Development of Ultra-low Doped-Pt Cathode Catalysts for PEM Fuel Cells

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Overview

Timeline

- Start date: June 2010
- End date: May 2015
- Percent complete: 85%

Budget

- Total Funding Spent as of 3/31/2014: $2,660,608.22
- Total Project Value: $4,750,000
- Cost Share Percentage: 20.0

Barriers

A. Durability

- Retain kinetic activity and high current density performance in H_2/air after potential holding (support durability) and potential cycling (catalyst durability) experiments.

B. **Cost**

- Decrease in PGM content
- Cost effective synthesis procedures

C. **Performance**

- Obtain high current density performance in H_2/air and maintain the power density

DOE Technical Targets

Electrocatalyst/MEA	2017 Targets
PGM Loading (mg/cm^2)	0.125
Mass Activity (A/mg_{PGM})	≥0.44
Mass activity and ECSA Loss after 30k Cycles (Catalyst Stability) (%)	≤ 40
Mass activity and ECSA Loss after 400 h (Support Stability) (%)	≤ 40
Potential loss after 30 k cycles (Catalyst Stability)	≤30 mV
Potential loss after 400 h (Support Stability)	≤30 mV

Project Lead

- University of South Carolina (USC)

Additional Interactions

- Rudiger Laufhutte (UIUC)
- Dr. Lax Saraf (Clemson University)
- Dr. Alan Nicholls (UIC)
- Electron Microscopy Center, USC

Relevance

- Develop cost effective high volume synthesis procedure to manufacture highly stable activated carbon composite catalyst (A-CCC) support.
  - Achieve onset potential of 0.9 V vs. SHE for ORR.
  - Achieve ≤30 mV loss in H_2/air after 400 h potential holding (1.2 V).
- Develop low cost procedures to synthesize a catalyst with:
  - Enhanced activity due to the synergistic effect of pyridinic-nitrogen catalytic sites from the support and suppressed Pt-lattice catalyst.
  - Demonstrate mass activity of ≥0.44 A/mg_{PGM} in H_2/O_2 fuel cell, initial high current performance under H_2/air (<0.125 g_{PGM}/kW rated power density) and stability of mass activity (≤ 40% loss) and stability of high current density performance under H_2/air using DOE potential cycling and potential holding tests.

Develop a low cost catalyst with optimized average mass activity, stability of mass activity, initial high current performance under H_2/air (power density), catalyst and support stability able to meet 2017 DOE targets.

Approach

- **Develop doped Pt/A-CCC catalyst with high activity for ORR through synergistic effect of pyridinic nitrogen containing A-CCC support and suppressed Pt-lattice catalyst.**

Support Development

- ✓ Develop a corrosion resistant support with desired BET surface area to sustain potential cycling and potential holding experiments.
  - ❖ Surface modification with acid and inclusion of oxygen groups.
  - ❖ Metal-catalyzed pyrolysis with N-containing compounds to (i) dope the support, (ii) include pyridinic nitrogen active sites and (iii) increase graphitization.
  - ❖ Chemical leaching to remove excess metal used to dope the support.

Catalyst Development

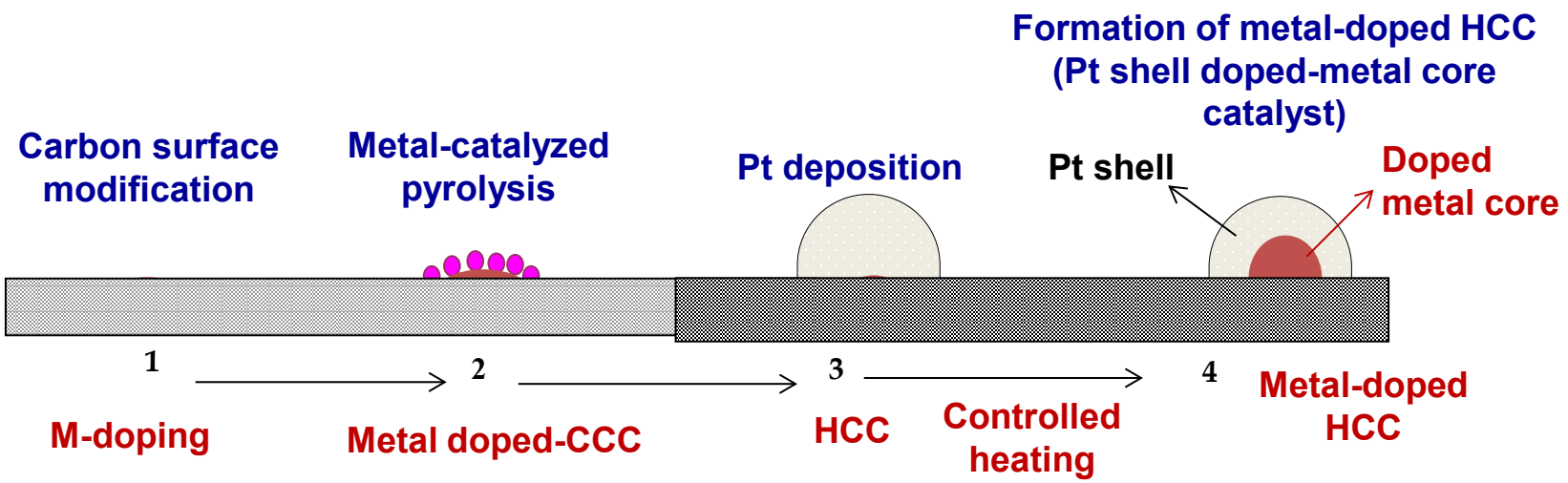
- ✓ Development of doped Pt/A-CCC catalyst.
- ✓ Two in-house developed procedures contribute to the high activity of the catalyst with the following electrocatalytic properties:
  - ❖ Enhanced activity due to synergistic effect of pyridinic nitrogen containing A-CCC support and Pt towards oxygen reduction reaction.
  - ❖ Suppressed Pt-lattice catalyst having Pt-shell/doped-metal core structure (with different doping metal content from 0 to 50%).
- ✓ In order to synthesize doped Pt/A-CCC catalyst with high activity and stability:
  - ❖ Modified polyol process was developed for uniform Pt deposition.
  - ❖ Heat treatment process was optimized to control the particle size between 3 and 5 nm.

Approach

Synthesis of Metal-doped HCC Catalyst (Doped Pt/A-CCC)

Development of Ultra-low Pt Catalysts

- **Development of Pt/A-CCC [Hybrid Cathode Catalyst (HCC)]**
- **Development of metal-doped HCC (Doped Pt/A-CCC)**



Project Timeline (According to Revised SOPO Dated 01/23/2014)

01/01/14 — 05/31/15

Phase II

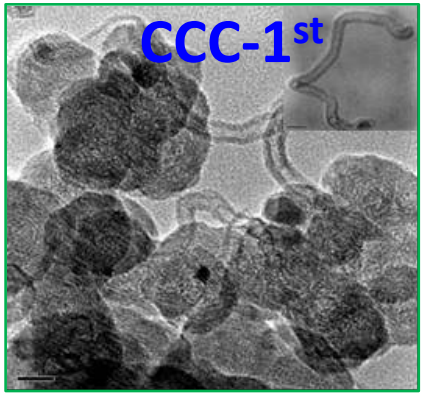
Q1	Q2	Q3	Q4	Q5	Q6

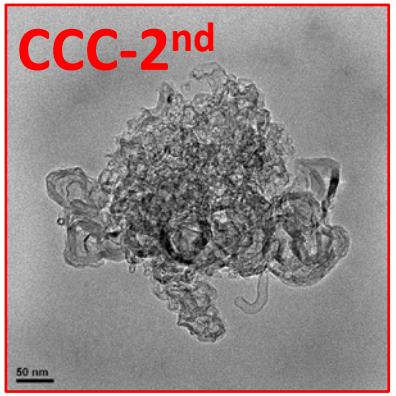
- Task 1. Optimization studies of A-CCC support and doped Pt/A-CCC catalysts (Initial mass activity of at least 0.3 A/mg_{PGM}
- Task 2. Stability of mass activity of (≤40% loss of initial value) at least 0.26 A/mg_{PGM} after 30k cycles.
- Task 3. Support stability to demonstrate 0.26 A/mg_{PGM} and 30-50 mV loss after 400 h.
- Task 4. Initial high current density performance of at least 1.5 A/cm^2 at 0.6 $V_{iR\text{-}free}$ and power density of ≤0.24 g_{PGM}/kW.
- Task 5. Demonstration of high current density performance loss of 30-60 mV (at 0.8 A/cm^2) after 30k cycles and 30-50 mV loss (at 0.8 A/cm^2) after 400 h.
- Task 6. Demonstration of most promising catalyst to meet initial mass activity of 0.3 A/mg_{PGM}, stability of mass activity of at least 0.26 A/mg_{PGM} and 30-60 mV loss at 0.8 A/cm^2 after 30k cycles.

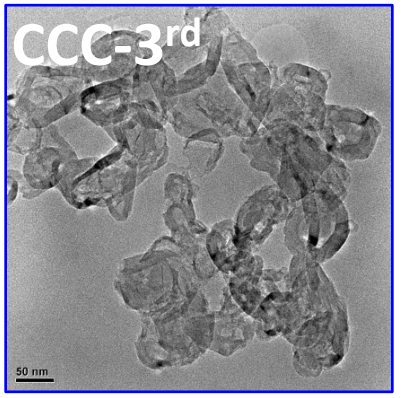
◆ End of task.

From 2013 AMR Presentation

- Development of three generations of carbon composite catalyst supports with increasing graphitization and support stability.
- Two methodologies were used at USC to synthesize ultra-low Pt loading catalysts:
  - Metal impregnation followed by high temperature pyrolysis and leaching (**Details are given in Reviewer Only Slides 46-51**).
  - Metal doped Pt catalyst by diffusing the metal previously embedded in the support (**USC method – This presentation**)
- Synthesis of catalysts with initial high kinetic activity (0.38 - 0.44 A/mg_{PGM}) and good stability of mass activity (32 - 50% loss in mass activity) after 30k cycles.
  - However, high mass activity does not translate into ORR activity in high current performance under H_2-air operating conditions.







Catalyst	Particle size (nm)	Mass activity (A/mg_{PGM})		
		Initial	30 k*	400h**
HCC	4.0	0.38	0.2 (47% loss)	0.19 (50% loss)
Pt-alloy/CNC	3.5	0.44	0.3 (32% loss)	0.23 (48% loss)

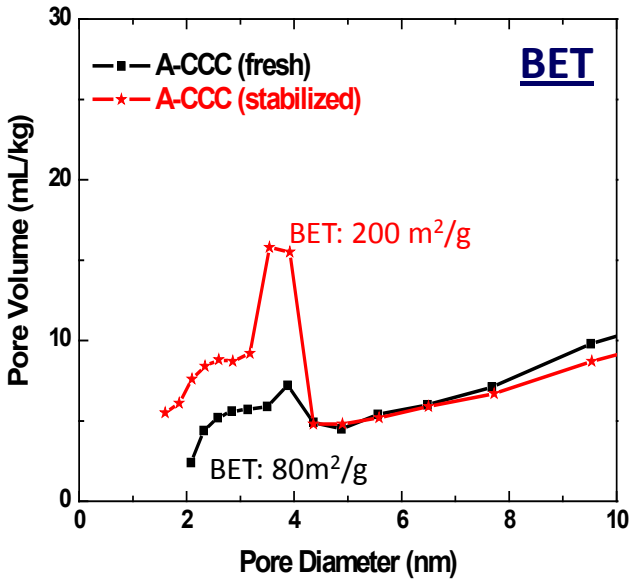
***30,000 cycles between 0.6 and 1.0V with rates of 50mV/s**

****keep at 1.2V for 400 hours**

Technical Accomplishments

1. Support Development

Development of Activated Carbon Composite Catalyst (A-CCC) Support



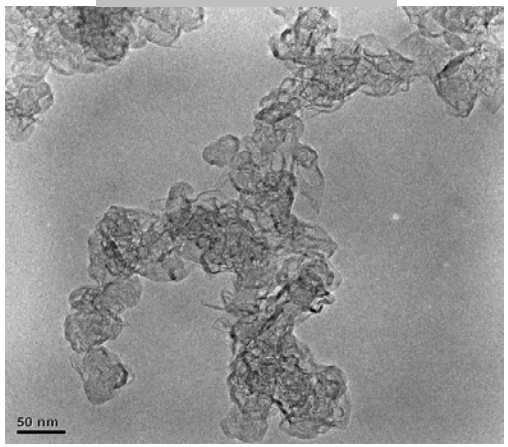
- Surface modification of carbon black with:
  - (i) O-containing group
  - (ii) N-containing group
- Pyrolysis

→

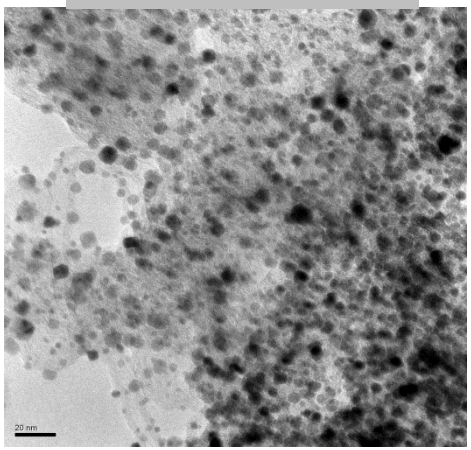
- "Metal-catalyzed pyrolysis" (Fe or Co) to increase the number of active sites by leaching

HRTEM

A-CCC Support



Pt/A-CCC Catalyst



HIGHLIGHT:

BET&BJH: The surface areas for A-CCC (fresh) and A-CCC (stabilized) are 80 and 200 m^2/g. BET shows presence of mesopores after stabilization step.

HRTEM: Graphitic carbon containing carbon nano fibers/tubes are formed during metal catalyzed pyrolysis.

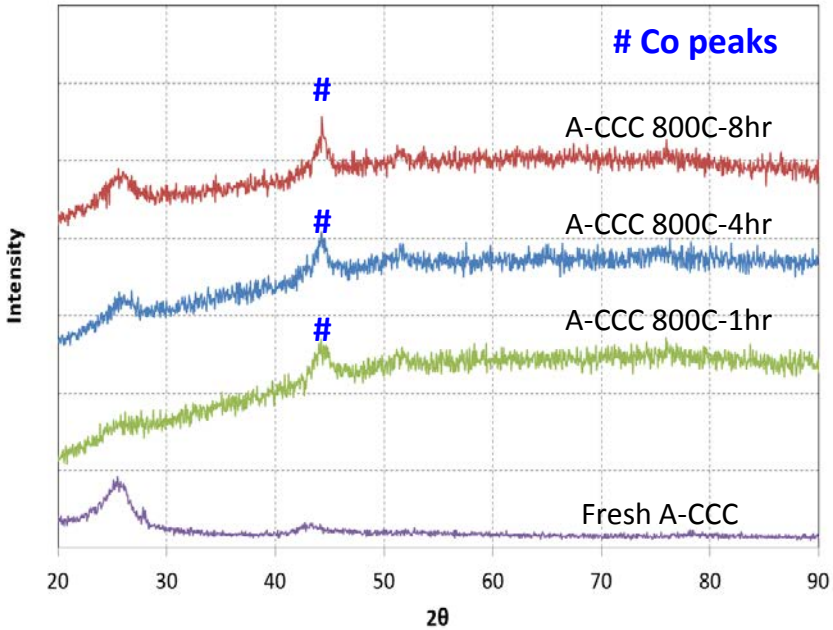
ADVANTAGE: The BET surface area and the pore-size of the A-CCC support can be tailored to achieve uniform Pt deposition (3-5 nm).

Technical Accomplishments

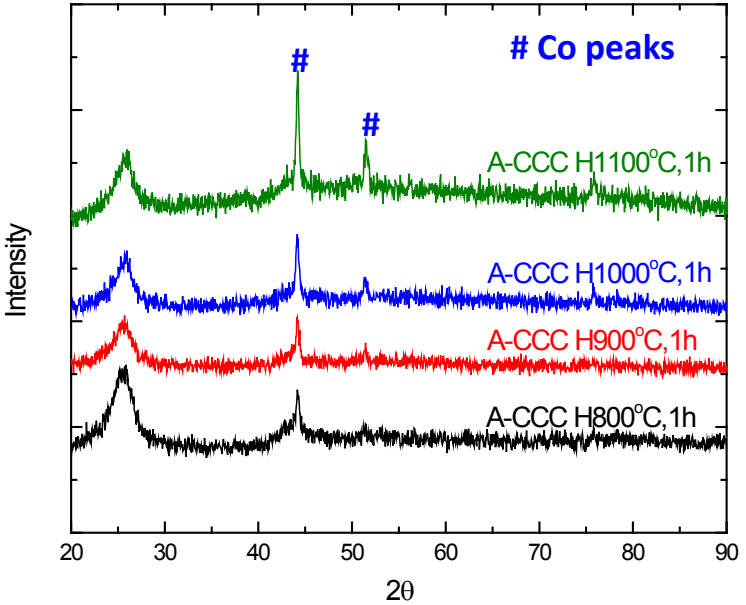
1. Support Development

Metal inclusion and Estimation of Metal Content in A-CCC Support

XRD as a function of heating time



XRD as a function of temperature



ICP analysis	Co amount (wt%)	BET surface area (m^2/g)
A-CCC H800	4.76%	137
A-CCC H900	6.84%	131
A-CCC H1000	8.13%	125
A-CCC H1100	10.69%	85

HIGHLIGHT

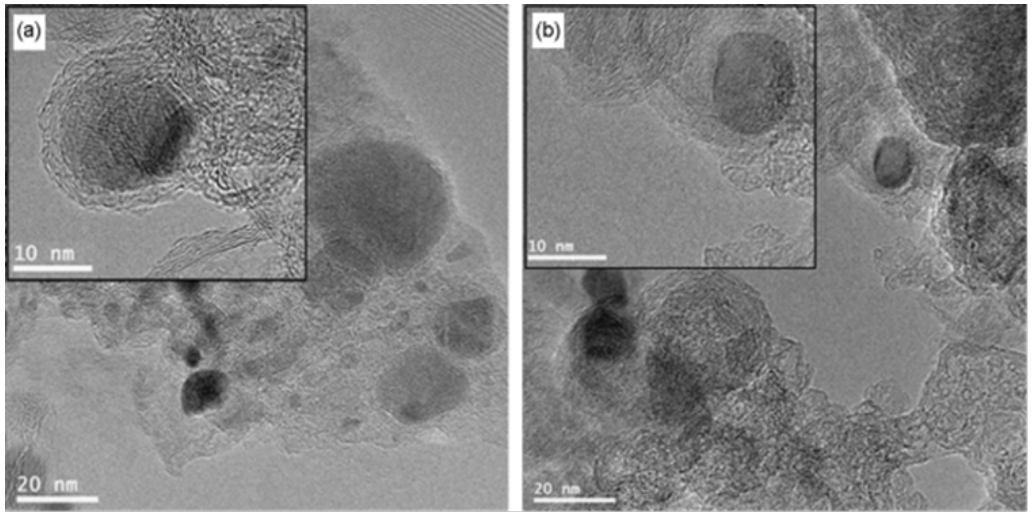
- **Cobalt amount in the support increased with the increase in heat treatment temperature.**
- **BET surface area decreased at temperatures >900 °C.**

Technical Accomplishments

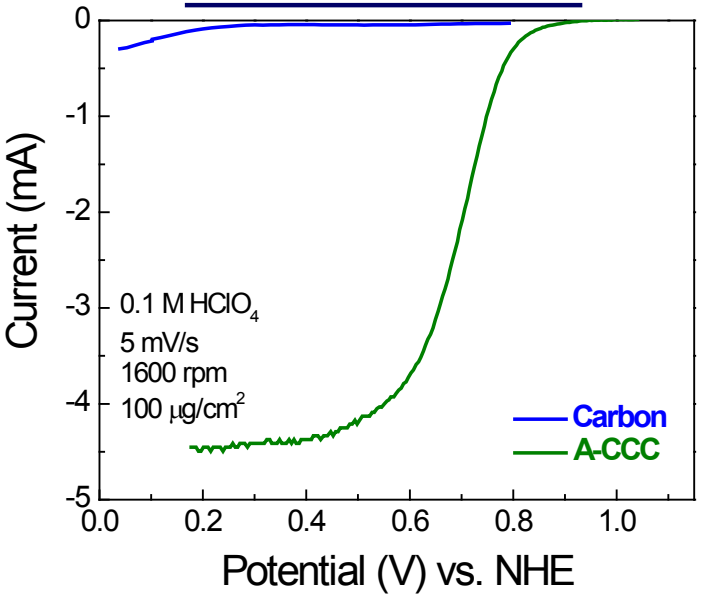
1. Support Development

Metal inclusion and Estimation of Metal Content in A-CCC Support

HRTEM images of A-CCC Support



ORR – RRDE Studies



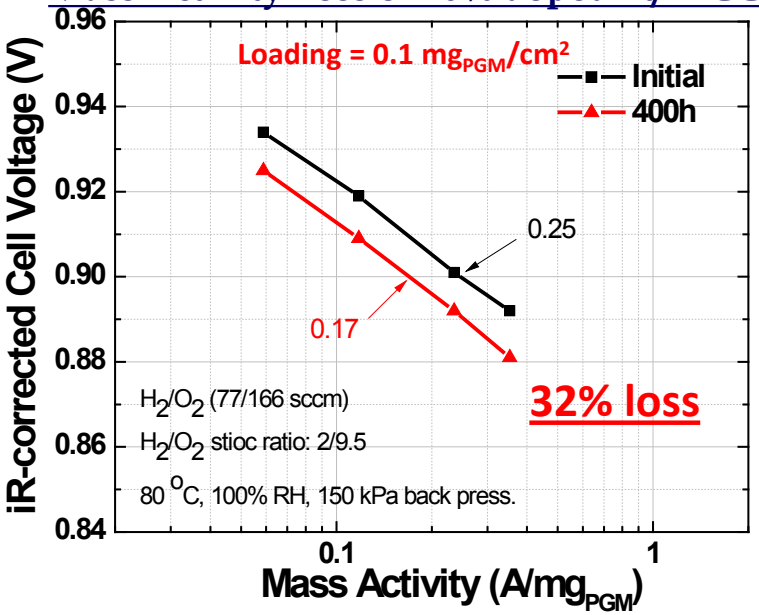
- Graphitic carbon formation through metal-catalyzed pyrolysis.
- Co particles are embedded in the bulk of the carbon during pyrolysis in the presence of Co-N chelate compound.
- Carbon nano fiber can be formed in the presence of Co at relatively low temperature (~800°C) which is more stable than amorphous carbon.
- The A-CCC catalyst showed an onset potential of ***0.9 V vs. RHE*** and well-defined kinetic and mass transfer regions.

Technical Accomplishments

1. Support Development

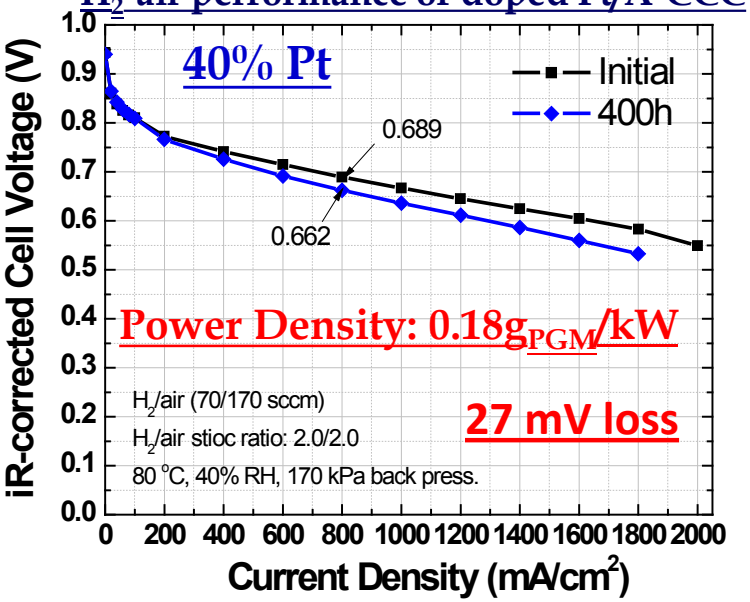
Support Stability—1.2 V Potential Holding

Mass Activity Loss of 40% doped Pt/A-CCC



DOE Test Protocol
Hold at 1.2V for 400 h, H_2/N_2, 80°C, 150kPa, 100 % RH, single cell 25cm^2
Polarization :
H_2/O_2 (2/9.5 stoic.), 80°C, 100% RH, 150kPa
H_2/air (2/2 stoic) 40% RH, 80°C, 170kPa

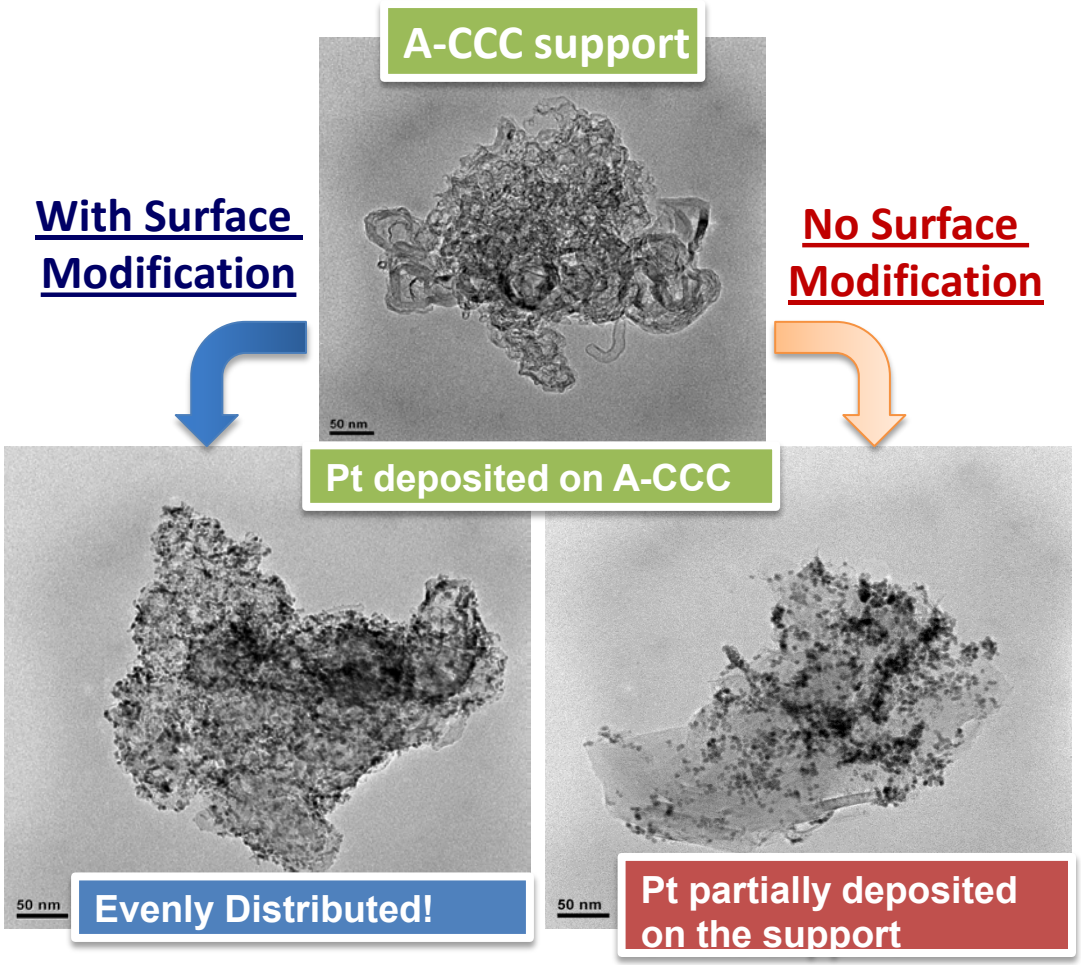
H_2-air performance of doped Pt/A-CCC

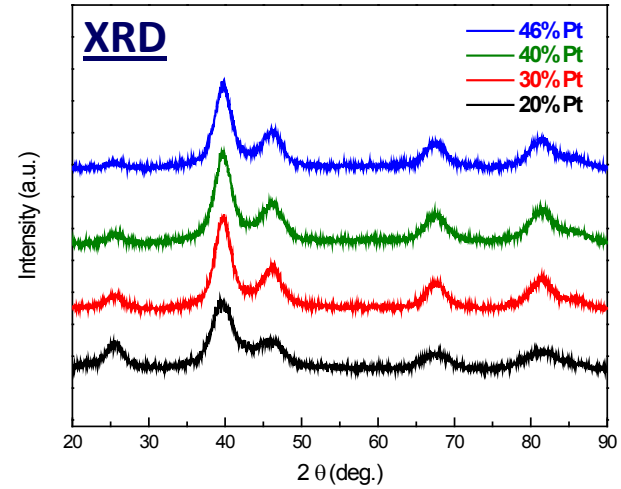


	Pt/A-CCC		Pt/C
	Initial	400h	Loss
Mass activity (A/mg$_{PGM}$)	0.25	0.17 (32% loss)	72% loss
ECSA (m^2/g)	31.4	29.5 (6% loss)	71% loss
$V_{iR\text{-}free}$ loss @ 0.8A/cm^2 (mV) (2.0/2.0 stoic.)	689	662 (27 mV loss)	No Activity

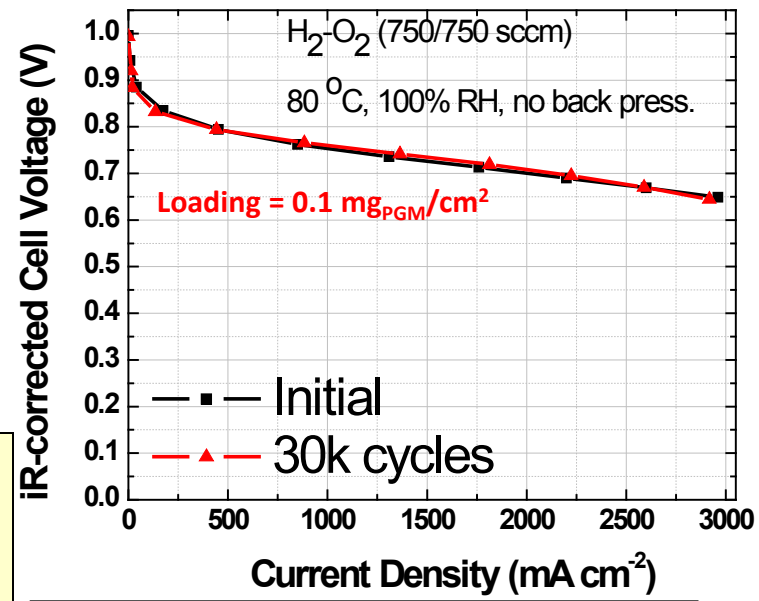
HIGHLIGHT:
(Status against 2017 DOE targets)
- The mass activity decreases from 0.25 to 0.17A/mg$_{PGM}$ (32% mass activity loss) after 400 h.
- The potential loss is 27mV after 400 h potential holding against the 2017 DOE target of 30 mV loss after 400 h, respectively.
- The rated power density is 0.18g$_{PGM}$/kW.
- Commercial Pt showed 72% mass activity loss, 71% ECSA loss and no activity after 400 h.

2. Catalyst Development (Pt Deposition)





Catalyst Stability of doped Pt/A-CCC in H_2/O_2



HIGHLIGHT:

- Surface modification increases the hydrophilicity of graphitic carbon.
- Uniform particle distribution with an average particle size of 2-3 nm is achieved with the USC developed modified polyol process.
- No loss in H_2/O_2 fuel cell performance after 30k cycles using DOE potential cycling test.

DOE Accelerated Stress Test Protocol
0.6 ~ 1.0 V, 50mV/s, 30,000 cycle, H_2/N_2, 80°C, 100 % RH, single cell 25cm²
Polarization : H_2/O_2, 750/750 sccm, 100% RH, 80°C

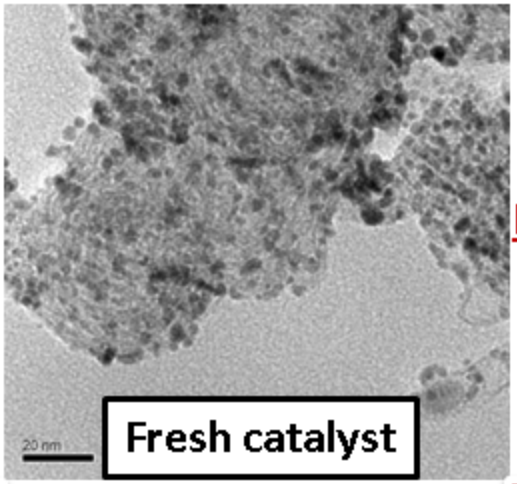
2. Catalyst Development

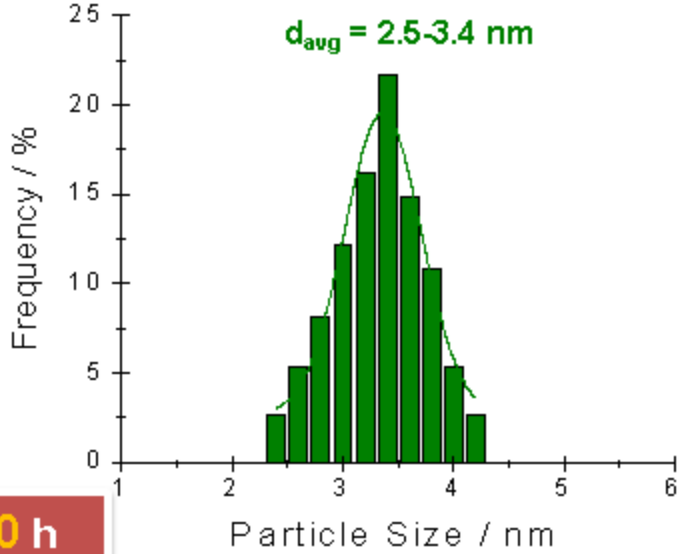
Doped Pt Catalyst Development

Development of a Process to Control the Particle Size During High Temperature Pyrolysis

Conventional Pyrolysis

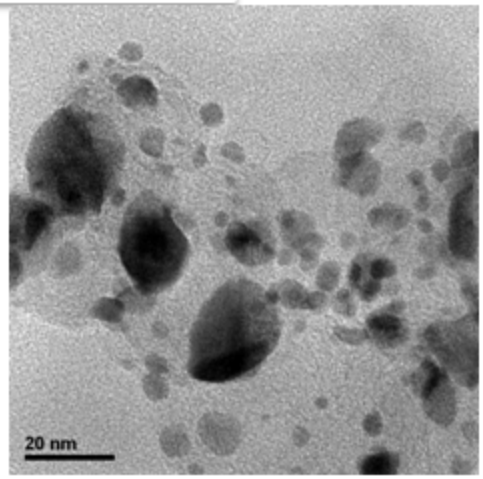
Modified Pyrolysis



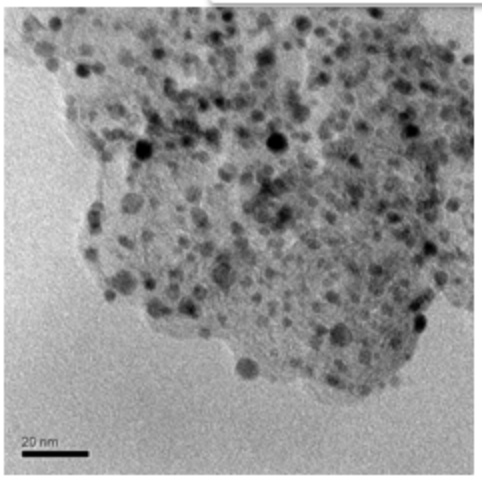


800°C for 0.5 h

800°C for 1.0 h



10-20 nm Particles



~3.5 nm Particles

HIGHLIGHT:

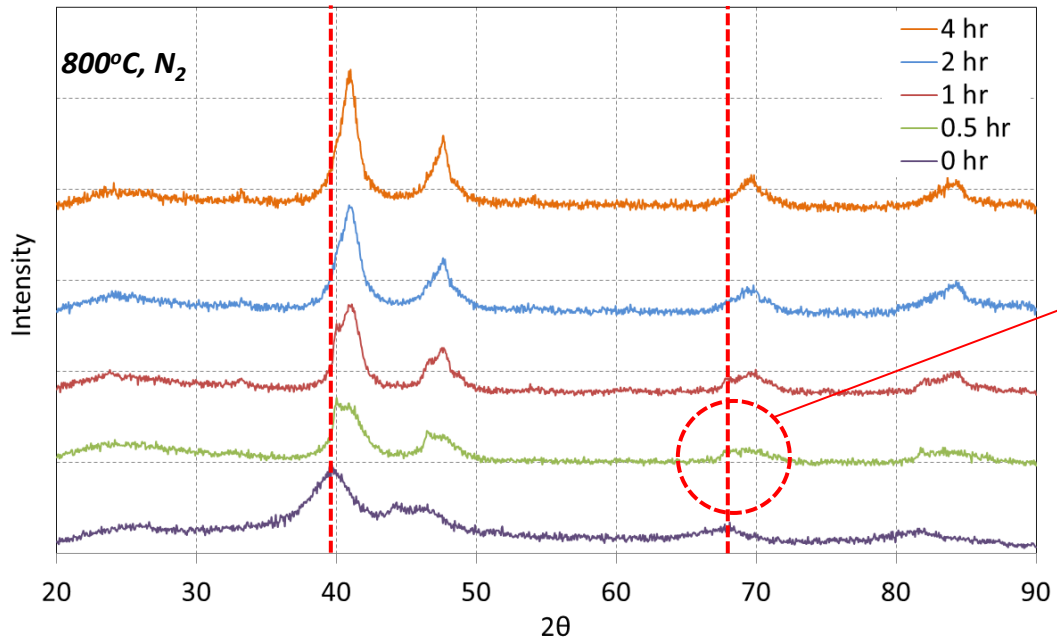
- Normal heat-treatment results in 10 to 20 nm particles.
- The new process yields uniform particle size distribution with ~3.4 nm doped-Pt catalyst particles.

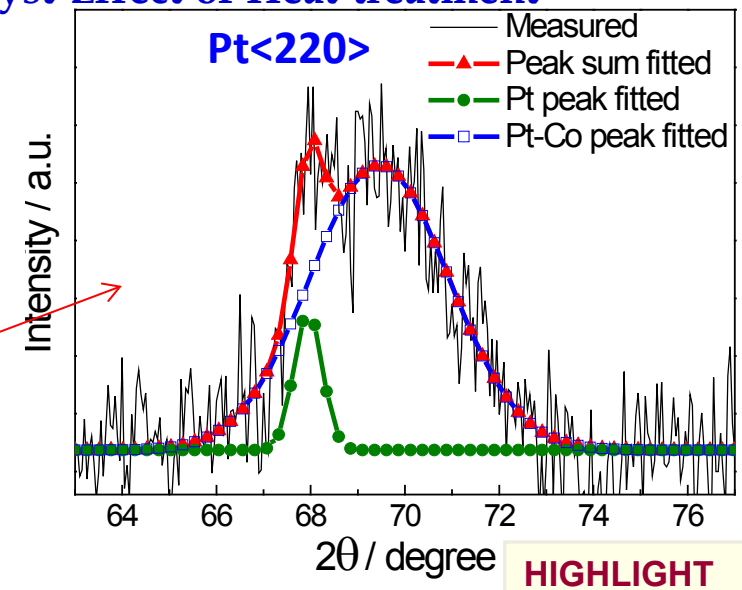
Technical Accomplishments

2. Catalyst Development

Doped Pt Catalyst Development

Formation of doped Pt/A-CCC catalyst-Effect of Heat-treatment





Heat treatment time (h)	Pt peak (deg)	PtCo peak (deg)	Particle size (nm)
0	67.3	--	2.5
0.5	67.9	69.4	2.8
1	67.8	69.5	3.9
2	--	69.4	3.9
4	--	69.5	4.5

Co doped Pt Composition	$Pt_{1.3}Co_1/C$
Co amount in the CCC (wt%)	10.32%
Pt amount (wt%)	30
Support(C+Co) amount (%)	70
Carbon amount (wt%)	62.776
Cobalt amount (wt%)	7.224
Pt amount (mol ratio)	0.154
Co amount (mol ratio)	0.123
Pt/Co mol ratio	**1.3**

HIGHLIGHT

- **XRD shows the presence of Pt and PtCo phases after 0.5 h heat treatment.**
- **Single-phase Co-doped Pt is formed after 2 h.**
- **The shift in 2θ can be varied by adjusting the heat treatment time.**

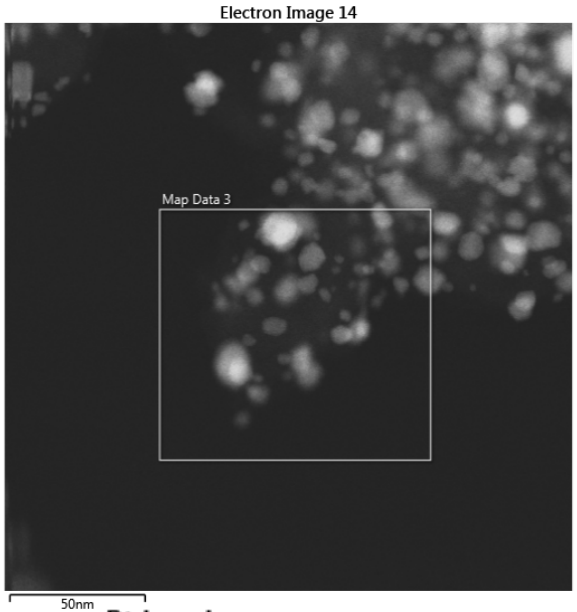
Technical Accomplishments

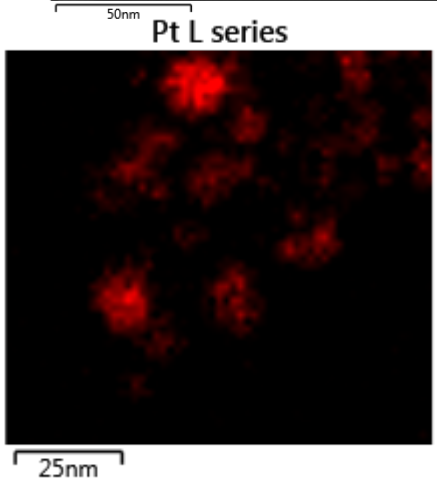
2. Catalyst Development

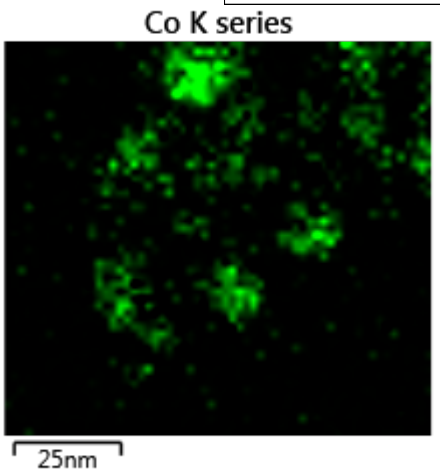
Doped Pt Catalyst Development

HRTEM and XEDS Analysis of Doped Pt/A-CCC Catalyst

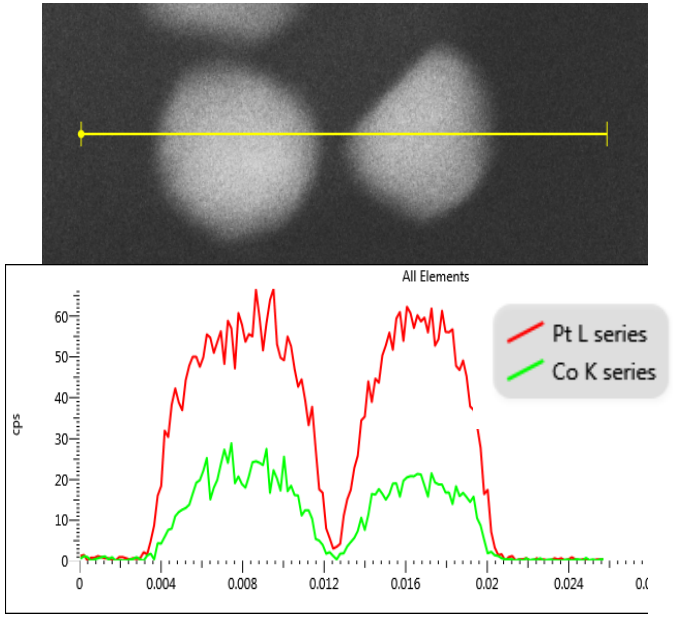
XEDS Mapping

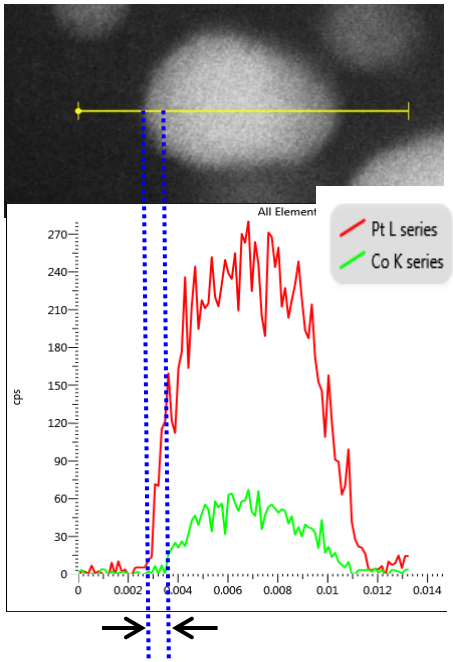






High resolution line-scanning





Pt shell thickness: 0.8nm

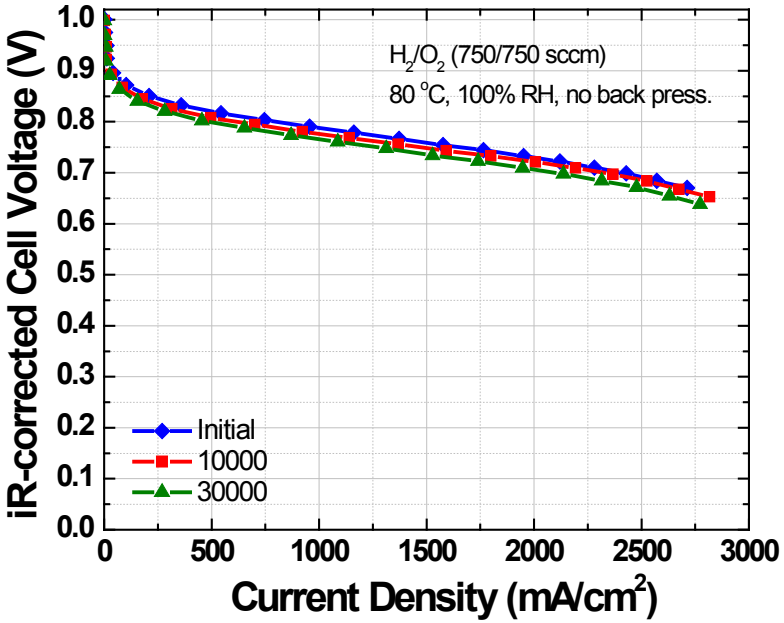
- Co is present within the A-CCC support and diffuses during controlled annealing in the presence of a protective coating to form Co-doped Pt catalyst.
- Line scan confirms the existence of Co in the core and a Pt-shell thickness of 0.5-0.8nm (**Core-shell structure**).

Technical Accomplishments

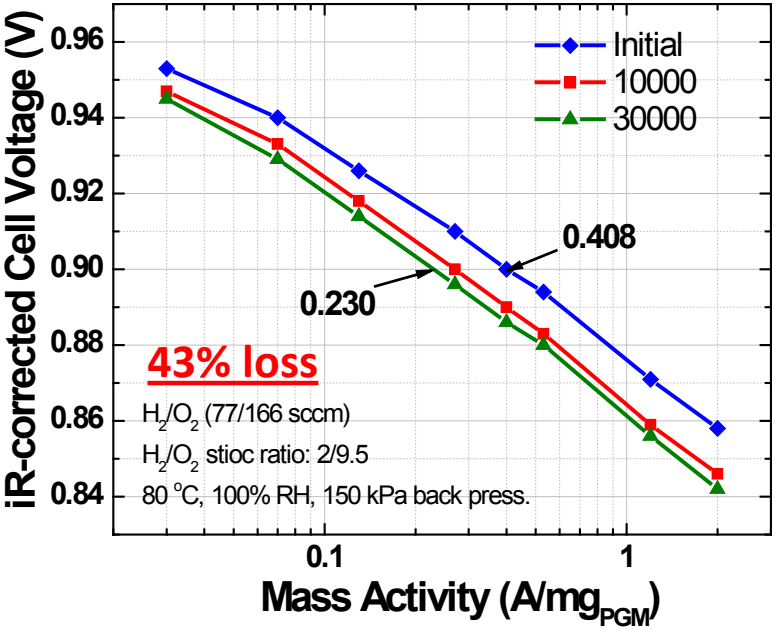
3. Catalyst Durability

Catalyst Durability Studies of Doped Pt/A-CCC (0.6-1.0 V Cycling)

H_2-O_2 Performance of Doped Pt/A-CCC



Mass Activity Loss of Doped Pt/A-CCC



DOE Accelerated Stress Test Protocol
0.6 ~ 1.0 V, 50mV/s, 30,000 cycle, H_2/N_2, 80°C, 100 % RH, single cell 25cm²
Polarization : H_2/O_2, 750/750 sccm, 100% RH, 80°C
Pt mass activity : H_2/O_2, 2/9.5 stoic, 100% RH, 80°C, 150kPa backpressure

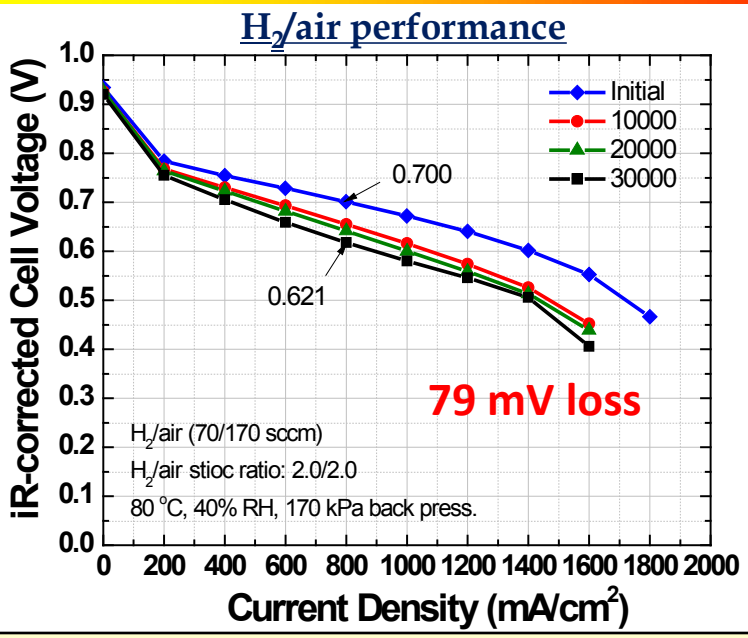
HIGHLIGHT: (Status against 2017 DOE targets)

- **H_2-O_2**: The initial cell potential at 2 A/cm² current density is 0.701 $V_{iR\text{-}corr}$ initially and 0.669 $V_{iR\text{-}corr}$ after 30k potential cycling corresponding to a loss of 32 mV.
- **Mass Activity**: The initial mass activity of the Co-doped Pt/A-CCC catalyst is 0.408 A/mg_{PGM} After 30k cycles, the mass activity decreased to 0.23 A/mg_{PGM} which corresponds to 43.6% decay from the initial value.

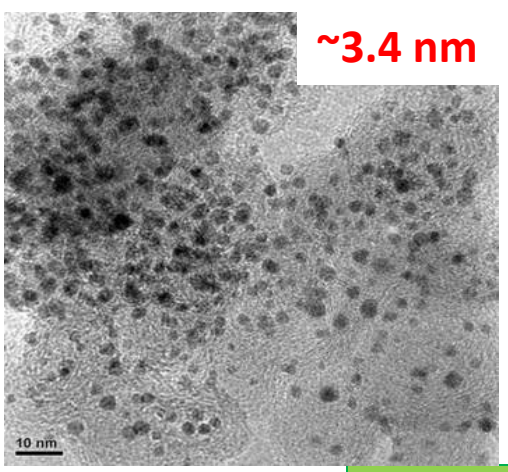
Technical Accomplishments

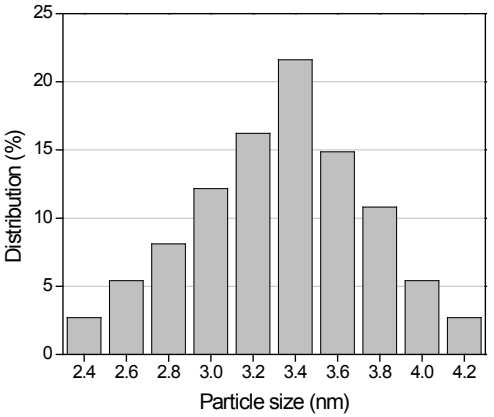
3. Catalyst Durability

Catalyst Durability Studies of Doped Pt/A-CCC (0.6-1.0 V Cycling)

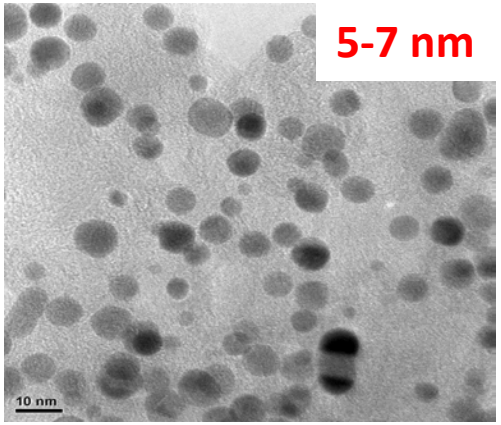


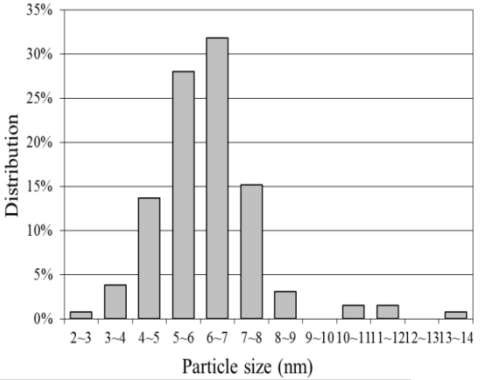
Fresh Catalyst HRTEM (Scale = 10 nm)





HRTEM After 30k (Scale = 10 nm)





HIGHLIGHT:

- **The doped Pt/A-CCC catalyst exhibits potential loss of 79 mV (from 0.700 $V_{iR\text{-}free}$ to 0.621 $V_{iR\text{-}free}$) after 30k cycles at 0.8 A/cm².**
- **Pt/C showed no activity after 30k cycles.**

DOE Accelerated Stress Test Protocol

0.6 ~ 1.0 V, 50mV/s, 30,000 cycle, H_2/N_2, 80°C, 100 % RH, single cell 25cm²

H_2/air: 2.0/2.0 stoic, 40% RH, 80°C, 170 kPa

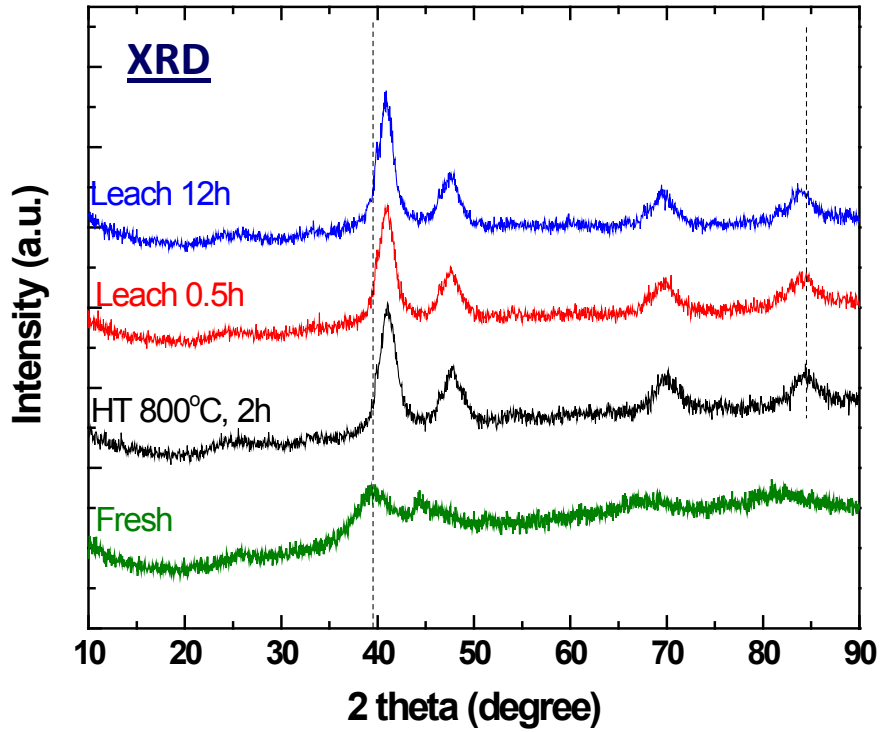
- The particle size increased from ~3.4 nm to 5-7 nm after 30k cycles

Technical Accomplishments

Catalyst Development

Doped Pt Catalyst Development

Formation of doped Pt/A-CCC$_1$ catalyst-Effect of leaching

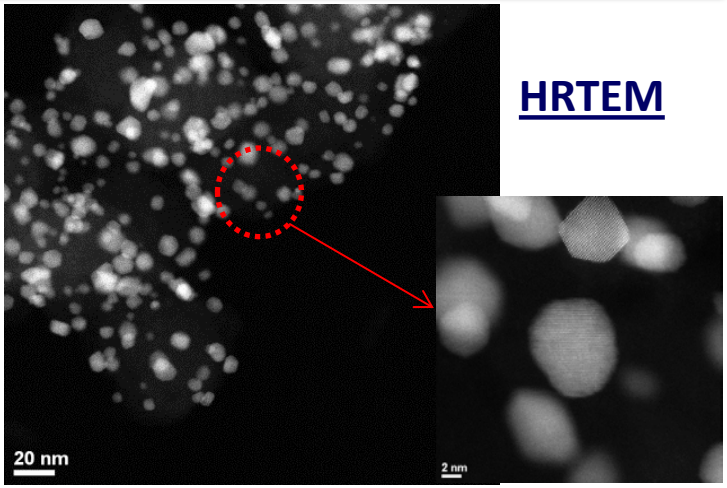


HIGHLIGHT:

- ❑ **XRD** shows after high temperature pyrolysis, Co present within the A-CCC$_1$ support diffused to the surface and doped into Pt lattice which is confirmed by the Pt peak shift in the XRD from 39.7 for pure Pt to 41.2° for the Co-doped Pt.
- ❑ **XRF & ICP** analysis show that **37% Co was removed from the catalyst after 0.5 h**. Further leaching for 12h did not leach out all the transition metal (only 18% more Co is leached out). 45% Co remains in the catalyst corresponding to a **Pt to Co ratio of 1 to 0.43**. The Co dissolution rate in the first half an hour is 49 times higher than the remaining 11.5 hours.
- ❑ **HRTEM** shows 3 to 6 nm doped Pt catalyst particles after controlled heat treatment process.

	Pt (wt%)	Co (wt%)	Molar ratio (XRF)	Molar ratio (ICP)
Fresh	78.4	21.6	Pt : Co = 1:0.93	Pt : Co = 1:1
HT800°C	78.4	21.6	Pt : Co = 1:0.93	Pt : Co = 1:0.85
Leach 0.5h	85.1	14.9	Pt : Co = 1:0.59	Pt : Co = 1:0.59
Leach 12h	88.8	11.2	Pt : Co = 1:0.42	Pt : Co = 1:0.43

HRTEM

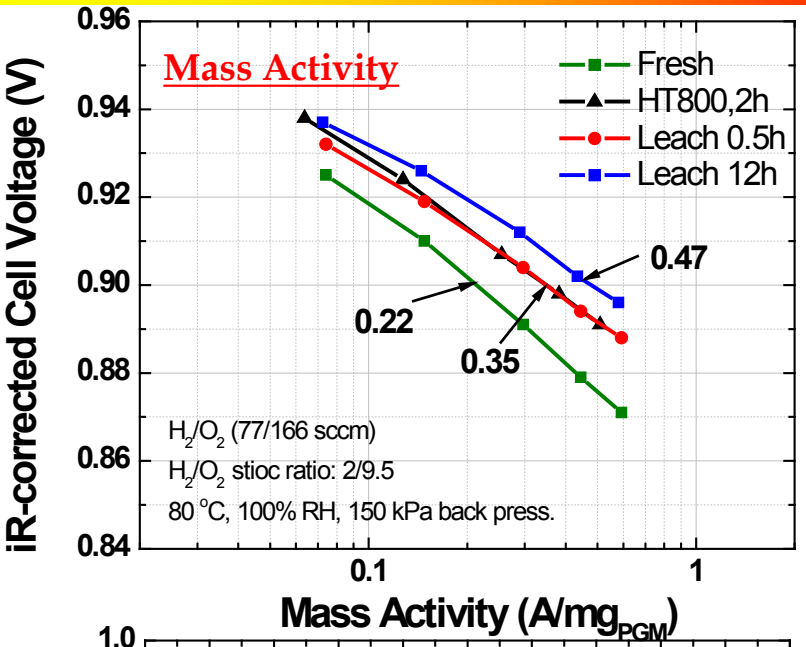


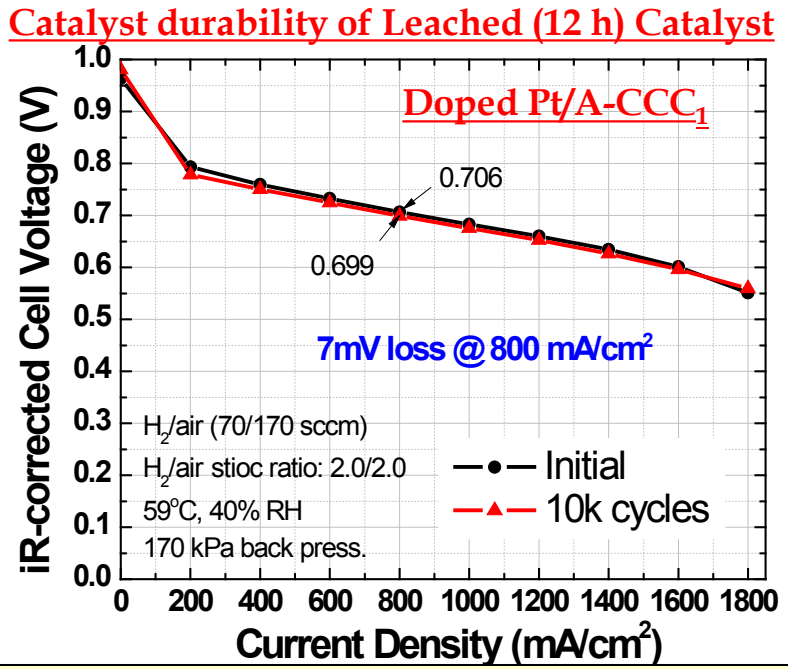
20 nm scale **2 nm scale**

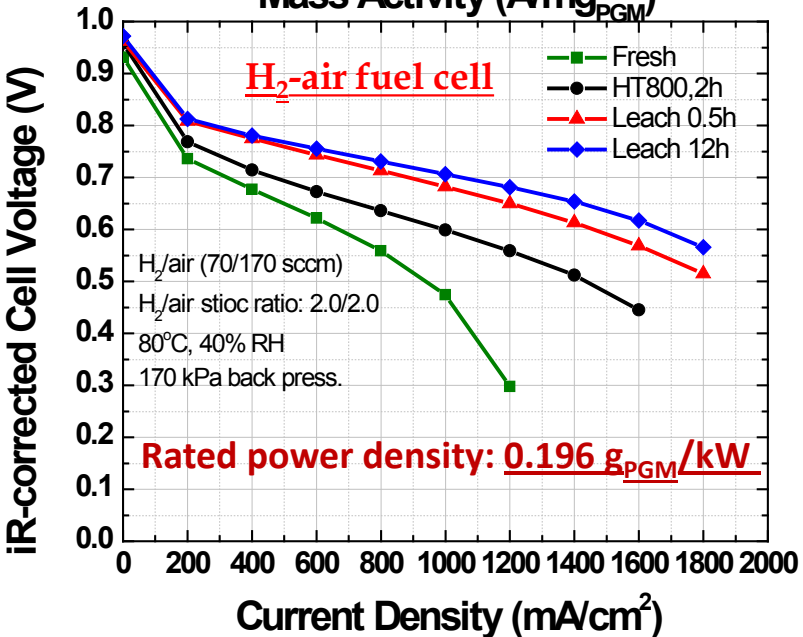
Technical Accomplishments

Mass Activity and High Current Density Performance Improvement

Effect of leaching on doped Pt/A-CCC_1 Formation







HIGHLIGHT:

- ❑ **Mass activity** increased from 0.22 to 0.35 A/mg_{PGM} after Co-doping. leaching leads to better catalytic activity at 0.9 V (0.47 A/mg_{PGM}).
- ❑ **H_2/air performance**: At 0.6 $V_{iR\text{-}free}$, the current densities are 0.68, 1.00, 1.45 and 1.70 A/cm^2 for fresh, heat-treated, leached for 0.5h and leached for 12h catalysts, respectively. The 12 h leached catalyst showed initial power density of **0.196 g_{PGM}/kW** (rated power).
- ❑ **Catalyst stability**: Doped Pt/A-CCC_1 (12 h leached) catalyst showed 7 mV potential loss after 10k cycles.

Collaborations

Characterization and Interactions

- **Rudiger Laufhutte** (University of Illinois, Urbana-Champaign): ICP analysis of doped Pt catalysts.
- **Alan Nicholls** (University of Illinois, Chicago): HRTEM & XEDS mapping.
- **Lax Saraf & Haijun Qian** (Clemson University): Transmission Electron Microscopy analysis.
- **EM Center** (University of South Carolina): HR-TEM analysis
- **Scribner Associates**: Design and construction of fuel cell test stations according to USC requirements.
- **Fuel Cell Technologies**: Design and construction of 25 and 50 cm^2 single cells according to USC specifications.

Summary of Accomplishment of Doped Pt/A-CCC Cathode Catalyst

Metric	Units	*Status (FY2014)*	Commercial Pt/C	2017 DOE target
Initial Mass Activity				
Initial Mass activity	A/mg_{PGM} @ 900 $mV_{iR\text{-}free}$	***0.25~0.47***	0.18	≥0.44
Catalyst Stability (0.6-1.0 V cycling)				
Loss in catalyst activity	% loss after 30k cycles	***43%***	68%	≤40%
Loss in ECSA	% loss after 30k cycles	***15%***	80%	≤40%
Potential loss @ 800 mA/cm^2	mV loss after 30k cycles	***79 mV***	No Activity	≤30 mV
Support Stability (1.2 V holding)				
Loss in catalyst activity	% loss after 400 h	***32%***	72%	≤40%
Loss in ECSA	% loss after 400 h	***6%***	71%	≤40%
Potential loss @ 800 mA/cm^2	mV loss after 400 h	***27 mV***	No Activity	≤30 mV
PGM Content and PGM Loading				
PGM total content (Power Density)	g_{PGM}/kW (rated)	***0.18~0.24***	0.3	≤0.125
PGM total loading	mg_{PGM}/cm^2_{geo}	***0.2***	0.2	≤0.125

Future Work

Task 1: Synthesis of metal doped Pt/A-CCC (HCC) catalysts

Task 2. Optimization studies of selected catalysts

- Initial and durability of mass activity and high current performance under H_2-air under potential cycling condition (0.6-1.0 V, 30k cycles).
- Increase the performance of Pt-M/A-CCC catalysts as a function of concentration of doped metal in the A-CCC support and pyrolysis temperature.

Task 3. Optimization of high volume production procedures for the A-CCC support and doped Pt/A-CCC catalysts.

Task 4. Performance evaluation of two selected catalysts

a) Durability of high current performance under H_2-air

b) Catalyst down selection

The goal is to select a best performing catalyst to demonstrate the following characteristics in single cells: (**According to Revised SOPO Dated 01/23/2014**)

(i) initial mass activity of 0.3 A/mg_{PGM} and stability of mass activity of at least 0.26 A/mg_{PGM} after 30k cycles

(ii) initial high current density performance of at least 1.5 A/cm^2 at 0.6 $V_{iR\text{-}free}$

(iii) stability of high current density of only 30-60 mV loss at 0.8 A/cm^2 following accelerated stress testing.

(iv) Evaluation of reproducibility of support and catalyst performance.

Deliverables:

- Supply of **a most promising catalyst** for independent evaluation. The amount to be determined by the DOE.

Publications Resulted from the Current Project

1. Ákos Kriston, Tianyuan Xie and Branko N. Popov, Impact of Ultra-low Platinum loading on Mass Activity and Mass Transport in H_2-Oxygen and H_2-Air PEM Fuel Cells, *Electrochim. Acta*, **121** (2014) 116-127.
2. Akos Kriston, Tianyuan Xie, Prabhu Ganesan, Branko N. Popov, "Effect of Pt Loading on Mass and Specific Activity in PEM Fuel Cells" *J. Electrochem. Soc.*, **160** (2013) F406-F412.
3. Ákos Kriston, Tianyuan Xie, David Gamliel, Prabhu Ganesan, Branko N. Popov,, "Effect of Ultra-Low Pt Loading on Mass Activity of PEM Fuel Cells" *J. Power Sources*, **243** (2013) 958-963.
4. Branko N. Popov, Tianyuan Xie, Taekeun Kim, Won Suk Jung, and Prabhu Ganesan, "Development of Ultra-Low Loading Pt Alloy Cathode Catalyst for PEM Fuel Cells," *ECS Transactions*, 58 (2013) 761-778.
5. Akos Kriston, Tianyuan Xie, Taekeun Kim, Won Suk Jung, David Gamliel, Brian Murphy Prabhu Ganesan, Branko N. Popov, Analyzing the effect of Ultra-Low Pt Loading on Mass and Specific Activity of PEM Fuel Cells, *ECS Transactions*, **50**, (2013) 1427-1438.
6. Tianyuan Xie, Taekeun Kim, Won Suk Jung, Kriston Akos Prabhu Ganesan and Branko N. Popov, "Development of Highly Active Pt_2Ni/C Catalyst for PEM Fuel Cell", *ECS Transactions*, **50** (2) (2013) 1615-1626.
7. Taekeun Kim, Won Suk Jung, Tianyuan Xie, Akos Kriston, Prabhu Ganesan, David Gamliel, Brian Murphy and Branko N. Popov, "Development of Hybrid Cathode Catalyst for PEM Fuel Cells", *ECS Transactions*, **50** (2) (2013) 1875-1885.
8. Branko N. Popov, Tianyuan Xie, Taekeun Kim, Won-suk Jung, Akos Kriston Brian Murphy and Prabhu Ganesan, "Development of Ultra-Low Pt Alloy Cathode Catalyst for PEM Fuel Cells", *ECS Transactions*, **50** (2) (2013) 773-785.
9. Xuguang Li and Branko N. Popov, Development of Non-Precious Metal Catalysts for Oxygen Reduction Reaction in Fuel Cells with High Activity and Stability, *ECS Trans.* 2010, *33*, 2333-2339.
10. Xuguang Li, Gang Liu, Prabhu Ganesan, Hansung Kim, Bumwook Roh, and Inchul Hwang, Development of Ultra-Low Pt Alloy Cathode Catalyst for PEM Fuel Cells, Branko N. Popov, *ECS Transactions*, 2011, 41 (1), 955-969.
11. Xuguang Li, Sheng-Yang Huang, Branko Popov, "Development of Low Pt Loading Cathode Catalysts for Polymer Electrolyte Membrane Fuel Cells", *ECS Trans.* 2010, *33*, 239-246.

Presentations from the Current Project

1. Development of Ultra-Low Loading Pt Hybrid Catalyst for PEM Fuel Cells, Tianyuan Xie, Taekeun Kim, Won Suk Jung, Prabhu Ganesan, and Branko N. Popov, *224th ECS Meeting*, San Francisco, CA, October 27-November 01, 2013.
2. Development of Ultra-Low Loading Pt Alloy Cathode Catalyst for PEM Fuel Cells, Branko N. Popov, Tianyuan Xie, Taekeun Kim, Won Suk Jung, and Prabhu Ganesan, *224th ECS Meeting*, San Francisco, CA, October 27-November 01, 2013.
3. Development of Ultra-Low Loading Pt/AGC Catalyst for PEM Fuel Cells, Taekeun Kim, Won Suk Jung, and Prabhu Ganesan, Tianyuan Xie, and Branko N. Popov, *224th ECS Meeting*, San Francisco, CA, October 27-November 01, 2013.
4. Analyzing the effect of Ultra-Low Pt Loading on Mass and Specific Activity of PEM Fuel Cells, Akos Kriston, Tianyuan Xie, Taekeun Kim, Won Suk Jung, David Gamliel, Brian Murphy Prabhu Ganesan, Branko N. Popov, *222nd ECS Meeting*, Honolulu, HI, October 7-12, 2012.
5. Development of Ultra-Low Pt Alloy Cathode Catalyst for PEM Fuel Cells, Branko N. Popov, Tianyuan Xie, Taekeun Kim, Won-suk Jung, Akos Kriston Brian Murphy, David Gamliel and Prabhu Ganesan, *222nd ECS Meeting*, Honolulu, HI, October 7-12, 2012.
6. Development of Highly Active Pt_2Ni/CCC Catalyst for PEM Fuel Cell, Tianyuan Xie, Won Suk Jung, Taekeun Kim, Kriston Akos Prabhu Ganesan and Branko N. Popov, *222nd ECS Meeting*, Honolulu, HI, October 7-12, 2012.
7. Development of Hybrid Cathode Catalyst for PEM Fuel Cells, Taekeun Kim, Won Suk Jung, Tianyuan Xie, Akos Kriston, Prabhu Ganesan, David Gamliel, Brian Murphy and Branko N. Popov, *222nd ECS Meeting*, Honolulu, HI, October 7-12, 2012.
8. Development of ultra-low platinum alloy cathode catalyst for PEM fuel cells, Branko N. Popov, Tae-keun Kim, Xie Tianyuan, Prabhu Ganesan, and Hansung Kim, *220th ECS Meeting*, Boston, MA, October 9-14, 2011.
9. Titanium Dioxide-Supported Platinum Catalysts, S. Huang, P. Ganesan, and B. N. Popov, *220th ECS Meeting*, Boston, MA, October 9-14, 2011.
10. Development of Non-Precious Metal Catalysts for Oxygen Reduction Reaction in Fuel Cells with High Activity and Stability, X. Li, G. Liu, T. Kim, S. Ganesan, P. Ganesan, and B. N. Popov, *220th ECS Meeting*, Boston, MA, October 9-14, 2011.
11. Development of Low Platinum Loading Cathode Catalysts for Polymer Electrolyte Membrane Fuel Cells, X. Li, S. Huang, B.N. Popov, *218th Meeting of the Electrochem. Soc*., Las Vegas, Nevada, October 13, 2010.
12. Recent Advances in Non-Precious Metal Catalyst for Oxygen Reduction Reaction in Fuel Cells," X. Li, B.N. Popov, T. Kawahara, H. Yanagi, *218th Meeting of the Electrochem. Soc*., Nevada, October 13, 2010.

Team Members who contributed to this presentation

University of South Carolina

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