Status of the Advanced Oxygen Generation Assembly Design

Kevin Takada[1]
NASA Marshall Space Flight Center, Huntsville, AL, 35812, USA

David Hornyak[2]
NASA Johnson Space Center, Houston, TX, 77058, USA

Alesha Ridley[3]
NASA Johnson Space Center, Houston, TX, 77058, USA

Steven Van Keuren[4]
S&K Global Solutions, Inc., Polson, MT 59860, USA

Phillip S. Baker[5]
Collins Aerospace, Windsor Locks, CT, 06096, USA

and

Stephen H. McDougle[6]
Sierra Lobo, Inc., Las Cruces, NM 88005, USA

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 system weight, crew maintenance time and spares mass while increasing reliability. Over the past year, the team has performed additional design reviews, testing and analysis in an effort to optimize upgrade efforts and achieve the best value that meets Exploration mission requirements. Upgrades that will be incorporated include: redesign of the electrolysis cell stack, redesign of the hydrogen dome, replacement of the hydrogen sensors, redesign of the recirculation loop deionizing bed, and incorporation of recirculation loop nitrogen purging and water flushing. The ISS OGA will be upgraded to an Advanced OGA (AOGA) configuration and its operation demonstrated in a relevant flight environment.

Nomenclature

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

[1] ECLSS Systems Engineer, ECLSS Development Branch, MSFC/ES62
[2] Exploration ECLSS Integrator, ISS Vehicle Office, JSC/OB311
[3] Exploration ECLSS Branch Manager, ISS Vehicle Office, JSC/OB311
[4] ECLS Systems SME, S&K Global Solutions, Inc., Polson, MT
[5] Research Engineer, Space Solutions
[6] Senior Project Engineer, NASA White Sands Test Facility, 12600 NASA Road, Las Cruces, NM

DMSO2 = dimethylsulfone
dP = Delta Pressure
H2ST = Hydrogen Sensor Technology Demonstration
ISS = International Space Station
LSR = Life Support Rack
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
TT&E = Test, Teardown, and Evaluation

I. Introduction

FUTURE deep space exploration missions will require 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 system weight, crew maintenance time and spares mass 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 simplified schematic is shown in Figure 1. The OGA consists of the following nine Orbital Replacement Units (ORUs): Water, Inlet Deionizing Bed, Hydrogen, Recirculation Pump, Nitrogen Purge, Oxygen Outlet, Hydrogen Sensor, Power Supply Module (PSM), and Process Controller. Feed water from the ISS potable water bus enters the OGA through the Water ORU and flows through an Inlet Deionizing Bed, which serves as an iodine remover and as a coalescer for any oxygen gas bubbles that may be present in the feedwater. If gas bubbles are detected by the gas sensor downstream of the deionizing bed, the feedwater is rejected by a three-way valve to the wastewater bus. This prevents any oxygen that may be present in the feedwater from mixing with the hydrogen in the Rotary Separator Accumulator (RSA). The wastewater interface includes a check valve to prevent backflow of wastewater into the OGA and Microbial Check Valve to prevent microorganisms in the wastewater from contaminating the feedwater. Water is electrolyzed by the cathode feed cell stack to produce

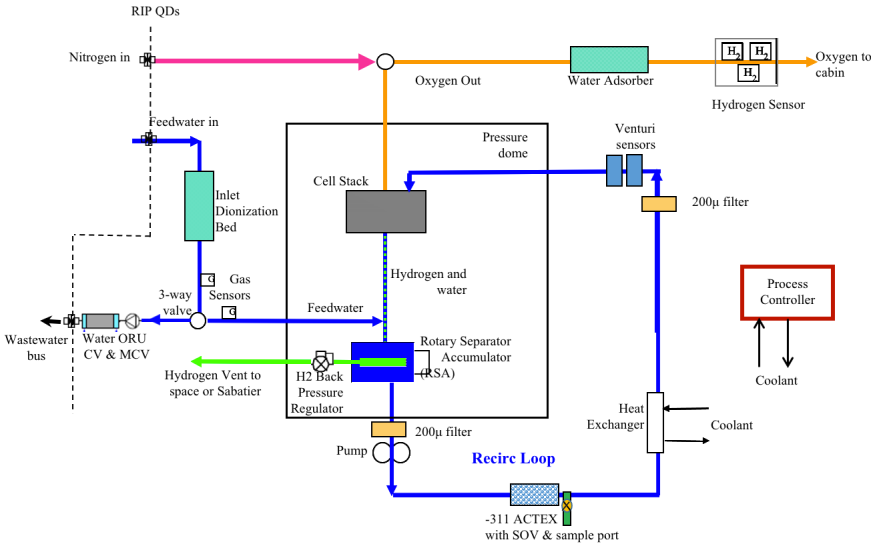


Figure 1. ISS OGA Simplified Schematic

oxygen and hydrogen. The RSA separates the cathode side product gaseous hydrogen from the water. The Hydrogen ORU consists of a dome which surrounds the components which contain hydrogen (cell stack, RSA, sensors, valves, etc.). The hydrogen dome provides a multiple leakage barrier protection in the event of a failure. The hydrogen dome is maintained at low pressure by periodically venting to space vacuum. The water is recirculated by the positive displacement pump. The pump contains an integral relief valve to protect against an unintentional deadhead condition. Downstream of the pump is an Activated Carbon Ion Exchange (ACTEX) filter. The ACTEX is a mixed resin bed deionizer, which removes fluoride generated from the cell stack and other contaminants. The heat exchanger removes 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, hydrogen) are used for system operational control and fault detection and isolation. The PSM ORU provides power to the OGA electrolysis cell stack. The PSM ORU provides a variable range of 10-46.9 amps (A) of current to the OGA cell stack during Process mode and 1.0 A during Standby mode.

The ISS OGA generates oxygen at a selectable rate, up to 20.4 lb/day (9.25 kg/day), at 46.9 A PSM current, 100% 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, as well as the Inlet DI Bed and ACTEX which are trended for water throughput and recirculation loop water quality to determine the preventative maintenance replacement intervals.

III. ISS OGA Current Status

The ISS OGA has been operating for over 14.5 years and is currently installed in Node 3 of the ISS. As of March 15, 2022, the ISS OGA has produced 24,355 lb (11,047 kg) of oxygen and 3,044 lb (1,381 kg) of hydrogen. The currently installed OGA electrolysis cell stack (installed in October 2021) has accumulated a total operating time of 2,101 hours. Several new issues have developed in the past year involving the pump, recirculation loop, cell stack, nitrogen purging, and quick disconnects (QD's). These issues will be described below.

A. Pump Lockup

On March 23, 2021, degraded Pump ORU serial number 1 (SN 1) was removed and replaced with new spare pump SN 3 (Reference 1). Pump SN 3 failed to rotate when power was applied to it. Pump SN 3 was then removed and new spare pump SN 4 was installed. Pump SN 4 also failed to rotate. Both spare pumps were stored for over 10 years, filled with deionized water, without being operated. At this point, degraded Pump SN 1 was reinstalled to regain functionality of the OGA. Ground spare pumps SN 2 and 6 (stored for 5.8 and 0.2 years respectively) were then pulled from storage, and both passed an abbreviated functional test. These two ground spare pumps were quickly launched on SpaceX Crew-2. Pump SN 7 was built in 2021 and launched on NG-16 and is currently on board as a spare. Ground spare pump SN 5 was pulled from storage (after sitting stagnant for approximately 10 years) and failed to rotate when powered. Pump SN 6 was installed in OGA on May 6, 2021 and successfully rotated and remains operational. Failed pump SN 3 was returned on SpaceX Crew-1 to the ground for a test, teardown and evaluation (TT&E). Failed pump SN 4 will be returned on SpaceX-25 in July 2022.

A TT&E of Pumps SN 3 and 5 have been performed. Green precipitation was discovered on the gears and passages of the pump, as seen in Figure 2. The green line is at the interface of a gear tooth to the side wall, essentially locking the gear in place. This precipitation was sufficient to prevent rotation of the pump gears, given the low torque rating of the pump motor. These deposits were determined to be nickel phosphate, with the source being from the lubrication coatings on the internal surfaces of the pump's quick disconnects (QD's).



Figure 2. Green Precipitation in Pump SN 5

Based on these findings, new QD's are being procured without the coating on the wetted surfaces. The lead time of these QD's are approximately 1 year. Future pump spares will be built with the new QD's. In the meantime, the spare pumps on-orbit, SN 2 and 7, with the older style QD's, will require periodic flushing (every 6 months) to minimize the potential for precipitation forming on the gears. As of April 2022, they have been stagnant for 13 months and 10 months respectively. A crew procedure has been released to power spare pumps outside of the system, via the OGA controller and flush 10 liters of deionized water through the pumps from a source Contingency Water Container – Iodine (CWC-I) to a destination CWC-I. Sampling of the stagnant water within the pumps will also be performed using a syringe. This sampled water and flush effluent will be returned to the ground for analysis. This analysis will help to gauge the effectiveness of the periodic flushing and likelihood of precipitation formation. The flushing and sampling of the spare pump SN 2 is planned for May 2022.

B. Low Recirculation Loop Pressure

Nominally, the water recirculation loop pressure is approximately 24 psia (165,474 Pa) while in Standby and Process. The pressure is maintained by the hydrogen back pressure regulator, which is integral to the Hydrogen ORU

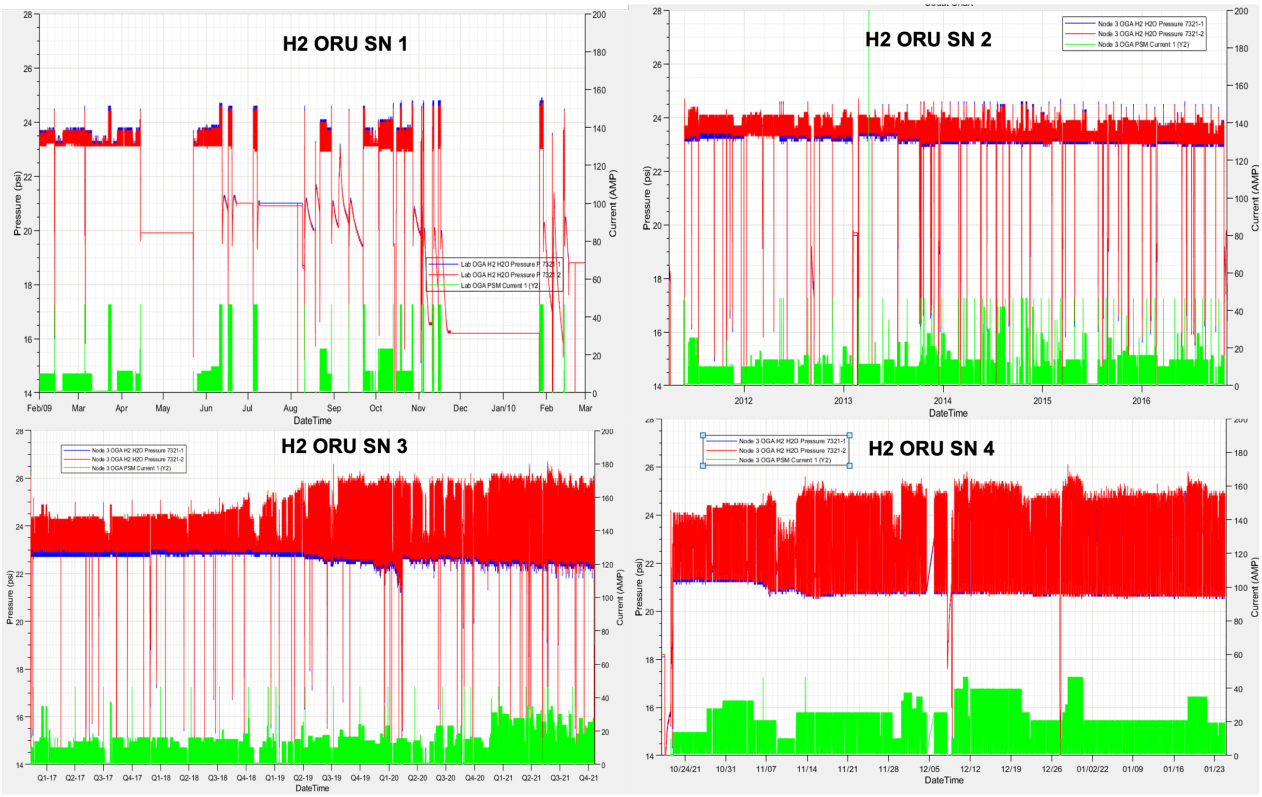


Figure 3. Recirculation Loop Pressure (shown in red)

(see Figure 1). The default software low limit shutdown value is set to 20.5 psia (141,343 Pa), to ensure the cell stack hydrogen pressure is maintained above the oxygen pressure (close to ambient pressure) so that cross cell leakage can be detected via the oxygen outlet pressure sensors and hydrogen sensors. On Feb 10, 2020, the OGA shut down due to a low recirculation loop pressure of about 20.2 psia (139,274 Pa) while in Standby, see Reference 1. The recirculation loop water pressure had been slowly degrading during Standby since late 2019. In 2021, the low limit was reduced to 20.3 psia (139,964 Pa) and then finally to 19.0 psia (131,000 Pa) in an effort to prevent the OGA from shutting down due to low recirculation loop pressure.

The recirculation loop pressure while Hydrogen ORU SN 3 was installed remained low, until the ORU was replaced on October 20, 2021 with SN 4. Hydrogen ORU SN 3 was removed due to a low cell stack voltage (see next section). Examining Figure 3, it can be seen that the recirculation loop pressure (in red), with Hydrogen ORU SN 3 installed, had a wider band than when SN 1 and SN 2 were installed. The recirculation loop pressure with the new Hydrogen ORU SN 4 installed is lower and also has a wider pressure band than when the previous three ORU's were

installed. Currently, the pressure is holding at around 20.5 psia (141,343 Pa) while in Standby, which is sufficiently above the temporary shutdown low limit of 19.0 psia (131,000 Pa). The regulators in Hydrogen ORU SN 1 and 2 are from one lot, while the regulators in Hydrogen ORU SN 3 and 4 are from another lot. The pressure will continue to be closely monitored by the OGA Team. The back pressure regulator in Hydrogen ORU SN 3 has been returned to the ground and will undergo a TT&E in May 2022 to determine the root cause of the pressure anomalies.

C. Cell Stack Low Voltage

The voltage of the 28 cells in the cell stack are regularly monitored for out of family conditions. Cell voltages (during startup, shutdown, Standby, Process) and polarization scans are trended over time. Cell voltage below 1.0 V

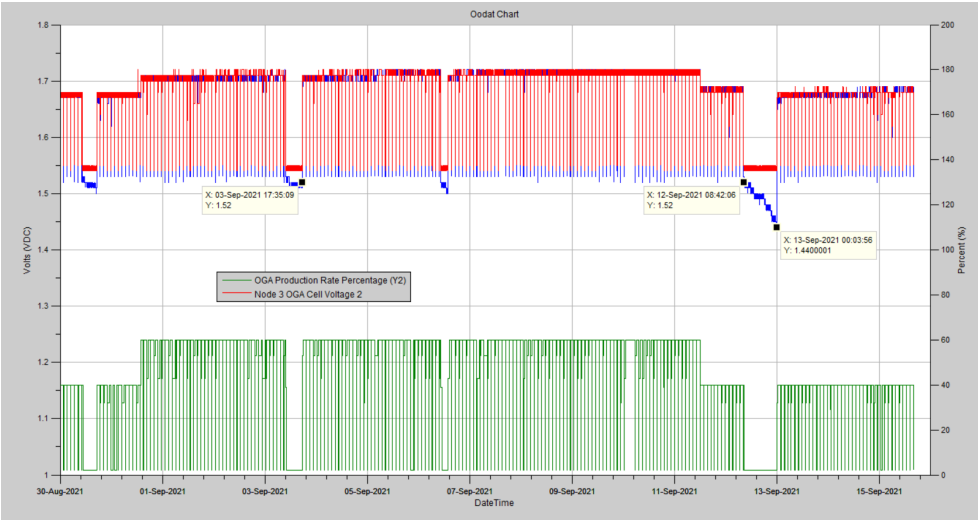


Figure 4. Cell Voltages (Cell 1 in blue), Hydrogen ORU SN 3

would indicate possible membrane thinning and a partial short. If the condition is not addressed, a localized hot spot could occur and a pinhole leak of hydrogen into oxygen could occur, leading to a possible combustion. The low voltage failure of the cell stack in Hydrogen ORU SN 2 is documented in Reference 2. Hydrogen ORU SN 2 was removed and returned to the ground in 2016. Hydrogen ORU SN 3 was installed in 2016. In September 2021, the OGA Team noted that the Cell 1 in Hydrogen ORU SN 3 starting to exhibit progressively lower voltages while in Standby. At that point, the cell stack had been under compression for 13 years, and operating for 5 years. Cell 1 dropped from ~1.52 V to 1.44 V during the brief Standby intervals on September 12, 2021, as shown in Figure 4 (cell 1 is shown in blue), while the other cells remained at ~1.52 V. Standby occurs when the production rate (shown in green) drops to 2%. In addition, it was noted that both cells 1 and 28 were the slowest cells to charge during activation, and the fastest to discharge during deactivation, as compared to the other cells. Cell voltages upon shutdown on August 18, 2021 are shown Figure 5. The voltage of cells 1 (in blue) and 28 (in brown) drop to 0 V significantly faster than others. This data is possibly indicative of thinning membranes, due to creep while under compression and chemical degradation during electrolysis, similar to what was seen with the previous cell stack. Given this data, the ISS Program decided to preemptively remove Hydrogen ORU SN 3 and replace it with new spare SN 4 on October 20, 2021. Although SN 3 was still functional, the risk of a hydrogen leak and combustion would be present. The cell stack in Hydrogen ORU SN 4 continues to operate nominally. Hydrogen ORU SN 3 was returned to the ground and a TT&E of the cell stack is planned for June 2022 to determine the root cause of the low voltage. The TT&E of the cell stack in Hydrogen ORU SN 3 will be similar to what has been done with SN 2. Steps will include: visually inspecting the cell stack exterior for anomalies, disassembling the cell stack, visual inspection of the cell membranes for pinhole leaks, debris and other anomalies, cross sectioning of the membrane to determine the degree of thinning, and analyzing the membrane material for contamination.

D. Nitrogen Leakage

The Nitrogen Purge ORU has a tank which is charged with nitrogen upon startup to ~ 76 psia (524,002 Pa). This nitrogen is stored in the tank until a system shutdown occurs. Upon shutdown, the nitrogen oxygen 3-way valve is unpowered and releases the nitrogen to purge the cell stack anode of oxygen to create a safe shutdown configuration. The nitrogen pressure nominally stays steady at 76 psia (524,002 Pa) indefinitely (for many weeks without requiring a recharge), until a shutdown occurs. The OGA controller will add additional nitrogen from the nitrogen bus if the pressure drops to 70 psia (482,633 Pa). However, in December 2021, the OGA Team noted frequent depressurization and re-pressurization cycles with Nitrogen Purge ORU SN 1 (18 years old), with the pressure dropping from 76 psia (524,002 Pa) to 70 psia (482,633 Pa), and then increasing back to 76 psia (524,002 Pa) when the controller repressurizes the tank. Re-pressurizations were occurring every ~5 hours (whereas they were never occurring prior to December 2021). Figure 6 shows the continual depressurization and repressurization of nitrogen (red line). This parameter should nominally be a flat line rather than a sawtooth line. The most likely cause is a small internal leak in the 3-way valve, which slowly releases nitrogen into oxygen outlet line and into the cabin. This small amount of leakage has a negligible effect on nitrogen reserves and cabin nitrogen partial pressure, however the leakage needs to be addressed before getting worse.

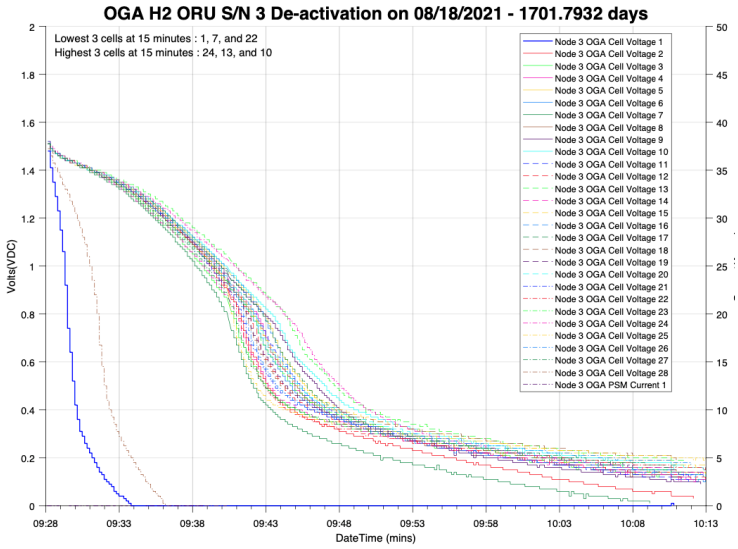


Figure 5. Cell Voltages upon Shutdown, Hydrogen ORU SN 3

The OGA Team performed troubleshooting and recovery steps in February 2022. An Inert Dome was commanded two times while the OGA was shut down. This command is normally used to fill the dome with nitrogen for long term storage. As part of the inerting process, the 3-way valve is cycled approximately 10 times, with pressurized nitrogen flowing through it. The intent of this troubleshooting was to exercise the valve in an attempt to release any debris that may be on the sealing surfaces of the valve and causing leakage. After the troubleshooting, the OGA was activated, and the nitrogen leakage was slightly worse. At that point Nitrogen Purge ORU SN1 was replaced with SN 2 on February 28, 2022. As of April 2022, SN 2 ORU continues to operate nominally, exhibiting no leakage. SN 1 ORU is planned to be returned to ground for TT&E.

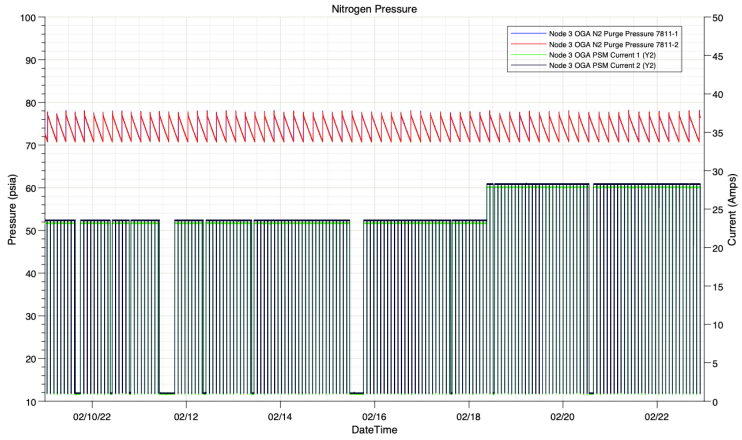


Figure 6. Nitrogen Pressure Cycling (red line)

E. Partial Mating of ¾ inch QD

While performing the Remove and Replace (R&R) of Hydrogen ORU's SN 3 and 4, in 2016 and 2021 respectively, the crew was not able to fully mate the ¾ inch QD on the ORU to the rack flexhose QD (which connects the RSA outlet to the pump inlet). The crew reported that the QD was about a quarter turn short of being fully mated. In this configuration, it is believed that only one of the two redundant QD seals is engaged. These partially mated configurations were index marked and taped in place, to minimize risk of QDs backing off during OGA operation. In

addition, the same issue was experienced when trying to mate Potable Water Adapters (SNs 1001 & 1002) to the rack flexhose QD.

An investigation of available ¾ inch QDs on the ground was initiated. A computed tomography (CT) scan of the Potable Water Adapter (SN 1001) QD showed a loose C-ring clip lodged within the spring area. C-ring clips are part of the female ¾ inch QD design. No other issues have been found with other ¾ QDs on the ground.

The QD partial mate failure investigation will continue after the ¾ inch QD from Hydrogen ORU SN 3 (returned to the ground on SpX-24) is removed and Adapter SN 1002 is returned to the ground on SpX-25 in July 2022. These two ¾ inch QD's will undergo CT scans. In 2024, the suspect rack flexhose will be removed, as part of the AOGA upgrade process, and returned to the ground for investigation.

IV. AOGA Upgrades

Previous AOGA design and analysis work is described in Reference 1 and 2. The AOGA design will focus on enabling component-level maintenance and modifying the existing cell stack design to improve both shelf and operating life and enabling dormancy. A 2017 supportability study (Reference 5) determined that enabling component level maintenance of the dome's internal components, would result in an estimated 617 lb (280 kg) of spares mass savings for a 1,100 day exploration mission. The proposed AOGA schematic is shown in Figure 7 and the list of proposed upgrades is summarized in Table 1. The system design is similar to the OGA, with the notable differences being that the AOGA will incorporate a redesigned cell stack, two independent domes, new hydrogen sensors, redesigned ACTEX, and a manual purge and flush capability for the water recirculation loop (as denoted by the "A" and "B" connection points). As previously mentioned in Reference 1, the obsolete systems electronics (Controller

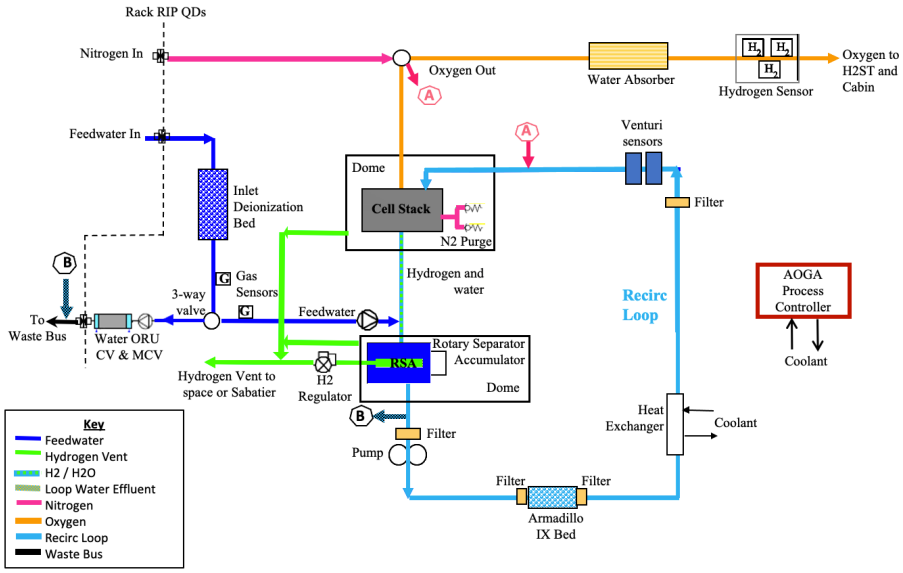


Figure 7. AOGA Schematic

and PSM) should be redesigned for Exploration, but the Program has decided not to demonstrate upgraded electronics as part of AOGA demonstration on ISS. The AOGA Critical Design Review (CDR) is scheduled for July 2022.

Table 1. AOGA Upgrades

Upgrade	Reason	Description
Redesign the cell stack	Implement corrective action based on the cell stack failure investigation to mitigate membrane thinning as well as implement current industry best-practices and standards	Provide better mechanical support for the cell membranes, replace the obsolete membrane with chemically stabilized Nafion
Replace the single dome with two domes	Reduce logistics resupply requirements	Crew will be able to access and maintain the cell stack, RSA and other components
Replace the hydrogen sensors	Reduce crew maintenance time, improve reliability, eliminate need for specialized purge tools	Replace hydrogen sensors with a more reliable technology that requires less crew intervention
Redesign the recirculation loop ACTEX	Increase installed life and reduce the delta pressure	The existing design is not optimal as it was not specifically designed for the OGA application
Manual recirculation loop purge and flush	Reduces contaminants within the AOGA recirculation loop that could be sent to Sabatier and cleans the system in preparation for dormancy	Purge hydrogen from the recirculation loop with nitrogen, then flush with potable water into a CWC-I bag or the ISS wastewater bus

A. Cell Stack Redesign

The drive for redesigning the cell stack started with the TT&E of cell stack SN 5 in Hydrogen ORU SN 2. The TT&E results are described in Reference 1. Cell stack SN 5 was returned from the ISS after a low voltage in cell 1 was observed. The TT&E found that cells 1, 2 and 28 had membranes with severe thinning, of up to 90%. This severe thinning might have eventually led to a membrane breach, allowing hydrogen to leak into the product oxygen. The cause of the excessive thinning in cell 1 is believed to be a unique compressive loading in comparison to other cells in the stack which resulted in progressively less resistive shunt paths and ultimately the low cell voltage failure. The TT&E of cell stack SN 4 (from failed Hydrogen ORU SN 3, returned to the ground in January 2022) in June 2022 will provide additional information.

The OGA cell stack was designed about 20 years ago. Since then, the industry has incorporated new materials, design improvements, and processing methods. The legacy design includes screens for membrane support, non-chemically stabilized membranes, and a now obsolete Membrane Electrode Assembly (MEA) processing method. While in storage, the legacy cell stacks experience water loss through the cell frame edges, necessitating regular water replenishment to prevent detrimental membrane dryout. The new AOGA cell stack design will incorporate improved membrane supports, chemical degradation mitigation, and new frame seals, while maintaining the same production rate and footprint. The AOGA cell stack layup has been designed to address the membrane thinning seen in the OGA cell stacks. Membrane creep resistance will be achieved by replacing the legacy screens with a porous metal support. Chemical degradation resistance will be achieved by using chemically stabilized membranes, a chemical degradation inhibitor, and improvements in the MEA processing method. Reduced water loss is achieved through a redesign of the edge seals to maintain cell stack hydration over longer periods without maintenance as will be required for expected Exploration dormancy operations. These modifications were made to enable an extended shelf life of 10 years plus an operational life of 5 years once installed.

The design of the AOGA cell stack layup has been finalized and initial testing was conducted to verify oxygen, hydrogen, and water flow are not hindered with the new design. Single cells, of the new AOGA design, have been built for development testing to be completed by September 2022. Single cell testing will include a 6 month endurance test (started March 2022), microbial challenge testing, and chemical challenge testing. Initial testing of the endurance single cell has demonstrated performance within cell stack design specifications. Performance data will be recorded to capture a baseline data set to compare to challenge testing to evaluate any performance impacts. The AOGA cell stack CDR is planned for May 2022. Two flight AOGA cell stacks will be built starting in October 2022.

B. Dome Redesign

The legacy OGA design houses all of the hydrogen containing components, including the electrolysis cell stack, RSA and associated sensors and valves, within a single vacuum dome referred to as the Hydrogen ORU. The Hydrogen ORU weighs ~300 lb (136 kg) in its launch configuration and has a high packing efficiency and tight tolerances when fitted together with the dome. This precludes maintenance of internal components by the crew. The Hydrogen ORU can only be maintained on the ground since the dome reinstallation requires specialized tooling, precision alignment and verification of specification leakages of the two independent seals to space vacuum to ensure proper operation on-orbit. One of the requirements of an Exploration mission is a system design that allows for maintainability such that failure of a single component does not require removal and replacement of the whole ORU. Therefore, for AOGA, there will be two independent removable domes, one around the RSA and the other around the cell stack. A concept is shown in Figure 8, the left cylindrical dome is the RSA dome and the right cylindrical dome is the cell stack dome. The configuration is called the Oxygen Hydrogen Dome Assembly (OHDA). The OHDA will allow the crew to access the internal components in each dome for maintenance. This approach will reduce spares mass and volume. The cell stack will be housed in one removable dome with the pressure sensors and PSM interface on the outside for access. The RSA, hydrogen backpressure regulator and associated sensors will be housed in the other removable dome, with the pressure sensors mounted externally. In this configuration, the two-phase hydrogen/water line that goes from the cell stack to the RSA will not be enclosed within a dome. This line will contain dual seals. It is anticipated that future analysis will determine that this inter-dome connection will be a safe configuration.

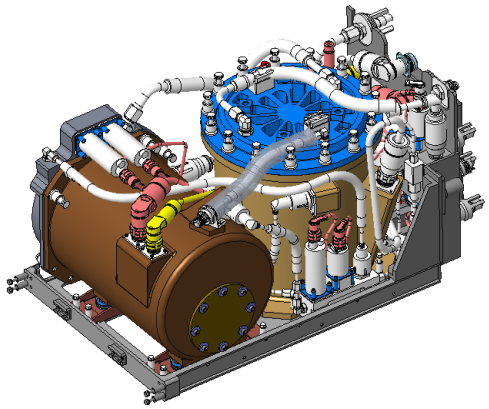


Figure 8. Two Dome Concept

A series of development tests is currently being performed to inform the OHDA design. These tests should be completed by September 2022. Various configurations of the dome cell stack harness, dome seals and RSA diaphragm seal are being tested to determine the optimum design configuration.

The domes will be connected to space vacuum and the dome seals prevent leakage of cabin air out to space vacuum. The new requirement for the dome seals is to be able to withstand multiple dome assembly and disassembly cycles on-orbit by the crew as they perform component level maintenance. After multiple crew maintenance activities, these seals could be damaged and cause overboard leakage. Various dome sealing configurations and geometries are undergoing repeated assembly/disassembly testing and proof/leak testing.

The RSA contains water and hydrogen at approximately 24 psia (165,474 Pa). The RSA is contained within a dome that is connected to space vacuum. Any leakage of the RSA will allow hydrogen and water from the recirculation loop to escape to space vacuum. One of the RSA seals is the diaphragm seal. This seal is part of the moving hydrogen outlet valve that is integral to the RSA. The original seal design did not meet Maximum Design Pressure (MDP) requirements and required a waiver. The seal is being redesigned to be more robust such that it can meet MDP requirements. A new diaphragm seal design will undergo development testing, which will include pressure cycle testing, burst testing, proof testing, and leak testing.

Dome pressure sensors and valves are being procured from new vendors due to issues with the legacy vendors not being able to provide the components within cost and schedule constraints.

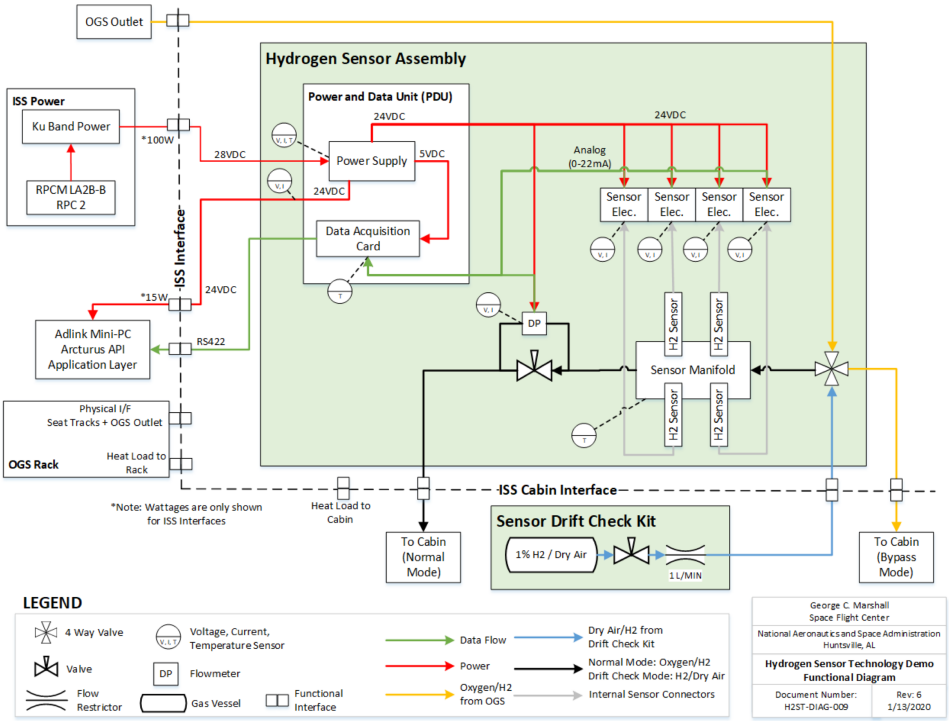


Figure 9. H2ST Schematic

C. Hydrogen Sensor Replacement

Issues with the legacy OGA hydrogen sensors are described in Reference 3. 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 new commercially available hydrogen sensor replacement candidates for 3 years while connected to the ISS OGA's oxygen outlet line to monitor for hydrogen. H2ST will ultimately be mounted to the front of the Oxygen Generation System (OGS) Rack. It is now temporarily mounted to the front of the Life Support Rack (LSR) in the Lab Module, as shown in Figure 10. H2ST cannot be mounted to the OGS Rack in Node 3 currently because it would interfere with crew exercise while using the treadmill. The OGS Rack will be moved to the US Lab in mid-2022. At that time, H2ST will be mounted to the OGS Rack and connected to its oxygen outlet line. In the temporary LSR location, no product oxygen will be flowing through H2ST. However, the benefit of this temporary installation will be the ability to verify the power and data configuration and obtain drift trend data every 90 days using the drift check bottles. The H2ST system schematic is shown in Figure 9. H2ST contains contain a four-way valve, a manifold with four hydrogen sensor candidates, an orifice and delta pressure (dP) sensor to measure flow, power supply electronics, and data acquisition electronics. H2ST will receive power from a Ku Band Power Supply, condition power, route power to the hydrogen sensors and dP sensor, convert the raw sensor readings, and send sensor telemetry to the ground via the Domain Adapter Node and Arcturus system for continuous monitoring and analysis on the ground. A picture of the H2ST internal components is shown in Figure 11. The H2ST accepts product oxygen from the OGA, which will flow past the hydrogen sensor candidates, the orifice and dP sensor, and then out to the cabin. The OGA product oxygen has a variable



Figure 10. H2ST, temporarily installed on the LSR Rack

flow rate, up to 4.5 slpm and dew point of up to 85 F (29.4 C). The oxygen nominally contains a trace amount of hydrogen, less than 0.1%. Nitrogen will also be present during startup. The orifice and dP sensor will function as a flow meter to verify that the OGA product oxygen is flowing through the hydrogen sensors and monitor for leaks. The manually operated four-way valve will allow for the periodic introduction of calibration gas through the sensors to perform a drift check. In the Bypass valve state, the OGA product oxygen will bypass the hydrogen sensor candidates and flow directly into the cabin. The calibration gas (1.0% hydrogen/air non-flammable mixture) will be introduced for 1 minute from handheld bottles by the crew through the hydrogen sensor candidates every 90 days. Once the drift check is complete, the crew will return the four-way valve back to the Normal position, allowing the OGA product oxygen to flow through the sensors. Sensor response to the calibration gas will be monitored and trended over time to determine the drift rate and sensor robustness in the flight environment. This drift rate will be compared to the legacy hydrogen sensors.



Figure 11. H2ST Internal Components

In 2021, H2ST successfully completed all ground acceptance tests: leak testing, vibration test, thermal cycle test, electromagnetic interference test, functional test, and burn-in. The final acceptance review and Phase III safety review were completed as well in November 2021. H2ST was launched on NG-17 in February 2022. H2ST was mounted to the LSR rack on April 14, 2022 and activated on April 15, 2022.

The first on-orbit drift check was performed on April 15, 2022, and the sensor response is shown in Figure 11. When exposed to 1.0% H2/air calibration gas, Sensor 1 reported 1.07%, Sensor 2 reported 1.20%, Sensor 3 reported

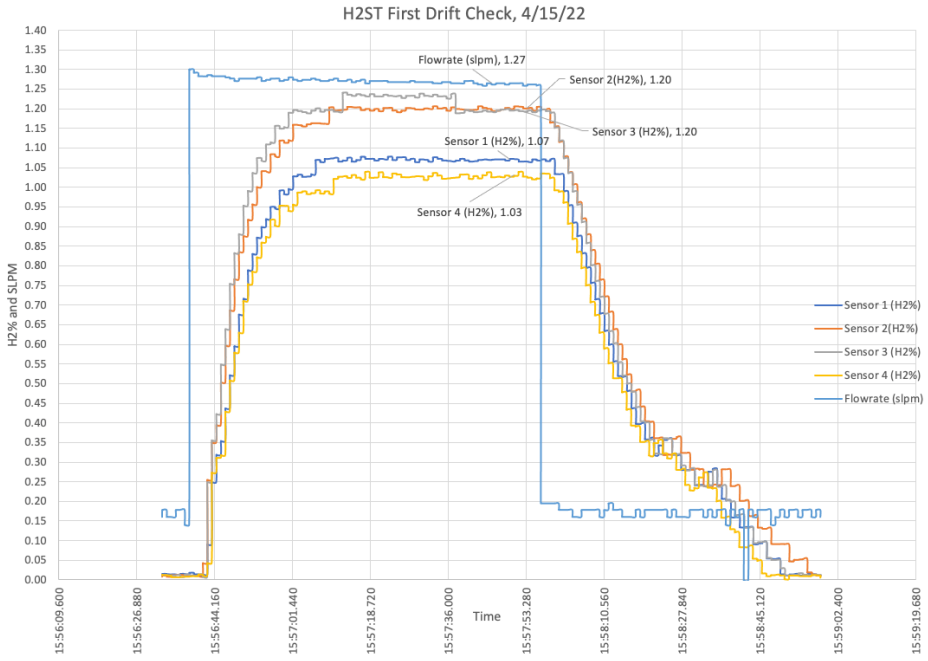


Figure 12. H2ST Sensor Response

1.20%, and Sensor 4 reported 1.03%. Readings higher than actual are conservative. When exposed to 0% H2/air, all sensors reported 0.01 – 0.02%. Additional drift checks will be performed every 90 days to characterize long term sensor drift.

The OGA's product oxygen will nominally have less than 0.03% H2/O2. Any measurable amount of H2 in the OGA's product oxygen (1.0% and above) would indicate a cell stack leak and require immediate shutdown for replacement. In the past 15 years of operation on ISS, there have not been any cell stack hydrogen leaks.

D. Redesign Recirculation Loop ACTEX

The OGA water recirculation loop contains an ACTEX deionization bed. 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 originally developed for the Extravehicular Mobility Unit (EMU) and not OGA. The OGA was retrofitted on-orbit with the ACTEX in 2011. As such, there are several issues that need to be resolved, including a very high DP of up to 16 psid (110,316 Pa) and non-compliance with seal redundancy requirements and MDP requirements. The ACTEX has a 1.85 year installed life which is less than the 3-year duration of an Exploration mission. The ACTEX should 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. Previously, the ARMADILLO team performed a feasibility study which provided a recommendation of several bed configurations (different length and diameter configurations) to resolve the issues seen with the ACTEX. Several different ARMADILLO test configurations have been tested in the ground OGA Testbed, and have demonstrated favorable DP. One example configuration (shown in Figure 13) demonstrated a DP of 1.5 psid (10,342 Pa). Although this configuration does not include all of the hardware required for flight (quick disconnects, hoses, filter, etc.) the DP is much lower than that of an ACTEX. An ARMADILLO flight unit (including the quick disconnects, hoses, filter) is predicted to have an overall DP of less than 6.5 psid (44,816 Pa).

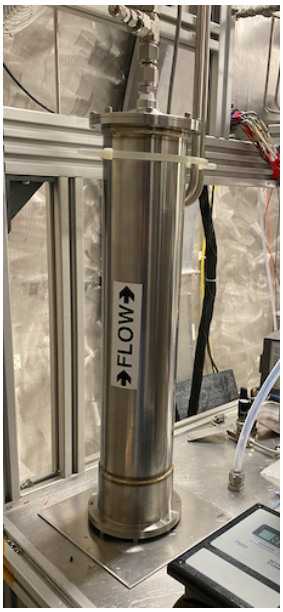


Figure 13. ARMADILLO Prototype

The ARMADILLO team was given the authority to proceed in 2021. The team is currently performing trade studies on the configuration of the various components, including a new integrated particulate filter, hoses, quick disconnects, and spring cavity. The CDR is scheduled for June 2022. Flight hardware builds are planned for September 2022 through May 2023. Final delivery is scheduled for the second half of 2023.

E. Manual Purge and Flush of the Water Recirculation Loop

A new capability to periodically purge and flush the recirculation loop water is required for AOGA. Water consumed during electrolysis is replaced in a batch process from the potable water bus. Over time, the recirculation loop can concentrate trace contaminants present in the incoming feed water. The feed water is known to contain trace amounts of dimethylsilanediol (DMSD), and dimethylsulfone (DMSO2), see Reference 3. Both of these compounds have a low affinity for removal through the installed ACTEX bed in the recirculation loop which allows them to slowly concentrate over as long as 12 months to equilibrium concentrations, as confirmed by periodic analysis of OGA recirculation loop water. Twice per year, the crew takes a water sample and returns it to the ground for chemical and microbial analysis. As the DMSD concentration increases the DMSD may deposit onto piping and other system components. DMSO2 is more volatile than DMSD and predominantly leaves the cell stack through the hydrogen stream which goes to Sabatier. DMSO2 is believed to have poisoned the Sabatier catalyst in the past (Ref. 3). Neither of these species have shown a detrimental impact to cell stack on-orbit performance of the OGA. Further, elemental analysis performed during the cell stack failure investigations did not show an increased concentration of sulfur or silica compounds on the electrode interface or within the membrane.

Because of the long build up to equilibrium concentrations, periodic flushing of the recirculation loop is going to be implemented to maintain low concentrations of these species 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 will temporarily connect the nitrogen supply at the oxygen outlet 3-way valve to the recirculation loop upstream of the cell stack, as indicated by the two "A" connection points on the schematic (Figure 7) using a new hose. Then a modified version of the existing "Inert Dome" command will be used to introduce nitrogen into the recirculation loop. Hydrogen in the cell stack and RSA will be replaced

with nitrogen as the hydrogen gets pushed out of the RSA. This nitrogen purging capability of the recirculation loop also enables safe maintenance and replacement of hydrogen components by eliminating the risk of a hydrogen release near crew members.

Next, the recirculation loop water flush will be performed. The crew will temporarily connect the recirculation loop upstream of the pump to the wastewater bus or a CWC-I, as shown by the two "B" connection points on the schematic. Water will be flushed out of the recirculation loop using a modified version of the existing Standby command. Software overrides will be in place to ensure that the cell stack is powered down so no additional hydrogen is being produced. The previous nitrogen purge will remove almost all of the hydrogen from the cell stack and RSA, although some residual hydrogen could remain in other parts of the system, such as the ARMADILLO and heat exchanger. The RSA and recirculation loop pump will be running and the back pressure regulator will be closed. Recirculation loop water will drain out of the recirculation loop through the hoses temporarily installed by the crew. The system will be monitoring the water level in the RSA, and fresh water will be added periodically in a batch process. A minimum of 3 volume changes of water will be required to significantly reduce the level of contaminants. The crew will manually open and close the temporarily installed valves to control the flush and purge operation.

Although an initial nitrogen purge will performed, to be conservative it is assumed that up to 2% hydrogen will remain in the RSA. Therefore, some dissolved or gaseous hydrogen could be present in the flush water that will ultimately end up in the Water Processor Assembly's wastewater tank. Based on previous experience, this bellows tank can have air its ullage volume, in addition to wastewater. Some amount of dissolved hydrogen gas in the wastewater could come out of solution, per Henry's law, and mix with the air in the ullage volume.

An analysis was performed to determine the optimal purge and flush system AOGA architecture that would minimize the risk of a combustion in the wastewater tank. The different AOGA flush configurations include:

1. Installing a water drain port upstream of the cell stack (at the "A" connection point in Figure 7). This drain port would be connected to the wastewater bus. This is the simplest configuration, but could allow any hydrogen gas released from the ARMADILLO into the wastewater bus.
2. Same as option 1, except removing ARMADILLO from the recirculation loop before flushing. This would eliminate the possibility of the ARMADILLO releasing gas into the wastewater bus, but would not allow flushing of ARMADLLO.
3. Installing a drain port downstream of the RSA. This drain port would be connected to the wastewater bus, as shown in Figure 7 ("B" connection points). This configuration resolves the issues of options 1 and 2, due to the drain port being downstream of the RSA, but does require additional hardware.
4. Installing a drain port downstream of the RSA, and routing the water to the 3-way valve upstream of the wastewater leg of AOGA. This configuration would have one of the system gas sensors in line, and the system would be able to detect and prevent hydrogen gas from entering into the wastewater bus, but is the most complex operationally.

The amounts of water, air and hydrogen that could be in the wastewater tank could vary widely and are difficult to quantify. Due to this, a parametric analysis was performed. Various volumes of water, air and hydrogen in the wastewater tank were assumed and the different hydrogen in air percentages were calculated. Hydrogen in air mixtures between 4.6% to 70.3% are considered flammable in this tank configuration.

All four of the options were analyzed. Options 1 and 2 could release hydrogen gas into the wastewater bus to create a flammable mixture within the wastewater tank. Options 3 and 4 did not pose a combustion hazard within the wastewater tank. The AOGA team selected option 3 to incorporate into the AOGA design.

V. Future Plans

The AOGA will be demonstrated on ISS for a minimum of 3 years. The ISS OGA will be upgraded to the AOGA configuration via separately launched kits.

The first kit, which enables the move of the OGS rack from the Node 3 location (rack location NOD3A5) to the US Lab (rack location LAB1P1), was delivered and flown to ISS in late 2021. ISS Software was updated to support the move in January 2022. The OGS rack will move to the US Lab in mid-2022, following an additional software update to support an alternate power configuration which was identified in mid-2021. The LSR is currently in the LAB1P1 location, so it will be moved to the NOD3A5 location at the same time. The OGS rack was previously located in the US Lab, from July 2006 to Feb 2010. The LAB1P1 location has a modified Z-Panel located within the X3 standoff and requires jumper cables and hoses between the Z-Panel and the OGS Rack Interface Panel. The NOD3A5 location does not have a Z-Panel and therefore the Node 3 distribution lines are connected directly to OGS Rack Interface Panel. The OGS rack fluid, power and data jumpers were stowed on ISS after the OGS rack move to

NOD3A5 in 2010. Half of the jumpers were returned to ground since there was no crew time available to remove the jumpers from the returning stowage bag. The jumper cables and hoses returned to ground were refurbished and are back on-orbit in preparation for the OGS rack move back into the US Lab. Once the OGS rack is moved to the US Lab, it can support the H2ST and the ARMADILLO.

The second kit, which will convert OGA to AOGA on orbit, will be delivered in the 2024 timeframe. A new OGS left rack door with a 9 inch (22.9 cm) bumpout will be required to support the larger Sabatier 2.0 and new CO2 accumulators when they are delivered. The bumpout will also have an access hatch feature to allow the crew easy access for inspection and cleaning of the Avionics Air Assembly Inlet Filter Block Assembly.

In order to confirm that the existing Lab port overhead vent valve can be used, a leak check was performed in December 2021. The element vent valve has a known internal leak when the valve is closed to space vacuum that had to be characterized in advance so that newly made connections for AOGA can be verified as part of moving the rack. In addition, the low pressure sensors within the OGA H2 Dome ORU and AOGA OHDA must be accurately trended during periodic vent pressure decay response testing to determine if any commanded software offsets are required. While the Lab port overhead vent valve check did show that the leak rate has increased, analysis confirmed that it is still acceptable and will allow for pressure sensor characterization when required.

References

[1]Takada, K., Ridley, A., Van Keuren, S., Baker, P., McDougle, S., "Status of the Advanced Oxygen Generation Assembly Design," ICES-2021-264, *50th International Conference on Environmental Systems*, July 2021.

[2]Takada, K., Ridley, A., Velasquez, L., Van Keuren, S., Baker, P., McDougle, S., "Status of the Advanced Oxygen Generation Assembly Design," ICES-2020-190, *50th International Conference on Environmental Systems*, July 2020.

[3]Yu, P., Goberman, D., Gavin, L., Garr, J., Ulrich, B., "Poisoning Evaluation of On-Orbit Sabatier Assembly," ICES-2020-378, *50th International Conference on Environmental Systems*, July 2020.

[4]Takada, K., Velasquez, L., Van Keuren, S., Baker, P., and McDougle, S., "Advanced Oxygen Generation Assembly for Exploration Missions", ICES-2019-107, *49th International Conference on Environmental Systems*, Boston, Massachusetts, July 2019.

[5]Takada, K., Ghariani, A., Van Keuren, S., and Owens, A., "Oxygen Generation Assembly Design for Exploration Missions", ICES-2018-113, *48th International Conference on Environmental Systems*, Albuquerque, New Mexico, July 2018.

[6]Takada, K., Ghariani, A., and Van Keuren, S., "Advancing the Oxygen Generation Assembly Design to Increase Reliability and Reduce Costs for a Future Long Duration Mission", ICES-2015-115, *45th International Conference on Environmental Systems*, Bellevue, Washington, July 2015.

[7]Carpenter, J., Gentry, G., Diderich, G., Roy, R., Golden, J., Van Keuren, S., Steele, J., Rector, T., Varsik, J., Montefusco, D., Cole, H., Wilson, M., and Worthy, E., "Investigation into the High-Voltage Shutdown of the Oxygen Generation System Aboard the International Space Station", AIAA-2012-3613, *42nd International Conference on Environmental Systems*, San Diego, CA, July 2012.

[8]Bagdigian, R., Prokhorov, K., "On-Orbit Checkout and Activation of the ISS Oxygen Generation System," SAE 2007 2007-01-3182, *37th International Conference on Environmental Systems*, Chicago, IL, July 2007.

[9]Bagdigian, R., Cloud, D., and Bedard, J., "Status of the Regenerative ECLSS Water Recovery and Oxygen Generation Systems", SAE 2006-01-2057, *36th International Conference on Environmental Systems*, Norfolk, VA, July 2006.

[10]McDougle, S., "Analysis of Possible Combustion Hazards from Hydrogen Gas Liberated from AOGA Fill/Flush Water Entering the Water Processing Assembly Wastewater Tank", HMEM.025, July 28, 2020.

[11]Baker, P., Italia, L., "Minimizing Impact of Nafion Creep on OGA Replacement Cell Stack Lifetime during Storage", AN20-122, October 29, 2020.