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Advanced Oxygen Generation Assembly for Exploration Missions

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Future Exploration missions will require an Oxygen Generation Assembly (OGA) to electrolyze water to supply oxygen for crew metabolic consumption. The system design will be based on the International Space Station (ISS) OGA but with added improvements based on lessons learned during ISS operations and technological advances since the original OGA was designed and built. These improvements will reduce system weight, crew maintenance time and spares mass while increasing reliability. Currently, the design team is investigating the feasibility of the upgrades by performing ground tests and analyses. Upgrades being considered include: redesign of the electrolysis cell stack, deletion of the hydrogen dome, replacement of the hydrogen sensors, deletion of the wastewater interface, redesign of the recirculation loop deionizing bed and redesign of the cell stack Power Supply Module. The upgrades will be first demonstrated on the ISS OGA.

Nomenclature

ACTEX = Activated Carbon Ion Exchange
dP = Delta Pressure
ECLSS = Environmental Control and Life Support Systems
ISS = International Space Station
MDP = Maximum Design Pressure
NASA = National Aeronautics and Space Administration
OGA = Oxygen Generation Assembly
OGS = Oxygen Generation System
ORU = Orbital Replacement Unit
PSM = Power Supply Module
RSA = Rotary Separator Accumulator

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I. Introduction

FUTURE deep space exploration missions will require an Oxygen Generation Assembly (OGA) 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) 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. Currently, the design team is investigating the feasibility of the upgrades by performing ground tests and analyses. Significant future work is planned. The ISS OGA will be modified to an Exploration based Advanced OGA (AOGA) configuration. The current status of the redesign effort will be presented in this paper.

II. ISS OGA Description and Current Status

As of April 21, 2019, the ISS OGA has produced over 16,184 lbm of oxygen and 2,023 lbm of hydrogen. The currently installed OGA electrolysis cell stack has accumulated a total operating time of 21,198 hours. See Figure 1 for a plot of oxygen produced over time.

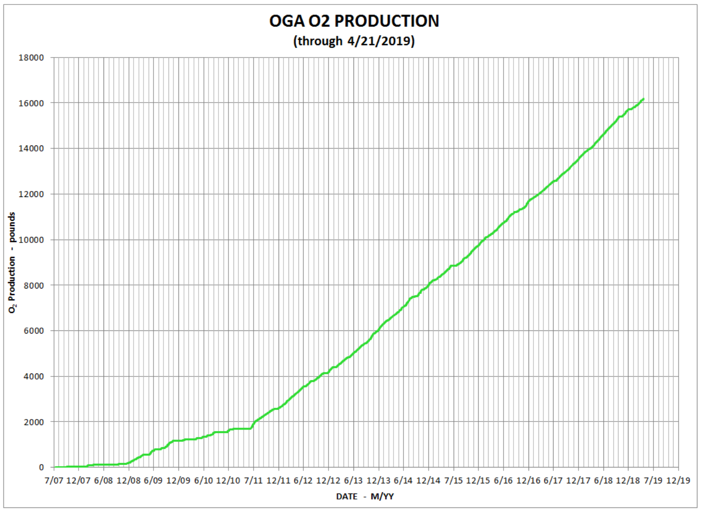

Figure 1. Total Oxygen Produced by the ISS OGA

A simplified schematic of the OGA is shown in Figure 3. The OGA consists of the following 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 DI bed, the feedwater is rejected by a three-way valve to the waste water bus. This prevents any oxygen that may be present in the feedwater from mixing with the generated hydrogen in the Rotary Separator Accumulator (RSA). Water is electrolyzed by the cell stack to produce oxygen and hydrogen. The RSA separates the cathode side product gaseous hydrogen from the water. The Hydrogen ORU consists of a dome which surrounds the components which contain hydrogen (cell stack, RSA, sensors, valves, etc.). The hydrogen dome provides a multiple leakage barrier protection in the event of a failure. The hydrogen dome is maintained at low pressure by venting to space vacuum. The water is recirculated by the positive displacement Pump ORU. Downstream of the pump is an Activated Carbon Ion Exchange (ACTEX) filter. The ACTEX is a mixed 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, 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. The OGA sensors are used for fault detection and fault isolation purposes. 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 Power Supply Module (PSM) ORU provides 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 amps (A) during Standby mode (2% oxygen production rate).

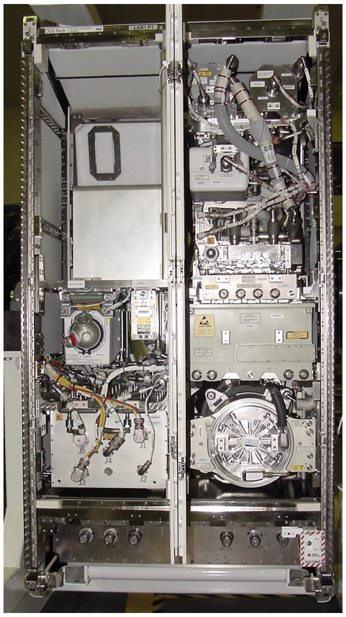

Figure 2. ISS OGS Rack

The ISS OGA was originally designed to generate oxygen at a nominal rate of 12 lbm/day when operated on day/night orbital cycles (53 minutes at 100% production, 37 minutes in standby which produces 0.44 lbm/day of oxygen), and also at a selectable rate between 5.1 and 20.4 lbm/day or 22 to 100% oxygen production rate when operated continuously. At the nominal rate, the ISS OGA can support oxygen needs for 4 crew, while at the maximum rate it can support 10.88 crew (assumes 1.874 lbm oxygen/day/crew metabolic rate). The OGA has been and will continue to be operated continuously, as the electrical power constraints originally defined are no longer of concern. The product oxygen meets quality specifications for temperature, free water, dew point, and hydrogen content. The ISS OGA is packaged into nine ORUs, residing in the OGS rack, as shown in Figure 2. Most of the OGA ORUs are run to failure except for the calibration life limited Hydrogen Sensor ORU and the mixed-resin containing ORUs (Inlet DI Bed and recirculation loop ACTEX) which are trended for water throughput and recirculation loop water quality to determine the Preventative Maintenance (PM) replacement intervals.

Major ISS OGA events from January 2016 through March 2019 are timelined in Figure 4. Other than OGA component preventative maintenance replacements, periodic dome sensor vacuum zero point offsets, drifting hydrogen sensor inhibits and recirculation loop sample returns, there were previously three failures associated with the Hydrogen ORU and a recirculation loop pump anomaly, as documented in Reference 1. The current Hydrogen ORU s/n 3 has been installed since November 2016. The cell voltages during steady state operation are nominal. However, cell 1 voltage after shutdown is of possible concern, as it is the fastest cell to discharge, as shown in Figure 5 (Cell 1 is the blue line). Also, during startup, it is the slowest to charge. This behavior is similar to the previous Hydrogen ORU s/n 2 cell 1 prior to its failure. At this time, the OGA team will continue to closely monitor Hydrogen ORU s/n 3 cell 1 voltage trend.

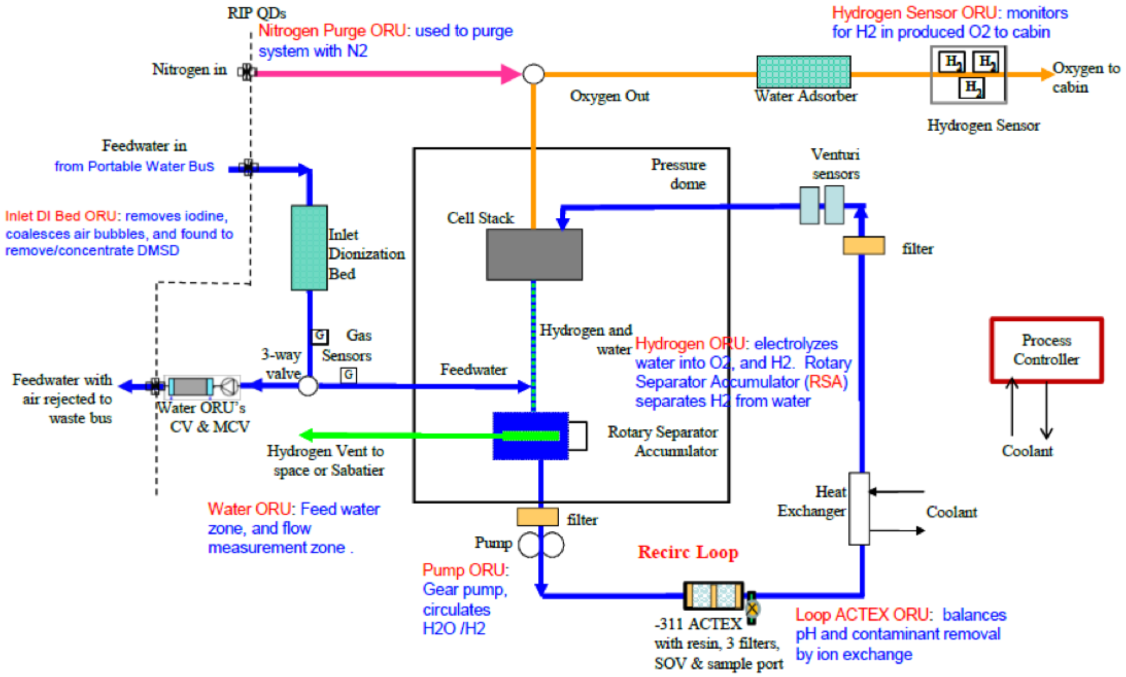

Figure 3. ISS OGA Simplified Schematic

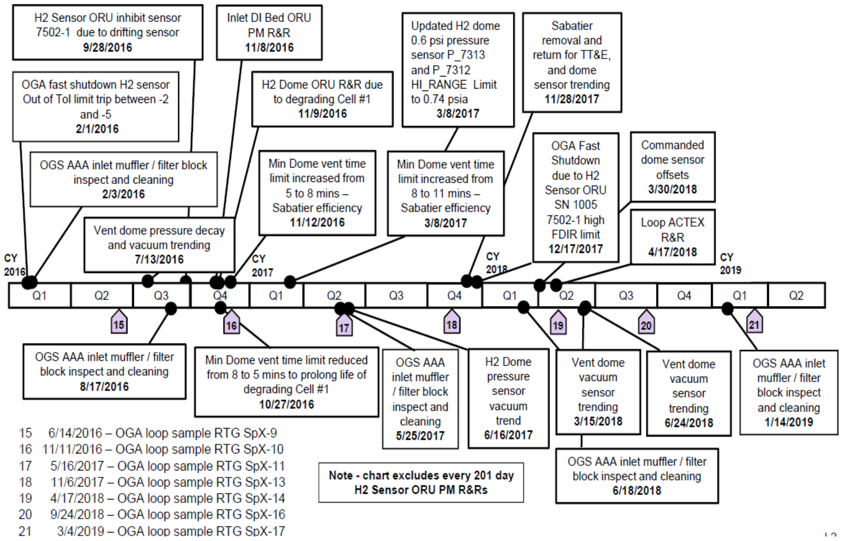

Figure 4. Timeline of Recent OGA Events (1/2016 to 3/2019)

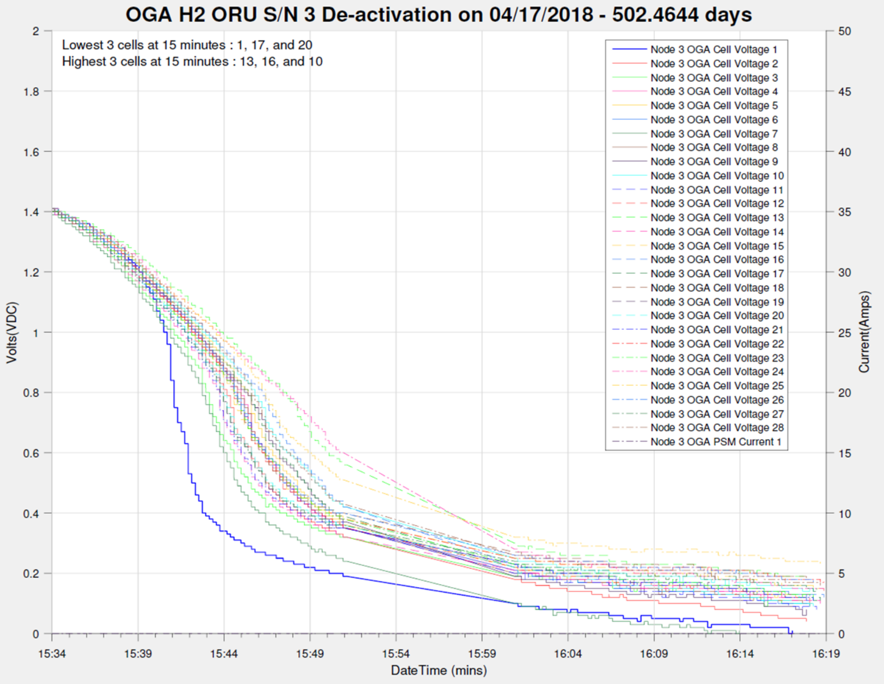

Figure 5. Hydrogen ORU s/n 3 Cell Voltages Upon Shutdown

Pump ORU s/n 1 has a cumulative operating time of 8.4 years (well beyond its 2 year design life). Over the past year the pump has exhibited a gradual increase in speed from 2000 to 2040 rpm and decrease in motor temperature from 90 to 80°F, as shown in Figure 6 (the blue line is the pump speed, the red line is temperature). The recirculation loop is under software flow control, based on the venturi dP/flow sensors, which maintains constant loop water flow by adjusting the positive displacement pump speed. The pump contains an integral bypass relief valve, which will crack open at approximately 30 psid. A fault tree of potential root causes has been developed. Potential causes include: pump gear wear leading to a less efficient pump, the pump bypass relief valve cracking open caused by recirculation loop delta pressure (dP) increase, and sensor/controller drift. Unfortunately, the pump dP sensor failed in 2010, so there is no direct insight into recirculation loop dP. Future troubleshooting will command a lower recirculation loop flow rate set point to create a lower recirculation loop dP to attempt to reseat the relief valve. The pump speed will be monitored to determine if the upward trend continues with a reseated relief valve.

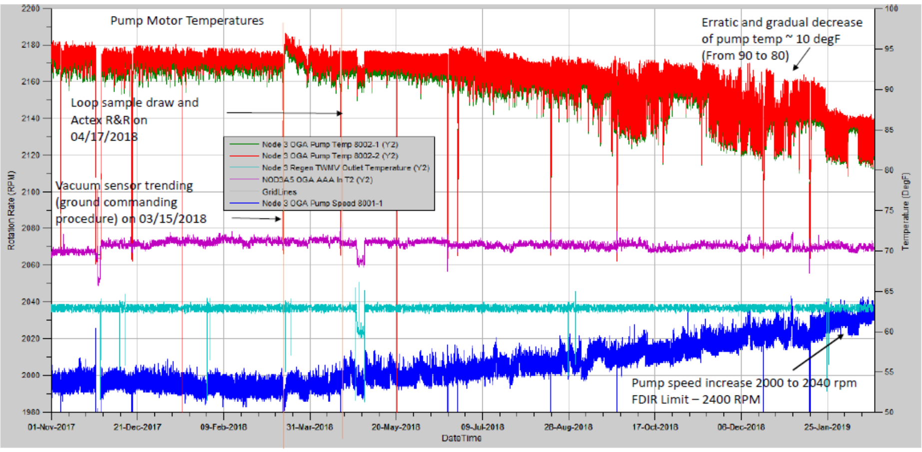

Figure 6. Pump Speed Increase and Temperature Decrease

Analysis of the recirculation water is a critical part of monitoring cell stack and loop health. The WPA has exhibited multiple, increasing TOC (Total Organic Carbon) trends of potable water which is fed to the OGA recirculation loop. The source of previous TOC trends has been two organosilicons: Dimethylsilanediol (DMSD) and monomethylsilanetriol (MMST). There is an unknown risk that DMSD could potentially affect cell stack performance by coating the inner surfaces of the cell stack and preventing water transport within the membrane. Recirculation loop samples (~120 mL) are taken and returned for ground chemical and microbial analyses twice a year to monitor the health of the closed loop which concentrates contaminants. Two loop water samples taken on 4/17/2018 and 9/24/2018 were returned and analyzed. The sample drawn on 3/4/2019 remains on-orbit awaiting return on SpX-17. pH and conductivity have been within acceptable ranges, with the pH averaging 5.5 and conductivity averaging 1.9 uS/cm. Over the past two years there have been increasing concentrations of TOC (9 to 21 ppm), DMSD (<1 to 3.8 ppm), MMST (<1 to 4 ppm) and total silicon (0.06 to 4 ppm – includes DMSD and MMST) since a partial flush in November 2016. Sample microbial enumerations ranged from 6.15E+03 to 3.45 E+05 CFU/mL with predominant microbial species identified as *Ralston Pickettii*, which has the ability to survive and thrive in low nutrient (oligotrophic) conditions. It is theorized that in ultrapure water systems, the bacteria may be able to scavenge from the polymers in plastic piping. Studies have shown that *R. pickettii* may pass through a 0.2-mm filter. Other techniques for monitoring the cell stack health include polarization scans (5 amp step-ups to plot current density versus voltage for each cell) and weekly trending of cell voltages. Quarterly polarization scans have been all in family to date.

III. Proposed Upgrades

Based on the lessons learned during ISS operations and the 2017 supportability study recommendations (Reference 1), several upgrades to the OGA design have been proposed. Table 1 lists each of the proposed upgrades.

Table 1. Proposed Upgrades

Proposed Upgrade	Reason	Description
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
Delete the nitrogen purge equipment	Reduce system mass and complexity	Delete nitrogen purging of the cell stack anode during shutdowns and startups
Replace the hydrogen sensors	Reduce crew maintenance time and improve reliability	Replace hydrogen sensors with a more reliable technology that requires less crew intervention
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
Remove the hydrogen dome	Reduce logistics resupply requirements	Crew will be able to access and maintain the internal dome components
Redesign the PSM	Reduce system mass/volume	The current PSM design is oversized for a future mission and contains obsolete parts
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 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

A. Cell Stack Redesign

Cell stack s/n 5 (in Hydrogen ORU s/n 2) was removed from the ISS OGA in November 2016. It was assembled in 2007 and installed in the ISS OGA in 2010, accumulating approximately 5 years of run time when removed. The OGA team recommended removal due to cell 1 voltage trending lower during Standby from the nominal 1.5 V towards the shutdown limit of 1.0 V. On Oct 21, 2016, cell 1 voltage (green line) decreased to 1.17 V in Standby for 7 hours, as shown in Figure 7, while the other 27 cells remained above 1.5 V. In addition, cell 1 was the slowest to charge during activation and the fastest to discharge during deactivation.

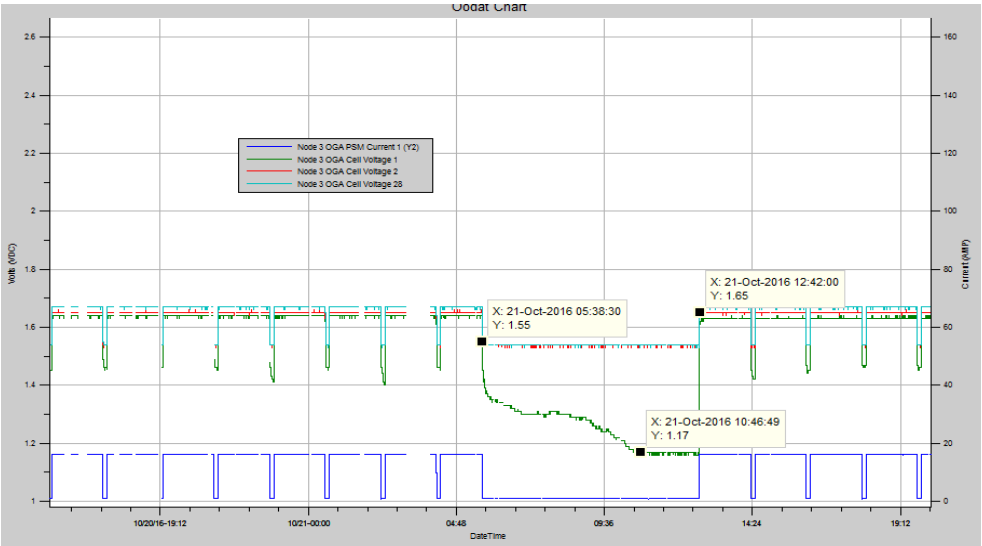

Figure 7. Cell Stack s/n 5, Cell Voltages

When cell stack s/n 5 was returned to the ground, a test, teardown and evaluation (TT&E) was performed and cells 1 and 2 were removed for analysis. The TT&E started in 2017 and completed in 2018. The membrane of cell 1 was found to be have thinned to 20 µm or approximately 90% loss of material in some areas, as shown in Figure 8. In comparison the membrane of cell 2 had thinned about 50%. The cause of the excessive thinning in cell 1 is believed to be a unique compressive loading in comparison to the other cells in the stack. The loading in cell 1 increased the steady state creep of the membrane compared to its peers leading to excessive thinning at load points at the membrane interface. Another factor that contributed to the increased creep is the support material for the membrane on the cathode uses a smaller landing than the anode backing material and may have been a contributor to the failure. Additionally, chemical degradation of the membrane from radicals generated during operation can contribute to overall or localized membrane thinning. The membranes used at the time of assembly were more susceptible to chemical degradation and the material has been replaced with a chemically stabilized Nafion by the manufacturer Chemours. The thinning of the membrane in cell 1 resulted in progressively less resistive shunt paths and the low cell voltage failure. Cell membrane material creep characterization testing at multiple temperatures and compressive loading combinations over time (both with and without electrolysis) is in-work and expected to be completed by the end of 2019. Early phase of creep rate testing results determined that the Time-Temperature-Superposition (TTS) principle was effective in predicting long-term creep behavior. Stress/load tends to dominate temperature effects. There is forward work to determine the contribution of electrolysis on membrane thinning due to mass loss within local high stress areas at the interfaces of membrane to cathode / anode supports. Redesign of the cell stack will focus on alleviating the unique loading of cell 1 by balancing the load profile across the stack, improving support of the MEA by increasing the number of landings on the anode and cathode membrane supports, minimizing creep through reduction of volume available for the membrane to move into, and reducing chemical degradation through incorporation of chemically stabilized Nafion.

Figure 8. Cell 1 Membrane Cross Section

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 for two purposes. The first is 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 mixture of hydrogen and oxygen in the anode from forming over time when the system is unpowered. At startup, a nitrogen purge removes any hydrogen that may have permeated through the membrane to the anode.

The second purpose is to fill the hydrogen dome prior to removal from the system with nitrogen to create an inert condition for transportation. If the hydrogen dome is deleted, as discussed elsewhere in this paper, the need for inerting the dome will be obviated.

The benefit of deleting the nitrogen purging equipment is a reduction in system complexity and weight. In addition, the vehicle design will be simplified since it will not be required to supply nitrogen to OGA. The 2017 supportability analysis (Reference 1) determined that nitrogen purge equipment accounted for 204 lb (93 kg) of spares upmass on a 1,100-day mission. Removal of the nitrogen purge equipment could lower total spares mass by this amount as well as reduce the OGA system mass.

However, there are four safety concerns with eliminating the nitrogen purge equipment that will need to be addressed. These concerns would occur during a shutdown and subsequent startup. First, hydrogen could cross over the cell membranes from the cathode to the anode and create an unsafe hydrogen/oxygen mixture. Second, oxygen could cross over the cell membranes from the anode to the cathode and create an unsafe hydrogen/oxygen mixture. Third, water could cross over the cell membranes from the cathode to the anode and flood the oxygen outlet line. Fourth, the recirculation loop pressure could drop below ambient and allow air to leak in, creating an unsafe hydrogen/air mixture. Nitrogen purging pressurizes the cell stack anode and in turn the cell stack cathode and recirculation loop when the OGA is shutdown.

When nitrogen purging is disabled, ground testing to date has not indicated any detectable hydrogen in the product oxygen, based on the hydrogen sensor readings during startup and gas chromatograph (GC) sampling of the product oxygen. In addition, the testing to date has not indicated any oxygen in the product hydrogen, based on GC sampling of the product hydrogen.

The major operational concerns with disabling nitrogen purging are: water in the oxygen outlet, low RSA quantity on subsequent startup, and low recirc loop pressure on subsequent startup. When nitrogen purging is disabled in the OGA testbed, a large amount of water (up to 330 mL) is observed in the oxygen outlet line upon every subsequent startup. This amount of water at every startup is undesirable, since it would damage the hydrogen sensors in the oxygen outlet line. In addition, liquid water is not allowed to exit the oxygen outlet port into the cabin. This additional water would have to be captured by the oxygen outlet line water absorber, and a method for drying the absorber would need to be developed. Without nitrogen purging, the cathode pressure is higher than the anode pressure. The pressure gradient pushes water across the membrane from the cathode to the anode. The second related issue is the low RSA quantity upon subsequent startup when nitrogen purging is disabled. Testing has shown that a significant reduction of RSA water quantity occurs when nitrogen purging is disabled, from a nominal 25 – 30 cu-in to as low as 0 cu-in. This reduction in RSA water quantity during shutdown with nitrogen purging disabled can make the subsequent startup more difficult. There is an Independent Shutdown Monitor (ISM) interlock which prevents the system from starting up if the RSA quantity is too low. The related third issue is the low recirculation loop pressure on subsequent startup when nitrogen purging is disabled. When nitrogen purging is enabled, the cell stack anode compartments are pressurized with nitrogen upon shutdown. The nitrogen in the anode compartments permeates across the cell stack membranes to the cathode compartments and helps keep the recirculation loop pressure at a desirable level for the next startup. When nitrogen purging is disabled during shutdown of the OGA testbed, the anode pressure is at ambient pressure, and the recirculation loop pressure drops close to ambient pressure within two days after the system is unpowered, as shown in Figure 9. When the system is in Process, the recirculation loop pressure (blue line) is at about 26 psia. Once the system is unpowered, the recirculation loop pressure decreases to approximately 15.5 psia within 3 days. This pressure decrease makes the subsequent startup more difficult, as this is below the low shutdown limit for the recirculation loop pressure of 20.5 psia during Standby. Given these operational issues, the design team will need to decide whether these issues can be managed if nitrogen purging were to be deleted.

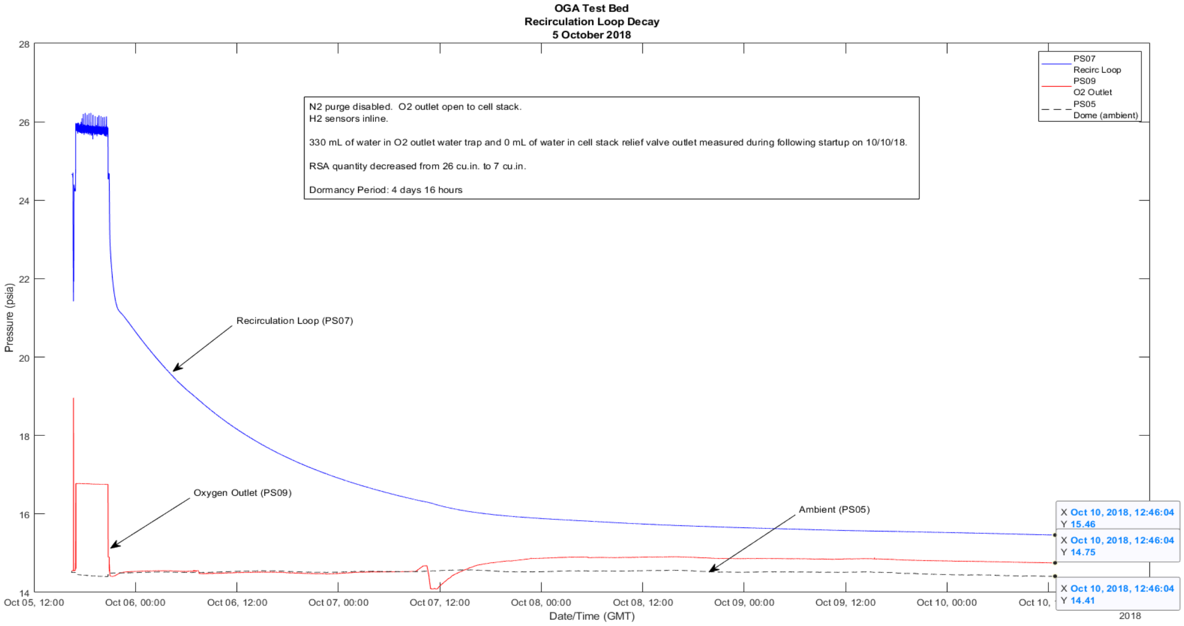

Figure 9. Recirculation Loop Pressure and Cell Stack Anode Pressure During Shutdown, No N2 Purge

C. Replace Hydrogen Sensors

The ISS OGA Hydrogen Sensor ORU contains three independent semiconductor dies (custom manufactured by a university) to monitor for hydrogen in the product oxygen prior to being released into the ISS cabin atmosphere. The process controller shuts down the OGA if any of the sensors detect more than one percent hydrogen in oxygen (25% of the lower flammability limit, [LFL]). The presence of hydrogen in the product oxygen indicates a possible cross cell leak within the cell stack. There are four issues with the hydrogen sensors which need to be addressed for an Exploration mission, as documented in Table 2.

Table 2. Issues with the ISS OGA Hydrogen Sensors

Issue	Description
Susceptible to damage from moisture	If the sensor is powered with moisture on the die, damage will occur. The crew is required to perform a dry oxygen purge, using specialized tools, after every shutdown.
Significant upward drift on some sensors dies during on-orbit operation	Some of the sensor dies experience significant upward drift, above the shutdown limit. Requires ground operators to disable the offending sensor to prevent a nuisance shutdown. The root cause is unknown and this issue has not been experienced during ground test.
Sensitivity to nitrogen	Exposure to nitrogen (during a shutdown or startup nitrogen purge) can cause the sensors to go off-scale high. Ground operators are required to disable the sensors and operate the system in standby to clear the fault.
Requires return to the ground every 201 days for recalibration	Installed life is limited by a known downward drift of 2 Pascals per day (worst case). The sensors cannot be recalibrated on-orbit.

Based on the past experience with the ISS OGA hydrogen sensors, AOGA hydrogen sensors requirements are defined in Table 3.

Table 3. Replacement Hydrogen Sensor Requirements

Requirement	Comments
Capable of measuring hydrogen in oxygen	Almost all commercially available hydrogen sensors are marketed as hydrogen in air sensors
Minimal offset due to high relative humidity oxygen	The current ISS OGA hydrogen sensors are susceptible to damage if powered after being exposed to high humidity gas.
Minimal offset due to nitrogen exposure	The current ISS OGA hydrogen sensors exhibit significant (temporary) offset after exposure to nitrogen. Nitrogen purging occurs after every system shutdown and start up.
Limited downward drift in calibration over time	Downward drift is in the non-conservative direction and if significant enough is a hazard since the sensor will report less hydrogen than actual. Downward drift limits the calibration life.
Fast response time	Fast response time is required to detect a hazard (hydrogen leaking into the product oxygen) and shut down the system. The current ISS OGA hydrogen sensors are required to have a 6 second response time (time to indicate 1% when exposed to 4% H_2 in O_2).
Long calibration life	The current ISS OGA hydrogen sensors are limited to a calibration life of 201 days, after which they must be returned to the ground for recalibration.

Reference 1 provides details on the past work to identify commercially available replacement hydrogen sensor candidates, starting in 2017. Initial bench testing in 2017 identified two viable candidates (Sensor A and Sensor B). Next, they underwent 1,000 hours of endurance testing in the OGA Test Bed. This testing exposed the sensors to flight-like conditions: product oxygen from a cell stack at the expected humidity, temperature and flow rate. Finally, the two hydrogen sensor candidates underwent final bench testing in 2019. The bench test rig is shown in Figure 10. Hydrogen and oxygen are introduced into the sensor in precise mixtures from 0 – 3% H2 in O2. The Mass Flow Controllers (MFCs) meter the amount of hydrogen and oxygen gas. The total flow rate is set to either 1.2 lpm, 2.25 lpm or 4.5 lpm, equivalent to ISS OGS setpoints (equating to 3, 5.5 and 11 crew level respectively). The sparger humidifies the bottled gas to bring the dew point from approximately -20 deg F up to dew points representative of OGS product oxygen dew points (65, 72.5 and 85 F). A combustible gas sensor (CG) measures the H2 in O2 % of the input and output. A dew point sensor measures the dew point of the input and output. A pressure sensor monitors inlet pressure. A solenoid valve introduces nitrogen purge gas into the system in the event a failure is detected. A 3-way valve directs gas flow to either the hydrogen sensor or to the vent. A second 3-way valve directs either inlet gas or outlet gas to the CG sensor and dew point sensor. The hydrogen concentration value reported by the hydrogen sensor is compared to the actual hydrogen concentration.

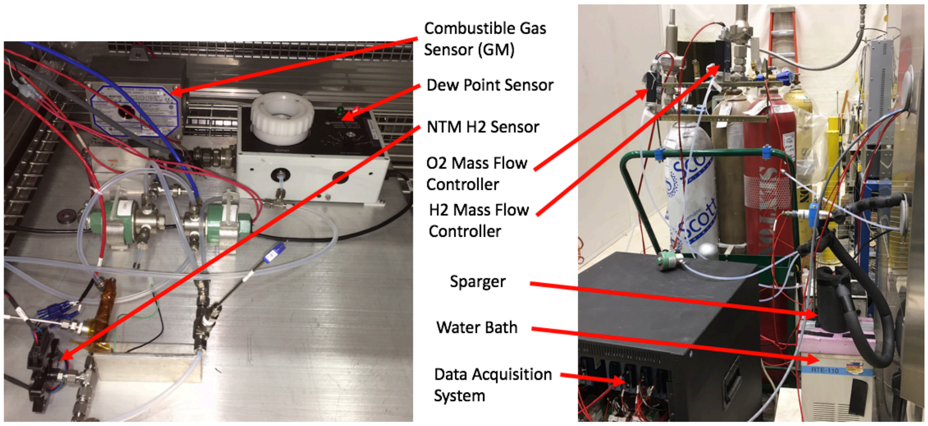

Figure 10. Bench Test Configuration

Sensor A has been selected as the preferred sensor for a flight demonstration on the ISS OGA in 2020 based on the final bench test results. A comparison of the initial bench test results in 2017 and the final bench test results in 2019 at the 85 deg F dew point for Sensor A are shown in Table 4. For the 1.2 and 2.25 lpm flow rates, there is a 0 to 5% positive drift, for the 4.5 lpm flow rate there is a -3 to -5% negative drift. Sensor A's response to a 3.5% H2/O2 mixture is shown in Figure 11. As a reference, the legacy hydrogen sensors have a requirement to indicate 1% H2/O2 within 6 seconds of being exposed to 4% H2/O2. Sensor A output is above 1% within 5 seconds of being exposed to 3.5% H2/O2.

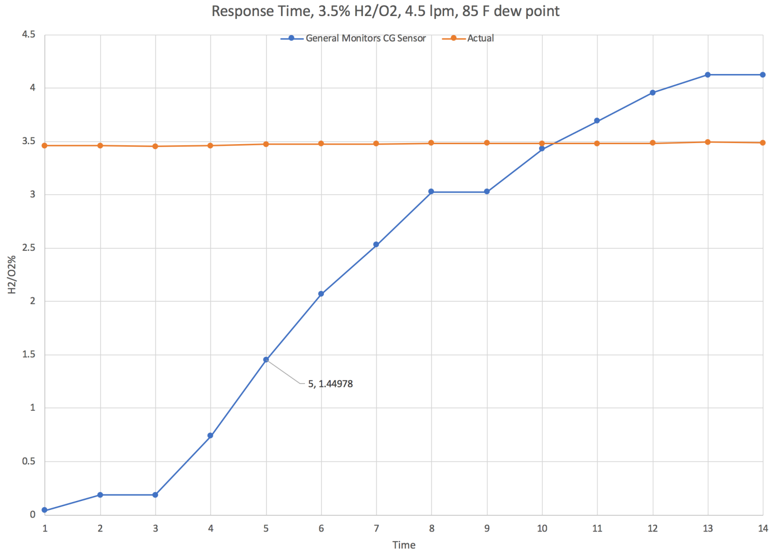

Figure 11. Sensor A's Response to 3.5% H2/O2 Mixture

Table 4. Sensor A Test Results, 85 deg F Dew Point

Flow Rate (lpm)	Actual H2/O2%	Sensor Output (2017)	Sensor Output (2019)	Drift (% full scale)
1.2	0.0	0.2	0.0	+5
	1.0	1.0	1.1	+3
	2.0	2.1	2.2	+3
	3.0	3.2	3.4	+5
2.25	0.0	0.0	0.0	0
	0.5	0.6	0.6	0
	1.0	1.2	1.2	0
	2.0	2.3	2.4	+3
	3.0	3.6	3.8	+5
4.5	0.0	0.1	0.0	-3
	0.5	0.8	0.7	-3
	1.0	1.5	1.3	-5
	2.0	2.7	2.6	-3
	3.0	4.2	4.1	-3

A hydrogen sensor flight demonstration unit will be installed on the ISS OGA in 2020. The mechanical, electrical and software design is currently ongoing. Delivery of the flight unit is planned for June 2020. The flight demonstration unit will be installed at the OGA oxygen outlet port and will be mounted externally to the OGS rack. The sensors will remain installed for at least 3 years. A notional schematic is shown in Figure 12. The unit will contain a four-way valve, three hydrogen sensor candidates, a flow meter, and electronics. The OGA product oxygen will flow through the hydrogen sensor candidates. The flow meter will verify that the OGA product oxygen is flowing through the hydrogen sensors and monitor for leaks. The four-way valve will allow the periodic introduction of calibration gas through the sensors. In this valve state, the OGA product oxygen will bypass the hydrogen sensor candidates and flow directly into the cabin. The calibration gas (2% H2/air) will be introduced from handheld bottles through the hydrogen sensor candidates every 90 days. Sensor response to the calibration gas will be monitored and trended over time. The electronics will provide 28 V power to the sensors, convert the raw sensor readings, and send sensor telemetry to the ground 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.

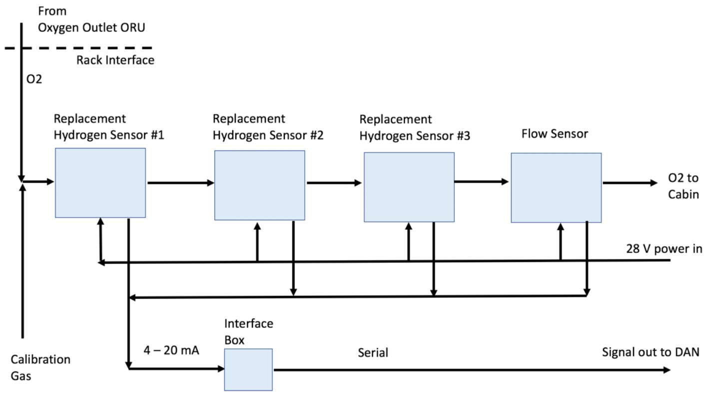

Figure 12. Hydrogen Sensor Flight Demonstration Notional Schematic

D. Delete the Wastewater Interface

Feed water is batch supplied to the ISS OGA to replace water consumed by electrolysis. Feed water flows through an inlet deionizing bed to remove iodine. Oxygen in the feedwater can coalesce in the inlet deionizing bed and oxygen bubbles will be released periodically out of the bed. Two gas sensors will detect this release and a three-way valve will divert the feed water to the wastewater bus and prevent oxygen gas bubbles from entering the RSA where it could mix with hydrogen gas. Once the feed water is clear of oxygen bubbles, the three-way valve is repositioned to allow water flow into the RSA.

After eleven years of operation, gas bubbles in the feed water have been detected occasionally. There are eight known events (8/21/09, 11/14/09, 4/14/10, 12/19/13, 7/30/14, 8/12/14, 9/4/15, 10/15/15) where the feed water was diverted to the wastewater bus due to gas detected in the feed water. On 12/19/13, oxygen gas was detected in the feed water and allowed to go into the RSA (because the gas was detected downstream of the 3-way valve, it was not possible to send this oxygen bubble to the wastewater bus). After this event, the OGA continued to operate nominally. There are no known events since 2015.

The 2017 supportability analysis study (Reference 1) determined that 216 lb (91 kg) of logistics upmass could be saved for a 1,100-day mission by deleting the waste water interface from the design. The waste water interface is part of the Water ORU, as shown in Figure 2. While the waste water components account for only 22% of the mass of the Water ORU, they contribute 66% of the failure rate of that ORU. As a result, removing the waste water components from the Water ORU nearly triples the MTBF of that ORU, lowering the probability of failure and reducing the number of spares that would need to be carried. This provides incentive for deleting the waste water interface. However, the burden for providing gas free water would be placed on the Water Processor Assembly (WPA). This could potentially increase WPA system complexity and logistics upmass. At this time, the waste water interface will remain in the AOGA design, due to the desire to retain the capability to shunt potable water to the wastewater bus to recover from off nominal events within the WPA.

E. Remove the Hydrogen Dome

The ISS OGA hydrogen dome encloses all hydrogen containing components: cell stack, RSA, solenoid valves, relief valves, pressure sensors, temperature sensors, and connecting tubing. The dome is connected to space vacuum and is maintained at a vacuum. The purpose of the dome is to detect hydrogen leakage out of the cell stack or RSA (via a pressure rise in the dome), contain hydrogen leakage and contain any accelerated debris from a possible combustion event after multiple failures.

There are commercial and military cell stacks that have operated safely for thousands of hours without a dome. During ground testing, the ISS OGA cell stacks are regularly operated safely without a dome. The dome was incorporated into the ISS OGA design out of an abundance of safety conservatism. The disadvantage of the dome is that the internal components are inaccessible to the crew for maintenance. If one of the components fails (such as a valve), the entire dome assembly (288 lb launch weight) will need to be replaced. In over twelve years of operation on ISS and on the ground, no external hydrogen leakage out of the cell stack or RSA has occurred.

The 2017 supportability study (Reference 1) determined that deleting the dome and allowing component level maintenance of the internal components, would result in an estimated 617 lb (280 kg) of spares mass savings for a 1,100 day exploration mission. However, removing the dome from the OGA design is not a trivial task. With a no-dome design, a specific failure scenario is of concern. After multiple failures, a leakage of hydrogen into the rack or cabin could potentially occur. The leak could be a small undetectable continuous leak or a large sudden release. Small undetectable leaks will likely not pose a hazard as they will remain below the flammability limit with proper ventilation and eventually will be removed by the Trace Contaminant Control System. Large sudden releases of hydrogen are considered to be a hazard. If this were immediately ignited, a nearby crew member could potentially be harmed. In order to quantify the risk, testing and analysis will need to be performed. Table 5 documents the additional testing and analysis which will need to occur.

Table 5. Additional Tasks Required to Support Dome Removal from the Design

Task	Description	Status
Remove the dome from the OGA Test Bed	Demonstrate safe operation without a dome	Dome removal in the OGA Test Bed is complete. Testing is ongoing.
Perform hydrogen release analysis	Determine the maximum amount of hydrogen that could instantaneously be released externally by the undomed components in the event of multiple failures	Initial analysis is complete. However, the analysis will need to be updated as the redesign progresses.
Perform flash fire testing and analysis	Determine effect on a nearby crew member of a hydrogen release (due to multiple failures) and combustion	Complete
Perform cell stack burst test	Test to demonstrate that an undomed cell stack will not leak at the Maximum Design Pressure (MDP)	Complete
Redesign internal components to have redundant seals	Most internal components currently have a single seal preventing hydrogen from leaking externally.	Not started

	Redesign will be required for certain parts to incorporate redundant seals to meet safety requirements	
Perform Maximum Design Pressure (MDP) analysis of undomed components	Determine the MDP of undomed components (cell stack and RSA)	Analysis is ongoing and will complete in 2019
Add hydrogen and oxygen flow sensors to the design	Supplement existing leak detection methods	Demonstrated feasibility of flow sensors in the OGA testbed. Testing is ongoing.
Rack ventilation computational fluid dynamics (CFD) analysis	Verify that rack ventilation will dilute a hydrogen leak below the LFL	Started in 2019

The vacuum dome was removed from the OGA Test Bed in 2015, and since then has operated safely for over 1,000 hours. No external hydrogen leakage has been detected by facility hydrogen sensors. The cell stack, RSA, and all other hydrogen containing components are exposed to the ambient air. The OGA Test Bed will continue to be operated in this configuration for the foreseeable future.

A hydrogen release analysis was performed in 2018 to determine the worst case amount of hydrogen that could be instantaneously released from an undomed OGA in the event of multiple failures during non-operation. A preliminary worst case estimate determined that approximately 92 cu-in of hydrogen could be released from the cell stack in the event of multiple failures. This estimate will likely change as the AOGA design matures. Additional hydrogen release above 92 cu-in will occur if a failure occurs during operation. The amount of hydrogen that can be released during operation will depend on the sensitivity and responsiveness of the new hydrogen and oxygen flow meters. As discussed below, ground testing of the new flow meters is ongoing, therefore the worst case amount of hydrogen release during operation has not yet been determined.

The hydrogen flash fire testing was completed in 2018. The results were summarized in Reference 1. The results were presented to the ISS Safety Review Panel (SRP) in April 2018. Combustion of hydrogen releases up to 115 cu-in were categorized as low risk of long term hearing effect, and there were no concerns identified with overpressure or total radiative exposure. Therefore, releases below 115 cu-in will not be considered a catastrophic hazard, but rather a critical hazard. Based on these results, the SRP concurred with the AOGA dome-less design (contingent on closure of assigned actions). Personal Protective Equipment (PPE) will be an effective control to the acoustic hazard.

Figure 13. Water Leakage of the Cell Stack at 1,000 psig

The cell stack burst test was completed in 2018. A development cell stack of the proposed AOGA 22-cell design was built. All components which would affect external leakage were flight like, including the end plates and cell frames. Internal components which would not affect external leakage were substituted for lower cost equivalents, including the cathode and anode screens and membrane catalyst. The test plan called for hydraulically pressurizing the cell stack until leakage or burst occurred. The test stand had the capability to pressurize the cell stack up to 3,000 psig. High speed video cameras were in place to capture any destructive burst of the cell stack. In addition, calipers were in place to measure the growth in height of the cell stack as it was pressurized. During the test, the stack pressure was increased in 50 psig increments. As the cell stack was pressurized, it grew in height. No leakage or deformation was observed until the cell stack was pressurized to 1,000 psig. At this pressure, water droplets were observed on the outer edges of the cell stack hydrogen manifold, as shown in Figure 13. In addition, it was observed that the cell stack grew in height by approximately 0.018 inch, which allowed some loss of compression between the cell frames, and paths for external leakage to form. When the pressure was removed, the cell stack returned to its original height and no permanent deformation was observed. Normal operating pressure of the cell stack is approximately 10 psig. The expected MDP (worst case pressure due to a failure of internal components) of the AOGA cell stack is expected to be under 500 psig. Although this test is a single data point, it provides confidence that the cell stack does not require redesign. Future analysis will be required to corroborate the test results.

Existing OGA sensors can provide an indication of external hydrogen leakage from the un-domed cell stack or RSA. Pressure sensors monitor the recirculation loop pressure and dP sensors monitor the quantity of water in the RSA. An external leak can cause a drop in the recirculation loop pressure and RSA water quantity if the leak is large enough. To provide finer leak detection, new sensors are required. Flow sensors in the hydrogen vent line and the oxygen outlet line are proposed for AOGA. An external leak of hydrogen will cause a decrease in flow of hydrogen out of the hydrogen vent line. A cross cell leak, allowing hydrogen to flow out of the oxygen outlet line, will cause an increase in total flow out of the oxygen outlet line. Gas flow can be sensed in various ways. One method of detecting flow is to sense delta pressure across an orifice installed in the line. A valve (acting as an orifice) and a delta pressure sensor were installed in both the hydrogen vent line and oxygen outlet line of the OGA testbed. The modified hydrogen vent line is shown in Figure 15. Accurately sensing flow at different production rates was demonstrated in 2018 and described in Reference 1. In 2019, the response of the hydrogen flow sensor to hydrogen leaks was demonstrated in the OGA testbed. External hydrogen leaks in the hydrogen vent line and two phase water/hydrogen leaks in between the cell stack and RSA were purposely introduced to determine the sensitivity and response time of the hydrogen flow meter. If the actual hydrogen flow rate is less than the theoretical hydrogen flow rate, then this could indicate an external leak upstream of the flow meter. However, sensor drift, controller electronics drift, and system/sensor noise can affect the smallest size of leak able to be detected. Also, if a leak occurs at the same time as a transient event (such as a production rate change or RSA water fill), then the leak may be masked for a period of time. Hydrogen and two phase leaks were introduced during steady state operation and transient events. The size of the leaks introduced were 15%, 20%, 50%, 75% and 100% of the hydrogen production rate. An example of hydrogen flow meter response to an external hydrogen leak during steady state operation is shown in Figure 14. Nominally, the dp (as indicated by the blue line) is approximately about 0.28 psid at 10 A, corresponding to a production rate of approximately 0.23 lb/hr of hydrogen. When a 20% leak, 0.0047 lb/hr, is introduced, (as indicated by the orange line) the dp sensor reading decreases by 25%, from 0.28 to 0.21 psid. Based on these test results a worst case hydrogen release can be calculated.

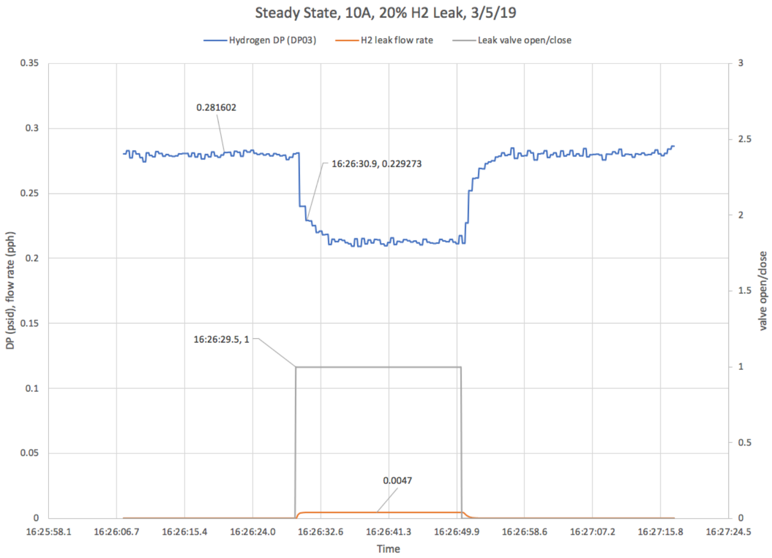

Figure 15. Hydrogen DP Sensor Response to a 20% Hydrogen Leak

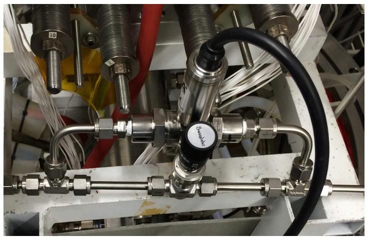

Figure 14. Hydrogen Flow Sensor

The MDP of the components previously inside the dome (cell stack, RSA, and associated components) needs to be reassessed. Previously, it was assumed that the dome would contain the bursting of the cell stack and RSA in the event of an internal combustion event. Therefore, the MDPs of the cell stack and RSA were set to the maximum pressure due to a non-explosive event, such as valves failing. Now that the dome has been deleted from the AOGA design, it must be confirmed that these components can withstand the worst case pressure due to an internal combustion event without bursting. The MDP of the cell stack and RSA now needs to be set to the pressure of a worst case internal combustion event.

The original MDP of the ISS OGA cell stack in a dome was set to 80 psig due to the valves in the Nitrogen Purge ORU failing open. Without a dome, the new AOGA cell stack MDP must be set to the pressure due to a worst case combustion event within it. As a part of the additional safety analyses, worst case credible cross-cell leakage scenarios inside the cell stack were evaluated to determine the potential for a combustion event, deflagration, or detonation and the resulting overpressure within the cell stack. A worst case scenario was identified where a failure would allow hydrogen and water to enter the oxygen header. This could happen if a seal between the hydrogen-water header and the oxygen header fails or a Nafion membrane in one of the cells develops a tear or hole. The gas phase composition would be 45.2% hydrogen, 54.8% oxygen by volume. The water would be in the liquid phase at a ratio of nine volumes water to one volume of gas. Therefore, the leak in this case will result in the oxygen outlet line being filled with liquid water at 90 % by volume. The resulting gas mixture is within the flammable and detonable range. However, for a detonation event to occur one of two other conditions must be satisfied. Either the gas mixture must be exposed to an ignition source that is a sufficiently strong shock to directly initiate a detonation or a weak ignition source sufficient to promote combustion and sufficient confinement with detonable gas mixture to permit flame acceleration (FA) until deflagration to detonation transition (DDT) can occur. No sufficiently strong ignition source could be found that would produce a shock strong enough to directly initiate a detonation for either mixture. The possibility of a weak initiation source sufficient to promote combustion (perhaps a stray catalyst particle) and sufficient confinement with a detonable gas mixture to permit flame acceleration (FA) until DDT could not be ruled out. However, the presence of 90% liquid water by volume will reduce the possibility of ignition, and should ignition occur will cool the flames, absorb energy, and essentially hamper all combustion processes. Therefore, deflagration or detonation occurring within the cell stack is not indicated. Then, the worst-case scenario for overpressure is what can arise from an adiabatic, isochoric (constant volume), complete combustion (AICC). AICC overpressures can be calculated from the well-established NASA Chemical Equilibrium with Applications (CEA) computer program also known as Gordon-McBride computer code, which indicates a maximum overpressure of 147 psia (preliminary estimate) within the cell stack. However, there is the distinct possibility of a combustion event in another section of the AOGA creating a higher overpressure within the cell stack, and this must still be examined and accounted for.

The original MDP of the ISS OGA RSA was set to 50 psig, due to a cell stack leakage failure. Without a dome, the new AOGA RSA MDP must be set to the pressure due to a worst case internal combustion event. The worst case scenario is when an oxygen bubble dislodges from the Inlet DI Bed and is inadvertently allowed to enter the hydrogen and water filled RSA due to two valve failures (the water inlet valve failing open and the 3-way valve failing in the deliver position). The system detects the oxygen release into the RSA and shuts down, however cannot prevent it due to the valve failures. The largest size oxygen bubble that could be released from the Inlet DI Bed is estimated to be 3.3 cu-in. at 25.7 psia based on prior ground test. It is assumed that the RSA runs long enough before shutdown to thoroughly mix the oxygen with the hydrogen. In the end, there is a water volume of 56 in3, and a gas volume to 9.2 in3, pressurized to 45.2 psia. The gas is a mixture of 20.5 % oxygen and 79.5 % hydrogen. This is a flammable and possibly detonable mixture. The center of the RSA contains dry gas. Should a catalyst particle find its way there, it could act to ignite a flammable mixture and create a detonation in the central shaft region. Flame propagation and acceleration is impeded in the outer drum region, due to it being largely occupied by water. This combustion in the outer portion of the RSA can be conservatively characterized by an AICC event. Analysis of the RSA simulator test data at WSTF in 2015 shows a two-step combustion: a rapid acceleration and the possibility of a DDT in the central region of the RSA, followed by pressurization of the outer RSA region (pressure piling) followed by an AICC combustion. The detonation in the central region will cause the gas to expand approximately 18 times its original volume into the gas volume in the drum. AICC combustion of the now pressurized gases pushes on the surrounding water to exert a pressure on the case estimated to be approximately 630.5 psia. This pressure is well above the 50 psig MDP of the RSA motor housing. Other connected AOGA components such as the cell stack and water pump would be subjected to this pressure. The design team is currently investigating methods for preventing this worst case overpressurization event from occurring. This worst case event requires two valve failures. One method of preventing this worst case event from occurring would be to add a third valve (a redundant water inlet valve) to the design.

Additional MDP analyses will be performed in 2019. Other sections requiring analysis include the oxygen outlet line, feedwater inlet and recirculation loop.

In the absence of a dome surrounding the cell stack and RSA, the potential of external hydrogen leakage after a failure must be considered. The design team has just started to analyze this scenario, and will continue work throughout the remainder of 2019. Within the OGS rack there is an existing Avionics Air Assembly (AAA) mounted on the center shelf on the left side of the rack. Its original purpose is to ventilate the rack to prevent a buildup of oxygen above 28.5% given a worst case oxygen leak, prevent condensation, provide cooling to Sabatier and to provide ventilation for the proper operation of the rack smoke detector. Air is pulled in from the cabin, the rack, and Sabatier into the AAA and returned to the rack with leak paths back to the cabin. CFD analysis has shown that the current rack ventilation design using the AAA will not provide the proper airflow around the cell stack and RSA (located in the bottom right section of the rack) to prevent the hydrogen concentration from exceeding 4% in the event of a failure leading to a hydrogen leak.

Several design options are being considered to provide proper ventilation around the cell stack and RSA. The first option involves placing the cell stack and RSA within an enclosure. This enclosure has a dedicated ventilation system provided by fans, which draw in cabin air, which is circulated throughout the box and exhausted back out into the cabin. Preliminary CFD analysis has determined that this configuration would provide the proper airflow to prevent a combustible mixture from forming in the event of a hydrogen leak. An additional concern with an enclosure is the potential for overpressure and acoustic noise in the event of a combustion resulting from leakage of hydrogen into the enclosure (especially when the ventilation system is unpowered). Two cases will be considered as boundary conditions: one is that the hydrogen mixes uniformly throughout the entire box free volume, the other is that the hydrogen mixes with a corresponding amount of air to form a stoichiometric mixture. An ignition source is assumed for each case. Assuming the free volume within the enclosure is 3,000 cu-in and a worst case leakage of 170 cu-in of hydrogen, a uniform mixture could form which would be 5.67% by volume. This mixture is above the lower flammability limit (LFL) in air and is theoretically combustible. But mixtures less than 8% v/v are barely flammable and when ignited do not completely burn. But, this analysis will assume complete burning as a worst case assumption. The lower confined detonability limit in air is usually given as a range of 11% to 18%. So this mixture will not detonate. A 5.67% hydrogen in air mixture combusted at pressure of one atmosphere will result in a pressure of approximately 1.2 atmospheres (17.6 psia). This assumes complete combustion at constant volume. This would be a momentary overpressure of approximately 2.9 psia. The second bounding case assumes that the escaped hydrogen forms the most sensitive mixture possible with the air inside the enclosure. This is a uniform, stoichiometric mixture containing 29.5% hydrogen by volume. This will release the maximum combustion energy and the analysis will assume that ignition happens at that time. If confined, this mixture could transition to a detonation. Further analysis will be undertaken to evaluate whether the stoichiometric mixture would result in a detonation due to confinement by the components in the enclosure or a deflagration due to the mixture only occupying 19% of the total free volume inside the enclosure. CFD analysis to calculate flow patterns around the components in microgravity will be a part of that work. The acoustic hazard outside of the enclosure from a combustion event inside the enclosure will also be considered.

A second option that will be analyzed involves a new duct which will route a portion of the AAA exhaust to the cell stack and RSA. A third option that will be analyzed involves a new duct from the AAA inlet routed to the cell stack and RSA that will draw in cabin air past those hydrogen containing components. Once all of the CFD analysis is completed in 2019, the AOGA ventilation configuration will be finalized.

F. Redesign the PSM

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 converter units along with filter boards, control board, relay, sensors, etc. The internal configuration is shown in Figure 16. The PSM has a weight of 100 lb and dimensions of 15 x 24 x 11 inches.

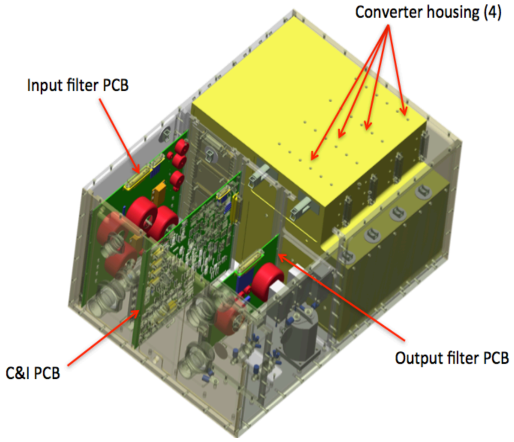

Figure 16. PSM Configuration

The PSM 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 space rated microcontroller. This one microcontroller could potentially take the place of dozens of discrete components. At this time, the ISS Program is electing not to fund redesign the PSM. The legacy PSM will be used for the ISS AOGA.

One concern is whether the legacy PSM can provide power to the AOGA cell stack, which will have 22 cells instead of 28 cells. Fewer cells will mean a lower total cell stack voltage. The PSM minimum specified voltage is 38 V. AOGA cell stack could have a beginning of life voltage of 33 V. There is a concern that the PSM could be unstable and electrically inefficient at 33 V. In January 2019, a single power converter was tested at the lower voltage. The testing indicated no issues at the lower voltage, however lower efficiency was observed. Based on the successful power converter results, the Engineering Unit PSM was successfully tested at lower voltages in April 2019. This provides confidence that the flight PSM will not require a redesign to power an AOGA cell stack. Future ground testing is recommended with a flight PSM and an AOGA cell stack (when it is available).

G. 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 2). The purpose of the ACTEX is to remove fluoride that is released by the cell stack membranes (as part of normal operation) and maintain a desirable pH level in the water recirculation loop. The ACTEX was not specifically designed for the OGA, and should be redesigned and optimized for AOGA. Table 6 describes the requirements for a redesigned ACTEX. The redesign of the ACTEX is expected to begin later in 2019.

Table 6. Requirements for a Redesigned ACTEX

Requirement	Current -311 ACTEX	Redesigned ACTEX
Life	1.8 years	3 years
Pressure drop	~16 psid	~3 psid
MDP	40 psig	160 psig
Seal redundancy	Single seals	Dual seals
Materials compatibility	Incompatible	Compatible

The resin within the redesigned ACTEX will not change, however the design of the housing will change to address the issues listed in Table 6. The amount of resin will need to increase to meet a 3 year life. With the current ACTEX design, the water flow rate through the bed is higher than recommended by the resin manufacturer for the bed volume, resulting in transitional flow and a relatively high dP. The volume, diameter and length of the housing will be increased to ensure laminar flow. To further reduce dP, the housing inlet and outlet bore diameter will be increased, a pair of quick disconnects (QDs) will be deleted and the mesh filter design will change. To address safety concerns, dual seals will be incorporated and there will be material changes.

H. Redesign the Process Controller

Two newly designed sensor boards will need to be installed into the process controller to accommodate the additional sensors and effectors in the new AOGA design. In addition, the backplane will need to be redesigned to get additional power and signals to the new boards. The thermal analysis will need to be updated to confirm that there is adequate cooling with the redesigned controller. New internal controller harnessing will be required to get power and signals from the backplane to the circular connectors that feed through to the external OGA harnessing. Rack electrical harnesses will have to be modified to mate to new electrical components. System software will be modified to control new effectors and monitor new sensors.

IV. Future Plans

Testing and analysis to inform the AOGA design will continue throughout 2019. Detailed design will start in 2019. Hardware delivery of kits to transform the ISS OGA to an AOGA configuration will be delivered in 2022. The ISS OGA will be upgraded to an AOGA configuration in the 2023 timeframe. This configuration is expected to incorporate a redesigned cell stack, hydrogen sensors, ACTEX, and process controller and delete the hydrogen dome. The intent is to demonstrate an Exploration based AOGA on ISS for a minimum of 3 years.

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