

V.E.5 Advanced Cathode Catalysts

Piotr Zelenay (Primary Contact),
Joseph Bradley, Jerzy Chlistunoff, Hoon Chung,
Steven Conradson, Fernando Garzon,
Christina Johnston, Partha Mukherjee,
Mark Nelson, Geraldine Purdy, Gang Wu
Materials Science and Technology Division
Los Alamos National Laboratory
Los Alamos, NM 87545
Phone: (505) 667-0197; Fax: (505) 665-4292
E-mail: zelenay@lanl.gov

DOE Technology Development Manager:
Nancy Garland

Phone: (202) 586-5673; Fax: (202) 586-9811
E-mail: Nancy.Garland@ee.doe.gov

Subcontractors:

- Debbie Myers (PI), Magali Ferrandon, Jeremy Kropf, Xiaoping Wang
Argonne National Laboratory, Argonne, IL
- Radoslav Adzic (PI), Kuanping Gong, Kotaro Sasaki, Miomir Vukmirovic, Jia Wang, Wei-Ping Zhou
Brookhaven National Laboratory, Upton, NY
- Paolina Atanassova (PI), Yipeng Sun
Cabot Fuel Cells, Albuquerque, NM
- Karren More (PI)
Oak Ridge National Laboratory, Oak Ridge, TN
- Yushan Yan (PI), Shaun Alia, Kurt Jensen
University of California, Riverside, CA
- Andrzej Wieckowski (PI), Cyril Delacôte, Stephanie Goubren-Renaudin, Xiuling Zhu
University of Illinois at Urbana-Champaign, IL
- Plamen Atanassov (PI), Kateryna Artyushkova, Dimitar Petsev, Svitlana Pylypenko
University of New Mexico, Albuquerque, NM

Project Start Date: March 2007

Project End Date: 2011

- Determine ORR mechanism on newly developed catalysts via extensive physicochemical characterization and electrochemical and fuel cell testing.
- Optimize electrodes with new catalysts and structures for maximum performance.
- Evaluate catalyst stability; minimize performance loss over time.
- Assure path forward for the fabrication and scale up of viable catalysts.

Technical Barriers

This project addresses the following technical barriers from the Fuel Cells section (3.4.4) of the Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan:

- (A) Durability (of catalysts and electrode layers)
- (B) Cost (of catalysts and membrane electrode assemblies [MEAs])
- (C) Performance (of electrodes, including (i) ORR overpotential and (ii) O₂ mass-transport rates)

Technical Targets

Non-platinum cathode catalysis research in this project focuses on DOE's 2010 technical targets specified in Table 3.4.12 (Electrocatalysts for Transportation Applications) of the Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan. The 2010 targets relevant to this research project together with the current status (where applicable) are:

Characteristics	Units	2010 Stack Target (Anode + Cathode)	2009 Status (Cathode)
PGM total loading (50 cm ² fuel cell)	mg _{PGM} /cm ² electrode area	0.3	0.28 ¹
Mass activity	A/mg _{PGM} @ 900 mV _{IR-free}	0.44	0.34 ² 1.2 ³
Non-Pt catalyst activity per volume of supported catalyst	A/cm ³ @ 800 mV _{IR-free}	> 130	54 ⁴

¹ Pt_{ML}/Pd/C catalyst from scaled-up synthesis by Cabot Fuel Cells, tested in 50-cm² single fuel cell at 80°C; cathode - 0.28 mg_{PGM} cm⁻² (0.06 mg_{Pt} cm⁻² + 0.22 mg_{Pd} cm⁻²); anode - 0.05 mg_{Pt} cm⁻² Pt/C; MEA not optimized

² Mass activity per mg_{PGM} in Pt_{ML}/Pd_{ML}/PdIr/C catalyst in RDE testing at 0.90 V

³ Mass activity per mg_{Pt} in Pt_{ML}/Pd_{ML}/PdIr/C catalyst in RDE testing at 0.90 V

⁴ CM-Fe-C catalyst tested in 5-cm² single fuel cell at 80°C; cathode - 4.0 mg cm⁻²;

anode - 0.25 mg_{Pt} cm⁻² Pt/C; MEA not optimized

PGM - precious group metal

Objectives

The main objective of this project is to:

- Develop an oxygen reduction reaction (ORR) catalyst alternative to pure Pt, capable of fulfilling cost, performance and durability requirements established by DOE for the polymer electrolyte fuel cell (PEFC) cathode.

Individual objectives of this research are as follows:

- Design, synthesize and characterize new catalyst supports and electrode structures for new-generation ORR catalysts.

Accomplishments

- Achieved substantial improvement in mass activity of core-shell catalysts, up to 1.2 A/mg_{Pt} at 0.90 V (in excess of 0.3 A/mg_{PGM}), through the introduction of a Pd interlayer between the nanoparticle core and outer Pt layer.
- Demonstrated much improved stability of nanoparticles in rotating disk electrode (RDE) cycling by (i) addition of Pd interlayer ($\Delta E_{1/2}$ after 30,000 potential cycles reduced from 39 mV with Pt/C to 19 mV with Pt_{ML}/Pd_{ML}/Pd₃Ir/C catalyst), (ii) new synthesis of Pt/Pd₃Fe/C catalyst ($\Delta E_{1/2}$ < 5 mV after 28,000 potential cycles), and (iii) deposition of Au clusters on Pt surface ($\Delta E_{1/2}$ limited to 16 mV after 50,000 potential cycles).
- Completed successful scale up of synthesis of PtIr_{ML}/Pd/C, Pt_{ML}/Pd/C, and Pt_{2ML}/Pd/C using three different methods and without a loss in ORR activity.
- Showed major improvement in ORR activity of non-precious metal catalysts (polyaniline [PANI]- and cyanamide [CM]-derived) in RDE and fuel cell testing; open-circuit voltage (OCV) up to 1.0 V, volumetric activity in excess of 50 A/cm³.
- Demonstrated a non-precious metal catalyst (PANI-Fe₃Co-C) that combines high activity (OCV > 0.90 V, $i_{0.80\text{ V}} = 27\text{ A/cm}^3$) with good stability (ca. 700 hours in H₂-air cell) and negligible peroxide generation (H₂O₂ < 0.5%).
- Determined changes in the chemical state of transition metals during pyrolysis by in situ X-ray absorption spectroscopy (XAS) methods; demonstrated enhanced surface-specificity of X-ray absorption near-edge spectroscopy (XANES) by operating at Co and Fe L-edge (important step in determination of the ORR active-site in non-precious metal catalysts).
- Initiated mechanistic analysis of ORR kinetics at non-precious metal catalysts and modeling of thick non-precious metal catalyst layers.
- Developed, catalyzed with Pt, and incorporated into MEAs cathode structures based on multi-walled carbon nanotubes with an unusually long length of ~300 μm , capable of delivering very good per-mass performance of 0.75 A/mg_{Pt} (overall performance in need of improvement).



Introduction

This multitask and multi-partner project focuses on the development of new oxygen reduction catalysts and electrode structures for the PEFC cathode, with either greatly reduced precious-metal content relative to that

presently used by stack developers, or entirely precious-metal-free. The main objective of this effort is to lower the catalyst cost in the fuel cell power system through improvements in ORR performance in terms of both electrocatalysis and oxygen transport to the reaction site.

Approach

The primary research goal of this project is the development of new oxygen reduction catalysts, in two different classes: (i) catalysts with ultra-low platinum content (stable metals or alloys as cores; non-precious-metal core catalysts; mixed metal shells for higher ORR activity) and (ii) precious metal-free catalysts (low- and high-temperature catalysts based on transition metals precursors). Catalyst characterization, both electrochemical (in aqueous electrolyte and in the fuel cell) and ex situ, is a major part of the effort, focusing on such key challenges as ORR active-site identification and catalyst durability.

Development of new catalysts is closely tied to novel electrode structures, tailored to maximize either catalyst utilization in the case of precious-metal-based ORR catalysts (e.g. core-shell Pt-based catalysts) or loading of non-precious metal catalysts with intrinsically lower than platinum volumetric ORR activity. The electrode-structure component of the effort concentrates on two groups of materials: (i) templated nanostructures, such as nanofibers and nanotubes, made of polymers (e.g. polypyrrole), carbon, and non-carbon inorganic materials, and (ii) open-frame catalyst structures obtained using microemulsion/reverse emulsion method and other techniques.

In addition to short-term testing and initial performance assessment, catalysts, supports, electrode structures, and MEAs, developed in this project are subject to long-term performance (durability) testing. Performance degradation mechanisms are being identified and, if possible, addressed. Fabrication and scale up of viable catalysts and supports is also being tackled through collaboration between partners in this project.

Results

Catalysts with Ultra-Low Pt Content – In the past year, we developed several core-shell catalysts in this category using Pd interlayer between non-platinum core and Pt-monolayer shell. Thanks to assuring better match with the lattice constant of Pt, “smoothing” the core surface, and providing oxide-free support for Pt layer, the Pd interlayer presence leads to catalysts with very respectable ORR performance relative to that of similar catalysts without the Pd interlayer or that of a standard Pt/C catalyst (Figure 1). The half-wave potential ($E_{1/2}$) of the most active catalysts in RDE testing (Pt_{ML}/Pd_{ML}/Pd₃Ir/C and Pt_{ML}/Pd_{ML}/PdIr/C) is by 50-60 mV

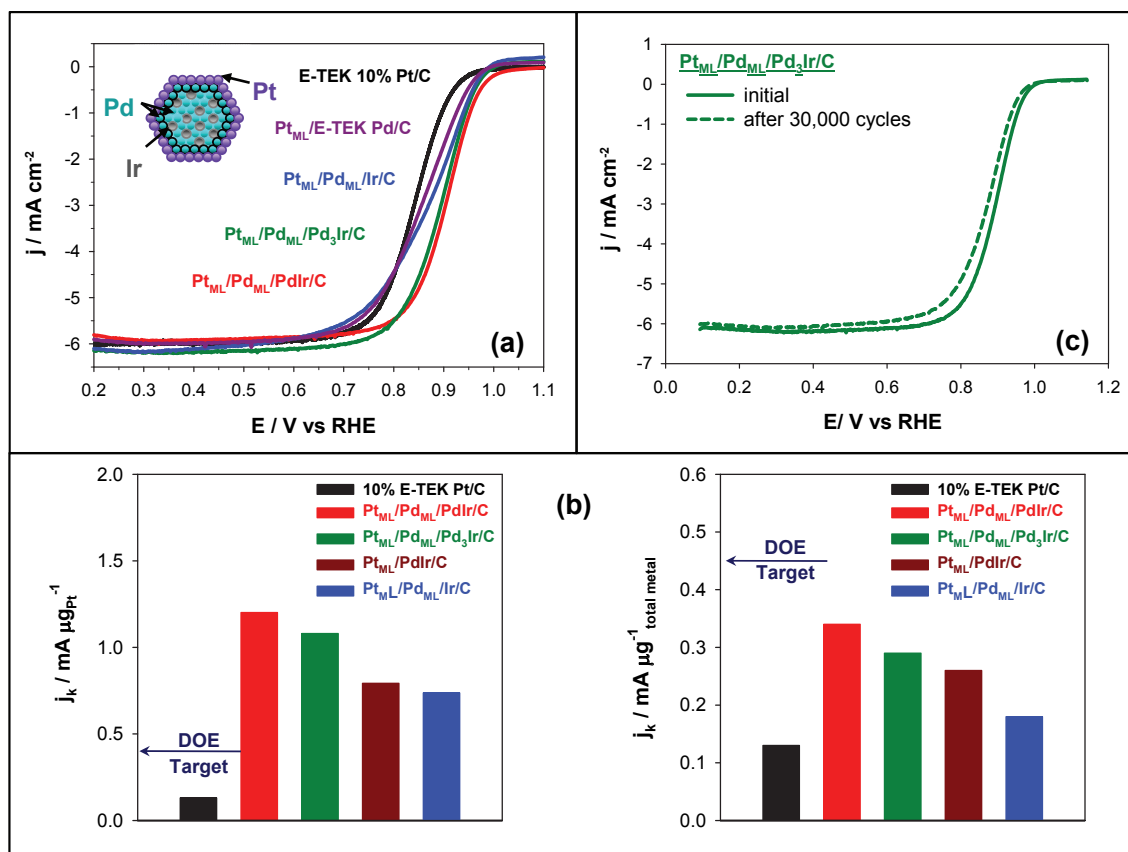


FIGURE 1. RDE performance of core-shell catalysts with Pd interlayer: (a) ORR polarization plots for five catalysts; (b) ORR activity per Pt mass (left) and total precious metal mass (right); (c) ORR polarization plots for Pt_{ML}/Pd_{ML}/Pd₃Ir/C before and after 30,000 cycles between 0.70 and 0.95 V vs. reference hydrogen electrode, cell temperature = 25°C.

more negative than that of the reference Pt/C catalyst (Figure 1a). This significant $E_{1/2}$ advantage is the reason for mass activity improvement when referred to the Pt mass and total PGM mass in the catalysts with Pd interlayer (Figure 1b). The mass activities at 0.90 V of the best performer in this group (Pt_{ML}/Pd_{ML}/PdIr/C) are 1.2 A/mg_{Pt} and 0.34 A/mg_{PGM} at 0.90 V (RDE testing, room temperature). The latter mass activity number comes within ~80% of the DOE target of 0.44 A/mg_{PGM}. Notably, the catalysts in this group combine high ORR activity with much improved performance durability. As shown in Figure 1c, the $E_{1/2}$ loss for a Pt_{ML}/Pd_{ML}/Pd₃Ir/C catalyst after 30,000 potential cycles between 0.7 and 0.95 V is only 19 mV, much less than a 39 mV loss observed with the Pt/C catalyst.

Better stability of catalysts in this category was also achieved by two other approaches: (i) addition of Au clusters to the surface of Pt nanoparticles and (ii) new synthesis of Pt/Pd₃/Fe/C catalysts. In the first case, the $E_{1/2}$ shift after 30,000 potential cycles is reduced from 43 mV for untreated Pt/C catalyst, 8 nm in average particle size, to 16 mV for the same Pt/C catalyst but modified with Au clusters (approximate stoichiometry of PtAu_{0.12}/C, nominal Au coverage of 0.6 monolayer,

ML). Given the partially non-precious character of the core, even more remarkable durability was achieved with the Pt/Pd₃/Fe/C catalyst (Figure 2). The well-alloyed ~10 nm nanoparticles of that catalyst (cf. transmission scanning microscopy [TEM] in Figure 2a) not only show very high ORR activity (~1.0 A/mg_{Pt}, $E_{1/2}$ 0.865 V) but also virtually no activity loss after 28,000 cycles (Figure 2b).

Scale-up Synthesis of Catalysts with Ultra-low Pt Content – Using two electrochemical techniques (Cu-underpotentially deposited [UPD] displacement and Cu-UPD-mediated layer-by-layer growth), the Brookhaven National Laboratory team scaled up the synthesis of three core-shell catalyst systems to 2-5 gram quantities in a single batch without a loss in the ORR activity of the catalysts. The mass activities of the three catalysts are as follows: PtIr_{ML}/Pd/C – 0.66 A/mg_{Pt} (0.24 A/mg_{PGM}), Pt_{ML}/Pd/C – 0.57 A/mg_{Pt} (0.21 A/mg_{PGM}), Pt_{2ML}/Pd/C – 0.38 A/mg_{Pt} (0.17 A/mg_{PGM}). The catalyst composition was confirmed using inductively coupled plasma and XAS analysis; the core-shell structure of nanoparticles was verified by high angle annular dark field scanning transmission electron microscopy imaging.

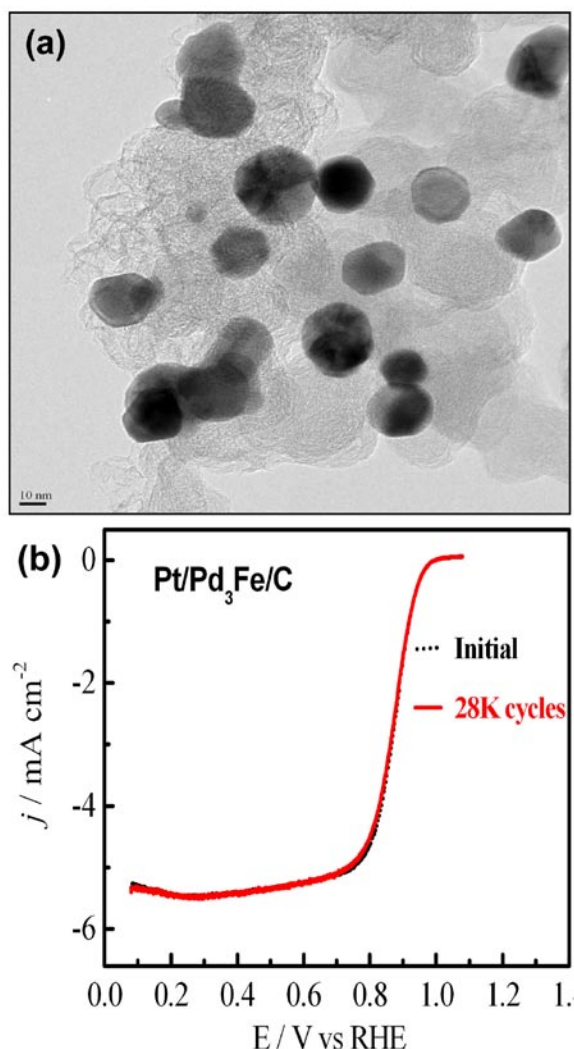


FIGURE 2. Pt/Pd₃Fe/C core-shell catalyst: (a) TEM image; (b) ORR polarization plots before and after 28,000 cycles between 0.70 and 0.95 V vs. RHE.

A gram-scale synthesis of the Pt_{ML}/Pd/C catalyst was independently accomplished by Cabot Fuel Cells using a spray-pyrolysis approach. The catalyst delivered very good performance in fuel cell testing (Figure 3), reaching mass-activity of 0.55 A/mg_{Pt} and 0.12 A/mg_{PdGM} at 0.90 V, much better than that of a reference Pt/C catalyst (Figure 3).

Precious Metal-Free Catalysts – The focus of research in this catalyst category was on materials obtained by heat-treating carbon supported precursors, predominantly polypyrrole (PPy), CM, and PANI, in the presence of transition metal salts, mostly salts of Fe and Co. In some cases, two transition metal salts were used at the same time. Several catalysts with very high ORR activity were synthesized, using both PANI and CM as precursors. In particular, PANI-derived catalysts were optimized for maximum ORR activity in RDE testing. These catalysts exhibit gradual improvement

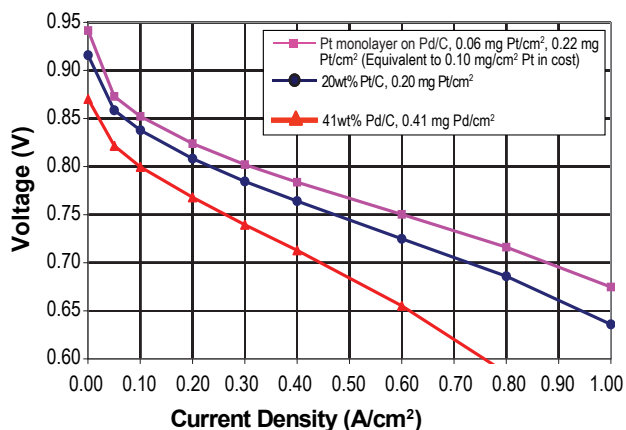


FIGURE 3. Fuel cell testing of a Pt_{ML}/Pd/C catalyst from a scale-up synthesis by Cabot. Anode – 0.05 mg_{Pt}/cm², 1.5× H₂ at 1 A/cm²; cathode – 2.5× air at 1 A/cm²; MEA area – 50 cm²; cell temperature – 80°C; anode/cathode relative humidity – 100%; anode/cathode backpressure – 30 psig; data acquisition – 10 min/point; membrane – Nafion® 212.

in performance as the composition and heat-treatment temperature are optimized (Figure 4a). Rotating ring disc electrode (RRDE) data show that an increase in ORR activity correlates well with enhanced selectivity for the four-electron reduction of O₂, i.e. with reduced hydrogen peroxide yield (Figure 4b). The best RDE performance to date was achieved with PANI-Fe-C and mixed-metal PANI-Fe₃Co-C catalysts, which produce ORR onset potential higher than 0.90 V, half-wave potential of ~0.77 V, and H₂O₂ yield lower than 0.5%.

High ORR activity of several PANI-derived catalysts was confirmed in fuel cell testing, both on neat oxygen and air. PANI-Fe₃Co-C generated the open-cell voltage of 0.91 V and 0.93 V on air and oxygen, respectively (Figure 5). Volumetric activity of the catalyst was measured at 19 A/cm³ on air and 27 A/cm³ on oxygen at 0.80 V. Notably, PANI-Fe₃Co-C and a few other PANI-derived catalysts combine high ORR activity with very promising stability. As shown in Figure 5b, little performance loss is seen with PANI-Fe₃Co-C catalyst during nearly 700 hours of testing in an H₂-air fuel cell at 0.40 V.

The highest ORR activity in an operating fuel cell was measured with a CM-Fe-C catalyst, heat-treated at 1,050°C. While trailing PANI-derived catalysts in durability, the CM-Fe-C catalyst yields OCV of ~1.0 V and volumetric activity of 54 A/cm³ at a fuel cell operating voltage of 0.80 V. RDE testing reveals very high selectivity of the CM-Fe-C catalyst, with peroxide yield remaining below 0.4%, regardless of the operating potential (down to 0.0 V) and independently of the catalyst loading at the disk (40-800 µg/cm² range).

We recently initiated mechanistic analysis of ORR kinetics at non-precious metal catalysts. The approach

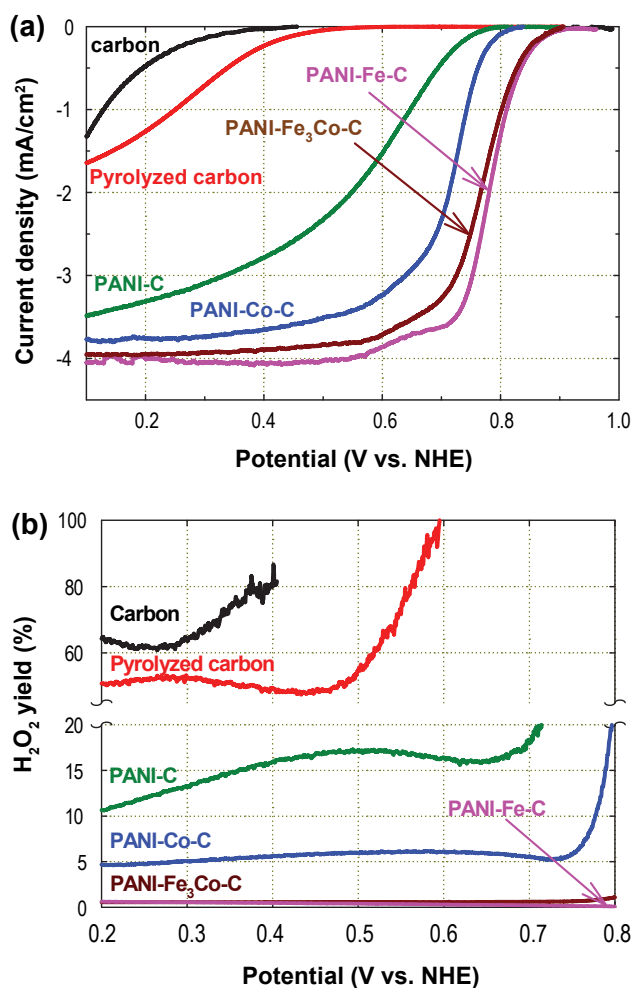


FIGURE 4. RDE/RRDE performance of PANI-derived catalysts at 25°C: (a) ORR polarization plots; (b) H₂O₂ generation plots as a function of potential (ring data). Catalyst loading – 0.12 mg cm⁻²; electrolyte – 0.5 M H₂SO₄; scan rate – 5 mV/s; disk rotation rate – 900 rpm; reference electrode – Ag/AgCl (3M NaCl); counter electrode – Au-mesh; cell temperature – 25°C.

assumes participation of a reversible redox couple on the surface of Fe-based catalysts (cyclic voltammetry data) as mediator in the ORR process. Preliminary calculations reproduced experimental ORR Tafel plots for PANI-Fe₃Co-C at various catalyst loadings. The calculations also point to the intrinsic properties of the catalyst as being responsible for the Tafel slope curvature at the most extreme overpotentials.

We also started modeling catalyst layers to minimize mass-transport losses in thick electrodes made of non-precious metal catalysts with relatively low volumetric activity (the result of low turnover frequency and/or low concentration of ORR active sites). The focus of this effort is water evaporation and capillarity as main factors contributing to catalyst flooding and mitigation strategies to prevent water accumulation.

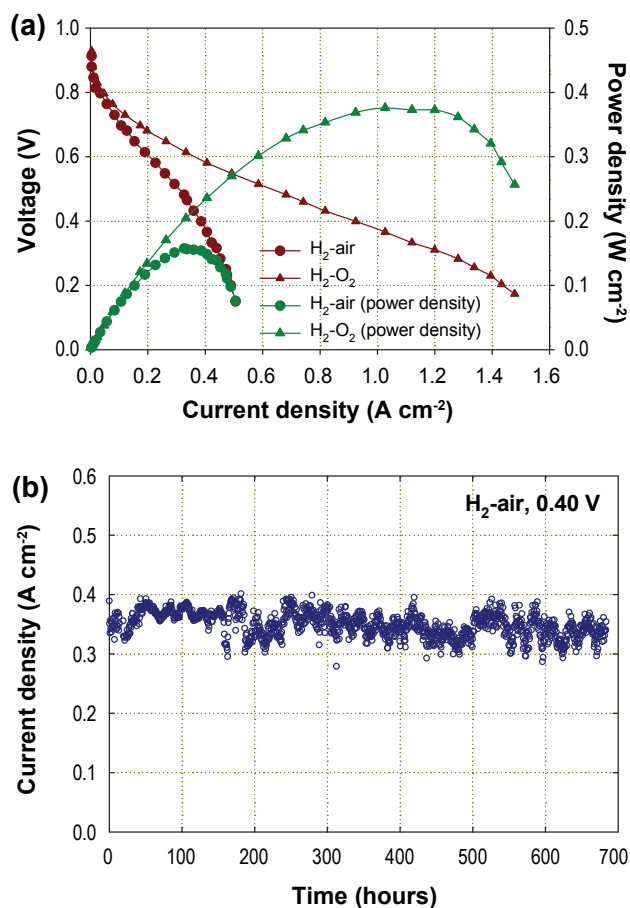


FIGURE 5. Fuel cell performance of a PANI-Fe₃Co-C catalyst: (a) polarization plots; (b) 700-hour life test on air at 0.40 V. Anode – 0.25 mg cm⁻² Pt (E-TEK), 30 psig; cathode – 4.0 mg cm⁻² PANI-Fe₃Co/C; 30 psig air/O₂; membrane – Nafion®1135; cell temperature – 80°C.

In X-ray absorption in situ and ex situ experiments at the Advanced Photon Source and Stanford Linear Accelerator Center, we determined chemical changes in the transition metal state during pyrolysis. We also demonstrated enhanced surface-specificity of XANES by operating at Co and Fe L-edge. The latter experiments may prove crucial in the effort aimed at identifying the ORR active site(s) in non-precious metal catalysts.

Catalyst Structures – One of many challenges facing cathode catalysis research is the development of new electrode structures. In the past year, our effort concentrated on catalysts supported on carbon nanostructures and also carbon-based electrodes with hierarchical porosity. Among other accomplishments, we developed, catalyzed with Pt, and incorporated into MEAs cathode structures based on multi-walled carbon nanotubes (MWNTs) (Figure 6). Once used in the cathode, the unusually long (~300 μm) Pt-catalyzed MWNTs are capable of delivering excellent per-mass ORR performance (0.75 A/mg_{Pt}). However, because of extremely low Pt loading used (12 μg/cm²), the absolute

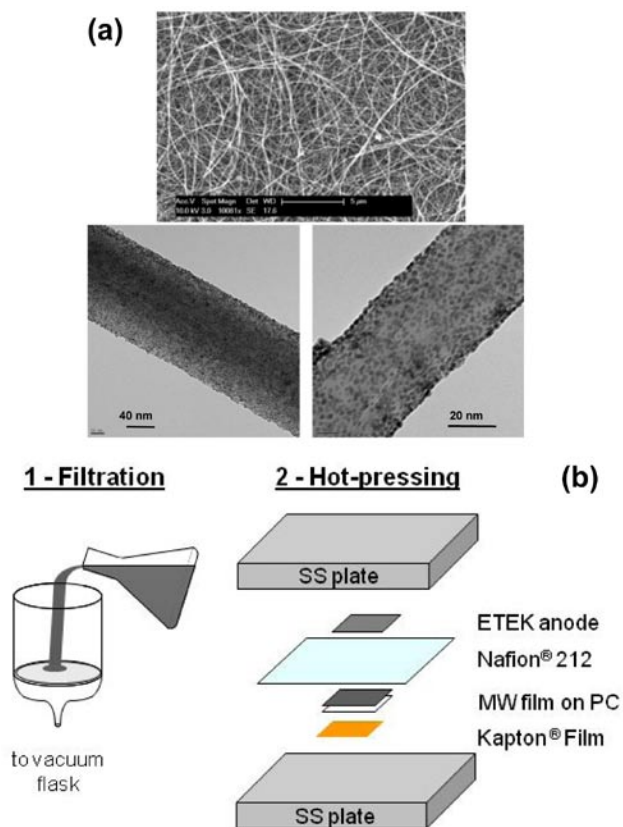


Figure 6. MWNT-supported Pt catalyst: (a) TEM images; (b) MEA fabrication method.

performance of a MWNT-based cathode is inadequate for meeting power requirements of most fuel cell systems and needs to be improved.

Conclusions and Future Directions

- Core-shell catalysts with greatly reduced Pt loading offer much better ORR performance in aqueous electrolytes and in hydrogen-air fuel cells than standard carbon-supported Pt catalysts; based on measured RDE activity, these catalysts stand a very good chance of meeting 2010 DOE stack performance targets, provided de-alloying and catalyst agglomeration can be avoided (recent durability data are very encouraging in that regard); development of a methodology for increasing the number of high-coordination surface atoms of core-shell nanoparticles to enhance their ORR activity and stability will be the main research task in this part of the project.
- Several non-precious metal catalysts, mostly PANI-derived, exhibit much improved ORR activity, very good selectivity for the four-electron

oxygen reduction and promising fuel cell stability for hundreds of hours; in spite of this significant progress, all non-precious metal catalyst are in need of further activity improvement, by at least of a factor of five; the focus of future research will be on (i) increasing ORR activity, (ii) assuring stability, and (iii) determination of the active ORR site using a wide range of available techniques, X-ray-based in particular.

- Susceptibility of carbon-rich non-precious catalysts to flooding continues to be a major performance issue for non-precious catalysts, especially at high current densities; future research will focus on designing electrode structure amenable to more efficient water management than traditional MEA designs.
- Novel electrode structures based on nanostructures potentially offer considerable performance advantages over dispersed carbons and improved catalyst utilization; future research will concentrate on taking full advantage of the unique morphological and, possibly, electrocatalytic properties of these materials.

Special Recognitions & Awards/Patents Issued

- “Method of Making Metal-Polymer Composite Catalysts,” P. Zelenay and R. Bashyam, U.S. Patent Application 2007/0082804A1 (notice of allowance received).
- “Microparticles with Hierarchical Porosity,” D. Petsev, P. Atanassov, S. Pylypenko, and N. Carroll; Patent Application 61/061,589 filed by the University of New Mexico on June 13, 2008.

FY 2009 Publications

- “Advanced Cathode Catalysts,” P. Zelenay, Z. Chen, J. Chlistunoff, H. Chung, S. Conradson, F. Garzon, C. Johnston, G. Purdy, T. Rockward, J. Valerio, G. Wu, D. Myers, J. Kropf, M. Smith, X. Wang, R. Adzic, W. Chen, K. Sasaki, M. Vukmirovic, J. Wang, W. Zhou, P. Atanassova, B. Blizanac, G. Rice, Y. Sun, K. More, Y. Yan, S. Alia, Z. Chen, P. Larsen, L. Xu, A. Wiecekowsky, P. Babu, A. Bonakdarpour, C. Delacôte, P. Atanassov, K. Artyushkova, D. Konopka, S. Pylypenko; U.S. Department of Energy, Hydrogen, Fuel Cells & Infrastructure Technologies Program; 2008 Annual Progress Report; pp. 892-898. http://www.hydrogen.energy.gov/pdfs/progress08/v_c_7_zelenay.pdf.
- “Transition Metal/Polymer Catalysts for O₂ Reduction,” C.M. Johnston, P. Piela, and P. Zelenay, in *Handbook of Fuel Cells: Fundamentals, Technology, and Applications*; vol. 5; Chapter 4, pp. 48-70, W. Vielstich, H.A. Gasteiger, and H. Yokokawa, Eds., Wiley & Sons; Chichester, United Kingdom, 2009.

3. "Platinum Monolayer Electrocatalysts for Fuel Cells;" F. Lima, R.R. Adzic, in *Handbook of Fuel Cells: Fundamentals, Technology, and Applications*; vol. 5; Chapter 1, pp. 5-17, W. Vielstich, H.A. Gasteiger, and H. Yokokawa, Eds., Wiley & Sons; Chichester, United Kingdom, 2009.
4. "Dissolution and Stability of Platinum in Oxygen Cathodes;" K. Sasaki, M. Shao, and R.R. Adzic, in *Polymer Electrolyte Fuel Cells Durability*; M. Inaba, F. Buechi, and T.J. Schmidt, Eds., p. 7-27, Springer, New York; 2009.
5. "Electrochemical Evaluation of Porous Non-Platinum Oxygen Reduction Catalysts for Polymer Electrolyte Fuel Cells;" T.S. Olson, B. Blizanac, B. Piel, J.R. Davey, P. Zelenay, and P. Atanassov, *Fuel Cells*, accepted.
6. "In situ XAFS Analysis of Cobalt-containing Fuel Cell Cathode Electrocatalysts;" A.J. Kropf, D. Myers, M.C. Smith, J. Chlistunoff, G. Wu, and P. Zelenay, *Prepr. Pap.-Am. Chem. Soc.*, **54** (1), (2009).
7. "XAS of Platinum Monolayer Fuel Cell Electrocatalysts - Anambiguous, Direct Correlation of Spectroscopy Data with Catalytic Properties;" K. Sasaki, and R.R. Adzic, *Synchrotron Radiation News*, **22** (1) 17-21 (2009).
8. "Intrinsic kinetic equation for oxygen reduction reaction in acidic media: The double Tafel slope and fuel cell applications;" J.X. Wang, F. Uribe, T.E. Springer, J. Zhang, and R.R. Adzic, *Faraday Discuss.* **140**, 347-362 (2009).
9. "A Non-Precious Electrocatalyst for Oxygen Reduction Based on Simple Heat Treated Precursors;" H.T. Chung, C.M. Johnston, F.H. Garzon, and P. Zelenay; *ECS Trans.*, **16** (2) 385-391 (2008).
10. K. Sasaki, M. Shao, R.R. Adzic, Dissolution and Stability of Platinum in Oxygen Cathodes, Polymer Electrolyte Fuel Cell Durability, T.J. Schmidt et al (Eds), Springer Science, in press.
11. "Polyaniline-derived Non-Precious Catalyst for the Polymer Electrolyte Fuel Cell Cathode;" G. Wu, Z. Chen, K. Artyushkova, F. Garzon, and P. Zelenay, *ECS Trans.*, **16** (2) 159-170 (2008).
12. "Aqueous-Based Synthesis of Ruthenium-Selenium Catalyst for Oxygen Reduction Reaction;" C. Delacôte, A. Bonakdarpour, C. M. Johnston, P. Zelenay, and A. Wieckowski; *Faraday Discuss.*, **140**, 269-281 (2008).
13. "Niobium Oxide-Supported Platinum Ultra-Low Amount Electrocatalysts for Oxygen Reduction;" K. Sasaki, L. Zhang, and R.R. Adzic, *Phys. Chem. Chem. Phys.*, **10**, 159 (2008).
14. "Pt monolayer electrocatalysts for O₂ reduction: PdCo/C substrates-induced activity in alkaline media;" F.H. B. Lima, J. Zhang, M.H. Shao, K. Sasaki, M.B. Vukmirovic, E.A. Ticianelli, and R.R. Adzic, *J. Solid State Electrochem.*, **12** (4), 399-407 (2008).
15. "Loading of Se/Ru/C "Electrocatalyst on a Rotating Ring-Disk Electrode and the Loading Impact on a H₂O₂ Release during Oxygen Reduction Reaction;" A. Bonakdarpour, C. Delacote, R. Yang, A. Wieckowski, and J.R. Dahn, *Electrochem. Commun.*, **10**, 611-615 (2008).

16. "A Catalyst Layer Flooding Model for Polymer Electrolyte Fuel Cells;" P.P. Mukherjee and C.Y. Wang, Proceedings of ASME FuelCell 2008, 6th ASME International Fuel Cell Science, Engineering, and Technology Conference, Denver, CO, USA, June 16-18 (2008).

FY 2009 Presentations

1. 237th Meeting of American Chemical Society, Salt Lake City, Utah, March 22-26, 2009. Title: "In situ XAFS Analysis of Cobalt-containing Fuel Cell Cathode Electrocatalysts;" A.J. Kropf, D. Myers, M.C. Smith, J. Chlistunoff, G. Wu, and P. Zelenay.
2. The 7th Spring Meeting of the International Society of Electrochemistry, Szczyrk, Poland, March 22-25, 2009. Title: "New Non-precious Oxygen Reduction Catalysts for Polymer Electrolyte Fuel Cells;" P. Zelenay, G. Wu, H.T. Chung (invited lecture).
3. Canada-USA PEM Network Research Workshop, Vancouver, Canada, February 16-17, 2009. Title: "Progress in the Development of Non-precious Fuel Cell Cathode-Catalysts at Los Alamos National Laboratory;" G. Wu and P. Zelenay (invited lecture).
4. 214th Meeting of The Electrochemical Society, Honolulu, Hawaii, October 12-17, 2008. Title: "A Non-Precious Electrocatalyst for Oxygen Reduction Based on Simple Heat-Treated Precursors;" H. Chung, C. Johnston, F. Garzon, and P. Zelenay.
5. 214th Meeting of The Electrochemical Society, Honolulu, Hawaii, October 12-17, 2008. Title: "Electronic Interactions Between Components and Adsorbates on Fuel Cell Catalysts - Combined XPS and Electrochemical Studies;" A. Wieckowski.
6. 214th Meeting of The Electrochemical Society, Honolulu, Hawaii, October 12-17, 2008. Title: "Polyaniline-derived Non-Precious Catalyst for the Polymer Electrolyte Fuel Cell Cathode;" G. Wu and P. Zelenay.
7. Center for Emerging Energy Technologies (CEET) Workshop on "Spectroscopic methods in structure-to-property correlation for catalysts and electrocatalysts", Sunrise Springs Resort, Santa Fe, New Mexico, September 25-26, 2008. Title: "Particle Size Dependence of Fuel Cell Reaction Rates;" A. Wieckowski.
8. Progress MEA 2008, First CARISMA International Conference, La Grande Motte, France, September 21-24, 2008. Title: "In Situ X-ray Absorption and Scattering Studies of Cathode Electrocatalysts;" D. Myers, M. Smith, and A.J. Kropf, J. Chlistunoff, C.M. Johnston, S.D. Conradson, and P. Zelenay.
9. 3rd LANL-AIST-NEDO Workshop on Fuel Cells and Hydrogen Storage, San Diego, California, September 8-11, 2008. Title: "New Non-precious Catalysts with High ORR Performance;" G. Wu, C. Hoon, Z. Lin, K. Artyushkova, F. Garzon, and P. Zelenay.

- 10.** 50th Annual Meeting of the International Society of Electrochemistry, Seville, Spain, September 7–12, 2008. Title: “Some Recent Advances and Existing Challenges in the O₂ Reduction and Ethanol Oxidation Reactions;” W-P. Zhou, W-F. Chen, K. Sasaki, M. Vukmirovic, M. Li, A. Kowal, P. Liu, J. Wang, R.R. Adzic.
- 11.** NANOCOMPOSITES 2008-Enabling Technologies and New Markets, September 2008, San Diego, CA. Title: “Recent Advances in Developing Platinum Monolayer Electrocatalysts for the O₂ Reduction Reaction;” M.B. Vukmirovic, K. Sasaki, W-P. Zhou, M. Li, P. Liu, J.X. Wang, R.R. Adzic.
- 12.** Xiamen University, Xiamen, China, August 13, 2008. Title: “Fuel Cell Science in Perspective of New Spectroscopic Research;” A. Wieckowski.
- 13.** Nanyang Technological University, Singapore, August 6, 2008. Title: “Synchrotron Photoemission of Metal/Alloy Nanoparticles in Reference to Fuel Cell Electrocatalysis;” A. Wieckowski.
- 14.** Faraday Discussion 140: Electrocatalysis - Theory and Experiment at the Interface, Southampton, United Kingdom, July 7–9, 2008. Title: “Aqueous-Based Synthesis of Ruthenium-Selenium Catalyst for Oxygen Reduction Reaction;” C. Delacôte, A. Bonakdarpour, C.M. Johnston, P. Zelenay, and A. Wieckowski*.
- 15.** The 6th International Symposium on New Materials for Electrochemical Systems, Montreal, Canada, June 24–27, 2008. Title: “Spectroscopy in Fuel Cell Catalysis Research;” A. Wieckowski.
- 16.** Hydrogen, Fuel Cells & Infrastructure Technologies Program, 2008 Merit Review and Peer Evaluation Meeting, U.S. Department of Energy, Energy Efficiency and Renewable Energy, Arlington, Virginia, June 9-13, 2008. Title: “Advanced Cathode Catalysts;” P. Zelenay. http://www.hydrogen.energy.gov/pdfs/review08/fc_3_zelenay.pdf
- 17.** 213th Meeting of The Electrochemical Society, Phoenix, Arizona, May 18-22, 2008. Title: “Oxygen Reduction on Se/Ru and Se/Ru-Fe Catalysts;” A. Wieckowski*, C. Delacôte, A. Bonakdarpour, A. Lewera, C. Johnston, and P. Zelenay.
- 18.** 213th Meeting of The Electrochemical Society, Phoenix, Arizona, May 18–22, 2008. Title: “Semi-empirical Modeling of Co-Polypyrrole Composites: Oxygen Reduction Catalysis;” J. Chlistunoff* and P. Zelenay.
- 19.** 213th Meeting of The Electrochemical Society, Phoenix, Arizona, May 18–22, 2008. Title: “New Metal Deposition Methods for Electrocatalysts Syntheses;” R.R. Adzic, M.B. Vukmirovic, J. Zhang, and K. Sasaki.
- 20.** 213th Meeting of The Electrochemical Society, Phoenix, Arizona, May 18–22, 2008. Title: “Oxygen reduction reaction on a Pt monolayer on Pd2Co(111) crystals;” W.-P. Zhou, M.B. Vukmirovic, K. Sasaki, and R.R. Adzic.
- 21.** 213th Meeting of The Electrochemical Society, Phoenix, Arizona, May 18–22, 2008. Title: “Non-Precious Metal Nano-Composite Oxygen Reduction Electrocatalysts: In situ X-ray Absorption Spectroscopy Studies;” M. Smith*, J. Kropf, D. Myers, J. Chlistunoff, C. Johnston, S. Conradson, and P. Zelenay
- 22.** 213th Meeting of The Electrochemical Society, Phoenix, Arizona, May 18-22, 2008. Title: “Polypyrrole-Carbon Based Non-Precious Metal Nanocomposite Electrocatalysts for Oxygen Reduction Reaction at PEFC Cathode;” Z. Chen*, C. Johnston, Y. Yan, and P. Zelenay.