

# NextGen Oxygen Generating Assembly (OGA) for Commercial Aerospace

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The current Oxygen Generating Assembly (OGA) on the International Space Station (ISS) utilizes a large variety of custom components including a cathode feed electrolyzer, rotary separator, containment dome and use of multiple seals to mitigate the risk of hydrogen leakage. While this system has operated on station since 2007, the considerable use of custom-made components makes it prohibitively expensive for future commercial aerospace applications. This paper describes a Next Generation (NextGen) OGA system utilizing commercially available hardware. A major change to the system architecture includes the switch from a cathode feed electrolyzer to an anode feed. While this presents challenges by adding an additional micro-gravity phase separator, recent investment in electrolyzer technology for supporting clean energy applications has caused a surge in commercially available stacks with proven reliability. These stacks are almost exclusively anode feed, sparking an interest in re-examining an anode feed based OGA. Despite the need for an additional separator, recent advancements in separation technology help to mitigate the risk and cost, with inexpensive commercial separators offering potential alternatives to custom rotary separators. In addition to switching to anode feed, the NextGen system examines an alternative hydrogen safety approach which eliminates the use of a dome, replacing it with ventilation and adapts a quantitative approach regarding sealing against H<sub>2</sub> leakage as opposed to the qualitative approach the ISS OGA used, as well as drawing on lessons learned from years of operating the OGA system on ISS.

## Nomenclature

AOGA	=	Advanced Oxygen Generating Assembly
COTS	=	Commercial off the shelf
DI	=	Deionized water
EOD	=	Electro-osmotic drag
ISS	=	International Space Station
NextGen	=	Next Generation
LFL	=	Lower flammability limit
MCL	=	Maximum credible leak
MAL	=	maximum allowable leak
OGA	=	Oxygen Generating Assembly
PEM	=	Proton exchange membrane
RSA	=	Rotary Separator Accumulator
THC	=	Temperature and Humidity Control
TRL	=	Technology readiness level
C <sub>H2</sub>	=	Concentration of dissolved hydrogen (mol/L)
F	=	Faraday's number (96,485 C/mol)
I	=	Current (amps)
k	=	Henry's constant (mol/(L-atm))
n	=	Electrons transferred per mole product

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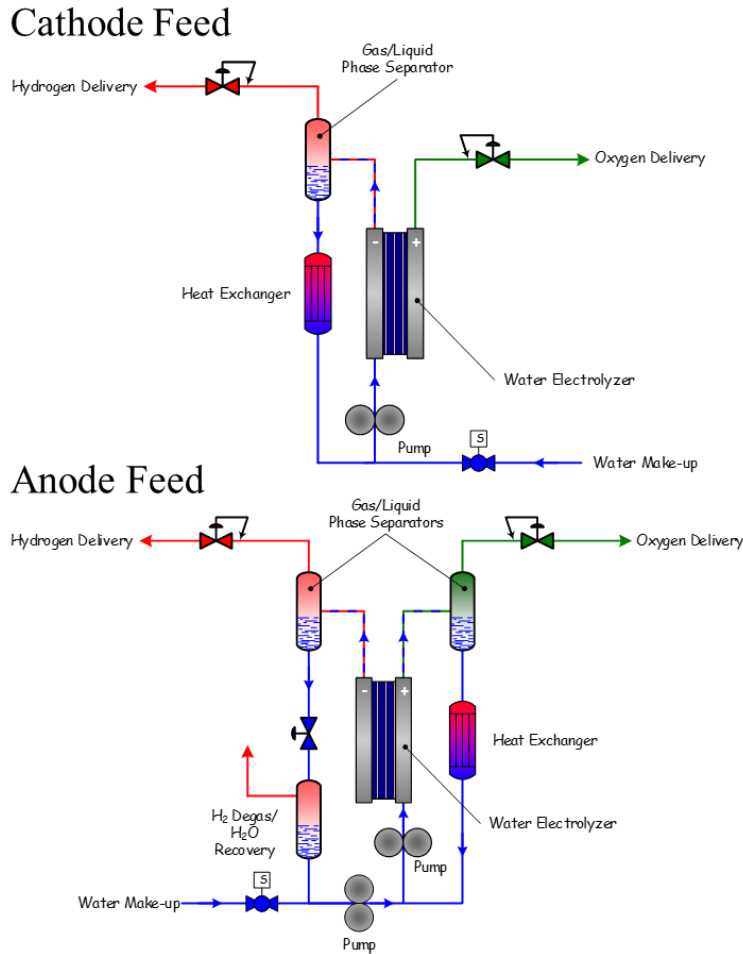
N	=	Number of cells
$\dot{n}$	=	Production rate (mol/s)
$n_d$	=	EOD coefficient
$\dot{n}_{H_2O}$	=	EOD rate (mol/s)
P	=	Pressure (atm)

## I. Introduction

The recent surge in commercial aerospace has generated a need for cost effective alternatives to previous Technology Readiness Level (TRL) 9 hardware that has flown successfully for years<sup>1,2</sup>. To achieve cost targets, commercial off the shelf components (COTS) are being assessed as potential replacements to existing hardware. One example of this is the Oxygen Generating Assembly (OGA) currently operating on the International Space Station (ISS). The current OGA utilizes a custom-made proton exchange membrane (PEM) water electrolysis stack operating in a liquid cathode feed configuration, which eliminates the need for an oxygen-water phase separator. In a typical anode feed configuration, a phenomenon known as electro-osmotic drag (EOD) drives water from the anode to the cathode, which is then ejected as liquid slugs, requiring phase separation to prevent liquid water from entering downstream systems<sup>3,4</sup>. By circulating the liquid water on the cathode, the same side where the EOD water collects, the oxygen gas can be kept free of liquid water. The downside to the liquid cathode feed configuration is the stack production rate is limited by the diffusion rate of water from the cathode to the anode, where it is electrolyzed. Eventually, the diffusion rate is insufficient to sustain the reaction rate and the cell dries out. In a liquid anode feed configuration, water is supplied directly to the electrode where electrolysis occurs. Anode feed electrolyzers are routinely run at 2-5 A/cm<sup>2</sup> current density (directly proportional to production rate) versus cathode feed which is normally run at <0.5 A/cm<sup>2</sup>. This makes the anode feed configuration the preferred method for hydrogen production which is the predominant terrestrial use-case for water electrolysis. This paper reviews the design considerations for the anode feed electrolyzer system that is the baseline for the NextGen OGA and provides performance test data for a candidate commercial cell stack.

## II. Anode Feed System Design Considerations

The basic schematic for an anode vs. a cathode feed electrolyzer system is shown in **Error! Reference source not found.**. For brevity, the various sensors, valves, and other subsystems such as nitrogen purge are not shown. Both approaches involve circulating deionized (DI) liquid water as a reactant and coolant, with the main difference being which electrode receives the liquid water via the recirculation loop. The electrolyzer stack requires high purity water to avoid undesired ion exchange with the PEM or potential poisoning of the catalysts. In the anode feed configuration, the water is circulated on the electrode where it is reacted. The two-phase water and oxygen mixture is separated prior to delivering the oxygen gas to the cabin, with the water pumped back to the cell stack. A heat exchanger in the recirculation loop provides heat rejection for the cell stack which generates waste heat based on operating voltage and current. Due to the migration of protons through the PEM from the anode to the cathode to produce hydrogen, water is driven to the cathode. This EOD water leaves with the hydrogen, typically as water slugs in a 1-G environment. This necessitates additional phase separation on the cathode side of the system. It is normally desirable to save this EOD water, even in terrestrial applications, due to the high purity requirement of the influent water and the rate of EOD. For production rates relevant to life support applications, up to 0.3 L/hr will be driven to the cathode for each crew member supported. Depending on the operating pressures of the anode and cathode, additional off-gassing might be necessary from the EOD water to eliminate as much dissolved hydrogen as possible before returning it to the oxygen separator. If high-pressure hydrogen saturated water is delivered directly back to the oxygen phase separator, the resulting off-gassed hydrogen has the potential to produce combustible mixtures. Additionally, if there is an insufficient pressure gradient between the hydrogen phase separator and oxygen phase separator, a second pump will be necessary to return the water. A water make-up connection on the system provides additional water to offset what's lost to electrolysis or leaves with the humid hydrogen and oxygen streams. Dew point targets for the outlet gases are typically below the cabin temperature to prevent condensation forming, about 18°C. However, the electrolyzer stack produces gases at or near saturation for a given operating temperature, necessitating a balance between humidity control and electrolyzer performance since higher temperature improves operating efficiency.



**Figure 1. Cathode (top) vs anode (bottom) feed simplified schematic.**

The cathode feed configuration is simpler from a balance of plant perspective. EOD is always from anode to cathode, so circulating water on the cathode ensures there is only liquid water present in the cathode during normal operation. This eliminates the need for additional phase separators and eliminates the logistics of attempting to return hydrogen saturated water to the DI recirculation loop on the anode. Despite this, almost all commercial electrolysis systems are anode feed. This is because the water is fed directly to the electrode electrolyzing it. In the cathode feed configuration, the water must diffuse through the internal PEM from the cathode to the anode to be electrolyzed, limiting the achievable electrolysis rates. Anode feed electrolyzers routinely operate at 2-5 A/cm<sup>2</sup> current densities (a metric directly related to production rate) while cathode feed electrolyzers are typically limited to <0.5 A/cm<sup>2</sup>. Given the capital cost investment of PEM electrolysis stacks, it's economically infeasible to run cathode feed when maximizing hydrogen production. Therefore, the NextGen OGA system utilizing a COTS electrolysis stack is limited to anode feed. While a major driver is commercial availability, the anode feed stacks running at higher production rates also translates to a smaller, lighter package which is an added benefit in commercial space. This may be offset by the need for an additional phase separator, but the rotary separator accumulator (RSA) used in the current OGA system on station is a heavier component owing to the electric motor and active rotating assembly. If passive separation technology such as membranes or inertial separators can be used, a net reduction in power, weight, and complexity will be achieved. One may question why an anode feed stack cannot be used in a cathode feed system. Typically, the design of the stack purposely employs highly open porosity flow fields in the anode to facilitate high water flow rates with low pressure drops. Conversely, many cathodes flow fields are constructed with carbon papers or other highly restrictive porous media not designed for sufficient water flow.<sup>5,6</sup> Other options exist, including modifying a

commercial stack, but this inevitably drives up the cost significantly and raises questions about the reliability of the modified article versus the COTS one.

With the general system outlined, operational requirements can be defined and tuned to simplify the system to some degree. Table 1 gives some general operational ranges that can be expected in an anode feed system.

**Table 1. Operational ranges for an anode feed electrolysis system for life support applications**

Parameter	Range	Rationale
Oxygen production rate	0-4.6 SLPM (9.5 kg/day)	Up to a crew of 10-11 <sup>[7]</sup>
Hydrogen production rate	0-9.2 SLPM (1.2 kg/day)	Byproduct of oxygen production
Operating temperature	<30 °C	Control humidity
Hydrogen pressure	>O <sub>2</sub> pressure, <65 psia (448 kPa)	Safety and driving force
Hydrogen-water quality	>99% gas by volume	Dictated by EOD
Oxygen pressure	Ambient	Vented directly to cabin
Oxygen-water quality	30-50% gas by volume	Driven by production rate and DI water flow rate

The oxygen and hydrogen production rates are determined by Faraday's law and relate directly to the operating current of the stack.

$$\dot{n} = \frac{IN}{nF} \quad (1)$$

Where  $\dot{n}$  is the production rate in mol/s, I is the operating current in amps, N is the number of cells, n is the number of electrons transferred per mole of product generated, and F is Faraday's number. In reality, some of the product gases are lost to permeation through the membrane, but for a low-pressure system, Faraday's Law matches closely with the observed gas production rate.

The operating temperature of the system for life support applications is typically low compared to commercial systems. Most commercial systems operate in the range of 50-80°C to maximize efficiency of the cell stack. Increased temperature increases the conductivity of the membrane, which represents the largest resistance in the cell. This elevated temperature range is more relevant at higher production rates, i.e. operating currents, due to the stack's voltage following closely with Ohms Law. If the operating current is kept low, lower operating temperatures are possible while maintaining cell voltages within an acceptable range. The benefit to the lower operating temperature is the lower saturation pressure of water which limits condensation entering the cabin with the oxygen, reducing the burden on the Temperature and Humidity Control (THC) system. Additionally, excessive moisture in the hydrogen gas can foul downstream processing systems or freeze ventilation lines directed to space vacuum.

Typical operating pressures for the OGA system are approximately ambient on the oxygen side with the hydrogen pressure slightly elevated with respect to the oxygen pressure. The elevated hydrogen operating pressure serves multiple purposes. Elevated hydrogen pressure over oxygen allows for the EOD water to be returned to the oxygen side without the use of an additional pump while also providing some driving force for delivering the hydrogen to downstream processes such as the Sabatier, which converts hydrogen and carbon dioxide into methane. Consideration needs to be given to an upper pressure limit to avoid excessive amounts of dissolved hydrogen from off-gassing in the oxygen stream. It can be determined using Henry's Law and the EOD rate, that a notional maximum pressure of 65 psia results in a theoretical hydrogen in oxygen content of <0.1%.

$$\dot{n}_{H_2O} = n_d \frac{IN}{F} \quad (2)$$

$$c_{H_2} = kP \quad (3)$$

Where  $\dot{n}_{H_2O}$  is the EOD rate in mol/s,  $n_d$  is the electro-osmotic drag coefficient,  $c_{H_2}$  is the concentration of dissolved hydrogen in mol/L, k is Henry's constant in mol/(L-atm) and P is the partial pressure of hydrogen in atm. The other advantage of elevated hydrogen pressure is to maintain a bias of hydrogen over oxygen pressure. By doing so, any

leak that develops in the internal membrane separating the hydrogen and oxygen will result in hydrogen leaking into oxygen which can be detected by a combustible gas sensor downstream. Commercial electrolyzer stacks typically operate with ambient pressure oxygen and elevated hydrogen pressure, on the order of several hundred psi, to facilitate downstream processing. This makes the commercial electrolyzer naturally suited for the commercial NextGen OGA system from the pressure perspective.

As stated above, a major difference with the anode feed configuration is the presence of liquid water in both the oxygen and hydrogen streams. In the case of the oxygen stream, the quality of the two-phase flow is approximately 30-50% gas by volume depending on the water flow rate. For these ratios, proven microgravity phase separators such as a RSA can be considered. In the case of the hydrogen side, the quality is determined by the EOD rate (Eq. 2). Comparing the EOD rate to the hydrogen production rate for the operating current results in a two-phase mixture that is >99% gas by volume and constant regardless of production rate if permeation losses are neglected. The low liquid water content leaves the question of whether an RSA would be suitable for this separation or if other microgravity phase separators would be more appropriate. Future work will evaluate the performance of different candidate phase separators.

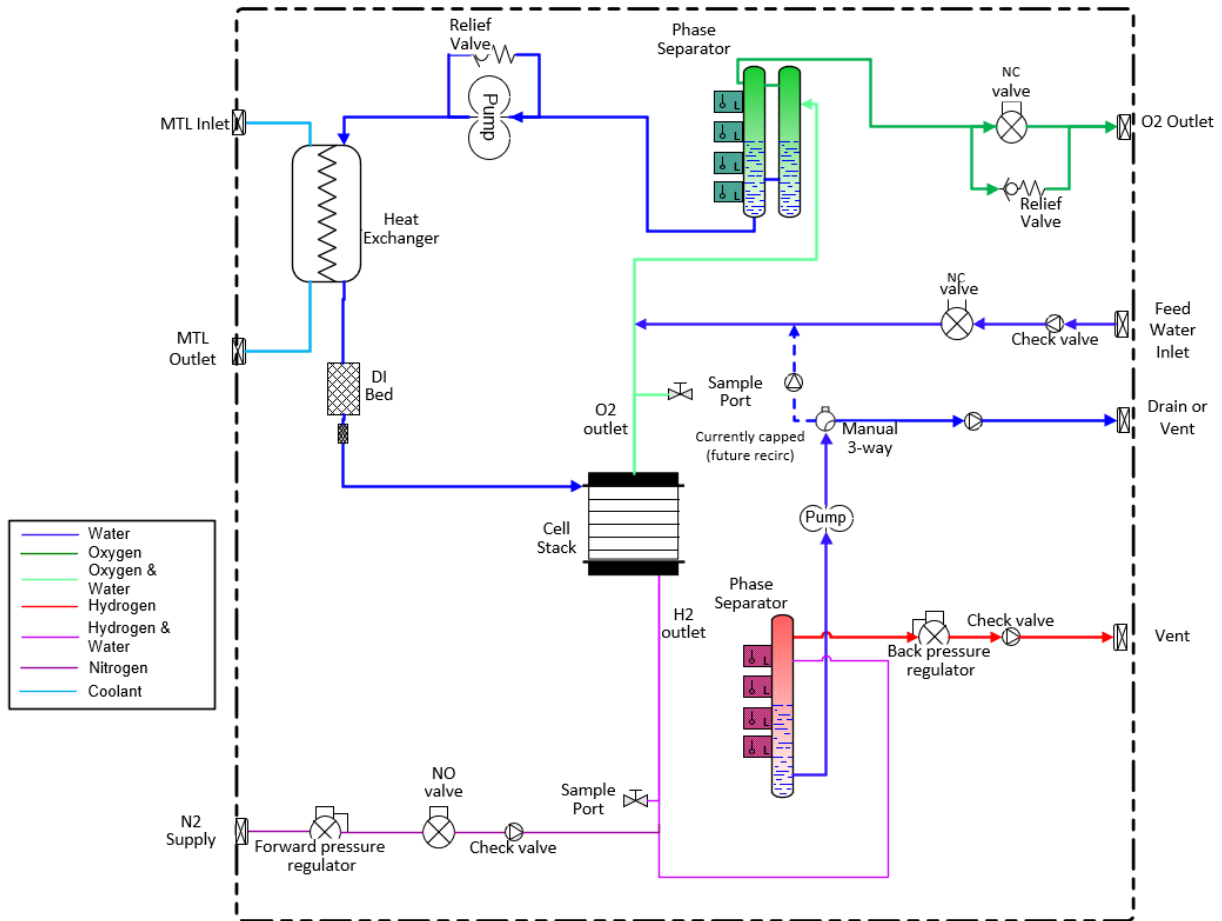
The recirculation water flow rate, which impacts the two-phase quality on the anode side, is determined based on two basic requirements, heat rejection and gas removal. While water must be supplied at sufficient rates to support electrolysis, the rate of water consumption through the reaction is orders of magnitude lower than the required flow to prevent overheating of the cells or to prevent gas binding and subsequent dry out. Section III discusses the results of preliminary testing in various orientations and the potential effect of microgravity on gas binding.

The NextGen OGA will adopt a quantitative philosophy regarding external leakage. With the legacy OGA on ISS, external leakage hazard severity was qualitative, based on the internal fluid alone, and the approach regarding external leakage was centered on preventing the leak. In many cases this drove dual and, in some situations, triple seals, as well as rigorous design measures in seal and groove design and processing. Additionally, the cell stack itself was installed in a sealed dome to contain leakage and any potential combustion events. This approach was taken for hydrogen leakage especially, because during the time of the legacy OGA development there was limited knowledge regarding safe hydrogen management. However, recent development in the usage and management of hydrogen, as well as other fluids, and the philosophy concerning leakage can be adapted. Instead of basing hazard severity on the fluid alone where it was assumed a leak would automatically manifest a hazard, now the actual leak rates are considered. In other words, the maximum credible leak (MCL), the worst-case leak rate that could credibly occur, is compared to a maximum allowable leak (MAL), the maximum leak rate before a critical or catastrophic hazard is induced, to determine if a hazard can be induced by a leak. This new approach does not eliminate the heritage approach but if anything, expands on it, establishing quantitative limits or thresholds for a given fluid, which are backed by testing and analysis, to deem hazard severity. The philosophy has shifted focus from preventing a leak, to preventing (to some degree) and limiting the leak such that its accumulation does not result in the manifestation of the hazardous affect.

To clarify, the approach can be broken down: first the fluids are defined in the system and an end hazardous affect is assumed to occur regardless of the quantity - this is again in sync with the original approach. Then, depending on the fluid and using thresholds backed by testing and analysis, a MAL rate is derived for each seal. Finally, using system operating conditions unique to the design of the system, a MCL rate is calculated and compared to the MAL. If the MCL (after 2 failures) is lower than the MAL then the hazard severity can be reduced to the next lower severity level (critical or marginal) from the severity at which the threshold used (catastrophic or critical) corresponded to. Coupling this analysis with suitable ventilation methods, the team hopes to eliminate the need for the containment dome that has been reviewed as part of the Advanced Oxygen Generating Assembly (AOGA) design<sup>8</sup>.

### **III. Cell Stack Testing**

The heart of the commercial NextGen OGA system is the electrochemical cell stack. As mentioned previously, a commercially available cell stack is being evaluated to reduce costs. As part of the evaluation effort, a test bed was designed and built to operate the COTS cell stack. Figure 2 shows a simplified version of the test bed.



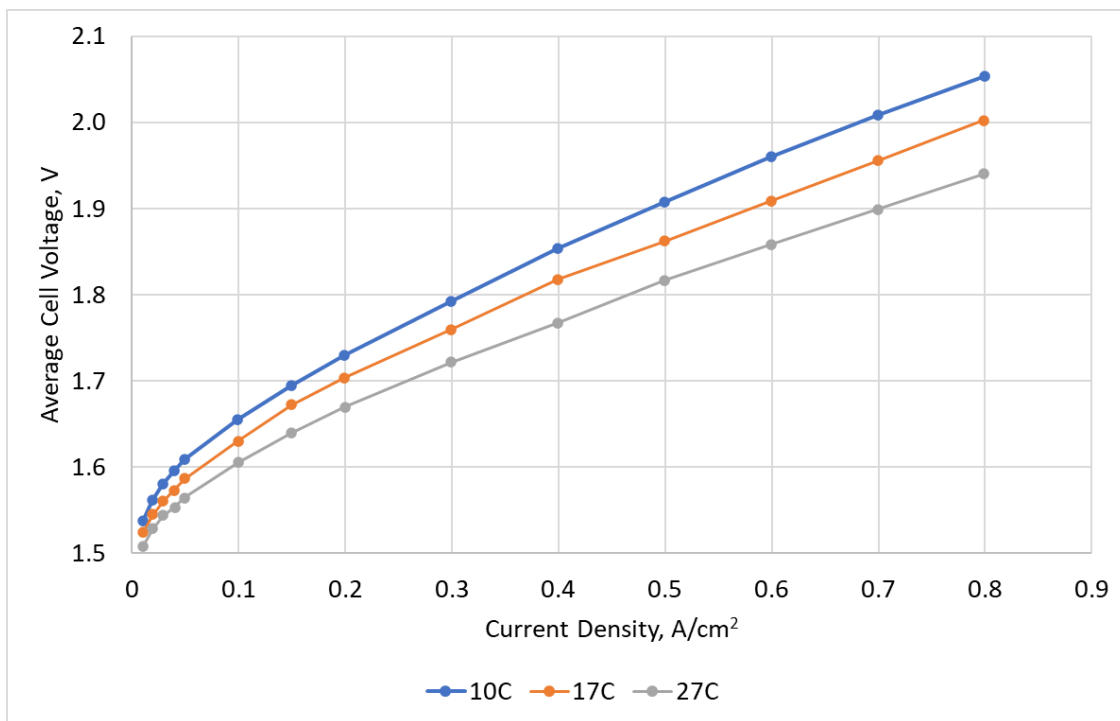
**Figure 2. Test bed for evaluating the commercial cell stack.**

The test bed includes a DI recirculation loop on the anode side of the stack with a heat exchanger to maintain constant DI water temperature, a DI polisher bed to prevent buildup of ionic contaminants leaching into the water from various system components in the loop which would poison the cell stack, a DI water makeup source, and a gravity phase separator to vent the oxygen produced. The cathode side outlet of the stack is directed to a gravity separator to collect the EOD water. The current iteration of the system drains the EOD water rather than returning it to the oxygen phase separator for safety purposes. As the test system evolves to resemble the flight configuration more closely, the water will be returned to the DI recirculation loop. For safety, the hydrogen phase separator is connected to a nitrogen purge source to inert the volume on shutdown and startup. Sample ports are installed on both outlets of the cell stack to sample water and gas.

Prior to operating the cell stack, health checks were performed including high frequency impedance, electrical short testing, overboard leakage, and cross cell permeation rates. Overboard leakage and electrical short tests were performed as pass fail checks to ensure the as-received hardware wasn't damaged or compromised. The impedance and cross cell permeation rates were collected as a baseline for future comparison after testing, or if anomalous behavior was observed during testing, to help diagnose any potential changes.

After completing health checks, the stack was installed in the test bed to measure baseline performance. The initial operational tests are focused on informing system design. These include beginning of life (BOL) polarization scans, pressure drop, EOD rates, particulate shedding, and multiple orientation testing. These tests are ongoing with the goal of completing them and then subjecting the stack to long-term endurance and on/off cycle testing at the anticipated nominal operating conditions of the NextGen OGA system. Long-term endurance testing will be used to measure the

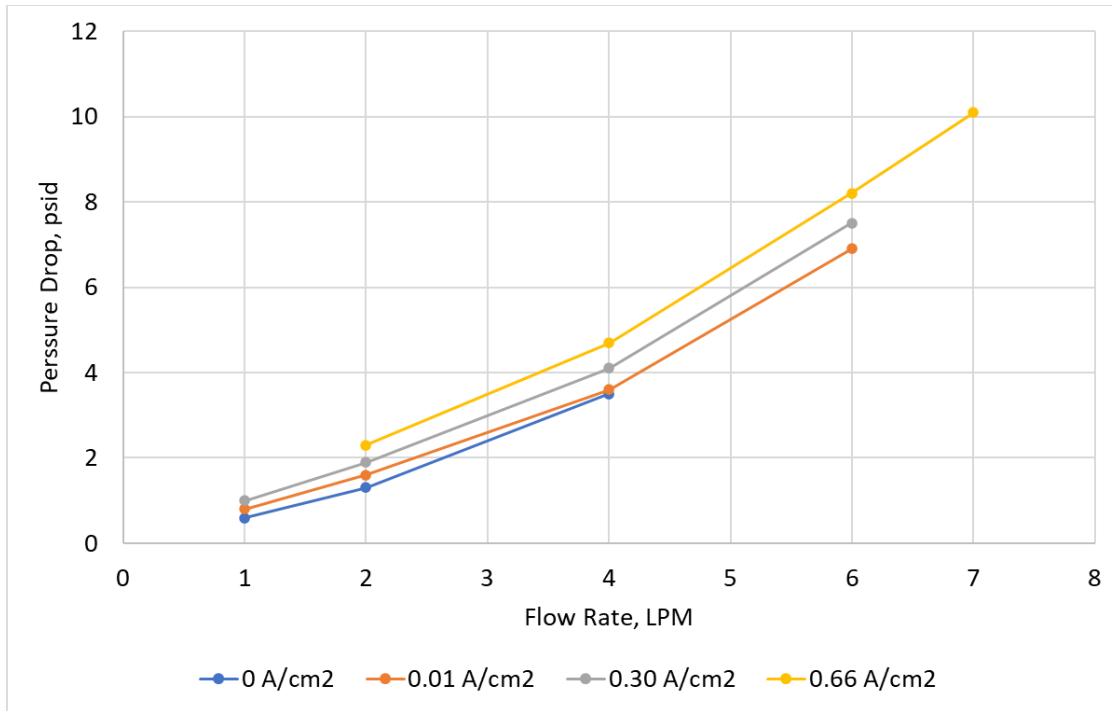
voltage decay rate and project operating life. On/off cycling is a harsher condition the stack experiences during service life and may accelerate performance degradation. Figure 3 shows the polarization curves for 10, 17, and 27°C for the commercial cell stack.



**Figure 3. Beginning of life polarization scans for the commercial cell stack. The polarization scan plots current density, which is directly associated with gas generation rate, against the required cell voltage and is a basic measure of electrolyzer efficiency and performance.**

It is anticipated that the stack will need to operate at a maximum of 0.7A/cm<sup>2</sup> to support a crew of 10 making the cell voltage at BOL of ~2V/cell at the worst case of 10°C. A typical end of life (EOL) voltage range for a PEM electrolyzer is 2.5-3.0V/cell giving plenty of margin for the commercial stack. If a 10-year life is considered, this equates to a voltage decay rate of ~6 μV/hr in the worst case. This seems achievable when comparing to the DOE's Technical Targets for Proton Exchange Membrane Electrolysis<sup>9</sup>. The 2022 status shows steady state degradation rates of 4.8 μV/hr with 2026 targets set at 2.3 μV/hr. Care should be taken when applying these degradation rates to the NextGen OGA application. The proposed operating temperature, current density, and pressure of the NextGen OGA are significantly lower than most commercial stacks and should serve to curtail the degradation rates. However, the water chemistry on station may also contain chemicals not normally found in terrestrial electrolysis plants which may or may not impact life. Furthermore, the NextGen OGA will likely follow a different load profile than most commercial systems which are designed to maximize hydrogen production. The impact of these discrepancies to the life of the electrolyzer requires further testing. Long term endurance testing will seek to evaluate the decay rate and project the life of the stack barring other degradation mechanisms (i.e. water quality, on/off cycling, etc.). Subsequent challenge testing will examine the impacts of water chemistry and varying load profiles. It is again highlighted that this is a commercial stack, typically designed to operate at ≥50°C to maximize electrolysis efficiency by reducing the ionic resistance of the membrane. By operating as low as 10°C, the voltages in Figure 3 are higher than what would be expected in a commercial system but shown to be viable for the NextGen OGA system.

The pressure drop of water flow through the stack was measured at the mid-temperature range of 17°C to inform the sizing of the pump in the commercial system. Figure 4 shows the pressure drop for varying flow rates and current densities.



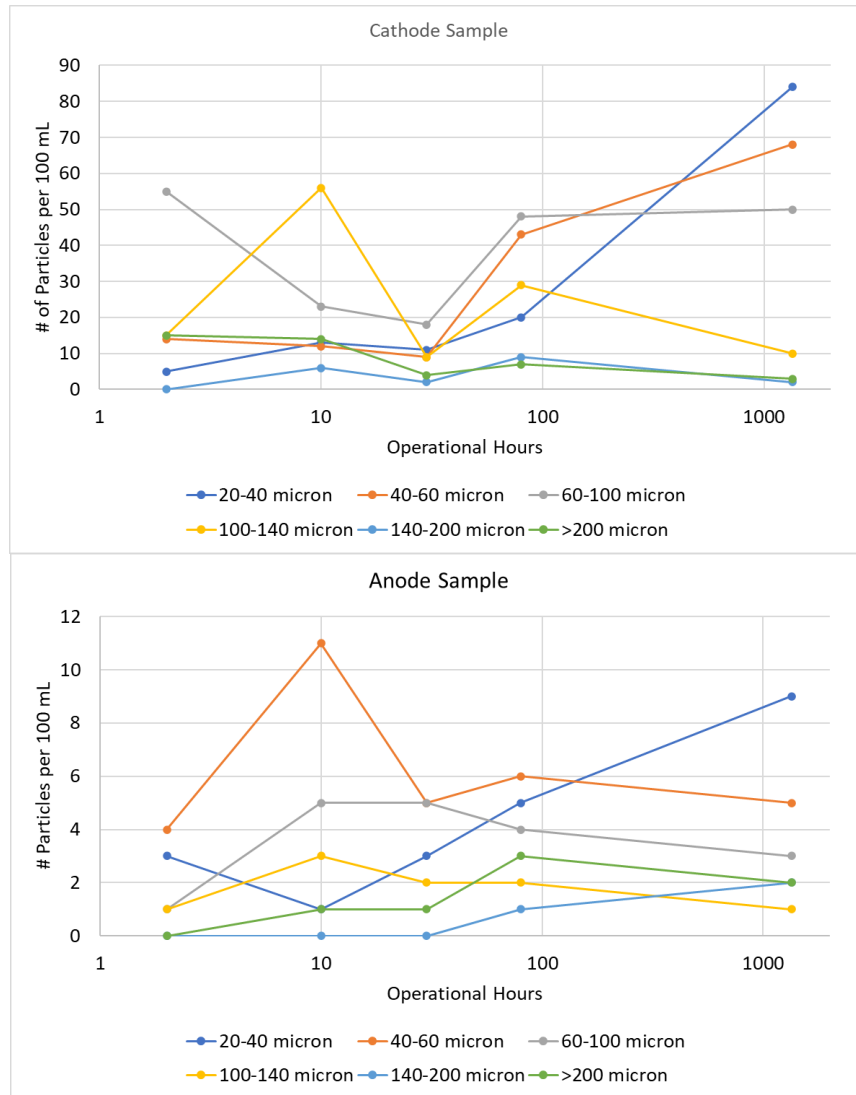
**Figure 4. Pressure drop through the commercial stack for varying flow rates and current densities at 17°C.**

Flow rates are selected to control temperature rise from inlet to outlet and supply sufficient cooling for the stack but also to ensure product gases are swept out and the membrane stays well hydrated. Challenge testing examining multiple orientations of the cell stack to impose negative gravity fields in place of microgravity tests, reveal higher flow rates may be necessary when buoyancy cannot be relied on to remove gas from individual cells. That testing is described in more detail below. Another characteristic of the pressure drop behavior is the slight increase with applied current density due to changing quality of the two-phase flow through the cell stack. The increase of pressure drop through the cell stack with current density is approximately linear.

Since the EOD water will be returned to the oxygen recirculation loop, it is important to characterize the rate of EOD to properly size the accumulator and to calculate the anticipated rate of dissolved hydrogen gas introduction to the oxygen stream. This is done by operating the cell stack at a fixed current density and collecting the effluent water from the cathode outlet using the sample port (Figure 2). A consistent rate of 0.05 kg/min of water was collected with the stack running at 0.7 A/cm<sup>2</sup> and 17°C. The EOD rate is known to be linear with current density since the mechanism involves the electromagnetic attraction of the conducting protons to the dipole of a water molecule (Eq. 2). In addition, the effect of temperature is weak, and within the expected operating window, the value is not expected to change significantly.<sup>3,4</sup> As noted in the previous section, the contribution of dissolved hydrogen in the EOD water is expected to be <0.1% of the total oxygen produced. Permeation of hydrogen through the internal membrane, and any escape of free gas during phase separation are the other sources of hydrogen in the oxygen stream that need to be considered. Permeation effects at low pressures and temperatures are expected to be minor but are the subject of ongoing gas quality measurements to confirm this assumption. The biggest challenge from a system design perspective is the effectiveness of the hydrogen phase separator. If the maximum allowable hydrogen in oxygen is set to be 1% or 25% of the lower flammability limit (LFL of 4%), the efficiency of the hydrogen phase separator must be >99.5%. In other words, if 0.5% by volume of hydrogen bypasses the separator, the hydrogen levels in the oxygen outlet will approach 1% by volume (ignoring the other sources of hydrogen, i.e. permeation and dissolved gas). This is normally trivial in a well-designed gravity phase separator but can pose challenges in microgravity separation. Despite this, there are promising phase separation technologies that have demonstrated the required efficiency such as passive inertial based devices.<sup>10-12</sup>



The particle shedding behavior from the commercial cell stack is of interest to size appropriate filters to protect downstream components. To investigate the shedding behavior of the stack, the test system was flushed with fresh DI water for several hours and a baseline water sample was collected and analyzed for particulates. The stack was then installed and run for various operational hours with a sample being collected from the sample ports of the anode and cathode at the stack outlet. The 100 mL samples were collected into precleaned flasks and filtered through 1 um filter paper for analysis using optical microscopy as outlined in ARP 598<sup>13</sup>. Figure 5 shows the summary of analysis performed to date.



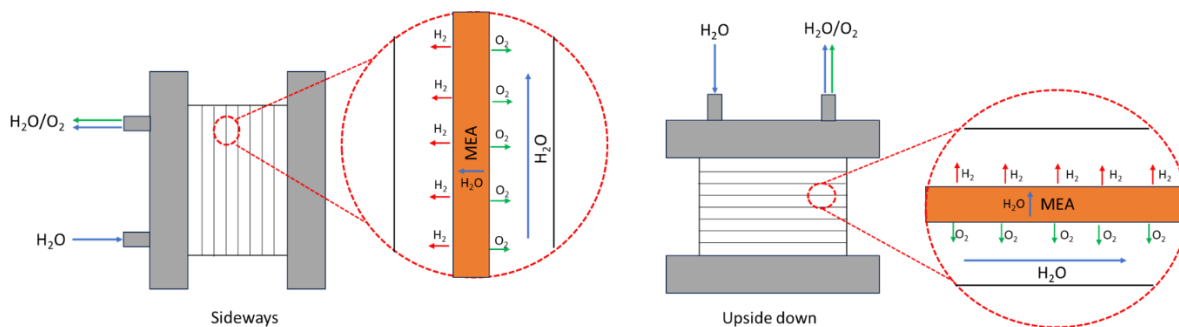
**Figure 5. Resulting particulate shedding from the commercial cell stack. Number of particles is normalized by 100 mL of water per sample. Different ranges of particulate sizes are plotted separately.**

From Figure 5, it is apparent that the cathode sheds approximately an order of magnitude more particles than the anode. This is not surprising given that the anode must be metallic since only certain, highly passive metals are known to stand up to the aggressive environment of a PEM electrolyzer anode. The cathode may be assembled with a relatively inexpensive carbon paper which is suitable for the lower cathodic potential environment. Carbon papers and cloths are known to flake and leave residues when handled which may cause higher particle counts. Interesting to note when looking at Figure 5, is the trending of the 20-40 micron particulates on both the anode and cathode. Continuous sampling is ongoing to determine whether the trend holds or is just an outlier. It is worth noting that particles <20 microns were not counted for most of the samples due to the high numbers collected. By the 1300-hour mark, the

anode count was 15 and the cathode count was 306, indicating the rate of shedding from these smaller particulates had slowed significantly.

In addition to the particle shedding behavior, the water in the test system was analyzed prior to installing the stack. The water was analyzed for nonvolatile residue (0.1 mg/100 mL), TOC (161 ppb), sodium (<10 ppb), chloride (<50 ppb), and silicon (16 ppb). During operational testing, the water resistivity in the anode recirculation loop was monitored continuously with a reading of >10 Mohm-cm throughout testing. It is worth noting that this testing is being performed with clean DI water sourced from the test facility and continuously polished in the test rig. In reality, the stack will be exposed to certain contaminants on station that are not readily removed by the water processor. The OGA went through chemical challenge testing to evaluate what effect these contaminants had on the electrolyzer stack.<sup>14</sup> Similar testing will need to be performed with the commercial electrolyzer stack. Additionally, with the emerging commercial space market, the sources of those contaminants may change as trace amounts of different personal care products not found on ISS make their way into the recirculation loop. For current testing, the only requirement applied to the water quality is the source water meets an internal facility requirement and the resistivity stays above 8 Mohm-cm.

A major barrier to advancing the cell stack to TRL 5 is operation in microgravity. The cell stack operation involves two-phase flow on the anode side that must be effectively removed to maintain proper hydration of the membranes within the cell stack. Normally, in a 1-G environment, the stack can be oriented in a way that allows buoyancy to assist in carrying the generated gas out of the cell. In microgravity, the only mode of force to remove gas will be pressure drop from the convective flow. A basic assessment of the stack's sensitivity to gravity can be performed by changing the orientation of the stack and observing any negative impacts on performance. To assess the stability of the cell stack at different orientations, the voltage decay rate and voltage spread (difference between the highest and lowest cell voltage) were monitored over 200-300 hours of operation. A baseline flow rate of 4 LPM was selected to allow for adequate cooling of the stack at the full production current density of 0.7 A/cm<sup>2</sup>. Figure 6 shows the two orientations tested so far.



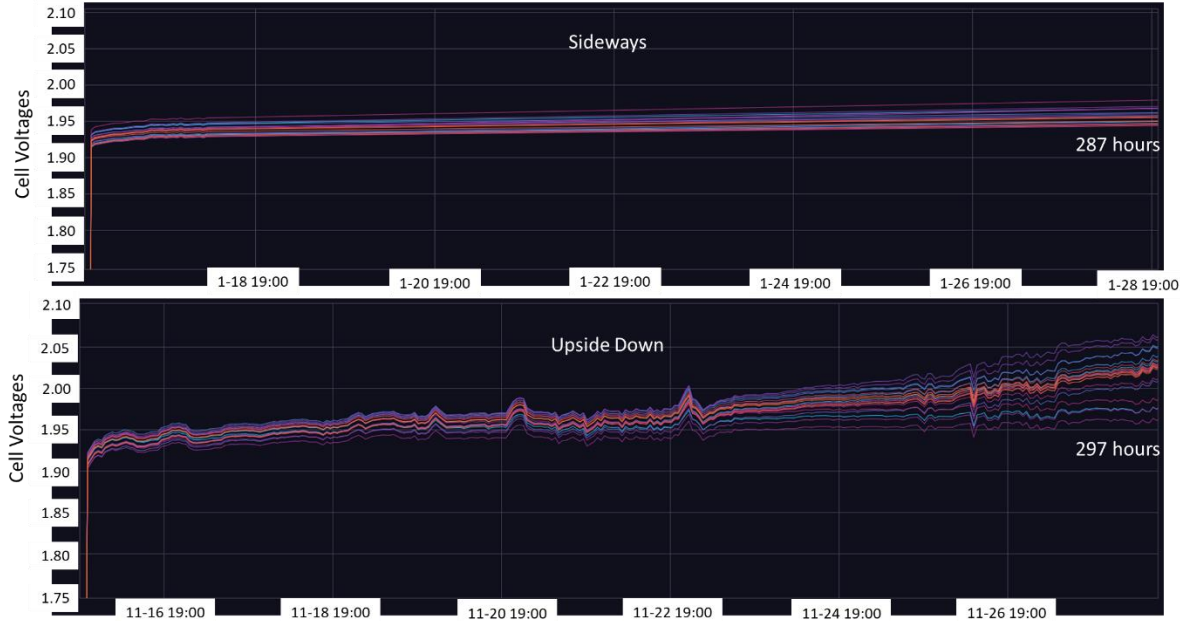
**Figure 6. Orientations tested to date.**

In the sideways orientation, the water inlet of the stack is in the 6 o'clock position while the two-phase outlet is located at the 12 o'clock position. All the flow fields in the stack are oriented parallel to gravity allowing buoyancy to carry the product oxygen gas out of the cells, making gas removal more effective. In the upside-down orientation, the stack is oriented with the flow fields perpendicular to gravity and the fluid connections at the top of the stack. In this orientation, the anode is located on the underside of the MEA. This means the generated gas must move downwards against buoyancy forces to be swept from the cells by the bulk water flow. If the flow and pressure drop in the stack is insufficient, the concern is the generated gas may blanket the MEA and create a barrier to the water. This would lead to higher ohmic resistances since the membrane will be in a dryer state and potentially mass transport limitations if the water vapor diffusion to the electrode is slower than the rate of electrolysis. Both issues present as unstable voltage with trends towards higher cell voltages over time. This test is ongoing but initial results are shown in Table 2 below.

**Table 2. Effect of orientation on voltage stability of the cell stack.**

Orientation	Flow Rate (LPM)	Operational Hours	Voltage decay rate (mV/hr)	Voltage spread (mV)
Sideways	4	287	0.1	35
Upside down	4	297	0.3	100
Upside down	5	203	0.1	34

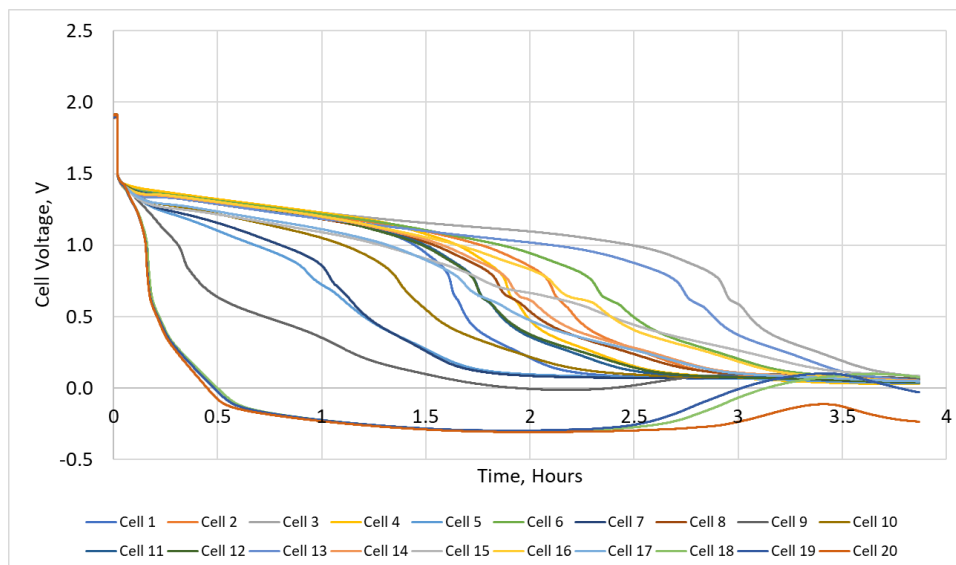
From Table 2, it's clear that there is a negative impact on the stack voltage when it is run in the upside-down orientation at the baseline 4 LPM. The voltage decay rate increases from 0.1 mV/hr to 0.3 mV/hr when compared to the more beneficial sideways orientation. It should be noted that the voltage decay rates listed in Table 2 are not representative of long-term decay rates. In a 200-300 hour operational window, with the stack starting from a shutdown state, there is conditioning of the catalyst that occurs as the stack comes to equilibrium. Therefore, these decay rates should not be used to predict stack life, they are only used here to compare the effect of orientation on the voltage stability in short operational windows. To get accurate lifetime voltage decay rates from an electrolyzer stack, the stack must be run for thousands of hours without interruption. Another indicator of stability is the voltage spread. If the stack is stable, the voltage spread should remain relatively constant over the operational window. A significant change in this spread would indicate potential differences in hydration between cell MEAs and subsequent gas binding occurring. The voltage spread for the stack increased from 35 mV after 287 hours of operation in the sideways orientation, to 100 mV after 297 hours of operation in the upside-down orientation. By adjusting the flow rate to 5 LPM on the anode, the voltage stability was greatly improved in the upside-down configuration. Figure 7 shows the comparison between the voltage profiles in the sideways orientation versus upside down at the baseline 4 LPM flow rate. It's clear there is significant voltage instability for the lower flow rate, with certain cells showing rapid voltage decay at seemingly random times. After that test, the stack was shut down and a high-water flow was circulated in a pulsing fashion through the anode to remove gas bubbles and rehydrate the stack. After restarting the stack, the voltages returned to normal indicating the issue was hydration.



**Figure 7. Comparison of the voltage stability for sideways and upside-down orientation at 4 LPM.**

Another area of interest when baselining the performance of the commercial cell stack is the voltage decay behavior on shut down. Cell voltage decay on shutdown is of interest to monitor for out of family cells decaying more rapidly than others, which might be indicative of a failure, and from the perspective of maintenance. An acceptable voltage limit of 30V for the cell stack was set for the OGA to eliminate the risk of a shock hazard when the system required

service<sup>15</sup>. For the legacy OGA stack, a bleed resistor across the stack is used to reduce the voltage more quickly on shutdown and reduce wait times for service events. An example of voltage decay on shutdown for the commercial stack with the pump running is given in Figure 8 without the use of a bleed resistor.



**Figure 8. Example discharge behavior of the commercial cell stack. The stack is oriented in the upside-down position and water is flowing at a rate of 4 LPM.**

When considering the maintenance issues, it's worth noting that a 20-cell stack will drop below 30 volts when the average cell voltage drops below 1.5 V/cell. This occurs within minutes for the commercial stack so wait times should be minimal. Observing the data trends, it is interesting to note that several cells discharge more rapidly than others, particularly cells 18-20. In the cathode feed OGA, this would be taken as a sign that those cells may have degradation issues since they do not hold charge as long as the other cells. However, in the anode feed configuration, water flooding in the cells contributes to the discharge behavior. In a cathode feed cell, the anode cavity of the cell is relatively dry on shutdown, and circulating the pump brings dissolved hydrogen through the cathode chamber. The reactants slowly recombine until there are none remaining, and the voltage dissipates. However, in the anode feed configuration, EOD water partially fills the cathode, limiting how much hydrogen may be in each cell. Even if dissolved oxygen is circulated through the anode with the pump on, certain flooded cathode cells will have limited hydrogen volume and those cells will discharge faster. Cells 18-20 are the bottom cells in the upside-down configuration and gravity dictates they are most likely to be flooded with liquid water. While it is uncertain how this behavior will translate to microgravity, the hydrogen volume of the cathode can be significantly limited with an anode feed configuration which has positive implications from a safety perspective.

#### IV. Future Plans

This work presented the initial testing performed using a commercial anode feed cell stack for use in the NextGen OGA commercial system along with system design considerations. While certain aspects of the stack performance are unique to the anode feed configuration, the commercial stack shows promise for the intended application. As of this writing, testing is ongoing for the commercial anode feed cell stack. Continued tests will examine additional challenging orientations, gas quality, long term endurance, and the effect of on/off cycling. An additional area of consideration is investigation into the materials of construction for the cell stack. NASA space flight has traditionally restricted the use of certain materials for oxygen service that are commonly used in PEM electrolyzers. However, testing to date to determine flammability of these materials has typically relied on ignition tests in dry oxygen environments which are not representative of the electrolyzer. Continued work will seek to develop tests more applicable to the electrolyzer to reevaluate the usability of these materials.

## Acknowledgments

The authors would like to thank Phillip Baker, Maria Keilich, Galen Kulp, and Robert Roy for their ongoing technical support for this work.

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