

V.C.1 Advanced Cathode Catalysts and Supports for PEM Fuel Cells

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Subcontractors and Federally Funded Research and Development Centers:

- Dalhousie University, Halifax, Nova Scotia, Canada (Prof. Jeff Dahn, Dr. David Stevens)
- Jet Propulsion Laboratory (JPL), Pasadena, CA (Dr. S. R. Narayanan, Dr. Charles Hays)
- Argonne National Laboratory (ANL), Argonne, IL (Dr. V. Stamenkovic, Dr. Dennis van der Vliet, Dr. Nenad Markovic)

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Projected End Date: March 31, 2011

Objectives

The objectives of this project are development of a durable, low-cost (both precious group metal [PGM] content and manufacturability), high-performance cathode electrode (catalyst and support), which is fully integrated into a proton exchange membrane electrode assembly (MEA) characterized by:

- total Pt group metal loading per MEA of ≤ 0.25 mg/cm²,
- short-stack specific power density of ≤ 0.3 g/kW at rated power,
- durability sufficient to operate at $>80^\circ\text{C}$ for 2,000 hours, $\leq 80^\circ\text{C}$ for 5,000 hours, with cycling for transportation applications,
- high prospects for 40,000 hours durability under operating conditions for stationary applications, and
- high-volume manufacturability.

Technical Barriers

This project addresses the following technical barriers from the Fuel Cells section of the Hydrogen, Fuel Cells and Infrastructure Technologies (HFCIT) Program Multi-Year Research, Development and Demonstration Plan (MYRDDP):

- (A) Durability
- (B) Cost
- (C) Performance
- (D) Water Transport Within the Stack

Technical Targets

This project is focused on improving the performance and durability of the 3M nanostructured thin film catalyst (NSTF) roll-good fabricated electrocatalysts and MEAs. Table 1 compares the NSTF current 2nd quarter, Calendar Year 2008 status with the electrocatalyst targets for 2010/2015 from Table 3.4.12 of the DOE HFCIT MYRDDP. Additional rows were added to summarize recent accelerated durability test results.

Accomplishments

- Improved baseline NSTF-MEA roll-good performance containing 0.25 mg-Pt/cm² total loading to obtain 0.61 V at 1.5 A/cm² under 150 kPa H₂/air inlet pressure at 80°C, 67% relative humidity (RH).
- Demonstrated 0% loss of electrochemical surface area (ECSA) (vs. 40% target), 2 mV gain at 0.8 A/cm² (vs. <30 mV loss target), 19 mV gain at 1.5 A/cm², $\sim -13\%$ loss of mass activity (vs. $<60\%$ loss target) after DOE accelerated test: 30,000 cell voltage (CV) cycles, 0.7-0.9 V step, 30-second hold, 80/80/80°C (cell temperature/anode dew point/cathode dew point).
- Demonstrated 16% loss of ECSA (vs. $<40\%$ loss target), 27 mV gain at 1.5 A/cm² (vs. <30 mV loss target), $\sim 0\%$ loss of mass activity (vs. $<60\%$ loss target) after DOE accelerated test: 200-hour hold at 1.2 V and 95°C, H₂/N₂, 150 kPa, 80% RH.
- Demonstrated 800-hour hold at open circuit voltage (OCV) at 90°C under 250/200 kPa H₂/air, 30% RH, versus 200-hour target.
- Demonstrated over 7,300 hours of operation under a load cycling protocol at 80/64/64°C (cell temperature/anode dew point/cathode dew point), exceeding the DOE 5,000 hour target and doubling the 3,500 hours previously demonstrated.

TABLE 1. Progress Towards Meeting Technical Targets for Electrocatalysts and MEAs for Transportation Applications

| Characteristic | Units | 2010/2015 Targets | 3M Status - Feb. 2008 (mfg'd roll-good) | Project Goal |
|---|--|----------------------------|--|------------------------------|
| PGM Total Content | g/kW rated in stack | 0.3/0.2 | 22 cell short stack: 0.47 50 cm² cell: 0.27g/kW @ 0.61 V, 150 kPa inlet | ≤0.25 stack |
| PGM Total Loading | mg PGM/cm ² electrode area | 0.3/0.2 | 0.25 (A/C = 0.1/0.15) | ≤0.25 |
| Durability with Load Cycling At operating T ≤80°C At operating T >80°C | Hours | 5,000/5,000 2,000/5,000 | >7,300 hours 50 cm ² cell, accelerated load cycling at 80/64/64°C | >5,000 |
| Mass Activity (150 kPa H ₂ /O ₂ 80°C, 100% RH) | A/mg-Pt @ 900 mV, 150 kPa O ₂ | 0.44/0.44 | 0.18 – 0.25 (≤0.2 mg/cm ²) | >0.5 |
| Specific Activity (150 kPa H ₂ /O ₂ at 80°C, 100% RH) | μ A/cm ² -Pt @ 900 mV | 720/720 | 2,900 (with 0.2 mg _{Pt} /cm ²) | >5,000 |
| Accel. Test loss, 30,000 cycles, 0.7–0.9 V at 80°C | - mV at 0.8 A/cm ² | < 30mV @ 0.8 | ~0 mV loss at 0.8 A/cm ² | 0 |
| | % ECSA loss | < 40%/40% | ~0% ECSA loss | 0 |
| Accel. Test loss, 200 hrs @ 1.2 V at 95°C | - mV at 1.5 A/cm ² | <30mV/30mV | +25mV gain at 1.5 A/cm² | mV Gain |
| | % ECSA loss | <40%/40% | ~17% loss ECSA | 0% loss |
| Accel. Test loss, ~10,000 cycles 0.6-1.2 V, 20 mV/sec 90°C, 270 kPa, H ₂ /N ₂ | % ECSA loss | Not specified | ~30 % loss of ECSA | <10% loss |

- Demonstrated a modified NSTF anode catalyst (0.1 mg-Pt/cm²) having improved activity for oxygen evolution to provide enhanced resistance to corrosion under “cell-reversal” conditions. Able to support 2 mA/cm² current for 5 hours with no loss in performance.
- Using multi-element compositional spread screening, 64 channel cell analyses, identified five new candidate catalyst materials, having increased surface area and increased high voltage cycling stability compared to pure Pt controls.
- Using rotating disc electrode (RDE) measurements, demonstrated the highest oxygen reduction reaction (ORR) specific activity and half-wave potential values for any catalyst to date: i_{kin} at 0.90 V = 4.3 mA/cm²-Pt (0.48 A/mg-Pt) and $E_{1/2}$ = 0.95 V.
- Demonstrated 52 mV/decade Tafel slope over 2.5 decades using a multi-electrode array of an NSTF binary catalyst with a novel electrochemical cell having a rotating electrolyte to simulate an RDE measurement.
- Identified a pathway to obtain a potential 3x gain in surface area of the NSTF support whisker compatible with existing roll-good manufacturing.
- Developed fuel cell test protocols for evaluating water management of ultra-thin electrodes under steady-state and transient conditions. Evaluated extensive material and process gas diffusion

layer (GDL) factors affecting cool start and high temperature operation.

- Demonstrated short-stack (11 cells, 312 cm²) start-up times of 17 seconds from room temperature with NSTF electrodes by controlled coolant introduction.



Introduction

State-of-the-art proton exchange membrane (PEM) fuel cell electrocatalyst technology utilized in today's prototype fuel cell vehicles is demonstrating significant limitations with respect to general durability and robustness under start-stop cycling, adequate performance with low PGM loadings, and low-cost manufacturability. To a large degree, these deficiencies are traceable to properties of the conventional carbon supported dispersed Pt catalysts in use today. The research and development of this project are focused on overcoming these three most critical barriers for fuel cell MEA automotive deployment by using an alternative catalyst support and deposition method.

Approach

The approach for attaining the above objectives builds on an 11-year DOE/3M funded development of the 3M NSTF catalyst and MEA technology. The NSTF

catalyst fundamentally has higher specific activity for oxygen reduction [1], removes all durability issues with carbon supports while demonstrating much lower losses due to Pt dissolution and membrane chemical attack [2,3,4,5], and has significant high volume all-dry roll-good manufacturing advantages [6].

The scope of work in the first two-year budget period includes high-throughput fabrication and characterization of new multi-element Pt alloys (ternaries and quaternaries) with Dalhousie University and JPL, extensive work at 3M to optimize the NSTF catalyst support films and deposition parameters to obtain increased surface area and catalyst utilization, and fundamental catalyst characterization studies with ANL. Research in the first year has focused heavily on high-throughput sample fabrication and compositional spread evaluation for screening new multi-element thin film materials, extensive testing in 50-cm² single cells using DOE accelerated aging protocols, integrated catalyst-coated membrane (CCM) development of optimized catalyst substrates with reduced Pt loading, development and characterization of NSTF whisker support structures with varying surface areas, and GDL material and process methods optimized specifically for cool-start and water management of the ultra-thin NSTF electrodes.

Results

The technical accomplishments for the first year fall into six areas of research and development. We briefly summarize the main results from each of these areas.

Improved high current density performance with reduced Pt loading was achieved by improving the catalyst/membrane interface and lowering both the cathode and anode loading. At the start of the project, our baseline CCM consisted of the NSTF PtCoMn ternary at a loading of 0.2 mg-Pt/cm² on both the anode and cathode sides of a 3M PEM (~35 microns, 850 equivalent weight, EW). This first year we reduced the size of the microstructure features of the NSTF roll-good substrate, which improved mass transport to the catalyst at high current densities. We also found that by reducing the anode loading to 0.1 mg/cm², and the cathode loading to 0.15 mg/cm², we obtained better water transport through the anode that reduced the high frequency resistance (HFR) and iR-loss at high current densities without kinetic losses. Figure 1 illustrates galvanodynamic polarization curves obtained at varying

inlet pressures for this improved MEA. The result was that for the first time we were able to exceed 0.5 V at 2 A/cm² and 0.61 V at 1.5 A/cm² with 150 kPa H₂/air inlet pressures. This correlates to 0.27 g/kW at 0.61 V, which is in-between the DOE 2010 and 2015 targets.

In the second results area, multiple accelerated durability tests were conducted using both the NSTF baseline MEA from the start of the project, and with the reduced loading MEA discussed in Figure 1. The protocols for the first three tests were DOE-specified.

Test 1 was a 30,000 cycle, 0.7 V (30-second hold) to 0.9 V (30-second hold) step-wise cycling test at 80°C and saturated conditions under H₂/N₂, with periodic interruptions for measuring catalyst surface area, activity and MEA performance. This test evaluates resistance to Pt dissolution. The target value for surface area loss was <40% and for mass activity <60% (measured at 900 mV, 150 kPa saturated H₂/O₂). The NSTF MEA demonstrated 0% loss in ECSA, and a mass activity loss of ~13%. The target performance loss was <30 mV at 0.8 A/cm² and we observed a 2 mV gain. This gain in performance was observed at all current densities and increased with current density and after each new measurement. After 30,000 cycles, the gain in potential at 1.5 A/cm² was 19 mV. The NSTF electrodes appear to be completely stable under this accelerated test.

Test 2 was a 200-hour hold at 1.2 volts and 95°C under 150 kPa H₂/N₂ at 80% RH. After each 24-hour period, the ECSA, activity and performance were remeasured. This test evaluates catalyst support

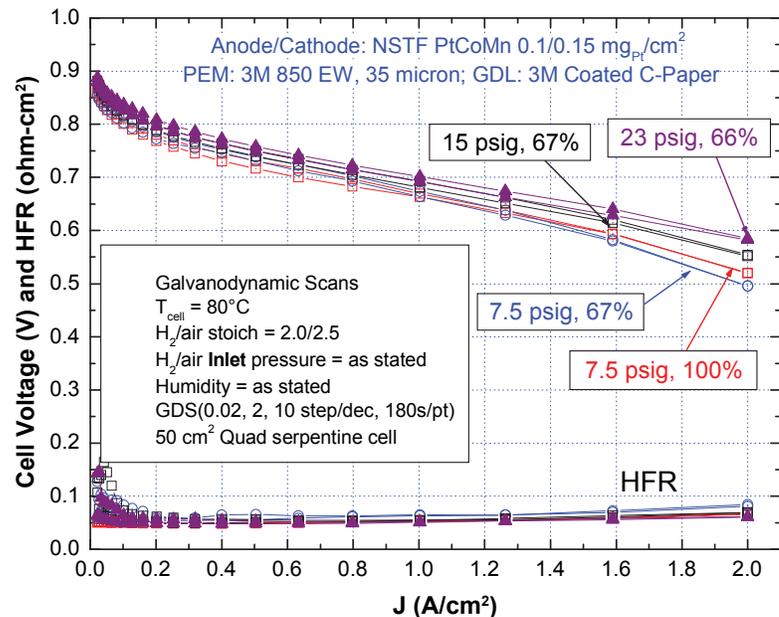


FIGURE 1. Galvanodynamic polarization curves from the improved MEA having reduced Pt loadings. High current density was improved by two factors – reduced anode loading and improved cathode/membrane interface.

corrosion resistance. The loss target for ECSA after the 200 hours was again <40% and the NSTF MEA demonstrated $\sim 16 \pm 1\%$ loss in 2 trials. The mass activity loss target was again <60% and the NSTF MEA demonstrated a 5% loss in one trial but a 15% gain in a second trial. The specific activity was found to increase $28 \pm 7\%$ for the two trials. The performance loss target was <30 mV at 1.5 A/cm^2 after the 200 hours, and a $27 \pm 1 \text{ mV}$ gain was measured for the two trials. The NSTF electrodes exceeded all the targets for this test also.

Test 3 was a 200-hour hold at OCV at 90°C under 250/200 kPa H_2/air at 30% RH. This test evaluates MEA chemical stability. The baseline NSTF MEA used had the NSTF PtCoMn ternary catalyst (0.2 mg-Pt/cm^2) on both anode and cathode sides of a neat (no chemical additives) 3M 850 EW, 35 micron thick PEM. Figure 2 shows the OCV versus time recorded for the MEA. When the target time was exceeded by over a factor of two at ~ 520 hours, the inlet RH was varied to observe the effect. The MEA finally developed a hole after 800 hours. The NSTF MEA exceeded the target for this test also.

Figure 3 shows OCV versus time under an 80°C cell temperature, 64°C dew point, load cycling protocol comparing lifetimes for various MEAs. The two sets of MEAs identified by the inserted boxes as “7 dispersed MEAs” and “4 NSTF MEAs” were measured before the start of the current contract and show that the NSTF electrodes confer a 7x gain in lifetime (defined when OCV falls below 0.8 V) compared to dispersed Pt on carbon electrodes when the same 3M membrane is used without additives for chemical stabilization. (These results were obtained during the prior 3M/DOE contract in which we also showed that the lifetime exceeded 5,000 hours with dispersed electrodes on a 3M PEM containing chemical stabilization.) Under the current project, by using a membrane stabilized dimensionally by incorporating the 3M ionomer into an expanded Teflon matrix (courtesy of W. L. Gore and Associates), followed by acid washing, the same NSTF MEA lifetime is more than doubled to 7,300 hours compared to the four NSTF MEAs without dimensional stabilization. Although done in a single cell, this test result with the lower loading NSTF electrodes exceeds the 5,000-hour lifetime target in Table 1. A second cell with the same type of MEA was put on test 4,000 hours after the first and is performing the same way.

As a final accomplishment in the area of accelerated durability testing,

we demonstrated a simple, high-volume compatible modification to our baseline NSTF PtCoMn catalyst that significantly improved its anode corrosion resistance under fuel starvation conditions. The accelerated test in this case was to force the anode to support a 2 mA/cm^2 oxidation current for five hours under nitrogen. Control experiments were made with the normal NSTF PtCoMn anode as well as with two dispersed Pt/C based MEAs, one having 0.2 mg/cm^2 of Pt and the other 0.4 mg/cm^2 of Pt. The Pt/C controls showed significant ($\sim 80\%$) HFR increases and permanent performance losses after the 5 hours, while the MEA with the normal NSTF PtCoMn

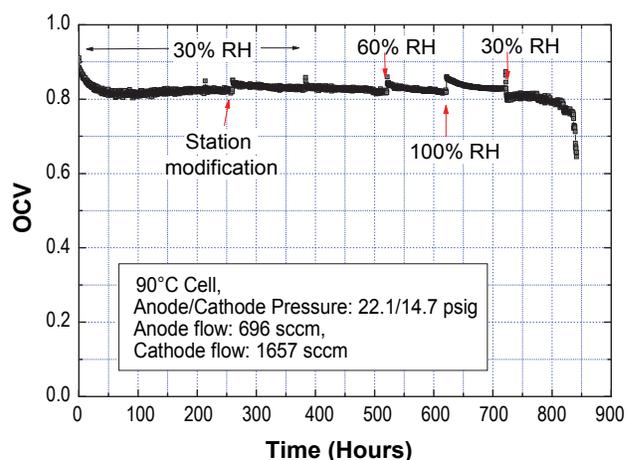


FIGURE 2. Results for the OCV hold test for MEA chemical stability.

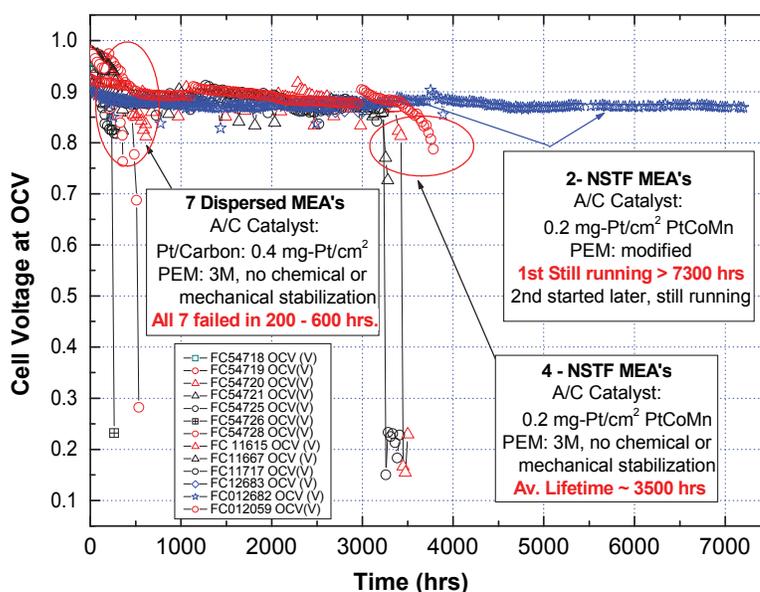


FIGURE 3. Open circuit voltage versus time is shown for various MEAs under an 80°C cell temperature, 64°C dew point, load cycling protocol. Under this project, the NSTF MEA lifetime was at least doubled to over 7,300 hours by adding reinforcement to the otherwise, non-chemically stabilized membrane.

anode (with 0.1 mg-Pt/cm²) showed only ~15% increase in HFR and correspondingly smaller performance loss. In contrast to these controls, the MEA with the modified NSTF PtCoMn anode (still 0.1 mg-Pt/cm²) showed no increase in HFR or performance loss. In commercial fuel cell stacks where individual cell potentials cannot be monitored for reasons of cost, having cell reversal tolerant anode catalysts is important and this is a promising result.

The third area of results includes all the work done with Dalhousie University to develop new catalyst compositions and structures using high-throughput compositional spread screening methods [5]. Samples comprising 64 electrode arrays of thin-film catalysts deposited onto the NSTF whisker supports are prepared at Dalhousie University, converted into MEAs at 3M and evaluated in 64-channel cells at Dalhousie. Over 60 libraries were fabricated and tested, involving 25 different material sets covering five distinct structural configurations. Duplicate samples are characterized ex situ for composition and structure by electron microprobe and X-ray diffraction, and for chemical stability by acid soak resistance [5]. Testing in the 64-channel cell includes measurements of ECSA before and after high voltage CV cycling, and also H₂/air polarization curves. One of the five new material configurations investigated, Pt_{1-x}M_x, (M = single or multi-atoms) showed promise for increasing the surface area of the catalyst and its stability. Eight new catalyst material sets within that new material configuration were found to have higher initial surface area compared to the two Pt control electrode dots embedded in each 64-electrode array. Of these eight, five indicated higher surface areas remaining after 3,000 CV cycles (0.6 to 1.2 V at 20 mV/s under Ar vs. 5% H₂ in Ar) than the pure Pt controls had initially. Figure 4 summarizes the average ECSAs measured for the eight different compositional spread material sets, Pt_{1-x}M_x, in the optimum range of x, before and after the CV cycling. These results indicate several promising new catalyst materials to simultaneously increase surface area (to increase mass activity) and electrochemical stability under high voltage cycling.

This area also includes work with JPL to screen new NSTF alloy catalysts deposited at JPL onto multi-electrode arrays and characterized in a novel

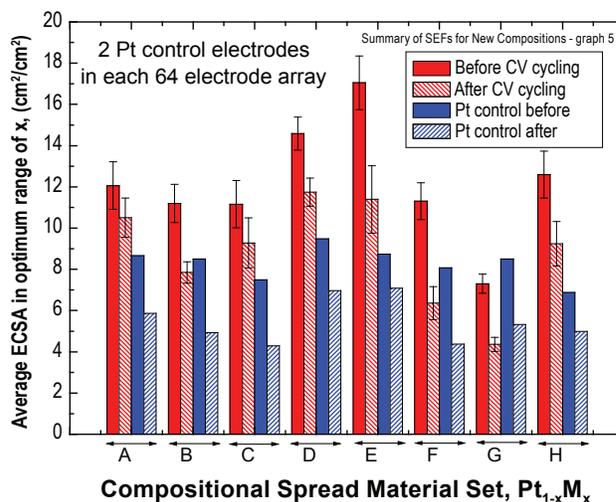


FIGURE 4. Average ECSAs at the optimum composition of eight new catalyst compositions coated onto the NSTF whiskers and evaluated in 64-channel cells with two embedded Pt control electrodes. The ECSAs are compared before and after 30,000 cell voltage cycles between 0.6 and 1.2 V.

JPL electrochemical cell with rotating electrolyte that simulates an RDE measurement. The equipment and techniques for depositing the thin film catalysts onto the NSTF support whiskers were successfully developed and the rotating electrolyte electrochemical cell successfully shown to produce very useful CV plots and remarkable Tafel plots with extremely linear slopes over 2.5 decades of current. The methods for depositing the catalyst and measuring activity are different from and therefore complementary to the Dalhousie approach. The JPL methodology now appears ready to begin screening new compositional arrays using an 18-electrode cell configuration.

The fourth area of results includes the fundamental NSTF catalyst characterization conducted with ANL to better understand the source of the much higher NSTF specific activity and possible methods to further enhance it. Increasing the specific activity is key along with surface area, to increase the mass activity. Table 2 summarizes RDE results measured at ANL for pure NSTF-Pt, two NSTF alloys and a Pt/C control. The

TABLE 2. Summary of RDE Activity Measurements at 60°C done at ANL

| NSTF loading = 65 μgPt cm ⁻² _{disc} | Specific Activity <i>i</i> _{kin} at 0.875 V (mA cm _{Pt} ⁻²) | Specific Activity <i>i</i> _{kin} at 0.90 V (mA cm _{Pt} ⁻²) | Specific Activity <i>i</i> _{kin} at 0.925 V (mA cm _{Pt} ⁻²) | Specific Activity <i>i</i> _{kin} at 0.95 V (mA cm _{Pt} ⁻²) | Mass Activity at 0.9 V (A/mg-Pt) |
|--|---|--|---|--|--|
| Pt - NSTF | 4.0 | 1.9 | 0.75 | 0.28 | 0.14 |
| PtCoMn - NSTF | 6.3 | 3.3 | 1.4 | 0.53 | 0.24 |
| PtNiFe - NSTF | 8.2 | 4.3 | 1.8 | 0.62 | 0.48 |
| 5 nm Pt/C (42 μgPt cm ⁻² _{disc}) | 0.78 | 0.41 | 0.19 | 0.08 | 0.22 |

measurements compare the kinetic specific and mass activities and show that specific activity for ORR is much higher for all the NSTF catalysts than the Pt/C control and that the NSTF PtNiFe specific activity is higher than the NSTF PtCoMn baseline catalyst. Although the NSTF PtNiFe is not new, these results are consistent with our fuel cell measurements and indicate a significant effect of the catalyst composition on activity. The last column shows the RDE derived mass activities and is significant in that the NSTF – PtNiFe value of 0.48 A/mg-Pt exceeds the 2015 DOE target value of 0.44 A/mg-Pt shown in Table 1. It remains to be seen if these same high values can be measured under the fuel cell test protocol of Table 1.

The fifth area of results derive from work focused at 3M on approaches to increase the NSTF support whisker surface area and optimize the thin film catalyst deposition parameters. Neither the sputtering conditions for the Pt alloy deposition nor the whisker support particle characteristics have ever been systematically varied for optimization of surface area or minimization of loading, electrode impedance or mass transport overpotential. In the past year, a systematic study was conducted to produce NSTF whisker support particles with controlled physical characteristics of areal number density, whisker length and diameter. Whiskers were fabricated under 24 different process condition parameter sets using the roll-good manufacturing equipment. Using scanning electron microscope characterization, the number density (number of whiskers per unit area), length and width distributions were determined. From these geometric parameters, it is possible to model the NSTF catalyst as a distribution of right circular cylinders and calculate the geometric surface area of the supports with and without catalyst coating. Excellent agreement was found with typical measured ECSA and the calculated geometric surface area for our standard NSTF catalysts. It was possible then to project how to configure the NSTF support films for increased surface area. The results indicate the potential for up to a three-fold gain in NSTF support surface area with optimized conditions. Fuel cell tests of these various conditions are under test.

Also in this area, the first systematic study of a key catalyst thin film deposition process parameter was studied. The results indicate a potential gain at high current densities and a reduction in start-up time may be achieved using an optimized value of this deposition process parameter.

Finally, the last area of work focused on development of GDL materials and process parameters, and fuel cell test protocols for improved water management with the ultra-thin NSTF type electrodes. Water management properties are fundamentally different for the NSTF electrodes which are 20-30 times thinner than conventional dispersed catalyst electrodes. This includes both operation under cold-wet conditions

and very dry-hot conditions. GDL materials and process development included the type of carbon paper used for the electrode backing, percent and type of fluoropolymer used for wet-proofing, the microporous layer (MPL) coating weight and drying conditions, type and amount of fluoropolymer used in the MPL, different approaches for incorporation of hydrophilic materials into the GDL and so forth. The materials sets were found to definitely affect, both positively and negatively, the cold-start and high-temperature performance, and much more evaluation work remains to be completed. One important result demonstrated experimentally was that performance in a single cell under cold-wet transient conditions does not represent the performance in a stack, where the heat capacity is dramatically different and temperature is controlled by a liquid coolant. It was shown that in a short stack (11 cells) with large area NSTF MEAs (312 cm²), start-up from room temperature was possible in 17 seconds (repeated four times) by controlled introduction of the coolant flow. This is not possible in a single cell.

Conclusions and Future Directions

The project has met or exceeded many of the specified DOE electrocatalyst and MEA performance and durability targets for 2010/2015, while clearly indicating the remaining gaps in mass activity and surface area stability under high voltage cycling. The project has identified multiple materials and process paths to meet or exceed these remaining targets. Future work will be strongly focused on the key remaining target gaps for mass activity, high voltage cycling stability, and water management, while using ≤ 0.25 mg-Pt/cm² total per MEA.

Mass Activity (Specific Activity and ECSA) Gain

- Continue to fabricate and test new catalyst compositions, structures and processes for a specific activity gain of 2x over current NSTF baseline without loss of durability under the most severe accelerated test. Move best candidates to 50 cm² sized electrodes.
- Achieve $\geq 100\%$ gain in catalyst surface area over current NSTF baseline without loss of specific activity or durability under the most severe accelerated test. Complete evaluation of six independent approaches to increase surface area now in progress.

Durability Improvement

- Reduce by at least 50% any losses in surface area, activity or mass transport over-potential under the current most severe accelerated test protocol (fast high voltage [>1 V] cycling). Complete evaluation of two independent approaches now in progress.

Water Management Improvement

- Optimize the GDL materials and process conditions for more effective liquid water transport at low temperatures without compromising high temperature performance under dry conditions. Tailor the GDL for both anode and cathode independently to optimize performance over a wider range of operating conditions.
- Evaluate NSTF with improved membranes for enhanced performance under cold and wet or dry and hotter conditions.

Special Recognitions & Awards/Patents Issued

1. Awarded a 2008 DOE Hydrogen Program R&D Award, at the DOE Hydrogen Program Annual Merit Review, June 9, 2008.

FY 2008 Publications/Presentations

1. Arman Bonakdarpour, Krystal Stevens, George D. Vernstrom, Radoslav Atanasoski, Alison K. Schmoeckel, Mark K. Debe, and Jeff R. Dahn, "Oxygen Reduction Activity of Pt and Pt-Mn-Co Electrocatalysts Sputtered on Nanostructured Thin Film Support," *Electrochimica Acta* (2007) 688.
2. A.J. Steinbach, C.V. Hamilton, Jr. and M.K. Debe, "Impact of Micro-molar Concentrations of Externally-Provided Chloride and Sulfide Contaminants on PEMFC Reversible Stability," *ECS Transactions* 889 (2007), and presented at the 212th ECS meeting, Washington, D.C. Oct. 7-12, 2007.
3. M.K. Debe and A.J. Steinbach, "An Empirical Model For The Flooding Behavior Of Ultra-Thin PEM Fuel Cell Electrodes," *ECS Transactions* 659 (2007), and presented at the 212th ECS meeting, Washington, D.C., Oct. 7-12, 2007.
4. M.K. Debe, "Solving Durability and Performance Issues of PEMFC's by Eliminating Carbon Supports and Highly Dispersed Catalysts," *Fuel Cells Durability and Performance 2007*, Knowledge Foundation's 3rd Annual International Conference, Miami, FL Nov. 15-16, 2007, *invited*.
5. M.K. Debe, "Meeting Durability, Performance and Cost Targets for Automotive Fuel Cells by using Thin Film Catalysts, Ultra-thin Electrodes and Eliminating Carbon Supports," "NRC Institute for Fuel Cell Innovation, Vancouver, BC, Canada, March 17-18, 2008, *invited*.
6. M. K. Debe, "Nanostructured Thin Film Electrocatalysts for PEM Fuel Cells - Fundamental Characteristics and Practical Properties to Meet Automotive Requirements," 213th ECS meeting, Phoenix, AZ, May 18-23, 2008, *invited*.
7. Lajos Gancs, Takeshi Kobayashi, Mark K. Debe, Radoslav Atanasoski, and Andrzej Wieckowski, "Crystallographic Characteristics of Nanostructured Thin Film Fuel Cell Electrocatalysts – A HRTEM Study," *Chemistry of Materials* **2008**, 20, 2444 - 2454.
8. R. Atanasoski, M. Debe, and T. Wood: "High Performance Platinum and Non-precious Metal Catalysts for PEM Fuel Cell Application", Opening key-note presentation at the 7th International Symposium on New Materials and Nano-Materials for Electrochemical Systems, June 24-27, 2008 Montréal, Canada.

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4. Steinbach, A.J.; Noda, K.; Debe, M.K., *ECS Transactions* 3(1) 835 (2006).
5. Bonakdarpour, A.; Lobel, R.; Atanasoski, R.T.; Vernstrom, G.D.; Schmoeckel, A.K.; Debe, M.K.; Dahn, J.R., *Journal of The Electrochemical Society* **153**, A1835 (2006).
6. M. Debe, A. Hester, G. Vernstrom, A. Steinbach, S. Hendricks, A. Schmoeckel, R. Atanasoski, D. McClure and P. Turner, in proceedings of the 50th Annual Technical Conference of the Society of Vacuum Coaters, Louisville, KY, May 1, 2007.