Development of Ultra-low Platinum Alloy Cathode Catalyst for PEM Fuel Cells

2010 DOE Hydrogen Program Fuel Cell Project Kick-Off

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September 28, 2010

Overview

Timeline

- Start date: June 01 2010
- End date: Nov 30 2012 (Phase I)
  : May 31 2014 (Phase II)

Budget

- Total project funding
  - DOE share: $ 4,400,000
  - Contractor share: $1,100,000
- Incremental funding received in FY10: $750,000
- Funding for FY11: $1,100,000

Barriers

- Catalyst cost
- Catalyst performance
- Catalyst Durability

Targets

- PGM loading of 0.2 mg/cm^2
- Mass activity of 0.44 A/mg$_{Pt}$ at 0.9 V (Year 2015).
- Specific activity of 720 μA/cm^2 at 0.9 V (Year 2015).
- Electrochemical surface area loss <40%
- Cycling performance for 5000 h at ≤ 80 ^{o}C and 5000 h at > 80 ^{o}C

Partners

- Hyundai Motor Company, S. Korea
- Yonsei University, S. Korea

Problem Definition – In Developing Low Loading Platinum Catalysts

- Catalyst Performance
  - ➢ Platinum and catalyst support ratio
  - ➢ Catalyst agglomeration during alloying process
  - ➢ Pt dissolution and agglomeration
  - ➢ Increase of inter-particle resistance and dis-bonding of catalyst particles during the leaching process
  - ➢ Loss of electrochemical surface area
  - ➢ Alloying metal dissolution and incorporation in to the membrane
  - ➢ Catalyst-ionomer interaction
  - ➢ Catalyst layer properties – thickness, porosity and pore-size distribution and hydrophilic/hydrophobic properties.
- Catalyst Support Stability
  - ➢ Water content.
  - ➢ Low pH (< 1).
  - ➢ High temperature (50 – 90 °C).
  - ➢ High oxygen concentration.
  - ➢ Carbon corrosion at high potentials (Increases between 1.2 and 1.5 V during start-up and shut-down cycles in automotive application)
    - ✓ $C + 2H_2O \rightarrow CO_2 + 4H^+ + 4e^-$ $E^0 = 0.118$ V vs. RHE at 25 °C
- Carbon oxidation results in:
  - ➢ Increase in the hydrophilic properties and affects the water removal leading to increased mass transport losses.
  - ➢ Decreases the thickness of the catalyst layers which increases the cell resistance.
  - ➢ Pt catalyst accelerates the rate of carbon corrosion.

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Project Objectives

- Ultra-low loading Pt catalysts for oxygen reduction reaction with high activity and good stability will be developed through:
  - ➢ Synthesis of hybrid cathode catalyst (HCC) consisting of carbon composite catalyst (CCC) developed at USC as support and activated platinum with high electrochemical surface area.
    - ✓ Platinum catalyst activation will be performed using USC developed leaching procedure for Pt-Co, Pt-Ni and Pt-Cu alloys.
  - ➢ Synthesis of activated low loading platinum catalysts with high electrochemical surface area using:
    - ✓ Stable conductive TiO_2 based supports synthesized by template assisted procedure developed at USC.
    - ✓ Stable and electrochemically active CCC-TiO_2 hybrid support with pyridinic active sites for ORR.
  - ➢ Synthesis of leached Pt-Ni alloy catalysts with high electrochemical surface area Pt deposited on activated graphitic carbon developed at HMC.
  - ➢ Synthesis of leached Pt-Cu catalysts with high electrochemical surface area Pt deposited on activated carbon developed at Yonsei University.
  - ❖ **Facile scale-up synthesis procedure for the production of all the suggested catalysts.**
  - ➢ Elimination of Pt-alloy particle agglomeration during annealing process at high temperature using a procedure developed at Yonsei University.
  - ➢ Decreasing the inter-particle resistance and prevent the catalyst particle detachment from the support through:
    - ✓ Introduction of a thin interlayer of Pt or Pd between the support and the catalyst
    - ✓ Optimization of Pt and alloying metal composition.

Project Objectives

- ➢ Synthesis of high distribution of Pt with high initial loading over carbon support without Pt loss. Initial results (HR-TEM) at Yonsei University indicated that the Pt particle size of 70 wt.% Pt/C is smaller than the commercial 40 wt.% Pt/C catalyst.
- ➢ Engineer membrane electrode assembly (MEA) with
  - ✓ thin catalyst layer
  - ✓optimize the catalyst-catalyst support ratio
- ➢ Study the activity and durability of different low loading Pt catalysts in single cell (50 cm^2) test conditions.
- ➢ Construct short-stack (50 cm^2, up to 10 cells) containing ultra-low Pt loading catalyst and evaluate the performance under simulated automotive operating conditions.

Previous Accomplishments at University of South Carolina

Development of Metal Free Catalyst

USC Strategy: HCC Catalyst

Strategy: Combine the catalytic activity of Pt at high potentials with that of carbon composite catalyst (CCC) at low potentials forming a hybrid cathode catalysts (HCC) having ultra-low Pt loading.

Carbon modification

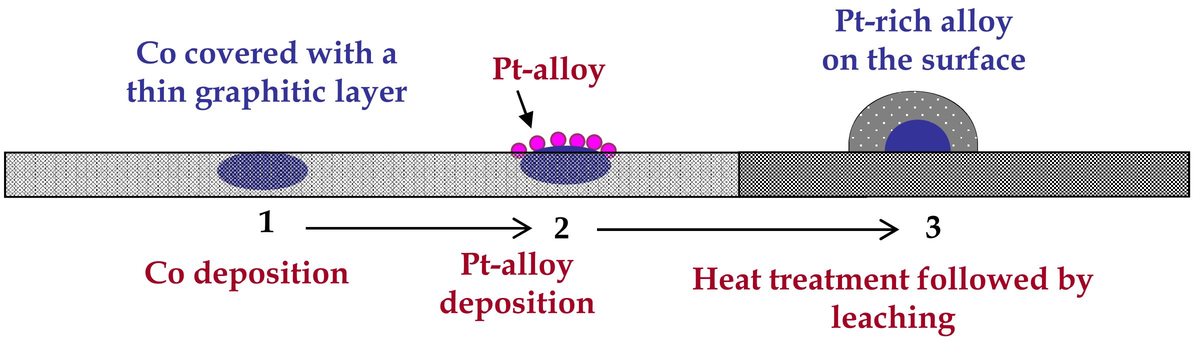
- **Surface modification of carbon black with:**
  - **(i) O-containing group**
  - **(ii) N-containing group**
- **Pyrolysis**

Carbon composite Catalyst

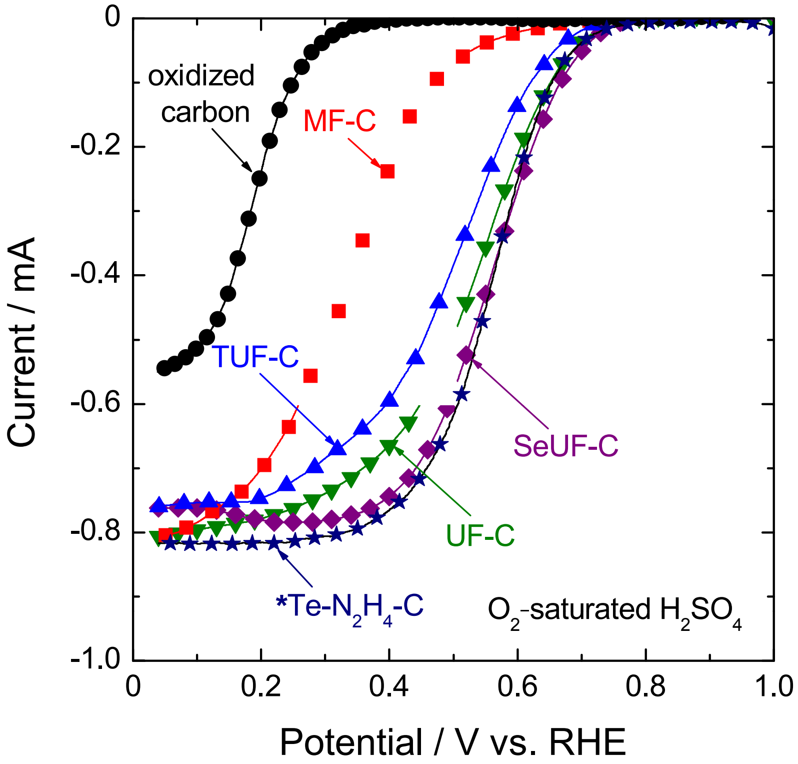
- **“Metal-catalyzed pyrolysis” to increase the number of active sites by leaching**

Hybrid cathode catalysts (HCC)

- **Pt deposition**
- **Pyrolysis**



Metal-Free Catalyst: Catalytic Activity and Selectivity



Nitrogen-modified carbon-based catalyst	% H_2O_2 at 0.5 V
MF-C	28
TUF-C	17
UF-C	3
SeUF-C	1
$Te-N_2H_4-C$	1

***Synthesis of $Te-N_2H_4-C$**

(1) Adsorption of telluric acid on carbon black

(2) Reduction by hydrazine

(3) Pyrolysis at 1000 °C

HIGHLIGHT

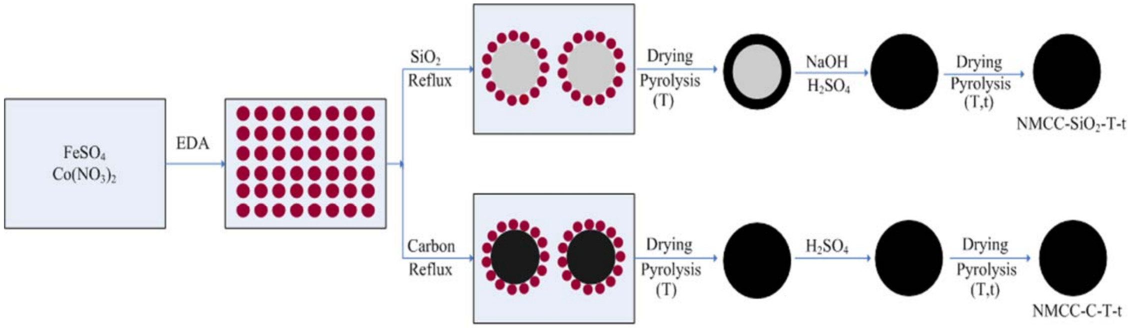
- **The nitrogen-containing polymer modification methodology increases the onset potential for oxygen reduction by ca. 400 mV, as compared with carbon black.**
- **The nitrogen modified carbon-based catalyst catalyzes oxygen reduction to water with low H_2O_2 production.**

Popov et.al., *J. Power Sources*, 182 (2008) 18-23.

Previous Accomplishments at University of South Carolina

Development of Carbon Composite Catalyst

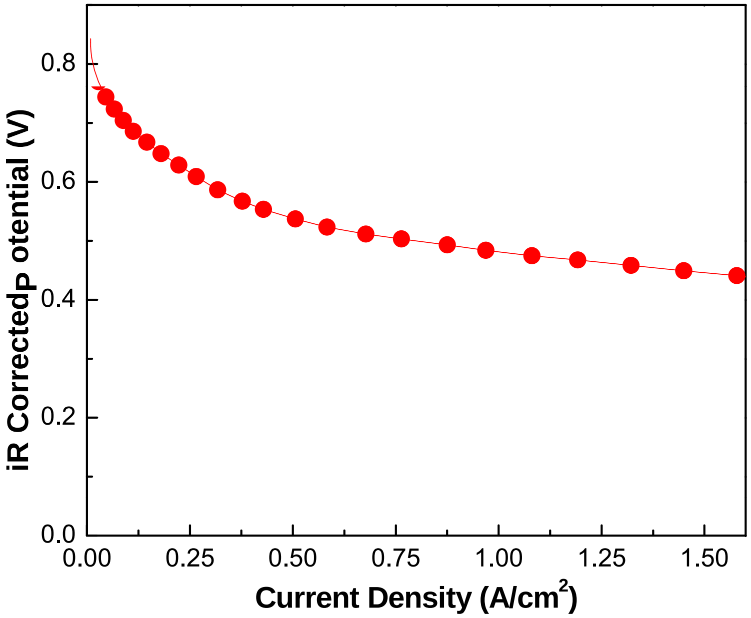
Synthesis of Carbon Composite Catalyst



HIGHLIGHT

The exclusion of carbon black in the catalyst synthesis can increase nitrogen content in the resulting catalysts, hence, increases the density of ORR active sites.

Popov et.al., *Electrochim. Acta*. 55 (2010) 2853-2858.



HIGHLIGHT

Iron has the ability to alloy with carbon and nitrogen and at 800 ºC the saturation of iron particles relives by the precipitation of carbon and nitrogen. (S. Maldonaldo and K. J. Stevenson , *J. Phys. Chem.* B, 109 (2005) 4707).

- **Anode: E-TEK 20% Pt/C (0.4 mg cm^{-2} Pt)**
- **Cathode: 2 mg cm^{-2} of carbon composite catalyst**
- **Membrane: Nafion^{TM} 112**
- **Operating temperature: 77 ºC (H_2); 75 ºC (O_2); 75 ºC (cell)**

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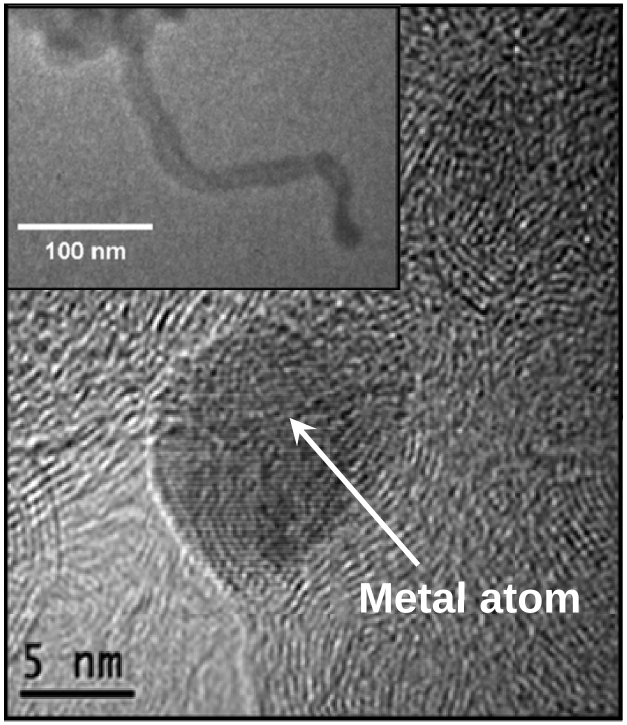
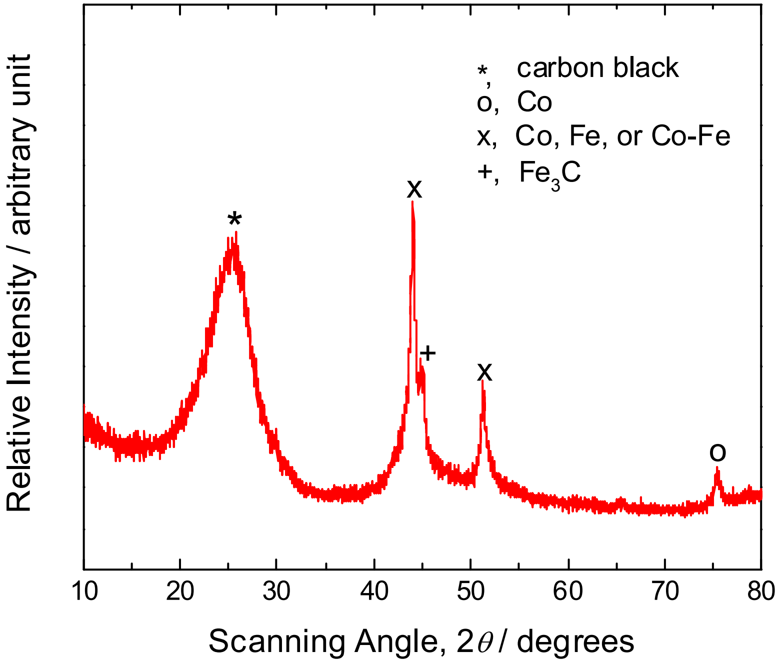
Active Sites: TEM and XPS





HIGHLIGHT

- **Metal atoms are covered with several graphitic layers.**
- **Nanostructured fiber of graphitic carbon was formed as a result of metal-catalyzed pyrolysis.**
- **No metal traces were detected on the surface of carbon-based composite catalyst.**

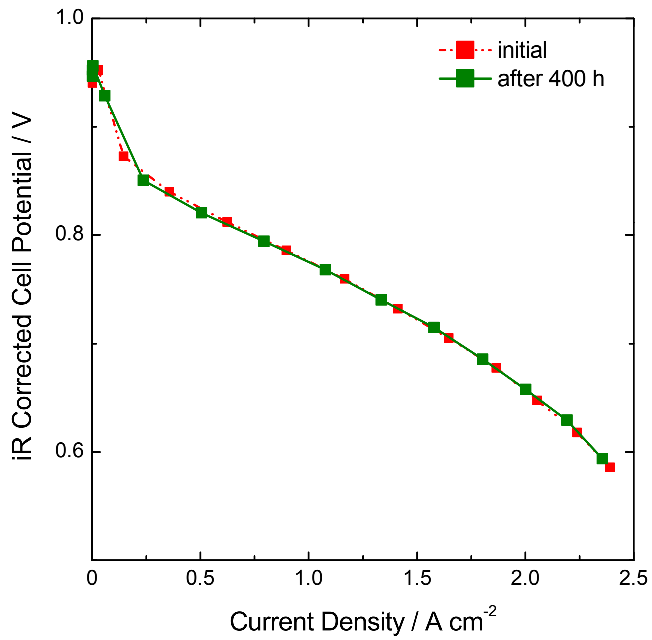
HIGHLIGHT

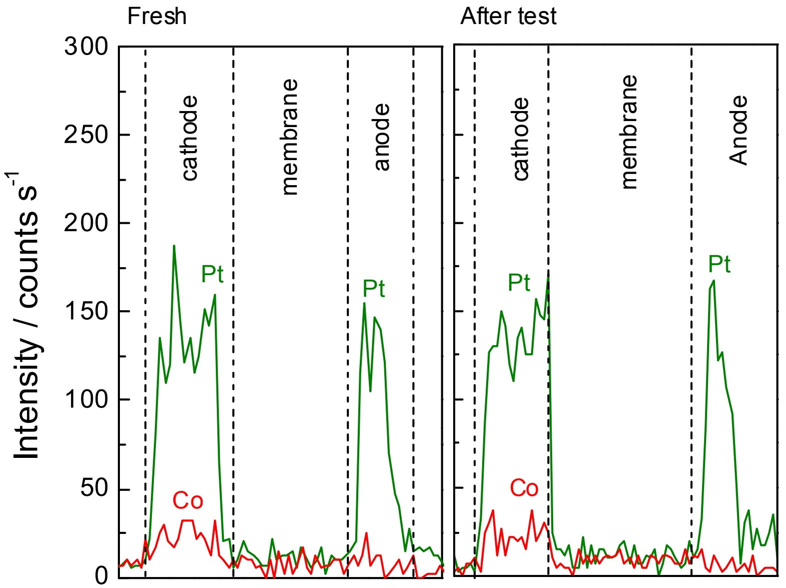
- **In carbon composite catalyst, metals and cementite (Fe_3C) species are present inside the carbon particles.**
- **No metallic element on the surface was detected by XPS.**

Previous Accomplishments at University of South Carolina

Development of Low Pt Loading Cathode Catalyst

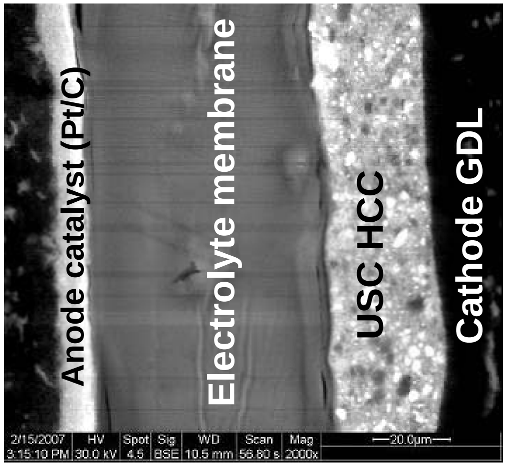
Stability of USC HCC in Fuel Cell





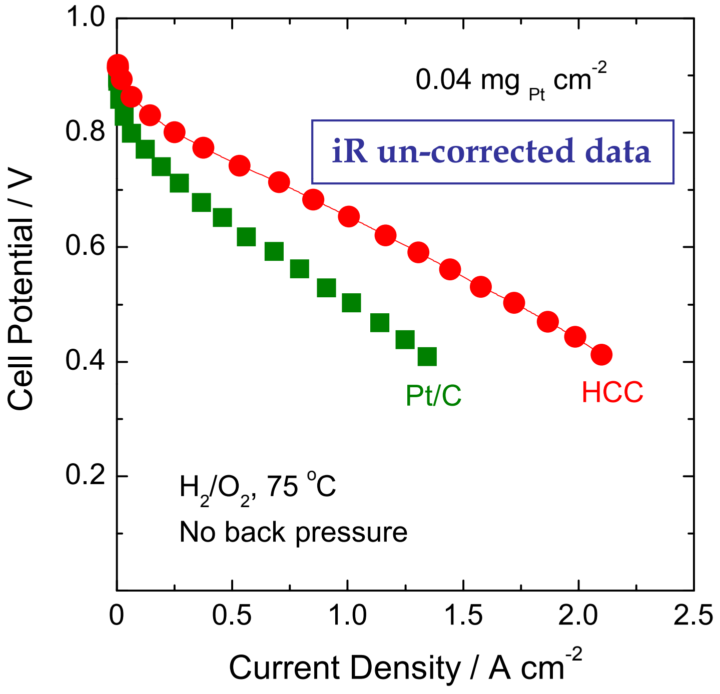
- *Cathode: 0.4 mg cm^{-2} Pt-Co*
- *Anode: 0.5 mg cm^{-2} ETEK Pt*
- *Membrane: Nafion 112*
- *Operating conditions:*

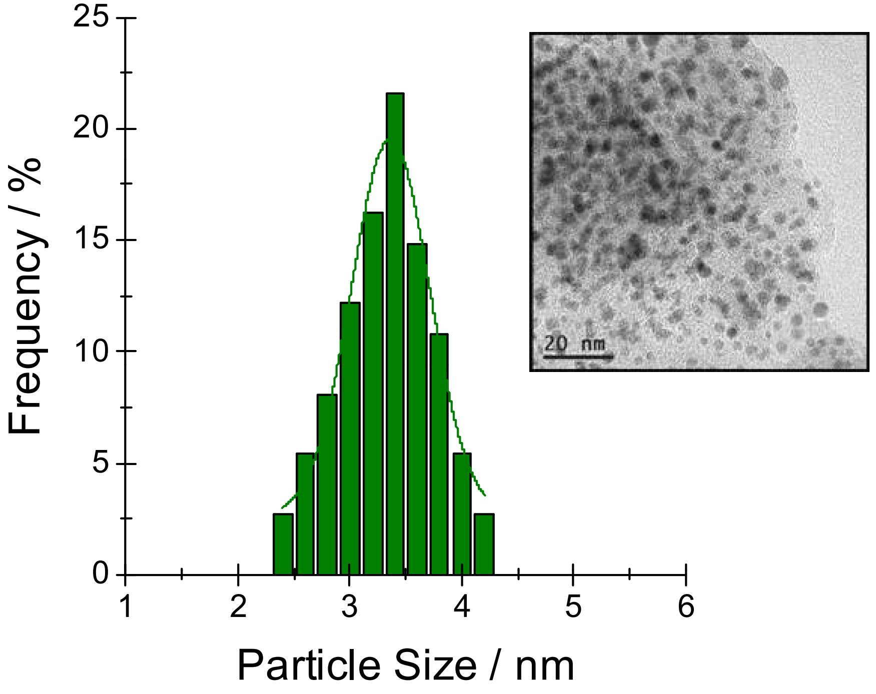
(i) H$_2$/O$_2$
(ii) no back pressure
(iii) 77/75 ^{o}C



No dissolution of Co from the catalyst and diffusion into the membrane after 400 h of continuous operation.

Comparison of Catalytic Activity: Fuel Cell Studies



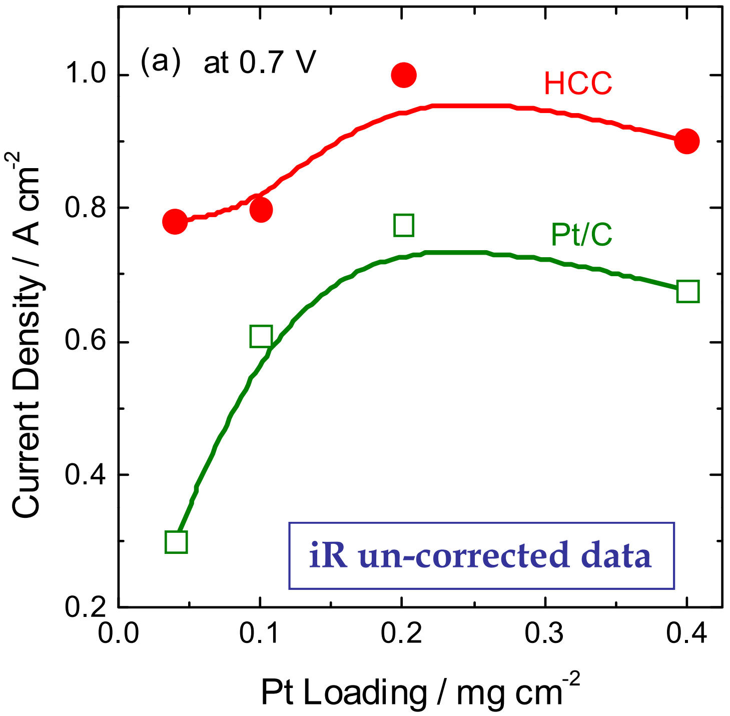


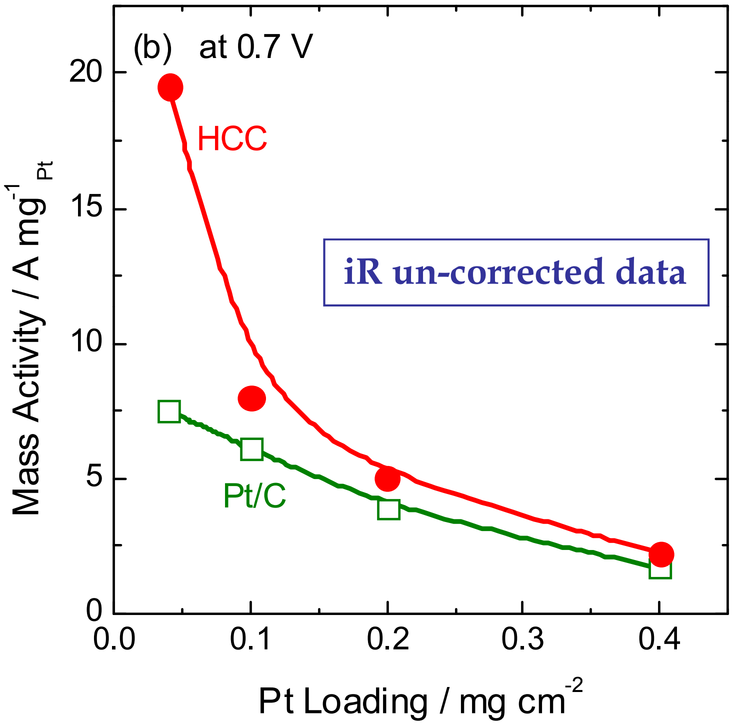
HIGHLIGHT

- **CCC is highly active for oxygen reduction, while carbon black is inactive.**
- **The catalytic performance of HCC is higher than Pt/C according to both RDE and fuel cell test.**

TEM: The USC HCC catalyst shows more uniform dispersion of particles over the active support with small average particle size and narrower distribution.

Effect of Pt Loading on Catalytic Activity: Fuel Cell Study





HIGHLIGHT

- **The mass activity of HCC shows a 150% enhancement when Pt loading is decreased from 0.1 to 0.04 mg cm^{-2} due to the contribution from the support at ultra-low Pt loading.**

Previous Accomplishments at University of South Carolina

Development of TiO_2 Supported Pt Catalyst

USC Strategy: Pt/TiO_2 Catalyst

Strategy: Modification of titanium dioxide support for the facile deposition of Pt and Pt-alloy catalysts.

TiO_2 surface modification

- **Surface modification using USC developed methodology.**

Pt and Pt-alloy deposition

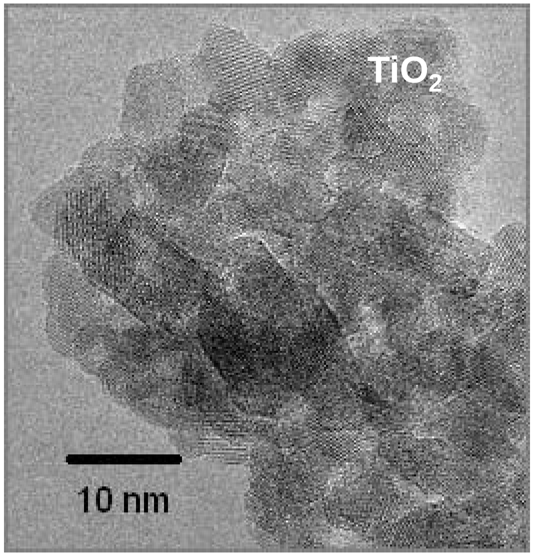
- **Surfactant assisted Pt and Pt-alloy deposition for uniform particle distribution.**

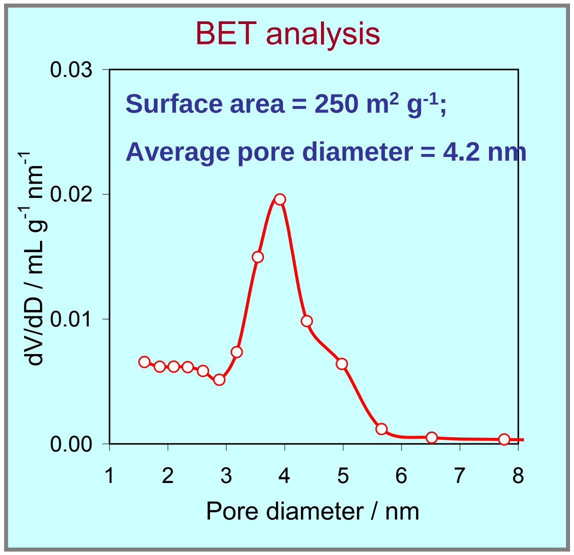
Catalyst activation

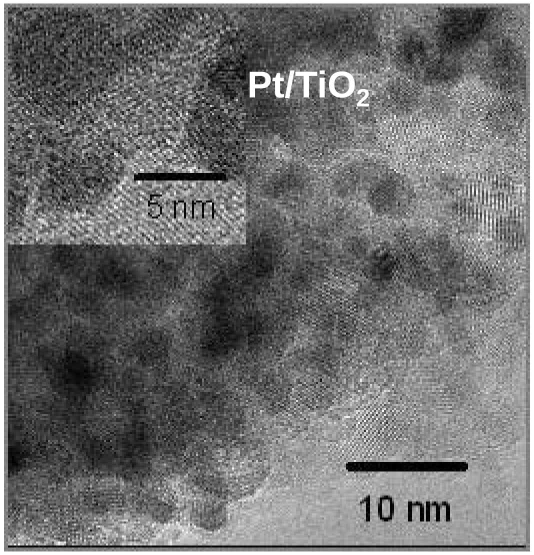
- **De-alloying and Heat-treatment to form high surface area Pt and Pt-alloy catalyst.**

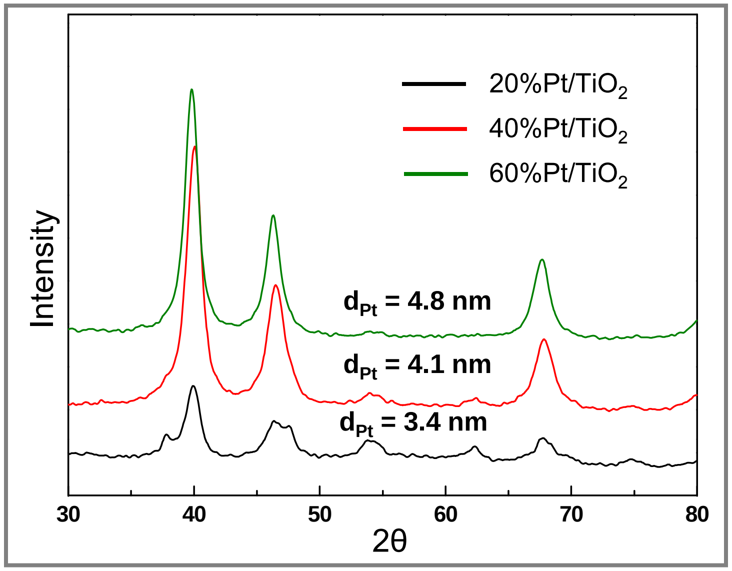
Popov et.al., *J. Am. Chem. Soc.*, 131 (2009) 13898-13899
Popov et.al., *Appl. Catal. B: Environmental*, 96 (2010) 224-231

Characterization – TiO_2 and Pt/TiO_2



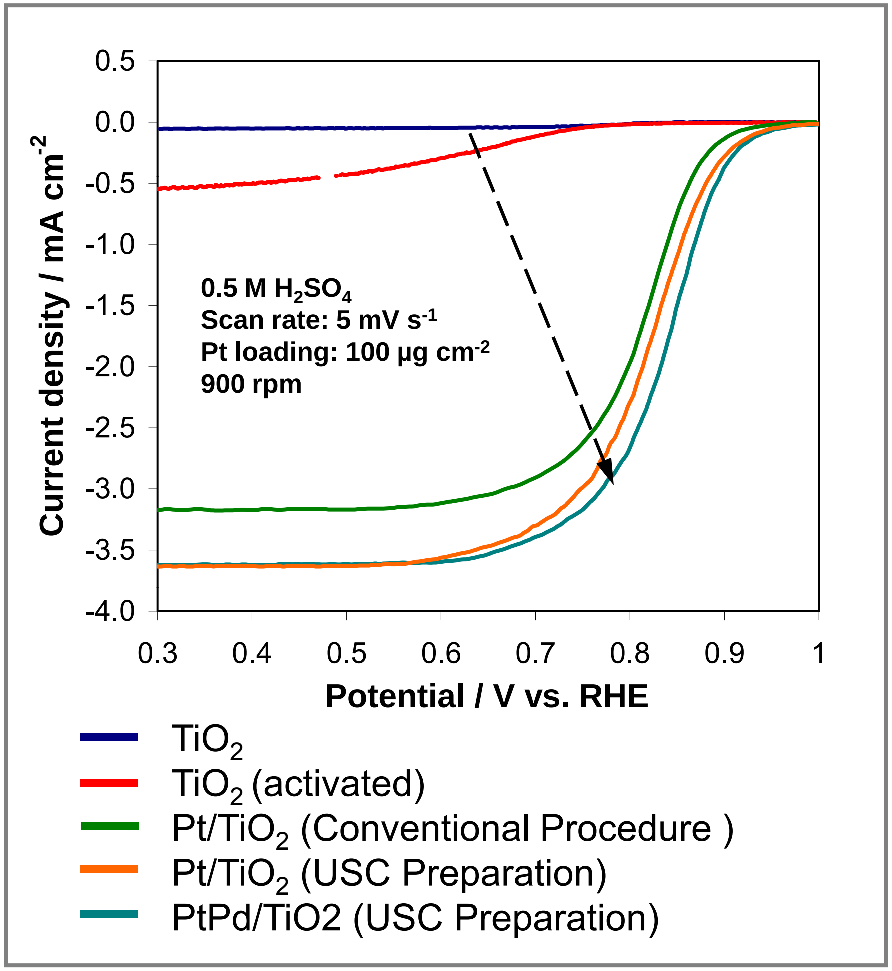






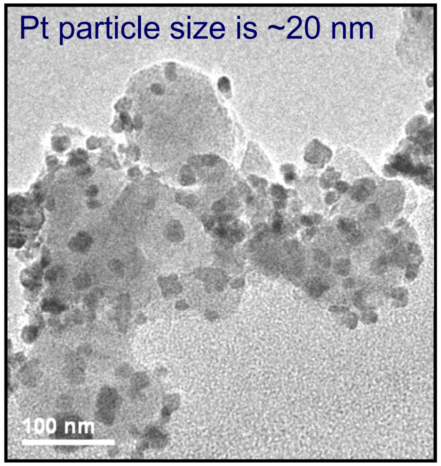
- **Surface area of TiO_2 = 250 m^2 g^{-1}.**
- **Pt particles with d_{Pt} = 3-5 nm were deposited on TiO_2.**
- **Pt particle size can be optimized by controlling the nucleation rate.**

Optimization Studies on Pt/TiO_2 Catalysts: LSV

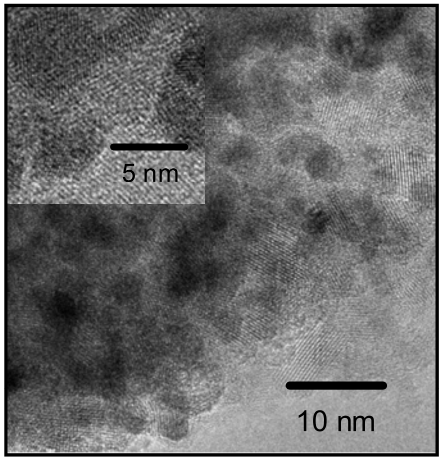


Pt and PtPd nanoparticles (3-6 nm) can be deposited on to TiO_2 supports using USC developed procedure.

Conventional procedure for Pt deposition

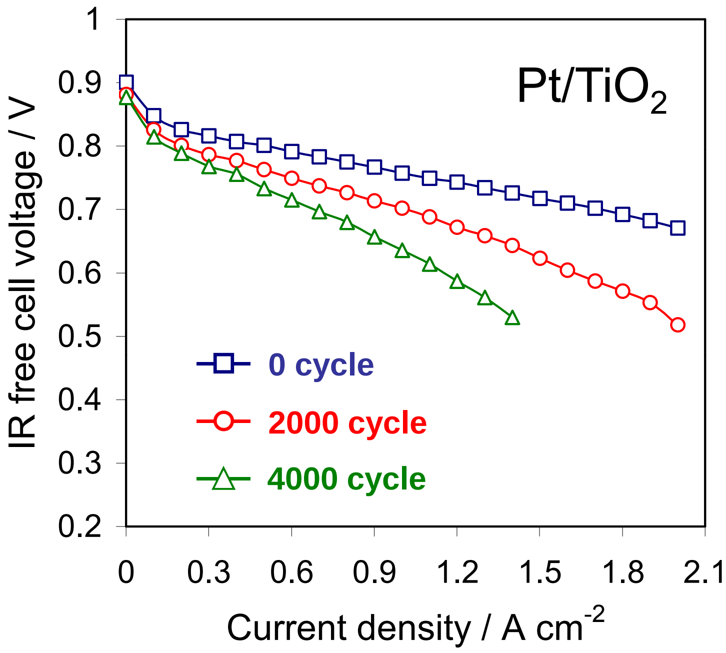


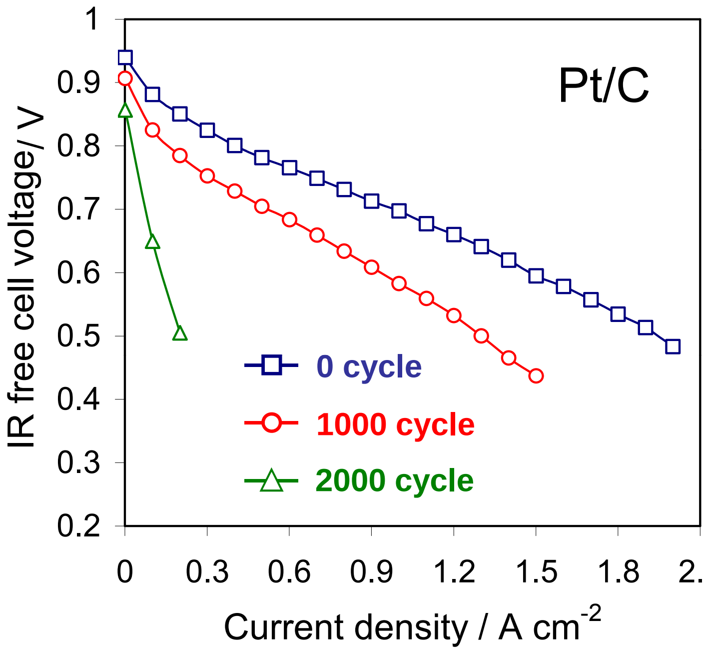
USC deposition procedure



Pt particle size is 3 – 6 nm

Accelerated Durability Test of Different Catalysts – CV Cycling between 0.6 and 1.4 V (Fuel Cell)





IV curves were obtained after CV cycles.

Membrane: Nafion® 112; Cell area: 25 cm^2 cell.

Anode: 0.5 mg Pt cm^{-2} (E-TEK); Cathode: 0.4 mg Pt cm^{-2}.

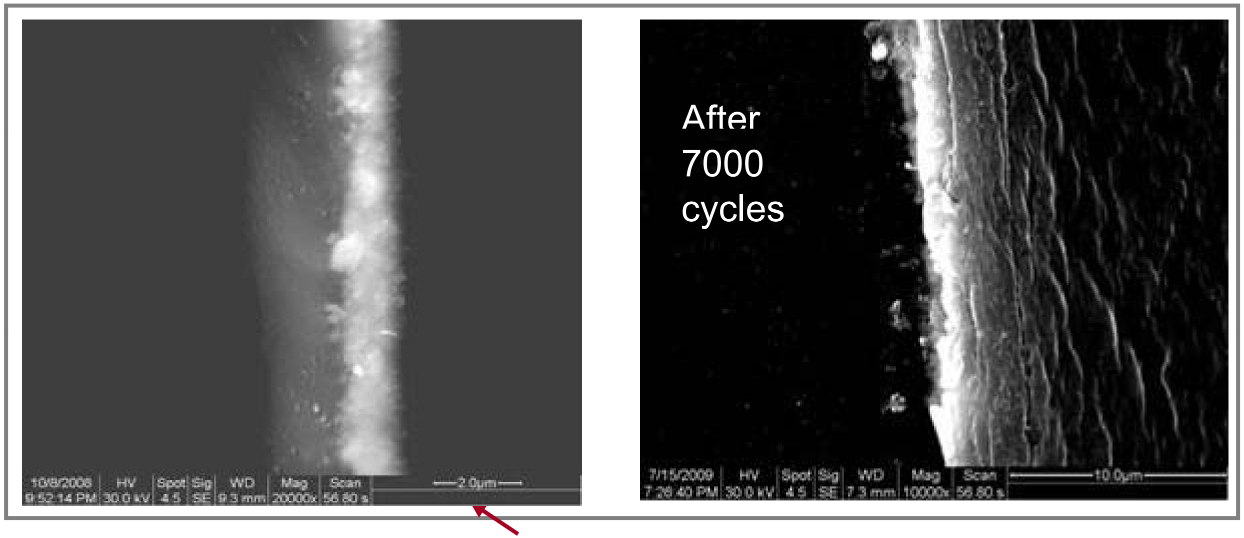
Operating conditions: (i) H_2/air; (ii) 25/25 psi; (iii) 80 °C.

Flow rate H_2/air: 1.2/2 Stoich; Humidity: 100% RH.

- **Slight decrease in cell voltage (0.09 V) at 0.8 A cm^{-2} was observed after 4000 cycles for Pt/TiO$_2$.**
- **Pt/C exhibited a large voltage drop after 2000 cycles due to carbon corrosion and detachment and agglomeration of catalyst particles.**

Cross-section Analysis of MEA with Pt/TiO_2 and Pt/C Cathodes

Pt/TiO_2 cathode

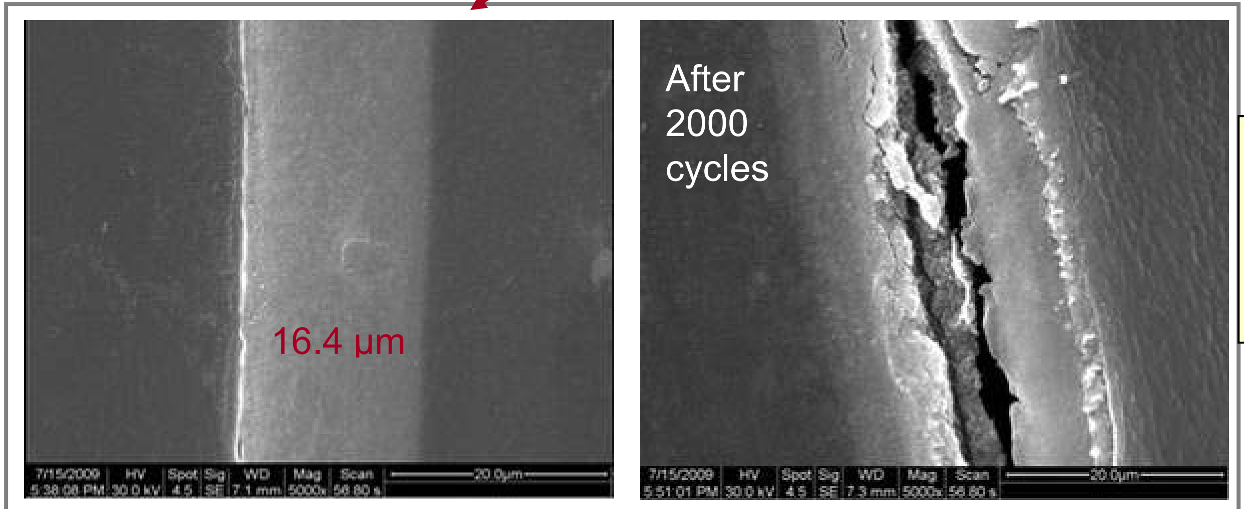


- Pt/TiO_2 electrode retained a similar morphology and catalyst layer thickness (1 μm) before and after ADT.

Pt/C cathode

Initial state

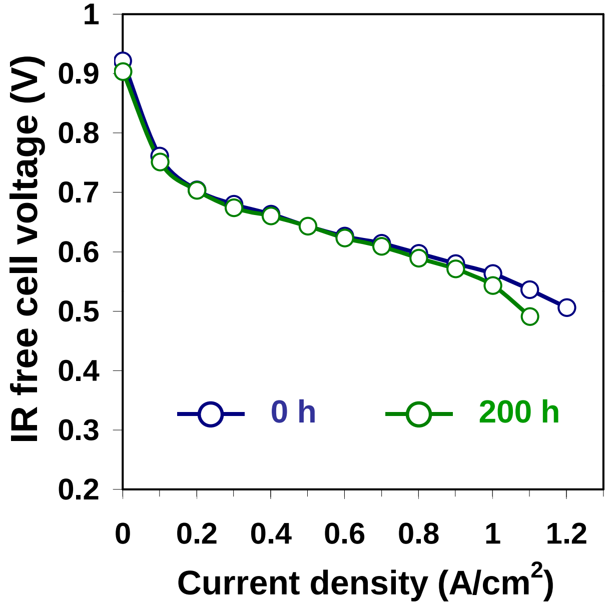
After test



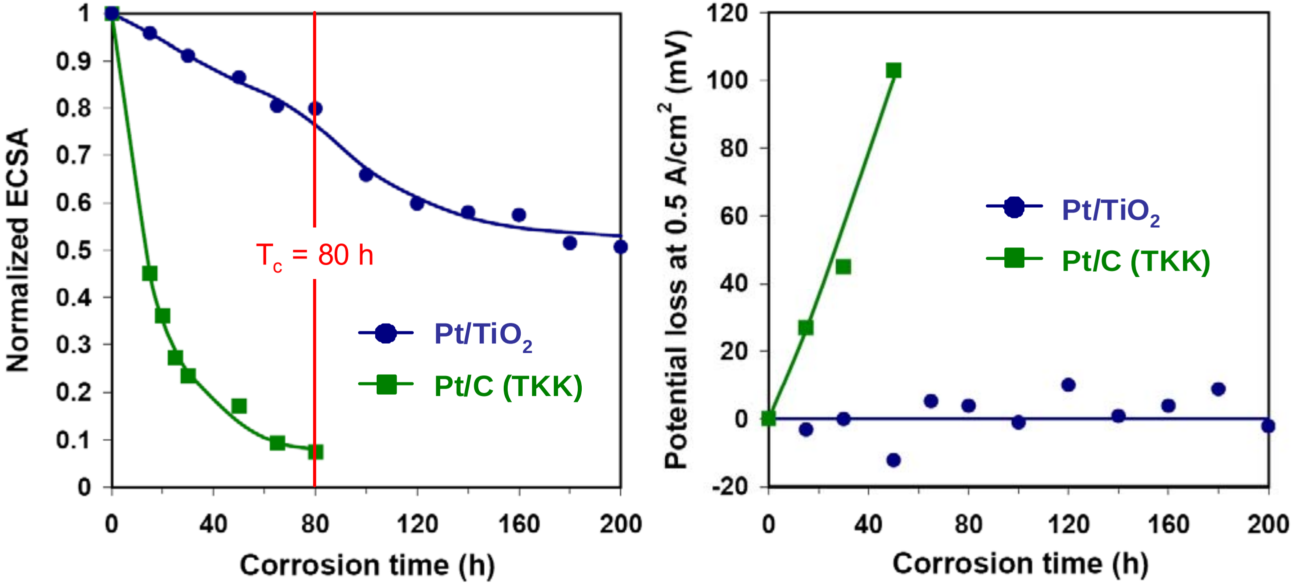
- Cracks were observed in the Pt/C cathode after ADT due to disintegration of the catalyst layer.

Accelerated Corrosion Test of Pt/TiO_2 and Pt/C Catalysts - Effect of Potential Holding at 1.2 V on Fuel Cell Performance

IV curves were obtained after potential holding experiment.



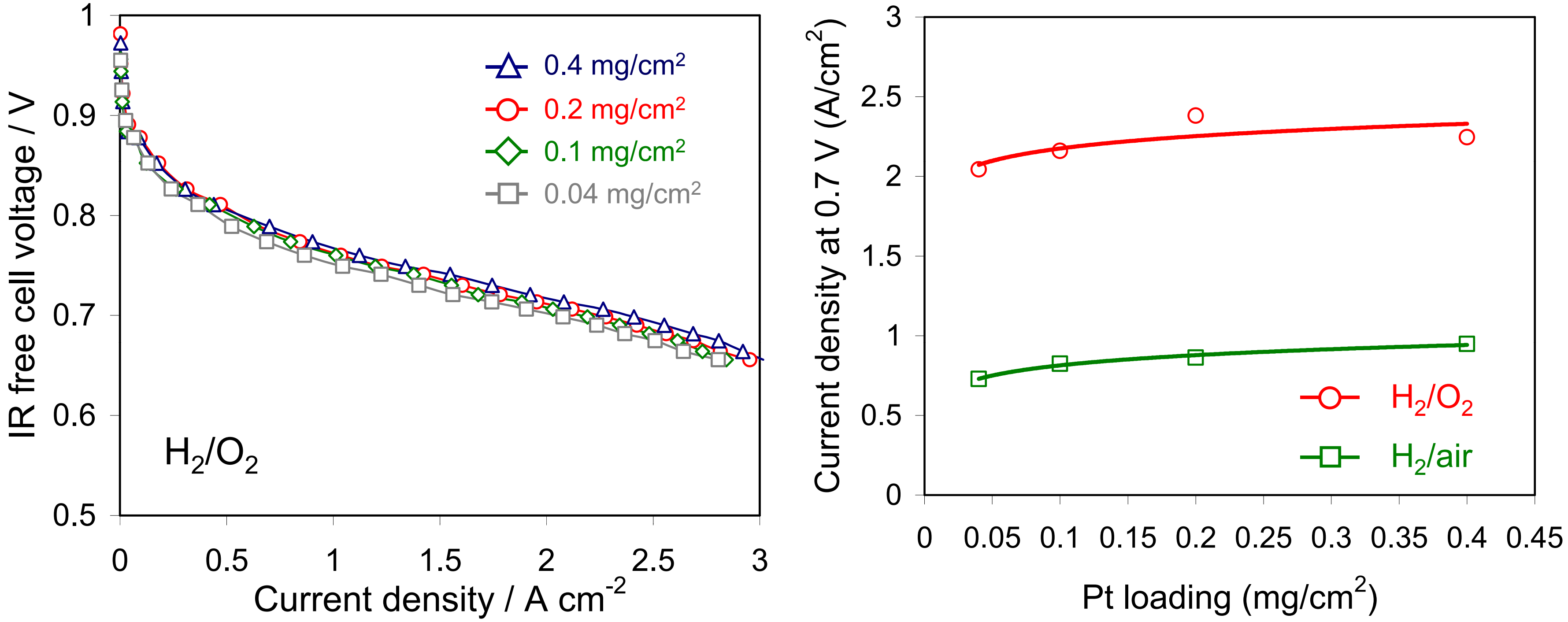
Normalized ECSA and potential loss at 0.5 A cm^{-2} as a function of corrosion time (T_c)



Membrane: Nafion® 112.
Anode: 0.5 mg Pt cm^{-2} (Pt/C, E-TEK).
Cathode: 0.4 mg cm^{-2} Pt catalysts.
Operating conditions: (i) H_2/air;
(ii) 150 kPa; (iii) 80 °C;
(iV) 25 cm^2 cell;
(v) flow rate H_2/air: 3/3;
(vi) humidity: 50% RH.

- **Pt/C electrocatalyst showed a rapid decay (93%) in ECSA at T_c = 80 h.**
- **For Pt/TiO_2 , total loss of ECSA is ~20% after T_c = 80 h.**
- **No decrease in catalytic activity up to 200 h when compared to Pt/C (45%, TKK) at 0.5 A cm^{-2} when polarized at 1.2 V.**

Fuel Cell Performance of Pt/TiO_2 Cathode Catalyst: Effect of Pt loading



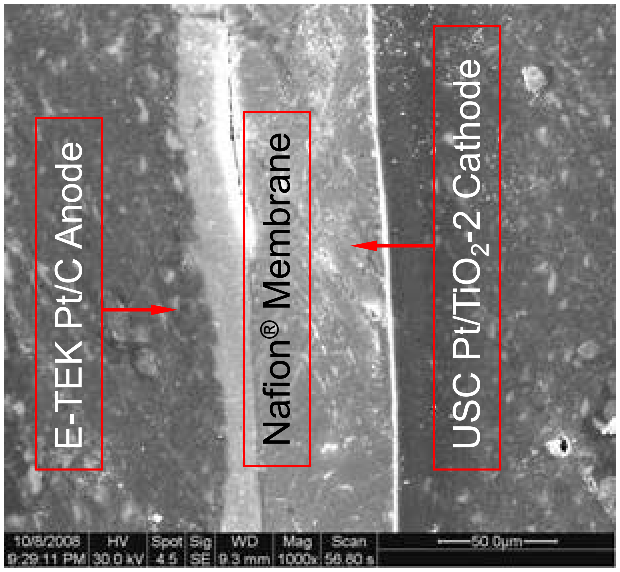
Membrane: Nafion® 112; Cell area: 5 cm^2 cell.

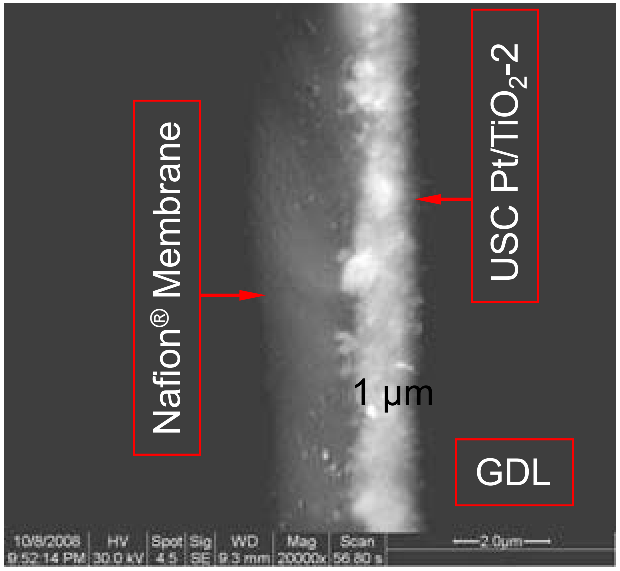
Anode: 0.5 mg Pt cm^{-2} (Pt/C, E-TEK); Cathode: Pt/TiO_2 catalyst.

Operating conditions: (i) H_2/O_2 or air; (ii) no back pressure; (iii) 77/75 °C; (iv) 5 cm^2 cell; (v) Flow rate H_2/O_2/air: 150/150/300 ccm; (vi) Humidity: 100% RH.

- **Current density at 0.7 V is 2.25, 2.38, 2.16, and 2.04 A/cm^2 for 0.4, 0.2, 0.1, and 0.04 mg$_{Pt}$/cm^2.**

Cross-section Analysis of MEA with Pt/TiO_2 Cathode





- **Very thin cathode catalyst layer (~1 μm) can be made using USC developed methodology.**
- **USC developed methodology enables to load Pt (3-5 nm) up to 60% uniformly on the TiO_2 support.**

Summary (Previous Accomplishments)

USC HCC Catalyst

❖ USC HCC catalyst shows higher performance than Pt/C at all loadings between 0.04 and 0.4 mg cm^{-2}.

❖ The mass activity of HCC shows a 150% enhancement when Pt loading is decreased from 0.1 to 0.04 mg cm^{-2} due to the contribution from the support (CCC) at ultra-low Pt loading.

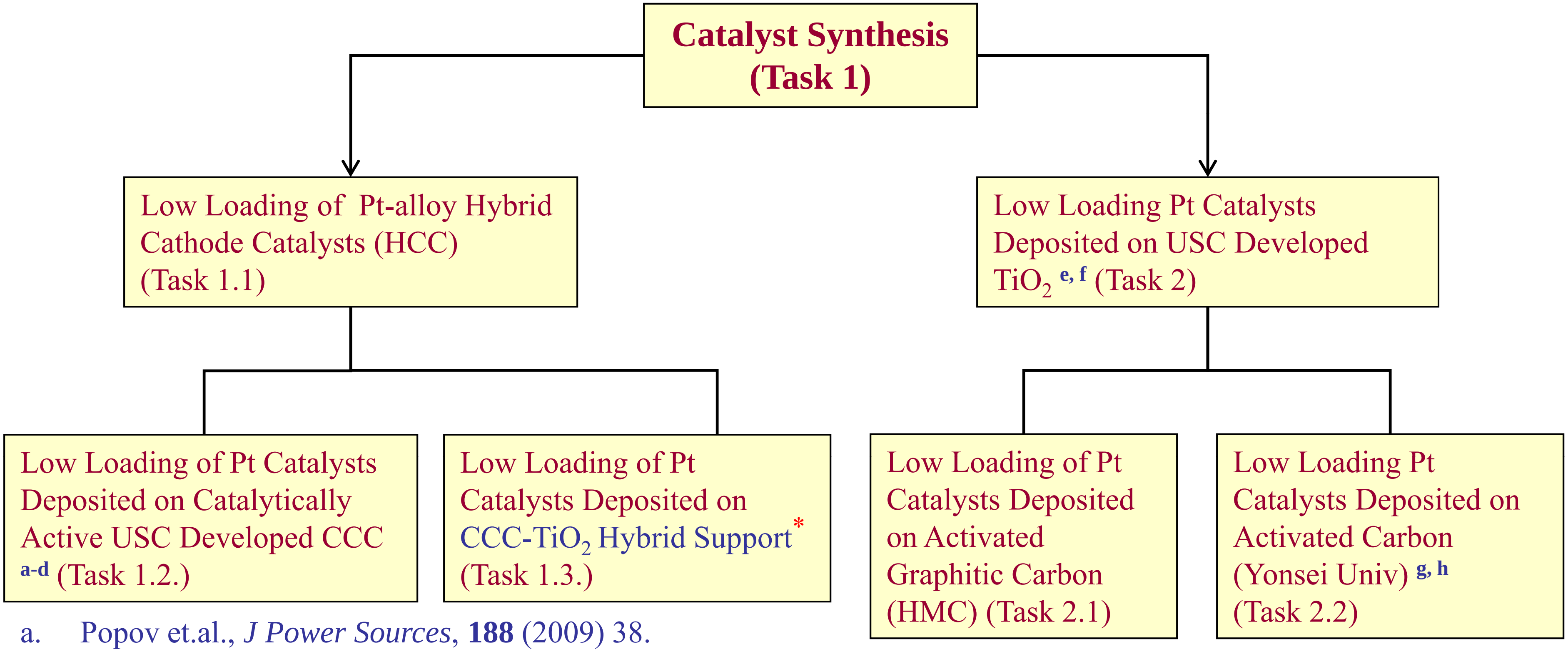
Low Loading Leached Pt Catalyst (USC Developed TiO_2 Support)

USC Pt/TiO_2 Catalyst

❖ Slight decrease in cell voltage (0.09 V) at 0.8 A cm^{-2} was observed after 4000 cycles (cycling between 0.6 and 1.4 V) for Pt/TiO_2. Pt/C exhibited a large voltage drop after 2000. cycles due to carbon corrosion and detachment and agglomeration of catalyst particles.

❖ Pt/TiO_2 do not show any decrease of fuel cell performance after 200 h DOE accelerated corrosion test. Pt/C electrocatalyst showed a rapid decay (93%) in ECSA after 80 h.

USC Approach and Future Work (Catalyst Synthesis Based on Leached Pt-alloy Catalysts Deposited on CCC, TiO_2, Activated Graphitic Carbon Supports)



Catalyst Synthesis (Task 1)

Low Loading of Pt-alloy Hybrid Cathode Catalysts (HCC) (Task 1.1)

Low Loading Pt Catalysts Deposited on USC Developed TiO_2 [e, f] (Task 2)

Low Loading of Pt Catalysts Deposited on Catalytically Active USC Developed CCC [a-d] (Task 1.2.)

Low Loading of Pt Catalysts Deposited on CCC-TiO_2 Hybrid Support* (Task 1.3.)

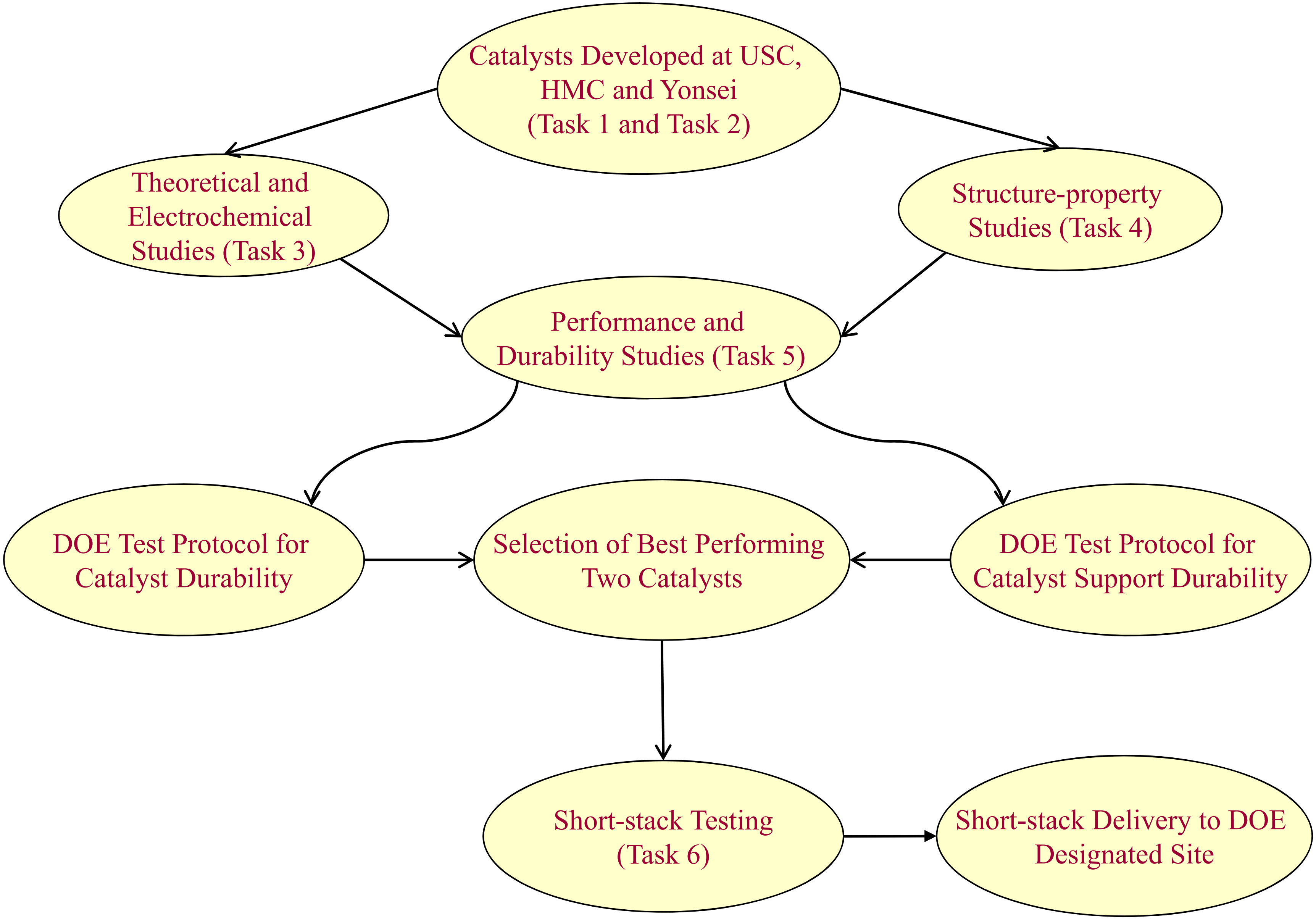
Low Loading of Pt Catalysts Deposited on Activated Graphitic Carbon (HMC) (Task 2.1)

Low Loading Pt Catalysts Deposited on Activated Carbon (Yonsei Univ) [g, h] (Task 2.2)

a. Popov et.al., *J Power Sources*, **188** (2009) 38.
b. Popov et.al., *Appl. Catal. B: Environmental*, **93** (2009) 156.
c. Popov et.al., *J Power Sources*, **183** (2008) 34.
d. Popov et.al. *J. Power Sources*, **157** (2006) 56.
e. Popov et.al., *Appl. Catal. B: Environmental*, **96** (2010) 224.
f. Popov et.al., *J. Am. Chem. Soc.*, **131** (2009) 13898.
g. Kim et.al., *Electrochem. Commun.*, 11 (2009) 1131.
h. Kim et.al., *Electrochim. Acta*, 54 (2009) 6515.

*Hybrid support made of carbon composite catalyst and metal oxide (TiO_2)

USC Approach and Future Work
(Catalyst Performance Evaluation)



Catalysts Developed at USC, HMC and Yonsei (Task 1 and Task 2)

Theoretical and Electrochemical Studies (Task 3)

Structure-property Studies (Task 4)

Performance and Durability Studies (Task 5)

DOE Test Protocol for Catalyst Durability

Selection of Best Performing Two Catalysts

DOE Test Protocol for Catalyst Support Durability

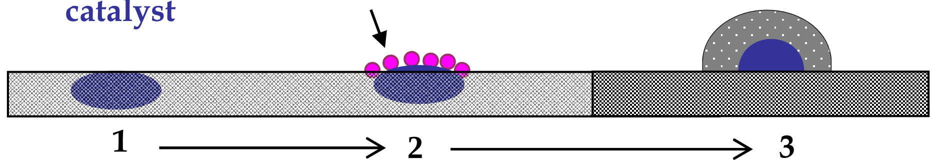
Short-stack Testing (Task 6)

Short-stack Delivery to DOE Designated Site

Proposed Future Work

- **Objectives**: To synthesize low cost, high stability leached Pt catalysts with high performance using different catalyst supports.

USC methodology 1 – Development of hybrid cathode catalyst



Carbon Composite catalyst

Pt

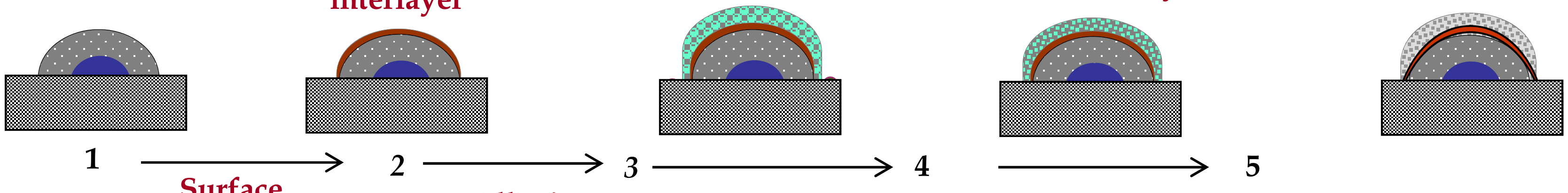
Pt-rich alloy on the surface (Pt-Co or Pt-Pd

1 → 2 → 3

Pt deposition

Heat treatment

USC methodology 2 – Development of leached hybrid catalysts



Carbon Composite Catalyst

Pt or Pd interlayer

Pt-Co or Pt-Ni or Pt-Cu deposit

Pt-Co or Pt-Ni or Pt-Cu alloy

Leached Pt catalyst

1 → 2 → 3 → 4 → 5

Surface treatment with Pd or Pt

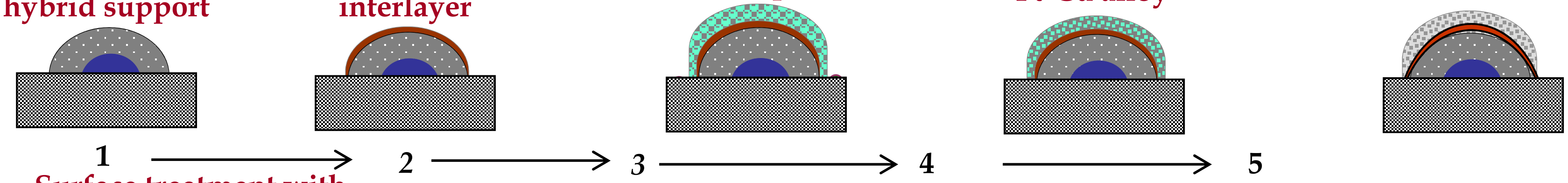
Alloying (Pt-Co or Pt-Ni or Pt-Cu)

Heat treatment

Leaching

Proposed Future Work

USC methodology 3 – Development of Pt leached hybrid catalysts



TiO_2 or CCC-TiO_2 hybrid support

Pt or Pd interlayer

Pt-Co or Pt-Ni or Pt-Cu deposit

Pt-Co or Pt-Ni or Pt-Cu alloy

Leached Pt catalyst

1 → 2 → 3 → 4 → 5

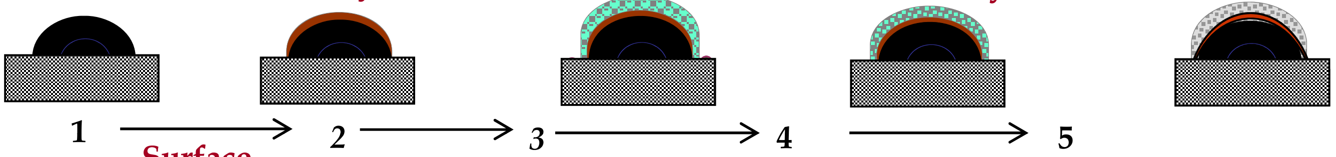
Surface treatment with Pd or Pt

Alloying

Heat treatment

Leaching

HMC methodology – Development of Pt leached catalysts



HMC Support (Activated graphitic carbon)

Pt or Pd interlayer

Pt-Ni deposit

Pt-Ni alloy

Leached Pt catalyst

1 → 2 → 3 → 4 → 5

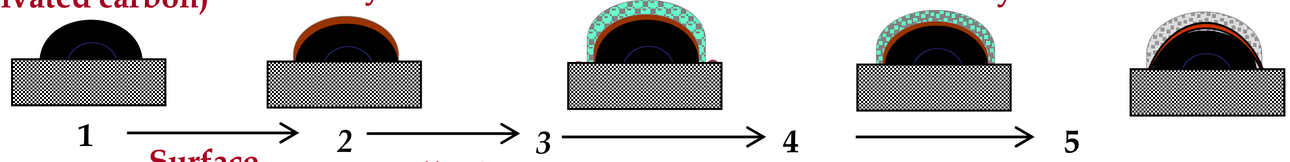
Surface treatment with Pd or Pt

Alloying (Pt-Ni)

Heat treatment

Leaching

Yonsei University methodology – Development of Pt leached catalysts



YU Support (Activated carbon)

Pt or Pd interlayer

Pt-Co deposit

Pt-Co alloy

Leached Pt catalyst

1 → 2 → 3 → 4 → 5

Surface treatment with Pd or Pt

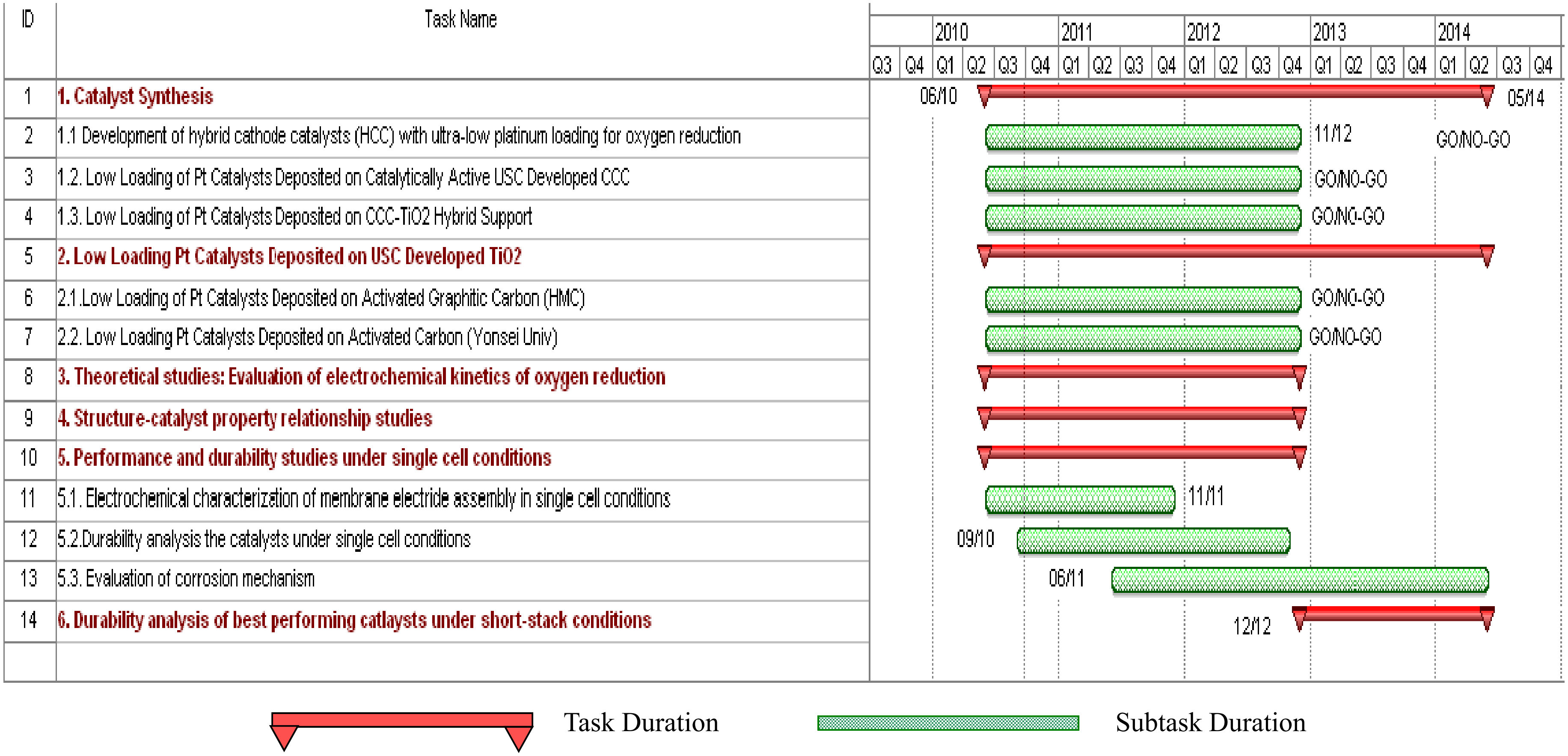
Alloying (Pt-Co)

Heat treatment

Leaching

Project Timeline

Catalyst Synthesis Based on Leached Pt-alloy Catalysts Deposited on CCC, TiO_2, Activated Graphitic Carbon Supports

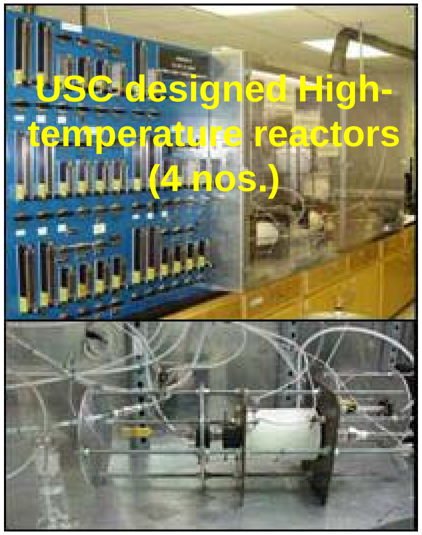


ID	Task Name
1	**1. Catalyst Synthesis**
2	1.1 Development of hybrid cathode catalysts (HCC) with ultra-low platinum loading for oxygen reduction
3	1.2. Low Loading of Pt Catalysts Deposited on Catalytically Active USC Developed CCC
4	1.3. Low Loading of Pt Catalysts Deposited on CCC-TiO2 Hybrid Support
5	**2. Low Loading Pt Catalysts Deposited on USC Developed TiO2**
6	2.1.Low Loading of Pt Catalysts Deposited on Activated Graphitic Carbon (HMC)
7	2.2. Low Loading Pt Catalysts Deposited on Activated Carbon (Yonsei Univ)
8	**3. Theoretical studies: Evaluation of electrochemical kinetics of oxygen reduction**
9	**4. Structure-catalyst property relationship studies**
10	**5. Performance and durability studies under single cell conditions**
11	5.1. Electrochemical characterization of membrane electride assembly in single cell conditions
12	5.2.Durability analysis the catalysts under single cell conditions
13	5.3. Evaluation of corrosion mechanism
14	**6. Durability analysis of best performing catlaysts under short-stack conditions**

Milestone Schedule

	Tasks	Milestone or Go/No-Go Decision
Phase I	1.	Catalyst synthesis **Go/No-Go decision**: Leached Pt-Co/CCC, Pt-Ni/CCC, Pt-Cu/CCC
	2.	Low Loading Pt Catalysts Deposited on USC Developed TiO_2 **Go/No-Go decision**: Pt/TiO_2, leached Pt-Co/TiO_2, Pt-Cu/TiO_2, Pt-Co/CCC-TiO_2, Pt-Cu/CCC-TiO_2, Pt-Ni/HMCS, Pt-Co/YUS
	3.	Theoretical/Electrochemical studies
	4.	Structure-property studies
	5.	Performance and durability studies under single cell conditions
Phase I Milestone		• Low peroxide formation (<1% H_2O_2) • Uniform Pt catalyst distribution with 3-4 nm size particle size • Pt loading < 0.2 mg/cm^2; 0.2 g/kW • Electrochemical surface area >50 cm^2 • Catalyst stability (≤30 mV loss at 0.8 A/cm^2 and support stability (DOE AST for catalysts and supports) • Durability > 2000 h at ≥80 ^{o}C • Construction of single cell with optimized catalyst
Phase II	6.	Durability analysis of selected catalysts under short-stack conditions
Phase II Milestone		• Durability analysis of best performing catalyst under short-stack conditions • Ultra-low Pt loading of 0.2 mg/cm^2 at power density of 0.2 g_{Pt}/kW • Delivery of short-stack (up to 10 cells) to DOE designated site.

Facilities at USC


USC designed High-temperature reactors (4 nos.)


FISCHER X-ray Fluorescence


RRDE – PINE (2 nos.)


BET surface area analyzer

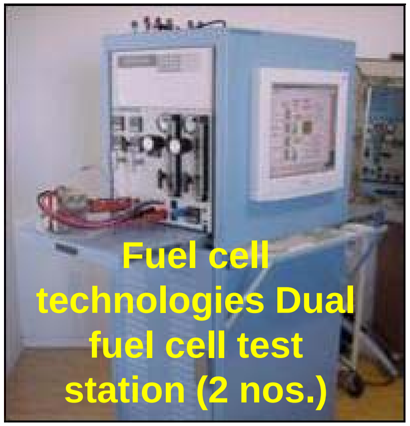

Micromeritics Hg Porosimeter


JEOL HR-TEM


Zeiss Ultra Plus HR-SEM


FEI Quanta ESEM

Automatic coater


Fuel cell technologies Dual fuel cell test station (2 nos.)

Scribner fuel cell test station (2 nos.)

Facilities at Eco-Technology Research Center (HMC)

100 kW Stack Test Station

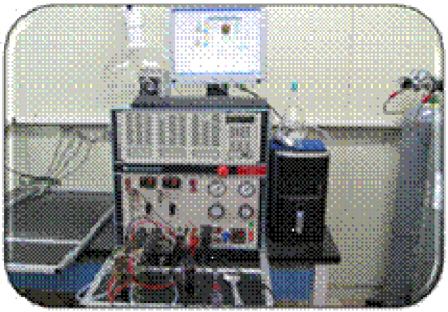
Environmental Chamber

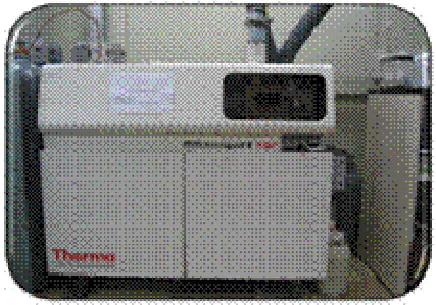
100W-1kW Test Stations

Multi Channel Test Station

Facilities at Yonsei University

No.	Facility	Qunatity	Purpose
1	Fuel cell test station	5	Single cell performance test
2	RRDE (Rotating Ring Disk Electrode)	1	Electrochemical characterization
3	Multi-Potentiostat / Impedance	6	Electrochemical characterization
4	Mass spectrometry	1	Qualitative and quantitative analysis of gas
5	ICP (Inductively Coupled Plasma)	1	Quantitative analysis of element
6	XRD (X-Ray Diffractometer)	1	Structural characterization
7	TGA (Thermogravimetric Analyzer)	1	Evaluation of thermal stability
8	BET	1	Measurement of the specific surface area
9	HR-TEM (High Resolution - Transmission Electron Microscope)	1	Fine structure analysis
10	AFM (Atomic force microscopy)	1	Surface morphology analysis


Fuel cell test station



ICP


TGA

Summary

- Ultra-low loading Pt catalysts for oxygen reduction reaction with high activity (high electrochemical surface area) and good stability will be developed through:
  - Synthesis of hybrid cathode catalyst (HCC).
  - Synthesis of activated low loading platinum catalysts with high electrochemical surface area deposited on conductive TiO_2 and active CCC-TiO_2 hybrid supports.
  - Synthesis of leached Pt-Ni alloy catalysts with high electrochemical surface area Pt deposited on activated graphitic carbon developed at HMC.
  - Synthesis of leached Pt-Cu catalysts with high electrochemical surface area Pt deposited on activated carbon developed at Yonsei University.
  - **Facile scale-up synthesis procedure for the production of all the suggested catalysts.**
  - Pt-alloy particle agglomeration during annealing process at high temperaturewill be eliminated using a procedure developed at Yonsei University.
  - The inter-particle resistance and the catalyst particle detachment from the support will be minimized by:
    - ✓ the introduction of a thin interlayer of Pt or Pd between the support and optimization
    - ✓ optimization of Pt and alloying metal composition.
  - Synthesis of high distribution of Pt with high initial loading over carbon support without Pt loss.
  - Engineer membrane electrode assembly (MEA) with thin catalyst layer and optimize the catalyst-catalyst support ratio

Team Members who contributed to this presentation

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