



# FC-PAD

## Fuel Cell – Performance and Durability

### FC136 – Electrocatalysts and Supports

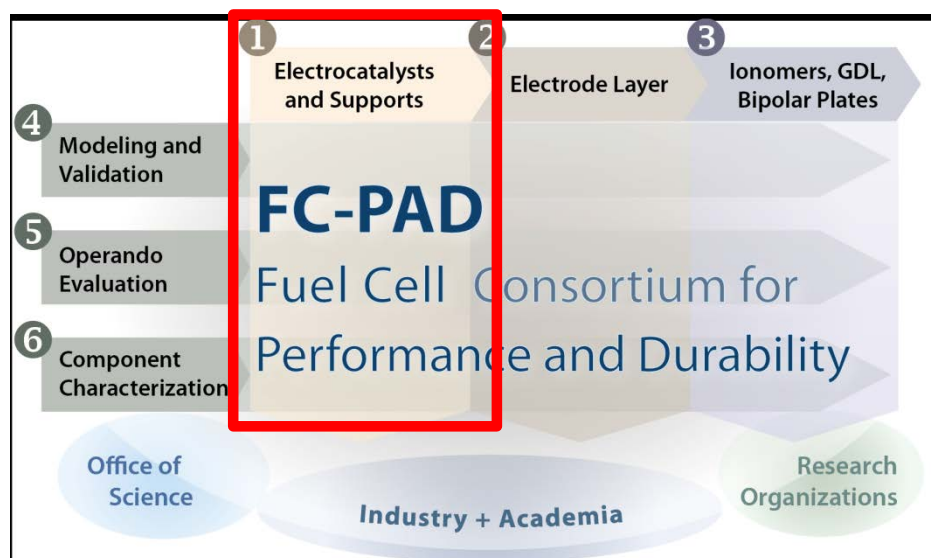
Thrust Coordinator: Debbie Myers

*June 8, 2016*



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# Component Thrust 1: Electrocatalysts and Supports



## Overview:

- Three component thrusts focusing on catalyst, electrode and ionomer/GDL/plates
  - Three crosscutting thrusts focusing on modeling, evaluation, and characterization
- 
- Thrust Area 1, Electrocatalysts and Supports, is the focus of this presentation
  - Thrust Area 1 is synergistic with Thrust Areas 2, 3, and 5 and supported by Thrust Areas 4 and 6

# FC-PAD contributors to this presentation



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## Current Collaborators



Karren More  
David Cullen

- IRD (Catalysts, MEAs)
- Umicore (Catalysts)
- Johnson Matthey (Catalysts, CCMs; as part of FC106)
- Ion Power (CCMs)
- Korea Institute of Energy Research (micro-electrode cell studies)

# FC-PAD Thrust 1: Overview

## Timeline

- Project start date: 10/01/2015
- Project end date: 09/30/2020

## National Labs

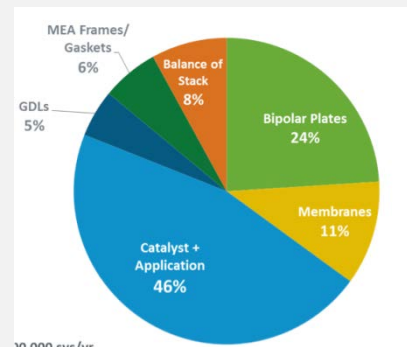
- ANL, LANL, NREL, and ORNL

## Partners/Collaborators To Date

- IRD, New Mexico
- Umicore, Germany
- NECC, Japan
- GM, USA
- Ion Power, USA
- Tanaka Kikinzoku Kogyo (TKK), Japan
- Johnson Matthey, United Kingdom
- Korea Institute of Energy Research (KIER)
- Partners to be added by DOE DE-FOA-0001412

## Barriers

- The electrocatalyst remains a challenge for reducing the **cost** to meet system cost targets



- **Durability** targets have not been met
- The **catalyst, its interaction with other electrode components, the stability of alloying components, and the effect of this instability** are not fully understood and are key to achieving performance, cost, and durability targets.

# Relevance and Approach

## ■ Thrust Area Objectives

- Realize the ORR mass activity benefits of advanced Pt-based cathode electrocatalysts in high current density, air performance for over 5,000 operating hours and with low PGM loading ( $<0.1$  mg-Pt/cm<sup>2</sup>)

## Approach - Achieve Objectives by studying:

### ■ Catalyst and catalyst support durability and degradation mechanisms

- *Elucidate catalyst and support degradation mechanisms as a function of catalyst and support physicochemical properties and cell operating conditions*
- *Quantify catalyst and support stability during accelerated stress tests and start-up and shut-down transients using in-cell measurements*
- *Determine stability of catalyst components, catalyst and support composition and structural changes*

### ■ Catalyst/support interactions

- Understand interplay between the catalyst and support properties and their mutual interactions
- *Determine the effects of carbon type (e.g., high, medium, and low surface area) and carbon dopants on the strength of the catalyst/support and ionomer/support interactions*
- Investigate the impact of these interactions on catalyst and support stability, durability, and performance

### ■ Ex-situ analysis of catalyst instability on cathode-catalyst-layer properties

- *Quantify the impact of catalyst degradation on the properties defining the performance of the cathode catalyst layer (e.g., impact of base metal leaching from Pt alloy catalyst on proton conductivity, oxygen permeability, and water uptake in ionomer)*

# Electrocatalysts currently under study in FC-PAD

## Commercial Sources

- **IRD:**
  - IRD CAT0023, 55wt% PtCo/C, 6.0 nm TEM ✓
- **Umicore:**
  - Elyst Pt50 0550; 45.9wt% Pt, 5.5 nm XRD ✓
  - Elyst P30 0670; 27.5 wt% Pt; 3 wt% Co, 4.4 nm TEM ✓
- **NEChemcat:**
  - PtCo/NE-GM ✓
  - Core-shell Pt ML/Pd/NE-H ✓
- **TKK:**
  - TEC10E50E, Pt/HSC, 47.5wt% Pt, 2.5 nm XRD ✓
  - TEC36E52, Pt<sub>3</sub>Co/HSC, 46.5 wt% Pt, 4.7 wt% Co, 5.7 nm TEM ✓
- **Johnson Matthey:**
  - Pt<sub>3</sub>Co/HSC, 40 wt% Pt, 4.9, 8.7, 14.3 nm TEM ✓
  - Dealloyed-Pt<sub>1.3</sub>Ni/HSC, 29.1 wt% Pt, 6.68 wt% Ni, 5.1 nm TEM ✓

## National Lab Sources

- NREL ETFECS ✓
- ANL Frame ✓

## Automotive

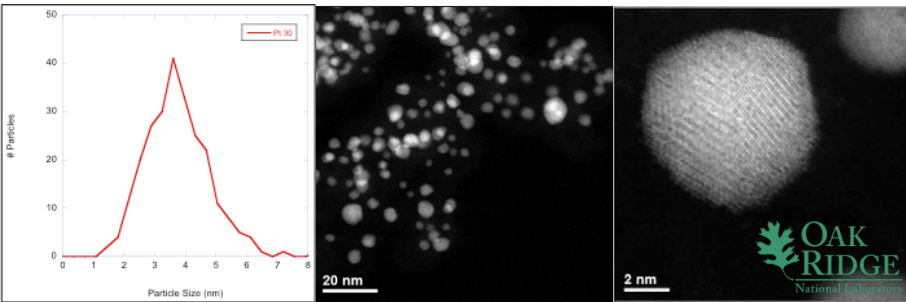
- General Motors
  - Proprietary ✓

## Academic

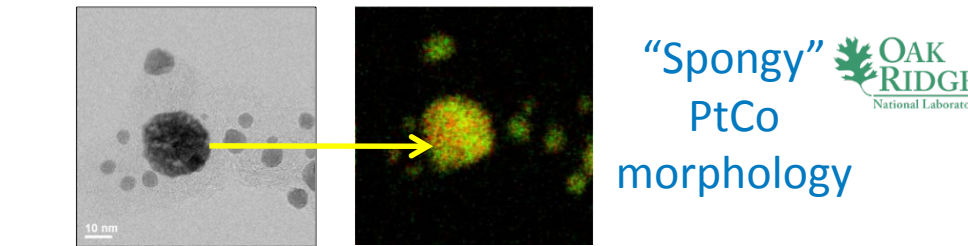
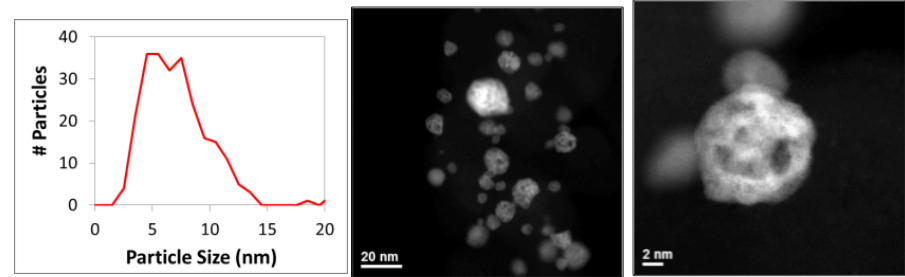
- USC Pt/ACCC ✓

Electrocatalysts being studied for foundational understanding of advanced catalysts

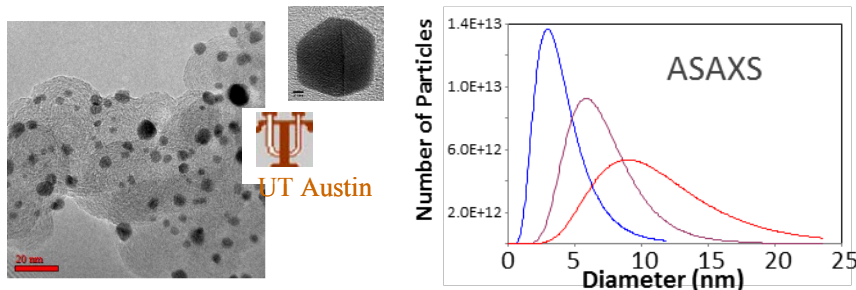
# Platinum Alloy Electrocatalysts in FC-PAD



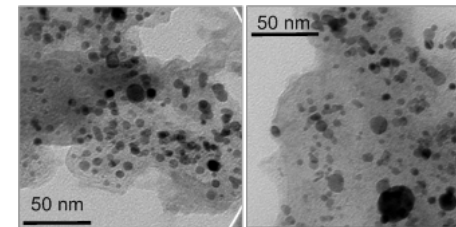
**Umicore Pt<sub>7</sub>Co<sub>3</sub>/C**  
 Mean particle size of 4.4 nm



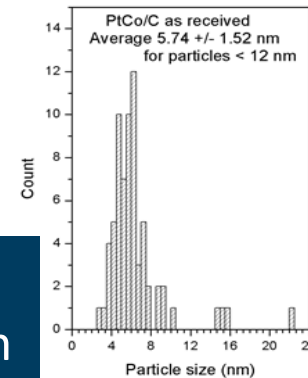
**IRD PtCo/C**  
 Mean particle size of 6.0 nm



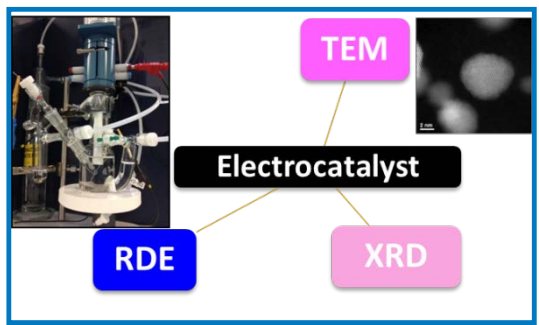
**Three JM Pt<sub>3</sub>Co/C**  
 Mean particle sizes of 4.9, 8.7, 14.3 nm



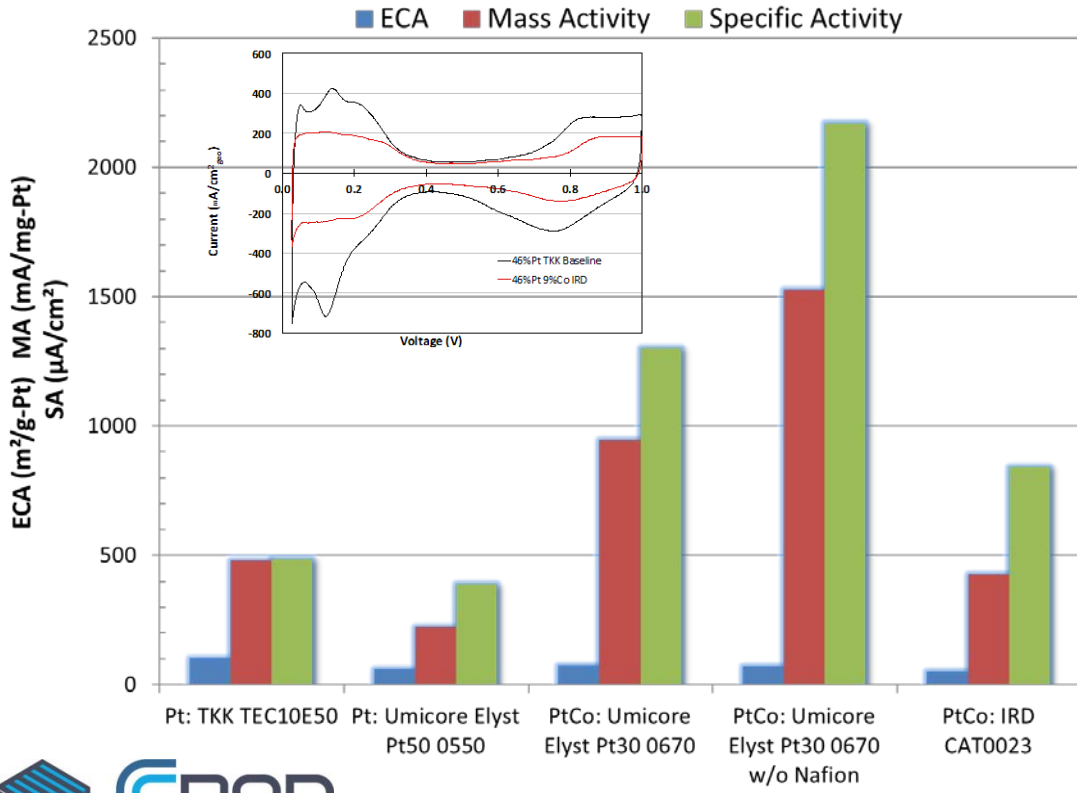
**TKK Pt<sub>3</sub>Co/C**  
 Mean particle size of 5.7 nm



# Accomplishment: *Ex situ* measurement of ORR Activity



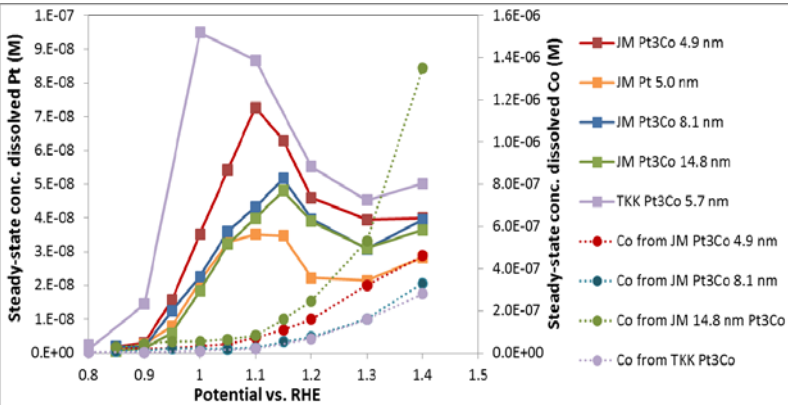
- Baseline oxygen reduction reaction (ORR) activity of catalysts determined using thin-film rotating disk electrode (RDE) method developed and described in FC111 (with ionomer in thin film)
- Electrochemically-active surface area of “baseline” high surface area Pt (TKK TEC10E50) is twice that of platinum alloy catalysts due to alloying heat treatment step leading to particle growth
- Ionomer in electrode suppresses ORR activity, by 40% for Umicore Pt<sub>3</sub>Co
- IRD PtCo catalyst showed lower ORR activity in RDE than in MEA (cf. FC137)
- **Platinum alloys under consideration meet or exceed DOE 2020 ORR activity target (>440 mA/mg-Pt)**



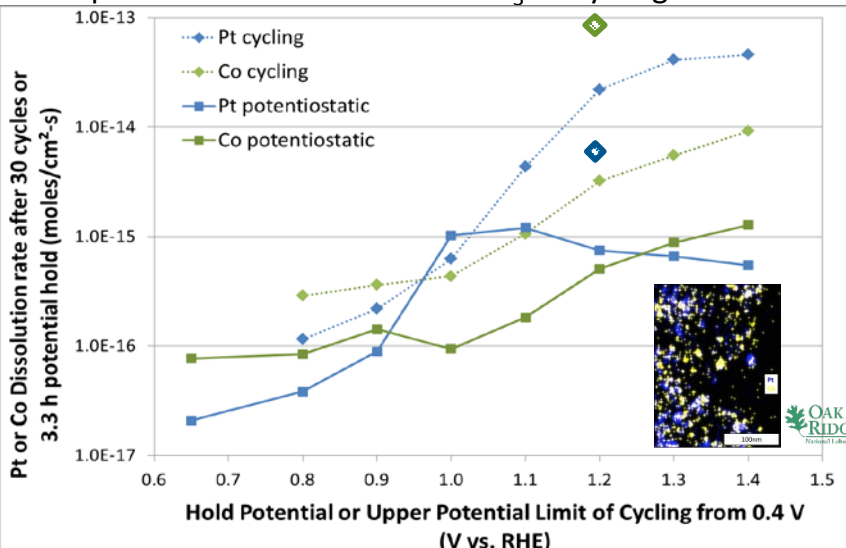


# Accomplishment: Potential Dependence of Pt and Co dissolution

ICP-MS detection of dissolved metals in 0.57 M HClO<sub>4</sub>

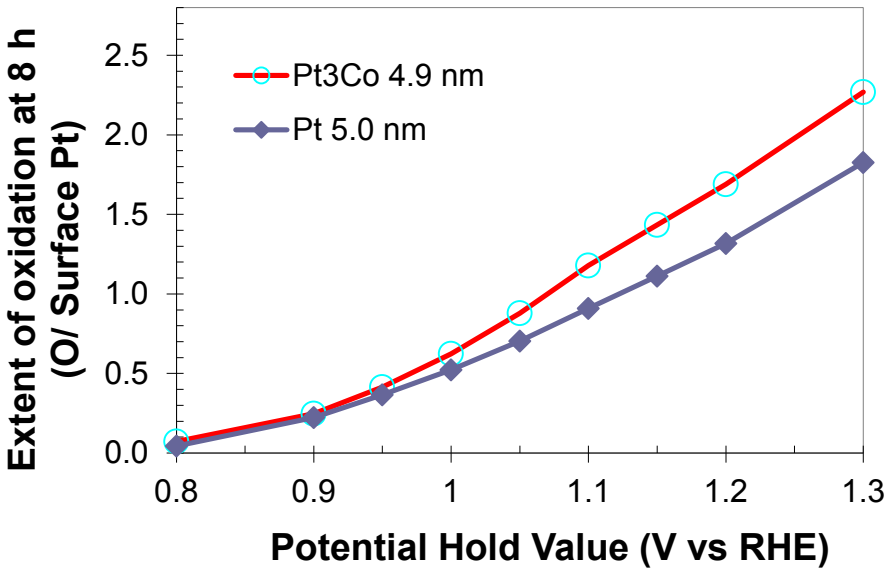


Solid Squares: TKK 5.7 nm Pt<sub>3</sub>Co potentiostatic  
 Solid diamonds: TKK 5.7 nm Pt<sub>3</sub>Co potential cycling  
 Open Diamonds: IRD 7.2 nm Pt<sub>3</sub>Co Cycling



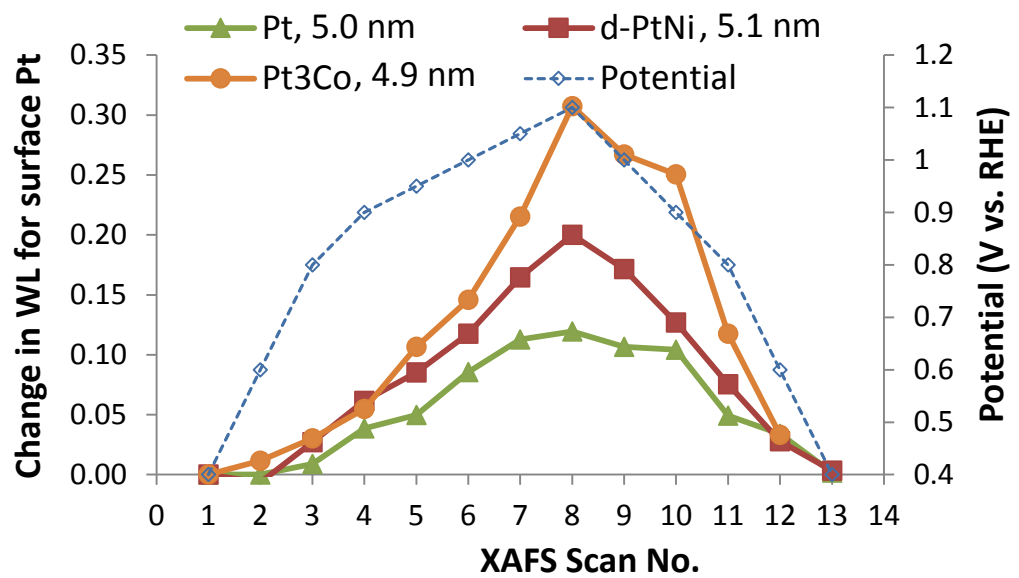
- Potentiostatic Pt dissolution increases with decreasing particle size for the JM Pt<sub>3</sub>Co catalysts
- Potentiostatic Co dissolution is highest for the JM Pt<sub>3</sub>Co/C catalyst with the largest particle size
- TKK 5.7 nm Pt<sub>3</sub>Co catalyst shows a higher extent of Pt dissolution than all of the JM catalysts, even those with much larger particle size
- Pt dissolution is higher for JM 4.9 nm Pt<sub>3</sub>Co as compared to that of a Pt catalyst with very similar PSD (5.0 nm Pt)
- Steady-state Co dissolution increases with increasing potential above 1.1 V, consistent with potentiostatic and potential cycling dissolution rate data
- Potential cycling Pt dissolution rate lower for IRD “spongy” Pt<sub>3</sub>Co compared to TKK “solid” Pt<sub>3</sub>Co, whereas **Co dissolution rate is much higher**
- Dissolution data illustrate detrimental impact of cell voltages >1.0 V on base metal retention in nanoparticles

# Accomplishment: Potential Dependence of Alloy Catalyst Oxidation



- Extent of Oxidation determined via voltammetric charge for oxide reduction after 8 hour potential holds in dilute aqueous HClO<sub>4</sub> electrolyte
- Extent of oxidation determined via height of Pt L<sub>3</sub> X-ray absorption “white line” after 30 min potential holds in dilute aqueous HClO<sub>4</sub> electrolyte

- Pt alloy particles show greater extent of oxidation of surface Pt than Pt particles having approximately the same size distribution.
- These data, and cyclic voltammetry data, are used as input to the dissolution model to find the links between oxide formation and dissolution under potentiostatic and potential cycling conditions.



# Accomplishment: Thermodynamics of PtO<sub>x</sub> Formation Pt<sub>3</sub>Co Alloy

## Solid solution model for PtO<sub>x</sub> formation

- $\text{Pt} + \text{H}_2\text{O} = \text{PtOH} + \text{H}^+ + \text{e}^-$
- $\text{PtOH} = \text{PtO} + \text{H}^+ + \text{e}^-$
- $\text{PtO} + \text{H}_2\text{O} = \text{PtO}_2 + 2\text{H}^+ + 2\text{e}^-$

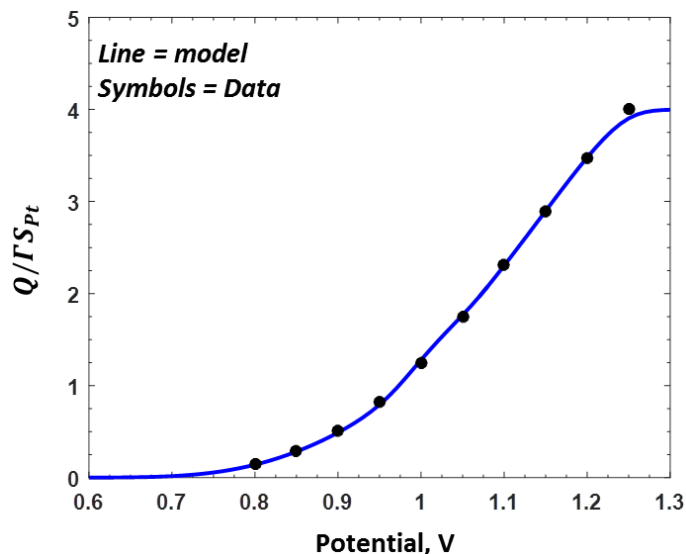
## XPS Study and DFT/Monte Carlo Simulations\*

- Potentials < 0.65 V, H<sub>2</sub>O<sub>(ad)</sub> is the dominant species
- Above 0.65 V, OH<sub>(ad)</sub> forms from oxidation of H<sub>2</sub>O<sub>(ad)</sub>
- Above 0.8 V, OH<sub>(ad)</sub> further oxidizes to O<sub>(ad)</sub>

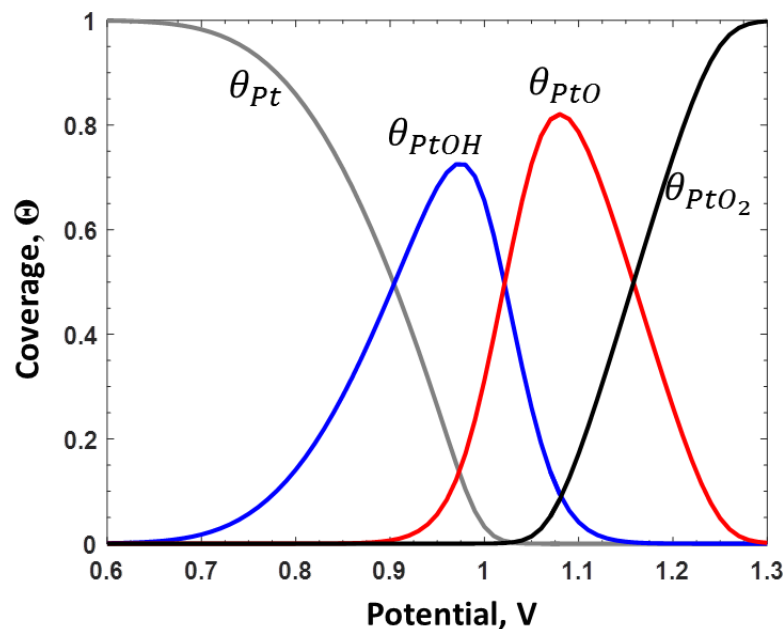
## Oxidation of Pt in Pt<sub>3</sub>Co to PtO<sub>x</sub> is only weakly dependent on particle size

- PtO<sub>x</sub> estimated from the CV reduction charge (Q) after 8-h hold at potential
- Developed a sequential procedure for determining the activities of Pt, PtOH, PtO and PtO<sub>2</sub> in the mixed surface oxide solution

$$K_i = c_{\text{H}^+} \left( \frac{\theta_i}{\theta_{i-1}} \right) e^{-\frac{nF}{RT}[E-E_{\text{O}i}]} = a_i e^{-\frac{\omega_i}{RT}\theta_i^{x_i}}$$



## All data from aqueous tests with 0.57 M HClO<sub>4</sub>



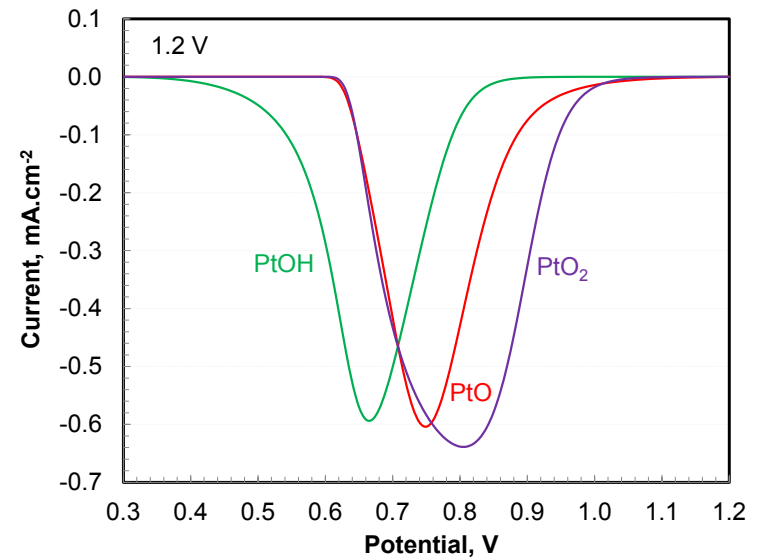
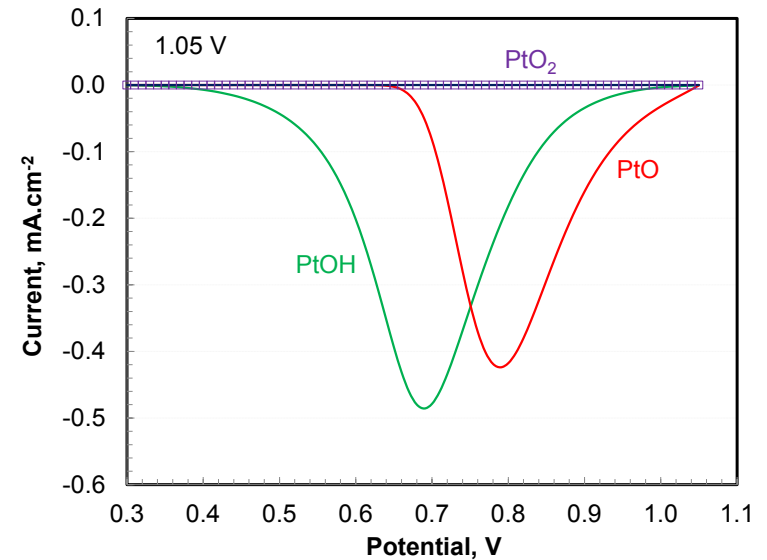
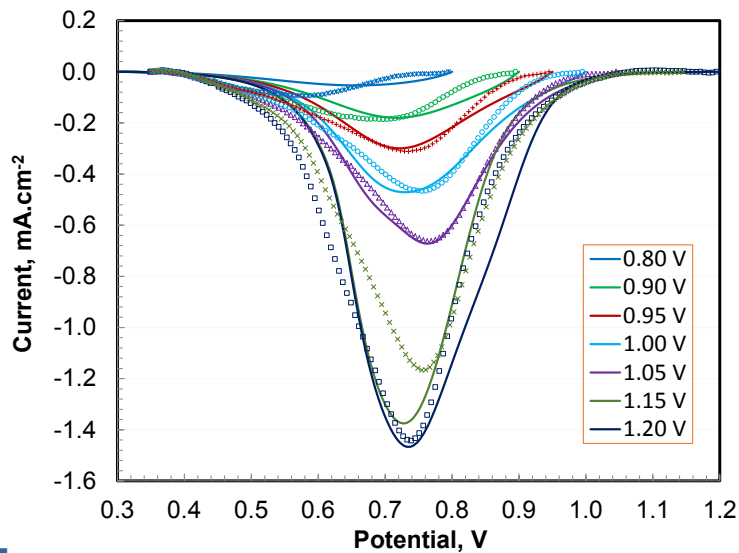
H.S. Casalongue, et al., "Direct observation of the oxygenated species during oxygen reduction reaction on a platinum fuel cell cathode", Nature Communications, Dec, 2013.

# Accomplishment: Kinetics of $\text{PtO}_x$ Formation for $\text{Pt}_3\text{Co}$ Alloy

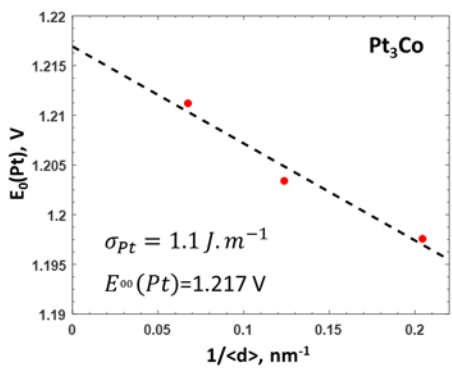
Developed a procedure for determining the rate constants for kinetics of  $\text{PtO}_x$  formation by using the CV oxidation and reduction scans (8 h hold at high potential, 10 mV/s scan rate)

- Only 10-30 s needed to form or reduce the oxides during the potential scans

	Oxidation Potential ( $E_0$ )	Symmetry Factor ( $\alpha$ )
$\text{Pt} + \text{H}_2\text{O} = \text{PtOH} + \text{H}^+ + \text{e}^-$	0.740 V	0.735
$\text{PtOH} = \text{PtO} + \text{H}^+ + \text{e}^-$	1.220 V	0.6
$\text{PtO} + \text{H}_2\text{O} = \text{PtO}_2 + 2\text{H}^+ + 2\text{e}^-$	1.045 V	0.55



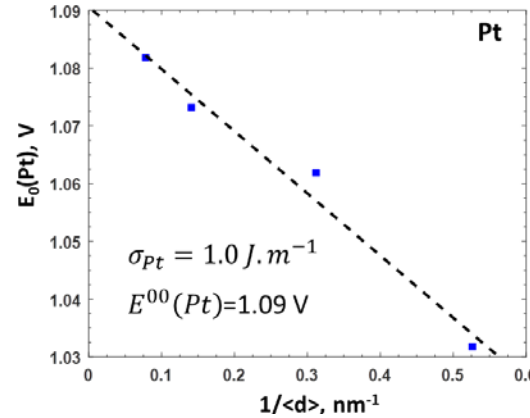
# Accomplishment: Thermodynamics of Pt dissolution from Pt<sub>3</sub>Co Alloy



Standard potential ( $E_0$ ) for Pt dissolution ( $Pt = Pt^{2+} + 2e^-$ ) from Pt<sub>3</sub>Co alloy and its dependence on particle diameter

- Pt<sub>3</sub>Co has higher  $E_0$  than Pt and is more stable at low potentials

Derived from dissolution data at 0.85 V



## Thermodynamics of electrochemical and chemical dissolution of Pt

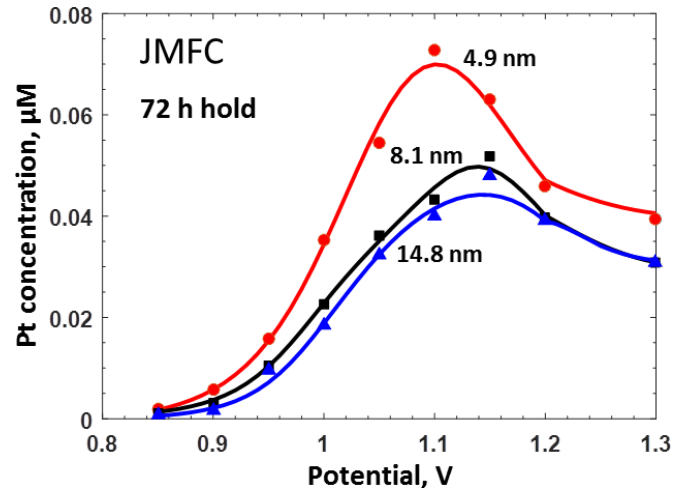
- $Pt = Pt^{2+} + 2e^-$
- $PtOH + H^+ = Pt^{2+} + H_2O + e^-$
- $PtO + 2H^+ = Pt^{2+} + H_2O$
- $PtO_2 + 4H^+ + 2e^- = Pt^{2+} + 2H_2O$

### Equilibrium Constants

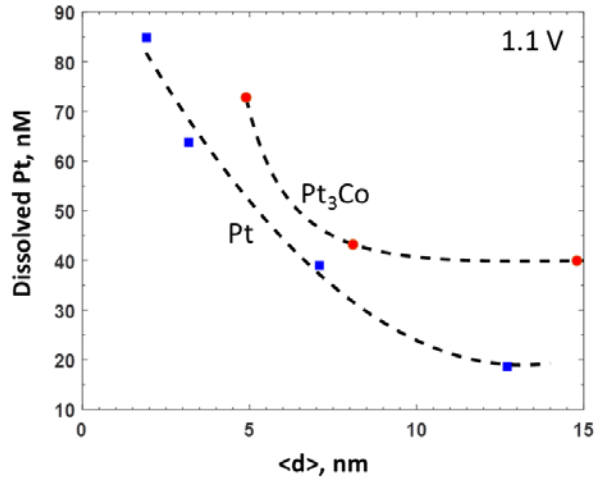
- Electrochemical dissolution
- Chemical dissolution

$$K_i = \left( \frac{C_{Pt^{2+}}}{\theta_i} \right) e^{-\frac{nF}{RT}[E - E_{oi}]}$$

$$K_{PtO} = \left( \frac{C_{Pt^{2+}}}{\theta_{PtO}} \right) \frac{1}{c_{H^+}^2}$$

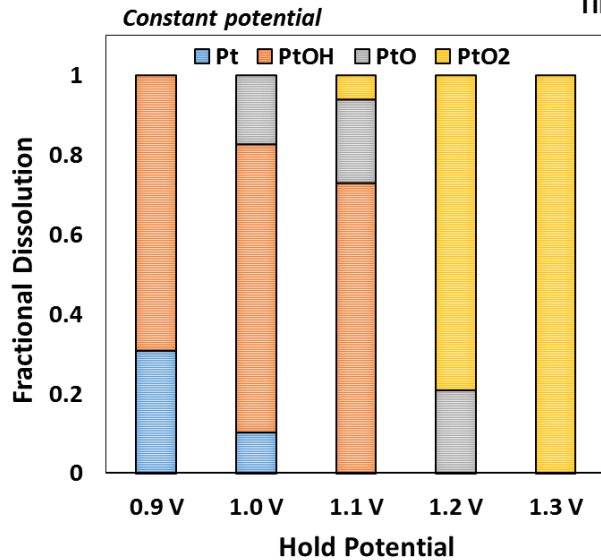
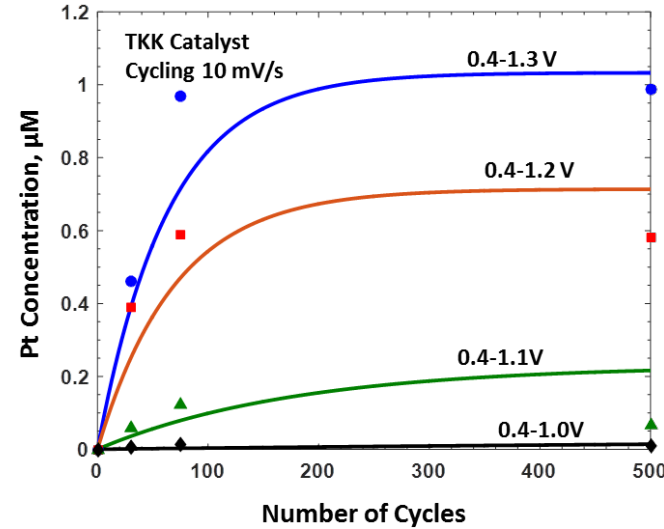
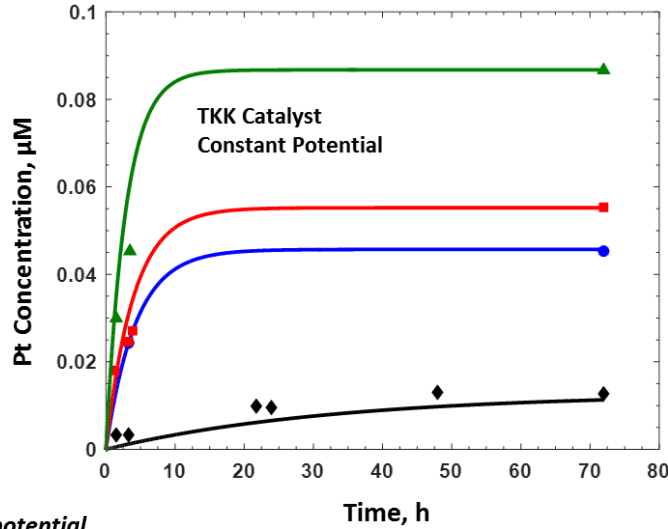


Pt<sub>3</sub>Co has higher dissolution potential, but is less stable than Pt at high potentials



# Accomplishment: Kinetics of Pt dissolution from Pt<sub>3</sub>Co Alloy

Rate constants derived from potentiostatic dissolution predict the behavior observed in cyclic tests: triangle wave, 10 mV/s scan rate, fixed lower potential limit (0.4 V), variable upper potential limit



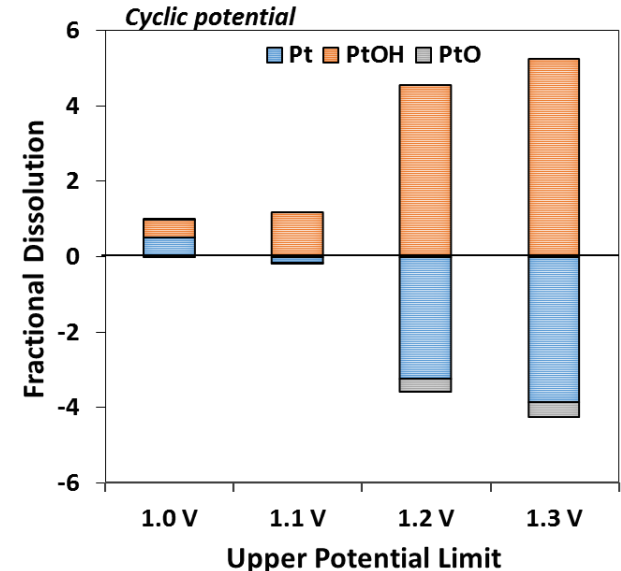
## Cyclic Potential Dissolution

Upper Potential Limit Above 1.1 V

- Pt dissolves as PtOH
- Pt<sup>2+</sup> re-deposits as Pt during cathodic scan

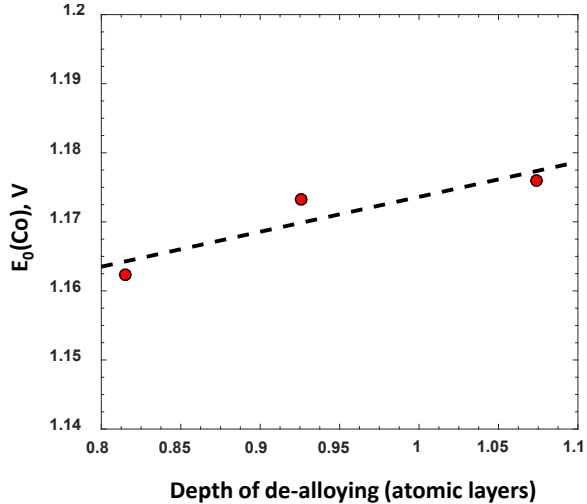
Upper Potential Limit Below 1.1 V

- Pt dissolves as Pt and PtOH
- No significant re-deposition during cathodic scan

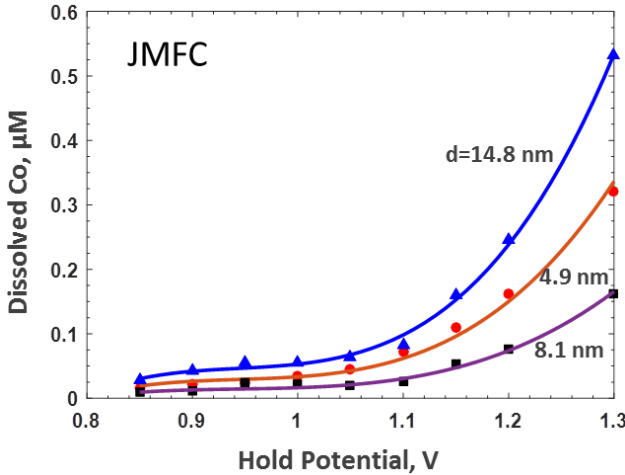
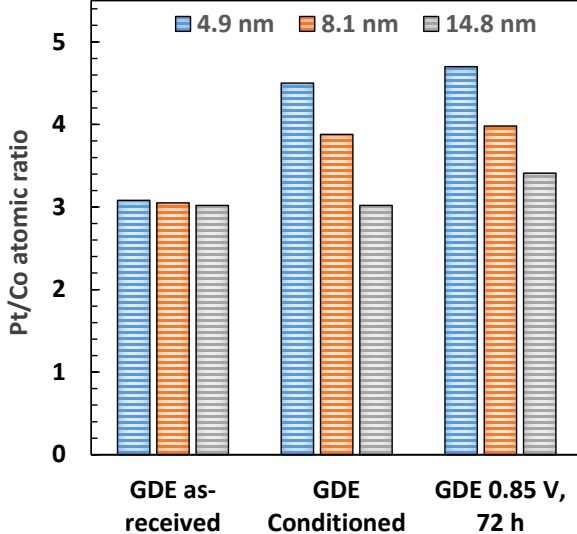


# Accomplishment: Thermodynamics of Co Dissolution from Pt<sub>3</sub>Co Alloy

Surface Co is thermodynamically unstable ( $E_0=0.280$  V) and dissolves during pre-treatment to create a core-shell structure. The thickness of Pt skin is proportional to particle size.

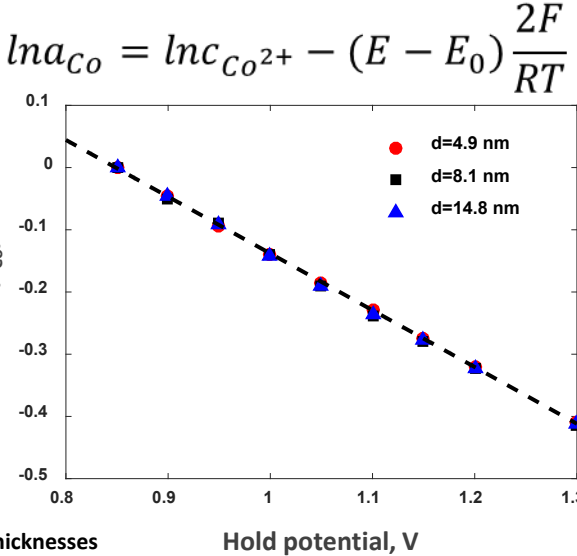


Sub-surface Co (SS-Co) has a dissolution potential ( $E_0$ ) of 1.158 V, and it increases as Pt skin gets thicker.



At higher potentials, SS-Co may be stabilized by the formation of sub-surface oxides of Co.

- Oxygen can coordinate with SS-Co:  $\Delta G = -166$  kJ/mol for  $\text{PtO} + \text{Co} = \text{Pt} + \text{CoO}$
- XANES measurements of  $\Delta\mu$  for dealloyed  $\text{PtM}_3$



KM Caldwell, et al., "Spectroscopic in situ measurements of the relative Pt skin thicknesses and porosities of dealloyed  $\text{PtM}_n$  (Ni, CO) electrocatalysts", Phys. Chem. C, 757-765, 2015.

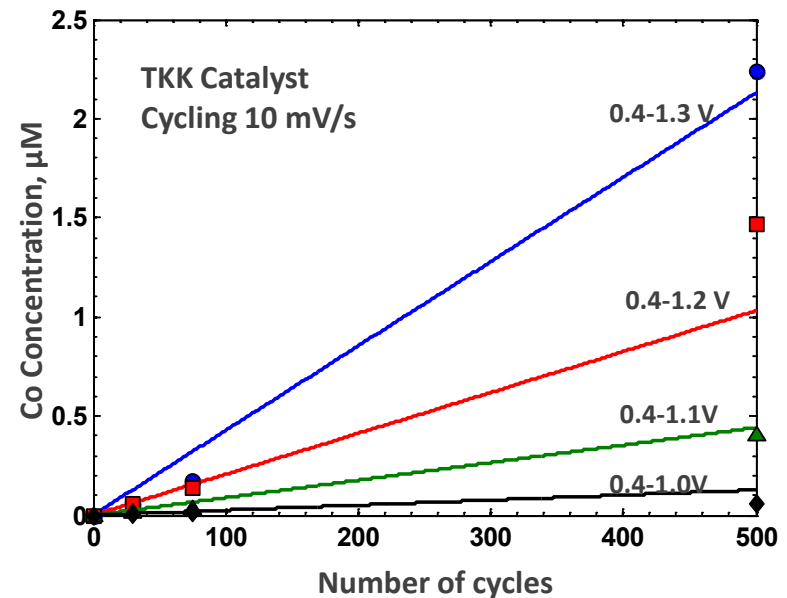
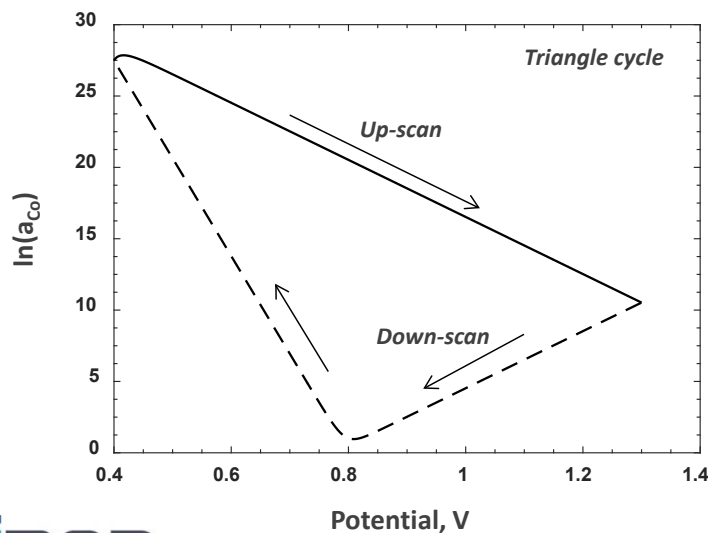
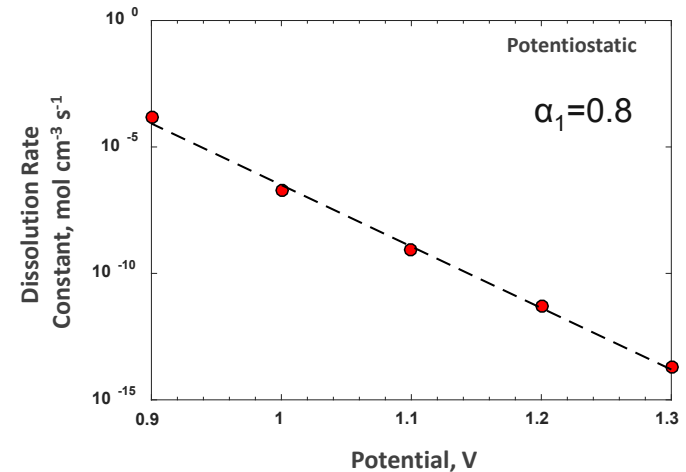
# Accomplishment: Kinetics of Co Dissolution from Pt<sub>3</sub>Co Alloy

The rate constant for SS-Co dissolution depends on potential/surface oxides

- Need fundamental understanding of oxygen coordination with Co in core-shell Pt<sub>3</sub>Co

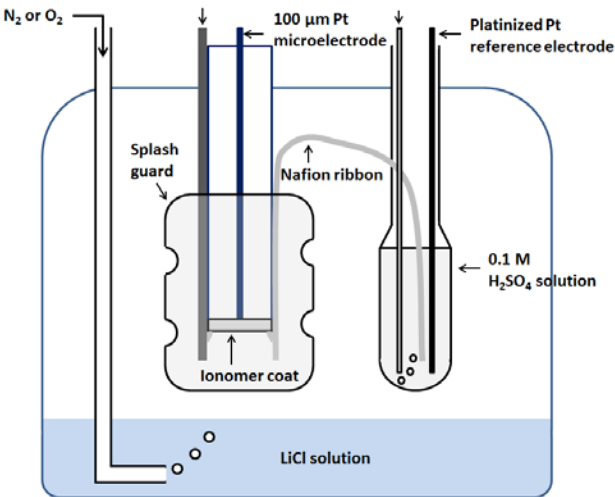
Under potential cycling, the kinetics of change in SS-Co activity are slow

- The derived activity on a repeat cycle is far from equilibrium and shows hysteresis
- 10-50 times higher Co dissolution after 500 triangle cycles (17-25 h) than potentiostatic hold for 72 h
- Difficult to correlate the changes in activities of SS-Co and Pt oxides in Pt<sub>3</sub>Co

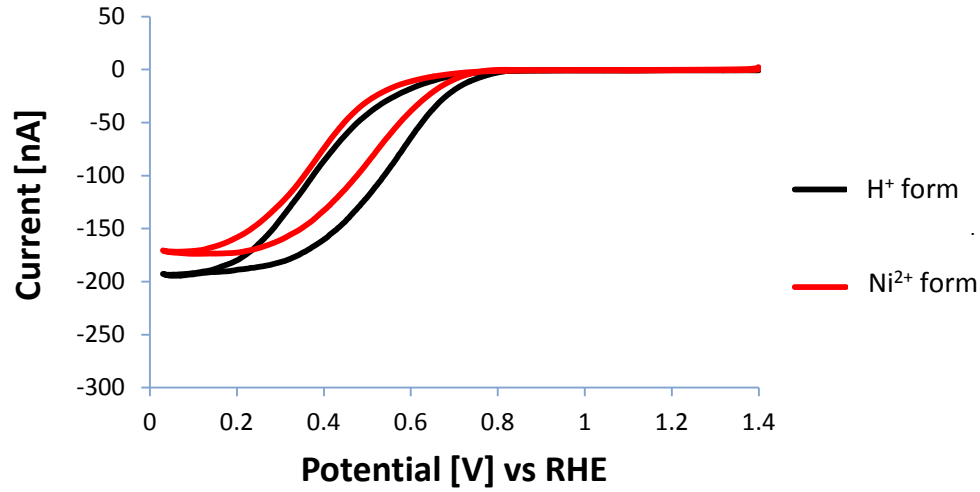
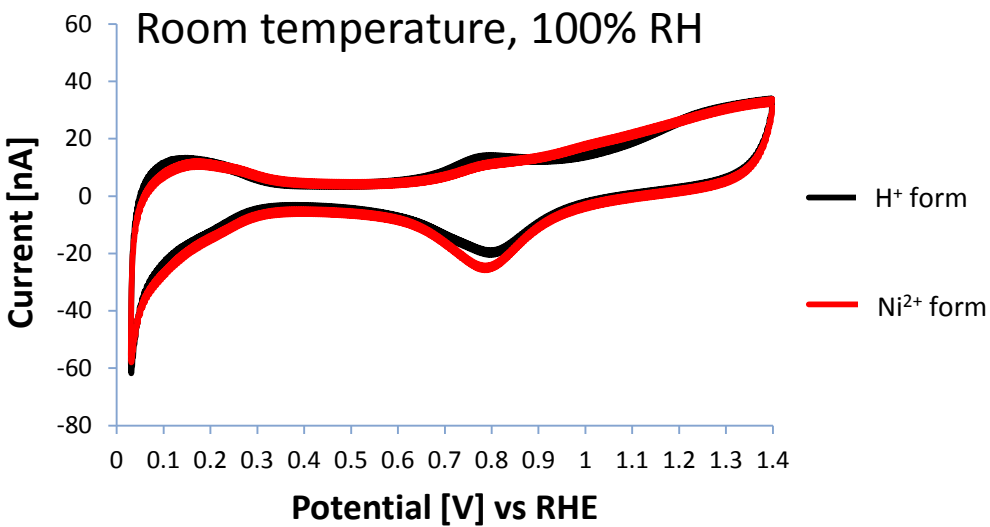




# Impact of Base Metal on Ionomer Oxygen Permeability

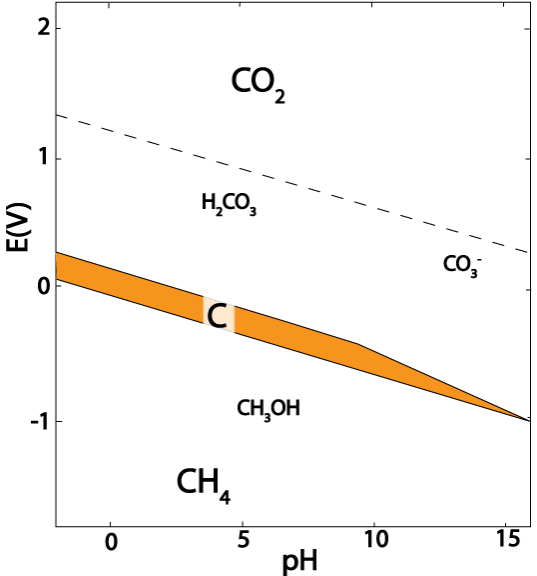


- RDE showed 6% decrease in oxygen permeability of 0.7 μm ionomer film for 10 mM Ni<sup>2+</sup> in 0.1 M HClO<sub>4</sub>; 29% decrease in ORR kinetic current at 0.9 V. (FC106; 2015 AMR)
- Solid state microelectrode cell showed ~15% decrease in oxygen permeability with addition of Ni(ClO<sub>4</sub>)<sub>2</sub> and decrease in ORR kinetics



# Carbon Corrosion Measurement Matrix for Mechanistic Definition

## Carbon thermodynamics



Adapted from M. Pourbaix, *Atlas of Electrochemical Equilibria* (1966)

- Experimentally measure carbon corrosion during operation
  - Direct CO<sub>2</sub> measurement by NDIR
- Modeling to identify carbon corrosion mechanism and rates related to carbon and Pt surface oxidation

### Three Types of Carbon Supports

<b>E (High Surface Area, Ketjen);</b> TEC10E20E; 18.5 wt% Pt/C, 0.15 mg-Pt/cm <sup>2</sup>
<b>EA (Graphitized or Low Surface Area);</b> TEC10EA40E, 38.7 wt% Pt/C, 0.25 mg-Pt/cm <sup>2</sup>
<b>V (Vulcan);</b> TEC10V40E, 33.9 wt% Pt, 0.17 mg-Pt/cm <sup>2</sup>

Ion Power MEAs with SGL 25BC GDLs in 50-cm<sup>2</sup> quad-serpentine flow field from Fuel Cell Technologies, 80°C cell temp.; H<sub>2</sub>: 670 sccm, 83°C dew point, 3.4 psig; Air: 1800 sccm, 83°C dew point

<u>Vary Upper Potential Limit</u>
0.95 V – 0.40 V
0.90 V – 0.40 V
0.85 V – 0.40 V
.....
0.55 V – 0.40 V

<u>Vary Lower Potential Limit</u>
0.95 V – 0.40 V
0.95 V – 0.45 V
0.95 V – 0.50 V
.....
0.95 V – 0.80 V

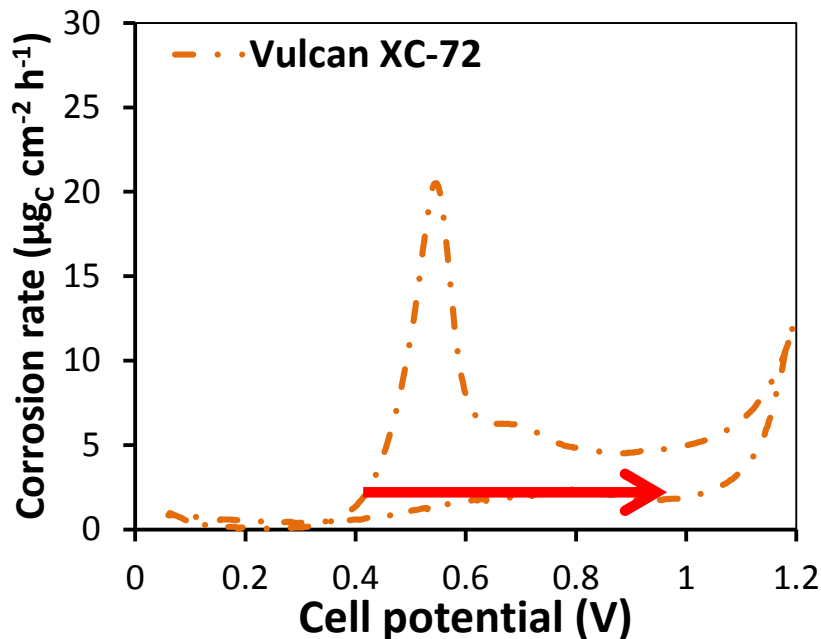
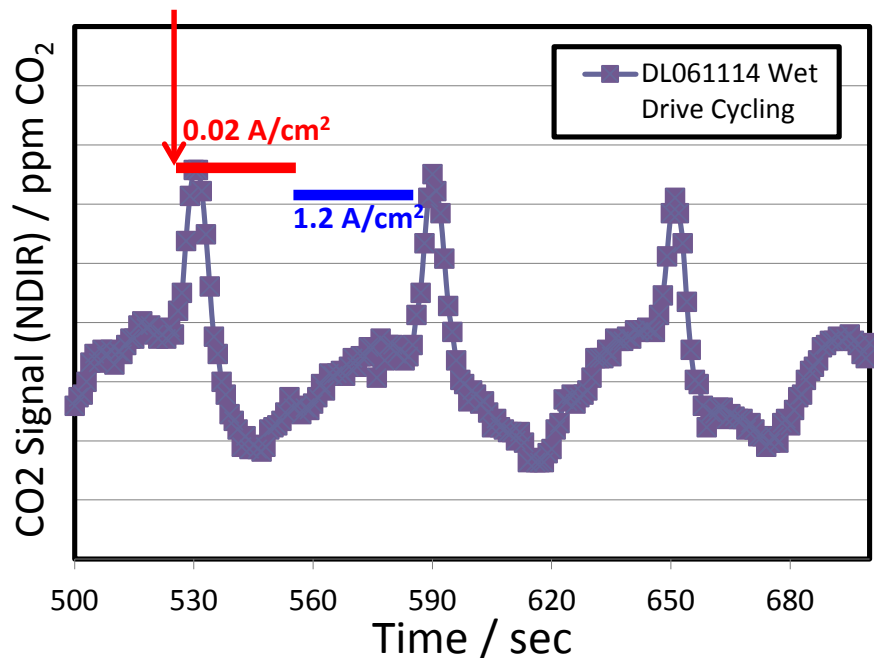
<u>Potential Reset Times</u>
0.5 min
1 min
2 min
5 min



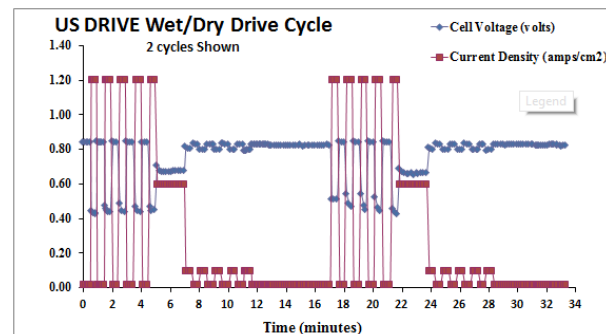
Fuel Cell operation largely as per DOE/FCTT Drive Cycle Protocol

# Measured Carbon Corrosion During Drive-Cycle

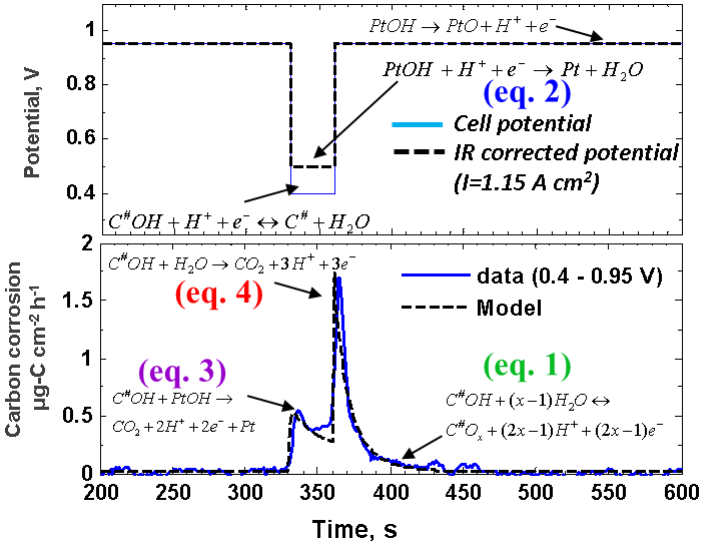
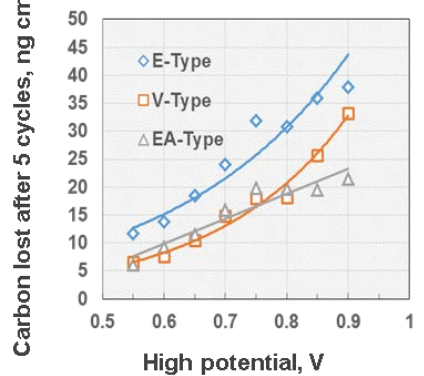
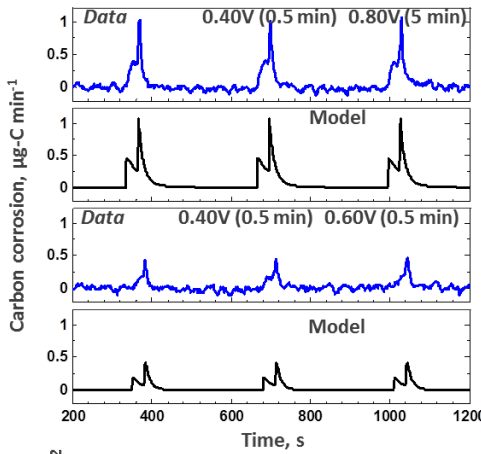
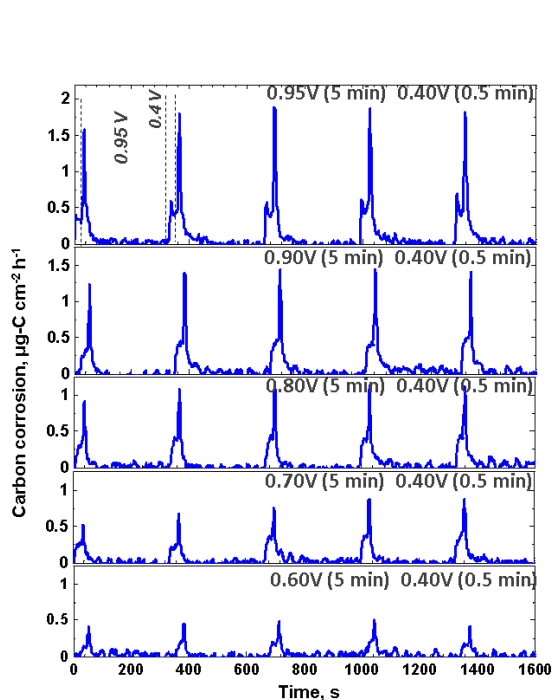
Transition from:  
1.2 to 0.02 A/cm<sup>2</sup>



- Non-zero CO<sub>2</sub> evolution with all carbon types during drive cycle
- As power decreases, voltage increases
- During voltage rises, CO<sub>2</sub> evolves from the catalyst
- After spike, CO<sub>2</sub> evolution is reduced
  - surface passivation
- Higher 'steady-state' CO<sub>2</sub> production at 1.2 A/cm<sup>2</sup>
  - reducing surface/forming adsorbed species



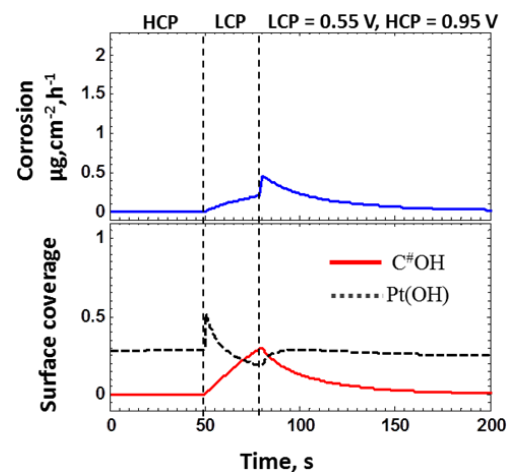
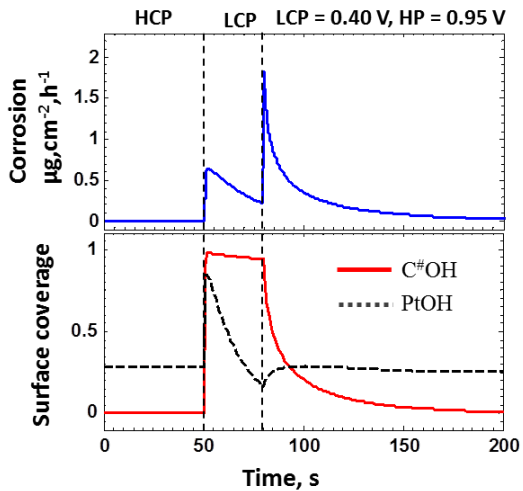
# Accomplishment: Comparison of corrosion of three carbon types



- 1) Formation of active ( $C^{\#}OH$ ) and passive ( $C^{\#}O_x$ ) carbon surface oxide species
- 2) Formation of OH and oxide surface species on Pt
- 3) Oxidation of active carbon surface species ( $C^{\#}OH$ ) with OH spill-over from Pt at intermediate potentials
- 4) Oxidation of active carbon surface species ( $C^{\#}OH$ ) with  $H_2O$  at high potentials

- For potential cycles to 0.8 V and higher (fixed 0.4 V low potential), corrosion rates are lower for graphitized carbon (EA-type) than for other carbons (E-type, V-type)
- For potential cycles below 0.8 V, the magnitude of corrosion upon a step change in potential is similar for all carbons
- Extents of corrosion linked to formation of carbon oxides and interaction of these oxides with Pt hydroxide and oxide and water

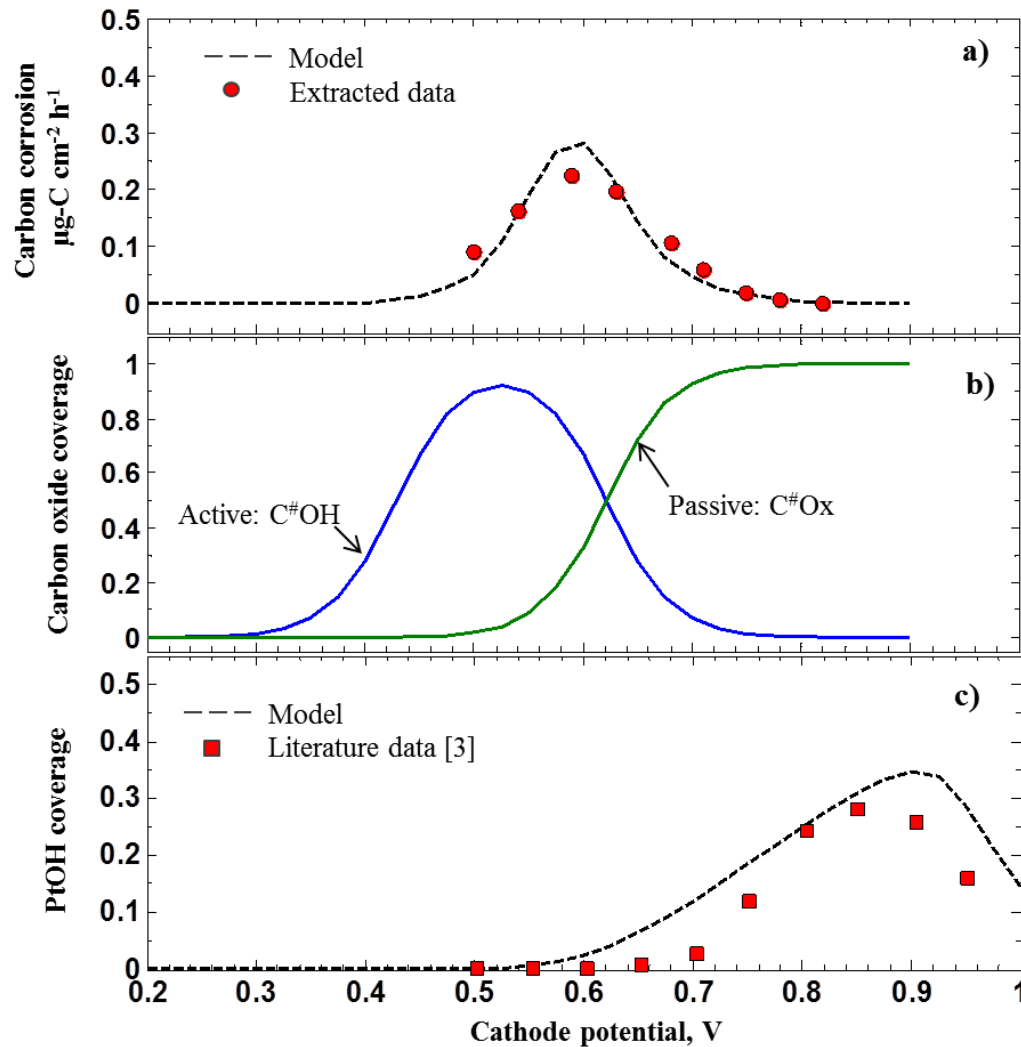
# Accomplishment: Transient Corrosion Mechanism



- Varied Upper Potential Limit**
- 0.95 V – 0.40 V
  - 0.90 V – 0.40 V
  - 0.85 V – 0.40 V
  - .....
  - 0.55 V – 0.40 V
- Varied Lower Potential Limit**
- 0.95 V – 0.40 V
  - 0.95 V – 0.45 V
  - 0.95 V – 0.50 V
  - .....
  - 0.95 V – 0.80 V

- Low corrosion rate if cell held at high cell potential**
  - Defect sites passivated by  $\text{C}^\#\text{O}_x$
  - Pt exists mainly as PtO at 0.95 V and as Pt at 0.6 V
- Small corrosion spike in transitioning from HCP to LCP**
  - $\text{C}^\#\text{O}_x$  begins to convert to active  $\text{C}^\#\text{OH}$
  - PtO converts to PtOH
  - Spikes due to reaction between  $\text{C}^\#\text{OH}$  and PtOH
  - Increasing lower cell potential from 0.4 to 0.55 V decreases corrosion during transition due to lower equilibrium  $\text{C}^\#\text{OH}$  coverage
- Corrosion rate slowly decreases as the cell is held at low cell potential**
  - PtOH converts to Pt
- Large corrosion spike in transitioning from LCP to HCP**
  - Spikes due to rapid reaction between  $\text{C}^\#\text{OH}$  and  $\text{H}_2\text{O}$  at elevated potential
  - $\text{C}^\#\text{OH}$  converts to  $\text{C}^\#\text{O}_x$  over longer time
  - PtOH converts to PtO over longer time

# Accomplishment: Steady-State Corrosion Model



- Steady-state corrosion rates determined from NDIR data for  $\text{CO}_2$  emission after 5-min hold at potential
- Over 0.4-0.95 V cathode potentials, steady-state corrosion rate peaks at  $\sim 0.6$  V
- Peak corrosion rates are similar for E-Type, V-Type and EA-Type carbons
- Steady-state corrosion rate slows above 0.6 V due to formation of passive oxides
- Pt converts to PtOH above 0.6 V
- PtOH converts to PtO above 0.9 V
- Since PtOH only forms above 0.6 V, the observed corrosion peaks are due to  $\text{C}^{\#}\text{OH}$  reacting with  $\text{H}_2\text{O}$ .**

[3] Casalongue, H.S., et al. (2013). *Nature Communications*, 4, 2817.

# Summary of Mechanism of Carbon Corrosion during Drive Cycles

## ■ Formation of surface oxides on carbon defect sites (C#)

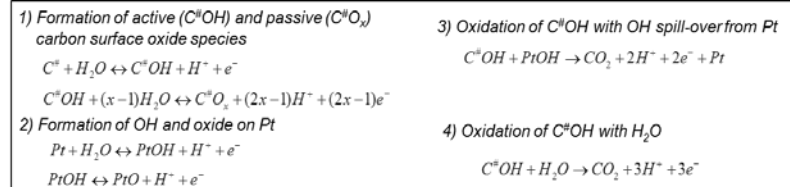
- Defect sites hydrolyze to form active oxides (C#OH) at cathode potential (E) >0.3 V
- C#OH converts to passive oxides (C#O<sub>x</sub>) at E >0.8 V

## ■ Carbon corrosion is catalyzed by PtOH

- PtOH begins to form at E >0.6 V
- PtOH converts to PtO at E >0.9 V

## ■ Steady-state corrosion mechanism

- Corrosion rate peaks at ~0.6 V cathode potential, small at 0.95 V
- Corrosion is primarily due to oxidation of C#OH by H<sub>2</sub>O
- All three carbons (Ketjenblack, Vulcan and graphitized Ketjenblack) show similar corrosion rates



## ■ Carbon corrosion under transient potentials can be much higher

- Spikes in corrosion rates while transitioning from high (0.95 V) to low cell potentials (0.4 V) are due to formation of C#OH and its reaction with PtOH
- Larger spikes in corrosion rates while transitioning from low (0.4 V) to high cell potentials (0.95 V) are due to accelerated oxidation of C#OH by H<sub>2</sub>O at elevated potentials

## ■ Transient corrosion rates: E-Type ~ V-Type >> EA-Type

# Proposed Near-term Future Work

- Potentiostatic and potential cycling dissolution and oxide coverage measurements for IRD Pt<sub>3</sub>Co and Umicore Pt<sub>3</sub>Co
  - Comparison of catalysts with “spongy” morphology to “solid” morphology
- Measurements of Pt re-deposition rates as a function of potential
- Application of catalyst corrosion model to cell data using TEM-EDAX and XRF quantification of Pt and Co in cell components
- EXAFS analysis of changes in Pt and Co coordination numbers and bond distances for catalysts from cycled MEAs
- Delta-μ XANES analysis of Pt<sub>3</sub>Co oxide structure as a function of potential (in collaboration with General Motors)
- Solid state microelectrode measurements of oxygen permeability
  - Impact of Co<sup>2+</sup> and Ni<sup>2+</sup> as a function of relative humidity and temperature
- Carbon corrosion studies for Pt alloys vs. Pt of similar particle size distribution
- Pt dissolution as a function of carbon type and correlation with changes in particle size distribution and electrochemically-active surface area



# Summary

- **Relevance:** Realize the ORR mass activity benefits of advanced Pt-based cathode electrocatalysts in high current density, air performance for over 5,000 operating hours and with low PGM loading ( $\leq 0.1$  mg-Pt/cm<sup>2</sup>)
- **Approach:** Studies of catalyst and catalyst support durability and degradation mechanisms, catalyst/support interactions, and effects of catalyst instability on cathode-catalyst-layer properties
- **Accomplishments and Progress:** Determined potential and potential cycling dependence of Pt and Co dissolution from several Pt<sub>3</sub>Co alloys, oxide formation kinetics and thermodynamics, and developed a model based on these data for the thermodynamics and kinetics of Pt and Co loss from catalyst particles; Initiated solid-state cell work for oxygen permeability measurements in ionomer thin films; Developed a model for carbon corrosion during drive cycle.
- **Future work:** Potentiostatic and potential cycling dissolution and oxide coverage measurements for IRD Pt<sub>3</sub>Co and Umicore Pt<sub>3</sub>Co and other advanced catalysts with alternative morphologies/properties; Measure Pt re-deposition rates; Apply catalyst corrosion model to MEA data; Determine changes in catalyst atomic composition and distribution using XANES; Solid-state measurements of effect of base metal on oxygen permeability; Refinement of cathode performance and durability model using *ex situ*-measured component properties.