U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

2016 Alkaline Membrane Fuel Cell Workshop

April 1, 2016

Sponsored by U.S. Department of Energy
Fuel Cell Technologies Office (FCTO)

Organized by National Renewable Energy Laboratory and
Los Alamos National Laboratory

2016 Alkaline Membrane Fuel Cell Workshop Summary Report

Workshop held April 1, 2016
Sheraton Grand Phoenix
340 N. 3rd St
Phoenix, AZ 85004

Sponsored by
U.S. Department of Energy (DOE) – Fuel Cell Technologies Office (FCTO)
Organized by
National Renewable Energy Laboratory and Los Alamos National

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NOTICE

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Executive Summary

The U.S. Department of Energy (DOE), Office of Energy Efficiency and Renewable Energy (EERE) Fuel Cell Technologies Office (FCTO) held the Alkaline Membrane Fuel Cell (AMFC) Workshop on April 1, 2016 at the Sheraton Grand Phoenix in Phoenix, Arizona to share information and identify the current status and the R&D needs for AMFC technology. Over 45 experts from universities, industries, government, and national laboratories representing the needs of AMFC material, membrane electrode assembly (MEA), and system & stack components attended the Workshop. The one day workshop began with a series of overview presentations on these topics to set the stage for the subsequent breakout sessions that assessed the current state of AMFC technology; identified limitations, performance potential, and key research and development needs for AMFC technology; identified early market and longer-term applications; and discussed test protocols, milestones and metrics for cells and components.

The technical advances of AMFCs since the 2011 AMFC Workshop[1] have been substantial. Around 2011, the performance of AMFCs was modest; typical peak power densities reported in the few hundreds of mW/cm^2. Additionally very few alkaline stable anion exchange membranes (AEMs) were available. Over the last 5 years, significant advances have occurred in the areas of AMFC performance, non-precious group metal (non-PGM) catalysts, and alkaline stable AEMs. These recent developments have continued to advance AMFC technology towards commercial relevance. However, technical challenges remain, and the research field still lacks standardization, protocols, and baselines inhibiting deployment of commercially competitive AMFC systems.

In this one-day workshop, two breakout sessions were held. The first one focused on AMFC research challenges and R&D needs while the second session centered on AMFC technology status, standardization of test protocols, and milestones. These topics were discussed in three parallel breakout groups focused on:

- Anion Exchange Membranes
- Catalysts
- MEA/System

The body of this report details the discussions that occurred within the breakout sessions. Table 1 shows a few selected highlights from the breakout sessions and compares these findings with the 2011 AMFC workshop report findings. It summarizes both the status of AMFC technology, illustrating the substantial advances made over the past 5 years particularly in the area of AEMs, as well as the challenges identified by the Workshop participants.

The key advances presented in 2016 include alkaline stable AEMs through cationic group and polymer backbone stabilization. This is perhaps the most critical and enabling aspect of AMFC technology advancement, as historically the ultimate ability of AEMs to meet durability concerns under operating conditions was always a potential Achilles' heel for the technology. Based on today's status, it seems this potential barrier will be overcome. However, large scale commercial AEMs are still not available, although scale-up production of promising AEMs are currently being explored. Beyond alkaline stability, further AEM challenges include mechanical stability, high conductivity (particularly at low RH), improved water transport, and environmentally-friendly, low cost synthesis routes.

Research progress on AMFC hydrogen oxidation reaction (HOR) catalytic activity and improved AMFC performance is also notable. The invited presentations highlighted status and challenges of HOR and AMFC performance including both precious and precious group metal (PGM)-free catalysis. For electrocatalysis, the technical challenges included development of electrochemically active PGM-free HOR catalysts, HOR mechanistic understanding, bifunctional (ORR and OER) catalyst development, and implementation of HOR and ORR PGM-free catalysts into AMFCs.

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[1] Pivovar, B. *2011 Alkaline Membrane Fuel Cell Workshop Final Report*; NREL, 2012, http://energy.gov/sites/prod/files/2014/03/f12/amfc_may2011_workshop_report.pdf

For MEAs and systems, high-performing ionomeric binders for catalyst layers, optimized MEA processing, and CO_2 mitigation and water management issues were denoted as challenges, among others. Many PEM-specific MEA fabrication techniques and components (e.g. gas diffusion layers) are commonly used with AMFCs at this time as little effort has occurred to develop and optimize these for the very different chemistries and operating characteristics of AMFCs. Also of note, AMFC MEA power densities as high as 1 W/cm^2 have now been reported.[2]

Table 1. Select Highlights of Breakout Groups

Breakout Group	Key Highlights	
	2011	**2016**
AEM	*Status* • AEMs demonstrated at a level approaching commercial relevance. • Minimal transport property data exists for AEMs.	*Status* • Identified several key degradation mechanisms not only for cationic group but also polymer backbone. • Demonstrated several chemically stable AEMs.
	Challenge • Inferior AEM stability to proton exchange membrane. • Significantly low hydroxide conductivity	*Challenge* • Mechanically stable and thin AEMs. • Highly conductivity AEMs under low RH conditions. • Lag between membrane development/ characterization and its evaluation in a MEA • Cost-efficient and environmentally-friendly AEM scale-up
Catalysts	*Status* • Demonstrated high performance, durable, non-precious electrocatalysts for oxygen reduction in RDE.	*Status* • Several classes of PGM-free ORR catalysts, besides metal-nitrogen-carbon catalysts, under development.
	Challenge • Unknown anode catalysis performance and durability	*Challenge* • Improved activity of PGM-free HOR catalysts. • Mechanistic understanding of the HOR process. • Development of bifunctional oxygen catalysts. • PGM-free ORR catalysts validation in AMFCs in addition to RDE

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[2] Wang, Y.; Wang, G. W.; Li, G. W.; Huang, B.; Pan, J.; Liu, Q.; Han, J. J.; Xiao, L.; Lu, J. T.; Zhuang, L., Pt-Ru catalyzed hydrogen oxidation in alkaline media: oxophilic effect or electronic effect? *Energ Environ Sci* **2015**, *8* (1), 177-181.

MEA and System	*Status* • Reported 500 mW/cm^2 peak power density for H_2/O_2 AMFC performance without the addition of free electrolyte. • Needed studies on system-specific requirement to produce viable devices	*Status* • Reported 1 W/cm^2 peak power density for H_2/O_2 AMFC performance without the addition of free electrolyte • MEAs typically use components optimized for PEM fuel cells
	Challenge • Mitigation of CO_2 impact from air or fuel on system design and performance.	*Challenge* • Development of advanced ionomeric binders that have good gas permeability, conductivity and less poisoning of electrocatalysts. • Optimized processing of AMFC MEAs. • Better diagnostics/modeling on water transport and membrane-electrode interfaces. • More AMFC operation data with H_2/CO_2 contaminated air to understand the CO_2 impact and develop CO_2 tolerant materials/system.

With the continued maturation of AMFC technology over the past 5 years, the need for standardized test protocols and metrics to assist in guiding AMFC development has risen in importance. The afternoon breakout session focused in this area. Despite recent significant advances in development of AEMs with good conductivity and stability, the membrane breakout group expressed concerns with translating these advances to MEAs (e.g. correlate *ex situ* and *in situ* studies) and validating results across the research community. A critical need identified is a standard, widely accessible membrane (e.g. the equivalent of PEMFC's Nafion) to use for developing and baselining test protocols as well as giving the research community a way to carry out valid comparisons of membrane and fuel cell results. The catalyst breakout group recommended several performance and durability protocols and targets for both HOR and ORR catalysts; details are provided in the body of this report. Considering the difficulties in preparing and testing high quality AMFC MEAs, the use of rotating disk electrode (RDE) technique as a screening tool was recommended with only the most promising catalysts being tested subsequently in MEAs. This group also identified the incorporation of an accurate reference electrode in MEA testing to be critical in order to better differentiate between cathode and anode overpotential losses, given the much slower HOR kinetics in the AMFC basic environment compared to the PEMFC acidic environment. The MEA/systems breakout group indicated a lack of consensus exists on testing protocols or applied diagnostics and provided a list of areas in which standardization is needed. Currently, because of this lack of standardization, it is critical that all conditions under which performance or diagnostic data have been obtained be reported. Also, the group believed that FCTO's existing AMFC MEA milestones are appropriate given the current state of AMFC technology.

Introduction

The U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy (EERE) Fuel Cell Technologies Office (FCTO) held the Alkaline Membrane Fuel Cell (AMFC) Workshop on April 1, 2016 at the Sheraton Grand Phoenix in Phoenix, Arizona to share information and identify the current status and the R&D needs for AMFC technology. The goals of the Workshop included assessing the current state of AMFC technology; identifying limitations, performance potential, and key research and development needs for AMFC technology; identifying early market and longer-term applications; and discussing test protocols, milestones, and metrics for cells and components. Over 45 industrial, academic, national laboratory, and government experts representing the needs of AMFC material, MEA, and system & stack components attended the workshop. The list of registrants is included in the Appendix.

The 2016 Workshop built on previous Workshops on the same topic held in 2006 and 2011. The continued growing interest in AMFCs is reflected in Figure 1 which shows search results using the Thomson Reuter Web of Science^{TM} search engine with the search terms “alkaline membrane” and “fuel cell” for the years 2003 to 2015. (From 1980 to 2002, ISI yielded only 23 hits). Over the past decade, interest in the field of alkaline membrane fuel cells has grown at a tremendous pace, and the advances over the past 5 years, discussed throughout this report, were a primary motivation for the Workshop itself.

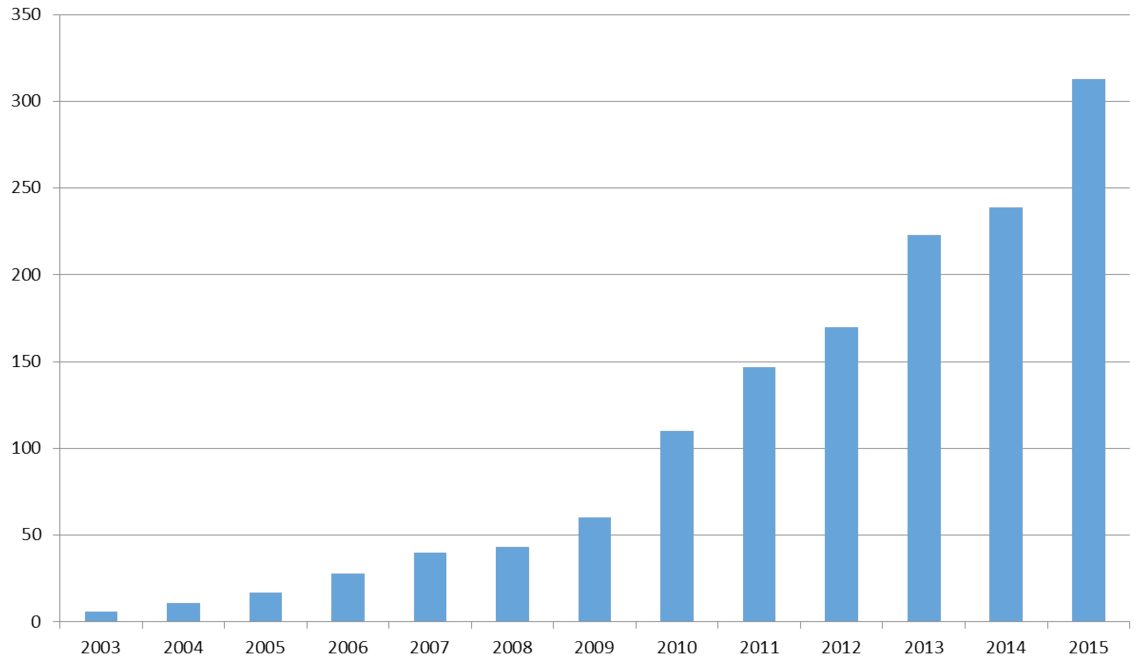

Figure 1. Publications with “alkaline membrane” and “fuel cell” from the Thomson Reuter Web of Science^{TM} search engine

The agenda for the Workshop along with overview information regarding the presentations and breakout session organization is presented below.

Workshop Agenda

FRIDAY, APRIL 1, 2016

8:00 – 8:15 am	**Welcome and Opening Remarks: Dimitrios Papageorgopoulos (DOE)**
8:15 – 8:30 am	**Workshop Overview: Bryan Pivovar (NREL)**
8:30 – 8:50 am	**AMFC Challenges – Anion Exchange Membrane: Chulsung Bae (RPI)**
8:50 – 9:15 am	**AMFC Challenges – Electrocatalysis: Yushan Yan (U. Delaware)**
9:15 – 9:30 am	**BREAK**
9:30 – 10:00 am	**AMFC Challenges – MEA: Yu Seung Kim (LANL)**
10:00 – 10:20 am	**AMFC Challenges – System/Other Issues (Water/Carbonate): Miles Page (Elbit Energy)**
10:20 – 12:00	**BREAKOUT SESSION**
	Session 1: Research Challenges/R&D Needs
	AEM – Leader: **Michael Hickner, ORNL (Estrella Main Room)**
	MEA/System – Leader: **Adam Weber, LBNL (Ahwatukee A Room)**
	Catalysts – Leader: **Jacob Spendelow, LANL (Ahwatukee B Room)**
12:00 – 1:20 pm	**LUNCH – ON YOUR OWN**
1:20 – 2:20 pm	**Joint Session – Out Brief from Breakout Session 1**
2:20 – 2:45 pm	**AMFC Status: Dario Dekel (Technion – IIT)**
2:45 – 3:00 pm	**BREAK**
3:00 – 4:10 pm	**BREAKOUT SESSION**
	Session 2: Status, Protocols, Milestones
	AEM – Leader: **Michael Hickner, ORNL (Estrella Main Room)**
	MEA/System – Leader: **Adam Weber, LBNL (Ahwatukee A Room)**
	Catalysts – Leader: **Jacob Spendelow, LANL (Ahwatukee B Room)**
4:10 – 5:00 pm	**Joint Session – Out Brief from Breakout Session 2**
5:00 pm	**Concluding Remarks: David Peterson (DOE)**

Workshop Main Session Presentations

The Workshop opened with a series of invited talks which provided the basis for the later discussions during the breakout sessions. Presentations were chosen for the breakout session topics and focus was placed on issues addressed after 2011 AMFC Workshop, including literature and unpublished results.

Dr. Bryan Pivovar from NREL presented the overview of 2016 AMFC Workshop and summarized the 2011 AMFC Workshop findings. Professor Chulsung Bae from Rensselaer Polytechnic Institute gave a talk on AEM challenges. Professor Bae addressed AEM issues in terms of cationic group and polymer backbone stability, mechanical property of AEMs, low RH hydroxide conductivity and AEM scale-up production. Professor Yushan Yan from the

University of Delaware discussed alkaline electrocatalysis. Professor Yan highlighted the impact of reverse current decay for carbon based ORR catalysts and the low intrinsic activity of HOR catalysts. Dr. Yu Seung Kim from LANL and Mr. Miles Page from Elbit Energy focused on MEA and system issues of AMFC technology, respectively. Dr. Kim talked about the importance of alkaline ionomer dispersion quality, hydrophobicity of ionomer, and the effect of cationic group adsorption on HOR activities. Mr. Page focused on handling CO_2 contamination, water management, and system issues associated with AEM development. Professor Dario Dekel from Technion –IIT summarized the current performance and durability status of AMFCs. Professor Dekel covered the performance of direct liquid fuel and H_2 AMFC using both PGM and non-PGM electrocatalysts. Many key points from these presentations were presented and are discussed further within the following breakout session reports.

These main session presentations can be found here: http://energy.gov/eere/fuelcells/downloads/2016-alkaline-membrane-fuel-cell-workshop.

Breakout Session Organization

There were a few minor differences between the 2016 and 2011 AMFC workshops regarding the breakout groups. For the 2016 AMFC workshop, two AEM breakout groups (stability and transport/conductivity) were combined into a single AEM group, and the MEA and system issues breakout groups were also combined into a single breakout group. The combined AEM breakout group reflects the recent progress on AEM technologies. The combined MEA and system issue breakout group reflects the cross-interest of the two subjects. Each of the 3 breakout groups had approximately 15 to 20 attendees and each had a facilitator to stimulate and guide discussions as well as a scribe to capture the discussions. In the morning breakout session, discussion focused on AMFC research challenges and R&D needs. The AMFC issues raised from each breakout group were prioritized by voting. In the afternoon breakout session, participants discussed the status, protocols, metrics, and milestones for the AMFC technologies. Following each breakout session, a joint session was reconvened in which the facilitator of each breakout group presented the session's findings.

Morning breakout session - AMFC Research Challenges/R&D Needs

1. Anion exchange membranes
2. Catalysts
3. MEA/system

Afternoon breakout session - AMFC status, protocols, and milestones

1. Anion exchange membranes
2. Catalysts
3. MEA/system

The following sections provide summaries from each breakout group for the morning and afternoon breakout sessions.

Morning Session: AMFC Research Challenges/R&D Needs

Breakout Group 1: Anion Exchange Membranes

There has been much progress in the synthesis, characterization, and analysis of polymer-based AEMs since the 2011 AMFC workshop. A number of groups have elaborated a range of strategies towards advanced polymeric hydroxide conducting membranes by varying the chemical structures of the polymer backbone, the tether, and the cationic functional group. Devices from a number of groups routinely reach 300-500 mW/cm^2 under fuel cell conditions, which is a step change from data reported 3-5 years ago. This change in performance has been due, in part, to better understanding of polymeric hydroxide conductors. In many cases the membrane performance characteristics, material stability, and device output have been disclosed to the community and there is a picture emerging on potential important directions to advance the field. However, there are still many unknowns in the engineering of high performance materials and devices and while some promising approaches have been identified, consensus on the key directions for materials development and techniques to identify baseline materials are still being sought. Additionally, consistent, validated device performance based on advances in materials is lagging the device insights established for PEMFC systems. This lag is largely due to a lack of investment in AEMFCs and focused materials synthesis and correlated device studies. The lag between material development and implementation and evaluation in AMFC devices is attributed to several factors that include: 1) groups with expertise in polymer synthesis and characterization have generated materials but do not necessarily have the means to construct MEAs or test fuel cells, 2) difficulty in making AMFC MEAs – mainly ascribed to the need of an AEM binder and a dimensionally stable membrane, and 3) lack of testing protocols for evaluating AMFC performance and stability across the field. With promising AEM chemistries emerging, the next step in AMFC development requires implementation of materials into devices and characterizing material stability under operational conditions. Up to now, device testing beyond initial demonstrations of feasibility has been a sparsely addressed area.

The discussions in the membrane breakout session revolved around the major topics of:

- Stability – hydroxide and oxidative stability
    - Chemical stability of polymer backbones and cations
    - Mechanical stability of thin membranes
    - *Ex situ* versus in-device stability
    - Degradation mechanisms under a range of stressors
- Conductivity – in hydroxide and other anion forms
    - Effects of CO_2 and mitigation strategies
    - Conductivity at high temperature and reduced relative humidity
- Standard Metrics, Materials, and Databases
    - Standard, off the shelf membrane as a baseline
    - Standardized characterization measurements
    - Database of current structures and properties
    - How to track progress at membrane/catalyst layer/device scales

- Ionomer Development
    - Polymer/catalyst interactions
    - Acceptable solvents for ionomer solutions/dispersions
    - Catalyst layer/membrane interfaces
    - Different metrics needed for membranes versus ionomers
- Other
    - Manufacturing (cost and availability)
    - Alternative membrane designs (new concepts in chemistry and membrane engineering, novel materials beyond polymers and organic cations, non-aqueous cells)
    - Fundamental science on mechanisms of conductivity, durability, and CO_2 effects (rejecting CO_2 or CO_2 phobic materials)

Breakout Group 2: Catalysts

Substantial progress in catalyst development and improved understanding of the limitations of current catalysts since the 2011 AMFC workshop has resulted in a clearer picture of the current state of AMFC electrocatalysis and the critical R&D needs.

PGM-free ORR Catalysts

Slow electrode kinetics on the AMFC cathode represent the single largest source of overpotential in state-of-the-art AMFCs. Therefore, development of improved ORR catalysts remains a critical need. The wider range of catalytically active materials that are stable at ORR-relevant potentials in the alkaline environment provides a larger set of materials to choose from compared with PEMFCs, with some relatively low-cost materials such as silver and other transition metals being viable candidates for the ORR in alkaline electrolytes. Furthermore, mechanistic differences between the ORR in alkaline and acidic media tend to make PGM-free catalysts perform better in alkaline media. DOE projects that have developed PGM-free catalysts for intended applications in PEMFCs have in some cases found that the same catalysts perform better in alkaline electrolytes, and in a few cases even outperform Pt.

Several classes of PGM-free ORR catalysts for AMFCs are under development, including metal-nitrogen-carbon (MNC) catalysts similar to those being developed for PEMFCs, but also including catalysts based on non-PGM transition metals (such as silver) and metal oxides (such as MnO_2). Related to MNC catalysts, some work has also been done on metal-free catalysts based on carbon and nitrogen, which could have advantages in terms of reduced peroxide production due to the lack of a metal site that could catalyze the Fenton reaction. Within the context of transition metal catalysts, silver has already been studied extensively for alkaline ORR in oxygen depolarized cathodes for chlor-alkali production, as well as for alkaline fuel cells. Silver may itself be a viable candidate catalyst for the AMFC cathode, but adequate performance and durability in state-of-the-art AMFCs has yet to be demonstrated.

Bifunctional oxygen catalysts, which can catalyze the ORR as well as the oxygen evolution reaction (OER), are of interest for reversible AMFCs (as well as alkaline electrolyzers). These reversible systems could have applications in energy storage and grid support, but the need for both electrodes to operate bifunctionally and the added materials challenges of operating throughout a wider voltage regime makes the technical challenges even more difficult than for conventional AMFCs.

PGM-based ORR Catalysts

The possibility of eliminating PGMs from the fuel cell cathode is arguably the strongest motivating factor that has driven interest in AMFC development. Therefore, efforts on the ORR should be limited to PGM-free catalysts.

PGM-free HOR Catalysts

While AMFC anode activation overpotentials are much lower than cathode activation overpotentials, the anode nevertheless represents an easier opportunity and greater need for performance and durability improvements, due to the lower technical maturity of anode catalysis vs. cathode catalysis. Some catalysts for AMFC cathodes have already been studied extensively due to their similarity to PEMFC catalysts (i.e. MNC catalysts), while others have been studied for chlor-alkali applications. In contrast, AMFC HOR catalysts have received scant attention to date, and could potentially see major improvements with a relatively small R&D investment. Most reports of PGM-free alkaline HOR catalysts to date have been based on nickel and have dealt with electrochemical performance in rotating disk electrode configuration. Pure nickel exhibits low HOR activity in AMFCs due to passivation by oxide formation, but alloys of nickel have shown significantly improved performance. Further improvements could be realized through the use of alternative materials, such as carbides or phosphides, but due to the relatively immature state of the field it is not yet known whether viable alternatives to PGM-based or nickel-based HOR catalysts exist.

PGM-based HOR Catalysts

The use of PGM-free electrodes is likely a requirement for AMFCs to become a commercially mature technology. Nonetheless, R&D on PGM-based HOR catalysts could be beneficial to improve mechanistic understanding of the HOR, which could lead to improved PGM-free HOR catalysts. Also, given the low maturity of AMFCs in general, the use of a stable, well-characterized PGM-based anode could be appropriate in the near term to enable other cell issues to be addressed without complication from the anode.

Prioritized R&D Needs

Due to the potential for significant improvements, development of improved HOR catalysts should be the highest AMFC R&D priority. The main focus of HOR catalyst R&D should be on development of PGM-free catalysts that are durable and have stable performance exceeding that of PGM-based HOR catalysts. However, limited PGM-based HOR catalyst development could be appropriate to improve mechanistic understanding and serve as a bridge to a PGM-free future.

While major opportunities exist for improvement on the anode, significant R&D on the cathode should be performed as well. Slow cathode kinetics still represent the largest cause of overpotential in AMFCs. Furthermore, for certain classes of catalysts that are applicable in both AMFCs and PEMFCs, knowledge gained from AMFC ORR studies could be leveraged to improve ORR catalysis in PEMFCs. AMFC cathode catalysts have not been investigated as thoroughly as equivalent PEMFC catalysts, so significant opportunities for improvement still exist.

Since viable PGM-free cathode catalysts have already been demonstrated, and since the ability to operate without PGMs is the strongest argument for pursuing AMFC technology, all future AMFC cathode R&D should be focused on PGM-free materials. The most promising materials at this point are MNC catalysts, similar to those under investigation for PEMFCs, but silver should also be investigated. A thorough study of silver nanoparticles or other nanostructures would be helpful in terms of benchmarking, as well as in establishing whether silver could serve in a commercially mature AMFC or whether it is just a stepping stone to better catalysts.

Bifunctional catalysts for both cathode and anode should be investigated, though given the challenges of developing even mono-functional catalysts, the additional requirement to catalyze both forward and reverse reactions with acceptable performance and durability represents a major obstacle.

For all AMFC catalysts, improved characterization techniques would be helpful in improving understanding of chemical and physical properties at the nanoscale. Techniques that could be performed *in situ*, such as TEM on catalyst nanoparticles during operation in a liquid electrolyte, would be especially helpful.

Breakout Group 3: MEA/System Issues

The discussion was broken into 4 subtopics; 1) Ionomers, 2) Catalyst Layers, 3) MEAs, and 4) Systems.

Ionomers

At present, there is a dearth of commercially available ionomers for AMFC fabrication. There is a need in the research community for a high quality commercially available ionomer that has been well characterized for gas permeability, conductivity, and electrocatalyst interactions. While characterization methods should be easily adaptable from those used to probe acidic ionomers little work has been performed thus far for alkaline ionomers. Furthermore, due to the unique water management issues involved in AMFC systems, it is possible that different ionomers need to be developed for each electrode.

Catalyst Layers

Building off of the discussion surrounding ionomers, it was noted that alkaline ionomers are typically not soluble in the commonly used solvents for PEMFC fabrication (e.g. water and propanol). Consequently, little is known about the deposition of catalyst layers from solutions based on the solvents necessary for alkaline ionomer dispersion. There was some discussion about the benefit of simultaneous vs. independent catalyst/ionomer deposition and the possible need for new catalyst layer/MEA fabrication techniques. New deposition methods would be of particular interest, since little is known about either the ionomer catalyst interactions for AMFCs or the desired catalyst layer properties (e.g. ionomer volume fraction, electrode porosity, electrode hydrophilicity/hydrophobicity). The need for advanced *in situ* and in-operando diagnostics was also discussed. In contrast to PEMFC systems, where the anode contributes little overpotential to the net reaction, multiple studies have shown the exchange current density for the HOR/hydrogen evolution reaction (HER) on Pt to be 100 times slower in AEM systems,[3] making the subsequent overpotential non-negligible. Consequently, there is a clear need for *in situ* reference electrode development to better characterize potential losses within AMFC MEAs and catalyst layers. Furthermore, as non-noble metal catalysts become the focus of AMFC catalyst layers and MEAs, the development of a diagnostic to estimate *in situ* electrochemical surface area may be required. Most PGM-free electrocatalysts lack the pronounced hydrogen underpotential deposition and electrochemical CO adsorption and subsequent stripping peak the electrochemical community has come to rely on to estimate ECSA in PEMFCs.

MEAs

There is naturally some overlap between the needs for MEAs and catalyst layers so much of the content in the catalyst layer section above is relevant here as well. Since water is consumed at the cathode and produced at the anode, alkaline systems have an inherently more complex water management challenge as compared to PEMFCs. Thus, examinations of gas diffusion layer properties, such as hydrophilicity and thermal properties, and their effect on MEA performance should be inspected. (Note that some of this information may be leveraged from PEMFC studies.) Studies that can elucidate the phase and/or location of the water in AEM MEAs and systems are of primary interest. In particular, neutron imaging of AMFC MEAs and systems is of significant interest. It was noted that materials development alone may not be enough to reduce the water management induced over potentials evident in AMFCs and that new MEA fabrication techniques and/or multilayer MEAs or electrode layers may be necessary to reduced excessive anode flooding and cathode drying. Modeling of various MEA and electrode structures may be used as an alternative to empirical efforts. Corresponding with the aforementioned need for specialized ionomers in each electrode, the compatibility between polymers present in each electrode and those that comprise the membrane would need to be understood to limit possible electrode delamination and reduce interfacial contact between the layers of the MEA.

Systems

At the systems level, since most testing of alkaline systems has been performed in oxygen to avoid issues with carbonate formation that occur under operation with CO_2 contaminated air, there is a need to examine AMFC systems

[3] Sheng, W. C.; Gasteiger, H. A.; Shao-Horn, Y., Hydrogen Oxidation and Evolution Reaction Kinetics on Platinum: Acid vs Alkaline Electrolytes. *J Electrochem Soc* **2010**, *157* (11), B1529-B1536.

under air operation, perhaps while monitoring local pH changes. Additionally, the effect of CO_2 and subsequent carbonate formation on transport and electrocatalysis would need to be elucidated to provide a clear path for mitigating the associated voltage losses. It would also be helpful to understand how reversible these losses would be and if there are any materials or engineering solutions. Due to the limited lifetime of the current generation of ionomers and membranes, very few durability studies have been performed on the AMFC system level. At present, the research community largely depends on PEMFC "holdover" materials and hardware (e.g. diffusion media and flow fields) to examine AMFCs. Very few empirical or theoretical examinations of the effects of flow field geometries have been done with a focus on improving the water management issues surround AMFCs.

Afternoon Session: Status, Protocols, Milestones

Breakout Group 1: Anion Exchange Membranes

Significant progress has been made in understanding the stability and conductivity of AEMs. The reported conductivities of a number of AEMs are greater than 0.05 S/cm (T ≥ 50°C, fully hydrated), which is in the range needed for reasonable device performance. Stability has generally been reported upon exposure to aqueous base (NaOH or KOH, concentration ≥ 1 M, T ≥ 60°C) with several reports in the past 5 years showing remarkable stability up to and over one month at concentrations greater than 4 M and 80°C. It is likely that extended *ex situ* testing under these harsh conditions at 80°C or higher temperatures will be needed to identify the most outstanding materials. In many cases oxidative stability has not been addressed, but it is unknown the extent to which oxidative stability influences operational device lifetime. These *ex situ* conductivity and stability insights have informed materials development, but the relevance of fully hydrated conductivity measurements and stability in aqueous base to device performance and in-cell durability are still unknown. Additionally, the most outstanding results have not been validated across the community in a number of different labs. Despite these drawbacks, a promising picture of conductivity and stability is emerging – if these results can be translated to reliable device output and durability. There has clearly not been enough work on correlated *ex situ* and *in situ* studies and there is a lack of independent validation of the most promising materials. Additionally, there have not been in-depth device studies to provide *in situ* mechanistic insights into how materials properties and durability impact device output. Developing protocols to probe such mechanistic insights will be useful in screening new materials. The community is still in a "test and see" mode rather than a design mode facilitated by in-depth knowledge of how materials impact device phenomena.

Despite lagging device insights, the biggest need in the membrane community right now revolves around standardization of test protocols. Critical needs in this space include a standard commercially-available AEM for baselining results of various test protocols across research groups and development of standardized membrane and device testing. The lack of a recognized standard material is holding the field back in terms of: 1) developing insights into the effectiveness of characterization methodologies being developed across a number of programs, 2) enabling device testing to determine the relevance of *ex situ* characterization methods to progress in improving device performance, and 3) building consensus towards chemical strategies that will push the field forward. Nafion® is pervasive in the PEM community and serves as a baseline in the community for reporting fundamental and engineering advances. No such material exists in the AEM field. While there are some nascent commercially-available materials, they may not be particularly well suited to fuel cell studies (such as membranes from FUMATECH GmBH) or not widely accessible (Tokuyama – e.g., A201 or A901). A standard AEM with a thickness of 50 microns or less, even if not the best performer, sold through mainstream chemical suppliers in research quantities would help labs and industry benchmark their own work and would give the community a rallying point for real comparisons of membrane and device results.

The chemical and mechanical stability of AEMs was raised as an issue for promoting further device studies and connections between *ex situ* characterization and *in situ* measurements. Many AEMs have high water uptake and suspect durability in devices, despite having attractive conductivity values. Often, if a membrane has moderate intrinsic conductivity, but can be fabricated into thin membranes, the area specific resistance of the cell can be kept low. Membranes with low swelling and good dimensional stability will help promote device and electrode studies. Additionally, a durable membrane will enable optimization studies of cell conditions to allow engineering approaches to improve cell output. This is extremely important as water management requirements for AMFCs are likely different than their PEMFC counterparts. A stable membrane platform that is widely available will also foster improved studies of catalyst layer fabrication for MEAs and ionomer and catalyst development.

Overall, the outlook for membrane development in AMFCs is promising. The field has progressed drastically in the last 3-5 years and the known challenges are being surmounted with novel chemical structures and rational insights into improving materials performance. Mechanical durability of thin membranes is an important next step. There must be some standardization across the community for tracking the true progress in materials development and more device studies are needed. Ionomer development that is tailored to a specific catalyst or membrane is lacking. Part of this deficiency is the poor availability of materials, their processability into low boiling point, acceptable solvents (e.g., short-chain alcohol or alcohol-water mixtures), and the lack of a standard membrane as a platform to build upon. Themes in membrane development are emerging and some concentrated work on translating gains in materials development to device insights will continue to push the field forward. As a standard membrane comes to the fore, issues of ionomer development and ideal conditions in the device can continue to be refined. Without a stable, thin and widely accessible membrane to build upon, the field will be held back.

Breakout Group 2: Catalysts

Standardized test protocols and defined performance and durability targets for AMFC catalysts are needed to clarify the technical needs that novel catalysts are expected to meet for commercial applications, advance catalyst development, and enable comparison of results between different labs. The DOE could play a role in advancing the state of AMFC catalyst development and testing by specifying technical targets, publishing appropriate testing protocols, and ensuring that projects adhere to the specified protocols whenever feasible.

Protocols for AMFC catalyst testing should be provided for both MEA and RDE testing. Since demonstration of catalysts in operating fuel cells is the ultimate goal, a greater emphasis should be placed on MEA testing, and major milestones should be based on MEA testing. Nevertheless, RDE testing will also play a critical role in development and screening of AMFC catalysts. While RDE testing has already been widely used for testing of PEMFC catalysts, its use is even more critical for AMFC catalysts due to the greater difficulty in preparing AMFC MEAs and performing accurate MEA testing. Therefore, a reasonable framework for development and testing of AMFC catalysts would be to perform all initial testing of novel catalysts in the RDE environment, and only perform MEA testing on the most promising catalysts that have already been screened and optimized by RDE.

MEA Testing of AMFC Catalysts

MEA testing of AMFC catalysts is inherently more challenging than equivalent testing of PEMFC catalysts. Unlike PEMFCs, AMFCs do not by default contain a good internal reference electrode (RE). Whereas the hydrogen electrode of a PEMFC operating on pure H_2 can be used as a pseudo reversible hydrogen electrode (since HOR overpotentials are only a few mV), the much slower HOR kinetics in the AMFC environment precludes the use of the hydrogen electrode as an accurate RE. Therefore, for accurate measurement of electrode potentials, incorporation of an additional RE is required. A variety of techniques are available in the literature for incorporation of REs into PEMFCs, and some of these techniques could be adapted to AMFCs. While specifying a particular method of RE incorporation would overly constrain researchers, any AMFC MEA catalyst testing protocols published by DOE would benefit from some form of accurate and reliable RE.

An additional challenge in MEA testing of AMFC catalysts lies in the fabrication of MEAs that include relevant materials and are engineered to provide performance indicative of the true activity of the catalysts. At present, few commercial sources of AMFC membranes and ionomers exist, and not all researchers have access to the same materials due to the proprietary nature of the materials and restrictive agreements sometimes enforced by suppliers. The DOE program could help address this challenge by negotiating with AMFC membrane and ionomer suppliers, whether commercial or lab-based, to obtain state-of-the-art materials that could be used throughout the program.

Given the difficulties described above, MEA testing of AMFC catalysts will necessarily be performed to a lesser extent than with equivalent PEMFC catalysts, and some labs working on AMFC catalysts may not have adequate resources or capabilities to perform MEA testing in house. Partnering between labs that are more RDE-focused and those that have MEA capabilities could help address this challenge. In this scenario, future AMFC catalyst projects would perform most screening and optimization using the RDE technique, but the most promising catalysts would be analyzed at a partner lab selected based on MEA capabilities, where they would be incorporated into high-performance MEAs and tested, preferably using an accurate RE.

Catalyst Performance Protocols and Targets (MEA)

The existing DOE protocol and targets for PEMFC cathode catalyst performance can be adapted to AMFCs with only minor modifications. An appropriate protocol for AMFC cathode catalysts would be to perform a hold at 0.9 V vs. RHE as specified for PEMFC catalysts, but at only 60°C instead of 80°C to avoid excessive degradation of membrane or ionomer. A recommended protocol would be similar to the following:

> *Catalyst ORR activity should be measured at 150 kPa_{abs} backpressure at 0.9 V vs. RHE iR-corrected on H_2/O_2, 100% RH, 60°C, anode stoichiometry 2; cathode stoichiometry 9.5. A minimum hold time of 15 min is recommended, with the mass activity calculated based on the average current during the last 1 min. Multiple points should be measured at low current, and the 0.9 V iR-free potential should be determined based on these measurements. Measured ORR current may be corrected for H^2 crossover. Based on the protocol published by Gasteiger et al.*[4]

The target for this test should be 0.044 A/cm^2 @ 0.9 mV vs. RHE IR-free, equivalent to the PEMFC ORR PGM-free catalyst target. It would be premature at this point to specify a catalyst loading to use for the test, since appropriate loadings would vary markedly for different types of catalysts (e.g. metals, metal-carbon-nitrogen, oxide, etc.). Not specifying a loading carries the inherent risk that researchers may use inappropriately high loadings, which would make the catalyst activity appear better than it actually is, at the expense of high current density performance. This issue can be addressed in the same way that it has been addressed for PGM-free catalysts in PEMFCs: namely, by requiring that the same loading be used in testing of ORR performance at 0.9 V and also in testing of high current density performance.

For anode testing, a similar potential hold test should be used as for the cathode, but at 0.05 V vs. RHE in 1.5 bar H_2, with exchange current density reported as well. Also, since the cathode is not directly involved in the test, the use of air instead of O_2 on the cathode would be acceptable, and a lower stoichiometry (e.g. 2.0) could be used, though O_2 could still be used if preferred. The required level of anode catalyst activity may vary between applications and has yet to be adequately specified by developers and end users. Therefore, an appropriate AMFC anode catalyst performance target is yet to be determined.

Catalyst Durability Protocols and Targets (MEA)

Development of a durability testing protocol for AMFC cathode catalysts should be based on the equivalent tests for PEMFCs, with some changes to accommodate the specific challenges and requirements of the alkaline environment. The DOE recently specified a new accelerated stress test (AST) for cathode catalysts based on a potential stepping between 0.6 and 0.95 V, which replaces the previous triangle wave AST performed between 0.6 and 1.0 V. Both protocols were developed based on a mixture of application-specific operational requirements and material-specific degradation modes for Pt-based catalysts. The range between 0.6 and 0.95 or 1.0 V vs. RHE is an appropriate range for durability testing because it closely matches the expected range of potentials that a PEMFC cathode would experience during typical operation, with potentials around 0.6 V representing a maximum power case and 0.95-1.0 V representing a system idle case. Furthermore, Pt-based catalysts have a high degree of surface oxidation at 0.95-1.0 V, but are mostly in a reduced state at 0.6 V. The action of repeatedly oxidizing and reducing the surface has been shown to accelerate Pt dissolution, with the square wave providing a substantially stronger acceleration than the triangle wave.

For AMFCs, the cathode is expected to operate in a similar potential range as for PEMFCs, so the range from 0.6 to 0.95 or 1.0 V is an appropriate test window. However, the effect of the potential waveform is not yet well

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[4] Gasteiger, H. A.; Kocha, S. S.; Sompalli, B.; Wagner, F. T., Activity benchmarks and requirements for Pt, Pt-alloy, and non-Pt oxygen reduction catalysts for PEMFCs. *Appl Catal B-Environ* **2005**, *56* (1-2), 9-35.

understood for the different types of cathode catalyst materials under consideration for AMFCs. For now, it would be appropriate to select a protocol similar to the PEMFC protocol since there is no basis for making specific changes, but as understanding of relevant degradation modes of AMFC cathode catalysts improves, some modifications to the protocol may be required to adequately capture these modes. The only change to make at this point is in the temperature, where 60°C should be used instead of 80°C to minimize membrane and ionomer degradation. Therefore, an appropriate AMFC cathode catalyst durability testing protocol would be similar to the following:

> *Cathode catalyst durability should be measured using a square wave cycle. The cycle involves steps between 0.6 V (3 s) and 0.95 V (3 s) vs. RHE with rise time of ~0.5 s or less. The protocol should be performed on a single cell with area 25-50 cm^2. Cell temperature should be 60°C, and anode/cathode feeds should be atmospheric pressure H_2/N_2 at 200 sccm/75 sccm for a 50 cm^2 cell.*

Two of the targets from the equivalent PEMFC AST, of 30,000 cycles with <40% catalytic activity loss and < 30 mV loss at cathode potential of 0.8 V vs. RHE, can also be applied to AMFC catalysts, though the cathode potential must be measured vs. RHE, which is not the same as the anode potential for an AMFC. However, the 40% ECSA loss target does not apply since it is specific to Pt-based catalysts.

For PEMFCs, an additional AST has been specified to test catalyst support corrosion using a triangle sweep from 1.0-1.5 V. Corrosion of the cathode support in a PEMFC is most likely to occur during an unmitigated startup or shutdown of the fuel cell, in which passage of a H_2/air front occurs on the anode. During passage of such a front in a PEMFC, the rapid ORR kinetics of the Pt-based anode would keep the local anode potential at high levels in parts of the anode under O_2, forcing the adjacent parts of the cathode to potentials of 1.5 V or even higher. A key advantage of AMFCs is that they can use PGM-free anodes, which can be selected to have very low ORR activity. By preventing the ORR from occurring on the anode, cathode support corrosion can largely be avoided. Therefore, a support corrosion AST is not needed for AMFCs.

For the anode, no equivalent durability testing protocol has been specified for PEMFCs. Furthermore, due to the relative immaturity of AMFC anode technology, relevant degradation modes and accelerating factors are largely unknown. As an initial protocol, a simple survivability test would be appropriate. In this test, the anode potential would be scanned up to a specified target value under 100% RH H_2 at 5 mV/s. To pass the test, the anode catalyst should survive this scan with no significant change in HOR activity. An appropriate initial target would be 0.3 V vs. RHE, but a long term target of at least 1.0 V vs. RHE should be specified.

Protocols: MEA vs. RDE

The protocols discussed above are all specified for MEA testing, but essentially the same protocols can also be applied *ex situ* using the RDE technique. RDE testing should be performed in 0.1 M KOH at room temperature and ambient pressure. The use of dilute electrolyte is recommended to reduce the impact of contaminants, while KOH is suggested since it is a widely available electrolyte that can readily be obtained in high purity form and has already been used extensively in electrocatalytic testing. Alternatively, an electrolyte that is chemically more similar to an AMFC ionomer could be used, such as tetramethylammonium hydroxide. However, given the uncertainty in the chemical nature of the ionomers that will ultimately be used in AMFCs, it is more appropriate to use a simpler (perhaps cleaner) electrolyte such as KOH for initial testing.

Use of alkaline-stable materials (e.g. PTFE) and reference electrodes (e.g. Hg/HgO) is required, though glass cells could be used at ambient temperature for short periods of time and with fresh electrolyte. Alkaline electrolyte solutions should not be exposed to glass for extended periods, since contaminants from leaching and dissolution of glass could impact catalyst testing. For RDE testing, a rotation rate of 900 RPM is suggested to avoid removal of catalyst from RDE tip during rotation. Alternatively, 1600 RPM could be selected, which would better match the recently developed DOE RDE protocol but would be more susceptible to catalyst detachment.

Status

Due to the lack of extensive testing performed to date, available status numbers corresponding to the proposed targets are scarce. For ORR testing in RDE, the best known beginning of life (BOL) kinetic current density at 0.90 V is 8 mA/cm^2 for an iron and nitrogen doped carbon nanotube/carbon nanoparticle catalyst, though notably, the activity increased to 15 mA/cm2 after 5,000 cycles from 0.6-1.0 V at 50 mV/s.[5] Therefore, the durability is at minimum 5,000 cycles. The activity numbers are sensitive to catalyst loading, but an appropriate specification for the catalyst loading to use in the targets has yet to be determined.

For HOR testing in RDE, the best known BOL kinetic current density at 0.05 V is 2.3 mA/cm^2 for a catalyst consisting of nickel nanoparticles supported on nitrogen-doped carbon nanotubes.[6] Durability results were not presented, but the known issue of surface oxidation on nickel catalysts at elevated potentials suggests that stability at potentials above 0.1 may be insufficient.

The status numbers reported above represent results from RDE testing. There are no known reports of equivalent testing of single electrode performance in an MEA at this time.

Breakout Group 3: MEA/System Issue

The main feedback from the breakout group was that at the present time, no consensus existed on AMFC break-in, testing protocols, or applied diagnostics. Additionally, the attendees noted that because of the lack of material and protocol standardization it was critical that the research community at large report all conditions under which they have obtained their performance or diagnostic data. The following data/diagnostics were suggested as considerations when determining a recommended testing protocol; O^2 gain, H^2 gain, ECSA loss (if we know how to measure it), HFR and the use of an internal Reference electrode. While no formal consensus currently exists, the workshop participants agreed on a need for a standardization of 1) materials and diagnostics when testing AEMs (e.g. catalysts, diffusion media), 2) membranes and diagnostics when examining electrocatalysts (this one is much more difficult due to the lack of commercially available AEM membranes), 3) cell break-in/ MEA conditioning protocols (especially for new developers – a basic voltage hold until stable performance was obtained at 0.6V was suggested), 4) performance testing (catalyst loading and type, temperature, pressure, voltage/current hold time, gas type (Air/Oxygen/CO_2 free Air), relative humidity and reactant stoichiometry - constant current polarization curves were suggested in order to compare data at constant water consumption/production), 5) accelerate stress tests, and 6) methods for the determination of ECSA. With regards to the last topic, since the AMFC work is supposed to be targeting low or PGM-free performance, and the assessment of ECSA is limited on most of PGM-free materials, it was suggested that the milestones be written in terms of either a volumetric target or a Pt comparable cost target. Other than that, the existing AMFC milestones (listed below) in FCTO's Multi-Year Research, Development, and Demonstration Plan appeared to be appropriate for the current status of AMFC technology.

- **Q4, 2017:** Demonstrate alkaline membrane fuel cell peak power performance > 600 mW/cm^2 on H_2/O_2 (maximum pressure of 1.5 atm_a) in MEA with a total loading of ≤ 0.125 mg_{PGM}/cm^2 .
- **Q2, 2019:** Demonstrate alkaline membrane fuel cell initial performance of 0.6 V at 600 mA/cm^2 on H_2/air (maximum pressure of 1.5 atm_a) in MEA a total loading of < 0.1 mg_{PGM}/cm^2 , and less than 10% voltage degradation over 2,000 hour hold test at 600 mA/cm^2 at T>60°C. Cell may be reconditioned during test to remove recoverable performance losses.
- **Q2, 2020:** Develop non-PGM catalysts demonstrating alkaline membrane fuel cell peak power performance > 600 mW/cm^2 under hydrogen/air (maximum pressure of 1.5 atm_a) in PGM-free MEA .

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[5] Chung, H. T.; Won, J. H.; Zelenay, P., Active and stable carbon nanotube/nanoparticle composite electrocatalyst for oxygen reduction. *Nat Commun* **2013**, *4*.

[6] Zhuang, Z. B.; Giles, S. A.; Zheng, J.; Jenness, G. R.; Caratzoulas, S.; Vlachos, D. G.; Yan, Y. S., Nickel supported on nitrogen-doped carbon nanotubes as hydrogen oxidation reaction catalyst in alkaline electrolyte. *Nat Commun* **2016**, *7*.

Conclusion

There have been substantial advances in alkaline membrane fuel cell technology between the 2011 and 2016 workshops. A doubling of power density to 1 W/cm^2 in H_2/O_2 has occurred. Also, alkaline stable AEMs through cationic group and polymer backbone stabilization have now been demonstrated. This advance is particularly noteworthy since, historically, there have been concerns whether durable operation of membranes under realistic operation would ever be achievable. Despite advances, significant, further technological improvements are still needed for the technology to be commercially competitive. A major factor driving interest in AMFCs is the potential for fully eliminating PGM content from the electrodes. Improved PGM-free HOR and ORR catalytic activity has been demonstrated; however, much of this work has been at the RDE-level and performance in MEAs still needs significant improvement. Also, while promising membrane chemistries are emerging, implementation into MEAs with characterization of stability and performance under realistic fuel cell operating conditions is still needed.

MEA optimization for AMFCs is still in its infancy. There is a disconnection between catalyst and membrane development/characterization and success in obtaining similar, expected performance in an MEA. The AMFC chemistry and operating environment are substantially different from the PEMFC environment; however, PEM-specific MEA fabrication techniques and components are commonly used as only limited work has been performed to optimize these for AMFCs. Also, ionomers which are specific to the different operating environments of the anode and cathode need development. Water management is more complex than in PEMFCs; however, only limited modeling and other studies are available specific to AMFCs. Finally, CO_2 tolerance and mitigation remains a challenge.

The advances that have taken place since the last workshop have been significant enough that discussions on setting standardized protocols and metrics are warranted to assist in taking AMFC development to the next level. A critical need for the research community is a standard membrane that is widely available to baseline results of test protocols across research groups and to serve as a baseline for reporting fundamental and engineering advances. Tokuyama's membrane has served this role in the past to some extent; however, it is becoming increasingly difficult to obtain this material and it is unclear how much longer it will be available. There is no clear substitute for it.

The existing performance and durability protocols and targets for PEMFCs can be used as a solid starting point for developing ones that are specific to AMFCs. For catalysts, it will be necessary to develop protocols and targets for the HOR in addition to the ORR due to the more sluggish kinetics for HOR in a basic environment. These slower kinetics make it important to develop a separate, accurate reference electrode for evaluating electrode performance in AMFC MEAs as, unlike with PEMFCs, the hydrogen electrode cannot be used as a pseudo reversible hydrogen electrode in the AMFC environment and both the anode and cathode will have non-negligible activation overpotentials associated with them. Until standardization and protocols are more mature, it is critical that the research community provide as much detail as possible on all conditions under which performance and diagnostic data have been obtained.

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The list of references supports the text of the report but is by no means intended to be exhaustive.

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Appendix

List of registrants for 2016 Alkaline Membrane Fuel Cell Workshop.

AMFC WORKSHOP REGISTRANTS - PHOENIX, AZ, APRIL 1, 2016

Last Name	First Name	Affiliation
Albertus	Paul	Advanced Research Projects Agency - Energy
Arges	Chris	Louisiana State University
Bae	Chulsung	Rensselaer Polytechnic Institute
Britton	Benjamin	Simon Fraser University
Creager	Stephen	Clemson University
Dai	Liming	Case Western Reserve University
Dekel	Dario	Technion - Israel Institute of Technology
Elabd	Yossef	Texas A&M University
Fan	Chinbay	Gas Technology Institute
Farrell	James	University of Arizona
Gao	Yong	Southern Illinois University
Garland	Nancy	U.S. Department of Energy
Gervasio	Francis	University of Arizona
Grew	Kyle	U.S. Army Research Laboratory
Halevi	Barr	Pajarito Powder
Herring	Andrew	Colorado School of Mines (CSM)
Hibbs	Michael	Sandia National Laboratories
Hickner	Michael	Penn State University
Ho	Donna Lee	U.S. Department of Energy
Hu	Hongxing	Amsen Technologies, LLC
Isomura	Takenori	Tokuyama Corporation
Kim	Tae-Hyun	Incheon National University
Kim	Yu Seung	Los Alamos National Laboratory (LANL)
Kopasz	John	Argonne National Laboratory
Lambert	Timothy	Sandia National Laboratories

Last Name	First Name	Affiliation
Li	Lin-Feng	Bettergy Corp.
Lundgren	Cynthia	Army Research Lab (ARL)
Maurya	Sandipkumar	Los Alamos National Laboratory (LANL)
Mukerjee	Sanjeev	Northeastern University
Nelson	Jeffrey	Sandia National Laboratories
Neyerlin	Kenneth	National Renewable Energy Laboratory (NREL)
Owczarczyk	Zbyslaw	National Renewable Energy Laboratory (NREL)
Page	Miles	Elbit Energy
Papageorgopoulos	Dimitrios	U.S. Department of Energy
Park	Andrew	National Renewable Energy Laboratory (NREL)
Peterson	David	U.S. Department of Energy
Pintauro	Peter	Vanderbilt University
Pivovar	Bryan	National Renewable Energy Laboratory (NREL)
Rodriguez-Calero	Gabriel	Ecolectro, Inc.
Serov	Alexey	University of New Mexico
Shao	Yuyan	Pacific Northwest National Lab
Spendelow	Jacob	Los Alamos National Laboratory (LANL)
Varcoe	John	University of Surrey (UK)
Weber	Adam	Lawrence Berkeley National Lab (LBNL)
Wu	Gang	University at Buffalo, SUNY
Xu	Hui	Giner, Inc.
Yan	Yushan	University of Delaware
Yandrasits	Mike	3M - Energy Components Program
Yang	Hong	University of Illinois at Urbana-Champaign
Yu	Hongmei	Dalian Institute of Chemical Physics
Zelenay	Piotr	Los Alamos National Laboratory (LANL)
Zenyuk	Iryna	Tufts University
Zawodzinski	Tom	UT-Knoxville/ORNL

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DOE/Publication Number • April 2016