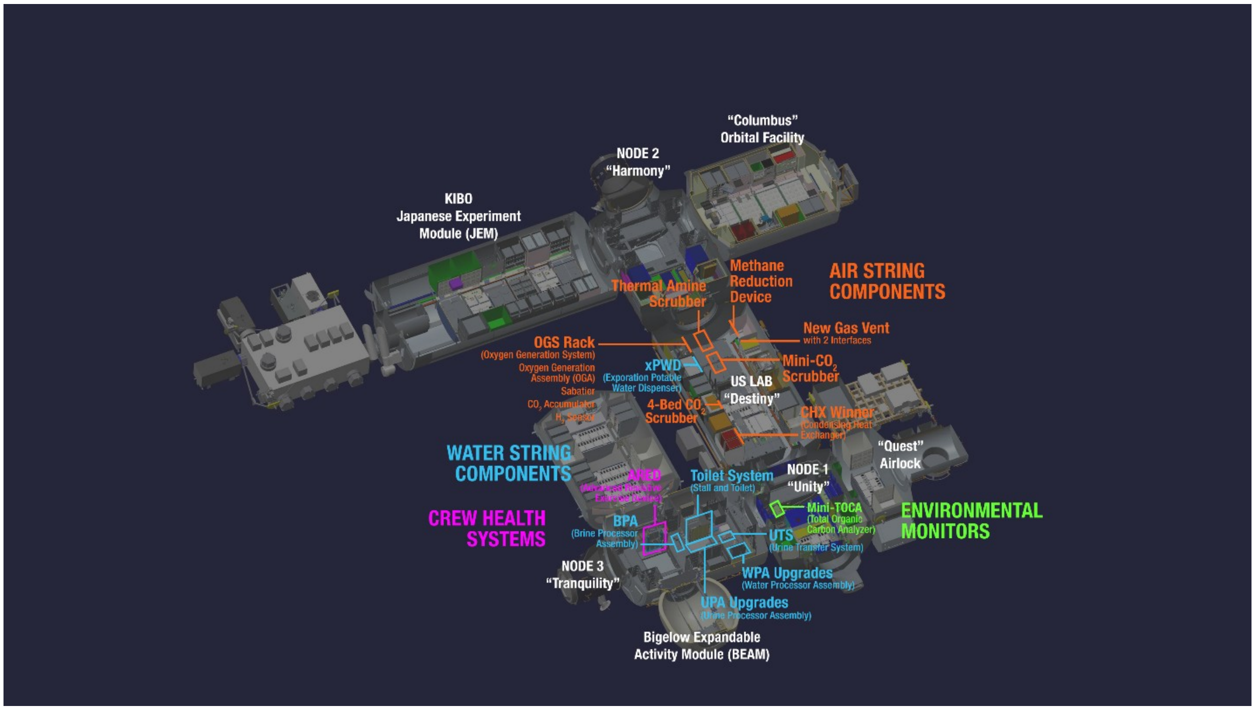


Figure 8. Exploration ECLSS Hardware Layout on ISS.

I. Operations and Certification Approach

The standalone demonstrations such as the CO_2 Removal candidates, the BPA, the new toilet, Exploration PWD, and Mini-TOCA are being developed as non-critical system technology demonstrations 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 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 will allow 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) will be 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.

J. 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 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 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 teamsat Johnson Space Center (JSC) and MSFC are working with a group from Ames Research Center (ARC) to develop automation concepts that can be applied in a ground test setting with eventual application on an Exploration Mission.

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 many challenges to overcome to outfit 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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