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International Space Station (ISS) Environmental Control and Life Support (ECLS) System Overview of Events 2023

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Nov 20th, 2023 marks the 25th anniversary of the beginning of construction of the International Space Station (ISS). The ECLS system is constantly changing to meet the needs of current missions and future exploration. The ISS has become the laboratory that was always envisioned, allowing for an ever-growing class of exploration level technologies that will propel the stage forward as humanity advances beyond Low Earth Orbit (LEO). This paper will review the past year, and look towards the future for each U.S. ECLS subsystem. The impacts, challenges, and successes related to the intermingling of incumbent and cutting edge technologies are summarily discussed in this paper.

NOMENCLATURE

AC = Assembly Complete
ACS = Atmosphere Control & Supply
ACTEX = Activated Carbon Ion Exchange Cartridge
AOGA = Advanced Oxygen Generation Assembly
AR = Atmosphere Revitalization
ASV = Air Selector Valve
BIT = Built In Test
BPA = Brine Processor Assembly
CHIPS = Charcoal HEPA Integrated Particle Scrubbers
CCAA = Common Cabin Air Assembly
CCA = Circuit Card Assembly
CDRA = Carbon Dioxide Removal Assembly
CHX = Condensing Heat Exchanger
ECLS = Environmental Control and Life Support
ECLSS = Environmental Control and Life Support System
EIA = Electrical Interface Assembly
FDS = Fire Detection and Suppression
HEPA = High Efficiency Particle Air
ISS = International Space Station
ITCS = Internal Thermal Control System
LTL = Low Temperature Loop
JSL = Joint Station LAN
MCA = Major Constituent Analyzer
NASA = National Aeronautics and Space

OGA = Oxygen Generation Assembly
OGS = Oxygen Generation System
OHDA = Oxygen Hydrogen Domes Assembly
ORU = Orbital Replaceable Unit
R&R = Remove & Replace
SDS = Sample Delivery System
S/N = Serial Number
SPRT = System Problem Resolution Team
SpX = SpaceX
THC = Temperature & Humidity Control
TT&E = Test, Teardown & Evaluation
UPA = Urine Processor Assembly
UTS = Urine Transfer System
USOS = United States On-orbit Segment
WHC = Waste & Hygiene Compartment
WM = Waste Management
WPA = Water Processor Assembly
WRS = Water Recovery Subsystem
WRM = Water Recovery & Management
WSS = Water Storage System
VES = Vacuum Exhaust System
VRS = Vacuum Resource System
VS = Vacuum System
VV = Visiting Vehicle

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1. Introduction

The International Space Station (ISS) program achieved "Assembly Complete" (AC) in 2010, with the Environmental Control and Life Support (ECLS) system supporting ISS crews and visiting Shuttle and Soyuz crews since assembly began in 1998.

Through AC a total of 16 pressurized elements have been added to the ISS. Since then, ECLS activity has focused mainly on maintaining the ISS systems currently onboard while acquiring on-orbit operational knowledge in microgravity. Additional changes to the "AC" ISS configuration continue to occur, including support for exploration ECLSS technology testing.

The future in Low Earth Orbit is uncertain, but bright. The ISS stands as the gold standard for testing, and proving out exploration class systems. As it stands today, the ISS will remain in-orbit until at least 2030, but it has been shown that the ISS can be safely operated into the 2040s. While there are other options potentially available on the horizon, there is only one platform that a research scientist or hardware developer can safely count on today. That is the ISS.

A. ISS ECLS OVERVIEW

The ISS on-orbit ECLS system comprises 6 major subsystems: Atmosphere Control and Supply (ACS), Temperature and Humidity Control (THC), Fire Detection and Suppression (FDS), Atmosphere Revitalization (AR), Water Recovery and Management (WRM), and Vacuum System (VS). The following sections briefly summarize each subsystem and its function within the ISS pressurized elements.

1. Atmosphere Control and Supply (ACS)

The ACS subsystem provides cabin atmosphere pressure control, overpressure relief, pressure equalization, rapid depressurization detection and response, nitrogen and oxygen distribution, and nitrogen and oxygen high pressure tank recharge from NORS tanks delivered on unmanned logistics vehicles.

2. Temperature and Humidity Control (THC) & Fire Detection and Suppression (FDS)

The THC subsystem provides airborne heat removal, air temperature control and monitoring, intra-module and inter-module ventilation, humidity removal, and airborne particulate/bacteria removal. The FDS subsystem includes smoke detection, fire isolation, fire extinguishment, and fire recovery.

3. Atmosphere Revitalization (AR) & Vacuum System (VS)

The AR subsystem revitalizes the habitable atmosphere by removing carbon dioxide, potentially hazardous volatile trace contaminants generated by inadvertent spills, crew metabolic processes, and equipment off-gassing such that cabin contaminant levels are maintained within limits. Additionally, the ISS habitable environment is monitored for atmosphere major constituents O_2, N_2, and CO_2, as well as H_2, CH_4, and H_2O. In the United States On-orbit Segment (USOS), the Sample Distribution System (SDS) carries sample cabin air through lines from the various modules to the Major Constituent Analyzer mass spectrometer.

The VS supplies the U.S. Lab module payload rack locations with access to space vacuum. The VS consists of two separate subsystems: the Vacuum Exhaust System (VES) and the Vacuum Resource System (VRS). Connected to all thirteen payload rack locations, the VES can vent payload gases overboard. The VRS provides high-quality vacuum to nine of the thirteen payload rack locations for user access. The VS is also currently being used to support two CO2 removal technology demonstration systems.

4. Water Recovery and Management (WRM) & Oxygen Generation Assembly (OGA)

The WRM subsystem supplies potable water, hygiene water, and water for payloads, as well as collecting humidity condensate. The WRM also provides excess wastewater venting; condensate storage; and potable and waste water distribution.

The WRM subsystem was expanded significantly prior to Shuttle retirement with the addition of the Regenerative ECLS Racks known as Water Recovery System (WRS) 1 and 2 and Oxygen Generation System (OGS), which include the Urine Processor Assembly (UPA), the Water Processor Assembly (WPA) and the Oxygen Generator Assembly (OGA). WRM includes Waste Management (WM) which, for ISS, is the Waste & Hygiene Compartment (WHC), a U.S. On-orbit Segment (USOS) bathroom that collects solid waste and collects, treats and transports liquid waste to the Urine Processor Assembly (UPA) for water recovery.

2. SUMMARY DISCUSSION OF MAJOR SUBSYSTEM EVENTS IN UNITED STATES ON-ORBIT SEGMENT BY FUNCTION

A. Temperature and Humidity Control & Fire Detection and Suppression

1. 1. Node 3 Common Cabin Air Assembly (CCAA) Troubleshooting

The CCAA provides the capability to control the cabin air temperature, maintain the cabin air humidity, and generate ventilation air flow in Node 2, Node 3, Lab (2 locations) and the Airlock. The Heat Exchanger (HX) Orbital Replacement Unit (ORU) and the Water Separator (WS) ORU are critical units of the CCAA. The HX cools and dehumidifies the air while the WS collects the condensate.

The Node 3 HX Liquid Sensor (LS) started experiencing wet indications at an increased rate, which means that water is being detected downstream of the HX. If not fixed, water can end up on the cabin diffusers or will stick to the ducting and evaporate back into the air. Typically, a wet indication is a sign of a degraded HX. From the Snorkel DTO in December 2019, which was conducted in the US Lab, it is known that HX wet indications do not pick up all HX carryover events and it is likely that many other carryover events are taking place within a degrading HX. However, the ducting in Lab and Node 3 do have different configurations. The Node 3 CCAA has high priority since the unit affects the management of Node 3 Carbon Dioxide Removal Assembly (CDRA) via flight rules. Therefore, a HX Remove & Replace (R&R) was performed in Node 3. However, the wet indications did not clear after the R&R of the HX ORU. The next step was to R&R the CCAA WS ORU. The condensate pressure in the WS was slowly increasing over time, which was initially interpreted as a pressure sensor shift. Once the WS pressure passes a certain limit, though, it will affect WS operations. Once the Node 3 WS was also R&R'd, the HX LS wet indications continued for about six days, but then stopped after that. It is still unclear if the indications stopped because of a temperature set point increase in Node 3 or the HX ORU started operating nominally. The CCAA unit will be tested in 2024 after some run time at different LTL configurations to help determine why the system continued to produce HX LS wet indications.

Figure 1. CCAA HX Packed for Return

Because the team was concerned that the WS may have been contributing to the Node 3 HX carryovers prior to the HX R&R, a wettability test was performed on-orbit on the removed Node 3 HX. The test included placing water droplets onto the HX to test its properties for water absorption. From this test, it was determined that the removed HX still had the capacity to support effective humidity removal. Therefore, it was decided to R&R this HX ORU unit with the one in A/L, which is degraded, and it is the first and only HX installed in A/L since the beginning of A/L operations in 2001. The A/L HX started having a high rate of wet indications in 2007 and has not been used for frequent condensate collection since approximately 2011. The unit is now only regularly used for sensible heat removal due to its limited ability to remove humidity. Installing the Node 3 HX into A/L will require swapping coolant hoses with the A/L HX's QDs on-orbit. After successfully breaking the high torque on the Node 3 HX coolant hose fittings on-orbit, the A/L HX R&R will be completed in 2024 and the A/L HX will return on SpX-30.

2. LAB1P6 CCAA WS Liquid Check Valve (LCV) R&R and BIT Test

The WS ORU's task is to pull the water from the fins of the HX and transport it to the Water Bus by means of the elevated water pressure provided by the WS Impeller. This elevated pressure is controlled by a spring check valve called the LCV, located at the interface between the WS and its internal Bus Line. When the HX fins are very cold, the WS pulls the condensate accumulated at the fins and drives it through the LCV, opening the poppet valve inside the LCV and passing the condensate downstream. For various reasons, the operation of this poppet valve and spring inside the LCV can be compromised so that the LCV becomes either stuck closed or open, historically causing earlier-than-expected R&Rs. For example, while the WS is designed for an on-orbit lifespan of 5 years, the previous Node 3 WS was installed in 2017 and replaced 2 years later, and the Lab P6 WS was installed in 2011 and was also replaced 2 years later, primarily because the LCV was not operating as required. The LCVs also have expected set and reseat pressures. Several of the installed LCVs appear to have an issue with the reseat value where they are reseating at a much lower value than expected. The concern is that this could allow air to be introduced to the Water Bus.

One such occurrence, when the LCV became stuck open, happened at the end of 2022 on the LAB1P6 WS. The pressure sensor that monitors the water pressure inside the WS started to closely follow the bus pressure while the WS was powered down, which is a clear indication that the LCV is stuck open. Therefore, the LAB1P6 WS LCV was R&R'd in August 2023 and the LAB1P6 CCAA reassumed control over temperature and humidity in Lab. The first analysis of water pressure in the LAB1P6 WS confirmed that the LCV R&R was successful, and the LCV also passed a visual check for the signs of leak or moisture. However, the new valve failed the BIT test because the new valve was not able to hold the high pressure provided by WS Impeller, nor was it able to hold the Water Bus pressure from downstream of the poppet valve. Therefore, there could be an internal leak in the LCV between the valve diaphragm/plunger interface. Further analysis and discussion of the data is needed to understand if this is a nominal internal leak, and data analysis of a dry cycle on the WS is also needed to understand the condition of the LAB1P6 WS LCV. In order to verify whether this internal leak is

Figure 2. CCAA LCV

nominal, another BIT test will be required as well, likely on LAB1S6 WS, as that unit is functioning nominally. In the end, though, while the newly-installed LCV did fail the pressure check, the internal pressure readings do appear nominal during operation, proving that the LCV can be R&R'd on-orbit.

3. Charcoal-HEPA Integrated Particle Scrubber (CHIPS) R&R and HEPA Life Extension

In 2019, 21 CHIPS Filters were installed throughout the USOS, replacing the preexisting Bacteria Filters in each location. Each CHIPS Filter contains a Charcoal Filter affixed on top of a HEPA Filter, and sits upstream of the CCAAs or Cabin Fans to filter particulates and volatiles out of the air that are harmful to Temperature and Humidity Control (THC) and Water systems, including trimethylsilanol (TMS) and dimethylsilanediol (DMSD). The initial life expectancy for the Charcoal Filters was 3 – 5 years, however, could actually be as short as 1.6 years, and the initial life expectancy for the HEPA Filters was 2 – 5 years, depending on location, based on data from the prior Bacteria Filters. Since the Charcoal Filters do not have a set life, the health of these filters has been monitored by DMSD levels measured in the potable water and total organic carbon (TOC) breakthroughs in the Multifiltration (MF) Bed. The HEPA Filters are monitored through CCAA/Cabin Fan pressure differentials. The HEPA Filter life was extended to the current 3.5 – 5 years, depending on location, in 2021 after successful inspections and good pressure differential trending across the modules at the time.

Figure 3. CHIPS Filter R&R

In early 2023, the R&R of the Charcoal Filters across Station was requested due to the DMSD levels in the potable water returning to pre-CHIPS installation concentrations. Based on continued ORU Inlet Fan pressure differential trending analysis, the Node 3 HEPA Filters were also requested to be R&R'd with the Charcoal Filters while the rest of the HEPA Filters across the USOS were requested to be inspected and cleaned. These R&Rs and cleanings were conducted in August 2023, and, based on this set of inspections and continued ORU Inlet Fan pressure differential trending, the lives of the HEPA Filters will be extended to be 5 years in every module. Following this on-orbit work, a Charcoal Filter from each module was returned on SpX-29 to be analyzed for loading patterns and to determine the official life of these filters. An additional Charcoal Filter and one HEPA Filter, both from Node 3, were also returned on SpX-29 to be analyzed for changes in performance following long-term continuous use, DMSD formation, and to complement efforts to determine the per-person particulate emission rates with data from the Airborne Particulate Monitor (APM) payload.

4. Node 2 Area Smoke Detector (ASD) 2 Grounding Wire R&R and Reconfiguration

In mid-2021, while relocating the Node 2 ASDs, crew was unable to find the required number of 20/22ga Ring Terminals to fabricate grounding wires for Node 2 ASD 2. Until more terminals could be flown, 10/12ga Ring Terminals were used because they could fit over the ASD fasteners. To ensure crew safety against potentially high levels of voltage, routine inspections of the wires were scheduled to ensure the grounding wires still fully grounded the ASD to ISS structure until the proper terminals could be flown on NG-18 in late 2022. Once the terminals arrived to ISS, new grounding wires were fabricated, installed, and went through several rounds of reconfigurations from late 2022 to mid-2023 before the configuration was finally deemed safe by the ECLSS and Power Systems teams.

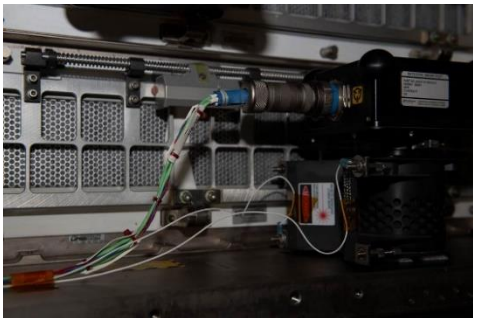

Figure 4. Smoke Detector & Wiring

B. Atmosphere Revitalization

1. Carbon Dioxide Removal Assembly (CDRA) Status

ASV 103 in the lab CDRA which feeds directly into the blower failed and stalled in mid travel starving the blower air intake. This happened during a half cycle transition so the blower was effectively tied to an evacuated adsorbent bed for several minutes. This resulted in failure of the blower likely due to air bearing damage. The air selector valve and blower were subsequently replaced and lab CDRA functionality was recovered. As part of the blower replacement effort NASA directed the use of a used Four Bed CO2 (FBCO2) blower, which happened to be a copy of a Honeywell CDRA blower. This blower had been in use in the FBCO2 until earlier in 2023 and was kept on board as a potential spare blower. The blower had been subjected to a mis-configuration event during ground testing which subjected it to an abnormally high current but the blower was still functional. Unfortunately the blower failed to start when installed in the lab CDRA and connected to a Honeywell motor controller. The difference in functionality (functional in FBCO2 but not in CDRA) is likely due to Hall Effect sensor damage incurred during the ground testing event. The FBCO2 motor controller did not rely on Hall Effect sensors for motor operation and the Honeywell motor controller needed to have functional Hall Effect sensors. So the Hall Effect sensor damage went un noticed until installed in the lab CDRA. A second blower replacement was performed on the lab CDRA using an unused spare blower from an existing on orbit blower/precooler ORU, which did successfully recover the lab CDRA operation. The damaged blowers will be repaired later this year for continued use as spare blowers.

System differential pressure has shown a marked increase in both CDRA units during 2023. Both CDRAs are operating with the latest -5 bed ORU design. The Node 3 beds were installed in 2015 and have operated since with the need of a bed cleaning. The Lab CDRA was updated to the -5 bed design in 2017. A subsequent bed replacement and bed cleaning due to dust buildup was performed in 2021 on a single bed. The latest differential pressure rise is indicative of a second bed cleaning needed (not the same bed that was cleaned in 2021). Note that the lab CDRA has significantly more run time on the -5 beds recently than the Node 3 CDRA.

2. Major Constituent Analyzer (MCA) Status

The MCAs are running under intermittent operations and ran approximately 18% (~64 days) of the year. Node 3 MCA was the primary and sole operating MCA during 2023. Node 3 MCA had received Error Code 63: ‘Plugged Line Pump Failure’ at the end of 2022. Troubleshooting attempts during the year determined that the error was most likely due to a partial blockage in the Sample Distribution Assembly (ORU 06). To fix this, ORU 06 will need to be R&R’d. This activity remains in work. The Lab MCA had also failed in late 2022 due to a filament failure in ORU 02. In June of 2023, the Mass Spectrometer Assembly (ORU 02) was R&R’d. Upon activating the MCA, various error codes occurred making the Lab MCA unusable. After much troubleshooting, it was thought that there was an intermittent connection of the Interface CCA in the electronics assembly. The Interface CCA is responsible for communications between ORU 01 and ORU 02 and for the communications internal to ORU 02. As of January, this year, the Lab MCA is operational after the CCA cards were reseated. Two of the CCA cards, the Interface CCA and Filament Control CCA, were found to be loose.

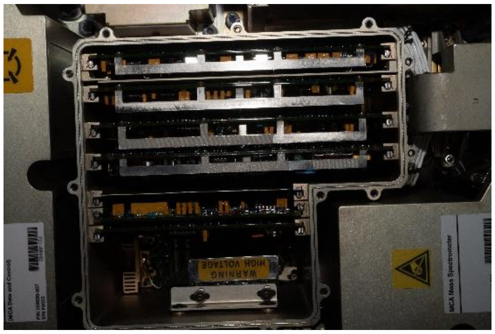

Figure 5. MCA Interface CCA

3. Lab Trace Contaminant Control System (TCCS) Anomaly - Loss of Function on Startup

On GMT 2023/136, the Lab Trace Contaminant Control System (TCCS) failed with a “Lab TCCS Loss of Function on Startup” error during the warmup phase following activation after a Lab CDRA Blower and valve R&R. The team reviewed failure signatures and performed ground troubleshooting and visual inspection of Lab TCCS rack cables by crew. Visual inspection reported no off-nominal configuration. The next nominal startup of Lab TCCS resulted in a recurrence of the “Lab TCCS Loss of Function on Startup” error, but was able to be recovered by going into Full Manual Control and overriding the fan, flow meter, and heaters on. Lab TCCS was restarted successfully and operated nominally until swapping back to Node 3 TCCS. Ground teams developed a new troubleshooting Flight Note to operate out of in case of another recurrence, which would further troubleshoot via utilization of a modified startup sequence from the original troubleshooting, and help to define a successful recovery procedure for future use. Teams also requested mirroring the manual override procedures on Node 3 TCCS to establish a baseline data trend for manual commanding on a nominal TCCS, and to understand how the fan, flowmeter, and heaters performed compared to Lab TCCS in order to gain additional insight to root cause of the error, which is suspected to either be the EIA or Blower. This mirrored commanding was completed on GMT 2023/341 and review of the data dump did not provide conclusion on the cause of the original fault, but the data will be saved as a reference for comparison in case of a recurrence. Lab TCCS was last restarted on GMT 2023/333, which was completed without a second recurrence of “Lab TCCS Loss of Function on Startup” error, and continues to operate nominally. Investigation of the faults is ongoing until more data can be collected.

C. Water Recovery Management

1. Urine Transfer System (UTS) Solenoid Valve Cycling Issue

In January, the UTS saw pressure responses through the P002 pressure sensor when WHC is not in use. Nominal response from UTS when the P002 detects a pressure higher than 0.02 psig is to open Solenoid Valve 03 (SV03) which will open the path (from WHC) to the Urine Processor Assembly Wastewater Storage Tank Assembly. The P002 is located in the flow path of WHC and will only detect pressures from WHC. Telemetry showed during offloading of EDVs through UTS, the pressure on the P002 showed responses when it was not nominally expected and the UTS controller responded by opening SV03. This unexpected P002 pressure will cause any other function of UTS to pause, due to the UTS controller responding accordingly to a WHC use, as if WHC was actually used. However, review of telemetry, showed no WHC use were performed. This was an indication that SV03 was open when it should be in the close position, but it could be cracked open a minimal amount for the P002 to detect pressure from other sources. Since the pressure responses from the offloads were small, the workaround was to slightly increase the pressure detection limit of 0.02 incrementally until P002 stops responding to these marginal pressures. Currently the pressure detection limit is at 0.03 psig and no reports of any false WHC use has been observed since the change was implemented.

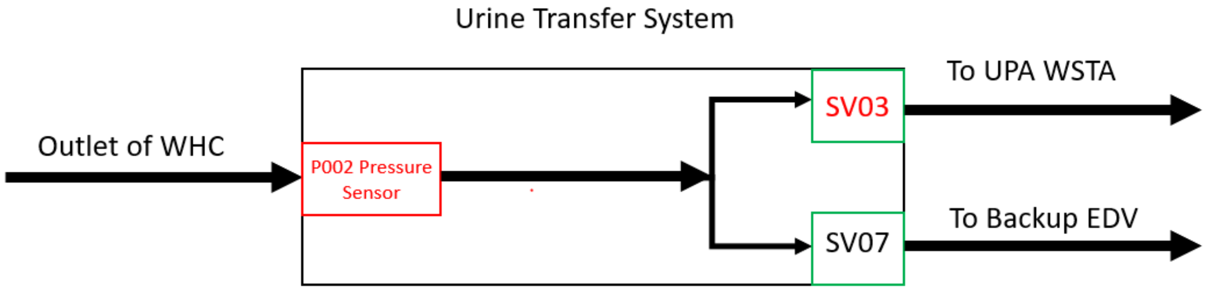

Figure 6. UTS Schematic

2. Multifiltration Bed use past 2nd ionic breakthrough

The Multifiltration Bed SN 11 is the second Multifiltration Bed with the new Ambersorb material. SN 11 saw its first ionic breakthrough in October after ~7000 lbs throughput. Comparing it to the first MF Bed SN 07, the first ionic breakthrough occurred earlier than SN 11 by ~1500 lbs throughput. However, MF Bed SN 11, after its first ionic breakthrough, saw much more throughput than SN 07. MF Bed SN 11 saw total throughput of ~24,000 lbs before telemetry suggested that the third ionic breakthrough was occurring. MF Bed SN 11 was removed and replaced with its spare, MF Bed SN 8.

3. Water Storage System (WSS) Solenoid Valve Stuck Open

The WSS saw two unplanned instances of Potable Tank 1 transferring out to other Potable Tanks. The data suggested that the Solenoid valve for Potable Tank 1 (SV10) was closed when commanding the other Potable Tank transfers, but the data also saw Potable Tank 1 quantity increase when trying to transfer to and from the other potable tanks.

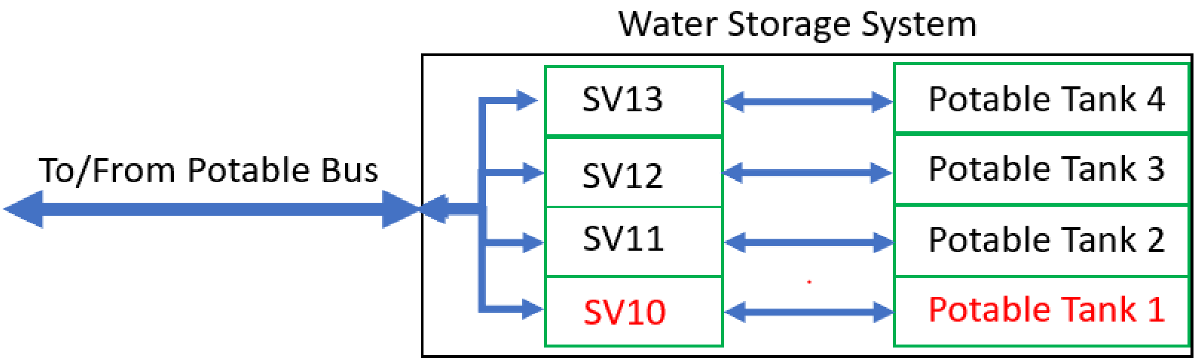

Figure 7. Simplefied Schematic of the Water Storage System

By design, the valve position status for SV10 shows only the commanded status and not the actual open or close position of the solenoid valve so the physical position cannot be determined by telemetry. Several troubleshooting steps were developed to see if SV10 was stuck and to dislodge it from its stuck position and also steps to determine if it was a hardware or software issue. After a power cycle of the WSS, the valves started behaving nominally and test transfers were performed to verify that SV10 is operating nominally. No further recurrences have occurred and WSS continues to operate nominally.

4. Product Water Sampling for Ion Exchange Bed Life Analysis

In the effort to determine the life of the Ion Exchange Bed in the Water Processor Assembly, samples were taken from the product water side of WPA to determine the levels of Iodine imparted by the IX bed resin. The original life of the IX bed was ~3 years, determined by ground test data, but the ground test was running in a different configuration than how WPA is currently operated on ISS. To better understand the life of the IX Bed on ISS, samples were taken to see if the IX bed is still imparting adequate levels of iodine into the product water of WPA. The first sample was taken at the end of 2022 and flown down and determined that the IX bed still imparted adequate amounts of Iodine to the product water. Since it has been a year since the last sample was taken, another sample was taken and flown down. Pending test results, the current IX Bed will continue to operate until the iodine levels in the product water are lower than required or breakthrough of the IX Bed.

5. Oxygen Generation Assembly (OGA):

The ISS Oxygen Generation Assembly (OGA) has been operating for over 16 years and is currently installed in Lab. As of December 31, 2023, the ISS OGA has produced a total of 28,328 lbm of oxygen and 3,541 lbm of hydrogen since initial activation in 2007. The OGS rack was moved from Node 3 to Lab in September 2022 to enable co-location and integration of exploration demonstration air string systems including future (2025) upgrades planned for an Advanced OGA (AOGA) that will be more reliable and maintainable while requiring less sparing. In 2025, ISS crew will reconfigure the OGS rack by replacement of the OGA's Hydrogen Dome Assembly ORU with the AOGA's Oxygen Hydrogen Domes Assembly (OHDA) and will be operated on-orbit until the end of ISS.Spare OGA Hydrogen Dome ORUs will remain prepositioned on ISS to revert back to the OGA configuration within two crew days should AOGA OHDA fail prior to AOGA spares becoming prepositioned on ISS

No OGA failures or new issues have evolved in the past year. OGA team continues to trend known issues (detailed in 2023 ICES paper)[13] associated with pump lockups andan out of specification recirculation loop pressure control band.

a. Spare Pump Lockups

In March 2021 crew attempted to replace a legacy design positive displacement gear Pump ORU to begin getting run time on an updated pump of similar design that included new wear couple materials, increased bearing thrust surface, journal bearing length change and additional hydrostatic bearing feeds to improve operating and cycle life. Both prepositioned on-orbit new design Pump ORU spares failed to spin-up upon initial activations. Crew reinstalled old design Pump ORU SN1 to successfully regain OGA operation.
After two ground spare Pump ORUs, S/N 2 (5.8 years in stowage) and S/N 6 (newly built), were both spin checked and expedited for launch to ISS in April 2021, the old design pump S/N 1 was replaced with a new design Pump ORU S/N 6 and OGA was successfully reactivated in May 2021.

Test Teardown and Evaluations (TT&E) and failure investigation performed on two failed pumps, S/Ns 3 and 5, determined that nickel phosphate and oxide precipitation deposited on the pump's gears and housing, causing gear lockup after 10 years of stagnant stowage. The deposits originated from degradation and corrosion of the water filled spare ORU's inlet and outlet Quick Disconnects' (QD) internal electroless nickel coating. Recurrence control is to use new QDs for all future refurbished Pump ORU QDs that do not have internal electroless nickel coatings to mitigate any precipitation induced pump lockups in the future. Pump ORU S/N 3 was successfully refurbished and launched on SpX-30 in March 2024. SN 5 refurbishment is in-work and is planned to be completed in May of 2024 and will remain as a LON spare launched to ISS in mid-2024 (becomes a spare without internal electroless nickel coatings in QDs). SN 1 Pump ORU (old pump design installed for over 10 years with hard-failed low differential pressure sensor) was returned on SpX-30 in April 2024 for TT&E and failure investigation.
In April 2022 crew collected and returned for analysis a 20 ml water sample from spare Pump ORU S/N 2. In May 2022 spare Pump ORU S/N 2 was also powered outside of the OGS rack and was successfully rotated while performing a 10 L water flush. The 10 L flush effluent was returned for chemical and particulate analysis. The 20 mL sample and 10 L powered flush effluent analysis did not show any significant particulates of interest (Ni or P containing). Analysis of the dissolved chemicals was used to evaluate current status of S/N 2 and to assess the possibility of minimizing precipitate formation over time using a periodic flush for future preventative maintenance until 2024 when newly refurbished spares arrive. Analysis results indicate power flushing spare pumps likely have limited value (not clearing precipitate). The best method to keep spares viable is to install them into the OGA.

NASA program directed removal of Pump ORU SN 2 (removed in May of 2023 after 6 months of operation) and installed prepositioned spare SN 6 into OGA to maintain viability of Pump ORUs due to susceptibility of pump gear lock-up due to precipitate formation.

b. Recirculation Loop Pressure

Water recirculation loop pressure is maintained by a hydrogen Back Pressure Regulator (BPR) located in the Hydrogen Dome ORU downstream of the Rotary Separator Accumulator (RSA) within the hydrogen vent line. Since early 2020

(S/N 3 H2 Dome ORU installed), there were several OGA fast shutdowns due to triggering a low pressure fault limit within the recirculation loop after transitioning into Standby. In 2020, ETHOS commanded an OGA software override to implement one minute standby holds to evacuate the dome every 100 minutes while in process (was 5 minutes) to reduce time in standby and enable OGA reactivation.

In 2021, the recirculation loop and oxygen outlet low pressure shutdown limits were lowered to avoid nuisance shutdowns while not violating any hazard controls nor flight rules which enabled continued OGA operations with the suspected BPR performance issues. A similar change in the regulated recirculation loop pressure signature in standby has also been observed with the currently installed S/N 4 H2 Dome ORU (installed in Oct 2021 to present due to S/N 3 H2 ORU cell stack failure).

After S/N 3 H2 Dome ORU was returned to ground in Jan 2022, the suspect BPR was removed for TT&E and failure investigation. Both the suspect and a nominally performing BPRs were CT-scanned and performance tested. A stepwise teardown of S/N 3 H2 ORU's BPR (S/N 006) was completed in April 2022. Corrosion residue was found in the tightly toleranced poppet / guide seat area of S/N 006 BPR. Root cause for back pressure regulator performance band increase was corrosion between tight-toleranced poppet stem and guide caused by improper passivation of metallics. The team has made changes to BPR manufacturing processes to ensure proper passivation of metallics and is currently procuring new configuration back pressure regulator components that have the proper passivation invoked for future OGA spare H2 ORU refurbishments and the AOGA OHDA's RSA Dome Assembly.

6. Advanced Oxygen Generation Assembly (AOGA):

The Advanced O2 Generation Assembly (AOGA) program is a partial redesign of the ISS OGA to support future long duration exploration missions to the moon and beyond. As part of the redesign effort, NASA program has a stated goal of reducing total weight and volume of the assembly and its spares through enhancing design maintainability. Program also wants to operate AOGA on ISS for three years minimum beginning in 2025.

AOGA is an upgrade to the OGA since system incorporates a new design cell stack (same maximum oxygen 20.4 lbm/day production rate as OGA), increases cell stack life by minimizing membrane thinning, allows for additional system maintenance, and incorporates manual dormancy nitrogen purge and deionized water flush of the recirculation loop to allow the system to be shut down for up to one year without biofouling and as a preventative maintenance feature to periodically reduce build-up of concentrating contaminants.

For ISS demonstration, the AOGA is controlled by the existing OGA Process Controller with its original software and firmware. Commanded software overrides will be utilized for unique AOGA system operation parameters and fault limits. The AOGA will be reusing most of the hardware that is in the OGA system but will be replacing the OGA Hydrogen Dome ORU (includes a fracture containment dome that is not removeable on-orbit rendering the cell stack, Rotary Separator/Accumulator (RSA), valves, pressure and temperature sensors non-maintainable) with the AOGA maintainable Oxygen Hydrogen Domes Assembly (OHDA) to enable significant reductions in spares mass and volume.

Figure 8. AOGA as would be installed in Node 3

The OHDA contains two smaller domes (cell stack and RSA) that are removable on-orbit for replacement of failed components with spares. The new AOGA pressure sensors are now located external to the domes. The OGA RSA Differential Pressure (DP) sensors will be reused and remain located within the OHDA's RSA Dome Assembly.

The OGA recirculation loop ACTEX will be replaced within the OGS rack with the AOGA ReMediation Advanced DeIonization and Limited Life Optimization (ARMADILLO) Ion Exchange Bed which has lower pressure drop, depth filter, meets AOGA MDP, has redundant seals and is designed for a three year operational life given it contains about five times the volume of mixed ion exchange resin compared to the ACTEX. ARMADILLO CDR occured in February 2023.

A H2 Sensor Tech Demo (H2ST) containing four commercial hydrogen sensors is currently mounted onto the front of the OGS rack and will remain installed on OGS after AOGA is installed to gain at least three years of operation time. The H2ST is connected to OGA's oxygen outlet port and monitors the OGA's product oxygen for hydrogen and is located in series with the upstream legacy OGA H2 Sensor ORU (provides FDIR and hazard control), allowing comparisons of H2ST new sensors' performance over time. The H2ST's new commercial hydrogen sensors are checked for drift every 90 days using a pressurized container of 1% in air calibration gas. Sensor #3 failed with 0 mA output in July 2022 for unknown root cause and it is not feasible for crew to remove sensor and return to ground for failure investigation. The latest 90 day drift check occurred in November 2023. Slight upwards drift in all three sensor outputs was evident throughout 2022 and appears to be leveling off. Next drift check is planned to occur in March 2024.

The H2ST sensors do not need to be returned to ground for recalibration (OGA H2 Sensor ORU is life limited to 201 powered-on days and must be recalibrated on ground), are not sensitive to nitrogen, water moisture, nor exhibit any significant upwards drift of voltage output, unlike the current H2 Sensor ORU.

As of December 2023, the AOGA has completed CDR, gained Phase 2 Safety Review Panel approvals of both AOGS Integrated Hazard Reports and Maintenance Hazard Analyses, completed delta CDR and delta Phase 2 Safety Reviews and all drawings are released. AOGA components and subassemblies are currently being manufactured. OHDA top level assembly planned to begin in 2024 and testing completed in 2025.

D. Conclusions

This paper documents ECLS system events encountered mostly between January and December 2023. with a few events dating back to previous years not documented in systems status papers. Twenty-four years strong, and the ISS National Laboratory still stands as one of the greatest, if not the greatest, international engineering achievement. The future is here. Artemis I's innaugeral launch of the Orion Capsule and NASA's newest heavy launch vehicle, the Space Launch System Rocket (SLS) has taken place, and Artemis II is on the horizon. Man will return to the moon for the first time since the Apollo program, inspiring a new generation of scientists, engineers, and astronauts.

Thre has been much churn in the commercial sector. There are still three different Commercial LEO Destination teams competing to put commercial elements in orbit. Blue Origin, Voyager, and Axiom all intend to pick up the ball from ISS with their Orbital Reef, Starlab, and Axiom Stations respectively. Northrop Grumman ended its plans for a commercial station, instead joining the Starlab team. Lockheed also left the Starlab team, with Airbus becoming a partner. Orbital Reef and Starlab are envisioned as free flyers, while the Axiom Station's life begins as an expansion of the ISS. Will one or multiple teams succeed, and become the easy access laboratory that ISS provides today? Will a deorbit vehicle be ready to safely dispose of the ISS should the baton be passed on to waiting CLD teams? There are a lot of questions that remain to be answered over the next few years. If history is any indicator, new programs will take time, and delays are inevitable. It is this author's opinion that the the ISS still has a bright future, and offers the one platform that guarantees access to low earth orbit.

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