TRANSIENT AND STEADY STATE CURRENT DENSITY DISTRIBUTION MEASUREMENTS IN A POLYMER ELECTROLYTE FUEL CELL

M. M. Mench\textsuperscript{1,2}, C. Y. Wang\textsuperscript{1}
Electrochemical Engine Center, and
Department of Mechanical and Nuclear Engineering
The Pennsylvania State University
University Park, PA 16802

and

Masatoshi Ishikawa
CD-adapco Japan Ltd.
Yokohama, Japan

ABSTRACT

There has been much recent interest and development in methods to accurately measure the current distribution in an operating polymer electrolyte fuel cell. This paper presents results from a novel technique that uses a segmented flow field with standard, non-altered membrane electrode assemblies and gas diffusion layers. Multiple current measurements are taken simultaneously with a multi-channel potentiostat, providing high-precision temporal and spatial distribution data. Current distribution data are shown over a wide variety of test conditions with significant variations across the fuel cell. In addition, the effects of cathode flooding and pore filling with time are investigated, and it is shown that the time scale for liquid accumulation in gas diffusion layer pores is much greater than that of any electrochemical process or gas-phase species transport. In order to facilitate state-of-the-art polymer electrolyte fuel cell (PEFC) model validation, an idealized single-pass serpentine flow field was used, and the exact geometry is presented.

INTRODUCTION

\textsuperscript{1} Electrochemical Society Active Member
\textsuperscript{2} Author to whom correspondence should be addressed: e-mail mmm124@psu.edu; Phone: (814) 865-0060; Fax: (814) 863-4848
The hydrogen polymer electrolyte fuel cell (PEFC) has tremendous promise as a future power system due to its low pollution, high efficiency, and stealth. Many studies, too numerous to completely list, have examined various aspects of PEFC performance as a function of operating conditions (1-10). Gottesfeld wrote an excellent review of PEFC components and operation, and the reader is referred to it for additional information on PEFC fundamentals (11). In addition to experimental characterization, much research has been focused on first-principles based modeling of the PEFC system (12-23). However, advances in modeling of the PEFC have thus far outpaced the ability to experimentally verify the predicted performance. In particular, scant experimental data are presently available regarding current density and species distributions. As indicated by Wang (24), it is this type of detailed validation that will permit an ultimate understanding of the physicochemical phenomena in PEFCs as well as development of useful computer-aided tools for design and development.

Determination of the current distribution is critical to understanding key phenomena including water management, CO poisoning, and reactant distribution effects. Weiser et al. described a novel technique utilizing a magnetic loop array embedded in the current collector plate to measure two-dimensional current distribution of a hydrogen PEFC (25). The authors showed that cell compression can drastically affect the local current density. Stumper et al. demonstrated three methods for the determination of current distribution of a hydrogen PEFC (26). First, the partial membrane electrode assembly (MEA) technique involves either masking different areas or partially catalyzing segments of the MEA to determine local current distribution. Secondly, the subcell technique involves electrically isolating individual locations of catalyzed anode and opposing cathode from the main cell in order to measure the performance of the desired location. In the passive current mapping technique, an array of shunt resistors are located normal to an unmodified MEA surface, between the flowfield and a buss plate. Voltage sensors passively determine the potential drop across each resistor and, through Ohm's law, current distribution though the flow plate is determined. Cleghorn et al. implemented another technique to utilize a printed circuit board for current distribution measurements using a segmented current collector, anode catalyst, and anode gas diffusion layer (27).

While each of the described methods for determination of current distribution has advantages, it is desirable to utilize a non-segmented MEA in order to preserve true fuel cell operation characteristics and avoid highly individualized specialty membranes. MEA segmentation is also undesirable because it does not simulate performance in a true fuel cell environment.

In addition to use of conventional MEAs and good spatial resolution, the ability to determine transient effects from sudden changes in operating conditions is desired. The non-segmented passive current mapping technique approach of Stumper et al. allows transient measurement and has good spatial resolution, but requires a vast array of embedded and highly precise shunt resistors (26). The magnetic loop method of Weiser et al. also allows transient measurements with unaltered MEAs and flowfields, but is more difficult to implement than the other methods and cannot be applied to stacks (25). Recently, Mench and Wang have demonstrated an improved technique for accurate current distribution measurements on direct methanol fuel cells that is applied to...
hydrogen PEFCs in this work (28). Independently, Noponen et al. (29) and Brett et al., (30) have developed and demonstrated a similar technique as well.

EXPERIMENTAL

Instrumented Cell Design

In order to construct an electrically segregated flowfield, forty-eight, 0.81 mm thick stainless steel current collecting ribs were gold-plated and embedded into an insulating polycarbonate slab with 0.89 mm wide gaps, as described by Finckh (31). The ribs were arranged to produce a single-pass serpentine flowfield. Each rib was affixed to a gold-plated wire that extended through the polycarbonate for current collection. Figure 1 is a schematic diagram detailing the relevant dimensions of the fuel cell flow field. The diameter of the current-conducting wires that interface the gold-plated ribs with the data acquisition source was 0.81 mm. The dimension of the flow channel was chosen to be 2.16 mm wide, 3.18 mm in depth and had an average pass length of approximately 71 mm. With a total of 22 serpentine passes, the total path length was 1577 mm.

Teflon® gaskets were press fit over the protruding gold-plated rib landings to form a flush surface with the polycarbonate slab. Two additional sealing gaskets surrounded both gas diffusion layers (GDL) of the MEA to compensate for GDL thickness. Gold plating and use of an optimized compression torque for the cell of 35 in-lbs minimized electrical contact resistance between rib landings and the GDL. Pressure indicating film (Pressurex® by Sensor Products, Inc.) was used to determine the in-situ pressure distribution of the landings onto the MEA, as a function of compression torque. The assembly was checked to ensure a homogeneous pressure distribution from all landings onto the gas diffusion layer, thus ensuring an even contact resistance distribution between the gold-plated landings and GDL. The entire fuel cell assembly was leak proof tested to 0.3 MPa under water.

A schematic of the test and control system is shown in Fig. 2. Ultra-high purity (>99.999%) hydrogen and standard compressed air were supplied from compressed gas-cylinders. A steam-injection humidifier system (Lynntech Inc.) was used to provide desired humidification to anode and cathode flows through control of the precise amount of water vapor added to the gas streams. Between humidifier and fuel cell, electric heating tapes were wrapped around the pipes to eliminate any condensation. Directly upstream of the inlet to the fuel cell, a gas sampling port was installed to directly measure the input humidity to the fuel cell by an Agilent 3000 MicroGC with PlotU column. This provided accurate measurement and control of the humidification entering the cell, as described by Mench et al. (32).

The fuel cell system, including all lines leading to the fuel cell, were heated to the desired temperature, which was maintained with several Omega Engineering, Inc. model 8500 PID controllers. The cell and input lines maintained a steady temperature after suitable time to eliminate thermal transients. This start-up time was determined to be about 90 minutes by system check-out tests using thermocouples affixed to the GDL under non-flowing conditions.
To control and measure accurate current/voltage polarization curves, the fuel cell was connected to a multi-channel potentiostat/galvanostat (Arbin Instruments). The active current density mapping method used in this paper is fundamentally similar, and essentially a modification of the passive current density mapping technique of Stumper et al. (26). However, an electrically segmented flowfield/current collector replaces the separate array of shunt resistors normal to the MEA. The segmented flowfield is in direct contact with the unaltered GDL on the anode and cathode. This technique eliminates the challenge to reduce current spreading due to high in-plane conductivity of the flowfield plates. Instead, a gold-plated, electrically segmented current collector is used, and repeatable current density data can be obtained. In this active current density mapping technique, the potentiostat system maintains a constant voltage and the current sensors measure amperage emerging from each segmented current collector location, without the need for shunt resistors.

It is important to note that this technique measures the true current density distribution of an operating cell, as it flows from the gas diffusion layer, not as it emerges from the catalyst layer. Although current spreading through the gas diffusion layer occurs, this is similar to the real operating system. Artificially segmenting the MEA disrupts the true current distribution reaching the current collectors and is therefore inappropriate for these measurements or model validation.

Calculation of Active Area Segments

To calculate the current density of a set of current collecting landings, the active area directly under the landings, and half of the adjacent gas channels, were taken. The reported measurement location along the cathode flow path is the center of this total area in the flow path. Area under current collection landings is counted toward current density calculations. It is important to note that the current density data are represented at a discrete distance along the flow path, when it actually is gathered from a distributed region. In order to represent this area as a discrete location, the distances have been weighted in order to take into account adjacent channels and more accurately represent the mean location of current collection. This discretization gave very consistent results.

The membrane electrode assemblies (MEA) used for testing consisted of Nafion™ 112 as the polymeric membrane, sandwiched between the catalyst and ELAT™ carbon cloth diffusion layers. All MEAs used had a catalyst loading of 0.5 mg Pt/cm² on both anode and cathode. Other general operating conditions are given in Table 1. It is important to note that due to the particular nature of the distributed current measurements, variation of the flow to achieve a constant stoichiometry is not possible. Therefore, the stoichiometry is set at a given current density and the flow rate was held constant for individual tests.

RESULTS AND DISCUSSION

Homogeneous Distribution

It is expected that at relatively high mass flow rates with full humidification and low pressures, a nearly uniform distribution of current would result. An experiment was...
designed to observe this condition. The distributed polarization curve for this experiment is shown in Fig. 3. There is some indication of flooding, as can be seen from the characteristic 'comma' shaped (26,28) local polarization curves for the channels closest to the cathode exit location. The two channels near the end of the cathode path, at \( x/L = 0.891 \) and 0.964 (corresponding to 89 and 96% along the length of the single serpentine cathode path), roll over into comma shapes at low cell voltage, while the overall bulk cell output increases. The current density versus fractional location along the cathode flow path at several cell voltages is given in Fig. 4. From Fig. 4, a nearly homogeneous current distribution can be seen, except at very low cell voltage (0.4V) corresponding to high current output and near depletion of hydrogen in the anode.

The Effect of Cathode Stoichiometry

In PEFCs, the performance is extremely sensitive to cathode stoichiometry, due to relatively sluggish oxygen reduction kinetics and mass transport. In order to isolate the effects of stoichiometry from accumulated flooding, a rapid-scan polarization curve was taken to prevent sufficient time for flooding to occur and affect measured performance. The results of the rapid-scan are therefore appropriate for model validation in the absence of two-phase effects. For the rapid-scan, the applied voltage was varied at a rate of 5 to 10 mV/s in increments of 50 mV from OCV. This provided very reproducible data with generally higher performance than steady state values, in which thirty minutes to an hour elapse between voltage variations at low cell voltage to allow time for flooding accumulation to reach steady state.

A high anode stoichiometry of 2.5 at 0.75 A/cm² was used for this series of tests, so that no appreciable mass transport limitation on the anode exists. Cell humidification was 100% at 90°C and 80°C on the anode and cathode, respectively. Cell temperature was maintained at 80°C and cell inlet pressure was maintained at 1.5 atm. Cathode stoichiometry was varied from 1.5 to 3.0 at 0.75 A/cm². It is important to recall that the stoichiometry is set at a given current density. That is, flow rate was held constant during these tests.

Low cathode stoichiometry of 1.5 @ 0.75 A/cm². Figures 5 and 6 are plots of the distributed polarization curves and current density versus fractional location along the cathode flow path for the case of low cathode stoichiometry. From Fig. 5, it can be seen that severe mass transport limitations exist at low cell voltage. The comma shaped curves resemble the characteristic shape of flooded distributions from Mench and Wang (28). As discussed, the polarization curves were taken with a high enough voltage scan rate to avoid significant flooding accumulation. Therefore, the performance limitation can be attributed to mass transport losses at the cathode, and the comma shaped curve is a characteristic feature of a fuel cell operating in a mass-limiting condition, whether from flooding or low stoichiometry. The distribution of performance along the cathode channel shown in Fig. 6 is in agreement with this conclusion, as performance decreases monotonically with distance along the cathode channel for high current densities. For low values of current density, a nearly homogeneous distribution is observed, corresponding to the abundant supply of oxygen for these low power conditions.
As discussed, the data on Figs. 5 and 6 were taken with a rapid-scan technique. Figures 7 and 8 are a distributed polarization curve and a performance variation versus location plot, deduced from data taken allowing adequate time to achieve steady state. That is, these figures show the steady state values for the performance at identical conditions of Fig. 5, except about an hour elapsed between each cell voltage increment below 0.6 V. It can be seen that the steady state curves all suffer reduced performance compared to the corresponding results taken with the rapid-scan, especially for lower cell voltage corresponding to larger current density (and hence cathodic water production). This reduced performance is attributable to the pore blockage effect of liquid accumulation in the GDL resulting from cathode flooding at high current densities.

**Increased cathode stoichiometry of 2.0 @ 0.75 A/cm².** As the cathode stoichiometry and flowrate of air is increased, it is expected that the severe performance limitations observed in Fig. 5 would be somewhat diminished. This is observed, as can be seen in Figs. 9-12, which are polarization and current density distribution plots for a cathode stoichiometry of 2.0 at 0.75 A/cm² for both rapid-scan and steady-state measurements. Although the performance is improved compared to the case of 1.5 cathode stoichiometry, significant mass transport limitations still exist at high current densities. In comparison of Fig. 5 to Fig. 9, the bulk fuel cell performance is increased, and the location and severity of the decrease in output has been pushed farther downstream the cathode flow channel. The point at which the distributed polarization curve rolls over into a mass-limited comma shape has been pushed from ~40% downstream to ~60% downstream. Once again, the steady state curves all suffer reduced performance compared to the corresponding results taken with the rapid-scan, especially at lower cell voltages corresponding to larger mean current density.

**Increased cathode stoichiometry of 2.5 @ 0.75 A/cm².** Figures 13 and 14 are a rapid-scan distributed polarization plot and a current density versus location plot for a cathode stoichiometry of 2.5 @ 0.75 A/cm². This condition is expected to exhibit decreased mass transport limitation on the cathode, compared to lower cathode stoichiometry. From Fig. 13 it is seen that the distributed polarization curves are more uniform, indicating a more homogeneous overall distribution compared to lower stoichiometry conditions. Also, the bulk fuel cell performance is increased, and the location and severity of the decrease in output due to mass transport has been pushed farther downstream the cathode flow channel. The location at which the distributed polarization curve rolls over into a mass-limited comma shape has been pushed from ~60% for the $\xi_c=2.0$ case to ~80% downstream for this case. Even at this high cathode stoichiometry, there is still some portion of the fuel cell that is not performing to full potential due to cathode reactant deficiency.

**Increased cathode stoichiometry of 3.0 @ 0.75 A/cm².** Figures 15 and 16 show a rapid-scan distributed polarization curve and a current density versus location curve for a cathode stoichiometry of 3.0 @ 0.75 A/cm². From Fig. 15 it is seen that the distributed polarization curves are much closer together, indicating a more homogeneous overall distribution compared to lower stoichiometry cases. There does not appear to be any location within the cathode that suffers severe performance loss due to oxidizer mass limitation at any current density tested. Each increase in cathode stoichiometry of 0.5 at 0.75 A/cm² pushed the location of performance rollover downstream 20%, beginning...
with a roll-over location of \( \sim -40\% \) at \( \xi = 1.5 \). This is not a universal result, and is a function of cell design and total performance at a given voltage.

**Discussion on flooding and definition of steady state**

It is appropriate to discuss the definition of steady-state used. This is because in a vast majority of PEFC publications, the definition is ambiguous. Much of the published work reports polarization data based on rapid-scan polarization curves, similar to those presented in this work where noted. While these data are highly useful for separation of the effects of flooding from stoichiometry mass transport limitations or humidity variation, it does not necessarily represent the true steady-state that would be achieved if the given cell condition was held indefinitely.

Where flooding occurs, the location of flooding will show a gradual decrease in performance corresponding to the gradual accumulation of liquid water. This process can take minutes to hours, depending on the initial condition of the MEA. Figure 17 shows flooding degradation for a sudden cell voltage perturbation from 0.55 to 0.50 V. Immediately following perturbation, the current density generally adjusts to a high value corresponding to the increased overpotential to drive the electrochemical reactions. The performance then degrades to a steady-state value. More interestingly, it is seen that the local current densities near the cathode inlet (i.e. \( x/L = 0.036 \) and \( x/L=0.109 \)) jump to high values and remain there due to the absence of pore flooding. In the middle section of the fuel cell (i.e. \( x/L = 0.370 \) and \( x/L=0.543 \)), the local current densities undergo substantial decay after the initial jump in performance due to liquid accumulation in pores and more moist air coming from the upstream. Near the cathode exit, the local current densities do not respond to the initial voltage perturbation much, due to depleted reactant, and then experience a similar decay due to flooding.

It has been observed that, depending on the initial state, there can be multiple steady states, depending on the history of operation. This is a result of the relatively long time scales of GDL pore filling and recovery compared to electrochemical and gas transport processes. As an example, once flooding has been allowed to fully saturate the gas diffusion layer, a sudden decrease in cell voltage will not induce much change in output. However, the same voltage perturbation occurring from a non-flooded initial condition will induce a sharp initial change, flowed by a gradual flooding process to nearly the same final “fully flooded” state. Therefore, transient flooding data are highly dependent on initial conditions. A thorough treatment of these transient flooding effects is beyond the scope of this paper.

**CONCLUSIONS**

A robust current mapping technique based on segmented flow field and a multi-channel potentiostat, previously implemented on a direct methanol fuel cell, was successfully used with \( \text{H}_2 \) PEFCs. Along with other diagnostic techniques such as water distribution mapping (32), this current mapping technique provides an important tool to understand water management and reactant distribution in PEFCs. While simple to
implement and convenient to measure, this technique has been demonstrated to provide spatial and temporal current distribution data with high-resolution. Specifically:

- Benchmark current and species distribution data have been obtained using a specially designed single-pass serpentine fuel cell. These data are particularly valuable for computational fuel cell dynamics (CFCD) model validation.
- Data were presented that systematically show the effect of cathode flow rate. The location within the cathode flow channel of mass-limited performance was shown to be a function of cathode stoichiometry.
- The time scale of cathode flooding was shown to be quite slow relative to other transport and electrochemical phenomena. Transient current density results demonstrate a slow flooding process that does not reach a steady state for several minutes of operation. Recovery is similarly slow.

ACKNOWLEDGEMENTS

Financial support of CD-Adapco Japan is gratefully acknowledged. Additionally, Chao-Yang Wang acknowledges partial support of DOE and Conoco under cooperative agreement No. DEFC26-01NT41098. The authors would also like to acknowledge the contributions of Oliver Finckh and Qunlong Dong in the design of the fuel cell and calibration of the test stand components.
REFERENCES

1. D. M. Bernardi, *J. Electrochem. Soc.*, 137, 3344 (1990).
2. A. Parthasarathy, S. Srinivasan, A. J. Appleby, and C. Martin, *J. Electrochem. Soc.*, 139, 2856 (1992).
3. A. Parthasarathy, S. Srinivasan, and A. J. Appleby, and C. Martin, *J. Electrochem. Soc.*, 139, 2530 (1992).
4. Y. W. Rho, O. A. Velev, S. Srinivasan, and Y. T. Kho, *J. Electrochem. Soc.*, 141, 3838 (1994).
5. J. C. Amphlett, R. M. Baumert, R. F. Mann, B. A. Peppley, P. R. Roberge, and T. J. Harris, *J. Electrochem. Soc.*, 142, 9 (1995).
6. R. Mosdale, and S. Srinivasan, *Electrochim. Acta*, 40, 413 (1995).
7. H. -F. Oetjen, V. M. Schmidt, U. Stimming, and F. Trila, *J. Electrochem. Soc.*, 143, 3838 (1996).
8. F. N. Büchi, and D. Srinivasan, *J. Electrochem. Soc.*, 144, 2767 (1997).
9. F. A. Uribe, S. Gottesfeld, and T. A. Zawodzinski, *J. Electrochem. Soc.*, 149, A293 (2002).
10. E. A. Ticianelli, C. R. Derouin, and S. Srinivasan, *J. Electroanal. Chem.*, 251, 275, (1988).
11. S. Gottesfeld, in Advances in Electrochemical Science and Engineering, C. Tobias, Editor, Vol. 5, Wiley and Sons, New York (1997).
12. T. E. Springer, T. A. Zawodzinski, and S. Gottesfeld, *J. Electrochem. Soc.*, 138, 2334 (1991).
13. D. M. Bernardi and M. W. Verbrugge, *AIChE J.*, 37, 1151 (1991).
14. D. M. Bernardi, and M. W. Verbrugge, *J. Electrochem. Soc.*, 139, 2477 (1992).
15. T. E. Springer, M. S. Wilson, and S. Gottesfeld, *J. Electrochem. Soc.*, 140, 3513 (1993).
16. T. F. Fuller and J. Newman, *J. Electrochem. Soc.*, 140, 1218 (1993).
17. T. V. Nguyen and R. E. White, *J. Electrochem. Soc.*, 140, 2178 (1993).
18. C.Y. Wang and W.B. Gu, *J. Electrochem. Soc.*, 145, (1998).
19. V. Gurau, H. Liu, and S. Kakac, *AIChE J.*, 44, 2410 (1998).
20. J. S. Yi and T. V. Nguyen, *J. Electrochem. Soc.*, 146, 38 (1999).
21. S. Um, C. Y. Wang and K. S. Chen, *J. Electrochem. Soc.*, 147, 4485 (2000).
22. Z. H. Wang, C. Y. Wang and K. S. Chen, *J. Power Sources*, 94, 40 (2001).
23. C. Y. Wang, S. Um, H. Meng, U. Pasaogullari, and Y. Wang, “Computational fuel cell dynamics (CFCD) models,” in 2002 Fuel Cell Seminar, Nov. (2002).
24. C. Y. Wang, “Two-phase flow and transport in PEM fuel cells,” in *Handbook of Fuel Cells*, John Wiley and Sons, (2002).
25. C. Wieser, A. Helmbold, and E. Gülzow, *J. of Appl. Electrochem.*, 30, 803 (2000).
26. J. Stumper, S. Campell, D. Wilkinson, M. Johnson, and M. Davis, *Electrochim. Acta*, 43, 3773 (1998).
27. S. Cleghorn, C. Derouin, M. Wilson, and S. Gottesfeld, *J. of Appl. Electrochem.*, 28, 663 (1998).

228 Electrochemical Society Proceedings Volume 2002-31
REFERENCES

28. M. Mench, and C.Y. Wang, *J. Electrochem. Soc.*, 150, A79 (2003).
29. M. Noponen, T. Mennola, M. Mikkola, T. Hottinen, and P. Lund, *J. Power Sources*, 106, 304 (2002).
30. D. Brett, S. Atkins, N. Brandon, V. Vesovic, N. Vasileiadis, and A. Kucernak, *Electrochem. Comm.* 3, 628 (2001).
31. O. H. Finckh, “Dilution effects and current distribution on hydrogen proton exchange membrane fuel cells,” MS Thesis, *The Pennsylvania State University*, May 2002.
32. M. M. Mench, Q. L. Dong and C. Y. Wang, “*In Situ* water distribution measurements in an operating polymer electrolyte fuel cell”, *Proceedings of the 202nd meeting of the Electrochemical Society: Proton Conducting Membrane Fuel Cells III*, J.W. Van Zee, M. Murthy, T.F. Fuller and S. Gottesfeld, Eds. (2003).
Figure 1. Schematic diagram of the 50 cm$^2$ instrumented test cell showing relevant dimensions.
National instrument FieldPoint I/O-system
(connected to PC with RS-232 running LabView)

Input of 7 Thermocouples, 2 Pressure Gauges, and Cell Voltage
Controlled Power-Output for Heating Tape and Cartridge Heater

Figure 2. Schematic of the experimental test stand and control system.
Figure 3. Steady-state distributed polarization curve for a low pressure, fully humidified, high flow rate condition. Cell temperature: 80°C, anode inlet humidity: 100% RH @ 90°C, cathode inlet humidity: 100% RH @ 80°C, $\xi_a$: 1.0 @ 0.7 A/cm$^2$, $\xi_c$: 2.5 @ 0.7 A/cm$^2$, anode and cathode exit pressure: 1 atm.
Figure 4. Performance versus fractional location along the cathode path for a fully humidified, high flow rate conditions. Cell temperature: 80°C, anode inlet humidity: 100% RH @ 90°C, cathode inlet humidity: 100% RH @ 80°C, $\xi_c$: 1.0 @ 0.7 A/cm$^2$, $\xi_c$: 2.5 @ 0.7 A/cm$^2$, anode and cathode exit pressure: 1 atm.
Figure 5. Distributed rapid-scan polarization curve for low cathode stoichiometry of 1.5 @ 0.75 A/cm$^2$, showing mass transport limited performance. Cell temperature: 80°C, anode inlet humidity: 100% RH @ 90°C, cathode inlet humidity: 100% RH @ 80°C, $\xi_e$: 2.5 @ 0.75 A/cm$^2$, anode and cathode exit pressure: 1.5 atm.
Figure 6. Rapid-scan performance versus fractional location for low cathode stoichiometry of 1.5 @ 0.75 A/cm², showing mass transport limited performance at high current density. Cell temperature: 80°C, anode inlet humidity: 100% RH @ 90°C, cathode inlet humidity: 100% RH @ 80°C, $\xi$: 2.5 @ 0.75 A/cm², anode and cathode exit pressure: 1.5 atm.
Figure 7. Distributed steady state polarization curve for low cathode stoichiometry of 1.5 @ 0.75 A/cm², showing mass transport limited performance. Cell temperature: 80°C, anode inlet humidity: 100% RH @ 90°C, cathode inlet humidity: 100% RH @ 80°C, ξ: 2.5 @ 0.75 A/cm², anode and cathode exit pressure: 1.5 atm.
Figure 8. Steady-state performance versus fractional location for low cathode stoichiometry of 1.5 @ 0.75 A/cm$^2$, showing mass transport limited performance at high current density. Cell temperature: 80°C, anode inlet humidity: 100% RH @ 90°C, cathode inlet humidity: 100% RH @ 80°C, $\xi$: 2.5 @ 0.75 A/cm$^2$, anode and cathode exit pressure: 1.5 atm.
Figure 9. Rapid-scan distributed polarization curve at a cathode stoichiometry of 2.0 @ 0.75 A/cm², showing reduced mass transport limited performance. Cell temperature: 80°C, anode inlet humidity: 100% RH @ 90°C, cathode inlet humidity: 100% RH @ 80°C, ξ₃: 2.5 @ 0.75 A/cm², anode and cathode exit pressure: 1.5 atm.
Figure 10. Rapid-scan performance versus fractional location at a cathode stoichiometry of 2.0 @ 0.75 A/cm$^2$, showing mass transport limited performance at high current density. Cell temperature: 80°C, anode inlet humidity: 100% RH @ 90°C, cathode inlet humidity: 100% RH @ 80°C, $\xi_a$: 2.5 @ 0.75 A/cm$^2$, anode and cathode exit pressure: 1.5 atm.
Figure 11. Distributed steady state polarization curve at a cathode stoichiometry of 2.0 @ 0.75 A/cm², showing mass transport limited performance. Cell temperature: 80°C, anode inlet humidity: 100% RH @ 90°C, cathode inlet humidity: 100% RH @ 80°C, ξa*: 2.5 @ 0.75 A/cm², anode and cathode exit pressure: 1.5 atm.
Figure 12. Steady-state performance versus fractional location at a cathode stoichiometry of 2.0 @ 0.75 A/cm², showing mass transport limited performance at high current density. Cell temperature: 80°C, anode inlet humidity: 100% RH @ 90°C, cathode inlet humidity: 100% RH @ 80°C, ξA: 2.5 @ 0.75 A/cm², anode and cathode exit pressure: 1.5 atm.
Figure 13. Distributed rapid-scan polarization curve for a cathode stoichiometry of 2.5 @ 0.75 A/cm². Cell temperature: 80°C, anode inlet humidity: 100% RH @ 90°C, cathode inlet humidity: 100% RH @ 80°C, Cₐ: 2.5 @ 0.75 A/cm², anode and cathode exit pressure: 1.5 atm.
Figure 14. Rapid-scan performance versus fractional location for a cathode stoichiometry of 2.5 @ 0.75 A/cm². Cell temperature: 80°C, anode inlet humidity: 100% RH @ 90°C, cathode inlet humidity: 100% RH @ 80°C, icks: 2.5 @ 0.75 A/cm², anode and cathode exit pressure: 1.5 atm.
Figure 15. Distributed rapid-scan polarization curve for a cathode stoichiometry of 3.0 @ 0.75 A/cm². Cell temperature: 80°C, anode inlet humidity: 100% RH @ 90°C, cathode inlet humidity: 100% RH @ 80°C, $\xi_a$: 2.5 @ 0.75 A/cm², anode and cathode exit pressure: 1.5 atm.
Figure 16. Rapid-scan performance versus fractional location for a cathode stoichiometry of 3.0 @ 0.75 A/cm². Cell temperature: 80°C, anode inlet humidity: 100% RH @ 90°C, cathode inlet humidity: 100% RH @ 80°C, $\xi_a$: 2.5 @ 0.75 A/cm², anode and cathode exit pressure: 1.5 atm.
Figure 17. Distributed performance data after perturbation from $V_{cell} = 0.55$ V to $V_{cell} = 0.5$ V. Slow flooding accumulation is seen to degrade performance over nearly 20 minutes. Transient performance: Cell temperature: 80°C, anode inlet humidity: 100% RH @ 90°C, cathode inlet humidity: 100% RH @ 80°C, $\xi_a$: 1.5 @ 1.0 A/cm², $\xi_c$: 2.5 @ 1.0 A/cm², anode and cathode exit pressure: 2 atm.
Table 1. Baseline operating conditions.

| Parameter                          | Value                                         | Units  |
|------------------------------------|-----------------------------------------------|--------|
| Electrolyte                        | Nafion 112                                    | NA     |
| Gas diffusion layer                | ELAT® (De Nora North America) anode and cathode| NA     |
| Catalyst loading (carbon supported)| 0.5                                           | mg/cm² |
| Cell temperature                   | 80                                            | °C     |
| Anode inlet temperature            | 90                                            | °C     |
| Cathode inlet temperature          | 80                                            | °C     |
| Anode and cathode pressure         | 0.1-0.2                                       | MPa    |
| Anode humidification               | 100% at 90°C                                  | NA     |
| Cathode humidification             | 100% at 80°C                                  | NA     |
| Anode gas                          | Ultra high purity H₂ (>99.999 %)               | NA     |
| Cathode gas                        | Commercial air (79% N₂, 21% O₂)                | NA     |