

V.C.7 Advanced Cathode Catalysts

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- ¹ Argonne National Laboratory (ANL), Argonne, IL
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- ³ Cabot Fuel Cells (CFC), Albuquerque, NM
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Project Start Date: March 2007
 Project End Date: 2011

Objectives

The main objective of this project is to:

- Develop oxygen reduction reaction (ORR) catalyst, alternative to pure platinum, 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.
- Determine the ORR mechanism on newly developed catalysts via extensive physicochemical characterization and electrochemical and fuel cell testing.

- Optimize electrode with new catalysts and structures for maximum performance and catalyst utilization.
- Evaluate catalyst stability; minimize performance loss over time.
- Assure path forward for 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
- (B) Cost
- (C) Performance

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)	2008 Status (Cathode)
PGM total content	g/kW (rated)	0.3	0.25 ¹
PGM total loading	mg _{PGM} /cm ² electrode area	0.3	0.11 ¹
Cost	\$/kW	5	7 ^{1,2}
Durability with cycling - At operating temperature of ≤80°C - At operating temperature of >80°C	hours hours	5,000 2,000	TBD TBD
Mass activity	A/mg _{Pt} at 900 mV _{iR-free}	0.44	0.43 ³ 0.86 ⁴
Non-Pt Catalyst Activity per Volume of Supported Catalyst	A/cm ³ at 800 mV _{iR-free}	> 130	TBD

¹ PtAuNi₂/C cathode tested in 5-cm² single fuel cell with Pt/C anode at 80°C (not optimized)

² Pt and Au prices from July 10, 2008

³ Mass activity per mg_{Pt+Au} in PtAuNi₂/C catalyst in RDE testing at 0.900 V

⁴ Mass activity per mg_{Pt} in PtAuNi₂/C catalyst in RDE testing at 0.900 V

PGM - platinum group metal

TBD - to be determined

Accomplishments

- Developed several “core-shell” catalysts, such as PtAuNi₅/C, Pt_{ML}/Pd₃Fe/C and Pt/Pd/C, with mass activity of Pt in oxygen reduction reaction at 0.9 V 6-16 times that of a Pt/C catalyst (rotating disk electrode [RDE] testing).
- Demonstrated more than 3× performance advantage of a PtAuNi₅/C catalyst over Pt/C per mass of Pt in hydrogen-air fuel cell testing (5-cm² cell at 80°C).
- Achieved partial (~30%) replacement of Ru by Fe in chalcogenide catalysts without a significant drop in the ORR activity.
- Synthesized thermally-untreated CoTPPS supported on polypyrrole (PPy) nanotubes with much improved durability relative to carbon-supported CoTPPS catalyst.
- Demonstrated new thermally-treated non-precious metal catalysts, PPy-, polyaniline (PANI)-, and ethylene diamine (EDA)-derived, capable of generating up to 0.5 W cm⁻² in power density and showing good stability at the fuel cell cathode for more than 100 hours.
- Built and experimentally validated an experimental setup for in situ fuel-cell studies of ORR catalysis using X-ray absorption.
- Developed several new electrode structures, either polymer or carbon-based obtained using anodic aluminum oxide (AAO) templates and silica-templated carbon spheres by microemulsion/reverse-emulsion method.



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 of the fuel cell power system through major 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 three 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); (ii) chalcogenide-based catalysts (surface chalcogenides, chalcogenides with non-precious metal

core); and (iii) 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 catalyst, Ru-containing chalcogenides) or loading of non-precious metal catalysts, which have intrinsically lower than platinum ORR activity. The electrode-structure component of the effort concentrates on two groups of materials: (i) open-frame catalyst structures obtained using microemulsion/reverse emulsion techniques and other techniques, and (ii) templated nanostructures, such as nanofibers and nanotubes, made of polymers (e.g. polypyrrole), carbon, and non-carbon inorganic materials.

In addition to short-term testing and initial performance assessment, catalysts, supports, electrode structures, and membrane-electrode assemblies, developed in this project are subject to long-term performance (durability) testing. Performance degradation mechanism is identified and, if possible, addressed. Fabrication and scale-up of practically viable catalysts and supports is also being tackled through collaboration with an industrial partner.

Results

Catalysts with Ultra-Low Pt Content. In the past year, we developed several different types of “core-shell” catalysts in this group, some with very high ORR activity. The catalysts included mixed Pt-metal monolayer catalysts, transition-metal core/precious-metal shell catalysts, and stable-metal core/precious-metal shell catalysts. The PtAuNi₅/C catalyst showed ORR half-wave potential by ~80 mV higher than a reference Pt/C catalyst in RDE testing. This significant half-wave potential ($E_{1/2}$) advantage was the reason for mass activity improvement by a factor of 16 and 8 when referred to the mass of Pt and total precious metal mass (Pt+Au) in PtAuNi₅/C, respectively (RDE data). Without any optimization of the catalyst composition and cathode structure, PtAuNi₅/C catalyst showed more than threefold Pt-mass performance advantage over a reference Pt/C catalysts in a hydrogen-air fuel cell (Figure 1). While very active in the ORR, the PtAuNi₅/C catalyst lost some performance during 200 hours of operation at a constant voltage of 0.5 V, a shortcoming that will be addressed in the future.

Also in this group, we developed catalysts with non-precious core, such as Pt_{ML}/Pd₃Fe/C, and precious metal core, e.g. Pt/Pd/C. Mass activity of Pt in Pt_{ML}/Pd₃Fe/C

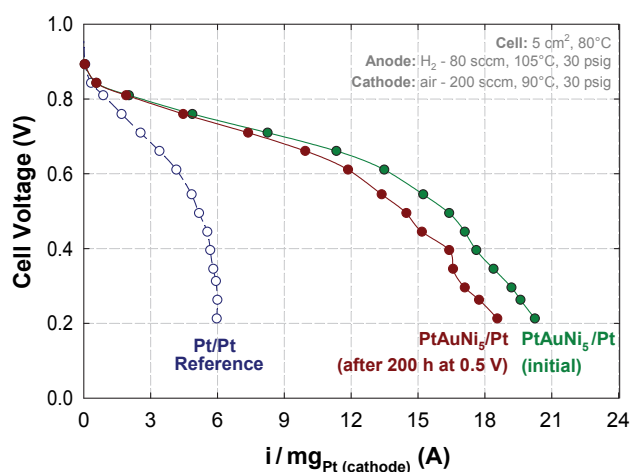


FIGURE 1. Pt-Mass-Based Performance Comparison of a PtAuNi₅ Catalyst and a Reference Pt Catalyst in a Hydrogen-Air Fuel Cell at 80°C. (BNL: 20 wt% Pt/C anode - 0.21 mg_{Pt} cm⁻²; 20 wt% PtAuNi₅/C cathode - 0.21 mg cm⁻². Reference: 20 wt% Pt/C anode - 0.21 mg_{Pt} cm⁻²; 20 wt% Pt/C cathode - 0.25 mg cm⁻²)

exceeded that of the Pt/C reference by approximately 6× at either 0.85 V or 0.90 V, as measured under RDE conditions. In turn, the ORR half-wave potential with Pt/Pd/C catalyst was 0.915 V, one of the highest measured (Figure 2a). Like the other two catalysts, Pt/Pd/C showed ORR activity several times higher than the Pt/C reference catalyst. Transmission electron microscopy (TEM) data revealed an ideal core-shell structure of Pt/Pd/C catalysts (Figure 2b).

Chalcogenide-Based Catalysts. Our technical approach in this part of research concentrated on the development of effective synthesis paths for first making a carbon-supported RuSe catalyst, followed by a gradual replacement of Ru with a non-precious Fe. Per Ru mass, a 10 wt% RuSe/C catalyst showed noticeable improvement in the ORR performance over a 20 wt% Ru/C catalyst (Figure 3). In the second phase of the chalcogenide research, part of Ru was replaced by Fe, initially in a mixed phase catalyst (Se/Ru-Fe/C), later in a “core-shell” catalyst, by controlled formation of thin layer of Ru around a Fe core. Energy dispersive X-ray analysis revealed that approximately 30 at% of Fe was retained in such a “core-shell” catalyst, an improvement over 20 at% of Fe in the mixed-phase” Se/RuFe/C sample.

Precious Metal-Free Catalysts. New catalysts in this group fall in two categories: (i) thermally-untreated ORR catalysts and (ii) heat-treated (pyrolyzed) materials. In the first category, we used a porous AAO template form PPy nanotubes as a support for a CoTPPS non-precious catalyst (Figure 4). This “low-temperature” catalyst showed significantly improved stability relative to carbon-supported CoTPPS catalyst. After 200 cycles in the potential range of 0-1.0 V, the ORR half-wave potential of a PPy-supported catalyst shifted by ~15 mV,

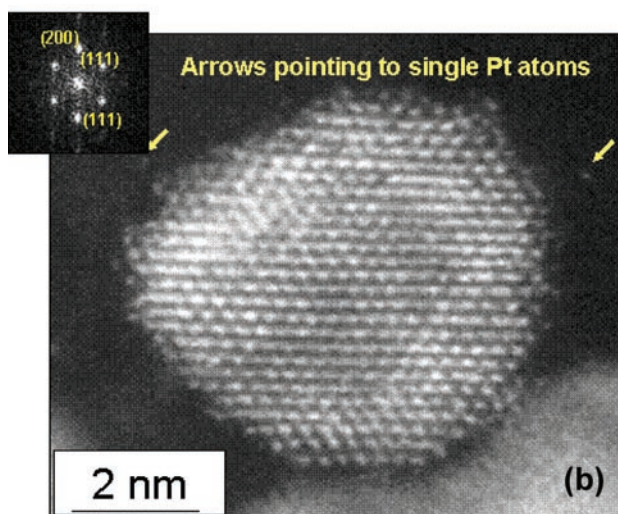
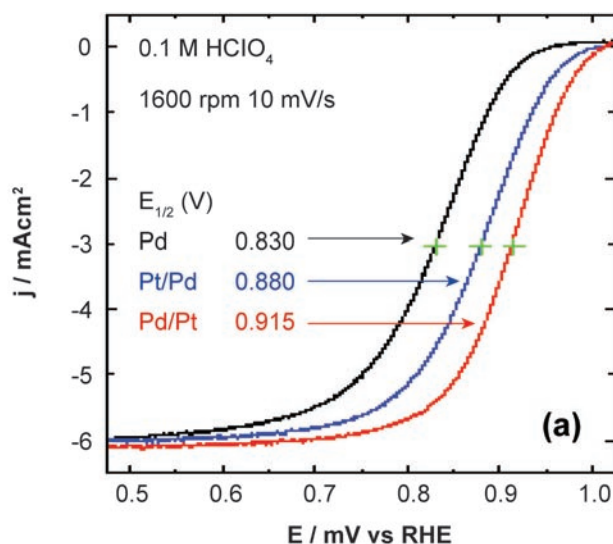


FIGURE 2. Pt/Pd/C “Core-Shell” Catalyst: (a) RDE Performance and (b) TEM Image

compared to ~100 mV for the CoTPPS supported on carbon. This result provides another evidence of strong interaction occurring between heterocyclic polymers and transition metals, and its role in oxygen reduction electrocatalysis [1,2].

In the past year, we developed several catalysts by thermally-treating PPy, PANI, EDA and other complexes of Co, Cu, Fe, and Ni. Several catalysts were capable of generating up to 0.5 W cm⁻² in power density and showed good stability at the fuel cell cathode for more than 100 hours. An example of a non-precious catalyst with promising combined activity and stability is CoFe-PPy-KJ300, which delivered more than 0.4 A cm⁻² at 0.5 V (maximum power density greater than 0.4 W cm⁻² at ~0.2 V) in a hydrogen-oxygen cell (Figure 5a). The catalyst performance loss was less than 10% during a 130-hour constant voltage life-test in a hydrogen-air

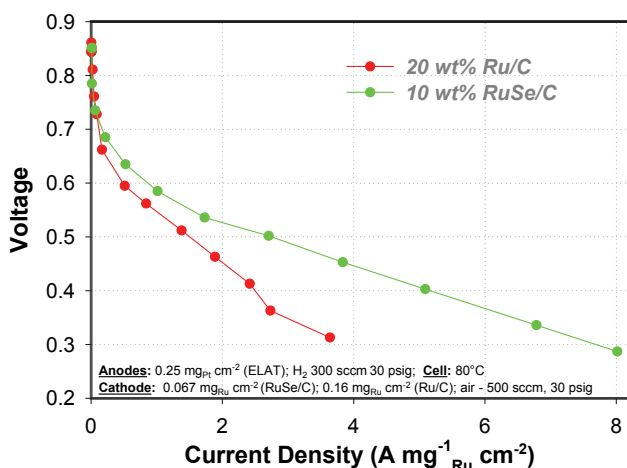


FIGURE 3. Fuel Cell Polarization Plots Recorded with 10 wt% RuSe/C and 20 wt% Ru/C Catalysts at 80°C (See figure for detailed operating conditions of the cell.)

fuel cell (Figure 5b). Numerous non-precious catalysts, including PPy-, EDA-, and PANI-derived catalysts containing both Co and Fe, and a new “nitrogen-free” thermally-treated catalyst, generated up to 40 A per cm³ of the catalyst volume. The best performing materials also showed good selectivity in four-electron reduction

of oxygen, with H₂O₂ yields dropping to less than 2% in some cases.

We continued to use semi-empirical methods, capable of handling large systems to model complexes of transitional metals (cobalt) with organic ligands to quantify interaction of molecular oxygen with such metal centers. We found good agreement between semi-empirical molecular modeling of a possible active ORR site in Co-PPy-XC72 catalyst and spectroscopic data obtained by X-ray absorption fine structure at the Stanford Linear Accelerator Center and the Advanced Photon Source at ANL (an in situ fuel cell experiment in the latter case) and by electron paramagnetic resonance. We also modeled free energies of four-electron ORR catalyzed by oligopyrrole complexes of Co.

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 polymeric nanostructures, such that shown in Figure 4, and also carbon-based electrodes with hierarchical porosity. We developed new silica templates, obtained using emulsion/reverse-emulsion method. The silica templates thus fabricated were used to create carbon replicas for catalyzation with various catalysts developed in this project. We recently demonstrated the first catalyzed carbon structure with

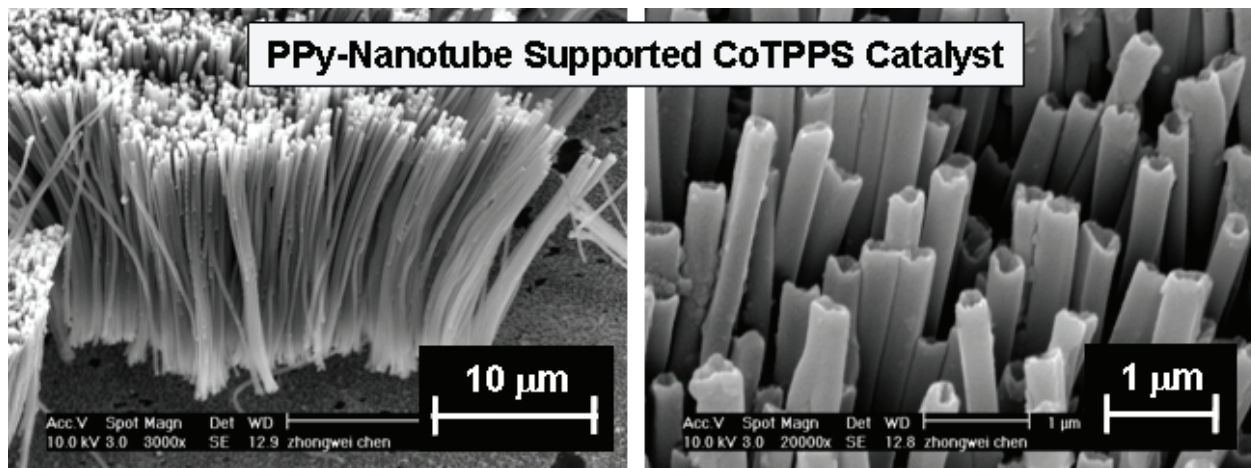
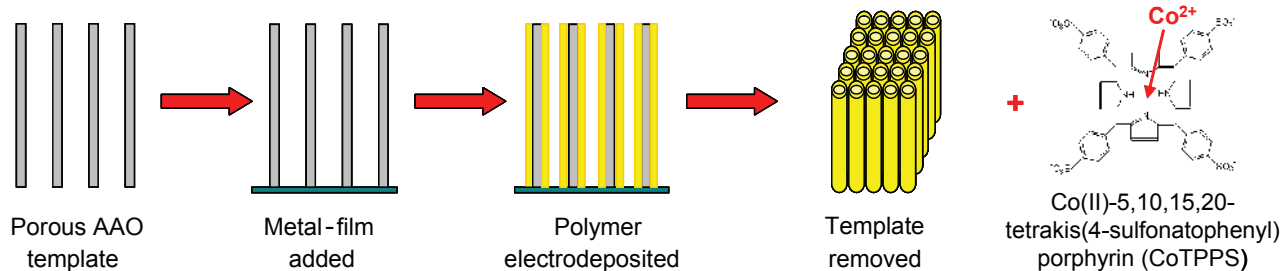


FIGURE 4. Synthesis and Micrography of a Low-Temperature CoTPPS Catalyst Supported on AAO-Templated PPy Nanotubes

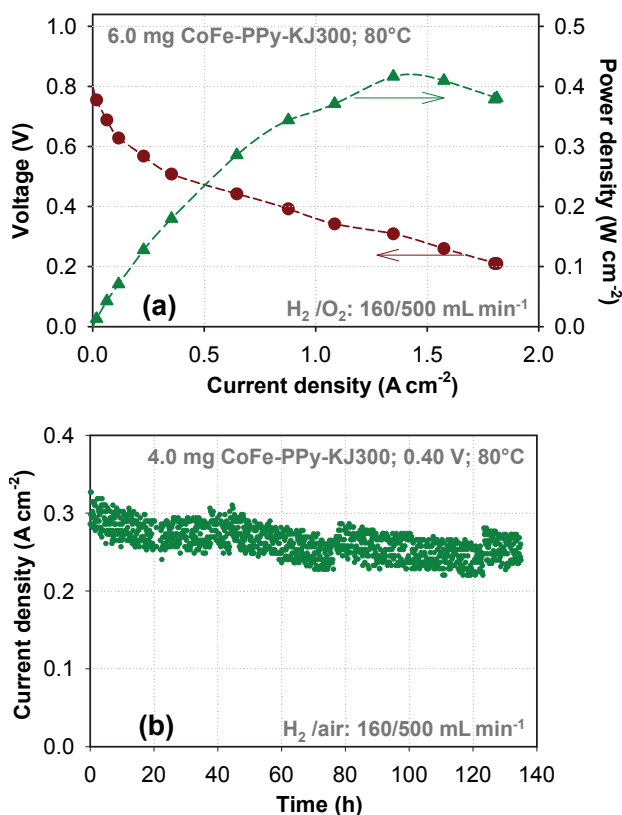


FIGURE 5. CoFe-PPyKJ300 Catalyst: (a) Hydrogen-Oxygen Fuel Cell Polarization and Power-Density Plots at 80°C and (b) 130-Hour Life Test in a Hydrogen-Air Fuel Cell at 80°C (See figure for other details.)

hierarchical porosity – a 30 wt% Pt/C (Figure 6). Such-catalyzed templated carbon structure was tested at RDE with promising results.

Conclusions and Future Directions

- Many “core-shell” catalysts with very significantly reduced Pt loading offer much better performance in aqueous electrolytes and in hydrogen-air fuel cells than standard carbon-supported Pt catalysts; based on the current measured, these materials stand a very good chance of meeting 2010 DOE stack performance targets, provided corrosion of less-stable component metals as well as de-alloying can be avoided and long-term stability maintained; improvements to nanoparticle stability will be the main research task in this part of the project.
- Partial replacement of Ru by Fe and other non-precious metals in chalcogenide catalysts appears possible, especially in catalysts with “core-shell” structure; as in the case of some other core-shell catalysts, preventing dissolution of non-precious metal from the bulk phase of nanoparticles represents a major challenge that will be addressed in future, together with further lowering of Ru content in the catalysts.
- While several non-precious metal catalysts, obtained either at low or high temperatures, exhibit promising activity and fuel cell performance for a few hundred

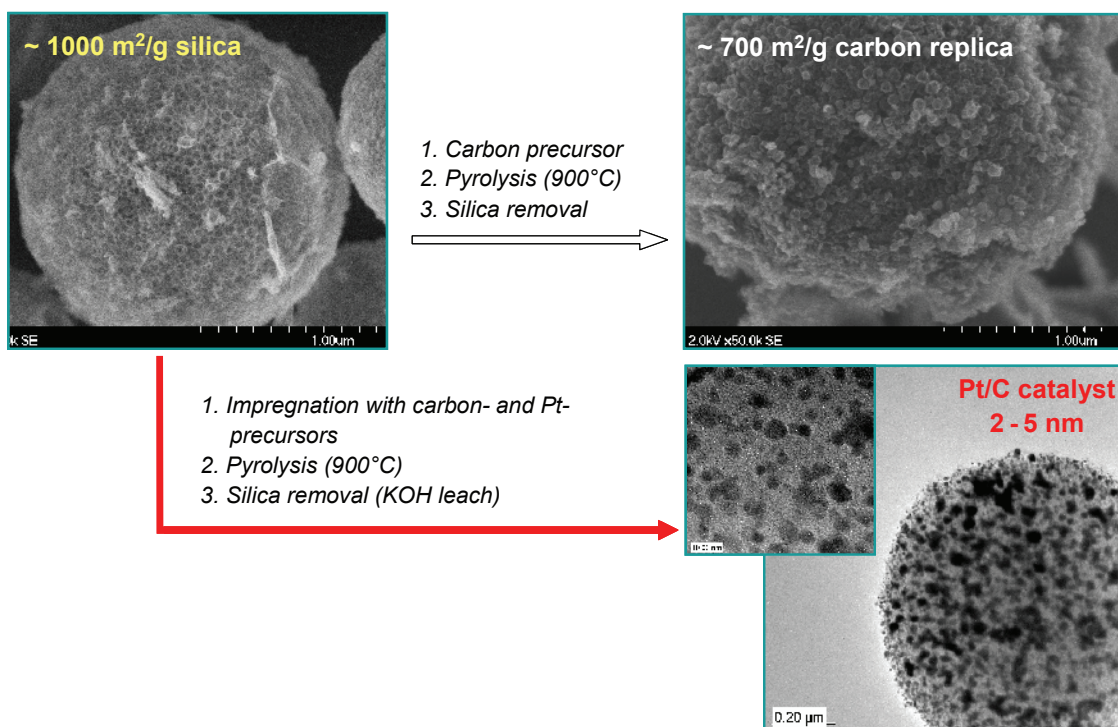


FIGURE 6. Schematic Diagram of the Synthesis of a Pt/C Catalyst on a Silica-Templated Structure (Silica with hierarchical porosity obtained using emulsion/reverse-emulsion method.)

hours, all non-precious metal catalysts are in need of further performance improvements before becoming a viable alternative to the state-of-the-art Pt and Pt-based ORR catalysts; the focus of future research will remain on (i) increasing ORR activity and (ii) assuring stability; much better understanding of the ORR mechanism on non-precious catalysts will also be pursued as vitally needed for faster progress.

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

Special Recognitions & Awards/Patents Issued

1. 2008 Los Alamos National Laboratory Patent & Licensing Award (May 2008; for year 2007).

FY 2008 Publications

1. "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.*, in press.
2. "Performance and Durability of Chalcogenide-Modified Ruthenium Catalysts for Oxygen Reduction: Hydrogen-Air MEA and RRDE Studies;" C.M. Johnston, J.-H. Choi, P.K. Babu, A. Wieckowski, and P. Zelenay; *ECS Trans.*, 6 (25) 117 (2008).
3. "Novel Chalcogenide-Based Materials for Oxygen Reduction Reaction;" C. Delacôte, C.M. Johnston, P. Zelenay, and N. Alonso-Vante; *ECS Trans.*, 6 289 (2008).
4. "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).
5. "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. Delacôte, R. Yang, A. Wieckowski, and J.R. Dahn; *Electrochem. Commun.* 19, 611 (2008).
6. "Pt monolayer electrocatalysts for O₂ reduction: PdCo/C substrate-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, 399 (2008).

7. "Advanced Cathode Catalysts;" P. Zelenay, R. Bashyam, E. Brosha, J. Chlistunoff, S. Conradson, F. Garzon, C. Johnston, R. Mukundan, J. Spendelow, J. Valerio, M. Wilson; US Department of Energy, Hydrogen, Fuel Cells & Infrastructure Technologies Program; 2007 Annual Progress Report; pp. 838-842. http://www.hydrogen.energy.gov/pdfs/progress07/v_e_6_zelenay.pdf
8. "Pd₃Fe and Pt Monolayer-Modified Pd₃Fe Electrocatalysts for Oxygen Reduction;" M.H. Shao, K. Sasaki, P. Liu, and R.R. Adzic, *Z. Phys. Chem.*, 221 1175 (2007).
9. "Scientific Aspects of Polymer Electrolyte Fuel Cell Durability and Degradation;" R. Borup, J. Meyers, B. Pivovar, Y.S. Kim, N. Garland, D. Myers, R. Mukundan, M. Wilson, F. Garzon, D. Wood, P. Zelenay, K. More, T. Zawodzinski, J. Boncella, J.E. McGrath, M. Inaba, K. Miyatake, M. Hori, K. Ota, Z. Ogumi, S. Miyata, A. Nishikata, Z. Siroma, Y. Uchimoto, and K. Yasuda; *Chem. Rev.*, 107, 3904 (2007) – invited article.
10. "Platinum Monolayer Electrocatalysts for Oxygen Reduction;" B. Vukmirovic, J. Zhang, K. Sasaki, F. Uribe, M. Mavrikakis, and R.R. Adzic. *Electrochim. Acta*, 52, 2257 (2007).

11. "XPS Structural Studies of Nano-Composite Non-Platinum Electrocatalysts for Polymer Electrolyte Fuel Cells;" K. Artyushkova, S. Levendosky, P. Atanassov, and J. Fulghum, *Top. Catal.*, 46 263 (2007) – invited article for special issue on fuel cells.

12. "Dual-Trap Kinetic Equation for the Oxygen Reduction Oxidation Reaction on Pt(111) in Acidic Media;" J.X. Wang, J. Zhang, R.R. Adzic, *J. Phys. Chem. A*, 111, 12702 (2007).

FY 2008 Presentations

1. 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*.
2. 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. M. Johnston, and P. Zelenay.
3. 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.
4. 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.

5. 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.
6. Indiana University-Purdue University Indianapolis, Purdue School of Engineering and Technology, Mechanical Engineering Department, March 18, 2008. Title: "Oxygen Reduction at Transition Metal/Heteratomic Polymer Catalysts;" J. Chlistunoff (*invited lecture*).
7. US-Canada Fuel Cell Workshop, Vancouver, Canada, March 17-18, 2008. Title: "Ruthenium Replacement by Transition Metals in "Chalcogenide" Cathode Catalysts", Title: C. Delacôte, A. Bonakdarpour, and A. Wieckowski* (*invited lecture*).
8. US-Canada Fuel Cell Workshop, Vancouver, Canada, March 17-18, 2008. Title: "Alternative Oxygen Reduction Catalysts for Polymer Electrolyte Fuel Cells;" P. Zelenay (*invited lecture*).
9. 2008 Mesilla Chemistry Workshop "New Frontiers of Electrocatalysis", Mesilla, New Mexico February 9-13, 2008. Title: "Platinum monolayer electrocatalysts for O₂ reduction: advances with alloy and oxide supports", J. Zhang, M. H. Shao, K. Sasaki, M. Vukmirovic, P.Liu, J. Wang, R. R. Adzic* (*invited lecture*).
10. 2008 Mesilla Chemistry Workshop: New Frontiers of Electrocatalysis, Mesilla, New Mexico, February 9-13, 2008. Title: "Oxygen Reduction at Transition Metal/Heteratomic Polymer Catalysts;" J. Chlistunoff.
11. 2007 AIChE Annual Meeting, Salt Lake City, Utah, November 04-09, 2007. Title: "Durability and Catalytic Activity Study of Carbon Nanotubes Supported Pt Nanoparticles Electrocatalysts for Proton Exchange Membrane Fuel Cells;" Z. Chen, M. Waje, W. Li, and Y. Yan.
12. 2007 AIChE Annual Meeting, Salt Lake City, Utah, November 04-09, 2007. Title: "Supportless Pt and Pt-Pd Nanotubes as Electrocatalysts for Oxygen Reduction Reaction;" Z. Chen, M. Waje, W. Li, and Y. Yan.
13. University of Tokyo, Department of Chemistry, Tokyo, Japan, November 2, 2007. Title: "Alternative Catalysts for Oxygen Reduction in Polymer Electrolyte Fuel Cells;" Piotr Zelenay (*invited lecture*).
14. LANL-NEDO-AIST Workshop, Tokyo, Japan October 29 – November 1, 2007. Title: "Alternative Catalysts for Oxygen Reduction Reaction at the PEFC Cathode;" P. Zelenay (*two invited lectures*).
15. 212th Meeting of The Electrochemical Society, ECS Washington, D.C., October 7-12, 2007. Title: "Supportless Pt and Pt-Pd Nanotubes with High Durability and Activity towards Oxygen Reduction Reaction for PEMFCs;" Z. Chen, M. Waje, W. Li, and Y. Yan.
16. 212th Meeting of The Electrochemical Society, ECS Washington, D.C., October 7-12, 2007. Title: "Durability and Activity Study of Single-Walled, Double-Walled and Multi-Walled Carbon Nanotubes Supported Pt Catalyst for PEMFCs;" Z. Chen, M. Waje, W. Li, and Y. Yan. 212th Meeting of The Electrochemical Society, ECS Washington, D.C., October 7-12, 2007. Title: "Supportless Pt and Pt-Pd Nanotubes with High Durability and Activity towards Oxygen Reduction Reaction for PEMFCs;" Z. Chen, M. Waje, W. Li, and Y. Yan.
17. 212th Meeting of the Electrochemical Society. Washington, D.C., October 7-12, 2007. Title: "Hydrogen Oxidation and Oxygen Reduction Reactions on a c(2 x 2)Pt-RuO₂(110) and the Single Pt Atom Activities, M. Vukmirovic, P. Liu, J. Muckerman and R. Adzic.
18. 212th Meeting of the Electrochemical Society. Washington, D.C., October 7-12, 2007. Title: "Double-Trap Kinetic Equation for the ORR: Mechanism and Rate-Determining Factors", J. X. Wang*, J. Zhang, and R.R. Adzic.
19. 212th Meeting of The Electrochemical Society, ECS Washington, D.C., October 7-12, 2007. Title: "Chalcogenide Catalysts for Oxygen Reduction in Fuel Cells;" P. Zelenay, C.M. Johnston*, C. Delacôte, N. Alonso-Vante, and A. Wieckowski.
20. 212th Meeting of The Electrochemical Society, ECS Washington, D.C., October 7-12, 2007. Title: "Non-Precious Metal Nanocomposite ORR Catalysts: RRDE and Single Fuel Cell Studies;" R. Bashyam, C.M. Johnston, S.D. Conradson, and P. Zelenay*.

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1. R. Bashyam and P. Zelenay, *Nature*, **443**, 63-66 (2006).
2. A.L. Mohana Reddy, N. Rajalakshmi and S. Ramaprabhu, *Carbon*, **46**, 2-11 (2008).