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Oxygen Generation Assembly Design 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. These improvements will reduce system weight, crew maintenance time and resupply mass from Earth 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

ECLSS	=	Environmental Control and Life Support Systems
EVA	=	Extra Vehicular Activity
ISS	=	International Space Station
LFL	=	Lower Flammability Limit
NASA	=	National Aeronautics and Space Administration
OGA	=	Oxygen Generation Assembly
OGS	=	Oxygen Generation System
ORU	=	Orbital Replacement Unit
POS	=	Probability of Sufficiency
PSM	=	Power Supply Module
RSA	=	Rotary Separator Accumulator
SA	=	Sabatier Assembly
SOA	=	State of the Art
TT&E	=	Teardown Test and Evaluation

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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 on a 1,100 day mission. The system design will be based on the International Space Station (ISS) OGA but with added improvements based on lessons learned during ISS operations. These improvements will reduce system weight, crew maintenance time and resupply mass from Earth while increasing reliability. Currently, the design team is investigating the feasibility of the upgrades by performing ground tests and analyses. Significant work has been performed since the last reporting in 2015 (Ref. 1). In addition, significant future work is planned. The current status of the redesign effort will be presented in this paper.

II. ISS OGA Description and Current Status

As of April 29, 2018, the OGA has produced over 14,202 lbm of oxygen and 1,775 lbm of hydrogen. The currently installed OGA cell stack has accumulated a total operating time of 12,711 hours. See Figure 1 for a plot of oxygen produced over time.

A simplified schematic of the OGA is shown in Figure 2. Feed water from the ISS potable water bus enters the assembly through the Water Assembly Orbital Replacement Unit (ORU) and flows through an Inlet Deionizing Bed, which serves as an iodine remover and as a coalescer for any 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 serves to prevent any oxygen that may be present in the feedwater from mixing with the generated hydrogen. Water is electrolyzed into oxygen and hydrogen in the Hydrogen Dome ORU, which contains the electrolysis cell stack, sensors, valves and a Rotary Separator Accumulator (RSA). The RSA separates the cathode side product gaseous hydrogen from the water which is recirculated by the positive displacement Pump ORU. 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. Separated hydrogen gas 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. 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

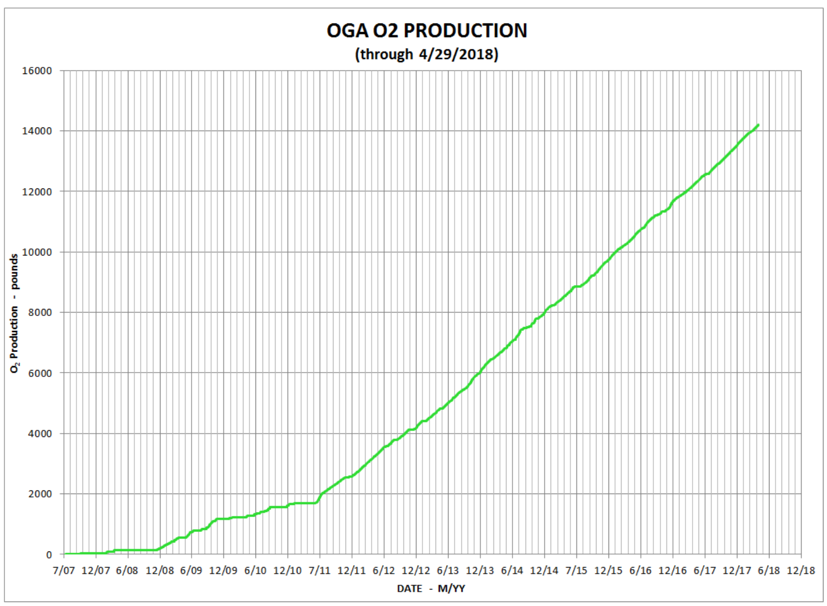

Figure 1. Total Oxygen Produced by the ISS OGA

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 during Standby mode (2% oxygen production rate).

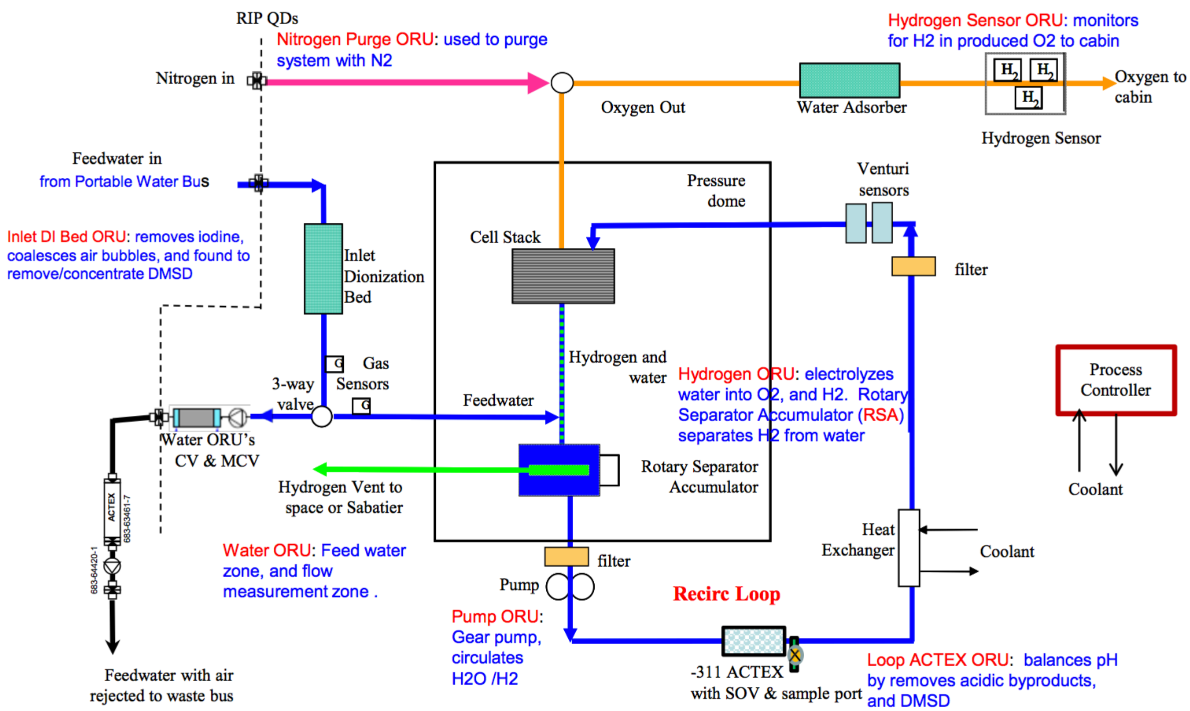

Figure 2. OGA Simplified Schematic.

The OGA is designed to generate oxygen at a nominal rate of 5.4 kg/day (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 2.3 and 9.2 kg/day (5.1 and 20.4 lbm/day) or 22 to 100% oxygen production rate when operated continuously. At the nominal rate, the OGA can support oxygen needs for 4 crew, while at the maximum rate it can support 10 crew. The product oxygen meets quality specifications for temperature, free water, dew point, and hydrogen content. The OGA is packaged into eight ORUs, residing in the OGS rack, as shown in Figure 3. 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 return water quality to determine the Preventative Maintenance (PM) replacement intervals.

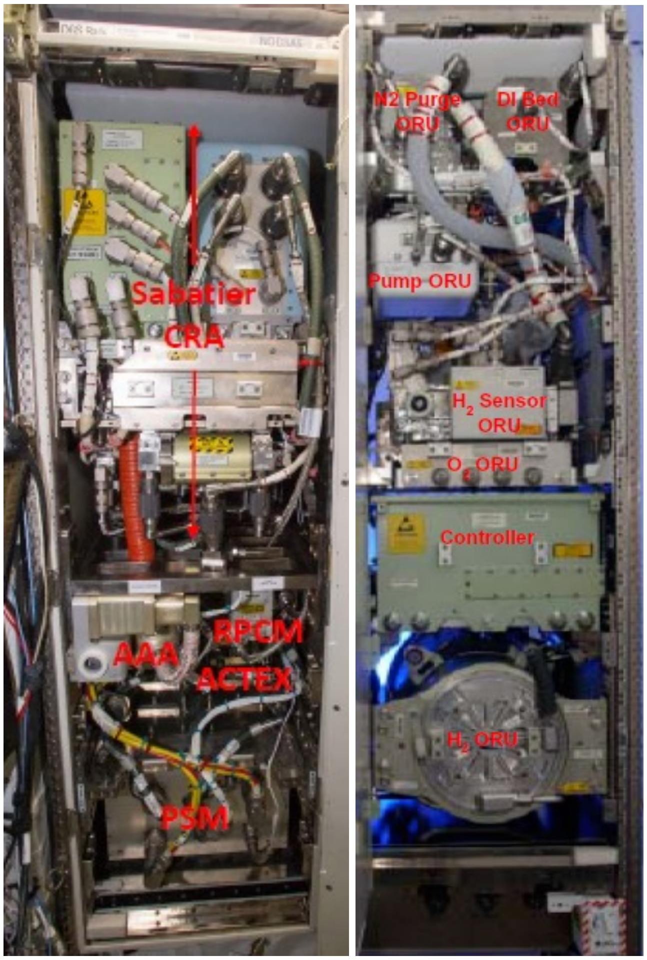

Figure 3. OGS Rack

III. Proposed Upgrades and Current Status

Several lessons learned, based on over a decade of ISS OGA operations, have been previously documented (Ref. 1). Recent major ISS OGA events 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, three failures associated with the Hydrogen (H2) ORU were investigated.

Since May 2014 the OGA team has been monitoring anomalous voltage trends in the installed SN 2 H2 ORU cell stack assembly's Cell #1 since first detected (fastest discharge rate upon deactivation, slowest charge rate to Standby and lowest voltage in standby or process compared to the other 27 cells). During an October 2016 reactivation to Standby attempt, OGA went to Fast Shutdown. Data dump indicated low voltage across Cell #1. Cell #1 voltage was progressively dropping lower than the electrolysis threshold voltage of 1.48 VDC towards the FDIR low voltage shutdown limit of 1.0 VDC during transitions from Process to Standby (nominal Standby voltage is 1.51 VDC). The failed ORU was replaced in early November 2016 with Hydrogen ORU s/n 3 and returned for Test, Teardown and Evaluation (TT&E) and failure investigation. Total cumulative on-orbit electrolysis time while SN 2 H2 ORU was installed was 5.28 years. The H2 ORU predicted design life is 5 years. Cells # 1 and #2 were removed from the cell stack and both non-destructive and destructive tests were performed. Significant narrowing was observed within Cell #1 cross-sectional thickness in the contact areas of the adjacent cathode and anode screen pack wires as compared to Cell #2. In addition, there was a metallic appearing, small contaminant compressed into 50% of the cell membrane under the cathode screen wire. Both findings could have contributed to the voltage shunting exhibited by Cell # 1 on-orbit. Failure investigation on Cells # 1 and #2 is nearly complete and a final report expected by June 2018.

The SN 4 H2 ORU ground spare failed during its every 180 day electrolysis preventative maintenance. The failure was determined to be caused by an internal ORU cell voltage sensing harness which had reflowed solder joints between resistor leads pairs. H2 ORU voltage sensing harness resistor wire solder joint defects were systemic and likely latent failures due to poor harness materials selection (higher shrink tube vs. solder eutectic temps), design and manufacturing processes. All of the spare (on-orbit and ground) H2 ORU harnesses have either a repaired or redesigned voltage sensing harness that mitigated the risk of reflowed solder joints. If the OGA installed SN 3 H2 ORU with the old suspect harness design (reflowed solder risk) fails due to bad harness solder joint(s) then the ISS program has approved continued operations of OGA at less than 45% O2 production rate and to allow inhibits on up to 6 voltage sensing lines per a NASA Safety Assessment Chit.

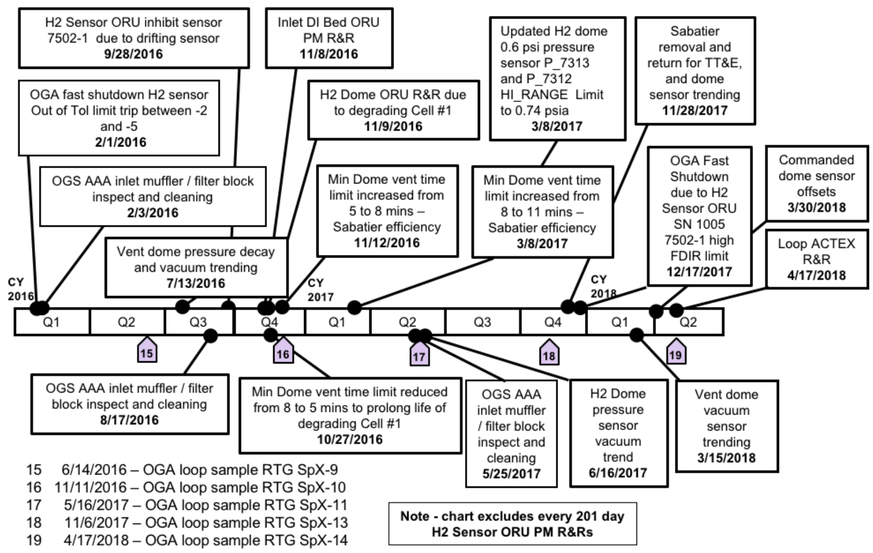

Figure 4. Timeline of Recent OGA Events

The crew was not able to fully mate the OGA SN 3 H2 ORU ¾ inch quick disconnect (QD) to the DIW from RSA flex hose QD after replacing SN 2 H2 ORU in November 2016. The same partially mated QD issue was experienced earlier in November 2016 due to an inability to fully mate a CRFH Water Adapter ¾" universal QD to the same OGS rack flex hose QD during setup for an OGA recirculation loop flush. Crew reported that the QD was at 90% connected or ¼ turn from fully mated in both cases. The mated QD pair was Kapton taped to minimize risk of QDs backing off given only one of the two redundant seals against external leakage is engaged (primary seal). Failure investigation continues with additional QD fit checks on the returned, suspect CRFH adapter and a new spare hose (QD procurement and hose build in-work) expected to be completed in early 2019.

Two studies were completed since the last reporting in 2015 (Ref. 1). A redesign study was completed in 2016 by UTC Aerospace Systems (UTAS). This study examined the existing ISS OGA design, identified areas of improvement, proposed a new configuration and documented the safety analysis of the redesigned system to support a crew of 4 on an 1,100 day mission. In 2017, a supportability analysis of this system was performed by the Space Mission Analysis Branch at Langley Research Center. This study examined the spare parts requirements for a 1,100-day deep space mission, assuming that spares are provided to achieve 0.995 probability of sufficiency (POS), where POS is defined as the probability that the set of spares provided are sufficient to repair failures during the mission. For the purposes of this study, ORU failure rates were assumed to be deterministically known, with no epistemic uncertainty; as a result, it is likely that the spares estimates presented here are lower than the values that would be calculated if epistemic uncertainty were accounted for. A more detailed discussion of the supportability analysis techniques used and the impact of epistemic uncertainty is presented in References 5 and 6. The OGA supportability study concluded that the OGA would be the third most logistically intensive system (out of 17) on a deep space exploration vehicle. In addition, the supportability study examined the impact of various proposed design changes on spares mass; for example, it found that lower level maintenance at the component level (rather than at the ORU level) has the potential to enable significant spares mass reduction, and provided the estimates of spares mass reduction impacts described in the sections below.

Based on the lessons learned during ISS operations and the study recommendations, 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
Cell stack membrane replacement	SOA membrane is obsolete	Replace obsolete Nafion membrane with chemically stabilized Nafion membrane
Delete the nitrogen purge equipment	Reduce system mass and complexity	Delete nitrogen purging of the cell stack anode during shutdowns and startups
Replace 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	SOA PSM is oversized for a future mission and contains obsolete parts
Redesign the recirculation loop ACTEX deionizing bed	Increase installed life and reduce the delta pressure	The existing design is not optimal as it was not specifically designed for the OGA
Redesign the process controller	Two newly design sensor boards to be installeded into the controller for additional sensor and effectors	New connectors and backplane harnesses and swap-out of two sensor circuit card boards

A. Cell Stack Membrane Replacement

The ISS OGA cell stack is a cathode feed design, with 28 cells to electrolyze water to generate oxygen and hydrogen. Each cell contains a cathode compartment and an anode compartment, separated by a Nafion membrane (originally manufactured by DuPont). Thin layers of catalyst are applied on each side of the membrane to form the anode and cathode electrodes of the cell. In this design, feed water is circulated on the cathode side of the cells, where hydrogen is generated. Excess water carries away the produced hydrogen and process heat. The membrane's high water permeability allows sufficient water transport to the anode, where the electrolysis actually takes place. Oxygen is generated at the anode, where it is virtually free of liquid water.

The original Nafion membrane material used in the ISS OGA cell stack is obsolete. Chemours now offers "chemically stabilized" Nafion, which has a much lower fluoride release rate. This chemically stabilized Nafion has not been incorporated into the ISS OGA cell stack or any spares. Another consideration is that the ISS OGA cell stack vendor, UTAS, no longer manufactures cell stacks for this application.

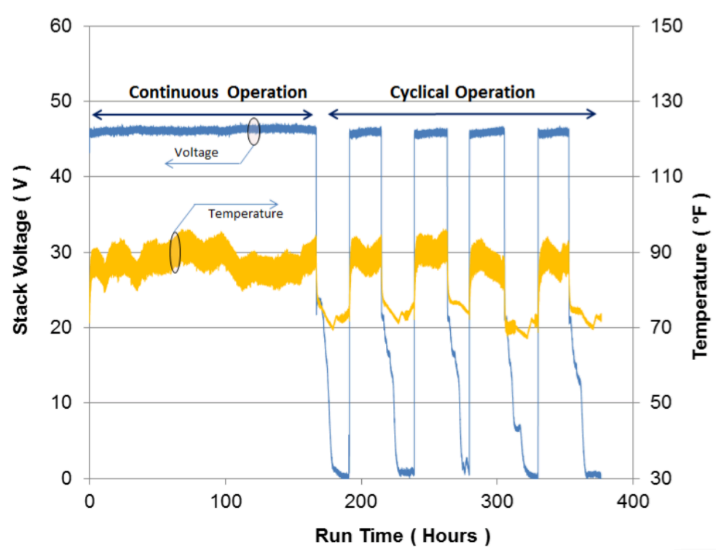

Figure 5. Giner Cell Stack Acceptance Testing

The buildup of hydrofluoric acid within the recirculation loop was the cause of the ISS OGA cell stack failure in 2010. Incorporating chemically stabilized Nafion, with its lower fluoride release rate, should improve system reliability.

As previously reported (Ref. 1), NASA contracted with Giner, Inc. to build three single cells. These single cells were of the same design as the ISS OGA cells (same physical dimensions, active area, and current density), except that the newer chemically stabilized Nafion was used for the membranes. Based on the acceptable results of the single cell endurance testing and post test health checks, Giner was funded to build a 28-cell stack in 2015. The 28-cell stack incorporates the chemically stabilized Nafion and the cells are the same design as the ISS OGA. After assembly of the cell stack, Giner performed two weeks of acceptance testing, as shown in Figure 5. The cell stack exhibited stable voltage performance during this test. Oxygen and hydrogen production rates were within 1.7% of the calculated theoretical values. The cell stack passed all leak tests, resistance tests and oxygen and hydrogen purity checks. Based on these successful results, the cell stack was accepted by NASA and installed into the OGA Test Bed at MSFC in 2016, as shown in Figure 6. To date, the cell stack has accumulated 300 hours of nominal operation. The stack will continue to be operated for the foreseeable future. Periodic polarization scans are performed to monitor for changes in performance in any of the cells.

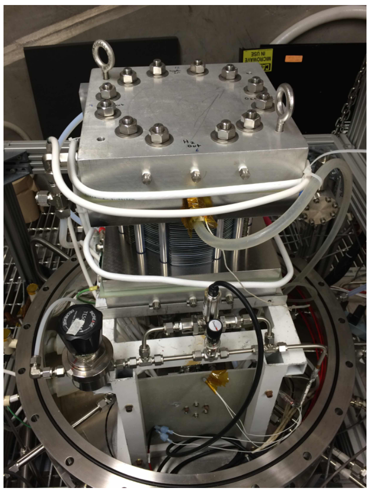

Figure 6. Giner 28 Cell Stack

In parallel with the 28 cell testing, a single cell with chemically stable Nafion (built in 2014) is undergoing ongoing endurance testing at UTAS. The single cell has accumulated over 14,000 hours to date with no voltage degradation and will be continuously operated for the foreseeable future.

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 upon system shutdown and startup. During prolonged shutdowns, hydrogen in the cathode compartment will migrate 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 supportability analysis determined that nitrogen purge equipment accounted for 204 lb (93 kg) of spares upmass on a 1,100-day mission, given a POS requirement of 0.995. Removal of the nitrogen purge equipment could lower total spares mass by this amount as well as reduce the OGA system mass.

In previous reporting (Ref. 1), it was proposed that the nitrogen purging equipment could be safely deleted. During the single cell testing (described in the previous section) at Giner, one of the cells was operated safely without any nitrogen purging for ten months. No safety issues or change in functional performance occurred. At UTAS, flight ISS OGA cell stacks are operated safely without nitrogen purging during ground testing.

The OGA Test Bed was modified in Feb 2014 to operate without nitrogen purging of the anode during shutdown and startup. The OGA Test Bed has operated for 135 hours safely without any nitrogen purging.

A trade study was performed in 2016 on whether to delete the nitrogen purge function. Without nitrogen purging a significant amount of water would form in the cell stack anode compartments during each shutdown. A new absorber would need to be incorporated to remove the water from the product oxygen, since the downstream hydrogen sensors would be damaged if exposed to liquid water. In addition, during each shutdown, the water recirculation loop would be driven to subambient pressures without nitrogen purging. Nitrogen purging pressurizes the anode and also helps maintain the proper pressure in the cathode and recirculation loop during unpowered periods, which facilitates the subsequent startup. Deleting the nitrogen purging would add new design risks and operational complexity. Based on the results of the trade study, the design team decided to keep the nitrogen purge function in the future advanced OGA design.

C. Replace Hydrogen Sensors

The ISS OGA contains three independent hydrogen sensors 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 cross cell leak within the cell stack. The hydrogen sensors are sensitive to moisture. Condensation on the hydrogen sensor dies while being powered will cause permanent damage. To prevent condensation, heaters maintain the temperature above the dew point of the oxygen coming from the cell stack. After every system shutdown, the crew must connect the hydrogen sensors to a dry oxygen source to remove condensation. The hydrogen sensors must be returned to earth every 201 days for recalibration.

In late December 2016, the ISS OGA went to fast shutdown due to one of the three redundant hydrogen sensors outputs going off-scale high within 0.1 second. The other two sensors remained nominal. Per the flight rule allowing one of three sensors to be inhibited, the failed sensor was inhibited during its remaining installed life. This failed hydrogen sensor is scheduled to be returned in July 2018 for failure investigation.

In 2017, a hydrogen sensor replacement study was initiated. A market survey was conducted to identify potential replacement candidates. The requirements for a replacement sensor are defined in Table 2.

Table 2. Hydrogen Sensor Requirements

Requirement	Comments
Capable of measuring hydrogen in oxygen	All commercially available hydrogen sensors are marketed as hydrogen in air sensors
No 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.
No 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.
No 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. This limited lifetime is also a driver of demand for crew time to replace the hydrogen sensors.

In 2017, a market survey of hydrogen sensors was performed. The H2Sense database of over 400 sensor models was reviewed. The technology type, packaging, range and design maturity were considered. Six potential candidates were identified which met the requirements. These candidates are currently undergoing testing, which will conclude in 2018. Testing is broken into three major sections: initial bench testing, endurance testing in the OGA Test Bed, and final bench testing.

The bench test rig is designed to supply humidified gas mixtures of oxygen, hydrogen and nitrogen to the hydrogen sensor under test. K-bottles of hydrogen, oxygen and nitrogen provide source gas. The oxygen and hydrogen are metered using mass flow controllers to provide precise mixtures from 0 to 3% hydrogen in oxygen. The gas mixtures are humidified, close to 100% relative humidity, to simulate the product oxygen from the cell stack. Periodic nitrogen purging is also performed during bench testing to simulate on-orbit shutdown and startup nitrogen purging. Sensor response is compared to the expected response. For example, when exposed to 1% hydrogen in oxygen, the actual response is recorded to determine the amount a particular sensor is under-reporting or over-reporting. An example response is shown in Figure 7. Two percent hydrogen in oxygen gas (as determined by the hydrogen and oxygen mass flow controllers) is flowed through two candidate sensors. Both sensors over-report the amount of hydrogen, by 6.3% and 15.2%. Over-reporting is considered conservative and not a safety risk (although could lead to nuisance shutdowns depending on the amount of offset). Over-reporting is not necessarily considered a disqualifying characteristic. During bench testing, five sensors were eliminated (see Table 3).

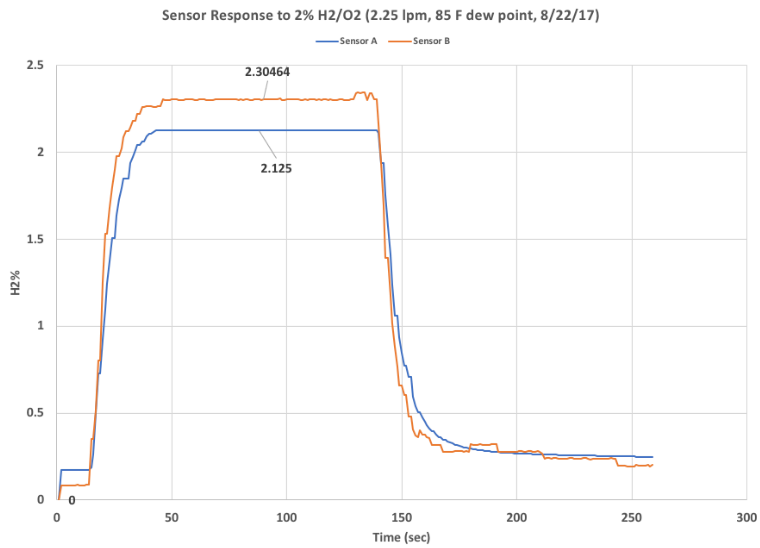

Figure 7. Hydrogen Sensor Response

Once the initial bench testing was completed, the two remaining candidate sensors were installed into the OGA Test Bed for approximately 1000 hours of endurance testing. This exposes the sensors to flight-like conditions: product oxygen from a cell stack at the expected humidity, temperature and flow rate.

After the endurance testing is completed later in 2018, the sensors will be reinstalled into the bench test rig. The bench tests will be repeated to determine what changes in performance as a result of being installed in the OGA Test Bed occurred, and if a drift rate can be determined.

The candidates, along with the current testing status as of March 20, 2018 are listed in Table 3.

Table 3. Hydrogen Sensor Candidates

Sensor	Technology	Current Status
Sensor #1	Catalytic bead	Endurance testing in the OGA Test Bed
Sensor #2	Metal oxide semiconductor	Eliminated – randomly goes in and out of alarm state during initial bench testing
Sensor #3	Metal oxide semiconductor	Eliminated – failed during initial bench testing
Sensor #4	Thermal conductivity	Eliminated – unstable during initial bench testing
Sensor #5	Catalytic reactor	Eliminated – failed to respond during initial bench testing after subjected to humid oxygen
Sensor #6	Thermal conductivity	Endurance testing in the OGA Test Bed
Sensor #7	Resistive	Eliminated – unstable when exposed to nitrogen during initial bench testing

D. Delete the Waste Water 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 determined that 216 lb (91 kg) of logistics upmass could be saved for a 1,100-day mission with a POS requirement of 0.995 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. A trade study will need to be performed to determine whether the waste water interface should be deleted from the OGA.

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 detonation 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 eleven 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 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, given a required POS of 0.995. However, going to a lower level of repair has other impacts on the system that must be considered. From a supportability perspective, lower level repair tends to increase the amount of crew time required for maintenance activities. Since crew time is a valuable and limited resource on space missions, the potential value of this change in terms of spares mass reduction should be weighed against its potential impacts in terms of crew time available for utilization. In addition, removing the dome from the OGA is not a trivial task. With a no-dome design, a specific failure scenario is of concern. After multiple failures, a release 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 4 documents the additional testing and analysis which will need to occur.

Table 4. Hydrogen Dome Removal Tasks

Task	Description	Status
Remove the dome from the OGA Test Bed	Demonstrate safe operation without a dome	Dome removal 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 MDP	Buildup is underway, testing will occur later in 2018
Redesign internal components to have redundant seals	Most internal components currently have a single seal preventing hydrogen from leaking externally. Redesign will be required for certain parts to incorporate redundant seals to meet safety requirements	Not started
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 2018
Add hydrogen and oxygen flow sensors to the design	Supplement existing leak detection methods	Demonstrated feasibility of flow sensors on the OGA Test Bed
Rack ventilation computational fluid dynamics (CFD) analysis	Verify that rack ventilation will dilute a hydrogen leak below the LFL	Not started

The vacuum dome was removed from the OGA Test Bed in 2015, and since then has operated safely for over 325 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.

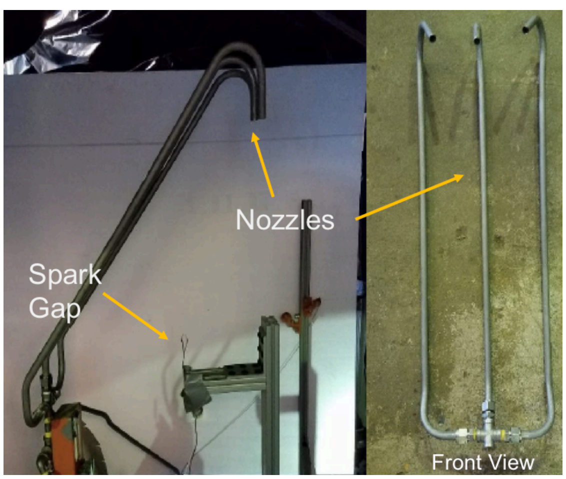

Figure 8. Hydrogen Flash Fire Test Rig

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. The cell stack, RSA and interconnecting plumbing contain pressurized hydrogen. Assuming a 22 cell stack and a standard sized RSA, the worst case release of hydrogen after multiple failures would be approximately 81 cu-in. This is a preliminary estimate and will likely increase as the redesign progresses.

Bangham Engineering was contracted to perform flash fire testing and CFD modeling in 2017. The purpose of this effort was to determine the effect on a nearby crew member of a sudden hydrogen release due to a failure and subsequent combustion (possibly due to an electrostatic discharge). Acoustic noise, overpressure, ultraviolet (UV) and infrared (IR) radiation exposure due to a hydrogen combustion could adversely affect a nearby crew member. A test stand was configured to inject specific quantities of hydrogen (100 – 250 cu-in) downwards into the open air. See Figure 8. Immediately after the injection (within a 5 ms), it is ignited before the hydrogen can rise and escape the test stand. Hydrogen released in air rises at a rate of 10 ft/s. Calibrated pressure sensors, UV and IR spectrometers, microphones, and a high speed camera captured each combustion event.

The test data was compared to established limits, summarized in Table 5. A person standing right next to a 100 cu-in hydrogen cloud that was injected into the air and immediately ignited in 1-g would not be harmed, i.e. would not suffer hearing damage, physical damage, eye damage or skin burning. The measured response was 132 dB acoustic level, 0.07 psi overpressure, 0.0002 J/cm^2 UV exposure level, 0.01 cal/cm^2 total energy.

Table 5. Limits of Exposure

	Limit	Source	Exceeded during 1-g testing, for 100 cu-in release?
Acoustic	140 dB	OSHA impulse noise limit	No
Overpressure	2 psi	WSTF	No
UV	0.003 J/cm^2	ACGIH	No
Total energy exposure	2 cal/cm^2	Industry	No

Only a fraction of the injected hydrogen in the test stand actually combusted. CFD modeling predicted for the 1-g test case that only about 50% of the total hydrogen at the moment of ignition would be available to participate in a combustion event, due to inefficient mixing. In other words, there would be areas of the injected hydrogen that would be too hydrogen rich to combust and there would be other areas that would be too hydrogen lean to combust. Of the 50% hydrogen available for combustion, testing revealed that only about 30% of that actually combusted in the 1-g environment. This is due primarily to two causes. First, drag acting upon the released gas causes some of the hydrogen to be stripped away and not participate in the combustion. This effect was confirmed with the CFD modeling. Second, the combustion pressure wave, which is ahead of the flame front, will push away a certain amount of hydrogen. This hydrogen that is pushed away will not participate in the combustion. This effect was confirmed by the high speed video of the combustion tests.

However, it is expected that in 0-g, more than 50% of the hydrogen leaked from an OGA system would be available to participate in a combustion. Hydrogen leaked from an OGA system in 0-g would stay relatively stationary and after time would diffuse and mix with the air better than what was observed in the 1-g test stand. Based on CFD modeling it is predicted that, worst case, 80% of the released hydrogen would be available for combustion. However, the drag and pressure wave phenomenon observed in 1-g would still be present in 0-g. Taking these factors into account, it is predicted that 60% (or less) of any released hydrogen in 0-g would combust. Since yields in 0-g are predicted to be higher than in 1-g, adjustments to the terrestrial test results are required. Taking this into account, a worst case hydrogen release of 81 cu-in and immediate ignition on ISS would result in an acoustic event greater than the 140 dB limit and therefore is considered a critical hazard. There is no concern of exceeding the established limits for overpressure, UV or total energy exposure. Future work will involve showing that proper controls will be in place (such as redundant seals and ventilation) to prevent the hazard after a worst case hydrogen leak.

With the previous dome design, the assumption was made that the dome would contain any leakage or burst of the internal cell stack and RSA due to a combustion event. Now that the dome will be removed from the design, the cell stack and RSA must be shown to contain any internal combustion. If they cannot, a redesign will be required.

Figure 9. Hydrogen Flow Sensor

A cell stack burst test demonstration program is currently underway. A non-operational cell stack pressure test article is currently being built. Most components have already been manufactured. The end plates are the major items still being machined. The frames and end plates are the same design as the ISS cell stack. Internal components, which do not affect external sealing, such as the cathode and anode screens are made with lower cost materials. Once the cell stack is assembled, it will be subjected to a pressurization test in mid-2018. The cell stack will be slowly pressurized until external leakage or burst occurs. The pressure at which a failure occurs will be compared to the pressure associated with a worst case internal combustion event. This will provide guidance on whether a redesign of the cell stack is required.

Existing sensors can provide an indication of external hydrogen leakage from the cell stack or RSA. Pressure sensors monitor the recirculation loop pressure and quantity 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. 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 Test Bed. The modified hydrogen vent line is shown in Figure 9. Reliably sensing flow at different production rates was demonstrated. Hydrogen flow, as sensed by the delta pressure sensor (in red), and cell stack current (in blue), is depicted in Figure 10. The relationship between flow rate and cell stack current is illustrated. Further analysis will be performed to determine how small of an external hydrogen leak can be detected with the flow sensors.

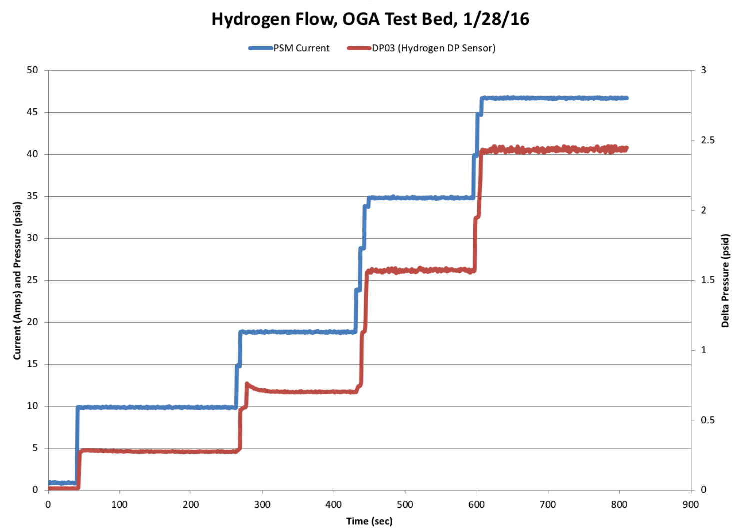

Figure 10. Hydrogen Flow and Cell Stack Current

The ISS OGA currently contains an Avionics Air Assembly (AAA) which provides ventilation within the rack. There is a software control in place that verifies ventilation is active while the OGA is producing oxygen. CFD analysis has been performed to verify that the ventilation will prevent an elevated oxygen concentration in the rack, which would be a fire hazard. Now that the OGA design will be modified to remove the hydrogen dome, there is a new concern of hydrogen buildup in the rack (after multiple failures). Future CFD analysis will determine if additional ventilation, in addition to the AAA, is required.

F. Redesign the PSM

The 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, etc. The internal configuration is shown in Figure 11. The PSM has a weight of 100 lb and dimensions of 24 x 15 x 11 inches.

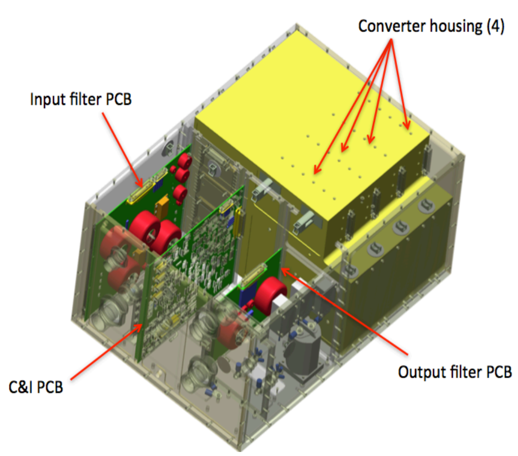

Figure 11. PSM Configuration

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 can be realized with a redesign and the PSM should be redesigned using a space rated microcontroller. This one microcontroller could potentially take the place of dozens of discrete components. At this time no funding is available to pursue a redesign, however, it is still recognized as a priority for the OGA redesign.

G. ACTEX Redesign

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 (Ref. 2). The purpose of the ACTEX (Figure 12) is to remove fluoride that is released by the cell stack membranes and maintain a desirable pH level in the water recirculation loop. The ACTEX was not specifically designed for the OGA, and should be redesigned to be optimized for a future exploration mission. The current ACTEX has a 1.8 year installed life. For a 3-year exploration mission, the ACTEX should be redesigned to increase its capacity. Another issue that should be addressed is that the ACTEX has a significant pressure drop of approximately 16 psid. When the ACTEX is used in the OGA, there are several non-compliance waivers, since it does not meet MDP requirements, seal redundancy requirements and materials compatibility requirements. Redesign options have been proposed which increase the canister volume, replace quick disconnects with fittings and incorporate redundant seals.

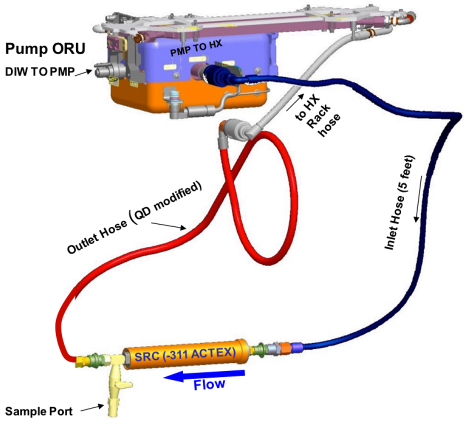

Figure 12. ACTEX Installation

H. Redesign the Process Controller

Two newly design sensor boards will need to be installed into the process controller to accommodate the additional sensor and effectors in the new advanced OGA 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

The ultimate goal is to demonstrate an exploration based OGA on the ISS in the 2021 timeframe. The existing ISS OGA will be modified to incorporate the proposed upgrades. This will allow several years of operation in an on-orbit environment and resolve any issues before an exploration mission. New special studies will be conducted in 2018 to further mature the system design and interfaces. A Systems Requirements Review (SRR) is tentatively planned for December 2018. The SRR will officially define the system requirements, after which the detailed design can begin. A major change request (CR) is currently out for review and estimates to develop, design, and deliver modification kits to establish a demonstration advanced OGA are being developed. In addition, the OGS rack is planned to be relocated from Node 3 to the US Laboratory Module.

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