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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
DMSD = dimethylsilanediol
DMSO2 = dimethylsulfone

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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, 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 dome provides a 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

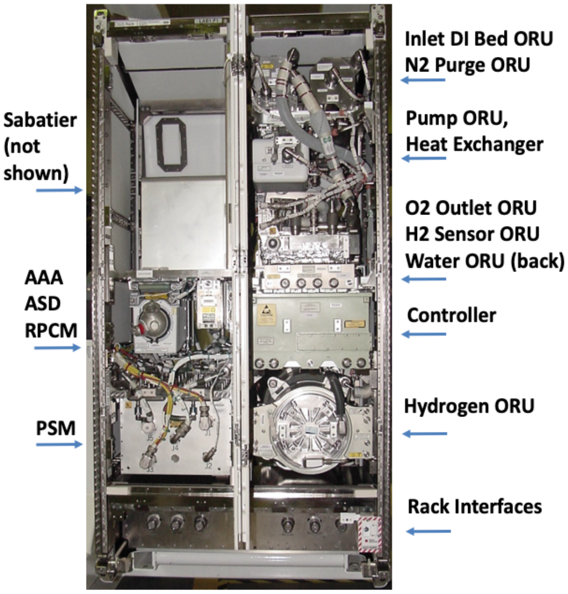

Figure 1. ISS OGA

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 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.

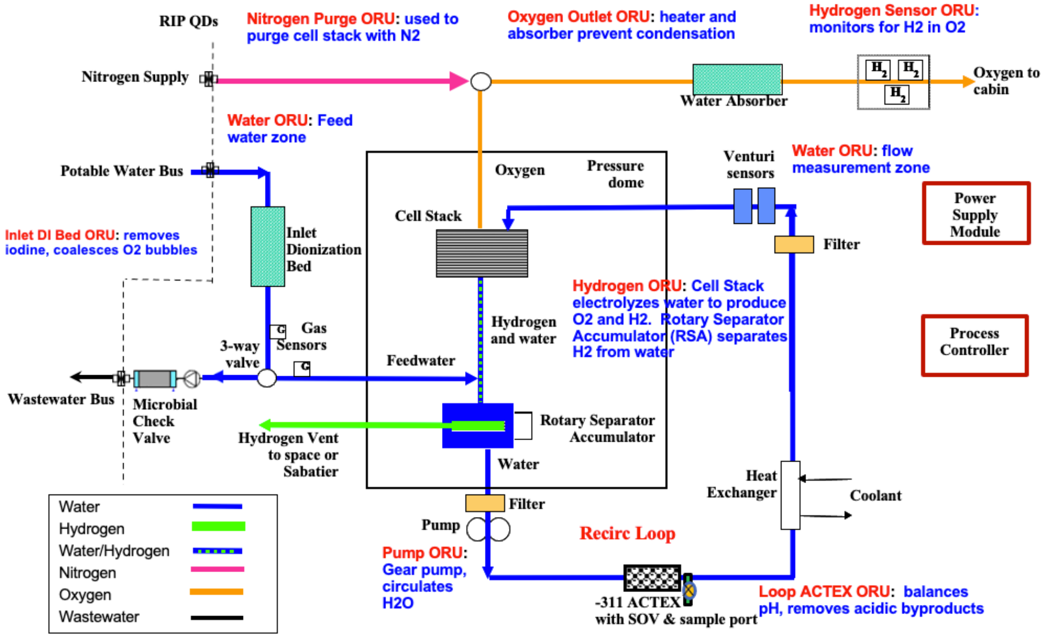

Figure 2. ISS OGA Simplified Schematic

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% 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), 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 16 years and is currently installed in the US Lab. As of May 13, 2024, the OGA has produced a total of 29,296 lbm (13,288 kg) of oxygen and 3,662 lbm (1,661 kg) of hydrogen since initial activation in 2007. The currently installed electrolysis cell stack (installed on October 21, 2021) has accumulated a total operating time of 2.5 years. 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.

Current and ongoing OGA issues will be discussed below. These include pump lockups, low recirculation loop pressure, cell stack low voltage, RSA high quantity faults, nitrogen purge valve leakage and partially mated quick disconnects (QD's).

A. Pump Lockup

Past investigative work on pump lockups is described in References 1 - 3. In 2021, there was a desire to gain on-orbit runtime on the redesigned pumps. Pump serial number (SN) 2 – 7 contain an updated design which include new wear couple materials, increased bearing thrust surface, journal bearing length change, and additional hydrostatic bearing feeds to improve operating and cycle life. In 2021, new spare pumps SN 3 and 4 failed to rotate when installed in OGA, and SN 5 failed to rotate during ground testing. A picture of failed pump SN 4, as installed in OGA briefly in 2021, is shown in Figure 3. As a result of Test Teardown and Evaluations (TT&E's) on failed pumps SN 3 and 5, 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. 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 was determined to be the electroless nickel coating used on the internal surfaces of the pump's two fluid quick disconnects (QD's). This coating was applied by the vendor to act as a lubricant. Failed pump SN 4 was returned to the ground in 2023 (on SpX-26), but has not been TT&E'd at this point in time, given other funding priorities and the likelihood that the root cause of its failure is similar to pump SN 3 and 5.

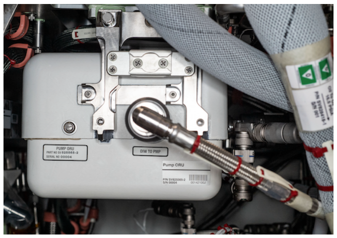
Figure 3. Pump SN 4 installed in OGA

The corrective action is to replace all pump QD's with ones which do not have the internal electroless nickel coatings. This will prevent any precipitation induced pump lockups in the future. Pump ORU SN 3 was successfully refurbished with new QD's in 2023 and is currently stored on ISS as a spare. SN 5 refurbishment is in-work and is planned to be completed in mid-2024. It will then become a launch on need ground spare.

Pumps SN 2, 6, and 7 (with the suspect QD's installed) remain on-orbit and remain susceptible to lockup. In May 2022, spare Pump ORU SN 2 was powered up briefly outside of the OGA, and was successfully rotated while performing a 10 L water flush. Analysis of the returned flushed water did not show any significant particulates (containing Ni or P), indicating brief flushing of spare pumps have limited value in preventing pump lockups. The best method to keep spares viable is to install them into the OGA and operate them for long periods of time. Pump SN 6 was installed in OGA in May 2021 and operated nominally. In May 2023, it was preemptively removed and replaced with pump SN 2. This was done to prevent pump SN 2 from locking up while in stowage. When pump SN 2 was installed in May 2023, it was noted its current and temperature were higher than pump SN 6's (0.45 A vs. 0.30 A, 135 F vs. 105 F [57 C vs. 41 C]). Over time, pump SN 2's current and temperature have been gradually decreasing (currently 0.35 A, 113 F [45 C]), coming closer to pump SN 6's. It is hypothesized that nickel phosphate precipitation may be slowly clearing from the gears, and potentially accumulating in the ACTEX. The DP was lower after Pump SN 2 was installed (18 psid vs. 19 psid [124.1 KPa vs. 131 KPa]). This is due to an offset in the pump SN 2 DP sensor. Pump SN 2 will remain installed for the foreseeable future.

Pump SN 1, which is of the older pump design, was installed for over 10 years, but was removed in 2021 due to decreasing flow rate over time and a failed DP sensor. It has remained on board as a degraded spare, and will eventually be returned to the ground. The need for a TT&E once it is on the ground is currently be discussed.

Although presumed to still be functional, Pump SN 7 will be returned to the ground on SpaceX-31. The proposed plan will be to remove the QD's to arrest any further buildup of precipitation on the gears and maintain it as a functional spare.

B. Low Recirculation Loop Pressure

Previous issues with low recirculation loop pressure are described in References 1- 3. Nominally, the water recirculation loop pressure should be approximately 24 psia (165.5 KPa) while in Standby and Process. The pressure is maintained by the hydrogen back pressure regulator, which is integral to the Hydrogen ORU. The default software low limit shutdown value is 20.5 psia (141.3 KPa), 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.

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 KPa) to allow system operation to continue. The current Hydrogen ORU SN 4 was installed on October 20, 2021. The recirculation loop pressure is consistently low (below the default shutdown limit) and erratic with Hydrogen ORU SN 4 installed. Figure 4 shows a typical example of the recirculation loop pressure (shown in blue) dropping below the default shutdown low limit value, 20.5 psia (141.3 KPa), when the system goes into Standby (when current, shown in black, temporarily decreases to 1 A) every 100 minutes.

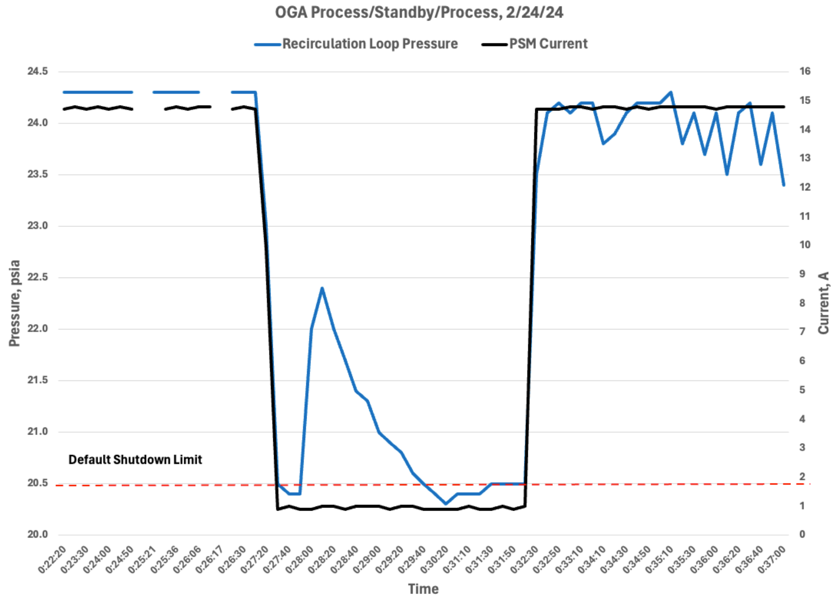

Figure 4. Recirculation Loop Pressure and PSM Current, 2/24/24

A TT&E of Hydrogen ORU SN 3 back pressure regulator determined improper passivation and corrosion of the tightly toleranced poppet shaft and guide as the cause of the erratic pressure regulation seen in operation. Changes that clarify the passivation method for future builds are being made to preclude recurrence of the erratic pressure regulation. The improved regulators are currently being manufactured and will be used in the future for OGA and AOGA.

C. OGA Cell Stack

The low cell voltage failure of the cell stack in Hydrogen ORU SN 2 in 2016, and TT&E results are described in Reference 6. The low cell voltage failure of the cell stack in Hydrogen ORU SN 3 in 2021 is described in References 2 and 3. In both instances, Cell 1's voltage in Standby continued to trend downwards out of family, indicating possible membrane thinning and a partial short. 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.[2] A TT&E of failed cell stack SN 5 (installed in Hydrogen ORU SN 2, 2010 – 2016) identified excessive thinning of the cell membranes as the root cause of the low cell voltage.[4, 6] A TT&E of failed cell stack SN 4 (installed in Hydrogen ORU SN 3, 2016 – 2021) is on hold, due to other funding priorities, and the likelihood that its failure is similar to cell stack SN 5.

Figure 5. OGA Spare Cell Stack

Hydrogen ORU SN 4 is currently installed. Starting in March 2024, the voltage of Cell 1 upon startup and shutdown has shifted out of family. The shutdown voltage profile from May 3, 2024 is shown in Figure 6. Upon removal of power to the cell stack, Cell 1 discharges faster than the other cells. This behavior started to appear after ~2.5 years of operation. Previously, with Hydrogen ORU SN 2 and 3, this startup/shutdown behavior started to appear after ~4 years of operation, with voltage instability during operation (Standby) appearing ~2 months later. The startup/shutdown voltage behavior of Cell 1 in Hydrogen ORU

SN 4 is similar to that of SN 2 and 3, although appearing sooner. The concern with the Hydrogen SN 4 cell stack is that this startup/shutdown voltage signature could be indicative of membrane thinning, and eventually lead to a leak or hotspot. The OGA team has agreed to keep Hydrogen ORU SN 4 installed until voltage instability appears during operation (in Standby). This is similar to the previous guidance for Hydrogen ORU SN 2 and 3. The OGA team will continue to closely monitor cell voltages. Meanwhile, the procedure to replace the Hydrogen ORU is being updated should it be needed soon. There are two spare Hydrogen ORU's on ISS (SN 1 and 5).

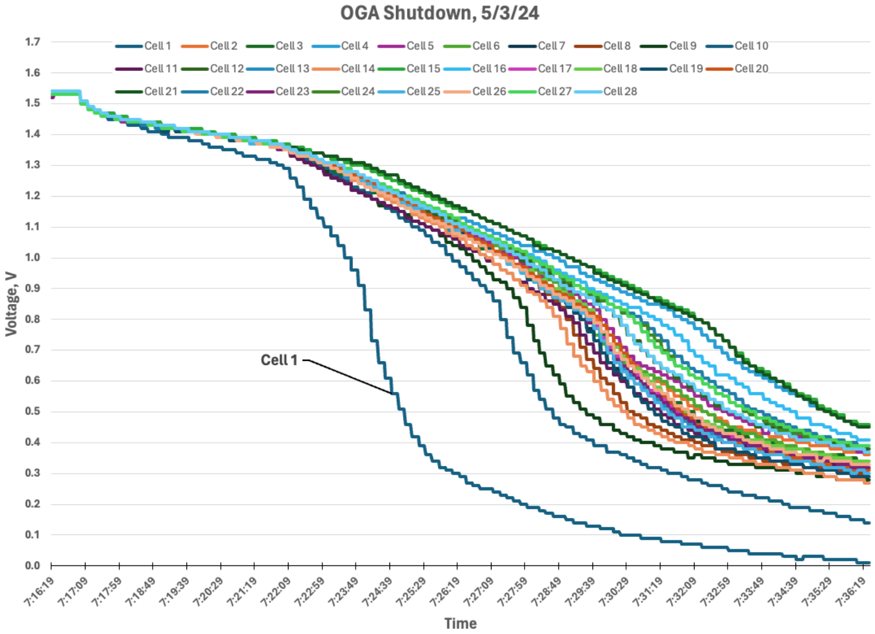

Figure 6. Cell Voltages Upon Shutdown (Hydrogen ORU SN 4)

The new OGA cell stack design, based on lessons learned from previously installed Hydrogen ORU's, incorporates design improvements to minimize membrane thinning, including: chemically stabilized Nafion membranes (reduce mass loss during operation), membrane additives to minimize chemical degradation, and new frame seals (minimize water loss). A new redesigned OGA cell stack was built and delivered in 2021, as shown in Figure 5. Since that time, it has been kept in ground storage. A spare OGA cell stack kit will be delivered in 2024.

In March 2023, after the spare OGA cell stack sat dormant for 15 months in ground storage, water samples from the cell stack were chemically analyzed. The results indicated a low pH (4.13), high conductivity (37 umho/cm), and the presence of nitrate (1.86 ppm), chloride, sulfate. These results were unexpected, and concern grew of the possibility of corrosion of metal parts within the cell stack. A fault tree was generated, and an investigation was performed, but no conclusive cause was identified. Several more water flushes and samples were taken in 2023, with similar results. Finally, in December 2023, another sample was taken. An even lower pH (3.98) and a higher level of nitrate was observed (4.82 ppm). These results were confounding because the samples were taken after only 3 months of stagnation (as opposed to the earlier 15 month dormant period). No fluoride or corrosion products have been found in the water samples. Fluoride would indicate degradation of the membrane. The cell stack will continue to be sampled every 3 months and trended.

D. RSA High Quantity Faults

So far, in 2024, there have been four faulted shutdowns when attempting to activate OGA, with the most recent being on May 3, 2024. These faults are due to high RSA water quantity. A fault occurs if the RSA water quantity increases more than 10 cu-in (164 mL). During the startup process, the RSA and pump are initially on, and no current is supplied to the cell stack. During this time, the RSA water quantity decreases, due to residual hydrogen and oxygen combining in the cell stack. Once the RSA quantity decreases below 26 cu-in, an automatic water fill occurs, raising the RSA quantity. Then when power is applied to the cell stack, the RSA quantity increases even further, due to generated hydrogen gas in the cell stack pushing water to the RSA. As a result of these two actions, the RSA quantity can increase by more than 10 cu-in (164 mL), and cause a shutdown. The OGA team has reviewed these 2024 high RSA quantity faults, as well as ones from 2021 and 2022. The OGA team understands why these RSA water increases faults are occurring during startup, but doesn't fully understand how to prevent them from occurring. The team has recommended several possible workarounds to allow system startup. These include disabling water fills during startup, expanding the 10 cu-in limit, and disabling the fault checking during startup.

E. Nitrogen Leakage

While Nitrogen Purge ORU SN 1 was installed, it experienced leakage issues as described in Reference 2. Starting in December 2021, the ORU was unable to maintain a pressure of 76 psia (524 KPa) 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 TT&E has not been funded.

F. QD Partial Mate

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, as described in References 1 and 2. The QD pairs were about a quarter turn from being fully mated. In this configuration only one of two redundant seals is engaged. The failure investigation is on hold until the currently installed rack hose is removed and returned to ground for TT&E in 2025, as part of the AOGA upgrade process.

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, modifying the existing cell stack design to improve both shelf and operating life, and enabling dormancy. A 2017 supportability study 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 for a 1,100 day exploration mission. Another important consideration is that a future Exploration vehicle will have a significantly smaller internal habitable volume compared to ISS. A future vehicle is expected to only be the size of one of ISS's modules. The ISS internal cabin volume has days worth of available oxygen, for crew metabolic consumption, compared to hours for an Exploration vehicle. As such, the maximum allowable maintenance downtime for ISS OGA is measured in days, while an Exploration AOGA's would only be hours.

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 ISS 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 AOGA design (less the manual recirculation loop purge and flush hardware) was reviewed and approved to proceed to manufacturing, assembly, integration and test. 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. This review covered the new hazard reports (hazards and controls related to combustion, overpressure, structural failure, and hazardous gases) and non-compliance reports (Maximum Design Pressure [MDP], sharp edges, dual seal verification) associated with AOGA. A delta-CDR was conducted in July 2023 to review the design of the manual recirculation loop purge and flush hardware. The final AOGA Phase III safety review will be in 2025. An Interim Design Review (IDR) was conducted in February 2024 to review the design of rack modification hardware for the existing OGS rack required to accommodate AOGA. A new rack bumpout (described in further detail below), new rack hoses, along with a structural analysis and maintenance analysis, is required.

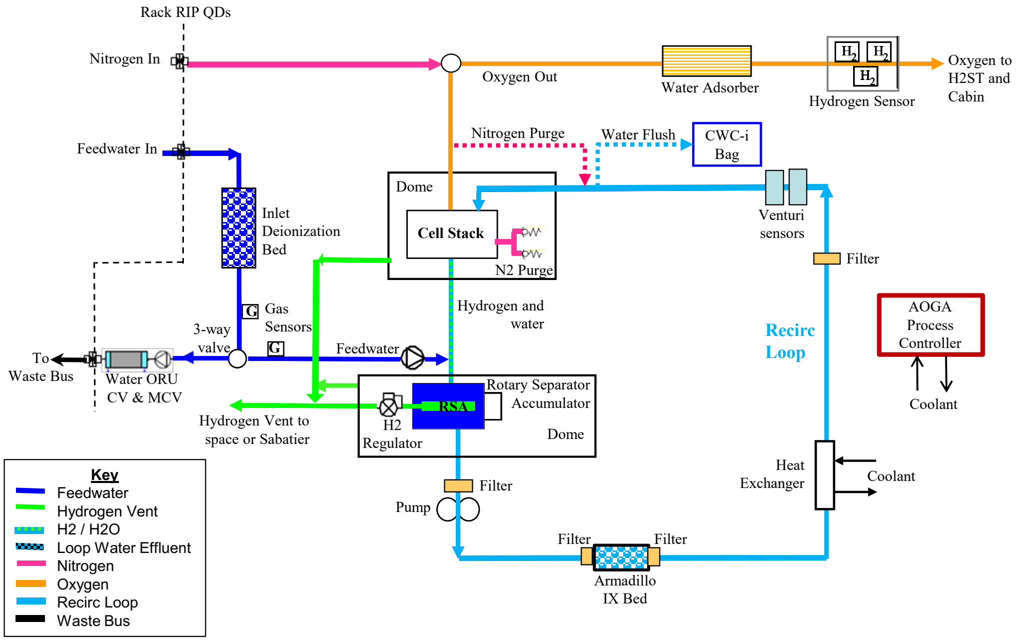

Figure 7. AOGA Schematic

Table 1. AOGA Upgrades

Upgrade	Reason	Description
Redesign 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

Due to the time criticality of oxygen generation on ISS, there is a requirement that the upgrade from the OGA to AOGA configuration must be completed in less than two days, and if there are any issues, the system must be returned to the OGA configuration within two days. An important risk reduction activity will be the integrated AOGA ground test (in 2025) properly demonstrating all operating modes prior to launch.

A. Cell Stack Redesign

Legacy OGA cell stack failures and TT&E results are described in Section III-C above. The AOGA cell stack design will be based on the OGA cell stack design, but will include improvements based on the lessons learned. 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), membrane additives (to minimize chemical degradation), and new frame seals (minimize water loss).

AOGA cell stack development testing is ongoing. A single-cell was built, and a 7-month endurance test was completed in October 2022. 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. Two AOGA single cells were used in a microbial challenge test. These cells were subjected to a microbial solution (consisting of microbes typically found in the ISS OGA's water recirculation loop). After a 4-week dormancy period, the cells had nominal voltage and polarization scan data. Four additional single cells were built in early 2023, and subjected to cycle tests from May – October 2023. The cells were subjected to 31,500 Process/Standby cycles and 1,000 on/off cycles, to simulate on-orbit operations. Throughout the cycle test period, periodic polarization scans and resistance checks were performed, indicating nominal performance and all cells remained in good health.

A chemical challenge test on two single cells is planned for March – May 2024. An initial baseline test will be performed with cell voltages recorded. Then the cells will be dormant for about 1 month, and subjected to trace contaminants (dimethylsilanediol, DMSD, and dimethylsulfone, DMSO2), typically found in the ISS OGA's water recirculation loop. After a dormancy period, cell stack voltage performance degradation 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 within ~10 minutes after shutdown to eliminate a shock hazard when the crew needs to perform maintenance on the cell stack. Without bleed resistors installed, this time will take over 2 hours. As previously mentioned, for future smaller Exploration vehicles, it is essential to minimize the maintenance downtime. However, the effect of bleed resistors on the new sintered metal membrane supports is unknown. There is a potential that the sinters could become embrittled and damaged after repeated on/off cycles with the bleed resistors attached. A development test will be performed May – June 2024 using an AOGA 3-cell development stack with bleed resistors. The cell stack will be subjected to 100 on/off cycles. Cell stack health checks will be performed throughout the test to determine if there is any performance degradation. If so, the bleed resistors may need to be removed from the AOGA cell stack design and another method of handling the shock hazard will need to be developed.

Finally, a particle shedding characterization test will be performed on a development stack in May 2024. The stack will be operated for 200 hours. Then the downstream water filters will be analyzed for particles coming off the cell stack. The legacy OGA cell stack shed catalyst particles. These particles could potentially collect in the RSA and become an ignition source. In addition, the particles could collect in valves and cause leakage. The new AOGA cell stack design has an improved membrane catalyst application process, which should have a reduced particle shedding rate. This test will confirm this assumption.

The flight AOGA cell stack build will start in July 2024. Major components, such as the baseplate and frames, are currently being manufactured. The build should be complete in August 2024. Following the build, acceptance testing and final delivery will occur.

B. Dome Redesign

The legacy OGA design houses all 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 (see Figure 8). The Hydrogen ORU is installed in the bottom right of the ISS OGS rack (see Figure 1). 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 any of the internal components by the crew. The failure of a single internal component requires replacement of the entire ORU. The Hydrogen ORU can only be repaired 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). Manufacturing of both the RSA and cell stack domes were started in 2023 and will be complete in June 2024.

Figure 8. Hydrogen ORU

The OGA will be upgraded to the AOGA configuration by replacing the Hydrogen ORU 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, as previously mentioned. 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.

The dome internal components (cell stack, RSA, tubing, etc.) contain hydrogen, oxygen and water. In addition, dome seals prevent cabin air from entering the dome. These components have a known leak rate, into the dome. Over time, hydrogen, oxygen, and air build up in the dome. These gases must be vented out of the dome (i.e. system transitions from Process to Standby) for 5 minutes, every 100 minutes, to prevent a buildup of a combustible mixture in the dome. This regular Process/Standby mode of operation keeps the pressure inside of the dome below 0.25 psia (1.7 KPa). During integrated operation with Sabatier, this constant cycling can result in loss of efficiency. When OGA goes into Standby every 100 minutes, Sabatier must also go into Standby, not processing hydrogen during that time, and after each Standby, Sabatier takes some time to return to production. The same concerns will exist for AOGA. AOGA will have two domes (with two sets of dome seals instead of one) and will have additional external feedthroughs, which increases the leak paths into the domes. In addition, the total volumes of the two AOGA domes will have a smaller internal volume than the legacy OGA dome, meaning the pressure in the domes will rise faster. AOGA component level leak testing and integrated system testing will be performed to verify total leakage into the AOGA domes and will be compared to the legacy OGA.

The OHDA design required several development tests to mitigate some design risks. The cell stack harness test and dome seal test were previously completed and described in Reference 1.

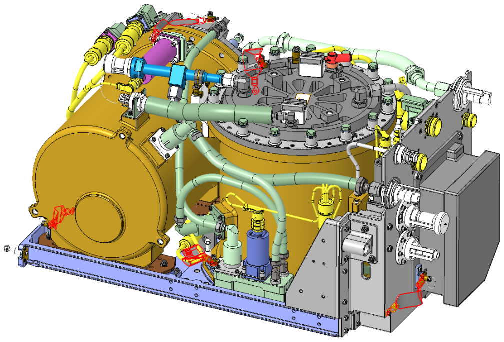

Figure 9. OHDA

A third development test involved the RSA diaphragm seal. The main function of the RSA is to mechanically separate water from gaseous hydrogen. The RSA has a rubber diaphragm seal that is part of the hydrogen outlet solenoid 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 is normally exposed to a 24 psia (165.5 KPa) pressure and has a defined maximum design pressure (MDP) of 50 psia (344.7 KPa), but the diaphragm design can only withstand 45 psia (310.2 KPa) before failing. As a result, a waiver was needed because this value is lower than the MDP requirement. As a result, for the AOGA program, the RSA diaphragm was redesigned to improve its pressure capability. This new design incorporated a fabric weave into the rubber and a redesign of the sealing edge to improve its structural strength. Development testing (proof, leakage, and cycle testing) of the redesigned AOGA RSA diaphragm was performed in 2023. The redesigned diaphragm was able to survive higher proof pressures, but failed leakage tests. Additional improvements would be required for the AOGA RSA diaphragm design. Further analysis of the systems failure modes was performed, and it was discovered that the MDP could be lowered to 30 psia (206.8 KPa), and proof pressure lowered to 45 psia (310.3 KPa), since the hydrogen outlet valve automatically closes and isolates the diaphragm in the event of a worst case upstream failure. This valve closure was not previously taken into account. The ISS Program has accepted the lowering of MDP, and as such, made the decision to revert to the legacy OGA RSA diaphragm seal design, rather than devote additional cost and schedule for redesigning the new AOGA diaphragm.

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. A development test was completed in 2023. The results showed the pressure drop in the 2-phase line to be higher than what the legacy OGA model predicted. The AOGA cell stack is expected to operate at a slightly higher pressure than OGA. This should result in better pressure regulation in Standby.

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 (see Figure 7, AOGA schematic). Operational 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 has been re-designed to provide tighter sealing at low reverse pressures, as well as the high reverse pressures. Development test data demonstrated that the check valve was able to provide sufficient sealing at a reverse pressure of a fraction of a psid and at MDP.

As mentioned in Section III-B above, the back pressure regulator for OGA and AOGA has been redesigned to incorporate the lessons learned from the TT&E conducted in 2023. The regulator will incorporate improved passivation to reduce the chance of stiction due to corrosion of the poppet and the poppet guide.

As previously mentioned, when the AOGA system is in operation, normal gas leakage from the dome internal components raises the domes' internal pressure over time. The system periodically switches from Process to Standby mode to evacuate the domes. The cell stack relief valves are being redesigned to reduce their leakage rates into the dome. The new design incorporates smaller-size filters than the original design. The smaller filters are selected to reduce the size of particulates that reach the seals of the relief valves and, thus, reduce leakage.

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 2025, it will be tested on the ground with lab hardware to simulate the AOGA operational conditions. The test will demonstrate proper startup, operation, shutdown and recirculation loop nitrogen purge and water flush.

C. Hydrogen Sensor Replacement

Issues with the legacy OGA hydrogen sensors are described in Reference 5. 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 at least 3 years while connected to the ISS OGA's oxygen outlet line to monitor for hydrogen. The H2ST design is described in References 2 and 3. H2ST was first powered up in a standalone mode in April 2022 (attached to the LSR Rack), and was successfully integrated with OGA in September 2022 (see Figure 10), after the OGA was moved from Node 3 to the US Lab. H2ST is installed on the right side of the OGS Rack.

Figure 10. H2ST Integrated With OGA

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 10 drift checks performed so far. The drift of the sensors over time is shown in Figure 11. After H2ST was first installed on-orbit, an upwards drift was noted. For the past year, no upwards drift has been noted on the three good sensors. When exposed to 1.0% H2/air, Sensor 1, 2 and 4 currently report 1.31%, 1.57% and 1.26% respectively. 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 684 days, and counting.

When OGA's product oxygen is flowing through H2ST (starting in September 2022), the sensors have been reporting between approximately 0.1 – 0.4% H2, as shown in Figure 12 (yellow, red, and green lines). The legacy OGA hydrogen sensors (blue, orange, and gray lines) have been trending upwards from 0.0 to 0.3% H2 in 2023 – 2024. In previous years from 2015 – 2022, there have been instances of individual legacy OGA hydrogen sensors going offscale high, as shown in the graph. 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 H2ST sensors would report close to

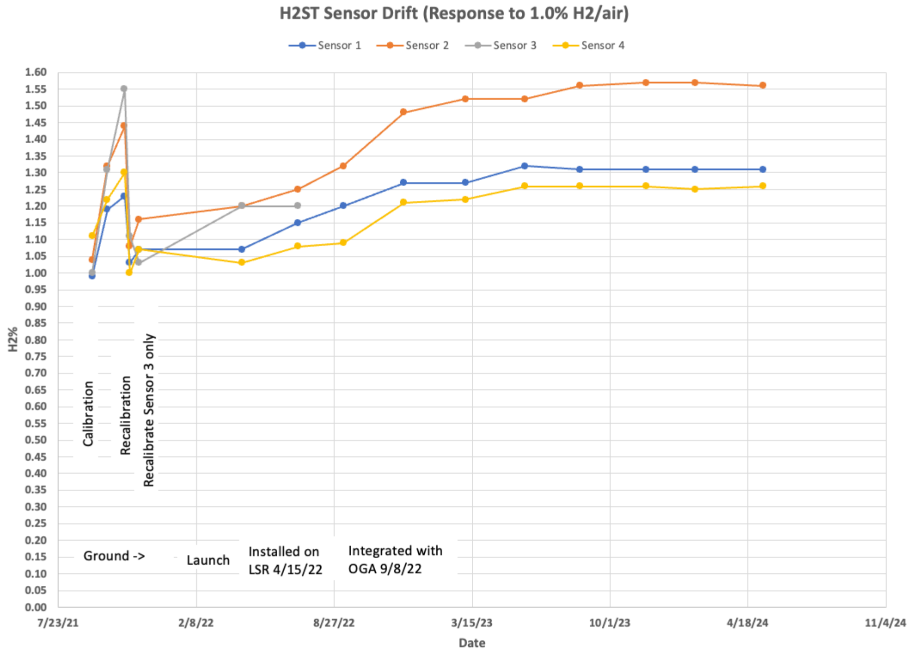

Figure 11. H2ST Drift Checks

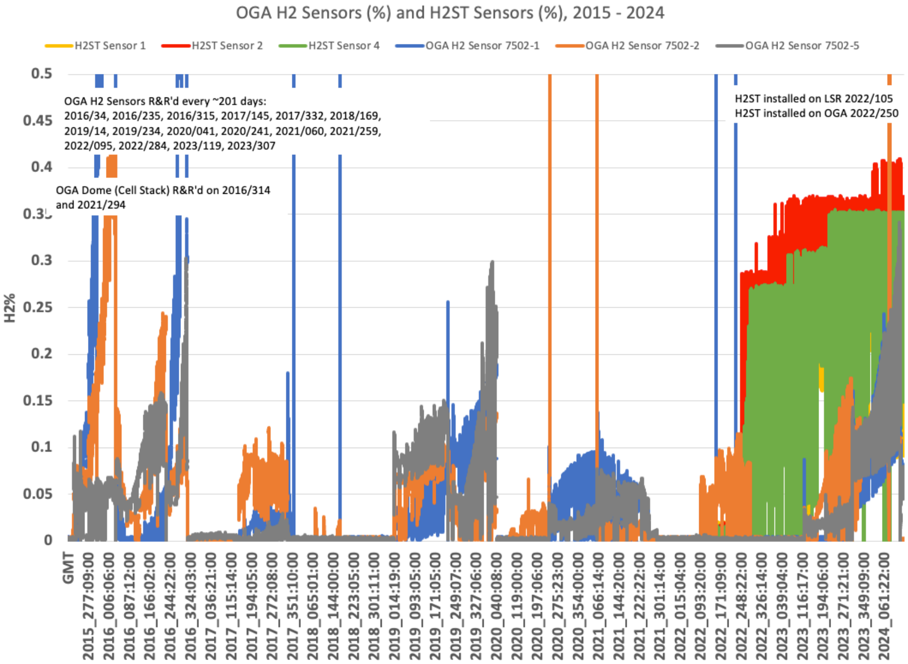

Figure 12. H2ST and legacy OGA Hydrogen Sensor Response

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 acceptance tested in 2013, and 0.06% H2/O2 was recorded.

The H2ST will remain installed for the foreseeable future. Drift checks and trending every 90 days will continue.

D. Redesign Recirculation Loop ACTEX

The OGA water recirculation loop contains an ACTEX ion exchange bed, as shown in Figure 2. The main 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 2. 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 (44.8 KPa). This is roughly a 10 psid (68.9 KPa) reduction from the typical 16.5 psid (113.8 KPa) 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 3.3 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.

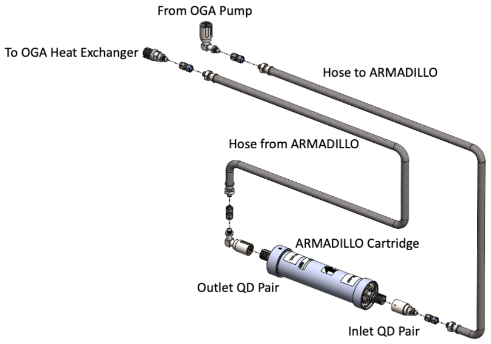

Figure 13. ARMADILLO

A total of four ARMADILLO cartridges will be built, starting in May 2024. 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 DMSD, and DMSO2, see Reference 4. Both 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. Due to cost impacts (related to software and controller changes), the decision was made to have the purge and flush be manually performed by the crew rather than be automated. The manual purge and flush operation will take longer than if it was automated (hours vs. minutes). For a future Exploration mission, this will need to be automated, to reduce maintenance downtime. As mentioned previously, reducing maintenance downtime is an important factor for an Exploration mission.

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 red dashed nitrogen purge line in the schematic (Figure 7). This hose assembly will contain a manual valve (to start and stop the purge), a metering valve (to control the nitrogen flow rate), a check valve (to prevent backflow), a pressure gauge (to monitor pressure), and a filter (to protect the OHDA from contaminants). In 2023, the design team removed the orifice from the design, as it was determined to be redundant to other orifices in the system. 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.

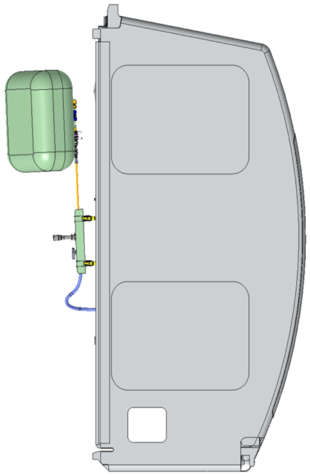
Figure 14. Water Flush Hose and CWC-I Attached to the OGS Rack

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 blue dashed line labeled water flush in the schematic, Figure 7). The configuration is shown in Figure 14. The hose assembly will contain a manual valve (to start and stop the flush) and a metering valve (to control the flow rate). In 2023, the design team removed the check valve and pressure gauge from the design, as they were determined to be no longer necessary, since the operations concept prevented any backflow of water from the CWC-I bag into the OGA. 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. After completing the water flush, the water hose will be connected to the Nitrogen Purge ORU to purge the remaining water out of the hose.

Commercial off the shelf (COTS) components will be used in the purge and flush hose assemblies. Development testing of these COTS components was completed in 2023. The tests included proof pressure, leakage rate, burst pressure, functional performance, vibration, cycles, and accidental loads. The development tests helped select some COTS components over others, as well as choose alternative features for some of the selected components. A delta CDR was held in July 2023 to review the design of the manual purge and flush hardware.

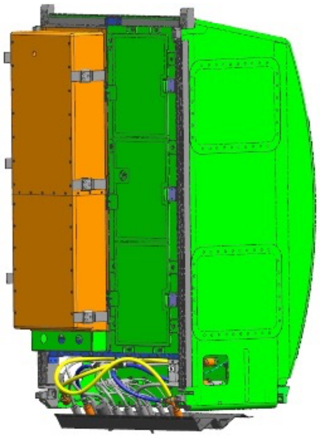
Figure 15. OGS Rack with Bumpout

F. OGS Rack Planned Upgrades

The OGS rack will be modified to include a new bumpout assembly replacing the left side closeout door on the rack. This is shown as the orange enclosure on the front of the rack in Figure 15. The bumpout will allow additional room to enclose Sabatier 2.0 (which has a larger volume compared to Sabatier 1.0) and new CO2 accumulator tanks. Figure 16 shows Sabatier 2.0 (in yellow) and the accumulator tanks (shown in blue).

Acoustic foam is used to seal around the perimeter of the bumpout faceplate for reduction of low frequency noise and to preclude rack airflow leakage paths to cabin. Attachment brackets will be incorporated to ease crew install and removal of the six hook and loop straps securing the bumpout faceplate door to the OGS rack seat track brackets. The Avionics Air Assembly (AAA) Cabin Air Inlet port, currently on the front of the original left side door, will to be relocated to the left side of the bumpout. A new AAA inlet port will be larger diameter to compensate for additional length and bend of passageway to the muffler filter block and port will contain an integral screen.

New replacement H2/N2 Vent Hose and Waste Water Hose Assemblies with contingency tee QDs for alternate venting and scarring for potential future flushing of the OGA recirculation loop water to the waste bus (instead of to a CWC-I) will be installed within the standoff volume between the OGS Rack Interface Panel (RIP), at the bottom of the rack, and Z-panels. Two CO2 Hose Assemblies from the ARS Rack will be installed at the OGS Rack Interface Panel (bottom of the rack). A new Scar Panel will be installed to accommodate potential future Methane Reduction Device (MRD) fluid QD hose connections.

A new rack secondary structure will be installed in the right side of the OGS Rack to allow for mounting of both OHDA and legacy Hydrogen ORU (should there be a need to revert to legacy configuration). A new RSA To Pump Hose Assembly will be installed. The new hose install will replace the existing hose, which has a suspect QD (only allows partial mating) as described in Section III-F above.

The six legacy CO2 accumulator tanks at the base of rack were abandoned in place due to suspected internal aluminum oxide corrosion and inaccessibility. The new CO2 Accumulator is planned to replace the legacy tanks and is comprised of two large accumulator tanks. The CDR was conducted in April 2024. The ARMADILLO will be installed behind the CO2 Accumulators.

Sabatier 2.0 has an expanded volume to ease crew accessibility for component replacement and maintenance. Existing mounting brackets and scar panel connections used for Sabatier 1.0 within the OGS rack will be utilized for Sabatier 2.0 without any OGS rack modifications. Sabatier 2.0 CDR is planned for the end of June 2024 with hardware delivery targeted for February 2026.

Sabatier 2.0 compresses the CO2 recovered from cabin air into the CO2 accumulator and reacts hydrogen from AOGA and CO2 from the accumulator tanks to form water (sent to the waste water bus), and methane which is vented to space vacuum. The methane along with excess H2 is targeted for a potential future MRD system to react and recover additional water along with other reactant gases that will be routed to a US Lab starboard mixed gas vent (conversion from existing water to mixed gas vent requires EVAs) to space vacuum.

An integrated design review (IDR) of the rack modifications was held in Feb 2024.

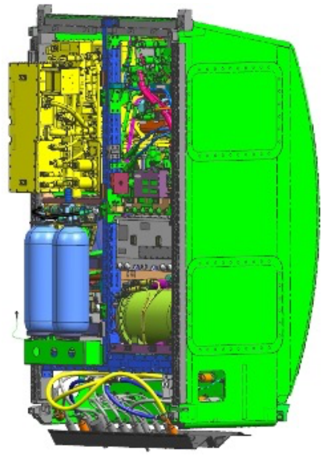

Figure 16. OGS Rack, Bumpout Cover Removed

V. Conclusion

Manufacturing of flight hardware components has started, with additional manufacturing to be completed in 2024. Several AOGA development tests have been completed, and more will be completed in 2024.

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.

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