

# **PEMFC STACKS FOR POWER GENERATION**

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## **Abstract**

Recently, much of the interest in polymer electrolyte membrane (PEM) fuel cell development has been shifting from transportation to stationary power applications. In contrast to molten carbonate or solid oxide fuel cell technologies which are most appropriate for large-scale power applications, PEM fuel cells are envisioned for small, home-based power sources on the roughly 3 - 5 kW level. Plug Power, LLC, a fuel cell manufacturer, is primarily pursuing the development of such systems. Technological advances in PEM fuel cells at Los Alamos National Laboratory (LANL) are of potential utility for the development of readily manufacturable, low-cost and high performance fuel cell systems operating at near-ambient reactant pressures. As such, the two parties are collaborating on addressing some of the more pressing issues. The primary tasks involve the investigation of both stainless steel and composite bipolar plates, CO tolerant anodes, and novel humidification and stack operation schemes.

## **Introduction**

Home-based stationary power applications are a relatively new area of emphasis for polymer electrolyte membranes. Some of the possible reasons for this increased attention is the recent demonstrations and development successes of the PEM fuel cell, the deregulation of the utilities and the slow maturation and competitiveness of the transportation market for fuel cells. While the majority of funding and interest in the PEM fuel cells has historically been for transportation

applications, meaningful penetration of that market will be difficult for many years yet because the competitive technology is well-entrenched and inexpensive. Despite the significant environmental advantages, fuel cell systems will still need to cost on the order of \$50/kW for transportation which will only be attained with enormous production levels. Until then, many of the fuel cell companies have been attracted to home-based stationary power as a possible fuel cell market that should still be sizable, should accommodate much higher unit costs and does not involve entrenched competition. Most domestic fuel cell companies have teamed up with utilities to explore such possibilities. The majority of home-based units will be designed to operate on natural gas because an extensive distribution network is already in place. By installing home-based units, utilities can increase generation capacity without needing to site and license new plants or build new power lines, both of which have become ever more costly and problematic due to public resistance and tightening regulations. Natural gas suppliers might also be interested in the home-based systems because of the possibilities of competing in a new market and relieving their susceptibility to natural gas prices.

Operating the home-based system on natural gas will require a fuel processor to provide hydrogen to the fuel cell. The reforming and/or partial oxidation fuel processor reactions produce byproducts such as CO and CO<sub>2</sub>. If the CO is not removed from the fuel stream in some manner before it reaches the fuel cell it will severely affect performance, especially with standard anode designs. The typical strategy is to remove the CO through a series of additional steps, but removing the last tens of ppms can not always be routinely assured with typical systems. Therefore, anodes that can tolerate higher levels of CO than conventional electrodes are of interest to withstand excursions that may occur with start-up of the fuel processor or during variations in load levels. Another issue with the use of natural gas is the operating pressure of the fuel processor system. Most other hydrocarbon fuels are usually liquids which can be efficiently pumped to allow the use of a pressurized fuel processor. This decreases the fuel processor volume (and cost) and increases the pressure of the hydrogen delivered to the fuel cell stack, which alleviates dilution effects. However, domestic natural gas is typically delivered into the house at less than 1 psig. Compressing the natural gas incurs a considerable power penalty and requires an additional piece of expensive equipment. The preferable option may be to operate a low-pressure fuel processor, however, the fuel cell anode will then need to operate at near ambient pressures. Anodes then need to be designed and optimized for both the low-pressure operation and CO tolerance.

Near ambient pressure operation is of interest for the air or cathode side for much the same reason as the anode side, that is, to minimize parasitic power losses and lower the component costs. If pressures can be kept low, a blower can be used to provide the air flow through the fuel cell. While not particularly efficient, a blower is obviously much less expensive than a turbine or positive displacement compressor, and with very low pressures, the PV work required is minimal and the device efficiency is not much of a factor. Since the cathode kinetics are roughly first order with respect to oxygen partial pressure, the stack power densities are not as high as with the pressurized cells, however, it can be shown that once the parasitic losses are taken into account, the net power densities are not very different. A number of issues arise with very low-pressure operation. Low pressure operation often results in drier operating conditions due to both lower current densities (less water produced) and the higher water vapor volume fractions (more water removed with the air effluent compared to pressurized). As such, the effectiveness of the

membrane hydration scheme becomes more significant at the lower pressures. Direct liquid water hydration of the membranes then appears to have advantages over the classical means of cell hydration, namely, reactant humidification. Avoiding reactant humidification also eliminates the pressure drop required to force the reactant air through the humidification module, which further decreases the parasitic power requirements. As such, major areas of emphasis are direct liquid membrane hydration and near-ambient system schemes.

Regardless of the fuel cell system or stack technology, one of the major limitations is currently the bipolar plate technology. Historically, machined graphite plates have been the material of choice, but are clearly too expensive for mass production. The bipolar plates also need to be highly electrically conductive, durable, impermeable and corrosion resistant, a surprisingly difficult combination to realize. Metal hardware is of interest because of its toughness and the versatile fabrication options, but corrosion is a significant difficulty. Previously in this program, we considered stainless steel (SS) alloys and have operated cells for as long as 2000 h using 316 SS with little evident effect, but the inclusion of metal ions into the membrane discourages operation on a much longer time frame. More like 40,000 h would be needed for stationary applications.

## **Discussion**

### **Metal Bipolar Plates**

Most of our work with metal hardware in this program has focused on the development of non-machined low-cost bipolar plates based on the use of untreated 316 SS screens and foils (Wilson and Zawodzinski 1998, Zawodzinski et al. 1998b). The performance of this hardware in polymer electrolyte fuel cells was initially monitored via polarization curves and high frequency resistance (HFR) data. In general the hardware performed well in several fuel cell tests including a 2000 h life-test and appeared to be corrosion resistant, in that cell performance and the HFR remained quite stable over the test period (Zawodzinski et al. 1998a). After the test, the membrane-electrode assembly (MEA) was examined by EDS (energy dispersive x-rays) and was found to be relatively clean. However, EDS can not quantitatively distinguish metal ions that are present in stainless steel because the scope itself is made from it. In order to accurately assess what metals were present in the MEAs, an x-ray fluorescence (XRF) spectrometer was obtained. When the MEA from the 2000 h test was reexamined with this instrument, it was found that metals such as iron and nickel were indeed present in appreciable quantities. While the cell performance was not yet unduly affected, significant losses can be expected over the much longer lifetimes that would be expected of stationary applications. While the membrane has some tolerance, eventually the active sites would be tied up by the polyvalent ions and ionic conductivity would be seriously impaired. The XRF finding prompted us to do more extensive work in the area of corrosion testing and to analyze other metal alloys that might provide better corrosion resistance than 316 SS but are still relatively low-cost.

### ***Screening of Metal Alloys for Corrosion Resistance***

Many types of alloys have been developed for applications where common stainless steels such as 304 or 316 SS do not provide adequate corrosion resistance. In general, the compositions of

these alloys are similar to their stainless steel or nickel-base counterparts except that certain stabilizing elements, such as nickel, chromium and molybdenum, are added and/or are present in much higher concentrations in order to obtain desirable corrosion properties. Different combinations of these elements and their concentrations can dramatically change the nature of the alloy and thus, alloy compositions are usually tailored for quite specific applications, such as marine water service. This poses a problem in choosing suitable materials for fuel cells because of the variety of conditions present that are all conducive to corrosion yet are very different in nature, i.e. chemical and electrochemical oxidizing and reducing environments, humidity, and possibly slightly acidic environments.

For example, nickel, which is common to all of these families of alloys, provides corrosion resistance in neutral and reducing environments and is essential to prevent chloride stress corrosion cracking. Thus, for applications such as seawater or caustic service, a high Ni content is required and most of the nickel-base alloys have been developed for these types of applications. In neutral to oxidizing media, however, a high chromium content (which is often accompanied by the addition of molybdenum) is necessary. Many of the stainless steel alloys have been developed along this vein and are used in a variety of corrosive environments, i.e. nitric acid service. Since both oxidizing and reducing conditions exist in a typical fuel cell environment, we screened a number of stainless steel and nickel alloy samples representing several categories of corrosion-resistant materials as possible alternatives to 316 SS or graphite-based bipolar plate materials.

The alloy samples were obtained through Allegheny-Ludlum and their specific compositions are summarized in Table 1 (only limited data were available for E-Brite and 316 SS was included for comparison purposes). The first alternative alloy, E-Brite 26-1, is a superferritic stainless steel. This family of stainless steels was developed primarily for use as a lower-cost alternative to nickel-base alloys for applications where chloride stress corrosion cracking is a problem, and can also be used for caustic service. However, E-Brite is similar to 316 SS in that it contains molybdenum in addition to a high chromium content, which gives it resistance to oxidizing environments as well. Alloy 2205 is a Duplex stainless steel. This type of stainless steel was also developed to provide resistance to stress corrosion cracking and is used for applications such as piping for oil and gas vessels. In this alloy, nitrogen is added to a Cr-Ni-Mo base to obtain a duplex material, which has features of being both ferritic plus austenitic in structure. This essentially gives it somewhat of a dual nature with respect to corrosion resistance as for the case with E-Brite, but the addition of nitrogen also makes it particularly strong. Alloys 201, 400, and 600 are nickel-base alloys with additions of cobalt and special additions of copper for AL400 and chromium for AL600. All of these alloys provide resistance to chloride stress corrosion cracking and are very suitable for reducing environments such as caustic service. AL600 has the additional benefit of corrosion resistance in weak oxidizing environments due to its high chromium content. The minimal amounts of Fe in these alloys are potentially of interest because iron is believed to adversely affect the kinetics of the oxygen reduction reaction at the cathode if it reaches the catalyst.

**Table 1. Typical Compositions of Selected Stainless Steel and Nickel-base Alloys**

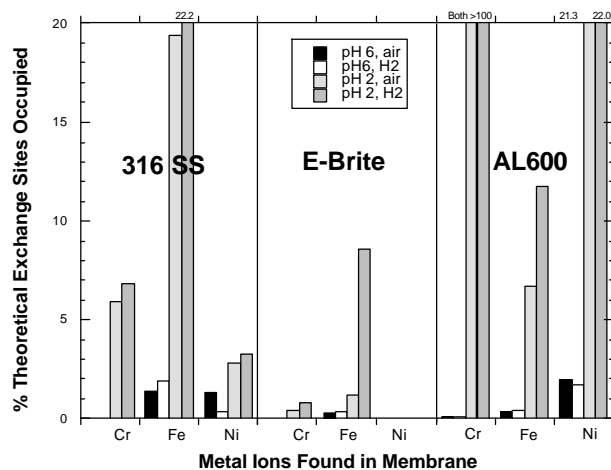
Alloy	% C	% Mn	% P	% S	% Si	% Cr	% Ni	% Mo	% N	% Fe	%Other
316 SS	0.08	2.0	0.045	0.03	1.0	16.0	10.0	2.0	0	balance	0
E-Brite 26-1						26.0		1.0			
AL2205	0.02	0.7	0.025	0.001	0.40	22.4	5.8	3.3	0.16	balance	0
AL201	0.02	0.02	0	0.002	0.05	0	balance Ni+Co	0	0	0.05	0
AL400	0.10	0.50	0.005	0.005	0.25	0	balance Ni+Co	0	0	1.0	32 Cu 0.02 Al
AL600	0.05	0.25	0	0.002	0.20	15.5	balance Ni+Co	0	0	8.0	0.1 Cu

To assess the corrosion resistance of these materials, samples of each alloy were subjected to aggressive immersion testing. In this type of test, the materials are immersed in acidic solutions and are exposed to conditions analogous to a fuel cell environment but are much more severe than what is actually present in an operating cell. The harsh conditions tend to accelerate corrosion of the materials and thus differences in the corrosion resistance of numerous alloys can be assessed relatively quickly (on the order of a few days or weeks). As a result, only the most promising alloys need be made into bipolar plates and tested in fuel cells, which is a time-consuming and much more expensive process.

Specifically, coupons of each of the alloys (1 in<sup>2</sup>) were immersed in solutions of pH 2 and pH 6 sulfuric acid, which were maintained at 80°C by means of a water bath. One set of solutions was continuously sparged with hydrogen (in forming gas -94% Ar, 6% H<sub>2</sub>) while another was sparged with air for about 125 hours. Each bottle also contained a piece of Nafion 112 (H<sup>+</sup> form) cation-exchange membrane to act as a sponge for metal ions that may have leached from the alloys. At the end of the test period, corrosion resistance was assessed gravimetrically based on weight loss of the material and the Nafion samples were analyzed by XRF to assess which metal ions, if any, were present and to what extent they occupied exchange sites in the membrane.

In general, corrosion of the alloys was accelerated for those samples immersed in pH 2 sulfuric acid and was exacerbated by the presence of hydrogen for the stainless steels and by air for the nickel-base alloys, except in the case of AL400. E-Brite was the best alloy in terms of its overall corrosion resistance. However, at pH 6, AL600 exhibited excellent corrosion resistance with corrosion rates of less than 1 μm/yr and virtually no leaching of metals to the membrane.

Based on these initial results, samples of E-Brite and AL600 were subjected to another immersion test cycle under the same conditions, but this time samples of 316 SS were included for comparison and the test was run for 300 h. Similar results were obtained, with corrosion rates increasing as the pH decreased. E-Brite provided the best overall corrosion resistance, with corrosion rates of less than 1 μm/yr for all conditions. AL600 and 316 SS also exhibited low corrosion rates at pH 6 but could not tolerate the pH 2 environment as well as E-Brite. These effects were especially observable in the Nafion samples that were included in the immersion test and are shown in Figure 1.



**Figure 1 - Metal Ion Inclusion Detected in Nafion Samples by XRF Analysis.**

Each piece of membrane in the sample solutions was analyzed by XRF for the presence of metal ions and the concentrations were converted to theoretical percentages of exchange sites taken up by those ions (based on a given number of equivalents per ion, i.e. 2 for Fe<sup>2+</sup>). Since XRF can not distinguish between different oxidation states or whether the metal is part of an oxide on the surface for example, these values are used as semi-quantitative indicators of the extent of metal ion inclusion.

As can be seen in Figure 1, though all three of the alloys had low corrosion rates at pH 6, E-Brite clearly withstood the environment much better than either 316 SS or AL600 when the membrane was considered. This is a particularly important factor when considering metal alloys for use in fuel cells because the membrane-electrode assembly is the most vulnerable cell component and keeping it clear of ion contamination will be critical for the long term operation that will be required for successful commercialization.

In addition to the immersion tests described above, a metal bipolar plate with an inexpensive proprietary coating was tested in a fuel cell for 200 h under conditions typical for pressurized systems. The cell voltage was maintained at 0.7 V to create a harsher electrochemical environment within the cell, but also because this is a common operating voltage for stationary power applications where metal hardware is most likely to be utilized. The cell's performance was monitored via polarization curves and high frequency resistance measurements throughout the run and the membrane-electrode assembly was later analyzed by XRF for metal ion contamination. The cell performance was not as good as that obtained with graphite plates, however, the performance was quite stable. The HFR values were not unreasonable and did not increase over time. Analysis of the MEA did show evidence of some uptake of metals from the coating, but visual analysis of the plate suggested that the corrosion occurred in areas adjacent to the gasket material where water can tend to be retained. The main portions of the flow-field appeared to be unaffected. Though some corrosion was observed, the results suggest ways to tailor the coating to be more effective in the presence of water and thus new coatings are presently being formulated for testing.

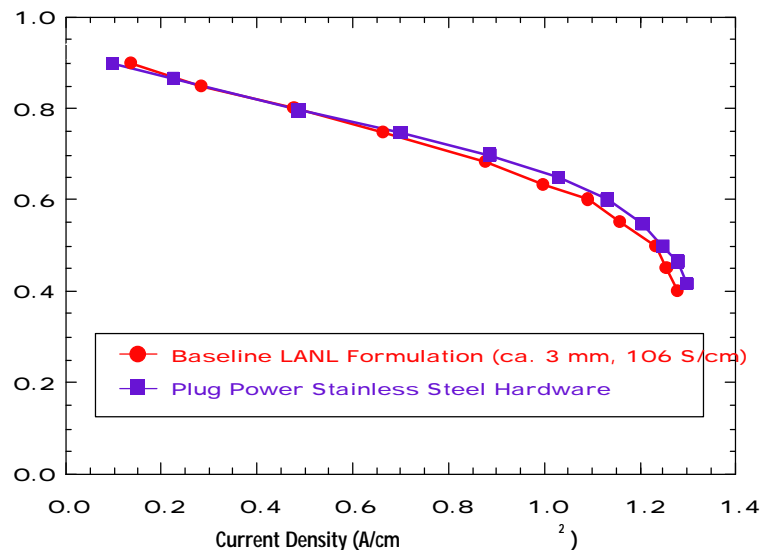
In general, it appears that prolonged contact with water and a low pH are the most significant contributors to corrosion of metal plates. Much can be done to decrease the incidence of stagnant water by appropriate design of cell components. Also, if the pH of the water in a PEFC can be maintained at its typical value of about pH 6-7, these results suggest several other possible low-cost alloys (or coatings) that may be suitable for use as bipolar plates.

## **Composite Bipolar Plate Materials**

Composite materials offer the potential advantages of lower cost, lower weight, and greater ease of manufacture than traditional graphite and metal plates. For instance, flow fields can be molded directly into these composites, thereby eliminating the costly and difficult machining step required for graphite or metal hardware. Most of the composites used in fuel cell bipolar plates have employed graphite powder in a thermoplastic matrix such as polyethylene, polypropylene, or, most commonly, poly(vinylidene fluoride) (PVDF), with or without short carbon fibers for reinforcement. Unfortunately, PVDF is relatively expensive, and any thermoplastic composite must be cooled before its removal from a mold, resulting in long cycle times. On the other hand, thermosetting resins (e.g., phenolics, epoxies, polyesters, etc.) generally offer shorter process cycle times than thermoplastics because, once cured, they become rigid and can be removed from the mold while still hot. While injection and/or resin transfer molding may be attractive from a mass-production standpoint, the solids content required to attain good electrical conductivity renders these processes impractical. A polymer melt or solution with high (> 50%) solids loading has poor rheology, and the thixotropic nature of the mixture would require exceedingly high molding pressures to achieve adequate fill, even if a homogeneous distribution of filler and polymer could be attained. Thus, from a processing point of view, compression molding is favored for both thermoplastic and thermoset matrix composites.

If compression molding is used, cost-effective mass production would tend to be more readily achievable with thermosets rather than thermoplastics because of their shorter cycle times. With the proper combination of resin additives and temperature, a compression molded thermoset composite can cure in comfortably less than 5 minutes, resulting in cycle times an order of magnitude less than those required for thermoplastics. One particular family of thermoset resins, vinyl esters, seems especially well-suited to bipolar plates (Busick and Wilson 1998). Vinyl esters are methacrylated epoxy difunctional polyesters, and as such are often described as a cross between polyester and epoxy resins. In addition to being noteworthy for their excellent corrosion resistance, vinyl esters are lightweight, strong, tough, and commercially available at low cost. By capitalizing on these properties of vinyl ester resins, we have developed new material formulations for producing low-cost, high-performance, easy-to-manufacture composite bipolar plates.

The most widely used conductive filler for composite bipolar plates is graphite powder and it is employed in the vinyl ester composites described here as well, although early tests revealed that the choice of graphite powder influences the conductivity of molded parts. Thus, the relationship between filler loading and electrical conductivity appears to depend somewhat on graphite particle size and particle size distribution. We have identified a particular type of graphite powder with a fairly narrow particle size distribution that offers relatively high conductivity for a given volume fraction and is reasonably easy to combine with the liquid resin to form a homogeneous mixture.



**Figure 2 - Fuel Cell Performances using Composite and Stainless Steel Bipolar Plates (Tested at Plug Power)**

Following the development of “baseline” composite materials, in-cell testing was performed. Plug Power has used these compounds to mold bipolar plates with and without integral flow fields. A set of these molded plates with 60 wt% graphite and machined flow fields was demonstrated in a fuel cell at Plug Power and performed as well as machined graphite. A thinner, more conductive (68 wt% graphite) set of plates molded at LANL and having machined flow fields was also tested at Plug Power. These plates exhibited cell performance comparable to their baseline bipolar plate materials (e.g., machined graphite and stainless steel). Polarization curves for these plates along with similar data for stainless steel are shown in Figure 2 for comparison.

### CO Tolerant Anodes

Eventually, the majority of stationary power systems will need to be designed for operation on natural gas, primarily due to its extensive distribution network. The simplest home-based units will use near-ambient pressure steam reforming to convert the natural gas to a hydrogen rich fuel stream. Figure 3 portrays the unit processes of a generic ambient pressure fuel processor. The thermodynamic reaction equilibrium at the high temperature steam reforming (e.g., 700 C) yields a roughly 10% concentration of CO by-product. As a result, the reformat is relayed to high and low temperature water-gas shift reactors to further lower the CO concentration (CO levels in the figure are approximate order of magnitude). Since even 0.1 % CO (1000 ppm) is easily enough to thoroughly poison the fuel cell anode, the effluent from the LT shift reactor is sent to a preferential oxidation (PROX) reactor. Here, the CO is selectively oxidized using oxygen from injected air to lower the CO to a level that can ideally be tolerated by the fuel cell. Unfortunately, it is difficult to assure sufficiently low CO levels so air bleeding into the fuel cell stack anode inlet is used to increase the anode tolerance. Another means of increasing CO tolerance is merely by increasing cell temperature, which lowers the CO sticking coefficient.



However, it is not possible to increase the operating temperatures much over the standard 80 C with near-ambient pressures. In any case, the amount of bleed air required to recover performance as well as the upper level CO tolerance of the anode is strongly dependent upon the anode design and catalysts.

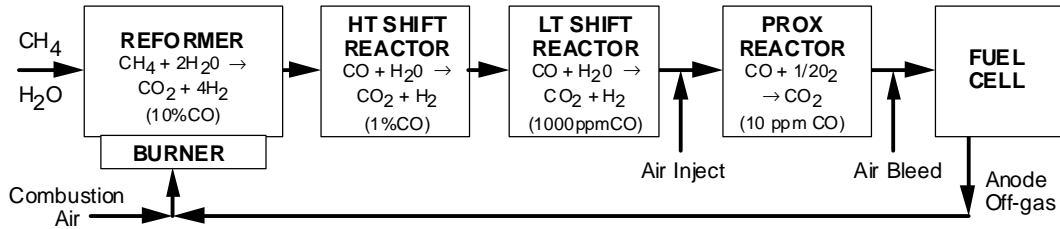


Figure 3 - A Generic Ambient Pressure Fuel Processor and Fuel Cell System

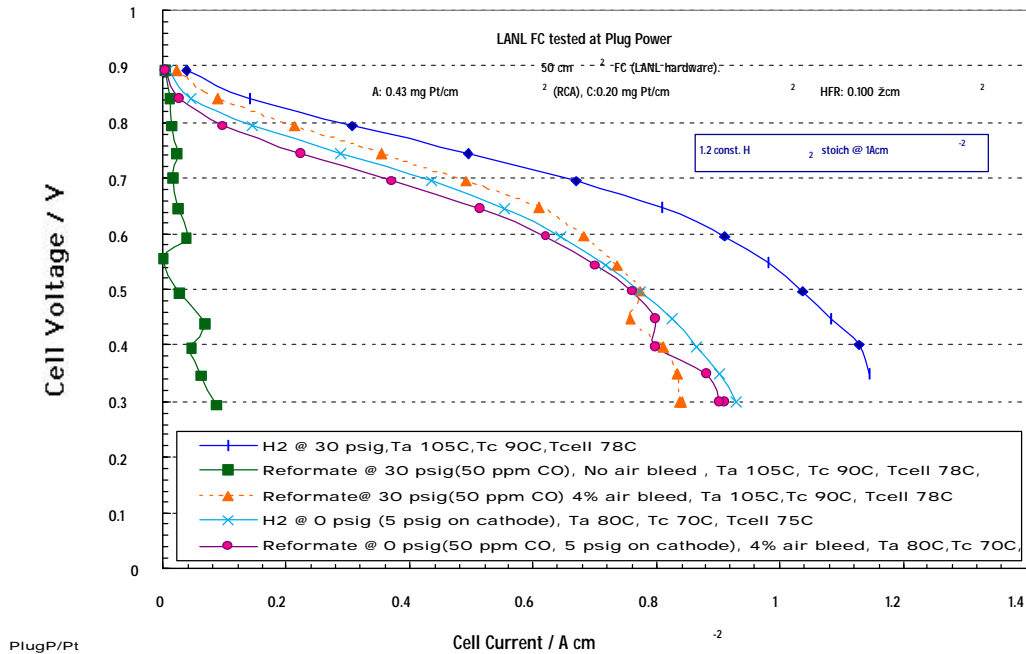


Figure 4 – Polarization Curves for a LANL RCA Anode under Various Conditions

At Los Alamos, we have developed a "reconfigured anode" (RCA) for pressurized transportation applications (30 psig) that demonstrates substantially increased anode tolerance compared to conventional anodes. Now, for this effort, the RCA designs need to be tailored for the near ambient pressures. The primary difference is that the hydrogen partial pressure is substantially lower compared to the pressurized system. As a result, it is expected that simple dilution effects (e.g., the effect of the presence of inert gasses on the hydrogen mass transport), would detrimentally impact the anode performance. The problem is further exacerbated if a partial oxidation reactor (POX) is used in the fuel processor in place of the steam reformer, as the hydrogen fraction of the reformate stream is yet further decreased. In most cases, it is indeed

difficult to attain neat hydrogen level performances using reformat at near ambient pressures. One compelling exception is portrayed in Figure 4 for one particular cell tested at Plug Power. First is shown the deleterious effects of 30 psig reformat with 50 ppm CO compared to 30 psig neat hydrogen and the 50 ppm CO reformat with 4% air-bleed. The air bleed does not recover the neat hydrogen level of performance quite so well as a number of other pressurized cells but secondary effects, such as mass transport or water balance limitations, appear to be compounding the dilution effect. On the other hand, at the stationary power relevant 0 psig conditions, changing from neat hydrogen to 50 ppm CO reformat plus 4% air the cell does surprisingly well. The reasons why this particular design shows the better ambient pressure reformat performances compared to other designs needs to be understood and hopefully even further improved.

### Novel Humidification and Stack Operation Schemes

Most of the motivation to develop an ambient pressure system instead of a more conventional pressurized system is to replace the relatively sophisticated compressor and expander (to recover some of the compression work) with a simple blower in order to substantially decrease costs, complexity, and parasitic power losses. However, operation at near ambient pressures is not only problematic from the perspective of decreased anode and cathode performances but also because of added difficulties with water management. Much more water is removed from the system at near-ambient pressures compared to 30 psig because of the higher water fraction in the cathode effluent, as is illustrated in Figure 5. Shown here are the results of a simple calculation considering the water balance in the cell taking into account the water formed in the fuel cell reaction and the water removed with a 70 C cathode effluent. At 3 atm (30 psig), the net water balance is positive as long as the stoichiometric flow is kept below four. At 1 atm, it is not feasible to maintain a positive water balance at a reasonable stoichiometric flow. As such, it is challenging to maintain a high level of hydration in the membranes, especially at the relatively high efficiencies (and corresponding modest current densities) of interest for stationary power.

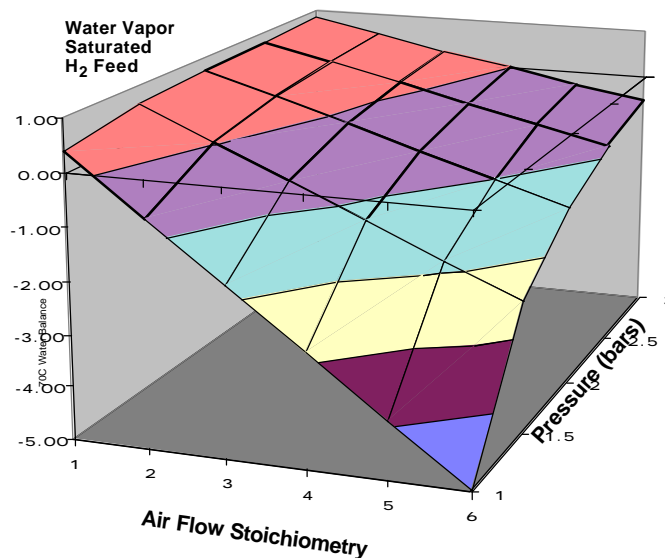
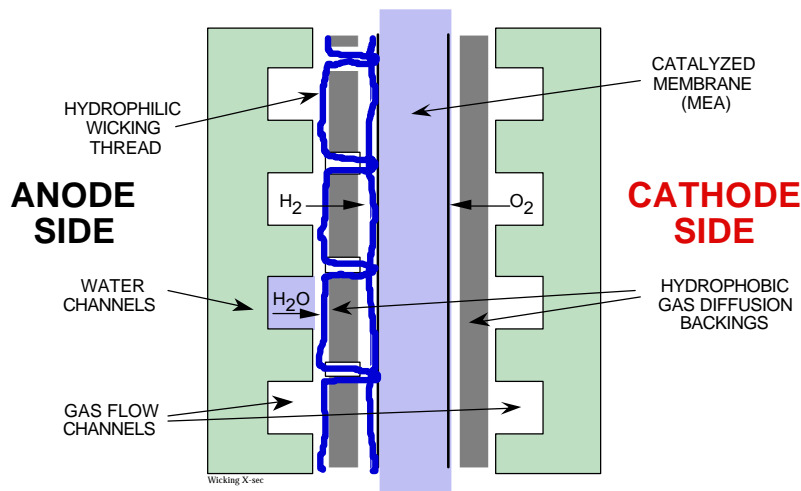


Figure 5 - Water Balance for a Fuel Cell with a 70 C Saturated Cathode Effluent

Thus, a method to directly humidify the fuel cell membrane electrode assembly (MEA) with liquid water (Wilson et al. 1998) is of interest for ambient pressure operation. The direct liquid hydration can be accomplished by the introduction of an anode wicking backing that conveys liquid water in the anode flow-field plenum directly to the membrane, as depicted in Figure 6. The technique of using direct liquid hydration of the MEAs has a number of advantages for a simple, low-cost fuel cell system in that it utilizes "ordinary" MEAs and bipolar plate technologies and eliminates the need for a number of auxiliary components. The approach supplies liquid water to all regions of the MEA to improve performance at higher stack temperatures and/or at lower cathode air pressures. Direct liquid hydration also separates the functions of gas supply and membrane hydration, which substantially simplifies the overall system as well as its control. The fine wicking threads were simply sewn into a conventional hydrophobic carbon cloth backing using a computer controlled embroidery machine to place the wicking in the desired regions and patterns.

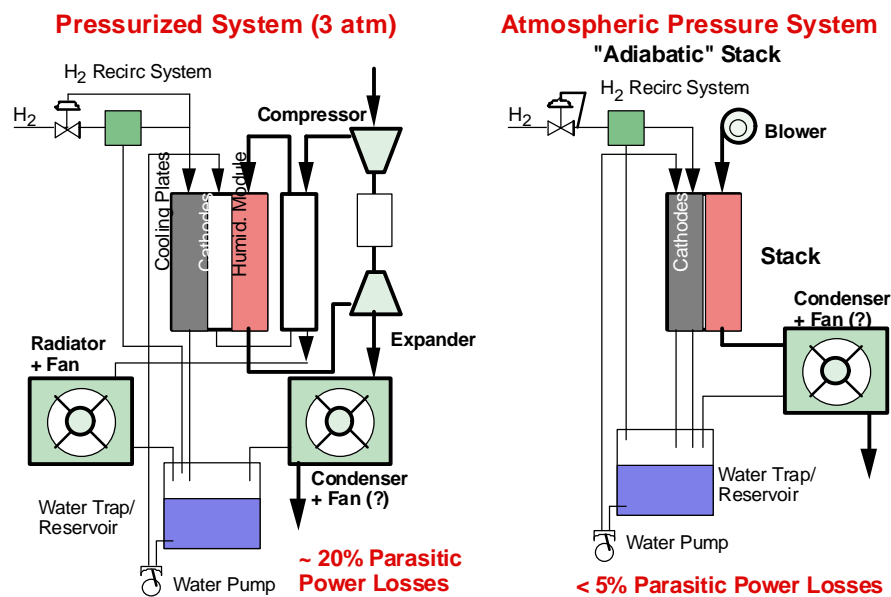


**Figure 6 – Scheme for Direct Liquid Hydration using an Anode Wicking Backing**

Since the air is supplied to the fuel cell dry, lower air pressures are needed than if a humidification module were required as with most other systems. Furthermore, the initially dry air is heated and humidified as it passes through the stack adjacent the well hydrated membranes. This reactant air humidification is sufficient to provide *in situ* evaporative cooling for the stack such that separate cooling plates are not required. The stack then assumes a substantial temperature gradient between the air inlet and outlet in contrast to most stack designs where the objective is to maintain isothermal conditions throughout. As such, the approach has been described as an "adiabatic" stack by Argonne National Laboratory for their system modeling efforts. In comparison to a conventional pressurized system using reactant humidification and cooling plates, the near-ambient "adiabatic" stack system is substantially simpler, as illustrated in Figure 7. Another major advantage with near-ambient pressure cathode operation is the lower parasitic power requirements compared to pressurized operation. For example, the 30 psig pressurized fuel cell system operating on hydrogen depicted in the figure requires about 20% of the electrical power produced to operate the system auxiliaries. The largest power loss is the air compressor even though the system runs at an efficient two-times stoichiometric flow at the cathode. The situation would be even worse except that an expander is used on the air effluent to recover as much of the PV work as possible. This compressor/expander package is becoming a major

technical and cost challenge in fuel cell system design. Thus, substantial advantages can be realized by operating the air side at ambient pressure. We are working on attaining pressure drops of less than 5" H<sub>2</sub>O (there are about 28" H<sub>2</sub>O per psi). Even such low pressure drops are important. If, for example, only two psig is still required to push air through a fuel cell stack at three times stoichiometric flow, then already about 3% of the stack output power would theoretically be required for the 2 psig compression requirement (assuming adiabatic compression). In reality, a compressor would at best be 50% efficient, so already 6% of the stack power is required just for a seemingly modest pressure.

One of the major concerns with ambient pressure operation is that much larger stacks would be needed because of the diminished cathode performance with the low oxygen partial pressure. In reality, the stack size with an ambient system should be similar to conventional pressurized systems when net power yields and system efficiencies are considered. For example, an (ambient pressure) system with 5% parasitic power losses operating at 0.7 V/cell provides the same net efficiency as a pressurized 20% parasitic power operating at 0.83 V/cell. For similar current densities of about 300 mA/cm<sup>2</sup>, the ambient cathode stack is thus not any larger and could conceivably be smaller than the pressurized stack because it does not require the separate cooling or humidification plates used in the latter. The auxiliaries should be smaller as well in the simpler ambient system. In general, it appears that ambient pressure does not necessarily mean a loss in performance when the overall system and efficiencies are considered.



**Figure 7 - Comparison of Pressurized and "Adiabatic" Stack Systems**

In stationary power applications, the condenser (and fan) could conceivably be eliminated in the adiabatic stack system if a water supply is available at the site and the system does not need to be water self-sufficient. Eliminating the cooling fan would increase efficiency about 1.5% but would require an effective water de-mineralizer. Water self-sufficiency and elimination of the fan may possibly both be accomplished if the condenser is used in a co-generation scheme to pre-heat water for domestic uses. The condenser heat exchanger would then most likely take the form of a conventional tube-and-fin condenser but with the air effluent on the fin side. This should be

lower cost than the two heat exchange units, a liquid-liquid heat exchanger and a condenser, that would be required for a conventionally cooled fuel cell system.

## Conclusions

Commercialization of home-based stationary power fuel cells will require reliable and inexpensive components and systems. Major steps to realizing these criteria can be achieved with the development of low-cost and reliable bipolar plates, stable and effective CO tolerant anodes, and near-ambient operating pressures with effective membrane hydration. If home-based power becomes a large market, other technologies will certainly be attracted to it. The polymer electrolyte fuel cell system will not be able to compete on higher efficiency advantages alone, it will still need to be as reliable and low cost as possible in order to compete effectively.

## Future Work

Further corrosion testing of the more promising alloys is needed to determine if any fuel cell testing is warranted. A significant portion of the effort will be expended on the somewhat different low-cost metal hardware direction briefly described above that is based on recent interactions with a materials company with unique capabilities. Very preliminary results appear quite promising (but may be misleading) for this speculative but intriguing technology. Otherwise, development of the composite plates and CO tolerant anodes for near-ambient operation will continue. Novel humidification and water management issues have yet to be integrated with Plug Power's efforts but will become a prominent issue in the future. These tasks need to be further investigated with or transferred to Plug Power to assist in the development and fabrication of a 3.5 kW hydrogen-fuelled system for home-based stationary power. Eventually, sufficient progress needs to be attained on the reformat fuel issues to allow the development of a fully integrated natural gas-fuelled system.

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