

Status of the Advanced Oxygen Generation Assembly Design

Kevin Takada¹

NASA Marshall Space Flight Center, Huntsville, AL, 35812, USA

Alesha Ridley²

NASA Johnson Space Center, Houston, TX, 77058, USA

Luis E. Velasquez³

HX5, Houston, TX 77058, USA

Steven Van Keuren⁴

S&K Global Solutions, Inc., Polson, MT 59860, USA

Phillip S. Baker⁵

Collins Aerospace, Windsor Locks, CT, 06096, USA

and

Stephen H. McDougle⁶

MEI Technologies, 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 mass, crew maintenance time and spares mass while increasing reliability. The design team has performed trade studies, tests and analyses to inform the redesign. Upgrades being considered 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 redesign of the cell stack Power Supply Module. The ISS OGA will be upgraded to an Advanced OGA (AOGA) configuration and its operation demonstrated in a flight environment.

Nomenclature

<i>AOGA</i>	=	Advanced Oxygen Generation Assembly
<i>ACTEX</i>	=	Activated Carbon Ion Exchange
<i>dP</i>	=	Delta Pressure
<i>ECLSS</i>	=	Environmental Control and Life Support Systems
<i>ISS</i>	=	International Space Station
<i>MDP</i>	=	Maximum Design Pressure
<i>NASA</i>	=	National Aeronautics and Space Administration
<i>OGA</i>	=	Oxygen Generation Assembly
<i>OGS</i>	=	Oxygen Generation System

¹ ECLSS Systems Engineer, ECLSS Development Branch, MSFC/ES62

² ECLS System Integration Manager, ISS Vehicle Office, JSC/OB311

³ OGS Subsystem Manager, Crew and Thermal Systems Division, NASA Johnson Space Center/Mail Code EC3

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

ORU = Orbital Replacement Unit
PSM = Power Supply Module
RSA = Rotary Separator Accumulator

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 1,100 days. 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 and Current Status

The ISS OGA (Figure 1) has been operating for over 13 years and is currently installed in Node 3. As of February 16, 2020, the ISS OGA has produced 18,105 lbm of oxygen and 2,263 lbm of hydrogen. The currently installed OGA electrolysis cell stack has accumulated a total operating time of 28,424 hours.

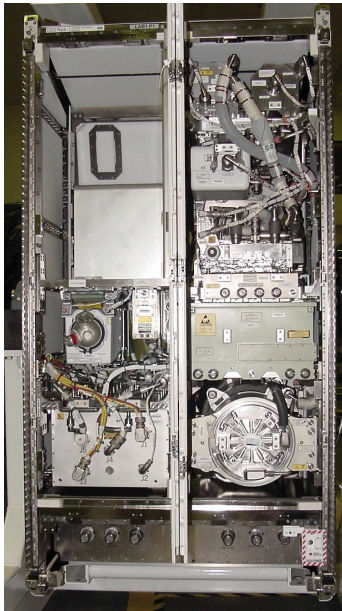


Figure 1. ISS OGS Rack

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 Nitrogen Purge ORU stores a pressurized volume of nitrogen gas from the ISS distribution line to purge the OGA cell stack 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/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/isolation. In addition, sensor data can be used to indicate that an ORU should be scheduled for change-out with a pre-positioned, on-orbit spare ORU. The PSM ORU provides

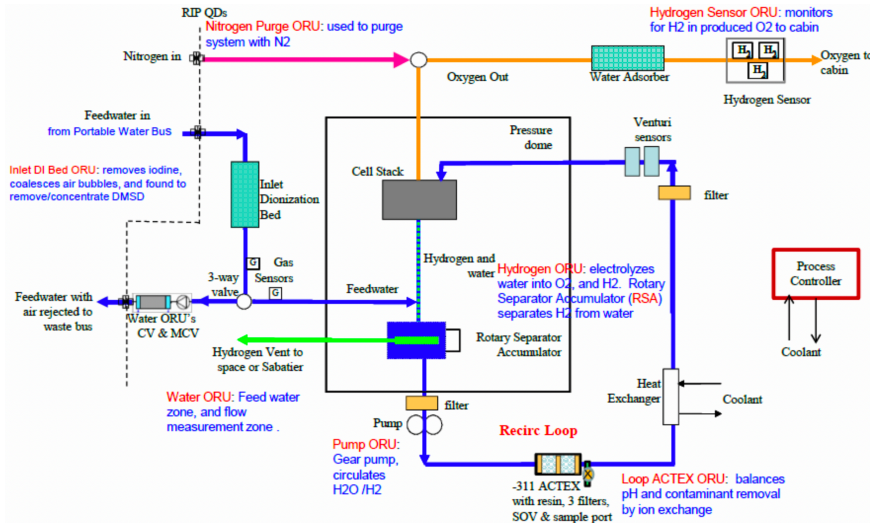


Figure 2. ISS OGA Schematic

power to the OGA electrolysis cell stack. The PSM ORU provides a variable range of 10-46.9 amps of current to the OGA cell stack during Process mode and 1.0 amp during Standby mode (2% oxygen production rate).

The ISS OGA generates oxygen at a selectable rate between 5.1 and 20.4 lbm/day. At the nominal rate, the ISS OGA can support oxygen needs for 3 crew, while at the maximum rate it can support 10.88 crew (assumes 1.874 lbm 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 (PM) replacement intervals.

Several lessons learned, based on many years of ISS OGA operations, have been previously documented (Reference 1 - 6). Major ISS OGA events from January 2016 through February 2020 are timelined in Figure 3.

The OGA recirculation pump has experienced several issues over the past year. This pump (s/n 1) has accumulated over 9 years of run time, well beyond its 2 year design life. In 2019, an increasing pump speed, from 2000 to 2060

rpm, was observed, as shown in Figure 4. A corresponding decrease in pump motor temperature, from 90 to 80 degrees F, was observed as well. It was postulated that the pump's integral bypass relief valve was cracking open due to a high delta pressure (dP), possibly due to the ACTEX (see below for further details on the ACTEX). Unfortunately, the actual pump dP is not known, due to a non-functional dP sensor. Over time, the OGA software increased the pump speed to maintain the set flow rate and the pump temperature decreased due to bypass flow through the integral bypass relief valve cooling the pump motor. As part of the troubleshooting

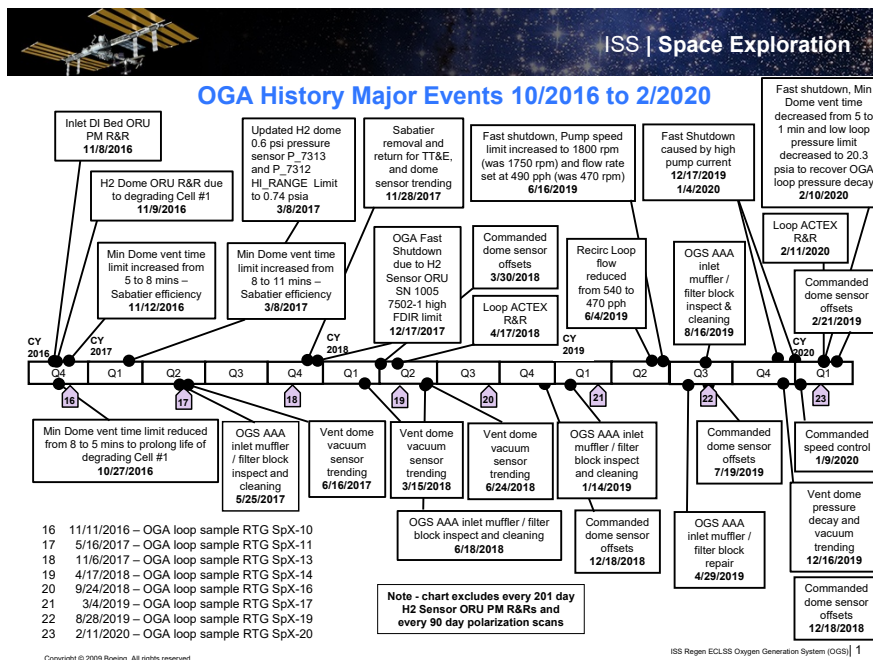


Figure 3. Timeline of ISS OGA Events

investigation, in June 2019 the commanded water flow rate was lowered from 540 to 470 lb/hr, and in response the

pump speed decreased from 2060 to 1800 rpm. The OGA team is still reviewing the long term data trend to determine the root cause of the anomaly.

On December 17, 2019 and January 4, 2020, the OGA experienced shutdowns due to pump current high spikes (0.61 A and 0.39 A) which were above the 0.35 A shutdown limit. Immediately prior to these shutdowns, it was noted

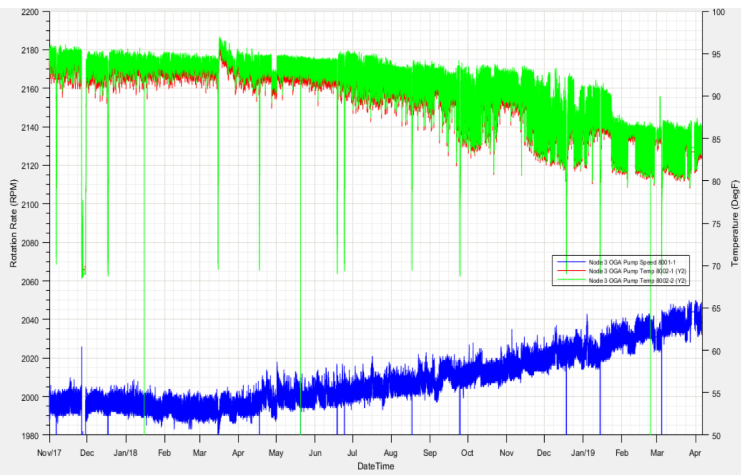


Figure 4. Pump Speed Increase (Blue) and Pump Temperature Decrease (Green/Red)

that there was instability in the recirculation loop water flow rate. The OGA software algorithm attempts to maintain a constant flow rate by varying the pump speed (i.e. increasing or decreasing pump current) as needed. On January 9, 2020, the OGA software was commanded to maintain a constant pump speed, rather than a constant water flow rate, in an attempt to prevent future high current spikes. The OGA team is continuing to monitor the effectiveness of this software change in preventing additional shutdowns.

On February 10, 2020, the OGA shut down due to a recirculation loop low pressure fault (pressure less than 20.5 psia) which annunciated when OGA transitioned from Process into

Standby Hold, which occurs every 100 minutes for a 5 minute duration to evacuate the dome. The recirculation loop water pressure had been slowly degrading during the Standby Hold since late 2019. The low loop pressure limit is in place to ensure cell stack cathode pressure is maintained above anode pressure to enable detection of cross cell leakage via the oxygen outlet pressure sensors and hydrogen sensors. In 2014, the standby duration between the 100 minute process cycles was set to 5 minutes (default 1 minute). This increased duration was to gain sufficient time to evacuate the dome while avoiding the dome pressure high limit nuisance shutdowns while both OGA and Sabatier were in process. After consensus was obtained, OGA was successfully reactivated by lowering the every 100 minute Standby hold time from 5 to 1 minute (default) and lowering the recirculation loop pressure low limit. As of 2/21/2020, the loop pressure minimum during every 100 minute Standby hold is consistently well above the low limit and the hydrogen dome pressure maximum during Process has leveled out well below the high limit. The most likely causes for the decay in recirculation loop pressure while in Standby are a sticking hydrogen back pressure regulator (causing fluctuations during Process mode and also preventing full valve closure during Standby) or a small regulator bellows leak that manifests during Standby. On March 4, 2020, OGA was commanded to Standby as a test to gather additional data. The recirculation loop remained stable and above the shutdown limit for the one hour test duration. Troubleshooting steps for internal regulator and internal dome leak checks are being developed to enable determination of root cause or refutation of some fault tree legs. Additional recovery steps are also being developed should loop pressure degradation reappear.

The team continues to closely monitor the cell voltages of the currently installed OGA cell stack, in Hydrogen ORU s/n 3, for signs of degradation. This cell stack has accrued 3.1 years of operation. The predicted life of the Hydrogen ORU is 5 years. The previously installed cell stack, in Hydrogen ORU s/n 2, had failed in 2016, after 5.28 years, when Cell 1's voltage decreased from the nominal 1.51 V in Standby towards the shutdown limit of 1.0 V (see Reference 2). Prior to the failure, Cell 1's startup and shutdown voltage signatures were out of family (slowest to charge and fastest to discharge) from the other cells. The currently installed cell stack startup and shutdown voltages are being monitored for similar behavior. In 2018, the currently installed cell stack cell 1 voltage had exhibited similar behavior to the previously installed cell stack, i.e., fastest cell to discharge, see Figure 6. But in early 2020, Cell 1 appears to be back in family, see Figure 5. The cause of the apparent recovery is unknown. The team will continue to monitor the startup and shutdown voltage trends and periodic polarization scans to discern cell stack health.

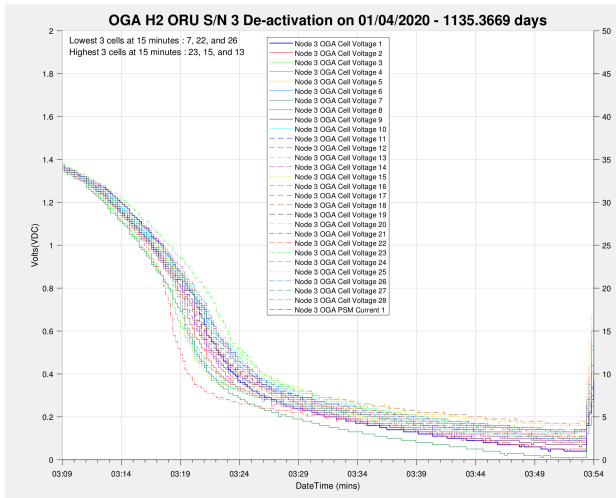


Figure 6. Cell Voltages During Shutdown 1/4/20 (Cell 1 in Blue)

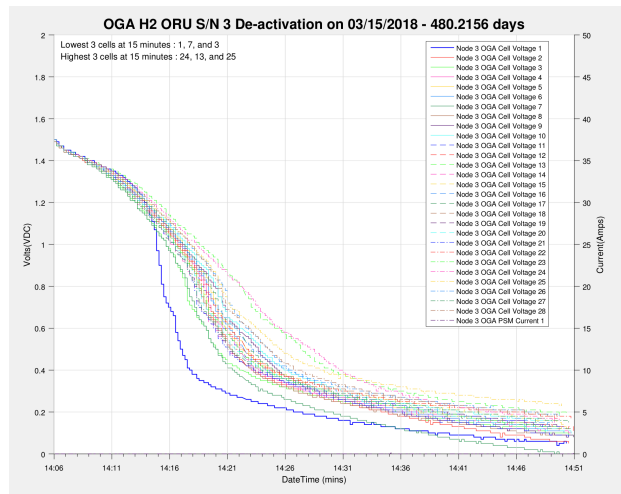


Figure 5. Cell Voltages During Shutdown 3/15/18 (Cell 1 in Blue)

III. Proposed Upgrades

The AOGA design was finalized at the end of 2019, based on the results of several trade studies. The first trade study examined several options for replacing the hydrogen dome. The second trade study examined whether nitrogen purging should be kept in the AOGA design. The third trade study examined whether an automated water recirculation

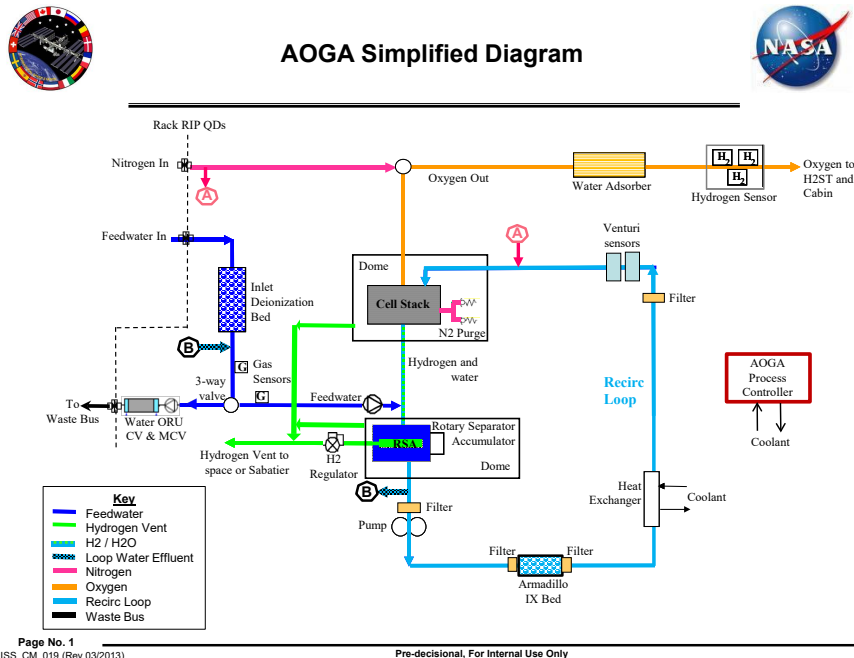


Figure 7. AOGA Schematic

loop flushing capability should be added to flush contaminants and to prepare the system for long periods of dormancy. In addition, the decision was made to keep the wastewater interface in the AOGA design to accommodate recirculation loop water flushing. The proposed AOGA schematic is shown in Figure 7 and the list of proposed upgrades is summarized in Table 1.

Table 1. AOGA Proposed Upgrades

Originally Proposed Upgrade	Reason	Description	Currently Proposed Upgrade
Redesign the cell stack	Implement corrective action based on the cell stack failure investigation	Provide better support for the cell membranes, replace obsolete membrane material	Redesign the cell stack
Delete the nitrogen purge equipment	Reduce system mass and complexity	Delete nitrogen purging of the cell stack anode during shutdowns and startups	Keep the nitrogen purge equipment
Replace the hydrogen sensors	Reduce crew maintenance time and improve reliability	Replace hydrogen sensors with a more reliable technology that requires less crew intervention	Technology demonstration on ISS of new hydrogen sensors
Delete the wastewater interface	Reduce system mass and complexity	Allow oxygen gas that may be in the feedwater into the RSA rather than being rejected to the wastewater bus	Keep the wastewater interface to facilitate recirculation loop flushing
Remove the hydrogen dome	Reduce logistics resupply requirements	Crew will be able to access and maintain the internal dome components	Implement two maintainable domes
Redesign the PSM	Reduce system mass/volume	The current PSM design is oversized for a future mission and contains obsolete parts	Use the legacy PSM for the ISS AOGA flight demonstration
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	Redesign the recirculation loop ACTEX
Redesign the process controller	Provide ability to interface with new sensors and effectors being added to the AOGA design	New connectors and backplane harnesses and swap-out of two sensor circuit card boards	Use the legacy process controller, with modifications for the ISS AOGA flight demonstration
Recirculation Loop Flush	Reduces contaminants that could be sent to Sabatier and cleans system in preparation for dormancy	New automated capability to purge all hydrogen from the cell stack and recirculation loop, then flush with potable water to achieve a 3x volume changeout	Add new automated recirculation loop purge/flush hardware

A. Cell Stack Redesign

Cell Stack s/n 5 (from Hydrogen ORU s/n 2) was returned to ground after the on-orbit low voltage failure in 2016 (Reference 1) and a test teardown and evaluation (TT&E) was performed with cells 1 and 2 being removed for analysis. The TT&E was started in 2017 and concluded in 2018. The membranes of cells 1 and 2 were found to have thinned out to as low as 19 μm or approximately 90% thinning of the membrane in some areas where pinch points were located. In these pinch point regions, cell 1 exhibited increased areas of thinning in comparison to cell 2. 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.

In 2019 cell stack s/n 5 was rebuilt with a new cell 1 and 2 to assess the feasibility of recovering the cell stack for future use. Following the rebuild, cell 28, which previously showed no out of family behavior, started to develop an out of family signature that resulted in a short. A TT&E was conducted on cell 28 to determine the cause of the short. Cell stack s/n 5 was rebuilt with a new cell 28 exhibiting no out of family signatures and is awaiting performance evaluation in the first half of 2020.

Cell 28 was sectioned in the same regions as cells 1 and 2 for comparison. An optical montage of the cell 28 sections was constructed to assess larger cross sections of the membrane. Cell 28 exhibited similar pinch points of 20 μm as was seen in cell 1 and 2, but only in the two phase outlet region (which contains both water and hydrogen gas). Pinch points in other regions showed thicknesses 3 to 5 times higher than in the two phase region with the thickest regions being at the water inlet region. Additionally, in comparing the optical montages of the four regions it is clear that the two phase port showed signs of accelerated general and localized thinning whereas the other regions exhibited less thinning and more uniform thicknesses across the sample. The cause of the thinning is from chemical degradation of the membrane during operation. The mechanism for this degradation is accelerated in drier conditions and the two phase region may restrict localized water transport across the membrane. The Nafion membranes used at the time of assembly were more susceptible to this chemical degradation and have been replaced with a chemically stabilized Nafion by the manufacturer Chemours. In general, the membrane in other regions of cell 28 was thicker in comparison to cell 1 and 2 which may support the unique compressive loading seen in cell 1. Another factor which may have added to the failure is that the membrane support used on the cathode uses a smaller landing than the anode which could have allowed for more creep of the membrane in the cathode direction over time. Creep characterization of the membrane material was started in 2019 to determine the impact that long term thinning may have contributed to the failure and also to determine the impact of creep on long term storage for OGA and AOGA cell stacks.

Redesign of the OGA cell stack has incorporated a finer mesh support to minimize creep response of the membrane, chemically stabilized membrane to reduce chemical degradation, chemical degradation mitigator to further enhance the membrane durability, and a redesign of the cell stack internals to balance loading and correct the unique compressive loading elements. Redesign of the AOGA cell stack will incorporate the previous changes made for OGA, and will further the design by including porous metal membrane supports, and inclusion of an edge seal gasket to minimize loss of water from the cell stack during long term storage.

Cell stack development testing has started in 2020. This will demonstrate the effectiveness of the new pressure pad material, membrane manufacturing techniques, new cathode and anode screen supports, and new edge seals. Cell stack challenge testing will also be performed in 2020, where test cell stacks will be subjected to microorganisms and contaminants, such as dimethylsilane diol (DMSD) and dimethyl sulfone (DMSO₂). Finally, endurance testing will be performed in 2020. These tests, which will inform the cell stack redesign, should be completed by the middle of 2020.

B. Delete the Nitrogen Purge Equipment

The ISS OGA requires an external source of nitrogen, provided by the ISS vehicle. The ISS OGA has approximately 50 lb of equipment to handle the storage and distribution of nitrogen. Nitrogen is used to purge the cell stack anode compartments upon system shutdown and startup. During prolonged shutdowns, hydrogen in the cathode compartment will permeate through the membrane to the anode compartment, which contains oxygen. At shutdown, a nitrogen purge will replace the oxygen with nitrogen, preventing a potentially combustible mixture of hydrogen and oxygen in the anode from forming over time when the system is unpowered. The shutdown nitrogen purge pressurizes the anode compartment and in turn helps maintain a desirable water recirculation loop pressure. At startup, a nitrogen purge blows out any accumulated hydrogen and water in the cell stack anode through relief valves out to the dome. This prevents liquid water from being pushed into the oxygen outlet line and to the hydrogen sensors, which cannot tolerate liquid water.

In 2018 and 2019 ground testing was performed with the OGA Testbed. During initial ground testing, with nitrogen purging disabled, the following was observed: significant water accumulation in the oxygen outlet line, low RSA water quantity, and low recirculation loop pressure. Various system configurations to mitigate these issues when nitrogen purging was disabled were tested as shown in Table 2.

Table 2. Test Configurations with Nitrogen Purging Disabled

	Shutdown Configuration Description	Water Accumulation in O ₂ Outlet (mL)	RSA Water Quantity Decrease (cu-in)	Recirculation Loop Water Pressure (psia)
1	Command three way valve to oxygen outlet position	330	25	15.5
2	Command oxygen outlet valves open	328	27	15.4
3	Run in Standby	280	26	15.6

4	Overfill the RSA	219	23.5	15.0
5	Disconnect cell stack bleed resistors	277	29	14.7
6	Perform cell discharge	8	15	14.8
7	Pressurize oxygen outlet to match recirculation loop pressure	164	18	15.0
8	Add cell stack isolation valves to cell stack water inlet and outlet, and relief valve to the cell stack water inlet	1	0	21.5

The configurations in tests 1 – 7, when nitrogen purging was disabled, did not significantly mitigate water accumulation, decrease in RSA water quantity or decrease in recirculation loop water pressure. The configuration for test 8, which involved adding a new isolation valve to the cell stack water inlet and also to the outlet along with a new relief valve to the water inlet, demonstrated favorable results. This configuration minimized water accumulation in the oxygen outlet line, RSA water loss, and recirculation loop pressure drop.

In 2019, a trade study was performed to decide whether to delete the nitrogen purging equipment from the AOGA design, based on the test results. The advantage was that the requirement for the vehicle to provide nitrogen to AOGA was eliminated, and the AOGA nitrogen purging equipment was eliminated, reducing vehicle and system complexity and mass. The nitrogen purge equipment (three valves, two pressure sensors and a nitrogen tank) could be eliminated. However, if nitrogen purging equipment were deleted, two new cell stack isolation valves and a relief valve would need to be added to the system. In addition, a new regenerative oxygen dryer and pressure sensors would be required to manage water in the oxygen outlet line. The team concluded that the benefit of deleting the nitrogen purge equipment from AOGA was marginal and involved new design risk. In the end, it was decided that the nitrogen purging equipment would be kept in the AOGA design.

C. Replace the Hydrogen Sensors

Issues with the legacy ISS OGA hydrogen sensor, the requirements for a replacement hydrogen sensor, and the downselection to a single commercial off the shelf (COTS) hydrogen sensor as a replacement candidate, are described in Reference 1. In 2019, the Hydrogen Sensor Technology Demonstration (H2ST) Project, which will design, build, launch and install replacement hydrogen sensors, was initiated. To date, the H2ST Project has completed its Systems Requirements Review (SRR), Interim Checkpoint Review (ICR), Phase 0 Safety Review, and Phase 1/2 Safety Review. The detailed electrical, mechanical, and software design is currently ongoing. In addition, safety, materials and thermal analyses are ongoing. The H2ST flight hardware will be built, tested and delivered in 2020. Planned acceptance testing on the flight hardware includes functional testing, proof/leak testing, vibration testing, thermal cycle testing and burn-in testing. On the ISS, it will be installed on the outside of the OGS Rack, as shown in Figure 8, for 3 years and hydrogen sensor performance data will be collected.

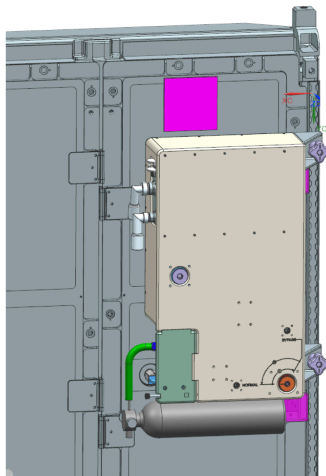


Figure 8. H2ST Mounting Concept

The H2ST system schematic is shown in Figure 9. The unit will contain a four-way valve, a manifold with four hydrogen sensor candidates, an orifice and DP sensor to measure flow, power supply electronics, and data acquisition electronics. The H2ST will accept product oxygen from the OGA, which will flow past the hydrogen sensor candidates, the orifice and DP sensor, and then the product oxygen will be vented to the cabin. The OGA product oxygen has a variable flow rate, up to 4.5 slpm and dew point of up to 85 F. The oxygen contains a trace amount of hydrogen, less than 0.1%. Nitrogen is also 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 the periodic introduction of calibration gas through the sensors to perform a drift check. In this valve state, the OGA product oxygen will bypass the hydrogen sensor candidates and flow directly into the cabin. The calibration gas (1% H₂/air non-flammable mixture) will be introduced 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 process 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. 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 (DAN) and Arcturus system for continuous monitoring and analysis. Once the flight experiment is complete, the sensors will be returned to the ground for additional testing to quantify the drift rate and direction.

An analysis was performed to ascertain the maximum overpressure within H2ST in the event of an AOGA failure. If the cell stack developed a cross cell leak, a flammable mixture of hydrogen and oxygen could enter H2ST, prior to the oxygen outlet valves closing, and ignite. A worst case mixture is estimated to be 34.5% hydrogen and 65.5% oxygen. This mixture is well within the detonation limits. Although a strong ignition source which could directly initiate a detonation is not credible in this case, an ignition source, even though relatively weak, should be assumed. With an inner diameter of 0.305 inches, any tubing length greater than 2.5 inches provides enough confinement for a deflagration to detonation transition (DDT). Therefore, once ignited, a DDT is indicated. The following results were calculated with the NASA CEA computer program. A detonation of a 34.5% H₂ / 65.5% O₂ from a starting pressure of 18.1 psia, will result in a pressure of approximately 292 psia. The detonation is very likely to propagate back through the unburned mixture in the oxygen outlet line towards the water separator/absorber. However, due to the presence of large amounts of water in the oxygen outlet line (between the cell stack and the water separator/absorber), accelerated flames and DDT are not possible. The shock wave moving through the line that goes to the cabin (normal mode) will tend to dissipate with distance and the restrictions from the valve and the orifice. The H2ST hardware is designed to contain this worst case combustion event.

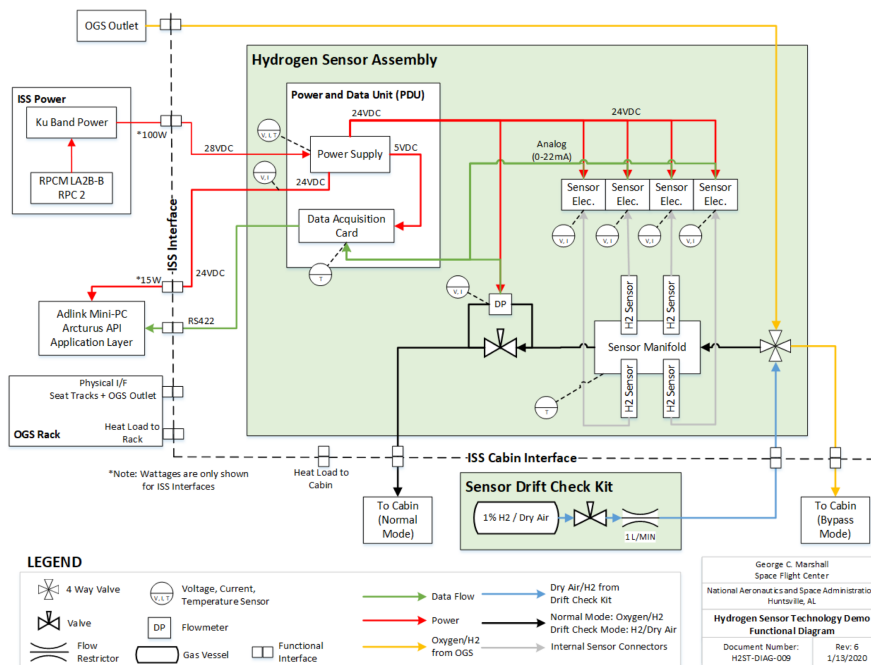


Figure 9. H2ST Schematic (Preliminary)

D. Remove the Hydrogen Dome

The legacy OGA design houses the electrolysis cell stack, RSA and associated sensors and valves within a single dome referred to as the Hydrogen ORU. The Hydrogen ORU weighs ~300 lb in its launch configuration and has a high packing efficiency and tight tolerances when fitted together with the dome that precludes maintenance of internal components by the crew. 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. Initially, the design team baselined a ventilated box concept to replace the dome. This allowed for maintainability of

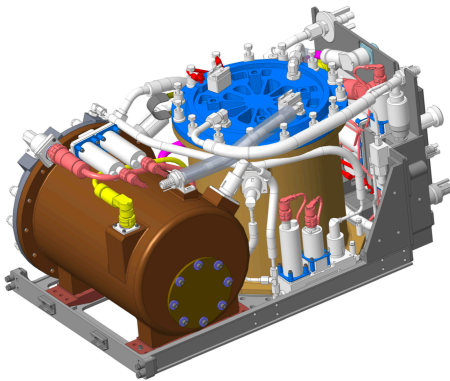


Figure 10. I-Domes Concept

internal components. Late in 2019, the team determined that the safety and design challenges of the ventilated box concept could not be fully resolved. A trade study was initiated, which compared the baseline ventilated box with three new options, including a modified removable legacy dome, a sealed box and two “independent domes” or I-Domes. The decision was made to change course and select the I-Domes as the baseline design which enabled access for maintenance of the cell stack, RSA and other hydrogen containing components. The approach will reduce spares mass and volume, as was the original intent, without the inherited challenges of a ventilated system. An early concept of the I-Domes is shown in Figure 10. The cell stack is housed in one removable dome (on the right) with the pressure sensors and PSM interface on the outside for access. The RSA, hydrogen backpressure regulator and associated sensors are housed in the other removable dome (on the left), with the pressure sensors mounted externally.

E. Redesign the PSM

The legacy ISS OGA PSM is a constant current power supply for the cell stack. It is able to provide over 3800 Watts of power for electrolysis. The PSM is a modular design, containing 4 Power Converters, along with filter boards, control board, relay, sensors, etc. The internal configuration is shown in Figure 11. The PSM weighs 100 lb and measures 15 x 24 x 11 inches.

The PSM for an Exploration AOGA will need to be redesigned for several reasons. The PSM design was performed approximately 20 years ago. A PSM redesign study was conducted in 2016 which concluded that the design is based on discrete components and some of these are obsolete. A reduction in mass and volume could be realized using a modern space rated microcontroller based design. This one microcontroller could replace dozens of discrete components.

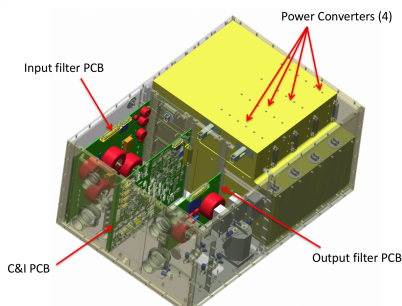


Figure 11. PSM Components

The ISS Program has elected not to fund the redesign of the PSM for the ISS AOGA. Therefore, the ability of the legacy PSM to be used in AOGA needed to be determined. The robustness of the PSM design to support various AOGA cell stack sizes at the full range of currents and worst case Moderate Temperature Loop (MTL) coolant temperatures was examined in 2019. Up to now, the ISS OGA PSM has been operated at low current levels (~35% of maximum) with nominal MTL coolant temperatures. For AOGA, the PSM would likely supply higher current levels, close to 100% of maximum with higher supplied MTL coolant temperatures. An AOGA cell stack might have a total voltage of 35 V, which is less than the minimum specified voltage for the PSM, 38 V. Testing with a single Power Converter and the

development PSM confirmed electrical stability down to 29 V at maximum current. A detailed thermal model of the PSM and Power Converters, using Thermal Desktop, was developed in 2019 to confirm thermal stability at maximum current and worst case MTL coolant temperature predicted for AOGA. Thermal testing of a single Power Converter with 36 thermocouples was used to refine the thermal model. With the worst case MTL coolant temperature, the thermal model confirmed that the hottest component in the PSM, a power Metal Oxide Semiconductor Field Effect Transistor (MOSFET) within the Power Converter, remained 20 degrees below its rated thermal limit. Based on the testing and analysis, the legacy PSM design will be acceptable for use in the ISS AOGA, but should be redesigned for a future deep space Exploration AOGA.

F. Redesign the Recirculation Loop ACTEX

A -311 ACTEX deionizing bed, with inlet and outlet hoses, was retrofitted into the ISS OGA recirculation loop in 2011 to prevent recurrence of the cell stack failure in 2010 (Reference 3). 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 another application and not OGA. The

OGA's flow rate through the ACTEX is 34 times higher than recommended by the resin manufacturer. As a result the flow is turbulent rather than laminar, contributing to a high dP. The ACTEX should be redesigned and optimized for AOGA.

The ACTEX redesign effort was approved and funded in 2019. The redesign will:

- lower the dP from 16 to ~3 psid
- extend the operational life from 1.8 to 3 years
- maintain the proper L/D ratio for the resin to operate at the optimal absorbance
- increase the rated MDP from 40 to 263 psia, eliminating the need for waivers
- incorporate dual seals
- incorporate tighter filtration to better protect the cell stack from particulates
- fit within the existing space in the OGS rack

A feasibility study named ARMADILLO (AOGA ReMediation, Advanced DeIonization and Limited Life Optimization) was completed in December 2019 to address these requirements. In order to accomplish this a ground test system had to be built to match the OGA flow rate and system pressure. Next, a series of test articles representative of potential design solutions were designed and built. The following test articles were characterized for pressure drop, as shown in Figure 12:

- 1 baseline ACTEX P/N SEG11100313-311 (resin-only)
- 8 ACTEX units packed with new resin formulations
- 4 Flanged Test Cartridges – larger than ACTEX, same L/D
- 2 Flanged Test Cartridges – larger than ACTEX, modified L/D
- 5 external particulate filters, 25-30 μm
- 10 ft. flex hose, ACTEX 0.25" inlet orifice, ACTEX inlet and outlet quick disconnects (QDs)

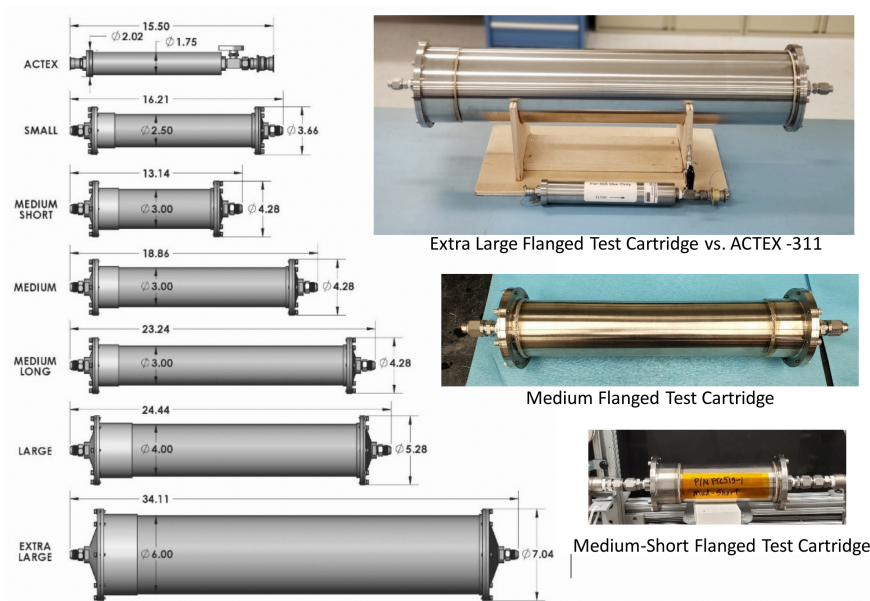


Figure 12. ARMADILLO Feasibility Study Test Articles

The feasibility study concluded that physical modifications were more effective at reducing pressure drop than new resin formulations. Another conclusion was that none of the redesign options could meet all of the following requirements: pressure drop of 3 psid or less, maintain L/D ratio, fit inside the OGS rack, and incorporate tighter filtration. A design solution is feasible with the Medium-Short cartridge only if L/D ratio is reduced and a design solution is feasible with the Medium cartridge if allocated dP is increased to 4 psid. Forward work includes downselecting between the medium or medium-short design and having the ISS crew conduct an on-orbit evaluation of the OGS rack to see if either design will actually fit.

G. Redesign the Process Controller

The legacy ISS OGA Process Controller (shown in Figure 13) consists of a firmware controller, based on a space

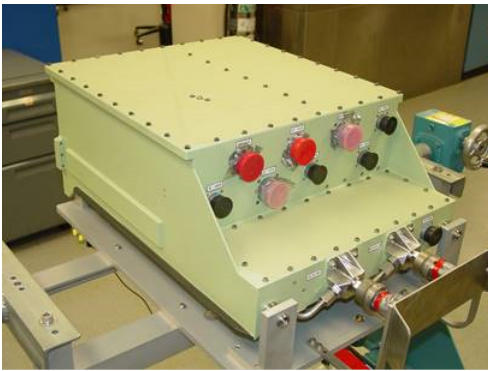


Figure 13. Legacy ISS OGA Process Controller

qualified microprocessor, a software independent shutdown monitor (ISM) section, and a conductive cooling assembly. The firmware controller section provides all power and signal conditioning, automated process control of effectors for all operational modes, safety monitoring, fault detection/isolation logic, and command/response communication with the higher level Multiplexer/Demultiplexer (MDM) via a MIL-STD-1553 interface. The ISM provides monitoring (independent of software) of select system parameters and ensures the OGA will not operate in an unsafe condition. It is understood that for a future deep space Exploration mission, newer technology will be used in the AOGA Process Controller. However, because technology related to electronics changes rapidly, it is likely that an upgrade for the upcoming ISS AOGA demonstration would also be obsolete or outdated by the time a system is built for a deep space mission. Therefore, AOGA will incorporate only

minimal controller modifications to support new AOGA functionality. The ISS AOGA Process Controller will not be a new design, but will be a modified legacy OGA Process Controller. Existing boards within the OGA Process Controller will be modified to control five new valves, used to support automated flushing (described below). Existing boards will also be modified to support a new pressure sensor to support automated flushing and the i-domes operation (described above).

H. Automated Recirculation Loop Purge and Flush

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. The feed water makeup contains trace amounts of DMSD, and DMSO_2 . 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. As the DMSD concentration increases the DMSD may deposit onto piping and other system components. DMSO_2 is more volatile than DMSD and predominantly leaves the cell stack through the hydrogen stream which is believed to have poisoned the Sabatier catalyst in the past. Neither of these species have shown a detrimental impact to cell stack on-orbit performance of the OGA. Further, elemental analysis performed during the 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. To effectively flush the system a 3x volume change of the recirculation loop must be performed periodically. To accomplish this the recirculation loop will be purged first with nitrogen to remove the gaseous hydrogen. Then, a batch feed process is commanded to first fill the RSA with fresh water from the potable water bus, and then drain the RSA water down to a set level, out to the wastewater bus. This process is then repeated until the 3x volume change out has been fulfilled. The flushing of the system will be conducted automatically (not requiring crew time), with the option to perform manual flushes in special circumstances. The safing and flushing process is also a key part of establishing a safe storage condition for the AOGA system during dormancy periods to protect the cell stack from water loss and microbial issues on return to operation. In order to support an Exploration mission profile, AOGA must be put into a dormant configuration, preferably without any required power, for up to 1 year. This would be needed when, on a mission to Mars, for example, the crew is on the Mars surface. It is desired that minimal crew interaction be necessary in order to put the system into its dormant configuration, both because the spacecraft will have many systems and some of them cannot avoid requiring crew intervention, but also because the AOGA is such an important piece of life support hardware that it will need to remain operational for as long as possible prior to crew departure.

IV. Future Plans

The AOGA will be demonstrated on ISS for a minimum of 3 years. The ISS OGA will be upgraded to an AOGA configuration with separately launched kits. The first kit, which enables the move of the OGS rack from Node 3 to Lab, will be delivered in late 2021. The second kit, which will convert OGA to AOGA on orbit, will be delivered in 2023. The OGS rack in Lab will also include the upgraded ACTEX (delivered in 2021 and capable of being tested with OGA ahead of AOGA delivery), accommodation inside the rack for an upgraded Sabatier when available, new rack-internal CO₂ accumulators to feed Sabatier, and H₂ST, which will reside on the rack face. Schedule for implementation is also tied to the ISS software update process – AOGA will require modifications to on-orbit software that is scheduled for uplink in late 2022.

At this time, it is assumed that the existing overboard vent valve in the LAB1P1 location will be viable for use with AOGA. However, that valve has a known internal leak that must be characterized in advance so that newly made connections for AOGA can be verified as part of moving the rack. NASA is coordinating with ESA to utilize the Life Support Rack system to perform this leak characterization. If the valve is not accepted due to uncertainties or safety risk, a new valve could be installed that would require a series of Extravehicular Activities (EVA's).

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