

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. These improvements will be incorporated into the Advanced OGA (AOGA), which will be launched to ISS in 2026 and its operation demonstrated in a relevant flight environment for at least 3 years. AOGA upgrades 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. AOGA design reviews, analyses, and

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development tests are now complete. Currently, AOGA flight hardware components are being manufactured. The design, build and plans for the AOGA will be reviewed in this paper.

Acronyms and Nomenclature

ACTEX	=	Activated Carbon Ion Exchange
ARMADILLO	=	AOGA ReMediation, Advanced DeIonization and Limited Life Optimization
AOGA	=	Advanced Oxygen Generation Assembly
CDR	=	Critical Design Review
COTS	=	Commercial Off The Shelf
CWC-I	=	Contingency Water Container - Iodine
DMSD	=	dimethylsilanediol
DMSO ₂	=	dimethylsulfone
dP	=	Delta Pressure
H2ST	=	Hydrogen Sensor Technology Demonstration
ISS	=	International Space Station
MDP	=	Maximum Design Pressure
OGA	=	Oxygen Generation Assembly
OGS	=	Oxygen Generation System
OHDA	=	Oxygen Hydrogen Dome Assembly
ORU	=	Orbital Replacement Unit
PSM	=	Power Supply Module
QD	=	Quick Disconnect
R&R	=	Remove and Replace
RSA	=	Rotary Separator Accumulator
SN	=	Serial Number
TT&E	=	Test, Teardown, and Evaluation

I. Introduction

FUTURE long duration, deep space Exploration 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 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.

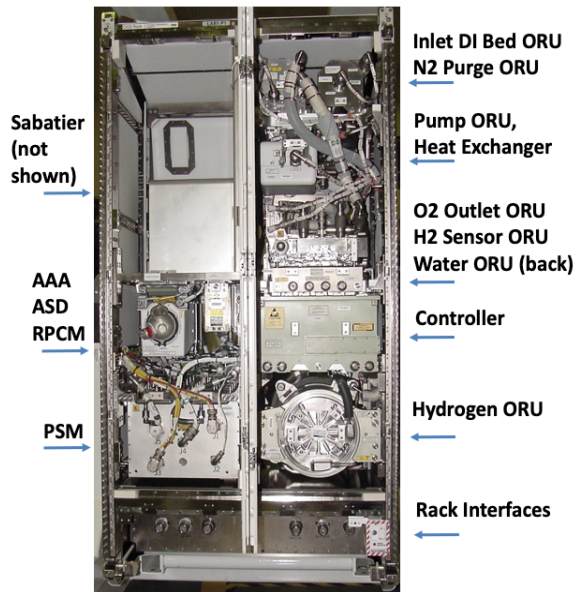


Figure 1. ISS OGA

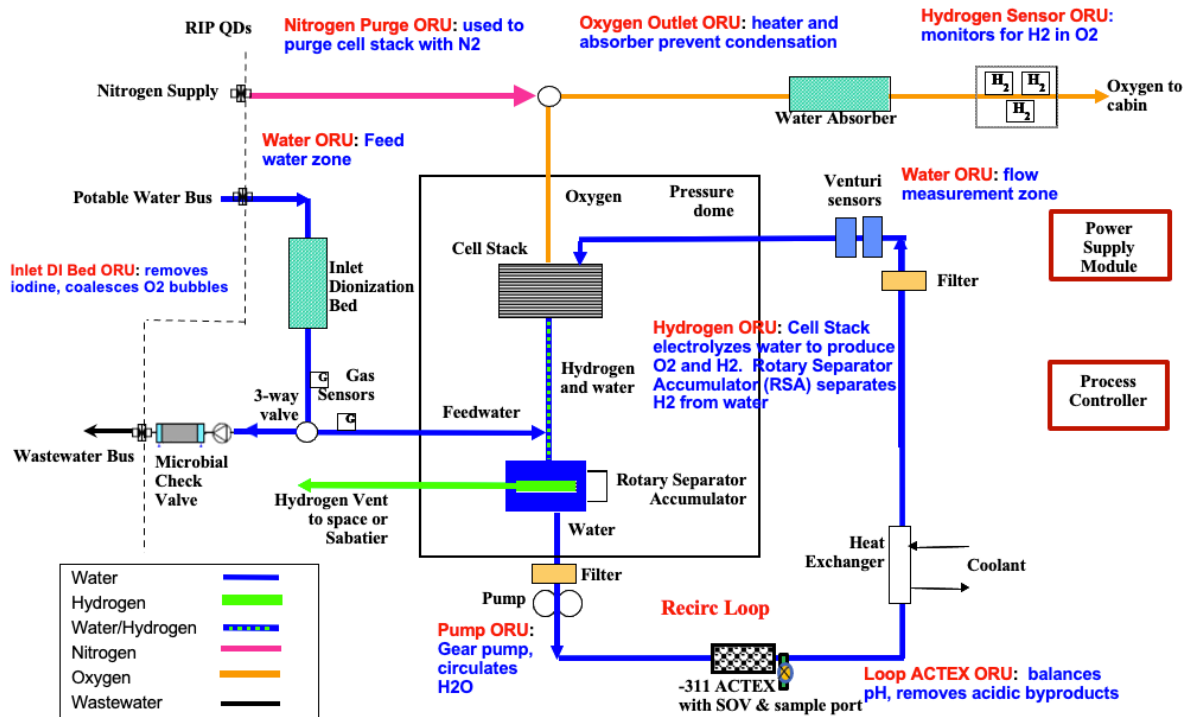


Figure 2. ISS OGA Simplified Schematic

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 electrolysis cell stack. The PSM ORU provides a variable range of 10-46.9 amps (A) of current to the cell stack during Process mode and 1.0 A during Standby mode. At 46.9 A, the cell stack generates oxygen at 20.4 lb/day (9.25 kg/day). This can support 10.88 crew (assumes 1.874 lb [0.85 kg] oxygen/day/crew metabolic rate). The system transitions from Process to Standby every 100 minutes for 5 minutes so that the dome can be vented to space vacuum. Dome pressure slowly rises over time during Process due to normal leakage of the dome internal components (cell stack, RSA, etc.), requiring periodic venting to stay below the 0.25 psia (1.7 kPa) shutdown limit.

Most of the OGA ORUs are run to failure except for the Hydrogen Sensor ORU (201 days), the Inlet Deionizing Bed (~8 years, depending on total water throughput) and ACTEX (527 days).

III. ISS OGA Current Status

The ISS OGA is operational. It has been operating for 18 years and is currently installed in the US Lab. As of April 30, 2025, the OGA has produced a total of 32,182 lbm (14,598 kg) of oxygen and 4,023 lbm (1,825 kg) of hydrogen since initial activation in 2007. The currently installed electrolysis cell stack (installed on September 18, 2024) has accumulated a total operating time of 139 days. 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 cell stack low voltage, low recirculation loop pressure, RSA high quantity faults, ACTEX life reduction, and other issues.

A. Cell Stack

The cell stack is contained in the Hydrogen ORU, shown in Figure 3. The low cell voltage failure of the cell stack in Hydrogen ORU serial number (SN) 2 in 2016, and TT&E results are described in Reference 1. The low cell voltage failure of the cell stack in Hydrogen ORU SN 3 in 2021 is described in Reference 2. In both instances, Cell 1's voltage in Standby continued to trend downwards out of family, indicating possible membrane thinning and a partial short. This legacy OGA cell stack design includes non-chemically stabilized membranes, screens for membrane support, and an obsolete Membrane Electrode Assembly (MEA) processing method.² A test, teardown, and evaluation (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.¹ 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.

Hydrogen ORU SN 4 was installed in 2021. Starting in March 2024, the voltage of Cell 1 upon startup and shutdown shifted out of family.² 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 low 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 OGA Team hypothesized that because Hydrogen ORU SN 4 was operating at a higher production rate than SN 2 or 3 (due to larger crew size), the voltage degradation appeared sooner. During August 2024, the OGA Team noted that Cell 1's voltage during Standby was decreasing, dropping from the nominal ~1.53 V. On September 16, 2024 (GMT 260), the voltage dropped to 1.42 V (below the 1.48 V thermoneutral electrolysis voltage). A graph of cell voltages (cells 1 – 8) is shown in Figure 4. As mentioned in Section II, OGA transitions from Process to Standby every 100 minutes for 5 minutes, so both the Process voltage and Standby voltage are shown for each cell. Cell voltage in Process can vary based on current/production rate. Cell voltages in Standby should typically be at ~1.53 V, but cell 1's Standby voltage (in blue) is shown decreasing out of family to 1.42 V on GMT 260. At this point, the ISS Program directed that the Hydrogen ORU be removed and replaced (R&R'd), even though the default shutdown low limit is 1.0 V and there were 12 crew aboard at the time. Given the rapidly decreasing voltage, Hydrogen ORU SN 4 did not appear to have much longer to safely operate, without creating a localized hotspot and pinhole leak in Cell 1's membrane. If a leak and combustion were to occur, there would be a risk of failing other ORU's. The OGA was shut down on September 16, 2024. On September 17, 2024, the crew performed flushing of the recirculation loop and other hoses, to remove trace



Figure 3. Hydrogen ORU

contaminants that may have built up over 3 years. On September 18, 2024, Hydrogen ORU SN 4 was removed and SN 5 was installed. As expected, the RSA outlet Quick Disconnect (QD) did not fully engage, indicating only one of two seals being in effect. This QD did not fully engage in prior Hydrogen ORU R&R's. Prior to starting OGA, the Vent Dome command is issued. This command evacuates the dome of gases and water (that may have diffused out of the internal components during years of storage) and brings the dome pressure to ~0.1 psia (689 Pa). This Vent Dome command was unsuccessful. After the third attempt, the command successfully completed. The cause was eventually understood to be due to issuing the command too early, before the dome 0.6 psia pressure sensors were in the proper range. Another issue was noted during the initial activation. With the pump off, the pump delta pressure (dP) sensor should be reading ~0 psid, however it was reading -1.3 psid (-8.96 kPa delta) after the Hydrogen ORU R&R. The cause for this is unknown and will need to be investigated further if the pump is returned to the ground in the future. The first Standby command was successful. The initial cell voltages were a little lower than expected (~1.47 V) during this first Standby. This was understood to be caused to be due to the membranes being well hydrated after years of storage. After several days, the Standby voltages increased to their nominal 1.53 V. The first Standby attempt ended with an unexpected Fast Shutdown, due to removing an override too early. On September 19, 2024, a second Standby was successful. After this, OGA was successfully commanded to Process. As of May 2025, the Hydrogen ORU SN 5 and cell stack continue to operate nominally. However, during several shutdowns in 2025, cell 1's voltage decay trend has appeared to be slightly out of family compared to the other cells. The OGA team will continue to monitor the cell voltage trends closely. As a precaution, the OGA team has recommended suspending on-orbit polarization scans (which slowly ramp up the current to 100% and check the corresponding voltage response) and also limiting production above 60% when practical. These steps may help extend the life of the cell stack, by reducing the chances of creating dry spots in the membranes.

Hydrogen ORU SN 4 has been returned to the ground for refurbishment. The goal is to complete the refurbishment as quickly as possible (by early 2026) for relaunch. The failed cell stack will be removed and a new redesigned OGA cell stack will be installed. The design improvements, which address the on orbit failures, include: chemically stabilized membranes (which should experience less mass loss during operation), membrane additives (that will minimize chemical degradation), a new cell stackup regime (that will minimize membrane deflection), and new frame seals (to minimize water loss). This redesigned cell stack (SN 1) was delivered in 2022. In 2023, water samples from the stack yielded unexpected results (including low conductivity and high pH) as described in Reference 1. The root cause was not fully understood. The team decided to institute regular water flushing and sampling while the cell stack was awaiting integration into the ORU.

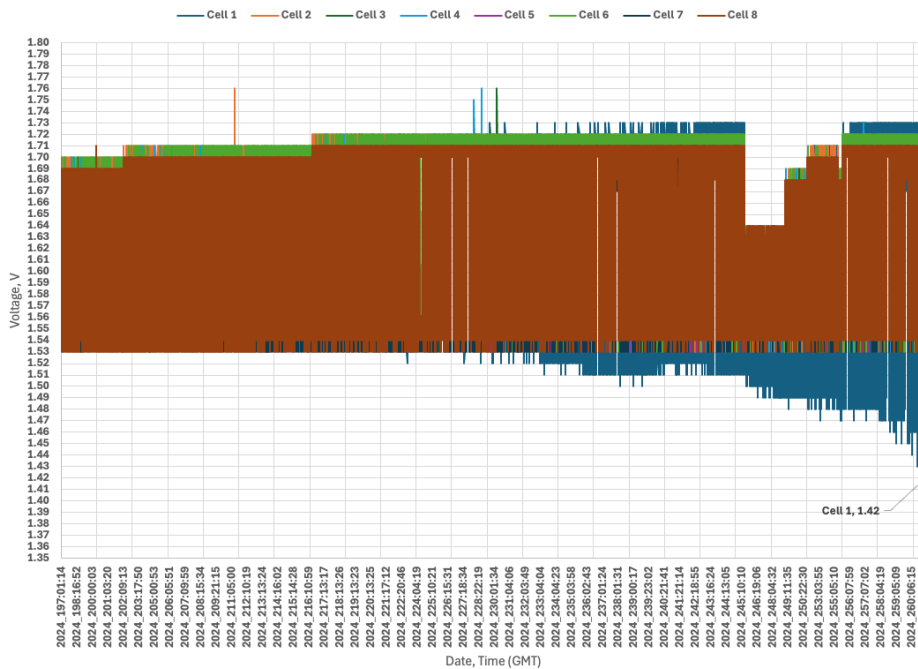


Figure 4. Cell Voltages for Hydrogen ORU SN 4 (2024)

B. Low Recirculation Loop Pressure

Nominally, the water recirculation loop pressure should be ~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. Past issues with low recirculation loop pressure are described in Reference 2. While Hydrogen ORUs SN 1 and 2 were installed, the pressure was stable at around 23 psia in Standby. However, 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. Hydrogen ORU SN 4 was installed October 20, 2021 through September 17, 2024. During this time the recirculation loop pressure was consistently low, at around 20.5 psia, as partially shown in Figure 5. Once Hydrogen ORU SN 5 was installed, on September 18, 2024, the recirculation loop has been fairly stable at 22.7 psia in Standby, as shown in Figure 5. Because Hydrogen ORU SN 5's back pressure regulator was from the same lot as SN4's, the OGA Team was expecting SN 5's recirculation loop pressure to be low, similar to SN 4. The OGA team will continue to monitor the pressure. If the good performance continues, the overrides might be removed.

After Hydrogen ORU SN 3 was returned to the ground, the back pressure regulator was removed and underwent performance testing, computed tomography (CT) scan, and a TT&E to determine the cause of the poor performance.⁴ Upon teardown, condensation and slight corrosion was found on some of the internal parts. Condensation can be expected since the hydrogen gas is saturated with water when leaving the RSA, but the corrosion was concerning. The corrosion 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.

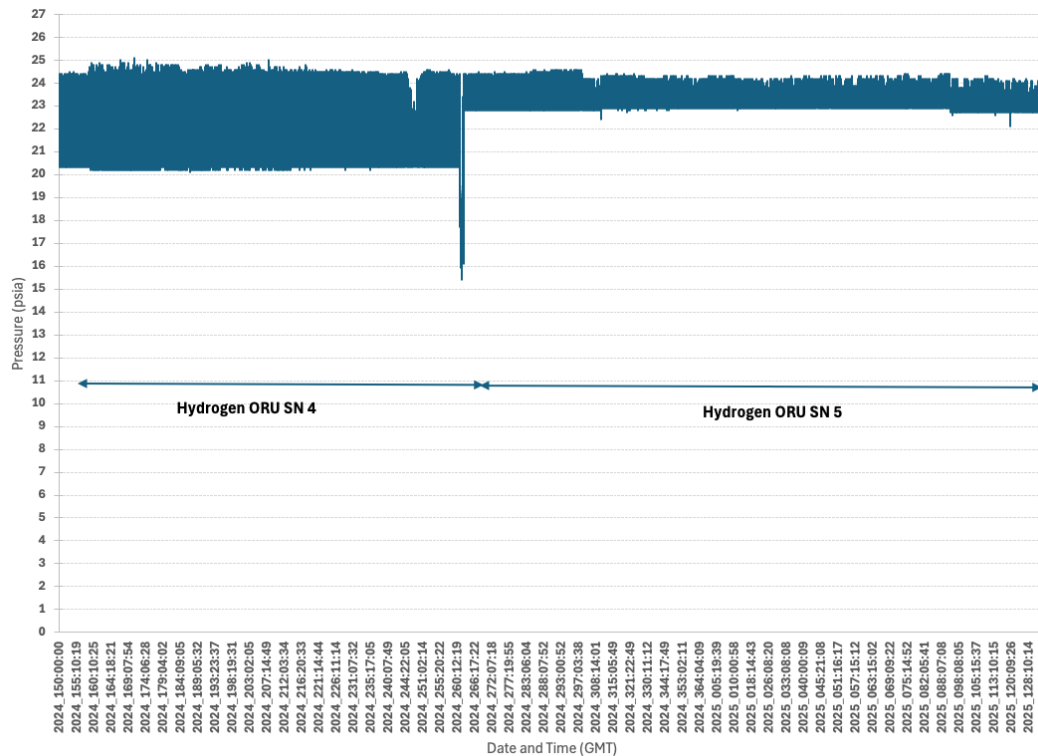


Figure 5. OGA Recirculation Loop Pressure

C. RSA High Quantity Faults

In 2024, there have been four faulted shutdowns when attempting to activate OGA. These faults were 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 team analyzed the faults and determined that the cause of the increases in RSA water quantity were due to gas in the Inlet Deionizing Bed and low recirculation loop pressure due to a faulty hydrogen back pressure regulator. This condition creates a delta pressure across the check valve between the feedwater section and the recirculation loop, and unintentionally pushes additional water into the RSA. The Inlet Deionizing Bed was R&R'd on May 3, 2024. The bed is launched with a nitrogen gas bubble to accommodate thermal expansion and prevent a pressure rise above Maximum Design Pressure (MDP). It takes about 6 months for the nitrogen gas to work its way out of the bed. The team traded two options: overriding the 3-way valve during startup to the wastewater bus position (to prevent water from being pushed into the RSA) or increasing the shutdown limit to 15 cu-in. The OGA team decided on the second option in August 2024. After implementing this option, there were not any more shutdowns. In addition, based on the feedwater pressure profile, the team determined that all of the gas has left the Inlet Deionizing Bed in November 2024. Since then, RSA increases during startup are now less than 10 cu-in. The OGA team will need to decide whether or not to restore the default shut down limit.

D. ACTEX life reduction

The ACTEX has always had a set installed life of 675 days. As previously mentioned, the ACTEX is a mixed resin bed, with its primary purpose being to remove fluoride (a byproduct of cell stack operation) from the recirculation loop to prevent corrosion. In October 2024, the OGA team decided to reevaluate the 675 day life for the ACTEX. The 675 day installed life assumed a 10% remaining resin capacity. Chemical analysis on 3 returned ACTEXs determined that fluoride was near the outlet, and that there was the potential for other chemical species, such as sulfate and bicarbonate, to displace the fluoride, increasing the risk of breakthrough, which would be detrimental to the cell stack. After reviewing this data, the team decided in 2024 to lower the installed life to 527 days, with an assumed remaining capacity of 30%. This would minimize the chance of fluoride breakthrough and better protect the cell stack.

E. Other Issues

Reference 1 describes other issues related to pump lockup, nitrogen leakage, and QD partial mate. There isn't any new progress to report on these issues, but should still be tracked until final closure.

Previously, several pumps locked up while installed in OGA, as described in Reference 3. The root cause and corrective action were identified. 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 QDs. This coating was applied by the vendor to act as a lubricant. The corrective action is to replace all pump QDs with ones that did not have the coating. Pumps SN 3 and 5 have been rebuilt with new QDs without the coating. SN 3 is an on-orbit spare and SN 5 is a ground launch on need spare. Pumps SN 2, 6, and 7 (with the suspect QD's installed) remain on-orbit and remain susceptible to lockup. Pump SN 2 was installed in OGA on May 2, 2023, and continues to operate nominally. When first installed, its current and temperature were higher than nominal². It was theorized that this was due to precipitation on the gears. After ~1.5 years, the current and temperature decreased to nominal values, possibly due to the gradual elimination of the precipitation. Pump SN 6 remains as an on-orbit spare, after previously being installed from May 7, 2021 to May 2, 2023. Pump SN 7 (last operated on the ground in June 2021) will be returned on SpX-33. Once on the ground, its suspect QDs will be removed. It will be tested to confirm it is a viable spare.

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. However, this TT&E has not been funded.

The crew was not able to fully mate the SN 3, 4, and 5 Hydrogen ORU 3/4 inch male QD to the rack flex hose 3/4 inch female QD in 2016, 2021 and 2024, as described in Section III-A and in References 2 and 4. 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 unless the currently installed rack hose is ever removed and returned to ground for TT&E.

The Hydrogen ORU contains three 0.6 psia pressure sensors of the same design. One sensor is in the hydrogen vent line and the other two are in the dome. Over the years, it has been noted that the hydrogen vent line pressure sensor consistently drifts downwards while the two dome pressure sensors do not significantly drift. This requires a complex on orbit recalibration every six months. Because the hydrogen vent line pressure sensor is continuously exposed to hydrogen, it is theorized that hydrogen permeates through the sensor diaphragm and into the vacuum reference chamber, causing the hydrogen vent line sensor to drift.

IV. AOGA Upgrades

Previous AOGA design and analysis work is described in References 2-4. 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 2019 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 typically measured in days, while an Exploration AOGA's would only be hours.

Several AOGA reviews have been successfully completed, as described in Reference 3. This includes: the AOGA Critical Design Review (CDR) (November 2022), various component level CDR's, AOGA Phase II Safety Review in Feb 2023, AOGA Delta-CDR in July 2023, and Interim Design Review (IDR) in Feb 2024. The final AOGA Phase III safety review will be in 2026.

The proposed AOGA schematic is shown in Figure 6 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.

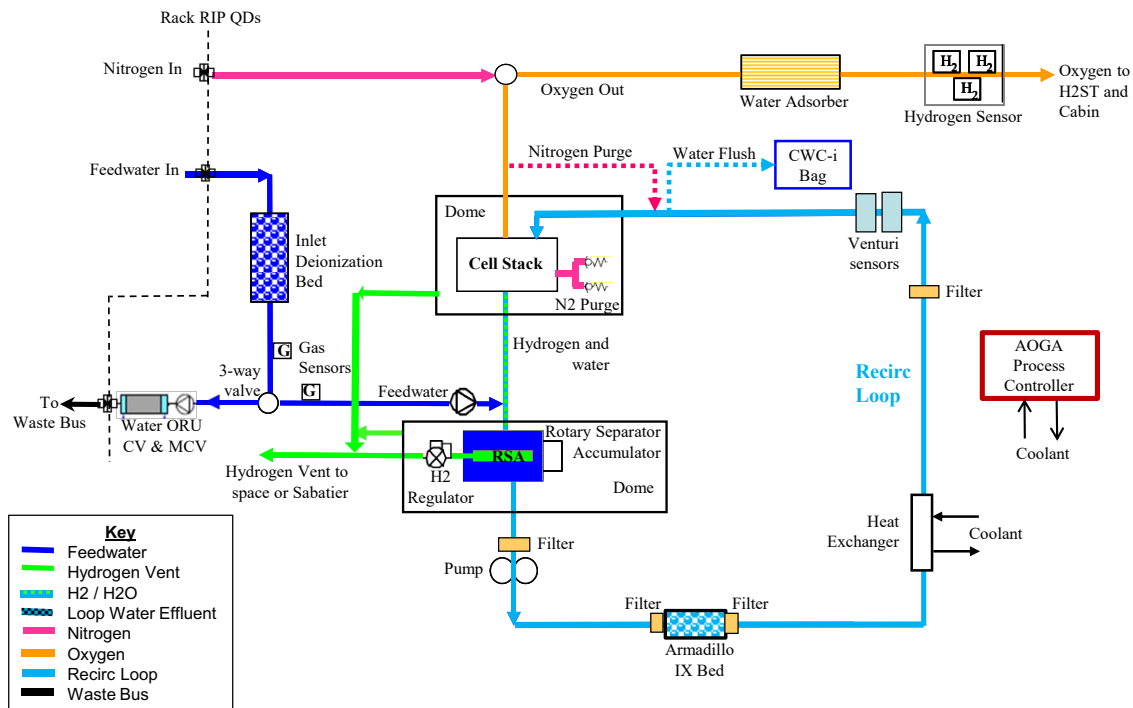


Figure 6. AOGA Simplified Schematic

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 a demonstration AOGA ground test (in 2026) properly demonstrating all operating modes prior to launch.

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 perform a 3x volume water flush

A. Cell Stack Redesign

Legacy OGA cell stack failures and TT&E results are described in Section III-A above. To address these failures, the OGA cell stack was redesigned as described in Section III-A. The AOGA cell stack will be based on the redesigned OGA cell stack, incorporating these design improvements to minimize membrane thinning: chemically stabilized membranes (reduce mass loss during operation), membrane additives (to minimize chemical degradation), and new frame seals (minimize water loss). A new AOGA cell stack feature will include sintered metal membrane supports to increase surface contact area to better distribute the load on the membranes.

AOGA cell stack development testing was completed in October 2024. Testing included: endurance test, microbial challenge test, cycle test, chemical challenge test, bleed resistor test, and particle shedding characterization test. The endurance test and microbial challenge test were completed in 2022 and described in Reference 3.

A chemical challenge test on two single cells (OGA single cell and AOGA single cell) was conducted between February 2024 and May 2024. An initial 5-day baseline test was performed with cell voltages recorded, then certain trace contaminants (dimethylsilanediol, DMSD, and dimethylsulfone, DMSO₂, typically found in the ISS OGA's water recirculation loop) were added to the recirculation loop and 5 days of additional electrolysis was conducted. Operation was then paused and the cells underwent 1 month of dormancy, after which operation was restarted for 5 days, and similar baseline and voltage tests were conducted to evaluate the post-dormancy cell performance. During the baseline test, both the OGA and AOGA single cells both had fairly stable voltages at around 1.75 V. After the contaminant introduction, the OGA and AOGA single cell voltages started to rise gradually, reaching 1.85 and 1.79 V respectively. After the dormancy period the OGA cell voltage spiked to above 1.90 V and could not sustain operation at the 100% production rate, while the AOGA cell voltage remained fairly stable at ~1.8 V. The AOGA cell design demonstrated better performance than the OGA cell design in the presence of contaminants.

Bleed resistors are part of the OGA cell stack design and are included in the AOGA cell stack design. Bleed resistors reduce the 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 was

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 was performed from June to September of 2024 using an AOGA 3-cell development stack with bleed resistors. The cell stack was first operated continuously at the 100% production rate for 720 hours to establish a baseline. Throughout this first test, all cell voltages were nominal, close to 1.7 V. Then the 3-cell stack was subjected to 100 on/off cycles (30 minutes on/6 hours off). At the end of the cycles test, all cell voltages were nominal (less than 1.7 V) and almost no cell voltage degradation was noted. Cell stack health checks, including polarization scans and resistance checks, performed at the beginning and end of the cycles test, showed virtually no degradation. Test results demonstrated that bleed resistor presence would have a negligible effect on the voltage performance or life expectancy of a full-scale cell stack, and the decision was made to keep the bleed resistors in the final AOGA design.

Finally, a particle shedding characterization test was performed on the same AOGA 3-cell development stack used in the Bleed Resistor Test. The legacy OGA cell stack is known to shed catalyst particles. The concern is that these catalyst particles could potentially collect in the RSA and become an ignition source. In addition, the particles could collect in the downstream relief valves and 3-way valve and cause leakage. The stack underwent a 2-day green run baseline test, then was operated for 200 hours while the downstream water filters were analyzed for particles shed from the cell stack. After the Bleed Resistor Test concluded, the stack was run for an additional 200 hours of testing, with the same filter analysis performed. The new AOGA cell stack design has an improved membrane catalyst application process, which was shown to significantly reduce the particle shedding rate such that it would have a negligible effect on the life expectancy of a full-scale cell stack and its downstream valves and fittings.

The flight AOGA cell stack (SN 1) was built in March 2025. All major components (baseplate, membranes, frames, etc.) finished their manufacturing processes and were built into subassemblies, and then stacked on the cell stack baseplate and compressed to produce the first flight AOGA cell stack. Two baseplates were machined by the vendor and delivered in May 2024. However, the first baseplate, planned for use in the first stack, was damaged. One of the threaded holes, used for the tie rods, was damaged beyond repair. The team analyzed different repair options, but in the end decided that the chance of a successful repair was low given the fracture critical nature of the part. The team decided to use the backup baseplate for the build of the first AOGA cell stack and procure another baseplate. Cell stack acceptance testing is ongoing, including: green run, proof/leak test, cell resistance test, polarization scan, and endurance test. Cell stack delivery is expected in July 2025. The build of the spare AOGA cell stack will begin later in 2025, after a replacement baseplate is delivered.

B. Dome Redesign

The legacy OGA design houses all the hydrogen containing components (including the 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 2 and 3). 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.

As mentioned above, 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, mounted on a removable tray. The design is shown in Figure 7, 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). Previously completed development tests are described in Reference 4.

The OGA will be upgraded to the AOGA configuration by replacing the Hydrogen ORU with the OHDA. The OHDA will have the same fluid and electrical interfaces as the legacy Hydrogen ORU. The OGS rack structure will need to be modified by the crew to accommodate 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.

Manufacturing of both the RSA dome forging and baseplate was completed in April 2024. The AOGA RSA was completed in August 2024. As mentioned in Section III-B above, the RSA back pressure regulator has been redesigned to incorporate the lessons learned from the TT&E conducted in 2023. The flight back pressure regulator was delivered from the vendor in June 2024. However, in March 2025, the qualification unit suffered a leakage failure after being subjected to 700,000 cycles. The team is currently determining what effect the qualification test failure would have on the flight unit, taking into account that the flight unit is expected to see much less than 700,000 cycles on-orbit. The current plan is to disassemble qualification unit to inspect the poppet and seat to determine the root cause of the leakage failure. The RSA delta pressure sensors, used to calculate internal RSA water quantity, are being reused from OGA. These sensors were recalibrated in 2023 by the vendor. The RSA dome contains pressure sensors to measure the water recirculation loop pressure (two 0 – 30 psia range sensors) and to measure dome pressure (one 0 – 20 psia sensor). These sensors are being redesigned for AOGA and procured from a new vendor, with delivery scheduled for June 2025. Delivery has been delayed due to weld and calibration issues. The RSA dome assembly will start in July 2025 and be complete by November 2025.

Manufacturing of the cell stack dome forging was completed in June 2024. As mentioned in Section IV-A, the baseplate was completed in November 2024 and the cell stack is projected to be delivered in July 2025. The cell stack dome (which is normally kept at vacuum) contains two pressure sensors (0 – 0.6 psia range) to measure dome pressure. These sensors are being redesigned for AOGA and are being manufactured by a new vendor. These sensors have a different diaphragm material, which should allow less hydrogen to permeate into the vacuum reference chamber, and are therefore expected to experience less drift than the legacy sensors (see Section III-E). The vendor is projected to deliver the sensors in July 2025. Similar to the 20 psia and 30 psia pressure sensors (mentioned above), the 0.6 psia sensors have experienced a delay in the delivery date. The cell stack relief valves (inside the cell stack dome) are being redesigned to incorporate finer mesh screens to better protect the valves from particulates. Previous TT&E's on relief valves have identified particulate on the seats which could have contributed to leakage failures. New relief valves are projected to be delivered from the vendor in May 2025. The cell stack dome assembly will start in May 2025 and be complete by October 2025.

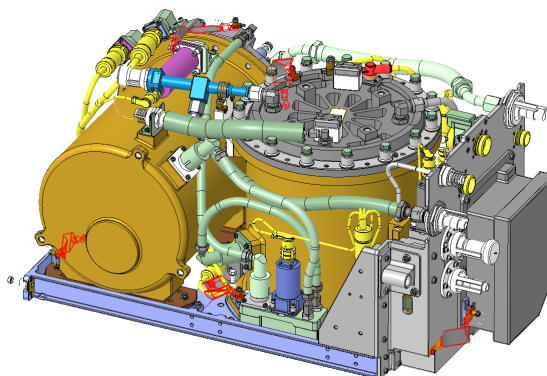


Figure 7. OHDA

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 during Process mode, due to normal leakage from the dome internal components. Dome pressure needs to be kept below the 0.25 psia (1.7 kPa) shutdown limit. 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 feedwater check valve allows feeding water to the system for electrolysis, while protecting the wastewater bus from the generated hydrogen that could flow back into it (see Figure 6). Operational data from the current OGA system showed that in certain conditions, there could be a 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 wastewater bus. 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. The AOGA check valve has been built and completed acceptance testing at the vendor. Delivery will be in May 2025.

The AOGA contains normally open and normally closed solenoid valves. These valves control the venting of hydrogen to space vacuum and the venting of the dome volumes of small amounts of hydrogen, oxygen and water. These valves are being redesigned for AOGA. The valves have been assembled by the vendor and are currently undergoing acceptance testing. The valves are projected to be delivered in May 2025.

QDs and flex hoses are currently being manufactured by the vendor. The QDs allow connecting/disconnecting the OHDA to the existing OGA. The hoses route water, hydrogen, oxygen, and nitrogen into and out of the domes. The QDs and hoses are projected to be delivered by the vendor in June 2025.

An assessment of normal leakage of the dome internal components into the dome during Process mode was conducted. It concluded that leakage is dominated by water diffusion through the cell stack membranes to the dome.

The new AOGA cell stack design with edge seals (as mentioned in Section IV-A) is predicted to significantly reduce that leakage and allow the system to run for at least 100 minutes in Process without reaching the shutdown limit. Once the OHDA is built, it will be tested on the ground in 2026 in a test rig 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

Hydrogen sensors are required in the oxygen line to monitor for hydrogen leakage coming from the cell stack. Nominally, the product oxygen contains <0.1% H₂/O₂. The cell stack must be replaced if the product oxygen ever contains greater than 1% H₂/O₂. Mixtures greater than 4% H₂/O₂ are considered hazardous.

Issues with the legacy OGA hydrogen sensors are described in Reference 1. 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 Commercial off the Shelf (COTS) catalytic bead 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 5 and 6. 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 8), after the OGA was moved from Node 3 to the US Lab. H2ST is installed on the right side of the OGS Rack.



Figure 8. H2ST Integrated with OGA

On July 14, 2022, Sensor 3 failed, after about 3 months of powered on operation, 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.

On January 19, 2025, Sensor 1 failed, after about 2.9 years of powered on operation. Similar to Sensor 3, Sensor 1's output dropped off scale low to -1% H₂. Its input current became erratic, alternating between 50 mA and 270 mA.

The root cause for both failures is unknown. As a point of reference, the H2ST ground engineering development unit has been powered on continuously in the OGA Ground Testbed since September 2022 without any failures. In addition, 3 standalone sensors have also been powered on continuously on the ground for about the same amount of

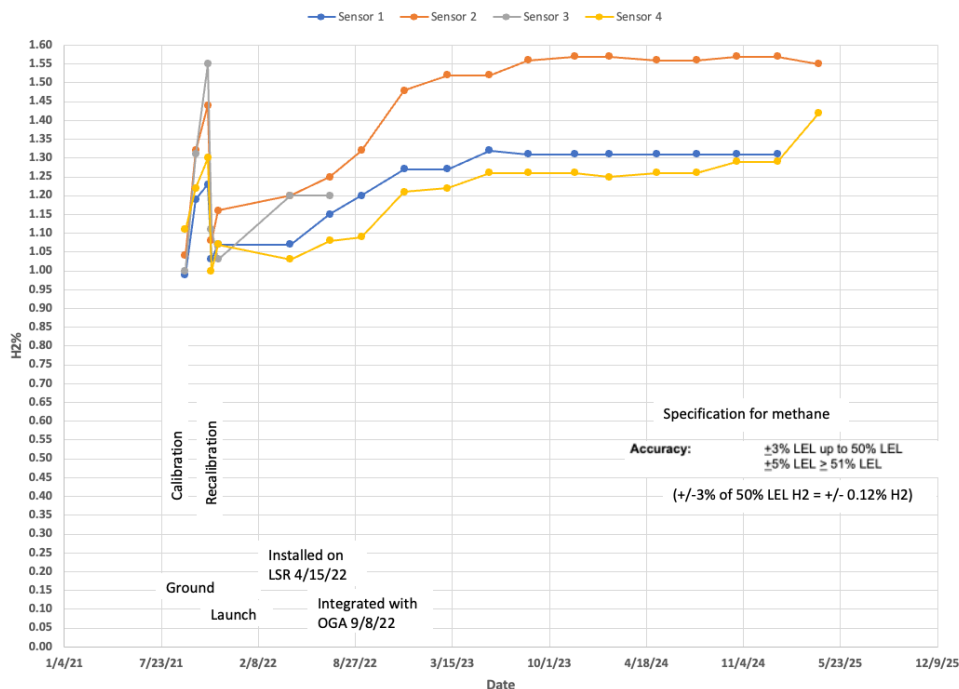


Figure 9. H2ST Drift Checks

time without any failures. The sensors are COTS and contain commercial grade Electrical, Electronic, and Electromechanical (EEE) parts. It is hypothesized that the flight sensors may have failed after their commercial EEE parts were exposed to the space environment, and that the catalytic bead hydrogen sensor technology is still viable.

The H2ST team is currently developing a proposal to troubleshoot and repair the two failed sensors. Troubleshooting might involve checking voltages at test points and installing a display board to determine if any error codes are displayed. Repair might involve replacing the electronics boards for the corresponding failed sensors. Potential concerns include having the crew manage non-captive fasteners and cutting and stripping wires.

Every 90 days, a drift check is performed: the crew flows calibration gas (1.0% H₂/air) from a drift check kit bottle through the H2ST sensors for 1 minute, and the sensor response is recorded. There have been 14 drift checks performed so far, as of May 2025. The drift of the sensors over time is shown in Figure 9. After H2ST was first installed on-orbit, an upwards drift was noted. From May 2023 to Jan 2025, no upwards drift was noted with the functioning sensors. When exposed to 1.0% H₂/air, Sensors 2 and 4 currently report 1.55% and 1.42% 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 and powered on for 3.03 years, and counting.

The on-orbit drift kit bottles (SN 1 and 2) will expire in July 2025. A new bottle (SN 5) will be launched on SpaceX-33 in August 2025. The plan is to return SN 1 and keep SN 2 on-orbit as a degraded spare.

Cell Stack SN 6 (installed in Hydrogen ORU SN 4) was R&R'd from OGA on Sept 18, 2024 (GMT day 261) due to low cell voltage (see Section III-A above). Prior to the R&R, the H2ST sensors (red, yellow, and green lines in Figure 10) were gradually increasing. In addition, the legacy OGA hydrogen sensors (blue, orange, and gray lines in Figure 10) were also gradually increasing. The decreasing cell voltage was suspected to be due to membrane thinning, which could potentially be allowing some small amount of cross cell leakage (hydrogen into oxygen). After the failed cell stack was replaced with a new cell stack (in Hydrogen ORU SN 5), a small but noticeable decrease in the H2ST sensor readings and legacy OGA hydrogen sensors is evident. The currently installed cell stack (SN 7) was acceptance tested in 2010, and 0.10% H₂/O₂ was recorded.

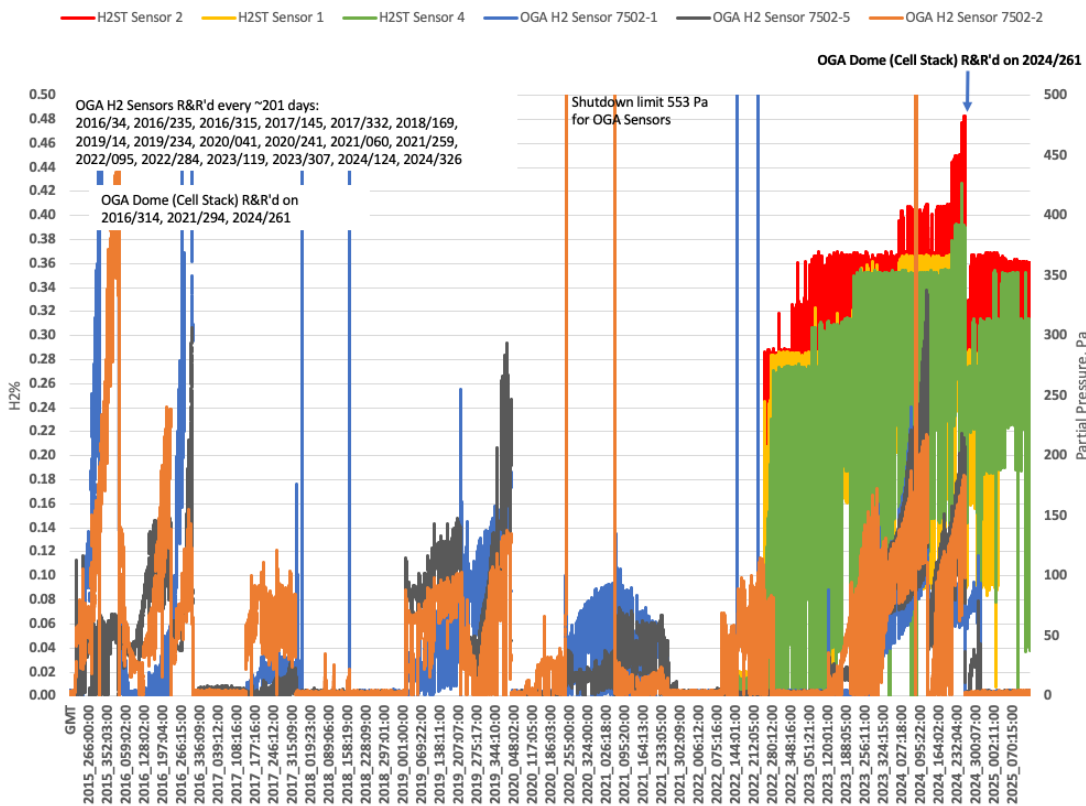


Figure 10. H2ST (H₂%) and Legacy OGA H₂ Sensor (ppH₂) Response

The H2ST will remain installed for the foreseeable future. Drift checks and trending every 90 days will continue. The H2ST team is awaiting approval to perform further troubleshooting and/or repair of Sensors 1 and 3.

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. The ACTEX was not specifically designed for the OGA application, and as such there are operational issues: high delta pressure, limited life, non-compliance with seal redundancy requirements and MDP requirements. These issues are further 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. Previous development and design work include: a resin capacity analysis (2022), particulate capacity analysis (2022), and the CDR (2023). These are further described in References 2 and 4.

The ARMADILLO design is shown in Figure 11. 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 design addresses the issues related to the legacy ACTEX design. The ARMADILLO will have a significantly reduced dP, contain redundant seals, and be properly designed to handle MDP. The design has eliminated welds to ease manufacture and refurbishment. ARMADILLO is projected to have a 3 year life, with a 30% remaining capacity at the end of life.

A total of four ARMADILLO cartridges will be built. The hardware piece parts have been fabricated. Assembly will begin in July 2025, with acceptance testing being performed in August and September 2025. Two ARMADILLO flight units will be delivered in October 2025. The first unit will be 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. 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.⁷ 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 the nitrogen purge hose 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). 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 the hydrogen vent line. 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.

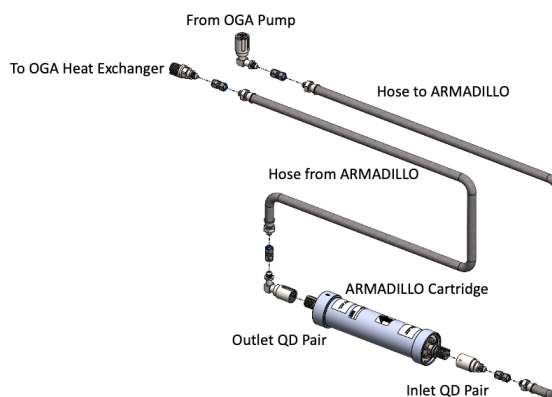


Figure 11. ARMADILLO Design

Next, a water flush of the recirculation loop is performed. The crew will connect the water flush hose and Contingency Water Container-Iodine (CWC-I) bag to the recirculation loop (the blue dashed line labeled water flush in the schematic, Figure 7). The hose contains a manual valve (to start and stop the flush) and a metering valve (to control the flow rate). 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 a 3x volume water flush has been performed, the manual 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.

A demonstration test was successfully performed in April 2025 using the OGA Ground Testbed and development nitrogen purge and water flush hoses. A nitrogen purge was performed which resulted in low cell stack voltage and a stable recirculation loop pressure while the pump and RSA were on and the cell stack was unpowered. This indicated that most of the hydrogen was removed from the RSA and recirculation loop. When there is hydrogen present, the pump continually delivers dissolved hydrogen from the RSA to the cell stack, and a fuel cell reaction takes place with the residual oxygen, causing increasing cell stack voltage and decreasing recirculation loop pressure. After the nitrogen purge, a water flush was performed. Nine liters of water was flushed into a CWC-I bag. This was a 3x volume exchange of the water recirculation loop with fresh DI water.

COTS components will be used in the flight nitrogen purge and flush hose assemblies. Development testing of these COTS components was completed in 2023. A delta CDR was held in July 2023 to review the design of the manual purge and flush hardware. Previous design decisions are documented in Reference 4. The purge and flush hose assemblies will be built in late 2025.

V. Conclusion

Manufacturing of AOGA flight hardware components is almost complete. Next, the top level OHDA assembly will be completed in 2025. An integrated AOGA system test will be performed in 2026. 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 2026 timeframe. The AOGA will be demonstrated on ISS for a minimum of 3 years.

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