Status of the Advanced Oxygen Generation Assembly

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Future Exploration missions will require an Oxygen Generation Assembly (OGA) to electrolyze water to supply oxygen for crew metabolic consumption. The system design will be based on the International Space Station (ISS) OGA but with added improvements based on lessons learned during ISS operations and technological advances since the original OGA was designed and built. The goal of these improvements will be to reduce spares mass and crew maintenance time while increasing reliability. Over the past year, the team has performed additional design reviews, testing and analysis in an effort to optimize upgrade efforts and achieve the best value that meets Exploration mission requirements. Upgrades that will be incorporated include: redesign of the electrolysis cell stack, redesign of the hydrogen dome, replacement of the hydrogen sensors, redesign of the recirculation loop deionizing bed, and incorporation of recirculation loop nitrogen purging and water flushing. The ISS OGA will be upgraded to an Advanced OGA (AOGA) configuration and its operation demonstrated in a relevant flight environment.

Nomenclature

ACTEX	=	Activated Carbon Ion Exchange
ARMADILLO	=	AOGA ReMediation, Advanced DeIonization and Limited Life Optimization
AOGA	=	Advanced Oxygen Generation Assembly
CDR	=	Critical Design Review
CT	=	Computed Tomography
CWC-I	=	Contingency Water Container – Iodine
DMSD	=	dimethylsilanediol

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DMSO2	=	dimethylsulfone
dP	=	Delta Pressure
H2ST	=	Hydrogen Sensor Technology Demonstration
ISS	=	International Space Station
MDP	=	Maximum Design Pressure
MEA	=	Membrane Electrode Assembly
OGA	=	Oxygen Generation Assembly
OGS	=	Oxygen Generation System
OHDA	=	Oxygen Hydrogen Dome Assembly
ORU	=	Orbital Replacement Unit
PSM	=	Power Supply Module
QD	=	Quick Disconnect
RSA	=	Rotary Separator Accumulator
SN	=	Serial Number
TT&E	=	Test, Teardown, and Evaluation

I. Introduction

FUTURE long duration deep space missions will require a regenerative life support system, as an open loop system will not be practical for a multi-year mission. A key part of the regenerative life support system will be an Advanced Oxygen Generation Assembly (AOGA) to supply oxygen for crew metabolic consumption. A deep space mission is envisioned to have a crew of 4 and a duration of 3 years. The system design will be based on the International Space Station (ISS) Oxygen Generation Assembly (OGA) but with added improvements based on lessons learned during ISS operations and technological advances made since the original OGA was designed and built. These improvements will reduce spares mass and crew maintenance time, while increasing reliability. The design team has investigated the feasibility of the proposed upgrades by performing trade studies, ground tests, and analyses. The ISS OGA will be modified to an Exploration based AOGA configuration and its operation demonstrated. The current status of the redesign effort will be presented in this paper.

II. ISS OGA Description

The ISS OGA is shown in Figure 1 and the simplified schematic is shown in Figure 2. The OGA consists of the following nine Orbital Replacement Units (ORUs): Water, Inlet Deionizing Bed, Hydrogen, Recirculation Pump, Nitrogen Purge, Oxygen Outlet, Hydrogen Sensor, Power Supply Module (PSM), and Process Controller. Feed water from the ISS potable water bus enters the OGA through the Water ORU and flows through an Inlet Deionizing Bed, which serves as an iodine remover and as a coalescer for any oxygen gas bubbles that may be present in the feedwater. If gas bubbles are detected by the gas sensor downstream of the deionizing bed, the feedwater is rejected by a three-way valve to the wastewater bus. This prevents any oxygen that may be present in the feedwater from mixing with the hydrogen in the Rotary Separator Accumulator (RSA). The wastewater interface includes a check valve to prevent backflow of wastewater into the OGA and Microbial Check Valve to prevent microorganisms in the wastewater from contaminating the feedwater. Water is electrolyzed by the cathode feed cell stack to produce oxygen and hydrogen. The RSA separates the cathode side product gaseous hydrogen from the water. The Hydrogen ORU consists of a dome which surrounds the components which contain hydrogen (cell stack, RSA, sensors, valves, etc.). The hydrogen dome provides a multiple leakage barrier protection in the event of a failure. The hydrogen dome is maintained at low pressure by periodically venting to space vacuum. The water is recirculated by the positive displacement pump. The pump contains an integral relief valve to protect against an unintentional deadhead condition. Downstream of the pump is an Activated Carbon Ion Exchange (ACTEX) filter. The ACTEX is a mixed resin bed deionizer, which removes fluoride generated from the cell stack and other contaminants. The heat exchanger removes

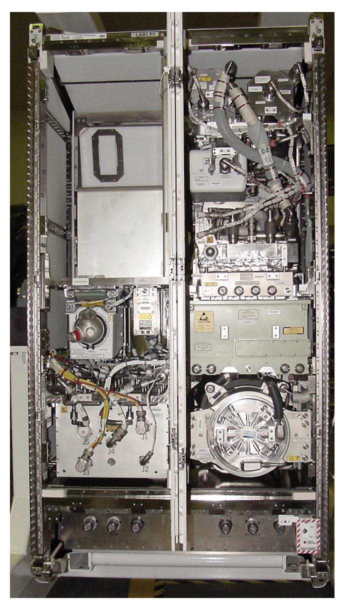

Figure 1. ISS OGA

heat generated by the cell stack, RSA and pump. The separated hydrogen gas from the RSA is sent either to the Sabatier Carbon Dioxide Reduction Assembly or optionally out to space through the vacuum vent. Oxygen produced by the cell stack passes through the Oxygen Outlet ORU containing a water absorber and heater, which protects the downstream hydrogen sensors from liquid water. The Hydrogen Sensor ORU monitors the product oxygen for the presence of hydrogen, which would indicate leakage within the cell stack and signal the OGA Process Controller to quickly shut down the OGA. The product oxygen is then vented directly into the cabin. The Nitrogen Purge ORU stores a pressurized volume of nitrogen gas from the ISS distribution line to purge the OGA cell stack anode oxygen compartments upon shutdown and startup. Nitrogen is utilized to mitigate the safety hazards associated with the mixing of oxygen and hydrogen within the cell stack or the dome. The nitrogen can also be used to inert the dome environment during extended periods of non-operation. The Process Controller ORU is responsible for OGA system command and control and communication with the ISS. Sensors (pressure, delta pressure, temperature, speed, gas, conductivity, voltage, current, and hydrogen) are used for system operational control and fault detection and isolation. The PSM ORU provides power to the OGA electrolysis cell stack. The PSM ORU provides a variable range of 10-46.9 amps (A) of current to the OGA cell stack during Process mode and 1.0 A during Standby mode.

The ISS OGA generates oxygen at a selectable rate, up to 20.4 lb/day (9.25 kg/day), at 46.9 A PSM current, 100%

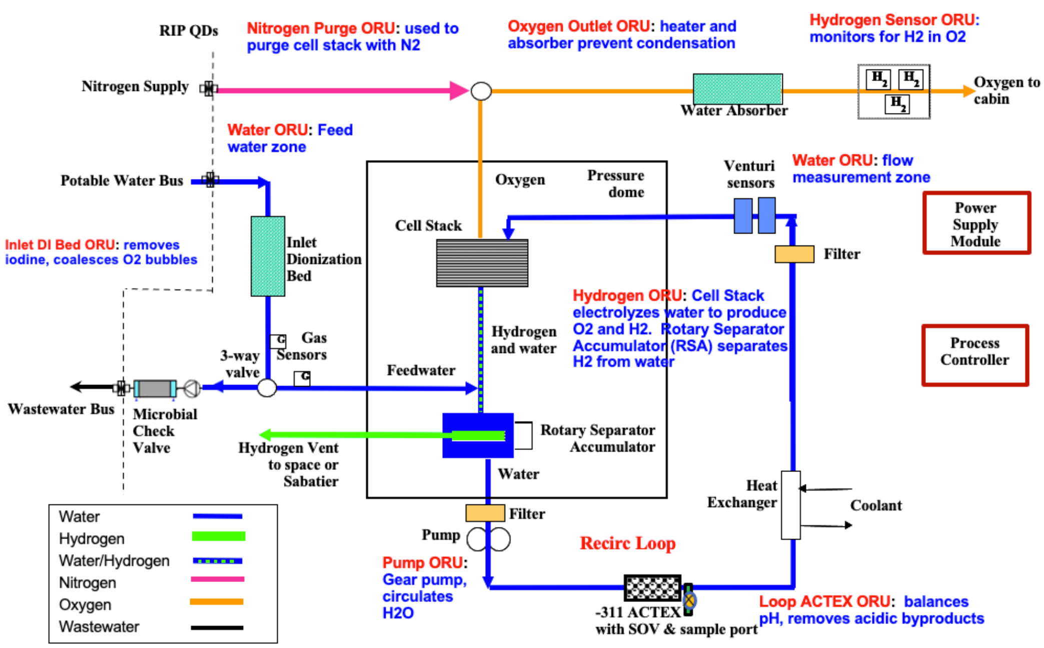

Figure 2. ISS OGA Simplified Schematic

production rate. This can support 10.88 crew (assumes 1.874 lb [0.85 kg] oxygen/day/crew metabolic rate). Most of the OGA ORUs are run to failure except for the calibration life limited Hydrogen Sensor ORU (201 days), as well as the Inlet DI Bed (~8 years, depending on total water throughput) and ACTEX (675 days).

III. ISS OGA Current Status

The ISS OGA has been operating for over 15 years and is currently installed in the US Lab. As of March 15, 2023, the OGA has produced a total of 26,242 lbm (11,903 kg) of oxygen and 3,280 lbm (1,488 kg) of hydrogen since initial activation in 2007. The currently installed OGA electrolysis cell stack (installed on October 21, 2021) has accumulated a total operating time of 12,062 hours. The OGS rack was moved from Node 3 to the US Lab in September 2022 to enable co-location and integration of Exploration demonstration air string systems. No new issues have developed with the OGA in the past year. However, progress has been made with previous issues associated with pump lockups, low recirculation loop pressure, hydrogen sensor output voltage off-scale high, cell stack low voltage, nitrogen purge valve leakage and partially mated quick disconnects (QD's). Progress in 2022 for resolving these on-going OGA issues will be described below.

A. Pump Lockup

Past investigative work on pump lockups in 2021 are described in Reference 1. At that time, new spare pumps serial number (SN) 3 and 4 to rotate when installed in OGA, and SN5 failed to rotate during ground testing. As a result of several Test Teardown and Evaluations (TT&E's), the root cause of the pump lockups experienced in 2021 is now understood. Over a period of years, nickel phosphate precipitation forms on the pump gears (which have tight clearances) while in storage, preventing rotation. Green precipitation was discovered on the gears and passages of disassembled pumps, as seen in Figure 3. The green line is at the interface of a gear tooth to the side wall, essentially locking the gear in place. This precipitation was sufficient to prevent rotation of the pump gears, given the low torque rating of the pump motor. The source of the precipitation is the NiFluor coating used on the internal surfaces of the pump quick disconnects QD's that act as a lubricant.

Figure 3. Green Precipitation in Pump SN 5

In April 2022, the crew collected and returned for analysis a 20 ml water sample from spare Pump ORU SN 2. In May 2022, this pump was powered outside of the OGA system and was successfully rotated while performing a 10 L water flush. The 10 L flush effluent was returned for chemical and particulate analysis. Analysis results indicate powered flushing of spare pumps has limited value (not clearing building precipitate). The best method to keep on-orbit pump ORU spares viable is to install them into the OGA for extended durations. The on-orbit pumps (SN 1, 2, 6, 7) are subject to lockup, since they contain QD's that have the suspect coating. It is believed that SN 6 has a low risk of locking up, due to it being continuously operational from 2021-2023. SN 7 is believed to also have a low risk of locking up in the near term, due to the limited time it has been in storage. SN 2 has the highest risk of locking up, due to its extended time in storage. SN 1 is a considered degraded spare, (previously installed in OGA from 2005 to 2021). It is assumed that the coating in SN 1's QDs is no longer present.

Because of the risk of lockup of new spare pump SN 2, SN 6 was removed from OGA, and SN 2 was installed on May 2, 2023. It started up without issue and continues to operate. As shown in Figure 4, pump SN 2 has a higher motor current than SN 6 (blue, 0.45 vs. 0.30 A) and a higher temperature (red, 135 vs. 105 F, 57 vs. 41 C). The high

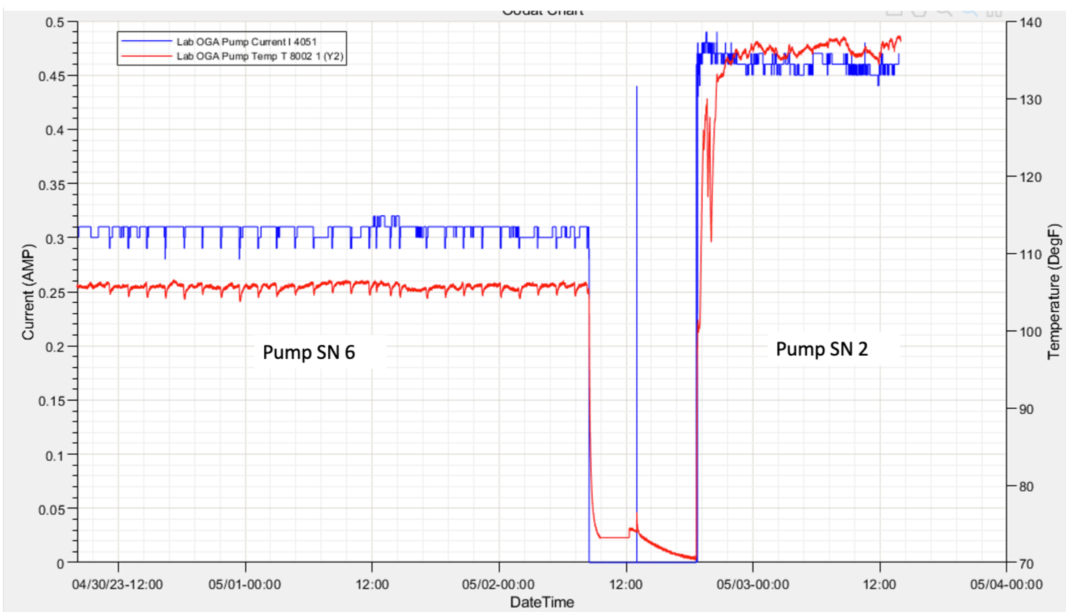

Figure 4. Pump SN 6 and SN 2 Current (blue) and Temperature (red)

shutdown limit for pump current is 0.9 A. Pump SN 2 provides a slightly higher flow rate than SN 6 at the same speed (536 vs. 518 lb/hr, 243 vs. 235 kg/hr). It is theorized that pump SN 2 may have tighter gear tolerances than SN 6, resulting in a slightly higher flow rate, current and temperature. Finally, it was noted that the pump's delta pressure (DP) sensor has a -1.4 psid (72 mmHg) offset, which is within the sensor's accuracy specification. The OGA team will continue to monitor the pump's performance over time.

Failed pumps SN 3 and 5 were returned to the vendor for refurbishment and installation of new QD's that do not have the NiFluor coating. As such, these refurbished pumps should not be susceptible to lockup in the future. These are expected to be delivered in early 2024.

B. Low Recirculation Loop Pressure

Nominally, the water recirculation loop pressure should be approximately 24 psia (165,474 Pa) while in Standby and Process. The pressure is maintained by the hydrogen back pressure regulator, which is integral to the Hydrogen ORU (see Figure 2). The default software low limit shutdown value is 20.5 psia (141,343 Pa), to ensure the cell stack hydrogen pressure is maintained above the oxygen pressure so that cross cell leakage can be detected via the oxygen outlet pressure sensors and hydrogen sensors. Past issues with low recirculation loop pressure are described in Reference 1. While Hydrogen ORU SN 3 was installed (2016 – 2021), the recirculation loop pressure was degrading over time, causing a shutdown. The low shutdown limit had been reduced to 19 psia (131,000 Pa) to allow system operation to continue. The current Hydrogen ORU SN 4 was installed on October 20, 2021. The recirculation loop

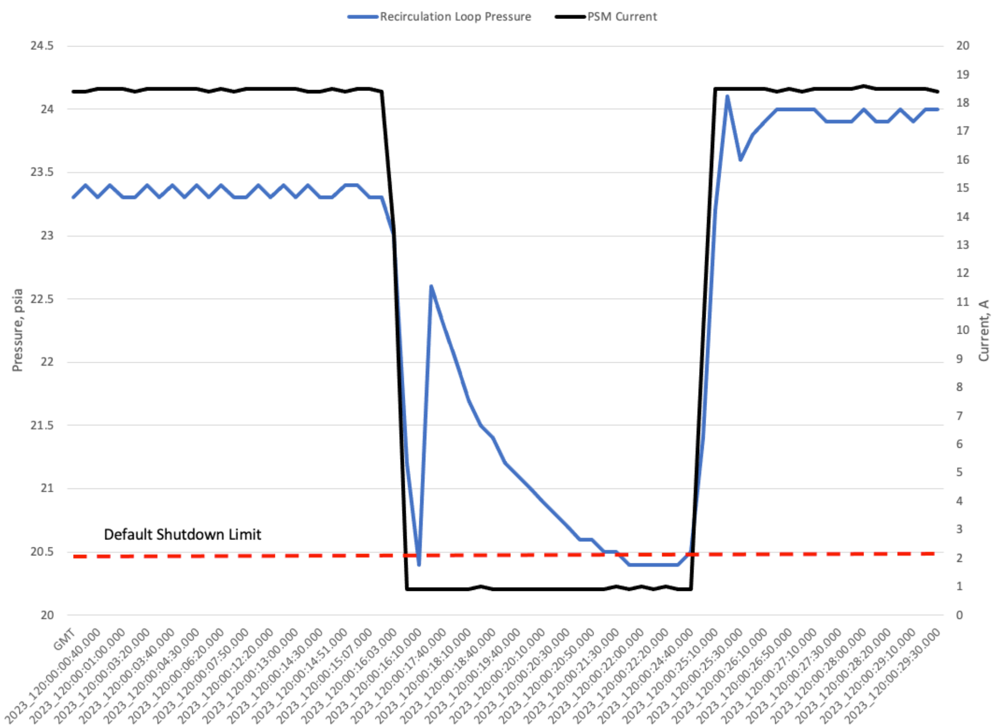

Figure 5. Recirculation Loop Pressure Process/Standby/Process

pressure has been consistently low with Hydrogen ORU SN 4 installed. Figure 5 shows a typical example of the recirculation loop pressure (shown in blue) dropping below the default low limit shutdown value when the system goes into Standby (current, shown in black, temporarily decreases to 1 A) every 100 minutes.

After Hydrogen ORU SN 3 was returned to the ground, the back pressure regulator was removed and has undergone performance testing, CT-scan, and a TT&E to determine the cause of the poor performance. Upon teardown, condensation and rust have been found in the parts that are wetted with hydrogen during operation. Condensation can be expected since the hydrogen gas is saturated with water when leaving the RSA, but the rust is concerning. The rust that was found is likely the cause of the erratic regulation seen in operation, interfering with the poppet operation. This has driven changes to the passivation method for the metal parts for AOGA back pressure regulators to help prevent this from happening in the future.

C. Hydrogen Sensor Output

The Hydrogen Sensor ORU detects hydrogen within the oxygen outlet stream. The controller will shut down OGA if 1% H2/O2 (¼ of the lower flammability limit) is detected, to prevent a hazard from occurring. Only two of three sensor dies are required to be operational to consider the ORU as a valid hazard control. The ORU has an installed life limit of 201 days and then it is replaced with a spare and returned to ground for refurbishment. In June 2022, Hydrogen Sensor ORU SN 1004 output in one of three hydrogen sensor semiconductor die spiked off-scale high (-1 sensor) and was inhibited as allowed by flight rule to enable continued OGA system operation. Hydrogen sensors have previously gone off scale high unexpectedly in 2014, 2015, 2016, 2018, and 2021 (corresponding to SN 1014, 1017, 1008, 1005, 1019).

In August 2022, OGA went to fast shutdown due to a power feed loss. Upon reactivation the Hydrogen Sensor ORU's -1 sensor voltage output was no longer off-scale high and was back in family with the other two sensors. The OGA team determined that likely cause was recovery from clearing a latched fault within the ORU's sensor board memory register after power reset. Hydrogen Sensor ORU SN 1004 was replaced in October 2022 and returned to the ground for recalibration and future relaunch.

D. Cell Stack Low Voltage

The low cell voltage failure of Hydrogen ORU SN 3 in 2021 is described in Reference 1. Cell 1's voltage in Standby continued to trend downwards out of family, indicating possible membrane thinning and a partial short. This ORU was returned to the ground in 2022. A TT&E of the cell stack is planned for 2023. The TT&E of the cell stack in Hydrogen ORU SN 3 will be similar to what has been done with SN 2. Steps will include: visually inspecting the cell stack exterior for anomalies, disassembling the cell stack, visual inspection of the cell membranes for pinhole leaks, debris and other anomalies, cross sectioning of the membrane to determine the degree of thinning, and analyzing the membrane material for contamination.

E. Nitrogen Leakage

While Nitrogen Purge ORU SN 1 was installed, it experienced leakage issues as described in Reference 1. Starting in December 2021, the ORU was unable to maintain a pressure of 76 psia (482,633 Pa) within its storage tank. This required the system to repressurize its storage tank every 5 hours. The ORU was replaced with SN 2 on February 28, 2022. Nitrogen Purge ORU SN 2 continues to operate nominally, with no leakage evident. Nitrogen Purge ORU SN 1 was returned to the ground in August 2022 for a TT&E to determine the root cause of the leakage and corrective action. This will occur in 2023. The 3-way valve in the ORU is suspected as having contamination in its valve seat area or wear of the valve seat, which would allow nitrogen leakage out to the cabin. This same ORU and valve will be used for AOGA, so it is important to understand the root cause of the valve leakage.

F. Partial Mating of ¾ inch QD

The crew was not able to fully mate the SN 3 and 4 Hydrogen ORU ¾ inch male QD to the rack flexhose ¾ inch female QD in 2016 and 2021. The QD pairs were about a quarter turn from being fully mated. In this configuration only one of two redundant seals is engaged. Also, the same partially mated QD issue was experienced when connecting the Contingency Regen Fluid Hoses (CRFH) Water Adapters ¾ inch male QD to the OGS rack flexhose ¾ inch female QD to perform recirculation loop flushes to remove built-up contaminants.

The Hydrogen ORU QD to rack hose QD connection was index marked and Kapton taped to minimize risk of QDs backing off given only one of the two redundant seals against external leakage is engaged. The OGA team closely monitors on-orbit telemetry data for RSA water fill rate and recirculation loop pressure to ensure no leakage is evident. One spare rack hose is prepositioned on-orbit and will be installed and rerouted for AOGA installation in early 2025.

Figure 6. Partially mated QD Pair

The only off-nominal finding was a C-clip (confirmed to be from a 3/4 inch QD) found by CT-scans within the returned SN 1001 CRFH Adapter's 3/4 inch male QD causing the inability to fully mate with a test QD, as shown in Figure 6. Normally, the female QD (top, with dark knurled sleeve) is threaded onto a male QD (bottom) and the female QD sleeve is rotated by hand until a notch in the female QD's sleeve engages with the tang on the male QD. This indicates a successful mate, with 2 seals engaged. However, during the ground test, the female QD (top) could not be fully rotated and engaged with the male QD (bottom). No other off-nominal findings were identified to date after extensive evaluations of all available ¾ inch QDs in ground inventory, including: borescope inspections to ensure no missing C-clips, CT-scans of spare Hydrogen ORU ¾ inch QD's, and a CT-scan of the CRFH adapter returned from ISS on SpX-25.

The failure investigation is on hold until the currently installed rack hose is removed and returned to ground for TT&E in 2025.

IV. AOGA Upgrades

Previous AOGA design and analysis work is described in References 1, 2, and 3. The AOGA design will focus on enabling component-level maintenance and modifying the existing cell stack design to improve both shelf and operating life and enabling dormancy. A 2017 supportability study[5] determined that enabling component level maintenance of the dome's internal components, would result in an estimated 617 lb (280 kg) of spares mass savings

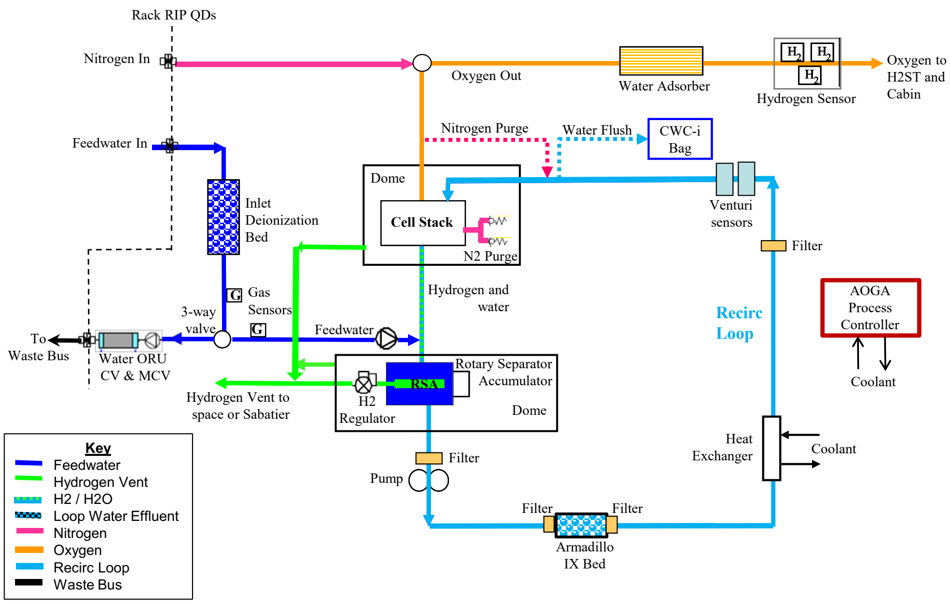

Figure 7. AOGA Schematic

for a 1,100 day exploration mission. The proposed AOGA schematic is shown in Figure 7 and the list of proposed upgrades is summarized in Table 1. The system design is similar to the OGA, with the notable differences being that the AOGA will incorporate a redesigned cell stack, two independent domes, new hydrogen sensors, redesigned ACTEX, and a manual nitrogen purge and water flush capability for the water recirculation loop (as denoted by the red and blue dotted lines in the figure). As previously mentioned in Reference 1, the obsolete systems electronics (Controller and PSM) should be redesigned for Exploration, but the Program has decided not to demonstrate upgraded electronics as part of the AOGA demonstration on ISS. The AOGA Critical Design Review (CDR) was conducted in November 2022. The review covered the design of the cell stack dome, RSA dome, new rack installation hardware. Separate component level CDR's were held for the new cell stack, dome pressure sensors, feedwater check valve, and back pressure regulator. An AOGA Phase II safety review was completed in February 2023. A delta-CDR is planned for July 2023 to cover the manual recirculation loop purge and flush hardware.

Table 1. AOGA Upgrades

Upgrade	Reason	Description
Redesign the cell stack	Implement corrective action based on the cell stack failure investigation to mitigate membrane thinning as well as implement current industry best-practices and standards	Provide better mechanical support for the cell membranes, replace the obsolete membrane with chemically stabilized Nafion
Replace the single dome with two domes	Reduce logistics resupply requirements	Crew will be able to access and maintain the cell stack, RSA and other components

Replace the hydrogen sensors	Reduce crew maintenance time, improve reliability, eliminate need for specialized purge tools	Replace hydrogen sensors with a more reliable technology that requires less crew intervention
Redesign the recirculation loop ACTEX	Increase installed life and reduce the delta pressure	The existing design is not optimal as it was not specifically designed for the OGA application
Manual recirculation loop purge and flush	Reduces contaminants within the AOGA recirculation loop that could be sent to Sabatier and cleans the system in preparation for dormancy	Purge hydrogen from the recirculation loop with nitrogen, then flush with potable water into a CWC-I bag or the ISS wastewater bus

A. Cell Stack Redesign

The legacy OGA cell stack design included non-chemically stabilized membranes, screens for membrane support, and a now obsolete Membrane Electrode Assembly (MEA) processing method.[1] A TT&E of failed cell stack SN 5 (installed in OGA 2010 – 2016) identified excessive thinning of the cell membranes as the root cause of the low cell voltage.[3, 5] The new AOGA cell stack design will incorporate design improvements to minimize membrane thinning, including: chemically stabilized membranes (reduce mass loss during operation), sintered metal membrane supports (increase surface contact area to better distribute the load on the membranes), additives to minimize chemical degradation, and new frame seals (minimize water loss). Another TT&E of failed cell stack SN 4 (installed 2016 – 2021) is scheduled for 2023, as described in Section III.

The AOGA cell stack CDR was held in July 2022, and development testing started afterwards. A single-cell was built and a 6-month endurance test was completed in September 2022. The test was further extended to October 2022 by another month. The endurance test confirmed that the new AOGA cell stack design delivered the expected performance, with nominal cell voltage (~1.7 V), resistance, polarization scan data, cross cell/external leakage, as well as minimal voltage degradation over time. Longer periods of testing will be needed to assess expected performance over the lifetime. Next, in mid 2023, challenge testing will be performed using single cells. The cells will be subjected to typical microbial and chemical contaminants found on ISS, and the effect on cell operation will be measured. Cycle testing of single cells will also be performed. The single cells will be subjected to thousands of Process/Standby and on/off cycles, that would be seen in flight, and the effect on cell operation will be measured. Bleed resistors are part of the OGA cell stack design and are included in the AOGA cell stack design. Bleed resistors reduce total cell stack voltage below 30 V after shutdown to eliminate a shock hazard when the crew needs to perform maintenance on the cell stack. A development test will be performed in 2023 using an AOGA short stack to determine whether these bleed resistors damage the new metal membrane supports. If so, the bleed resistors will need to be removed from the AOGA cell stack design and another method of handling the shock hazard will need to be developed.

Following these development tests, the flight AOGA 28-cell stack will start being built in late 2023. It should be noted that the cell stack vendor has experienced and continues to experience unexpected supply chain issues for cell stack components (including membranes, sinters, cell frames, and end plates) which could affect the upcoming cell stack delivery date.

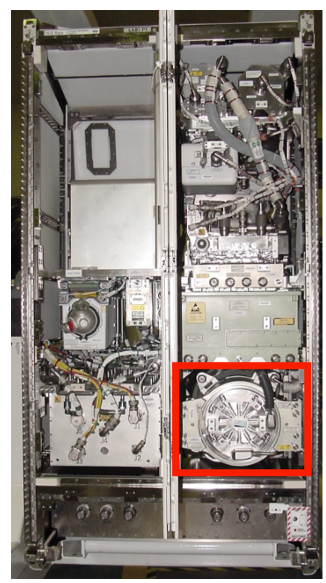

Figure 8. Hydrogen ORU Location

B. Dome Redesign

The legacy OGA design houses all of the hydrogen containing components (including the electrolysis cell stack, RSA, motor, 4 solenoid valves, 2 relief valves, a back pressure regulator, heater, relay, 9 pressure sensors, 5 temperature sensors, tubing, and wiring) within a single vacuum dome referred to as the Hydrogen ORU. The Hydrogen ORU is installed in the bottom right of the ISS OGS rack as shown in Figure 8. The Hydrogen ORU weighs ~300 lb (136 kg) in its launch configuration and has a high packing efficiency and tight tolerances when fitted together with the dome. This precludes maintenance of internal components by the crew. The failure of a single internal component requires replacement of the entire ORU. The Hydrogen ORU can only be maintained on the ground since the dome reinstallation requires specialized tooling, precision alignment and verification of specification leakages of the two independent seals to space vacuum to ensure proper operation on-orbit.

One of the requirements of an Exploration mission is a system design that allows for maintainability such that failure of a single component does not require removal and replacement of the whole ORU. Therefore, for AOGA, there will be two independent removable domes, one around the RSA and the other around the cell stack. A concept is shown in Figure 9, the left cylindrical dome is the RSA dome and the right cylindrical dome is the cell stack dome. The configuration is called the Oxygen Hydrogen Dome Assembly (OHDA). The OGA will be upgraded to the AOGA configuration by replacing the Hydrogen ORU, highlighted in Figure 8, with the OHDA. The OHDA design will allow the crew to remove each dome to replace internal components without the need for specialized tools or alignment fixtures. This component level maintenance approach (rather than ORU level maintenance) will reduce spares mass and volume. The cell stack will be housed in one removable dome with the pressure sensors and PSM interface on the outside for access. The RSA, hydrogen backpressure regulator and associated sensors will be housed in the other removable dome, with the pressure sensors mounted externally. In this configuration, the two-phase hydrogen/water line that goes from the cell stack to the RSA will not be enclosed within a dome. This line will contain dual seals at each fluid fitting (single fault tolerant). A waiver is being processed for approval that would accept single fault tolerance rather than the required two fault tolerance. A worst case leak, if both seals failed, at one of the QD's, would result in a flammable hydrogen volume of less than 10 in^3 (164 mL), which is considered a marginal hazard.

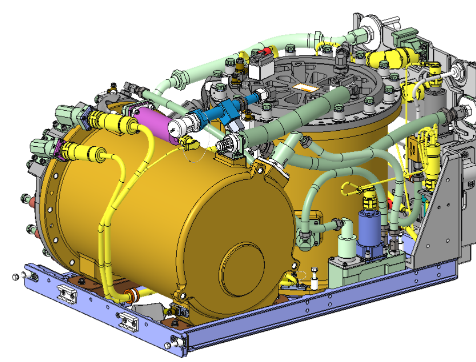

Figure 9. OHDA

The OHDA development required several development tests to mitigate some design risks. Among these tests are the cell stack harness test, dome seal test, RSA diaphragm test, and two-phase hose test.

On-orbit maintenance or replacement of the cell stack requires removing the cell stack dome by crew and reinstalling it. There is an internal electrical harness which goes from the cell stack to a dome feedthrough connector. This internal harness can't be seen by the crew during dome removal/installation, and could become damaged. The internal cell stack harness length and packaging must allow maintenance of the cell stack. A development test, using a clear dome, cell stack mockup and harness mockup, was performed to determine the optimum internal harness length and assembly method that would prevent damage.

Another development test involved the dome seals. Each dome is bolted to a baseplate. There are two seals at this interface to prevent leakage. When the system is in Standby or Shutdown, the dome internals are open to space vacuum. These seals prevent cabin air from escaping out into space. Removing and reinstalling the domes by the crew for maintenance multiple times could damage these critical seals. The dome seals development tests involved five different configurations: standard grooves, continuous dovetail grooves, standard grooves with additional lubricant for stiction, standard grooves with dovetail segments, and standard grooves with stretched seals. For pressurized testing (proof and leak), each configuration was tested with only the inner seal, only the outer seal, and both seals installed. The leak testing included testing at vacuum as well as MDP. There was also a 24 hour wait period after the leak test at MDP before a second leak test, followed by proof testing. All configurations passed these tests. The standard grooves offered the best leakage results but were not able to retain the seals. There were also concerns over the longevity of some of the other configurations, as well as the ease of installation. Therefore, it was determined to go with the half dovetail seal configuration in both grooves for both domes. This configuration should properly retain the seals and provide the necessary sealing.

A third development test involved the RSA diaphragm seal. One of the main functions of the RSA is to separate water from gaseous hydrogen. The RSA has a rubber diaphragm seal that is part of the moving hydrogen outlet valve. The diaphragm seal prevents hydrogen gas from escaping to the RSA dome when the outlet valve opens to allow hydrogen to flow towards the vent line. The RSA diaphragm for the legacy OGA could only withstand proof testing at 45 psi. As a result, a waiver was needed because this value is lower than the proof pressure requirement. A new AOGA design of the RSA diaphragm targets improving its proof pressure capability. This new design incorporates a fabric weave into the rubber and a redesign of the sealing edge to improve its structural strength. Development testing is currently underway to evaluate the proof, leakage, and cycling capabilities of the AOGA RSA diaphragm.

In order to allow maintenance of the two domes and their components, the two-phase hydrogen/water line connecting the cell stack to the RSA needed to be longer than the one in OGA, with a U-shaped bend for packaging within the OHDA frame. The additional length and bend pose a risk of increasing the two-phase pressure drop across the line and, hence, raising the operating pressure at the cell stack. Therefore, a development test is needed to evaluate the pressure drop in this line. This test is planned to be conducted in 2023 when the test hoses are ready.

Dome pressure sensors and valves are being procured from new vendors due to issues with the legacy vendors not being able to provide the components within cost and schedule constraints. The feedwater check valve allows feeding water to the system for electrolysis, while protecting the Waste-Water Bus (WWB) from the generated hydrogen that could flow back into it. Operating data from the current OGA system showed that some conditions result in very small reverse differential pressure across the feedwater check valve. Analysis on leakage at these small reverse pressures demonstrated that certain failures could lead to hydrogen leaking back into the WWB. Therefore, the check valve is being re-designed to provide tighter sealing at low reverse pressures, as well as the high reverse pressures. The back pressure regulator is being redesigned to incorporate the lessons learned from the TT&E described in Section III above.

As previously mentioned, the OHDA will be integrated into the ISS OGA to upgrade it to the AOGA configuration. Once the OHDA is built in 2024, it will be integrated with spare OGA hardware (e.g. Controller ORU, PSM, Water ORU, Nitrogen Purge ORU, Oxygen Outlet ORU, Pump ORU) on the ground. This will simulate an ISS AOGA. An integrated ground test will be performed to demonstrate proper startup, operation, shutdown and recirculation loop nitrogen purge and water flush.

Figure 10. H2ST Integrated with OGA

C. Hydrogen Sensor Replacement

Issues with the legacy OGA hydrogen sensors are described in Reference 4. Due to these issues, half of the legacy hydrogen sensor fleet (8 of 16) has been retired. The Hydrogen Sensor Technology Demonstration (H2ST) will demonstrate the performance of four new COTS hydrogen sensors for 3 years while connected to the ISS OGA's

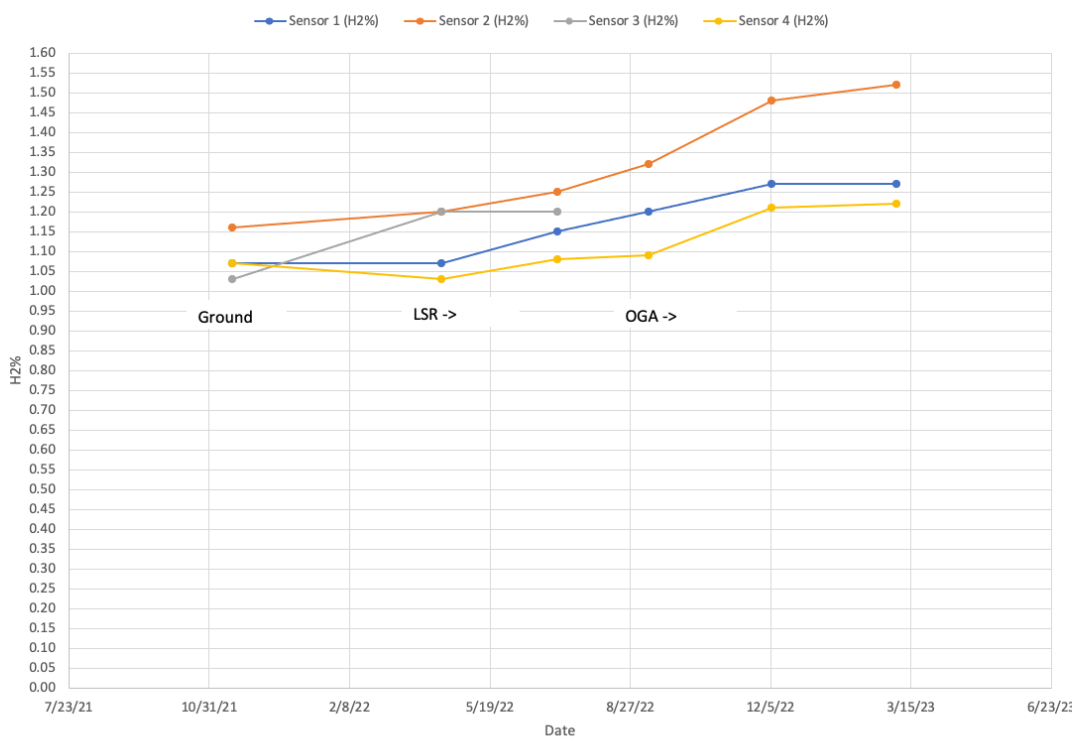

Figure 11. H2ST Sensor Drift Checks

oxygen outlet line to monitor for hydrogen. The H2ST design is described in References 1 and 2. H2ST was first powered up in a standalone mode in April 2022, and was successfully integrated with OGA in September 2022 (see Figure 10), after the OGA was moved from Node 3 to the US Lab.

On July 14, 2022, Sensor 3 failed, with its output dropping off scale low, from 0% to -1% H2, while the other sensors remained at the expected 0% H2. Nominal input current of all four sensors is approximately 150 mA. Sensor 3's input current has dropped from ~150 mA to ~70 mA. The root cause of the failure is unknown.

Every 90 days, a drift check is performed: the crew flows calibration gas (1.0% H2/air) through the H2ST sensors for 1 minute, and the sensor response is recorded. There have been four drift checks performed so far. The upwards drift of the sensors over time is shown in Figure 11. This overreporting of H2% is conservative, although not desirable as it could eventually lead to nuisance shutdowns. The legacy ISS OGA hydrogen sensors are known to drift downwards over time (under-reporting H2%), limiting their installed time to 201 days. H2ST has been installed for over 400 days.

The temperatures of the internal wetted components are close to what was predicted by thermal analysis. These temperatures need to be above the dew point temperature of the of the OGA product oxygen, to prevent condensation. The dew point temperature is between 63 – 76 F, depending on cell stack life conditions. The temperature of the sensor manifold, tubing, and 4-way valve have been consistently above 80 F. In August 2022, these temperatures dropped below 76 F. Upon further investigation, it was discovered that at this time an air diffuser was adjusted to blow cold air directly onto H2ST. After the crew adjusted the diffuser to blow the cold air away from H2ST, the temperatures returned to their nominal value.

When OGA's product oxygen is flowing through H2ST (starting in September 2022), the sensors have been reporting between approximately 0.1 – 0.3% H2/O2, as shown in Figure 12. The wide band in readings is due to the Process/Standby cycling that occurs every 100 minutes. Prior to integration with OGA, it was thought that the sensors would report close to 0% H2/O2, based on testing using a ground OGA test stand. The OGA specification allows up to 1% H2/O2. A review of cell stack acceptance test data was performed. The currently installed cell stack (SN 6) was tested in 2013, and 0.06% H2/O2 was recorded. The on-orbit spare cell stack (SN 7) was tested in 2018, and 0.06% H2/O2 was recorded. The previously installed cell stack (SN 4, installed from 2016 – 2021) was tested in

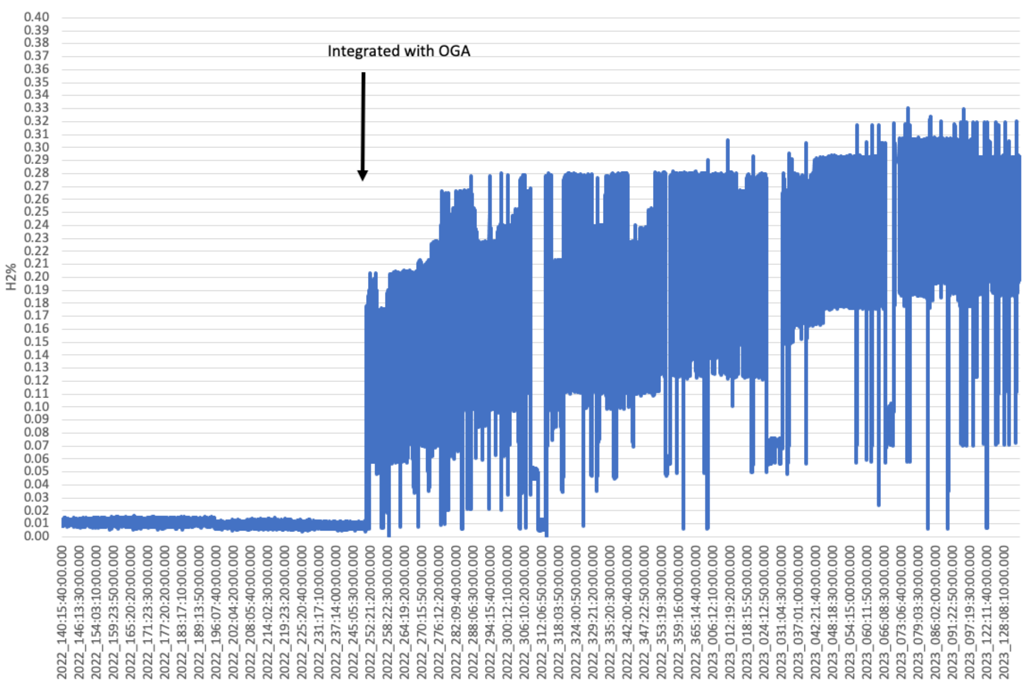

Figure 12. Average H2ST Sensor Readings (5/20/22 – 5/14/23)

2010, and 0.13% H2/O2 was recorded. The cell stack in the OGA ground test stand had 0.02% H2/O2 measured by the vendor prior to delivery to NASA in 2015. Based on the ground test data, the ISS OGA's product oxygen contains likely contains a small amount of hydrogen (well below the lower flammability limit). The legacy hydrogen sensors in OGA's Hydrogen Sensor ORU are reporting approximately 0.0% H2/O2. This is possibly due to how they are calibrated, where values below a certain low threshold are reported as 0.0%. The H2ST sensors and OGA's hydrogen sensors will continue to be trended and monitored in the future.

D. Redesign Recirculation Loop ACTEX

The OGA water recirculation loop contains an ACTEX ion exchange bed, as shown in Figure 2. The purpose of the ACTEX is to remove fluoride that is released by the cell stack membranes (as part of normal operation) and maintain a desirable pH level in the water recirculation loop. ACTEX operational issues (high delta pressure, limited life, non-compliance with seal redundancy requirements and MDP requirements) are described in Reference 1. The ACTEX will be replaced with a newly designed bed optimized for AOGA and Exploration missions. The AOGA ReMediation, Advanced DeIonization and Limited Life Optimization (ARMADILLO) will replace the ACTEX.

The ARMADILLO concept is shown in Figure 13. It will consist of a cartridge, inlet hose and outlet hose. The cartridge will contain the resin media, a new integral particulate filter, and QD's to allow the crew to remove and replace. The ARMADILLO team has worked to minimize the dP by optimizing fluid passage dimensions in the cartridge, hoses, and QDs. The resulting dP across the ARMADILLO has been reduced to less than 6.5 psid. This is roughly a 10 psid reduction from the typical 16.5 psid dP across the current ACTEX deionization bed in OGA. The cartridge and hoses will have redundant seals throughout and structurally designed to handle MDP pressures. Welds were eliminated from the design, and two removable end caps added, for ease of manufacture and refurbishment. The inlet hose will connect to the AOGA pump outlet and the outlet hose will connect to the OGA heat exchanger. The ACTEX will be mounted on the left side of the OGS rack, with hoses long enough to reach the pump and heat exchanger on the right side of the rack.

A resin capacity analysis was completed in 2022 to determine ARMADILLO's ionic capacity for fluoride and other contaminants. Fluoride is generated by the cell stack as part of the electrolysis process and must be removed from the recirculation loop. The fluoride generation rate for the AOGA cell stack is less than legacy OGA cell stacks, due to the incorporation of chemically stabilized membranes. The fluoride generation rate is assumed to be approximately 3 meq/year, based on several ground tests and analysis of returned ACTEX's from ISS. Based on this rate, the analysis determined that the operational life of the ARMADILLO is 3 years, with a 30% remaining capacity at the end of life. Assuming a degradation rate of 3% per year, the analysis determined that there is a 6 year shelf life prior to installation.

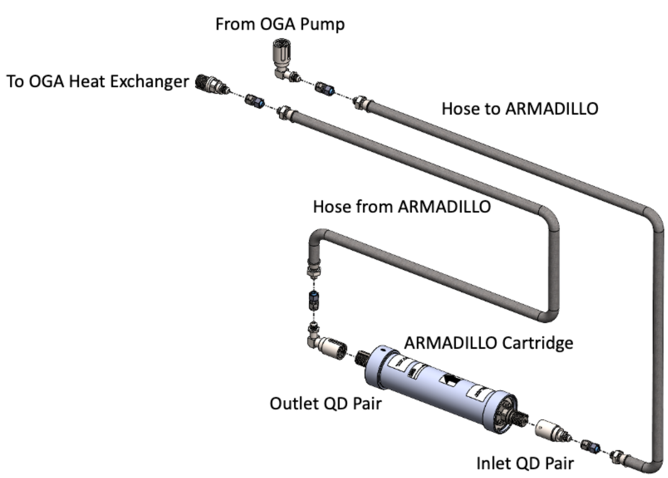

Figure 13. ARMADILLO

A particulate analysis was also completed in 2022 to predict the new particulate filter's percent occlusion and delta pressure drop after 3 years of installation in the AOGA recirculation loop. Water samples from the ISS OGA's recirculation loop are returned to the ground every 6 months. Over a span of 11 years, all of the particles in each sample were categorized by size. From this data, a particulate generation rate over 3 years can be predicted, as well as the area of ARMADILLO's new particulate filter that would be covered by particles. Based on this, the analysis determined that it would take 8.4 years for the filter to have a pressure drop of 0.5 psid.

The CDR was successfully completed in February 2023. Next, a total of three ARMADILLO cartridges will be built. The first cartridge will be delivered in 2025, and installed in AOGA's recirculation loop for 1 year (rather than 3 years) and returned to the ground for analysis. Subsequent cartridges will be installed for 3 years.

E. Manual Purge and Flush of the Water Recirculation Loop

A new capability to periodically purge and flush the recirculation loop water is required for AOGA. Water consumed during electrolysis is replaced in a batch process from the potable water bus. Over time, the recirculation loop can concentrate trace contaminants present in the incoming feed water. The feed water is known to contain trace amounts of dimethylsilanediol (DMSD), and dimethylsulfone (DMSO2), see Reference 4. Both of these compounds have a low affinity for removal through the installed ACTEX/ARMADILLO in the recirculation loop which allows them to slowly concentrate over time. As the DMSD concentration increases the DMSD may deposit onto system components. DMSO2 is more volatile than DMSD and predominantly leaves the system through the hydrogen stream which goes to Sabatier. DMSO2 is believed to have poisoned the Sabatier catalyst in the past.[4] Neither of these species have shown a detrimental impact to OGA's cell stack. Periodic flushing (every 90 days) of the recirculation loop is going to be implemented to protect the redesigned Sabatier and protect the AOGA from any undiscovered issues with these elevated concentrations.

First, a nitrogen purge of the recirculation loop will be performed to remove hydrogen and minimize risk to the crew while performing the subsequent water flush. The crew connects a hose assembly from the Nitrogen Purge ORU to the recirculation loop. This is shown as the dashed nitrogen purge line in the schematic (Figure 7). This hose assembly would likely contain a manual valve (to start and stop the purge), check valve (to prevent backflow), orifice (to limit the flow rate), and pressure gauge (to monitor pressure). Then, the system's Inert Dome command is used with several parameter overrides to push nitrogen from the Nitrogen Purge ORU into the recirculation loop. Nitrogen flows into the recirculation loop and dilutes the hydrogen. As nitrogen is introduced, it flows through the cell stack, into the RSA, and then out of the system in the same way hydrogen leaves the system during operation. After enough dilution is done, the Inert Dome is stopped, and the system is ready for the water flush. The nitrogen purge hose is disconnected.

Next a water flush of the recirculation loop is performed. The crew will connect a hose assembly and CWC-I bag to the recirculation loop (the dashed line labeled water flush in the schematic). The hose assembly would likely contain a manual valve (to start and stop the flush), metering valve (to limit the flow rate), pressure gauge (to monitor the pressure) and check valve (to prevent backflow). In future configurations, the hose will be connected to the wastewater bus. For the water flush, the system is commanded to the Standby state after many parameter overrides are put into place to keep the system from producing hydrogen and from shutting down due to the impending loss of water from the system. Then when the system reaches a certain point in the Standby state, the manual hose is opened to the bag. Once water starts flowing to the CWC-I bag, the system responds by performing water fills in quick succession into the recirculation loop. After enough water has been added and removed from the system for dilution, the manual hose valve is closed, and the system is shut off.

Commercial off the shelf (COTS) components will be used in the purge and flush hose assemblies. Development testing of these COTS components is ongoing and will end in June 2023. This testing includes proof testing, leak testing, burst testing, vibration testing, and DP testing. A delta CDR will be held in July 2023 to review the design of the manual purge and flush hardware.

V. Conclusion

CDR's for the AOGA and several major components were successfully completed during this past year. Manufacturing of flight hardware components was started. Several AOGA development tests have been completed, and more will be completed in 2023. ISS OGA continues to provide lessons learned that will be applied to AOGA.

The AOGA will be demonstrated on ISS for a minimum of 3 years. The ISS OGA will be upgraded to the AOGA configuration via a separately launched kit (consisting of the OHDA, purge/flush hoses, etc.) in the 2025 timeframe. Completed work to prepare the ISS OGA is described in Reference 1. On September 6, 2022, the OGS Rack was successfully moved from Node 3 to the US Lab (rack location LAB1P1). There were only two minor issues related to the relocation: the feedwater umbilical could not be mated due to an interference at the Z-panel at the base of the rack, the crew resolved this by rerouting the umbilical, and the ground controllers could not initially command the OGA, but this was resolved after troubleshooting.

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