V.A.1 Non-Precious Metal Fuel Cell Cathodes: Catalyst Development and Electrode Structure Design

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Project Start Date: April 1, 2013
Project End Date: March 31, 2016

Overall Objectives

Advance platinum group metal (PGM)-free cathode technology through the development of new materials and implementation of novel electrode concepts to assure:

- High oxygen reduction reaction (ORR) activity viable for automotive systems.
- Practical catalyst durability.
- High ionic/electronic conductivity within the cathode.
- Efficient oxygen transport and effective removal of the water product.

Fiscal Year (FY) 2016 Objectives

- Demonstrate improved ORR activity in fuel cell with advanced PGM-free catalyst.
- Determine corrosion and fluoride emission rates of PGM-free catalysts compared to Pt/C.
- Demonstrate enhancement of ORR activity of Fe-free catalysts.
- Complete electrode optimization study, including first-generation spray-coated membrane electrode assemblies (MEAs).
- Scale up MEA to at least 50 cm^2 with selected PGM-free catalyst.

Technical Barriers

This project addresses the following technical barriers from the Fuel Cells section of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan [1].

(A) Durability (catalysts, electrode layers)

(B) Cost (catalyst, MEAs)

(C) Performance (catalysts, electrodes, MEAs)

Technical Targets

PGM-free fuel cell cathode catalyst research in this project focuses on the DOE technical targets outlined in Table 3.4.7 in Section 3.4.4 (Technical Challenges) of the Multi-Year Research, Development, and Demonstration Plan [1]. The ultimate technical targets of the project are as follows.

- Catalyst activity in H_2/O_2 MEA at 0.044 A cm^{-2} (80°C): ≥0.90 V (internal resistance [iR]-free)
- Four-electron selectivity (rotating ring disk electrode [RRDE]): ≥99% ($H_2O_2 \leq$ 1%)
- MEA maximum power density at 80°C: ≥1.0 W cm^{-2}
- Performance loss at 0.80 A cm^{-2} after 30,000 cycles in N_2: ≤30 mV

TABLE 1. Progress towards Meeting Technical Targets for PGM-free Electrocatalysts and MEAs for Transportation Applications

Characteristic	Units	2018 Target	2020 Target	2016 Status
Voltage at 0.044 A/cm^2 *	$V_{iR\text{-}free}$	0.88	0.90	0.87

* Test at 80°C H_2/O_2 in MEA; fully humidified with total outlet pressure of 150 kPa (abs); anode stoichiometry 2; cathode stoichiometry 9.5 [2].

FY 2016 Accomplishments

- Improvements to ORR PGM-free catalyst activity in FY 2016 resulted in a fuel cell voltage of 0.87 V at the reference current density of 0.044 A cm^{-2} (0.01 V below

the intermediate 2018 target of 0.88 V)—nearly fourfold increase in activity over the life of this three-year project.

- A patent license agreement was executed on February 1, 2016, between LANL and Pajarito Powder, LLC, for LANL-developed PGM-free ORR catalysts.
- In addition to improvements in ORR activity, catalyst synthesis pursued in FY 2016 has focused, like never before, on PGM-free catalyst durability. Approaches involved:
  - Three catalysts derived from polyaniline (PANI) with amine side chains for high active site density.
  - Catalysts with Zn-induced microporosity for high activity ($E_{½}$ 0.81 V) and potentially improved durability (thanks to the use of a higher heat-treatment temperature).
  - Homemade "Fe-MOF" (metal organic framework) catalyst with best durability to date (collaboration with University at Buffalo).
  - Fe-free catalysts with improved ORR activity ($E_{½}$ only 30 mV lower than for Fe-based catalysts, activity likely to improve further based on the modeling study).
- CO_2 and F^- emissions from PGM-free cathode (Fe-based catalyst) have been found to be very similar to those measured with Pt-based catalysts under the same test conditions.
- Nitrogen has been found to be associated with Fe-to-N ratio of 1:4 on the PGM-free catalyst surface. This is possibly the first ever direct observation of FeN_4 (often suggested as the most likely ORR active site).
- Parametric study of cathode performance has revealed active site activity and density values and properties of the electrode/ionomer required to meet practically viable power density targets.
- Pre-selected (cyanamide [CM]+PANI)-Fe-C catalyst with specified target performance has been delivered to IRD for 50-cm^2 MEA optimization and project deliverable.

INTRODUCTION

Pt-based catalysts represent almost half of the entire polymer electrolyte fuel cell (PEFC) stack cost at high production rates and as much as 20% of the overall system cost [2]. Since Pt is a precious metal, its cost will not benefit from economies of scale and is subject to price fluctuations and monopolized global distributions. Reducing, or ideally replacing, expensive Pt and/or Pt-alloy catalysts in PEFC systems is highly desirable and has been a major focus of research and development efforts in fuel cell electrocatalysis. Owing to the inherently sluggish ORR occurring at the fuel cell cathode, higher Pt content is required at the cathode than at the anode. Successful development of PGM-free catalysts for ORR would provide the most significant economic advantage. However, hindering the successful elimination of Pt cathode catalysts from PEFCs is the lack of PGM-free catalysts that can provide sufficiently high ORR activity and, especially, high durability under the conditions of fuel cell cathode operation.

APPROACH

In this project, we have aimed to achieve major advancements in PGM-free cathode technology through the development and implementation of novel materials and concepts. The PGM-free catalyst development effort has focused on novel synthesis methods, including high-temperature catalyst synthesis using multiple nitrogen-containing precursors, advanced carbon supports, as well as transition metals alternative to iron. Comprehensive testing of materials, including initial performance screening by in situ electrochemical techniques and ex situ characterization to assess catalyst activity and durability, identify catalytic sites, and validate fuel cell performance of the most promising materials, represents a substantial fraction of the efforts.

The use of PGM-free ORR catalysts results in cathodes with increased thickness compared to that of Pt-based cathodes. Therefore, significant effort is required to address the resulting electrode design challenges. Key issues include oxygen mass transport, proton conductivity, and prevention of catalyst layer flooding. Our research has concentrated on the validation of an existing General Motors electrode model for PGM-free electrodes and parameter approximation using in situ microstructured electrode scaffold (MES) diagnostics. Electrode optimization is based on the insight obtained from the modeling, nanoscale X-ray computed tomography (XCT) imaging, and advanced microscopy analysis. In parallel to the catalyst and electrode development components of this project, MEA fabrication, optimization, and scale-up is being performed to obtain a 50-cm^2 (or larger, if needed) MEA with the best-performing materials for independent testing and evaluation at a DOE-approved facility.

RESULTS

- *Achieved fuel cell voltage of 0.87 V (iR-free) at 0.044 A cm^{-2} in H_2/O_2 fuel cell testing.*
  Fuel cell performance of advanced PGM-free (CM+PANI)-Fe-C catalyst was further improved through modifications to the catalyst synthesis as well as improvements in electrode design, enhancing O_2

transport within the catalyst layer and achieving fuel cell voltage of 0.87 V (*iR*-free) at 0.044 A cm^{-2} in H_2/O_2 MEA testing at 80°C (Figure 1a). Furthermore, new PGM-free catalyst development from unsupported homemade Fe-MOF precursor (collaboration with University at Buffalo) also achieved high activity in H_2-air (0.075 A/cm^2 at 0.80 V) and H_2-O_2 fuel cell (0.87 V at 0.044 A/cm^2, *iR*-free) (Figure 1b). High-temperature treated homemade Fe-MOF retained a unique cubic morphology and atomically dispersed Fe. The achieved fuel cell voltage of 0.87 V is only 0.01 V below the 2018 intermediate project activity target (see Table 1).

- *Achieved a half-wave potential of 0.77 V from alternative Fe-free catalysts.* PGM-free catalysts with alternative transition metals to Fe, namely Co, Mn, and Ni, have been synthesized via the high-temperature treatment of multiple nitrogen-containing precursors. Enhancement of ORR activity was obtained from alternative Co-based PGM-free catalysts achieving a half-wave potential of 0.77 V (Figure 2). Furthermore, durability cycling studies showed better stability than Fe-based PGM-free catalysts with only 10 and 11 mV drop in half-wave potential after 10,000 cycles for Co- and Mn-based materials, respectively.
- *Identified Fe-free target structures and durability descriptor using density functional theory (DFT)-based modeling.* DFT models including spontaneously formed *OH ligands explain experimentally observed trends in ORR activity with varied transition metal (Figure 3). An edge $MnCoN_5$ complex is calculated to have higher thermodynamic limiting potential (activity descriptor) than monometallic Me-N_4 edge structures (Me = Mn, Co, Ni). A first-principles molecular dynamics beam damage model was utilized to determine the knock-on displacement threshold energy for defected carbon structures. It is proposed that this figure of merit may be used as a durability descriptor for PGM-free catalyst structures, capturing the important kinetic contributions to atom removal during corrosion.
- *Made major progress in durability improvement of PGM-free catalysts at high fuel cell voltage.* Several new strategies were developed to improve durability of PGM-free catalysts: (i) active site templating *via* amine affinity to Fe^{3+}, (ii) Zn-induced microporosity with high-temperature treatments, and (iii) unsupported homemade Fe-MOF precursor with unique cubic morphology preserved after high-temperature treatment. Initial testing for the latter approach revealed for the first time promising durability performance of a PGM-free catalyst under viable fuel cell operating conditions: ambient air feed and high voltage (0.70 V).
- *Attained first direct imaging of Fe-N_x sites at the atomic level via high-resolution electron microscopy.* Advanced scanning electron microscopy was used to detect individual Fe atoms on the (CM+PANI)-Fe-C catalyst surface, providing an atomic-level insight of Fe-N_x sites for the first time. Probing of sites via high-resolution electron energy loss spectroscopy revealed nitrogen associated with iron at a ratio of 4:1. This observation is the first direct imaging of Fe-N_4 sites on the PGM-free catalyst surface (Figure 4).
- *Demonstrated synergistic collaboration modeling-characterization-testing to achieve PGM-free electrode structure optimization.* Microstructurally consistent cathode models with morphology and transport properties were obtained from nano-X-ray tomography imaging and analysis. These models highlighted the

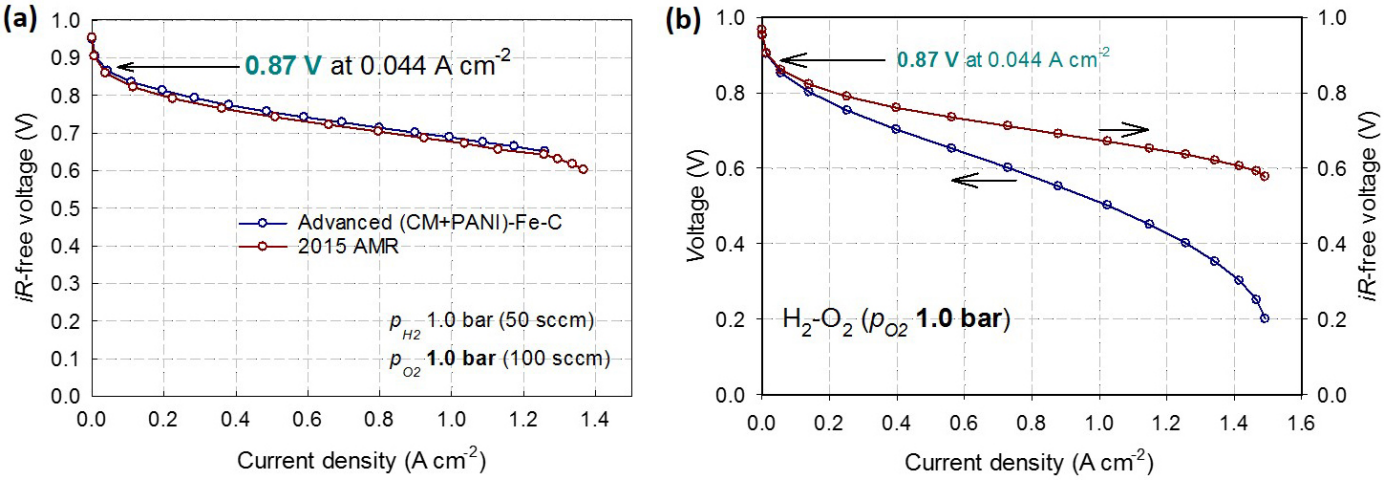
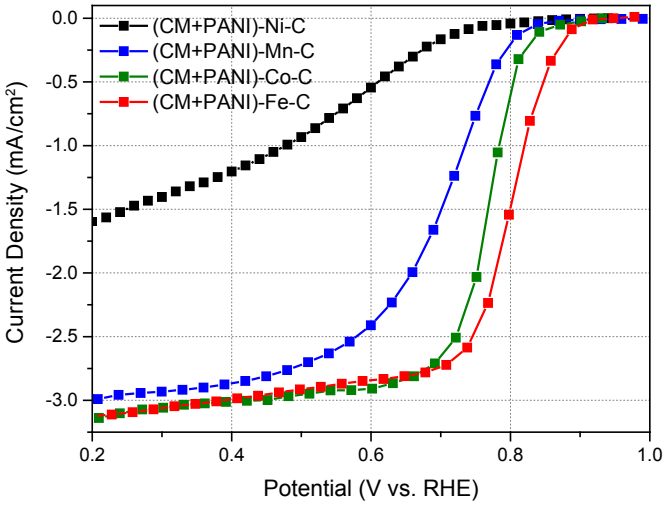
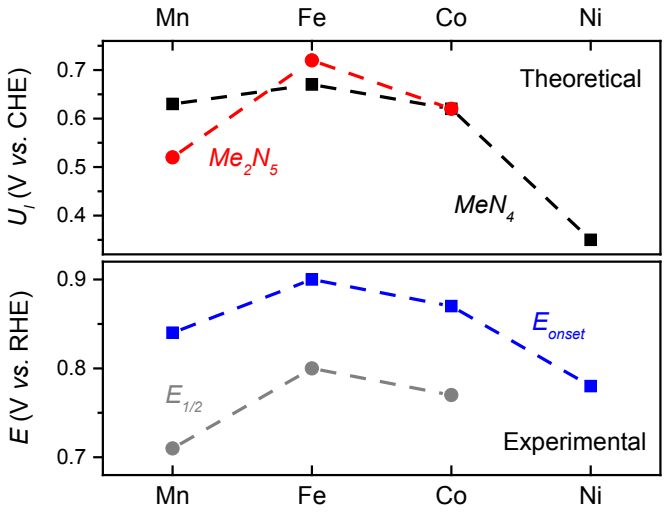


FIGURE 1. Fuel cell performance of two PGM-free catalysts demonstrating fuel cell voltage of 0.87 V (*iR*-free) at 0.044 A cm^{-2} in H_2-O_2. (a) Advanced (CM+PANI)-Fe-C catalyst and (b) PGM-free catalyst from homemade Fe-MOF precursor. Anode: 0.2 mg_{Pt} cm^{-2} Pt/C H_2, 50 sccm, 1.0 bar H_2 partial pressure, cathode: *ca.* 4.0 mg cm^{-2} air, 100 sccm, 1.0 bar air partial pressure, membrane: Nafion 117, cell size: 5 cm^2.



RHE - Reversible hydrogen electrode

FIGURE 2. Rotating disk electrode (RDE) results of Fe-free (CM+PANI)-Me-C catalysts (Me = Fe, Co, Mn, Ni) demonstrating $E_{½}$ of 0.77 V for (CM+PANI)-Co-C, only *ca.* 30 mV from (CM+PANI)-Fe-C. RDE: 0.5 M H_2SO_4, O_2-saturated, 900 rpm, 25°C, Ag/AgCl (3.0 M KCl) reference electrode, graphite counter electrode, steady-state potential program: 30 mV steps, 30 s/step.



CHE - Computational hydrogen electrode

FIGURE 3. Calculated activity descriptors, U_j, for all (CM+PANI)-Me-C catalysts for mono- and bi-metallic edge structures compared to experimental E_{onset} and $E_{½}$ values

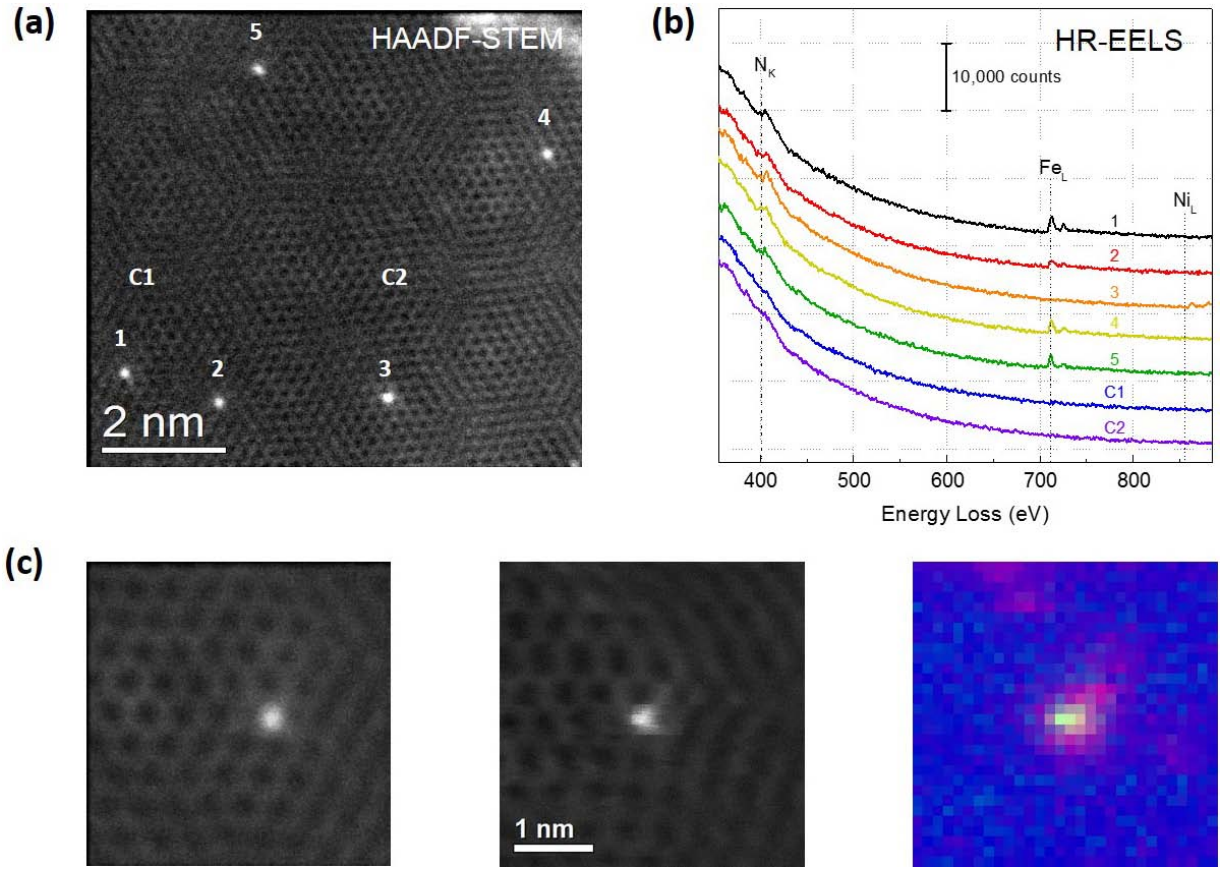
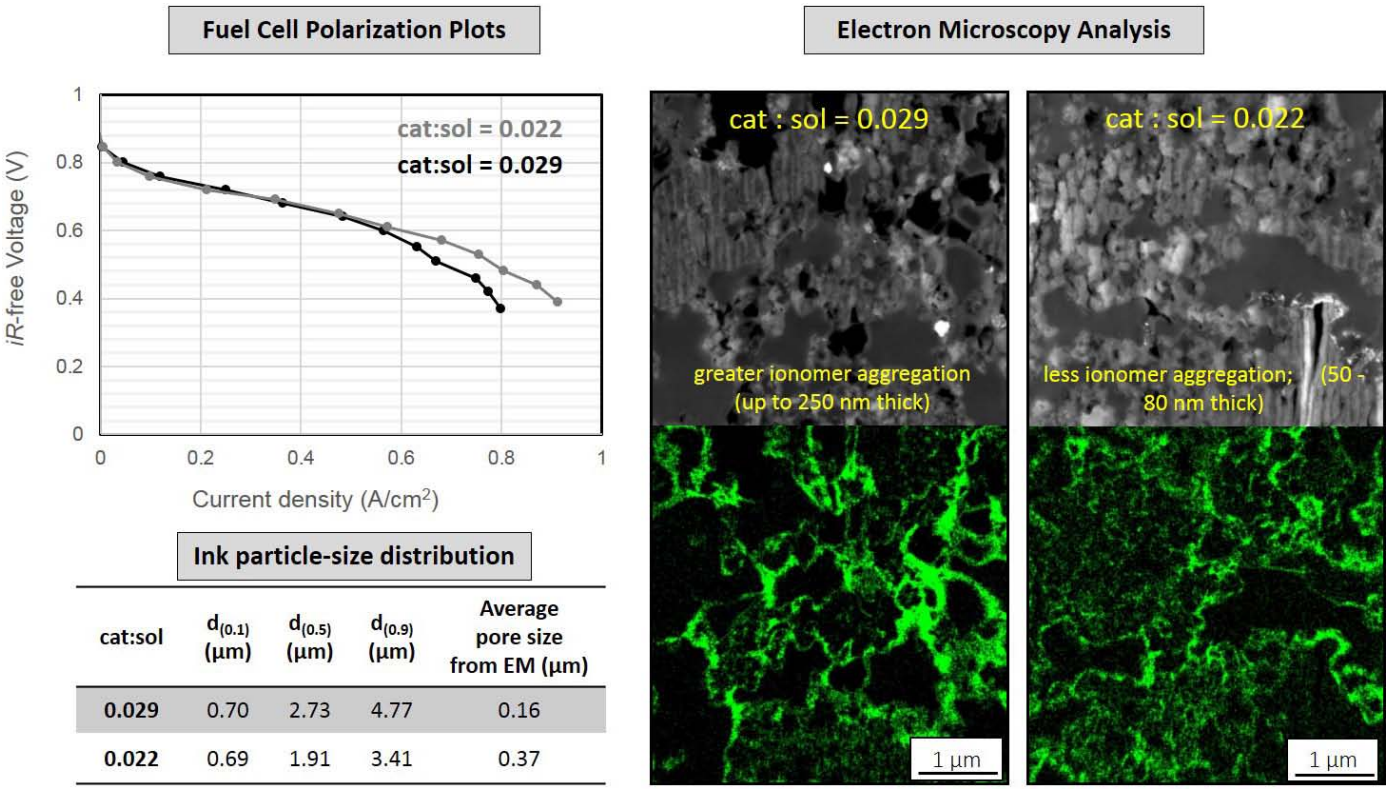


FIGURE 4. Atomic-level characterization of Fe-N_x sites on the surface of (CM+PANI)-Fe-C catalyst. (a, c) High-angle annular dark-field imaging – scanning transmission electron microscopy (HAADF-STEM) imaging of Fe-N_4 sites. (b) Elemental composition of various sites using high-resolution electron energy loss spectroscopy (HR-EELS), confirming the 1:4 ratio of Fe:N.



Ink particle-size distribution

cat:sol	$d_{(0.1)}$ (µm)	$d_{(0.5)}$ (µm)	$d_{(0.9)}$ (µm)	Average pore size from EM (µm)
0.029	0.70	2.73	4.77	0.16
0.022	0.69	1.91	3.41	0.37

FIGURE 5. Improved fuel cell performance in the mass transport region resulting from better ionomer distribution as observed from the electron microscopy (EM) analysis. Anode: 0.15 mg_{Pt} cm^{-2} Pt/C H_2, 1.5 bar H_2 partial pressure, cathode: 3.0 mg cm^{-2} air, 1.5 bar air partial pressure, 100% relative humidity, cell size: 5 cm^2.

importance of electrode hydrophobicity (reducing flooding) and higher conductivity or lower tortuosity of the ionomer for electrode development. Application of these models to modify ink preparation and deposition techniques allowed for better ionomer distribution into smaller pores, resulting in improved performance in the mass transport region (Figure 5).

CONCLUSIONS

- Continued development of PGM-free catalysts with improved ORR activity resulted in two different catalysts developed in FY 2016 with a fuel cell voltage of 0.87 V at the reference current density of 0.044 A cm^{-2} (0.01 V below the intermediate 2018 target of 0.88 V)—nearly fourfold increase in activity over the life of this three-year project.
- Major progress in durability of PGM-free catalysts has been demonstrated with homemade Fe-MOF and Fe-free catalysts.
- CO_2 and F^- emissions from PGM-free cathode (Fe-based catalyst) have been found to be very similar to those measured with Pt-based catalysts under the same test conditions.
- The first ever direct observation of FeN_4 (often suggested as the most likely ORR active site) has been demonstrated.
- All project performance measures have been met; final electrode design is nearing completion with the help of microstructural analysis of factors determining electrode performance. Project deliverables remain on schedule.

FUTURE DIRECTIONS

Although the official end date of this project is listed as March 2016, continuing PGM-free catalyst development in future projects should target:

- Molecular-level dispersion of transition-metal ORR active sites (for activity enhancement) in highly graphitized carbon matrices (for durability enhancement).
- Rational design of PGM-free catalysts based on the knowledge of ORR active-site(s).
- Improvement in the activity of Fe-free catalysts, e.g., via inducing strain in bimetallic catalysts.

- Full utilization of national laboratory capabilities, in particular through the recently established Electrocatalysis Consortium (ElectroCat), part of the DOE Office of Energy Efficiency and Renewable Energy's Energy Materials Network.

SPECIAL RECOGNITIONS & AWARDS/ PATENTS ISSUED

1. H.T. Chung and P. Zelenay, "Non-precious Metal Catalysts Prepared from Precursor Comprising Cyanamide," U.S. Patent 9,169,140 issued on October 27, 2015.

FY 2016 PUBLICATIONS

1. "First-Principles Molecular Dynamics Study of Carbon Corrosion in PEFC Catalyst Materials," E.F. Holby, *Fuel Cells,* In Press.

2. "Linking Structure to Function: The Search for Active Sites in Non-Platinum Group Metal Oxygen Reduction Reaction Catalysts," E.F. Holby and P. Zelenay, *Nano Energy*, available online 24 May 2016, ISSN 2211–2855, http://dx.doi.org/10.1016/j.nanoen.2016.05.025.

3. "Highly active and porous graphene encapsulating carbon nanotubes as a non-precious oxygen reduction electrocatalyst for hydrogen-air fuel cells," P. Zamani, D.C. Higgins, F.M. Hassan, X. Fu, J.Y. Choi, M.A. Hoque, G. Jiang, Z. Chen, *Nano Energy*, **26**, 267–275, 2016.

4. "Heat-Treated Non-Precious Metal Catalysts for Oxygen Reduction," H. Chung, G. Wu, D. Higgins, P. Zamani, Z. Chen, and P. Zelenay, in *Electrochemistry of N4 Macrocyclic Metal Complexes*, Volume 1: Energy, F. Bedioui and J.H. Zagal (*eds.*), Springer, pp. 41–68.

5. "Critical Role of the Removal of Intercalated Water for Electrocatalytically Active Graphitic Systems," U. Martinez, G.M. Purdy, E.F. Holby, K. Artyushkova, J.H. Dumont, A. Singh, N.H. Mack, P. Atanassov, D.A. Cullen, K.L. More, M. Chhowalla, P. Zelenay, A.M. Dattelbaum, A.D. Mohite, and G. Gupta, *Sci. Adv.*, **2**, e1501178, 2016.

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7. "The application of graphene and its composites in oxygen reduction electrocatalysis: A perspective and review of recent progress," D. Higgins, P. Zamani, A. Yu, Z.W. Chen, *Energy Environ. Sci.*, **9**, 357–390, 2016.

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9. "In-Situ through-Plane Measurements of Ionic Potential Distributions in Non-Precious Metal Catalyst Electrode for PEFC," S. Komini Babu, H.T. Chung, P. Zelenay, and S. Litster, *ECS Trans.*, **69** (17) 23–33, 2015.

10. "Non-Precious Metal Fuel Cell Cathodes: Catalyst Development and Electrode Structure Design," P. Zelenay, H. Chung, U. Martinez, E. Holby, U. Tylus, G. Purdy, J. Ziegelbauer, M. Odgaard, D. Schlueter, S. Litster, S.K. Babu, M. Neidig, J. Kehl, J. Kneebone, Z. Chen, D. Higgins, G. Jiang, M.-H. Seo, K.L. More, and D. Cullen, U.S. Department of Energy, Hydrogen and Fuel Cells Program, 2015 Annual Progress Report, V-43–V-50.

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FY 2016 PRESENTATIONS

1. U.S. Department of Energy, Energy Efficiency and Renewable Energy, Fuel Cell Technologies Office, 2016 Merit Review and Peer Evaluation Meeting, Washington, D.C., June 6–10, 2016. Title: "Non-Precious Metal Fuel Cell Cathodes: Catalyst Development and Electrode Structure Design," P. Zelenay (*DOE invited lecture*). https://www.hydrogen.energy.gov/pdfs/review16/fc107_zelenay_2016_o.pdf

2. 229th Meeting of the Electrochemical Society, May 29–June 2, 2016, San Diego, California. "Non-PGM ORR Catalysts Based on Transition Metal Alternative to Iron," U. Martinez*, E.F. Holby, J.H. Dumont, H.T. Chung, P. Zelenay.

3. 2016 MRS Spring Meeting & Exhibit, Phoenix, Arizona, March 28–April 1, 2016. "Non-Precious Metal Electrocatalysts for Oxygen Reduction," P. Zelenay (*invited lecture*).

4. 18th Topical Meeting of the International Society of Electrochemistry, Gwangju, South Korea, March 11, 2016. Title: "Precious Metal-Free Electrocatalysts for Fuel Cell Applications: In Pursuit of Performance and Understanding," P. Zelenay*, E.F. Holby, H.T. Chung, U. Martinez, G.M. Purdy, X. Yin (*invited keynote lecture*).

5. Korea Institute for Energy Research & Korea Advanced Institute for Science and Technology, Daejeon, South Korea, March 7, 2016. Title: "Recent Progress in PGM-free Oxygen Reduction Reaction Electrocatalysis at Los Alamos," P. Zelenay (*invited lecture*).

6. Workshop on New Generation Energy Storage Technologies: Challenges and Opportunities, Taormina, Italy, December 2–3, 2015. Title: "New Research Directions for Fuel Cell Systems," P. Zelenay (*invited lecture*).

7. Department of Chemistry, University of Warsaw, Warsaw, Poland, November 26, 2015. Title: "Catalysis of Selected Electrode Processes in Polymer Electrolyte Fuel Cells," P. Zelenay (*invited lecture*).

8. 2015 MRS Fall Meeting & Exhibit, Boston, Massachusetts, USA, November 29–December 4, 2015. Title: "Analytical Characterization of non-PGM Catalysts for PEM Fuel Cells," D. Cullen*, B. Sneed, H. Meyer III, K. More, H. Chung, and P. Zelenay.

9. Fuel Cell Seminar & Energy Exposition, Los Angeles, California, USA, November 16–19, 2015. Title: "A Disruptive Fuel in the System: Electricity from a Carbon-Neutral Fuel," E.S. De Castro*, P. Zelenay, V. Gregoriou.

9. 228th Meeting of the Electrochemical Society, Phoenix, Arizona, USA, October 11–15, 2015. Title: "Water Management in PEM Fuel Cells with Non-Precious Metal Catalyst Electrodes," D. Spernjak*, H.T. Chung, R. Mukundan, R.L. Borup, D.S. Hussey, D.L. Jacobson, G. Wu, and P. Zelenay.

10. 228th Meeting of the Electrochemical Society, Phoenix, Arizona, USA, October 11–15, 2015. Title: "Graphite-Based Non Precious Metal Catalyst for Oxygen Reduction Reaction", J.H. Dumont*, U. Martinez, A. Mohite, G.M. Purdy, P. Atanassov, P. Zelenay, and G. Gupta.

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12. 228th Meeting of the Electrochemical Society, Phoenix, Arizona, USA, October 11–15, 2015. Title: "In-Situ through-Plane Measurements of Ionic Potential Distributions in Non-Precious Metal Catalyst Electrode for PEFC," S. Komini Babu*, H.T. Chung, P. Zelenay, and S. Litster.

13. 228th Meeting of the Electrochemical Society, Phoenix, Arizona, USA, October 11–15, 2015. Title: "Non-PGM ORR Catalyst Active-Site Screening," E. Holby*, S. Choudhury, and P. Zelenay.

14. 228th Meeting of the Electrochemical Society, Phoenix, Arizona, USA, October 11–15, 2015. Title: "Solvent-Engineering of High-Performance Non-Precious Metal Catalysts," U. Martinez*, J. Dumont, G. Purdy, K. Artyushkova, H. Chung, P. Atanassov, A. Mohite, A. Dattelbaum, G. Gupta, and P. Zelenay.

15. 228th Meeting of the Electrochemical Society, Phoenix, Arizona, USA, October 11–15, 2015. Title: "Combining Nitrogen Precursors in Synthesis of Non-Precious Metal ORR Catalysts with Improved Fuel Cell Performance," H.T. Chung*, E.F. Holby, G.M. Purdy, S. Komini Babu, S. Litster, D. Cullen, K.L. More, and P. Zelenay.

16. 228th Meeting of the Electrochemical Society, Phoenix, Arizona, USA, October 11–15, 2015. Title: "Non-PGM ORR Catalyst Active-Site Screening," E. Holby*, S. Choudhury, and P. Zelenay.

17. 66th Annual Meeting of the International Society of Electrochemistry, Taipei, Taiwan, October 4–9, 2015. Title: "Non-Precious Metal Catalysts for Oxygen Reduction: Accomplishments and Challenges," P. Zelenay (*invited keynote lecture*).

18. New Devices for Energy Conversion and Storage, Hong Kong University of Science and Technology, Hong Kong, October 1–3, 2015. Title: "Oxygen Reduction on Non-Precious Metal Electrocatalysts," U. Tylus, U. Martinez, E.F. Holby, H.T. Chung, G. Purdy, and P. Zelenay* (*invited keynote lecture*).

19. CEA tech, Laboratoire d'innovation pour les technologies des énergies nouvelles et les nanomatérieux (Liten), Grenoble, France, September 18, 2015. Title: "Fuel Cell Electrocatalysis Research at Los Alamos National Laboratory," P. Zelenay (*invited lecture*).

20. EFCD2015 – Challenges towards Zero Pt for Oxygen Reduction, La Grande Motte, France, September 13–16, 2015. Title: "How much value there really is in non-precious metal ORR catalysts for fuel cells?" P. Zelenay (*invited plenary lecture*).

21. International Energy Agency, Annex 31 Meeting, Pfinztal, Germany, July 6–7, 2015. Title: "A Few Highlights from Recent Fuel Cell Electrocatalysis Research at Los Alamos National Laboratory," P. Zelenay.

22. 5th European PEFC and H2 Forum (EFCF2015), Lucerne, Switzerland, June 30–July 3, 2015. Title: "Electrocatalysis of Oxygen Reduction Reaction: Catalyst Development, Theory, and Model Systems," P. Zelenay (*invited keynote lecture*).

23. Turin Polytechnic, Turin, Italy, June 26, 2015. Title: "Non-Precious Metal Fuel Cell Cathodes: Catalyst Development and Electrode Structure Design," P. Zelenay (*invited lecture*).

24. U.S. Department of Energy, Energy Efficiency and Renewable Energy, Fuel Cell Technologies Office, 2015 Merit Review and Peer Evaluation Meeting, Arlington, Virginia, June 8–12, 2015. Title: "Non-Precious Metal Fuel Cell Cathodes: Catalyst Development and Electrode Structure Design," P. Zelenay (DOE invited lecture).

25. "Nano-scale X-ray computed tomography applied to fuel cell and battery electrode characterization and optimization," U. of Texas-Austin, Texas Materials Institute Seminar, Austin, TX, October 29, 2015, S. Litster (*invited lecture*).

26. "High Resolution Imaging, Modeling, and Characterization of Non-Precious Metal Fuel Cell Electrodes," Keynote - Society of Engineering Science 52nd Annual Technical Meeting, College Station, TX, October 28, 2015, S. Litster (*invited lecture*).

27. "Nano-scale X-ray computed tomography applied to fuel cell and battery electrode characterization and optimization," National Institute of Advanced Industrial Science and Technology (AIST) Kansai, Osaka, Japan, May 12, 2015, S. Litster (*invited lecture*).

28. "Nano-scale X-ray computed tomography applied to fuel cell and battery electrode characterization and optimization," Chemical Engineering, Kyoto University, Kyoto, Japan, May 11, 2015, S. Litster (*invited lecture*).

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