Polymer Electrolyte Fuel Cell Lifetime Limitations: The Role of Electrocatalyst Degradation

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Project ID# FC012

This presentation does not contain any proprietary or confidential information

Overview

Timeline

- Project start data: October, 2009
- Project end data: September, 2012
- Percentage complete: 83%

Barriers

- Barriers addressed
  - A. Durability
  - B. Cost
  - C. Electrode performance

Budget

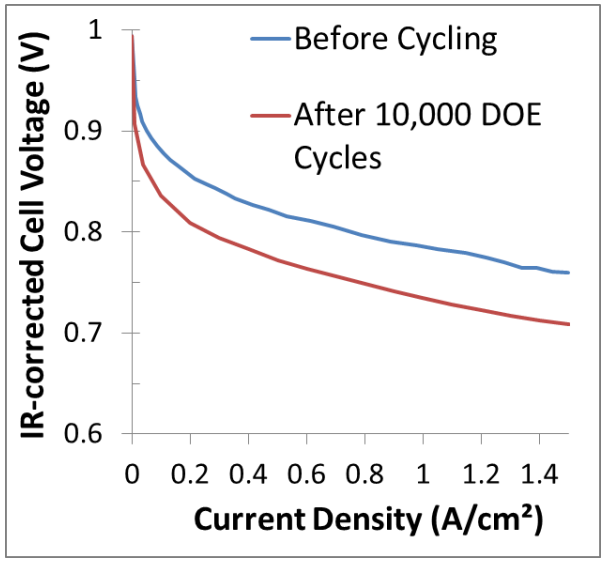
- Total project funding:
  - DOE: $3,754 K
  - Contractor share: $544 K
- Funding received in FY11
  - $626 K
- Funding expected for FY12
  - $ 1265 K

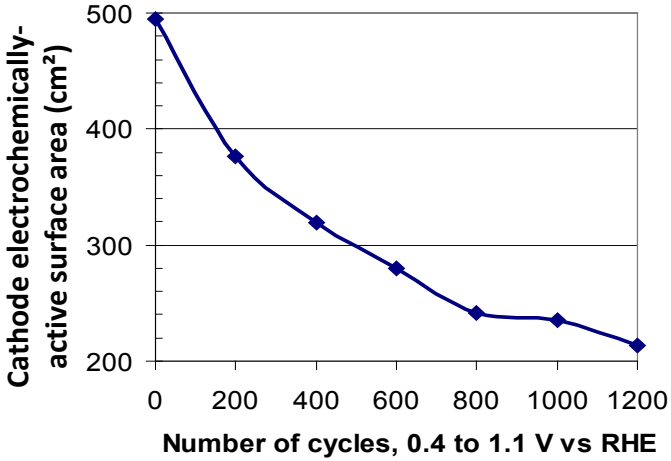
Partners

- Johnson Matthey Fuel Cells
  - Sarah Ball, Jonathan Sharman, Brian Theobald, Stephen Thorpe, Alex Martinez, Elvis Christian, and Graham Hards
- United Technologies Research Center
  - Mallika Gummalla, Zhiwei Yang, and Steve Zhitnik
- Massachusetts Institute of Technology
  - Yang Shao-Horn and B.H. Han
- University of Texas at Austin
  - Paulo Ferreira, Shreyas Rajasekhara, Daniel Groom, Stephanie Matyas, Somaye Rasouli, and Kang Yu
  - Jeremy Meyers, Preethi Mathew, and Seok Koo Kim
- University of Wisconsin – Madison
  - Dane Morgan, James Gilbert, and Brian Puchala

Relevance

- Objectives
  - Understand the role of cathode electrocatalyst degradation in the long-term loss of PEMFC performance,
  - Establish dominant catalyst and electrode degradation mechanisms,
  - Identify key properties of catalysts and catalyst supports that influence and determine their degradation rates,
  - Quantify the effect of cell operating conditions, load profiles, and type of electrocatalyst on the performance degradation, and
  - Determine operating conditions and catalyst types/structures that will mitigate performance loss and allow PEMFC systems to achieve the DOE lifetime targets.

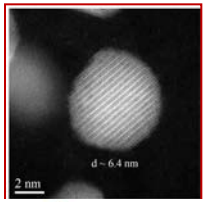




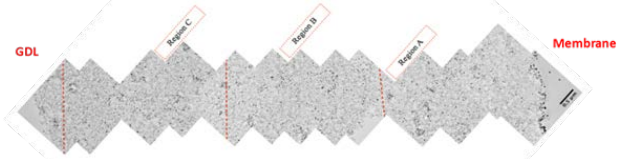
- Impact
  - To enable catalysts to achieve DOE Technical Targets
    - Durability with cycling 5,000 hours (≤80°C) and 2,000 hours (>80°C)
    - ≤40% loss of initial catalytic mass activity; <30 mV loss at 0.8 A/cm²

Approach: Methods and Variables

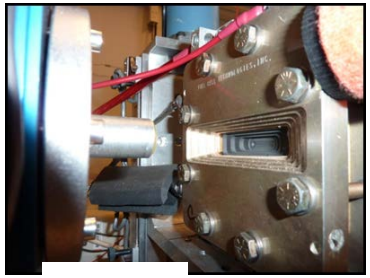
- Identify the degradation modes and factors contributing to degradation, using
  - Systematic cell degradation tests (JMFC and UTRC)
  - *In situ* and *ex situ* structural characterization of the catalyst (ANL and UT)
    - Small angle X-ray scattering, X-ray absorption spectroscopy, TEM, HAADF-STEM, etc.
  - Fundamental out-of-cell studies
    - Aqueous cell dissolution/corrosion measurements (ANL, MIT, and JMFC)
    - *"In situ"* TEM (UT)
  - Theoretical modeling
    - *Ab initio*-based modeling of Pt, Pt alloy, and core-shell dissolution (UW)
    - Cell kinetic and transport modeling, incorporating degradation effects (ANL and UT)



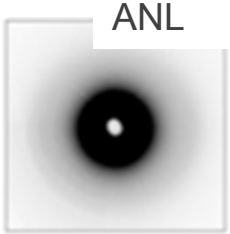
UT Austin

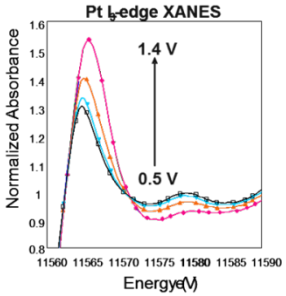


ANL

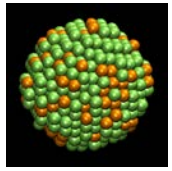


ANL





- Variables
  - Catalyst type and oxophilicity
    - Pt, Pt alloys, acid-leached Pt alloys, core-shell, 3M's NSTF
  - Catalyst particle size (Pt and one Pt alloy)
  - Catalyst impurities (e.g., chloride)
  - Type of carbon support
    - Surface area and pore size
  - Cell operating parameters
    - Potential cycling profile, upper potential limit, cell temperature, RH on cathode



UW

Approach

Project timeline

May, 2012

Project Schedule	Year 1				Year 2				Year 3			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Task 1. Catalyst and Membrane-Electrode Assembly Fabrication												
1.1 Benchmark Pt and one Pt alloy with varying particle sizes												
1.2 Pt alloys, acid-leached alloy, core-shell on standard support												
1.3 Pt alloy catalysts with varying degrees of oxophilicity												
1.4 Pt on supports with varying surface area, pore size, and pore size distribution												
1.5 Catalysts with post-doping of catalyst precursor impurities												
Task 2. Cell degradation studies/single cell cycling/parametric aging studies												
2.1 Accelerated stress testing of baseline MEAs and impact of operating conditions												
2.2 Advanced catalyst degradation mode identification												
2.3 Effect of carbon support on MEA electrode performance loss												
2.4 Effect of catalyst impurities on MEA electrode performance loss												
Task 3. Mechanisms of catalyst degradation and underlying physicochemical catalyst properties responsible for degradation												
3.1 Roles of catalyst oxophilicity, extent of oxide formation, and structure of oxide in catalyst degradation												
3.2 Influence of potential, temperature, and physical properties of catalyst on the rates and mechanisms of catalyst component dissolution												
3.3 Role of catalyst-support interactions and support degradation												
3.4 Effect of particle size and catalyst type on ORR activity												
Task 4. Ex situ microscopic and X-ray scattering characterization of catalysts and MEAs												
4.1 Optical microscopy, aberration-corrected STEM and high-resolution TEM w/ EDAX, EELS, XPS												
4.2 Small angle X-ray scattering												
Task 5. Modeling												
5.1 Ab initio based modeling of Pt, Pt alloy, and core-shell dissolution												
5.2 Catalyst degradation models including nature and role of oxide formation in catalyst degradation												
5.3 Cell kinetic, transport model incorporating degradation effects/kinetics												

- **Focus since 2011 AMR has been on compositional studies of Pt-Co alloys, Pt_3Sc, effects of acid-leaching, effects of potential profile, dissolution studies of Pt-Co alloys and NSTF, and Kinetic Monte Carlo-based modeling of Pt-Co alloys**

Approach: *Milestones and Go/No-Go Decision Point*

- FY'11 and FY'12 Milestones
  - Determine the effect of Pt alloy composition on the rates and mechanisms of cathode catalyst performance degradation - 09/11
    - Completed: results discussed here
  - Develop a macroscopic model of Pt dissolution and place exchange, and complete CV and ORR catalyst performance models - 09/11
    - Cyclic voltammetry, oxide coverage, and dissolution models have been completed; place-exchange is implicit in dependence of Pt activity on oxide coverage
  - Develop a Kinetic Monte Carlo model to predict alloy nanoparticle evolution in the fuel cell cathode environment - 09/11
    - KMC model has been developed and demonstrated for Pt-Co de-alloying: results discussed here
  - Prepare and evaluate 2 Pt-Co alloy compositions and 1 Pt-M alloy to correlate performance degradation with composition and alloying element, catalyst component dissolution, and extent of oxidation - 05/12
    - Completed 2 Pt-Co's and Pt_3Sc performance degradation and component dissolution
  - Prepare and evaluate 2 or more catalyst samples of Pt on different carbon supports and Pt samples with 2 different levels of chloride impurity to quantify the effects of support and precursor impurity on the rates and mechanisms of cathode catalyst performance degradation - 09/12
    - On-track: Samples have been prepared and characterized; cells are being fabricating
  - Complete cathode catalyst layer performance model that integrates ORR degradation and cathode transport property evolution - 09/12
    - Work in progress
- Go/No-Go Decision Point
  - Demonstrate link between aqueous electrolyte studies of degradation mechanisms of three classes of catalysts and degradation observed in MEA tests – 09/11
    - Aqueous dissolution and oxide coverage measurements are being used as input to degradation model. Degradation model accurately predicts evolution of particle size distribution

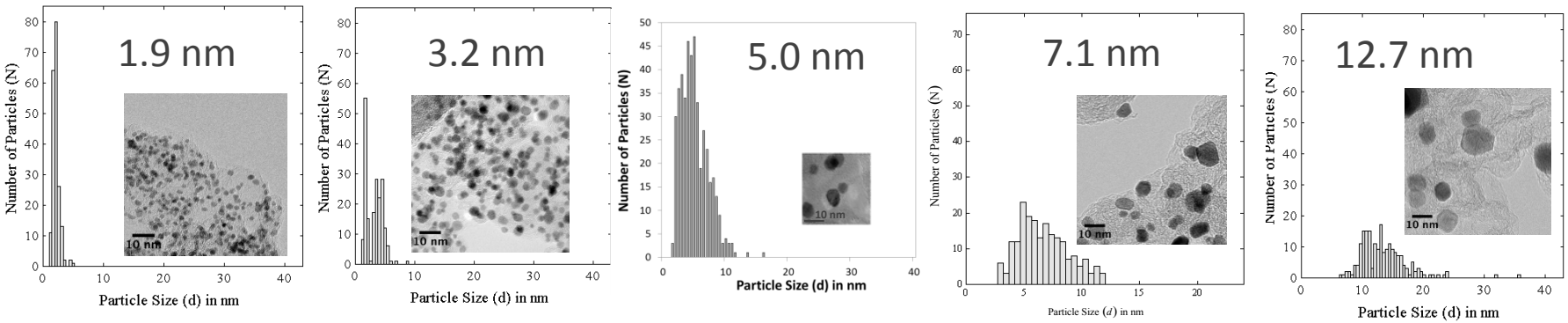
Proposed Future Work for FY12

- Task 1 (JMFC)
  - Supply membrane-electrode assemblies to project partners using prepared Pt-Ni/C materials
  - Provide Pt on alternative carbons and clean and doped versions of Pt/Ketjen to explore effect of impurities
  - Provide additional Pt_xCo_{1-x}/C materials for dissolution studies to validate KMC modeling parting limits
- Task 2 (UTRC)
  - Evaluate the impact of carbon types and advanced alloy formulation on performance decay
  - Post-test analysis of the membrane-electrode assemblies
- Task 3 (ANL and MIT)
  - Cycling dissolution rates for Pt_3Co/C catalysts of varying particle size, NSTF, and advanced alloy catalysts
  - Effect of temperature on Pt dissolution for "benchmark" Pt/C catalyst (3.2 nm dia.)
  - Oxygen reduction reaction activity of advanced alloy catalysts and evolution of activity with potential cycling
- Task 4 (UT-Austin and ANL)
  - Analysis of *in situ* ASAXS/X-ray absorption characterization of Pt/C and Pt_3Co/C membrane-electrode assemblies
  - TEM and ASAXS characterization of the membrane-electrode assembly cathodes from the Pt/C potential profile studies, Pt_3Sc, PtCo, and advanced catalyst studies
- Task 5 (UW and UT-Austin)
  - Further development of Kinetic Monte Carlo (KMC) model of Pt alloy nanoparticles under fuel cell conditions
  - Use KMC simulation to predict how de-alloying occurs in nanoparticles (de-alloying rate, the formation of pores, and the stability of core-shell and acid-leached structures)
  - Complete cathode performance and performance degradation model

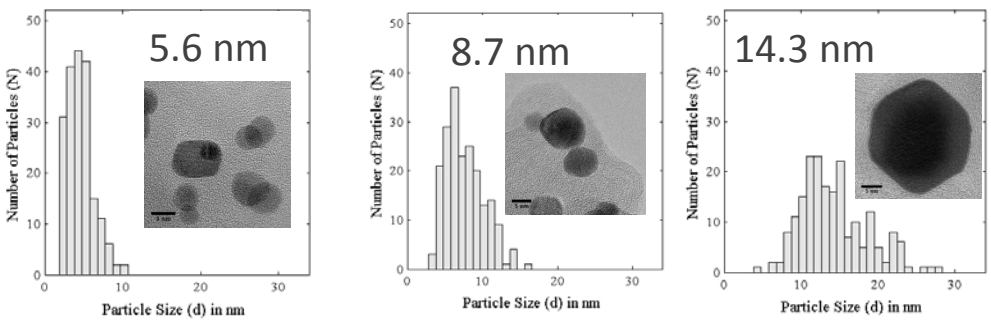
Technical Progress (Tasks 1 and 4)

Catalyst synthesis and characterization

40 wt% Pt/Ketjen: five particle sizes (1.9, 3.2, **5.0**, 7.1, 12.7 nm)



40 wt% Pt_3Co/Ketjen: three particle sizes (5.6, 8.7, 14.3 nm)



Acid treatment (pre-leaching):
80°C, 0.5 M H_2SO_4,
2 days

40 wt% Pt_3Co/Ketjen: one particle size (5.6 nm), acid treated (80 Pt:20 Co)

35 wt% PtCo/Ketjen: one particle size (4.1 nm), acid treated (71 Pt:29 Co)

40 wt% Pt_3Y (11 m^2/g) and 40 wt% Pt_3Sc (7.5 nm)

Technical Progress (Tasks 2.1 and 2.2)

Particle size and parametric studies

Cathode Cat.	TEM Mean Particle size (nm)	Cathode loading (mg-Pt/cm^2)	Anode loading (mg-Pt/cm^2)
Pt	1.9	0.20	0.2
Pt	3.2	0.21	0.18
Pt	5.0	0.23	0.25
Pt	7.1	0.21	0.2
Pt	12.7	0.21	0.2
Pt_3Co	5.6	0.23	0.20
Pt_3Co	8.7	0.22	0.20
Pt_3Co	14.3	0.22	0.20

Particle size studies:

- Triangle wave potential cycle: 0.6 V to 1.0 V, 50 mV/s (DOE-U.S. Drive Protocol)
- Cell Temperature: 80°C
- Fuel/Oxidant : 100% RH H_2 at 100 sccm and 100% RH N_2 at 50 sccm
- Pressure: Atmospheric

Parametric studies: effect of upper potential limit, RH, temp., and potential profile.

Pt: 3.2 nm mean particle size; Pt_3Co: 5.6 nm mean particle size; Pt_3Co and PtCo: Pre-leached

Cell ID	Potential cycle
BL	• Square wave potential cycle: 10s at 0.4V, 10s at 0.95V (20s / cycle) • Cell Temperature: 80°C • Humidity: Anode = Cathode = 100% RH • Fuel/Oxidant : 0.5SPLM 4%H_2 / 0.5SPLM N_2 • Pressure: Atmospheric pressure
1.05V	• Square wave potential cycle: 10s at 0.4V, 10s at 1.05V (20s / cycle) • All other parameters were same as BL
30%RH	• Humidity: Anode = Cathode = 30%RH • All other parameters were same as BL
90 °C	• Cell Temperature: 90°C • All other parameters were same as BL

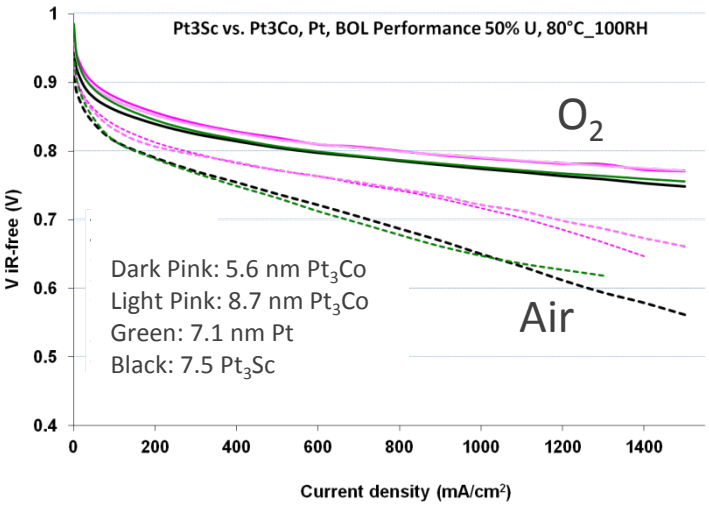
Diagnostics:

- Electrochemically-active surface area (ECA)
- Oxygen reduction activity per g Pt@0.9 V (MA)
- Polarization curves on oxygen and air
- Hydrogen pump - ionic resistance of electrode
- Post-test SEM, TEM, EMPA, and ASAXS

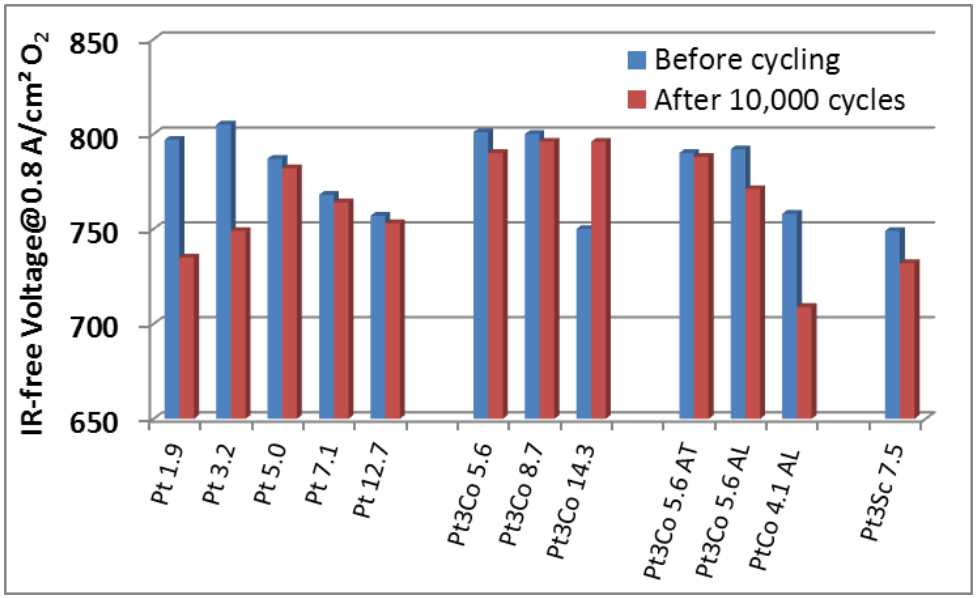
Technical Progress (Task 2.2)

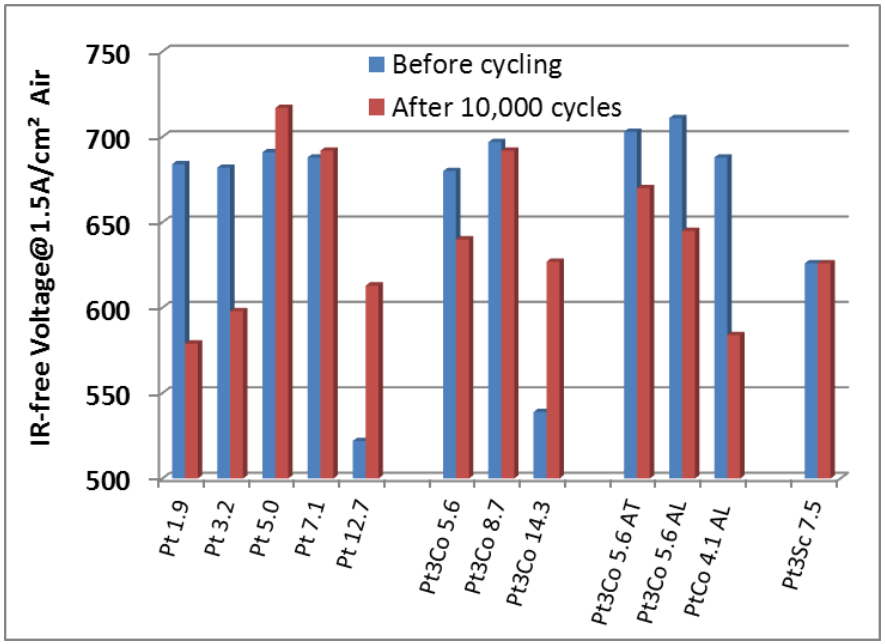
Summary of cell performances with different cathode catalysts

- General trends in initial cell performance
  - Higher kinetic performance with smaller particles and upon alloying with Co
  - Kinetic benefits offset by mass transport effects at higher current densities
- General trend in cycling durability
  - Higher stability with larger cathode catalyst particle sizes
  - Degradation increased by increasing upper potential limit and temperature, decreased by decreasing RH



DOE Cycling Protocol: 0.6 to 1.0 V Triangle, 50 mV/s





Technical Progress (Tasks 2.1, 2.2, and 4)

Characterization results DOE cycling - ECA, TEM, and ASAXS

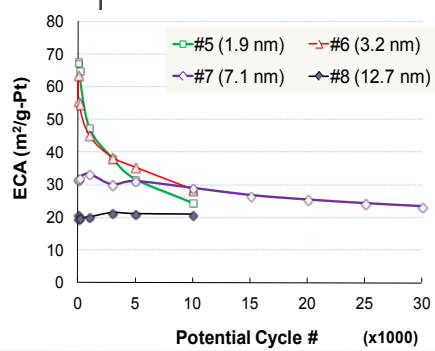
Pt in MEA before and after 10,000 DOE cycles

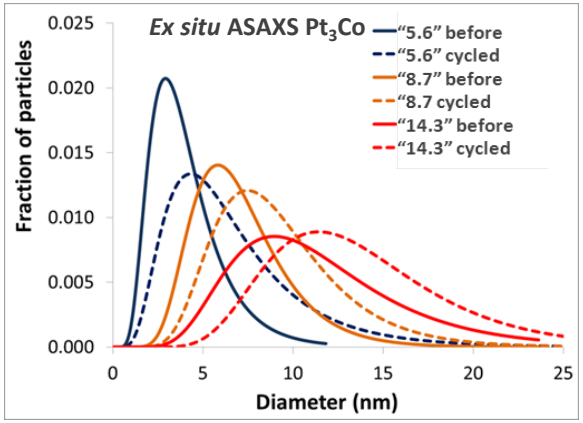
Initial mean particle dia. (nm)	TEM Final particle dia. three regions (nm)	ECA GSA from TEM PSD Cycled/Initial (m^2/g-Pt)
"1.9" 2.4 0.1	A: 10.3±0.9 B: 10.0 ±0.6 C: 7.7 ±0.4	24.5/67.9=0.36 19.4/105.4=0.18
"3.2" 3.4 0.2	A: 9.8±0.5 B: 9.1 ±0.5 C: 9.4 ±0.5	28.7/60.8=0.47 22.8/63.0=0.36
"7.1" 6.9 0.3	A: 6.5±0.3 B: 6.6±0.3 C: 6.5±0.3	29.1/33.3=0.87 35.6/35.1=1.01
"7.1" 6.9 0.3 (30,000 cyc.)	A: 10.0 ±0.6 B: 9.5±0.5 C: 9.3 ±0.5	24.0/33.3=0.72 21.3/35.1=0.61
"12.7" 13.8 ± 0.6	A: 16.6 ±2.2 B: 13.4 ± 0.6 C: 14.5 ± 0.7	21.0/21.1=1.00 16.3/21.2=0.77

Pt_3Co in MEA before and after 30,000 DOE cycles

Initial TEM mean particle dia. (ASAXS) (nm)	TEM Final particle dia. three regions (ASAXS) (nm)	ECA GSA from TEM PSD GSA from ASAXS PSD Cycled/Initial (m^2/g-Pt)
"5.6" 4.9 0.2 (3.7)	A: 6.2±0.3 B: 6.1±0.3 C: 6.2±0.4 (5.8)	22.6/37.0=0.61 43.2/57.6=0.75 42.9/59.2=0.71
"8.7" 8.1 0.4 (6.7)	A: 8.4±0.4 B: 8.5±0.4 C: 7.9±0.4 (8.6)	23.8/27.4=0.87 34.9/36.8=0.95 29.4/38.6=0.76
"14.3" 14.8 0.6 (10.6)	A: 12.5±0.6 B: 13.0±0.9 C: 13.0±0.7 (13.0)	17.6/22.8=0.77 21.6/20.2=1.07 19.9/23.1=0.85

- Particle size and ECA loss relatively stable at >6 nm initial size
- Pt and Pt_3Co show similar particle size dependence of particle growth and ECA loss
- Predominantly spherical particles, except "1.9", "3.2", and 30,000 "7.1" Pt



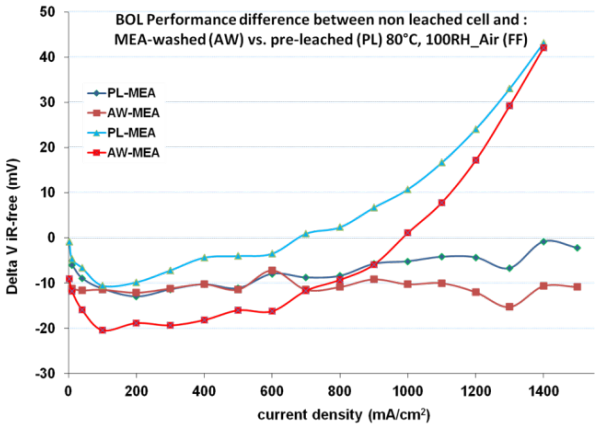


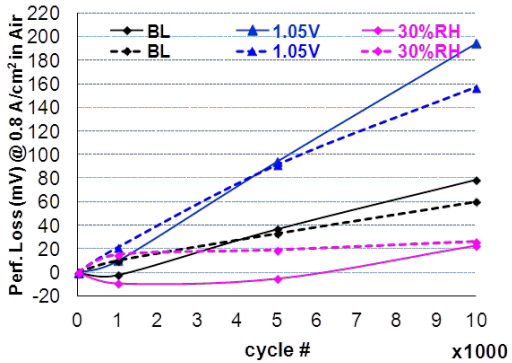
Technical Progress (Tasks 2.2)

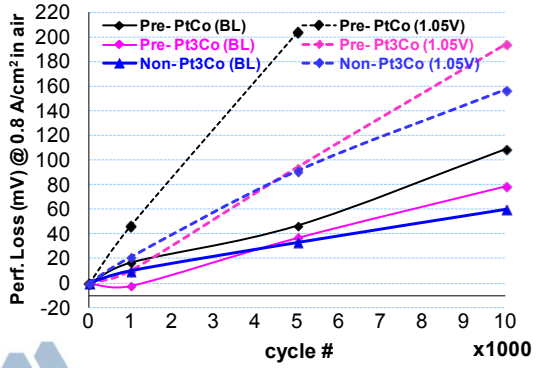
Impact of acid-leaching and Co content on Pt-Co MEA decay

DOE Cycling Protocol

- Pt_3Co catalyst – effect of acid-leach (AL) and MEA acid wash
  - AL and MEA acid wash: ~ 10 mV lower O_2 perf. (dec. in ORR activity); higher perf. in H_2/Air at high current (< H_2 pump resist.)
  - ECA, MA, SA, and O_2 performance decay trends with cycling are not effected by AL or MEA acid wash;
  - AL Pt_3Co vs. AL PtCo – effect of cobalt composition
  - Comparable initial performance at high currents
  - Comparable ECA, MA, SA, and perf. decay trends with cycling







Solid line – AL Pt_3Co
Dashed line – Pt_3Co

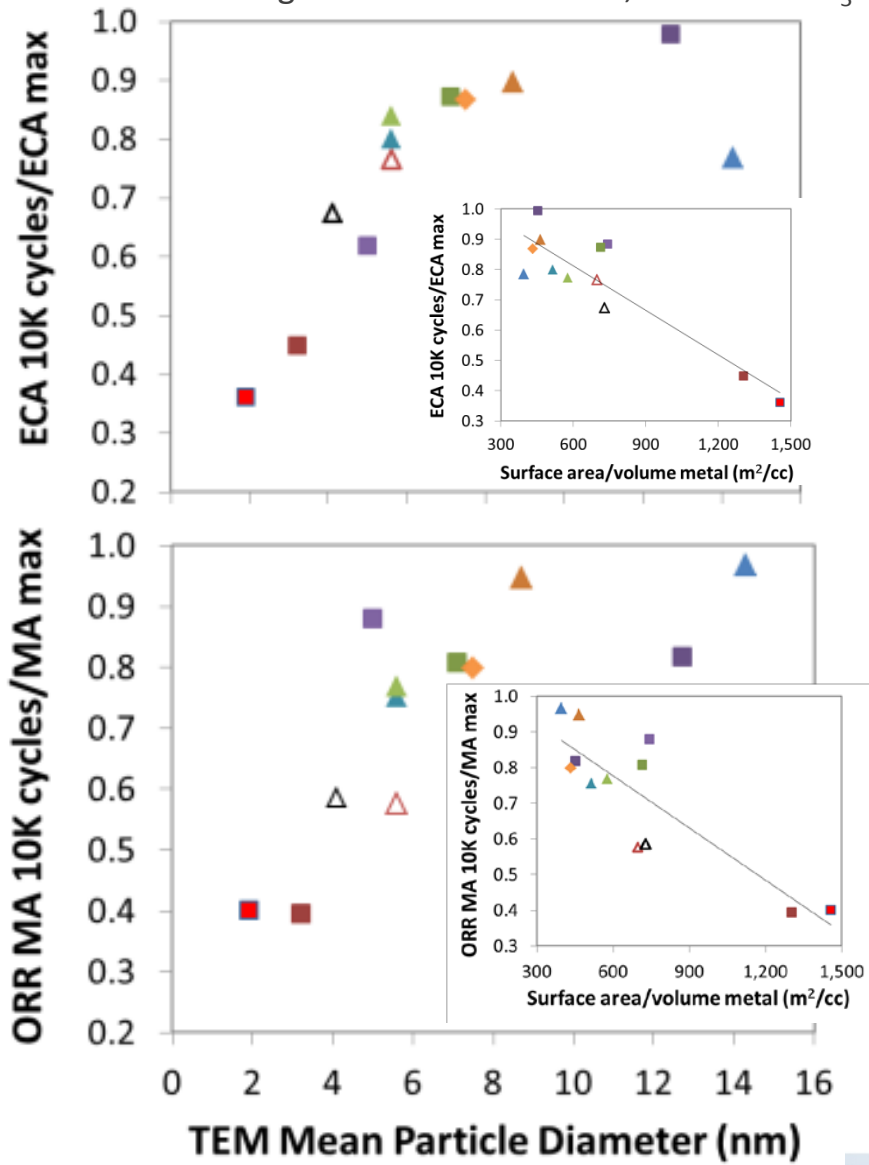
Parametric studies: Square wave – 0.95 (BL), 1.05 V, 30% RH

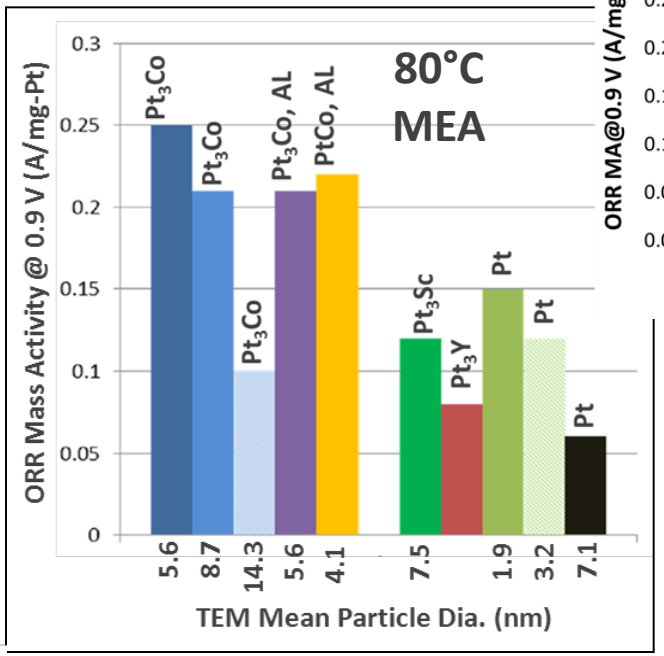
- Initial performances of MEAs with AL Pt_3Co and AL PtCo were lower than with Pt_3Co (>15 mV, low cd and >25 mV, high cd)
- No acid-leaching of Pt^3Co: higher decay in high cd air performance with BL cycling (>inc. in H_2 pump resist.)
- Acid-leaching of Pt_3Co does not effect the decay trends of ECA, MA, SA, and performance with cycling (1.05 V>BL>30% RH)
- MA durability: 0.95 V - AL Pt_3Co>Pt_3Co>AL PtCo; 1.05 V – AL Pt_3Co>Pt_3Co>>AL PtCo
- ECA durability: 0.95 V – Pt_3Co>AL Pt_3Co>AL PtCo; 1.05 V – Pt_3Co>AL Pt_3Co>AL PtCo
- Perf. Durability, air, 0.8 A/cm²: 0.95 V–Pt_3Co≥AL Pt_3Co>AL PtCo; 1.05 V – Pt_3Co>AL Pt_3Co>>AL PtCo

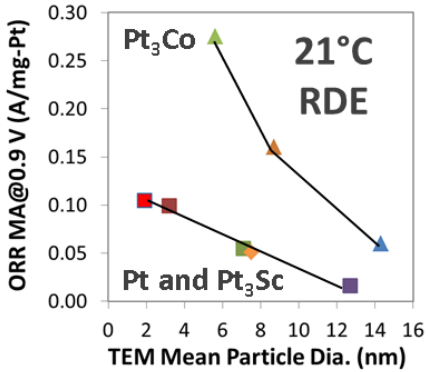
Technical Progress (Task 2)

ORR activity and DOE cycling-induced ECA and MA loss in MEAs

Triangle wave potential cycle, 0.6 V to 1.0 V, 50 mV/s; Squares: Pt, Triangles: Pt_3Co, Hollow Triangles: Acid-leached Pt_3Co, Hollow black triangle: Acid-leached PtCo, Diamond: Pt_3Sc





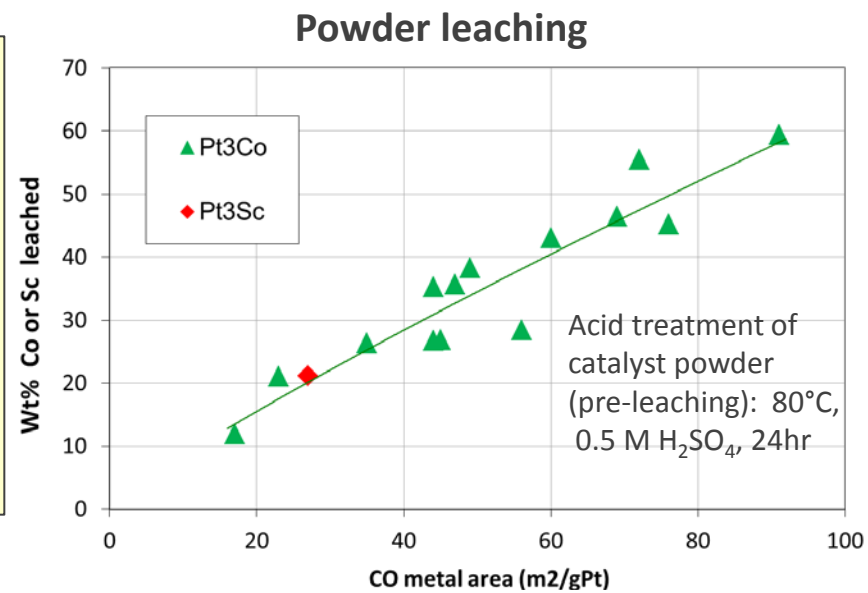


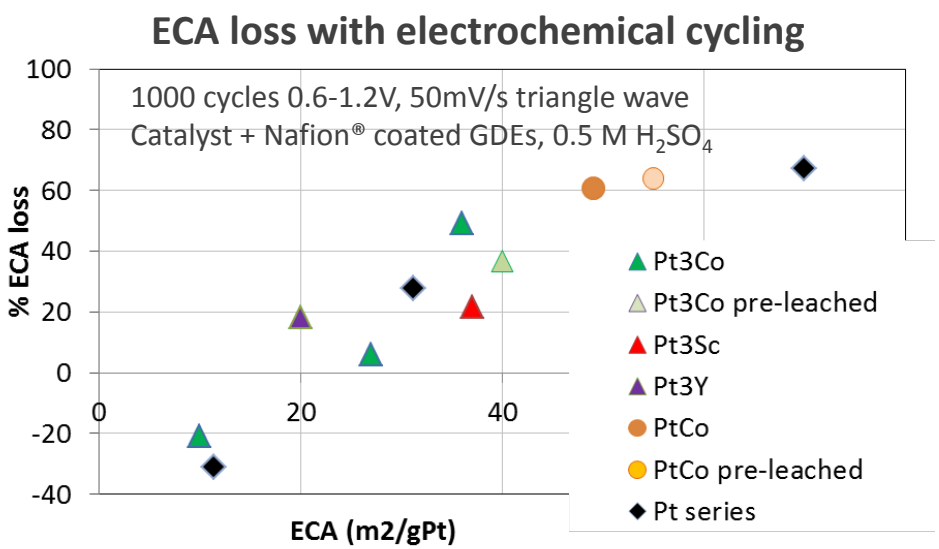
- Alloying with Co increases ORR activity of Pt
- Acid-leaching of Pt-Co lowers ORR activity
- No ORR activity benefit of alloying with Sc or Y
- ECA and ORR MA loss are dependent on initial mean diameter (surface area) of catalyst nanoparticles
- No clear effect of alloying or leaching on ECA and MA loss

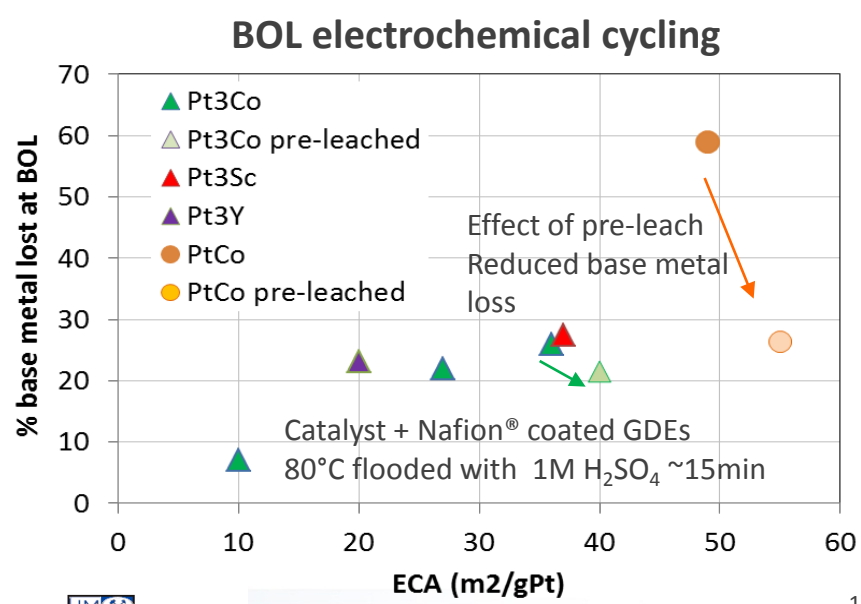
Technical Progress (Task 3)

Aqueous electrolyte leaching and ECA loss - Pt and Pt alloys

- Leaching of base metal from alloys is dependent on catalyst surface area (particle size), but independent of identity of base metal
  - no additional stabilization with Sc and Y versus Co
- Pre-leaching of catalyst decreases subsequent loss of base metal in acidic electrolyte
- ECA loss is dependent on initial catalyst surface area and not affected by alloying



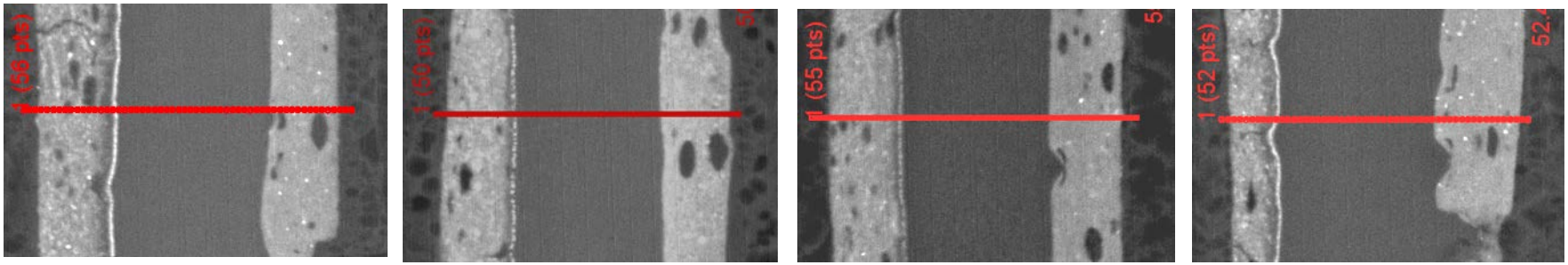


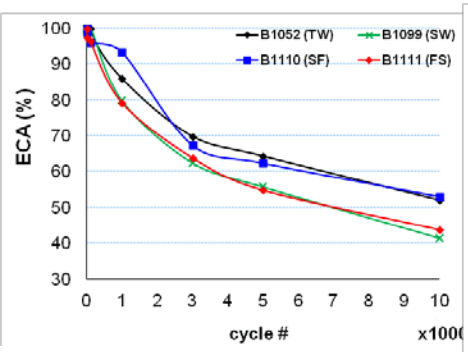


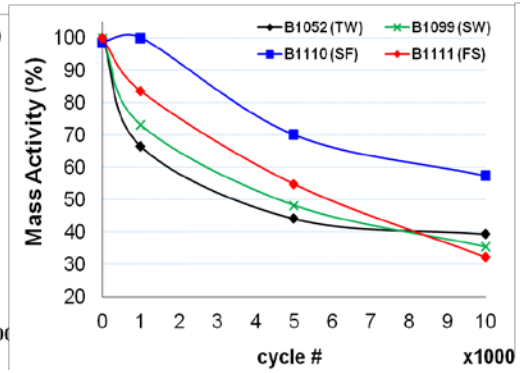
Technical Progress (Task 2.1)

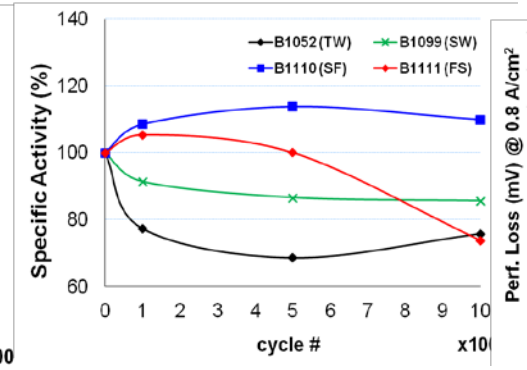
Impact of cycle profile on 3.2 nm Pt catalyst decay

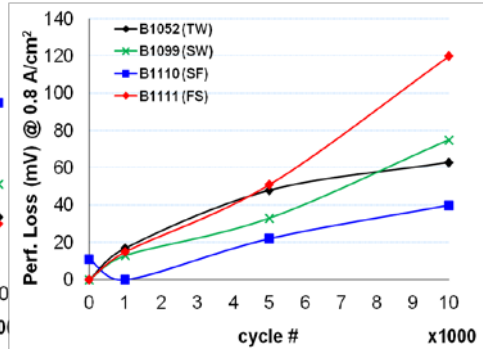
Middle











- Perf. loss : SW ≅ FS >TW > SF
- ECA loss with cycling: SW ≅ FS >> TW ≅ SF
- MA decay with cycling: SW ≅ FS ≅ TW >> SF
- SA loss with cycling: TW ≅ FS > SW>>SF
- Degree of Pt in membrane: SW ≅ FS >> TW ≅ SF

Technical Progress (Tasks 2.1, 2.2, and 4)

Characterization results parametric studies - ECA, TEM, ASAXS

Parametric study of 3.2 nm Pt; 10,000 square wave cycles

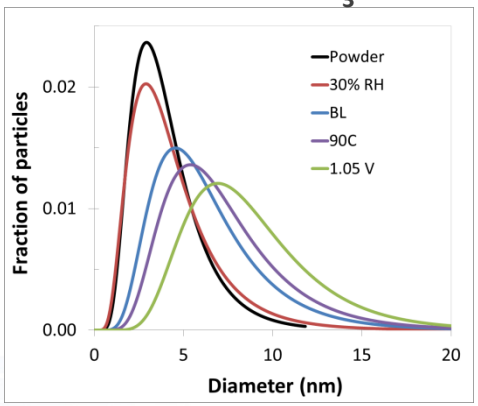
Cycling conditions	ECA GSA from TEM PSD Cycled/Initial (m^2/g-Pt)	Final particle dia. three regions (nm) A=near membrane C=near GDL
BL	26.0/45.0=0.58 47.5/63.0=0.75	A: 4.9±0.2 B: 5.2±0.2 C: 4.9±0.2
1.05V	16.0/43.0=0.37 25.3/63.0=0.40	A: 8.1±0.4 B: 8.3±0.4 C: 7.9±0.5
30%RH	39.0/46.0=0.85 55.7/63.0=0.88	A: 4.0±0.2 B: 4.3±0.2 C: 4.3±0.2
90 C	27.0/52.0=0.52 33.4/63.0=0.53	A: 6.6±0.6 B: 5.3±0.3 C: 5.4±0.2

Parametric study of 5.6 nm Pt_3Co; 10,000 square wave cycles

Cycling conditions	ECA GSA from TEM PSD GSA from ASAXS PSD Cycled/Initial (m^2/g-Pt)	Final particle dia. three regions TEM (ASAXS) (nm)
BL	27.4/35.0=0.78 50.5/57.6=0.88 36.4/59.2=0.61	A: 5.7±0.3 B: 5.8±0.3 C: 4.9±0.4 (5.7)
1.05V	18.0/33.0 =0.54 32.0/57.6=0.56 29.7/59.2=0.54	A: 9.2±0.4 B: 8.8±0.4 C: 8.5±0.4 (8.1)
30%RH	29.3/30.0=0.98 40.0/57.6=0.69 46.1/59.2=0.77	A: 6.6±0.5 B: 5.8±0.3 C: 5.2±0.2 (3.8)
90 C	19.8/31.6=0.63 36.1/57.6=0.63 33.5/59.2=0.56	A: 9.1±0.6 B: 7.3±0.3 C: 6.7±0.3 (6.6)

- Particle growth, surface area loss: 1.05 V>90 C>Baseline>>low RH
- Mass activity loss: 1.05 V>90 C>low RH>Baseline
- Specific activity loss: 1.05 V>Baseline=low RH>90 C (Pt_3Co); low RH>90 C≥1.05 V>Baseline (Pt)
- Significant "coalesced" particles evident only in 1.05 V Pt cell

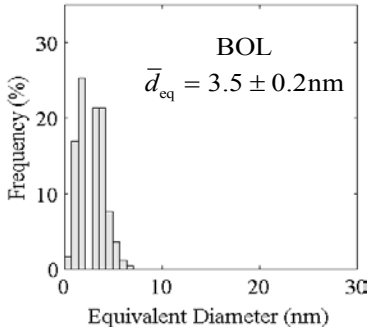
***Ex situ* ASAXS Pt_3Co**

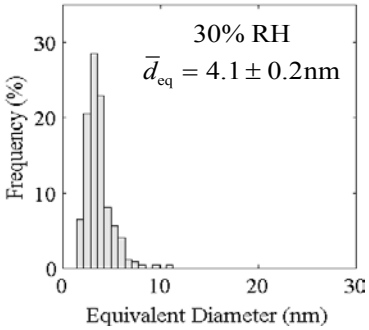


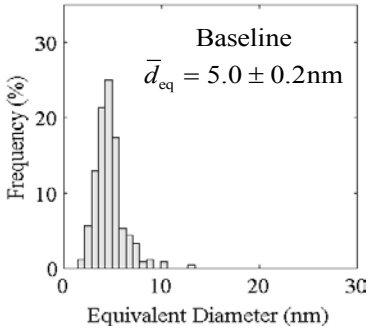
Technical Progress (Tasks 2.1 and 4.1)

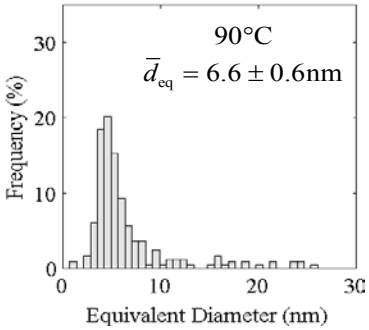
Parametric study - post-cycling TEM

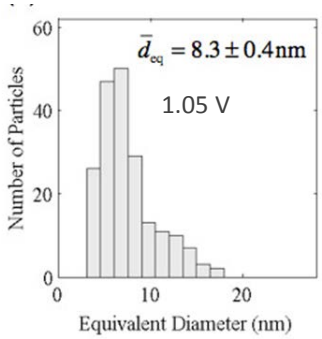
Pt

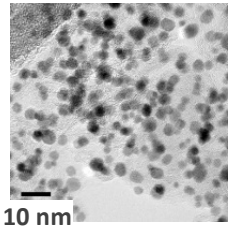


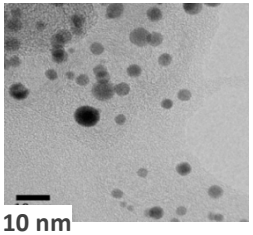


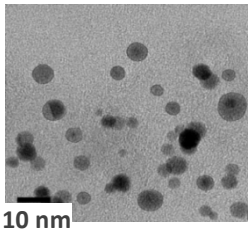


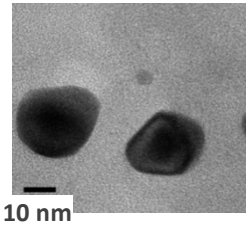


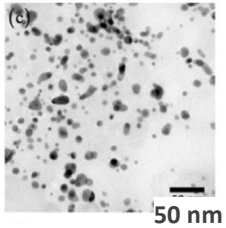




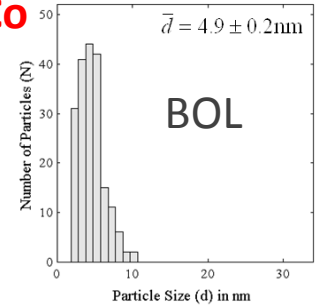


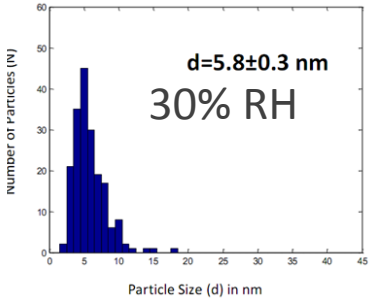


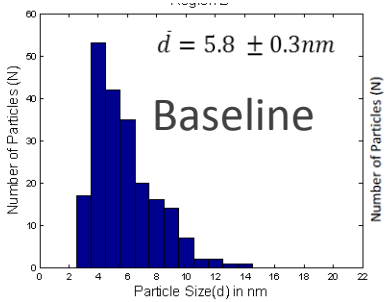


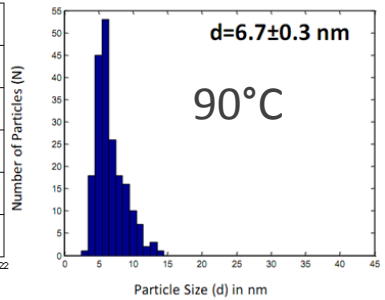


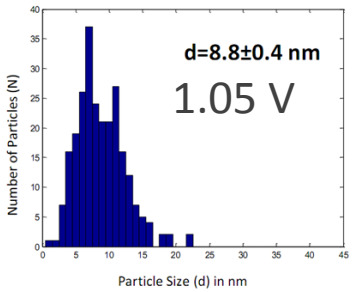
Pt_3Co

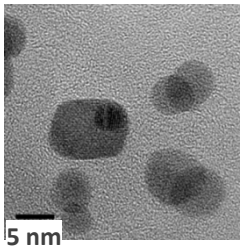


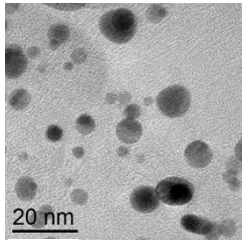


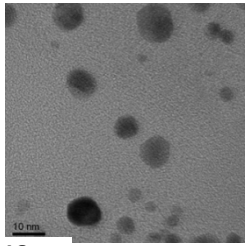


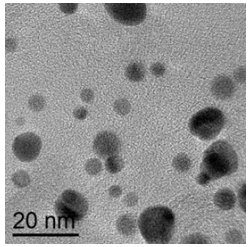


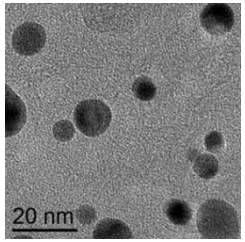










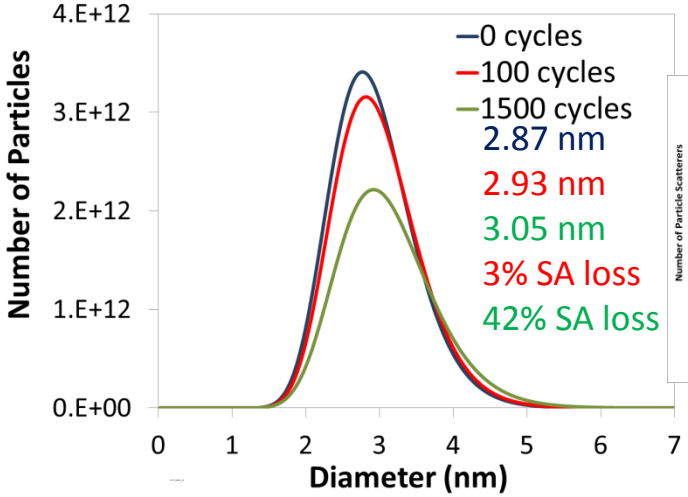


20 nm

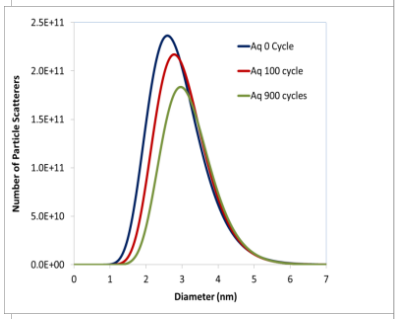
Technical Progress (Task 3)

In situ and in operando PSD evolution - small angle X-ray scattering

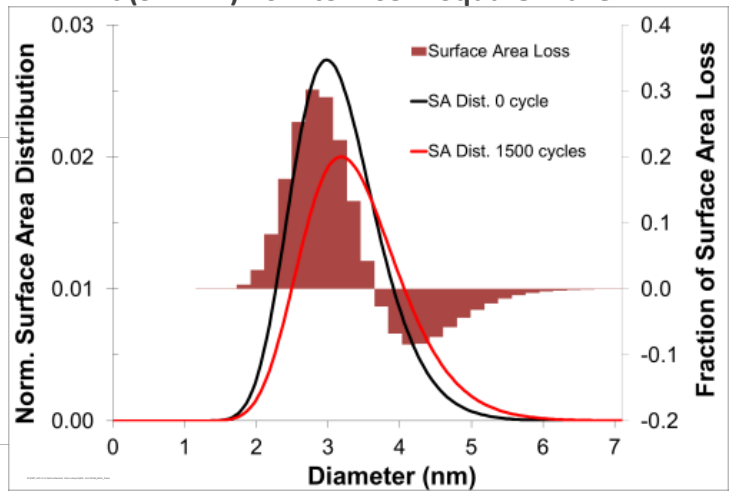
Pt (3.2 nm): 0.4 to 1.05 V Square Wave MEA



Aqueous

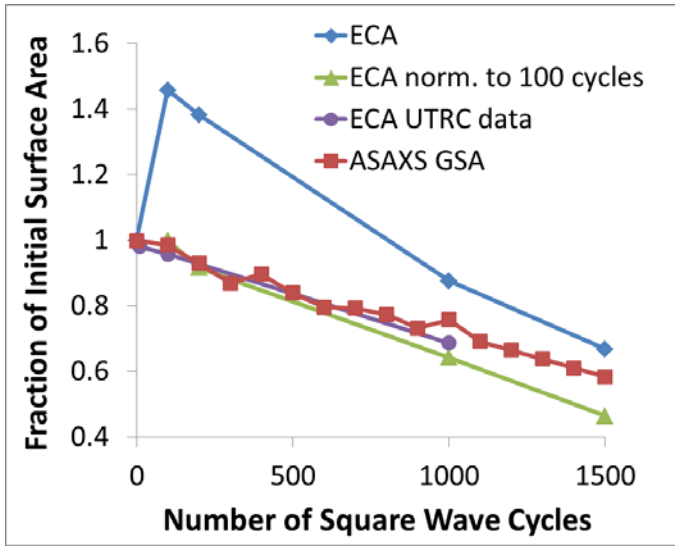


Pt (3.2 nm): 0.4 to 1.05 V Square Wave MEA



- Evolution of PSD in MEA differs from that in aqueous environment – effect of crossover hydrogen*
- Decrease in Pt surface area in aqueous and MEA environments is primarily due to loss of particles with diameters <~3.5 nm diameter
- *In operando* X-ray scattering shows that geometric surface area decreases during initial ECA increase (conditioning)

MEA Square wave cycles 0.4 to 1.05 V

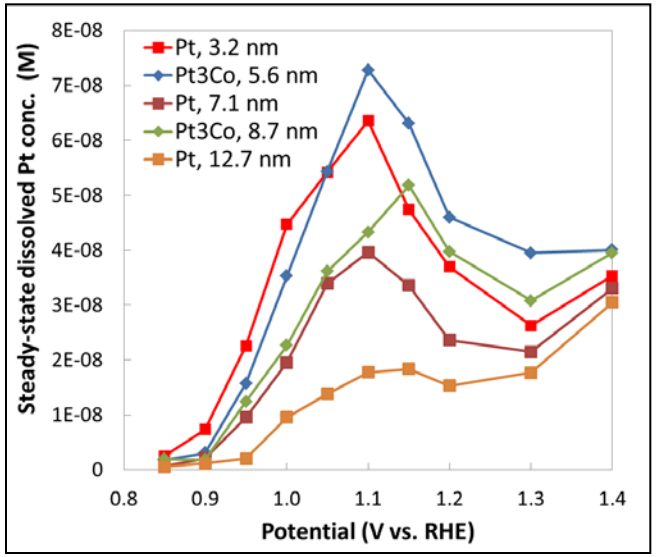


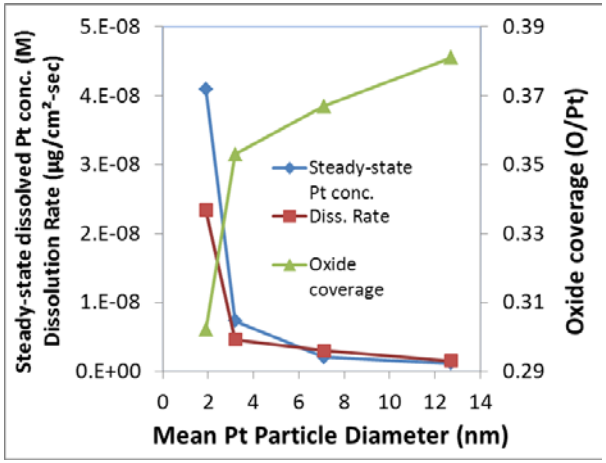
*Edward F. Holby, Wenchao Sheng, Yang Shao-Horn and Dane Morgan, Energy Environ. Sci., 2009, 2, 865-871.

Technical Progress (Task 3)

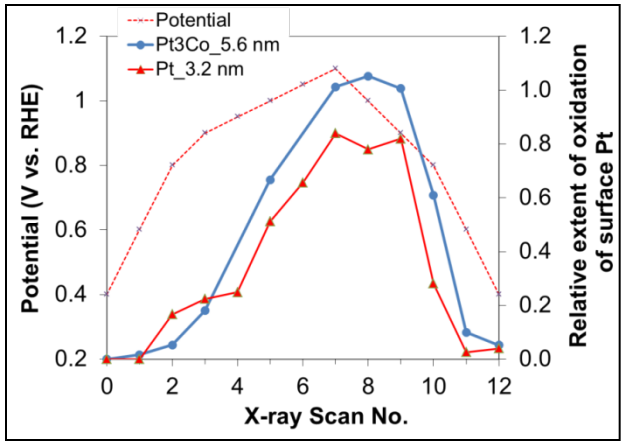
Aqueous electrolyte and X-ray studies of Pt dissolution and oxide coverage

Potentiostatic – 72h, room-temperature, 0.57 M $HClO_4$



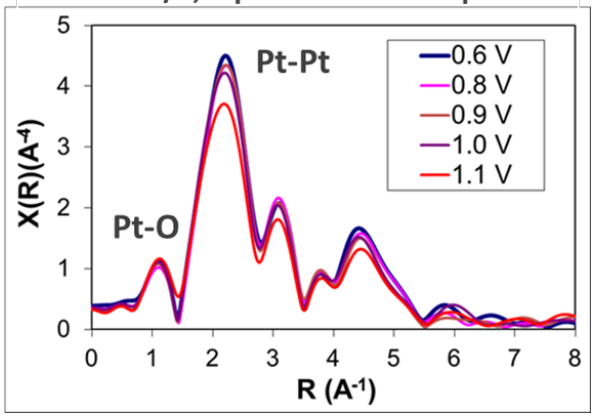


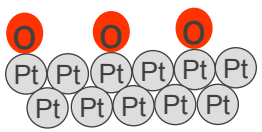
MEA, N_2 on cathode, 80°C



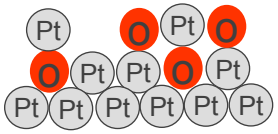
- Steady-state dissolved Pt concentrations and potentiostatic dissolution rates increase with decreasing mean particle size of Pt and Pt_3Co
- Steady-state oxide coverage of Pt decreases with decreasing mean particle size
- Dissolved Pt concentration peaks at an oxide coverage of ~1 O/Pt; XAFS evidence for change of oxide structure
- Oxide protects Pt against dissolution under steady-state conditions

3.2 nm Pt/C, aqueous room temp. XAFS





<1.1 V

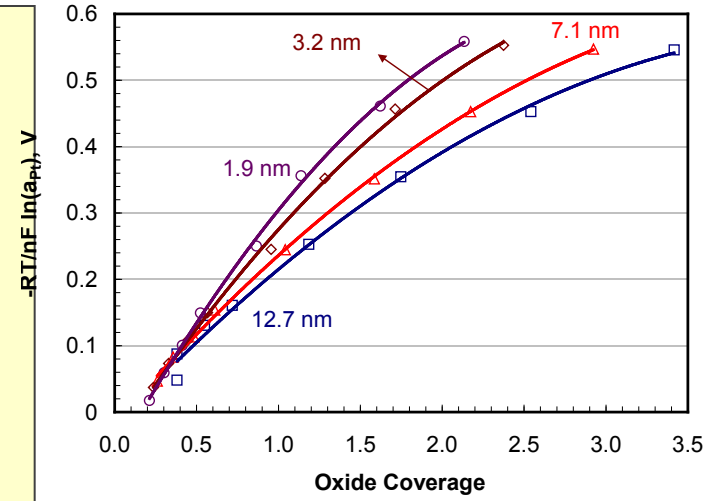


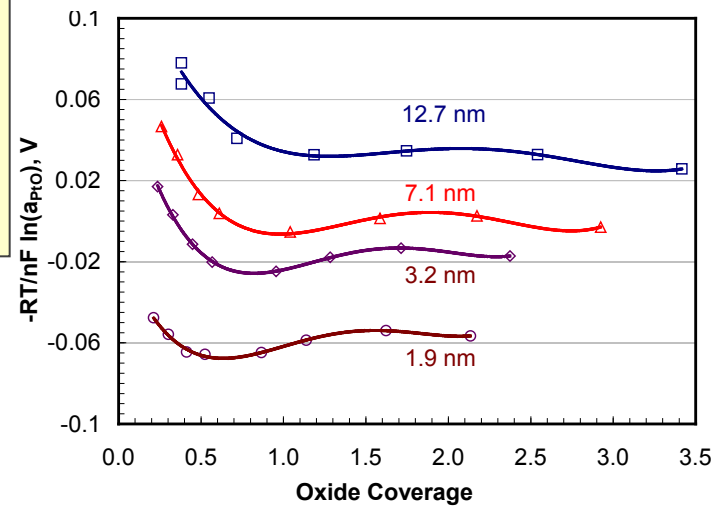
1.1 V

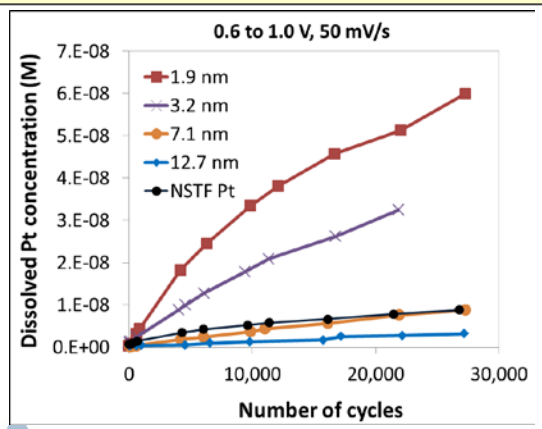
Technical Progress (Task 5.2)

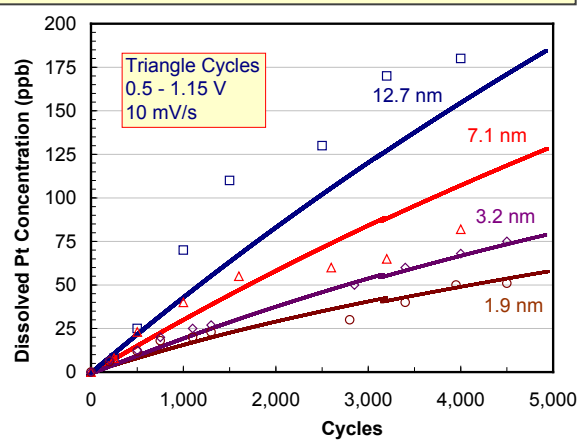
Catalyst degradation modeling

- Thermodynamics of Pt Dissolution and Oxide Growth:
  - Non-ideal solid solution formulation for Pt dissolution
  - Activity of Pt and PtO_x in solid solution related to equilibrium oxide coverage and particle size
  - Decrease in Pt activity with oxide coverage consistent with the changing slope in the measured Pt^{2+} concentration with potential and its peak at approx. 1.1 V
  - Changes in PtO_x activity beyond unity oxide coverage reflects multiple oxidation states (PtOH, PtO_2, etc.) with different E^0 and n
- Platinum dissolution – Cycling conditions:
  - Pt Dissolution kinetics modeled using transient data at 1.1 V
  - Oxide growth/reduction kinetics modeled using CV oxidation scans
  - Dissolution model validated with cyclic data: 40-cm² ECA GDE in 130 mL perchloric acid electrolyte
  - Dissolution rates are strong functions of upper potential limit, lower potential limit, scan rates, times, and oxide coverage







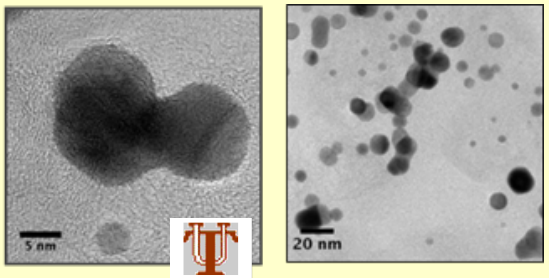


Collaboration with LANL (R. Borup) and Nuvera durability projects

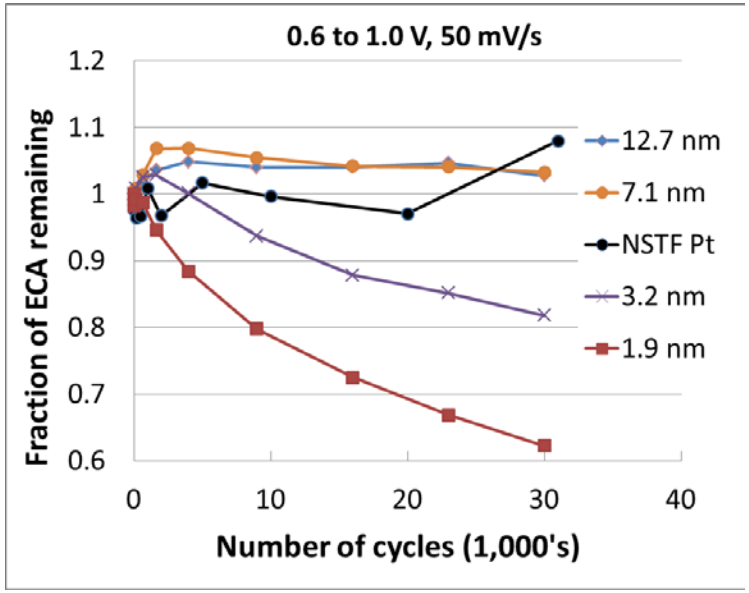
Technical Progress (Task 5.2)

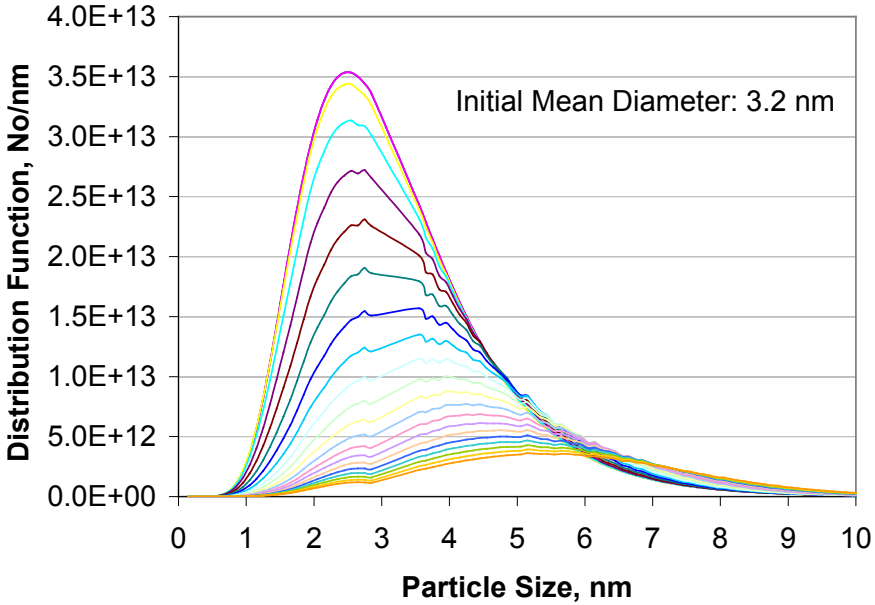
Catalyst degradation modeling - ECA loss and particle growth

- Measured ECA loss cannot be explained solely on the basis of Pt dissolution or change in size distribution due to preferential dissolution of smaller particles and re-deposition on larger particles
- Model expanded to include coalescence due to re-deposition
  - Smoluchowski equation with Pt dissolution, Pt re-deposition, and particle coalescence
  - Coagulation kernel function of re-deposition rate
  - Implicit finite-difference scheme in time and size coordinate*



UT Austin



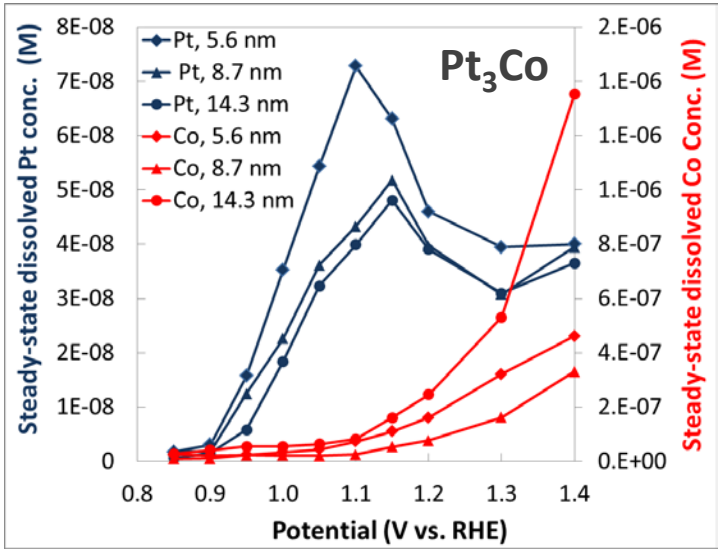


*Im, Ahluwalia, Chuang, Aerosol Science and Technology, 4 (2) 655-663, 1985.

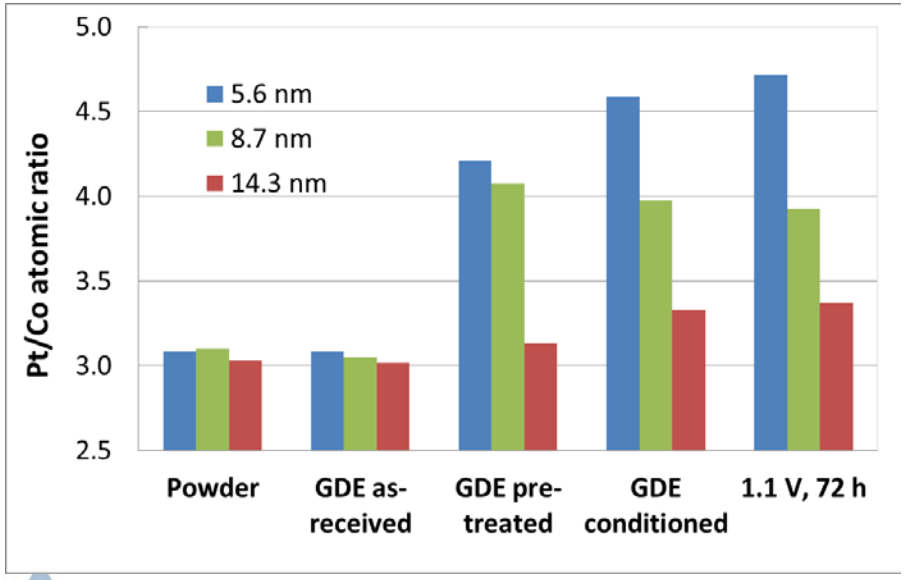
Technical Progress (Task 3)

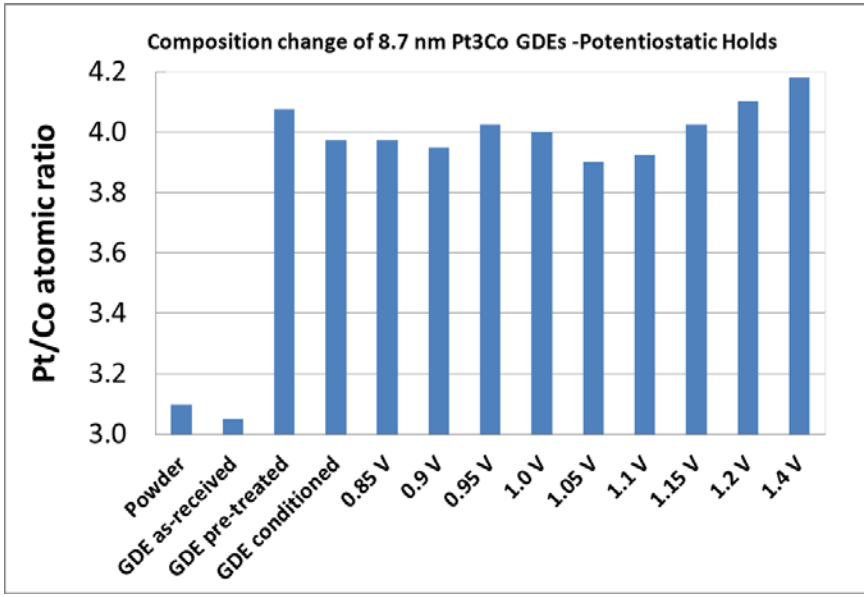
Aqueous electrolyte studies of Pt_3Co dissolution

- Largest loss of cobalt is observed during electrode preparation/wet-up
- Fraction of total cobalt leached from catalyst decreases with increasing particle size
- Loss of cobalt from catalyst is potential independent at potentials >0.85V and <~1.0 V
- Potential region for increased extent of cobalt dissolution coincides with decreased platinum dissolution



Pre-treatment: Soaking in room temp. H_2O;
Conditioning: potential cycling from 0.05 to 1.1 V, 15-20 cycles

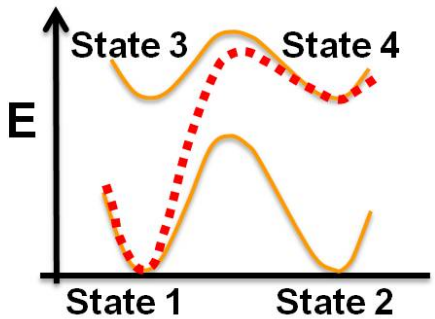




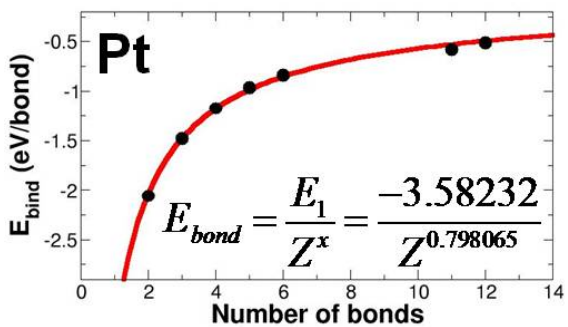
Technical Progress (Task 5.1)

Kinetic Monte Carlo (KMC) Model of Pt Alloy Nanoparticles: Structural Evolution and Dissolution

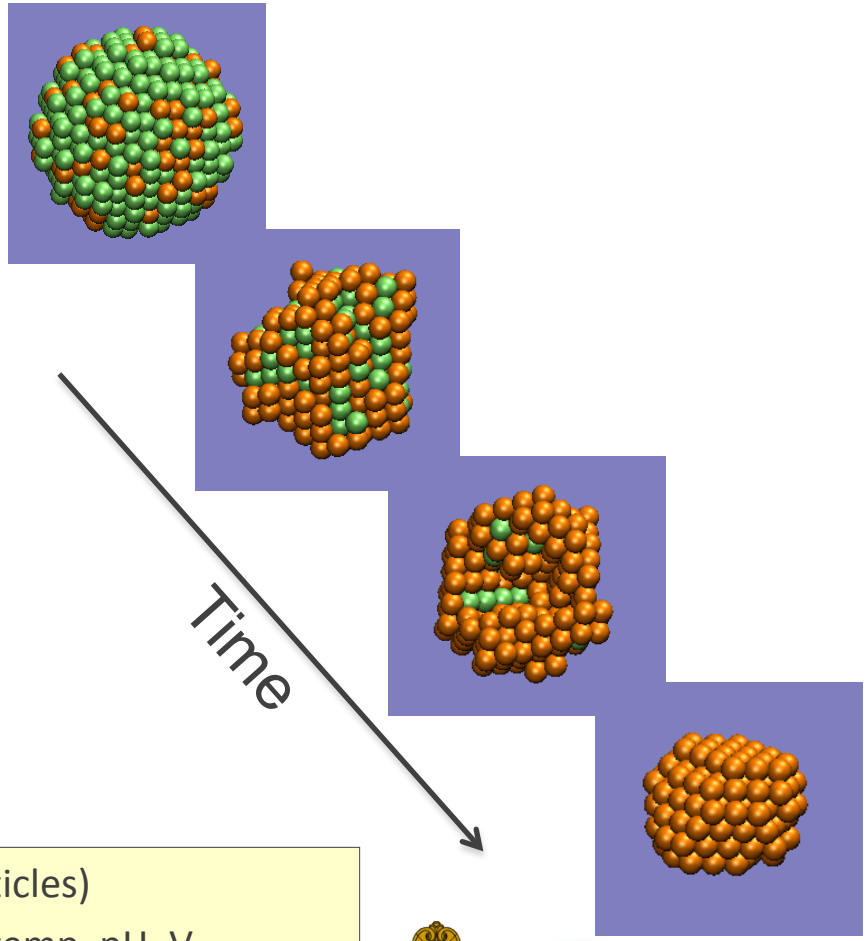
- **KMC Model of Pt-Co Diffusion and Dissolution.**



- **Bond-Energy Hamiltonian from DFT Fits**



- **Can simulate composition and structure of Pt-Co dealloying**

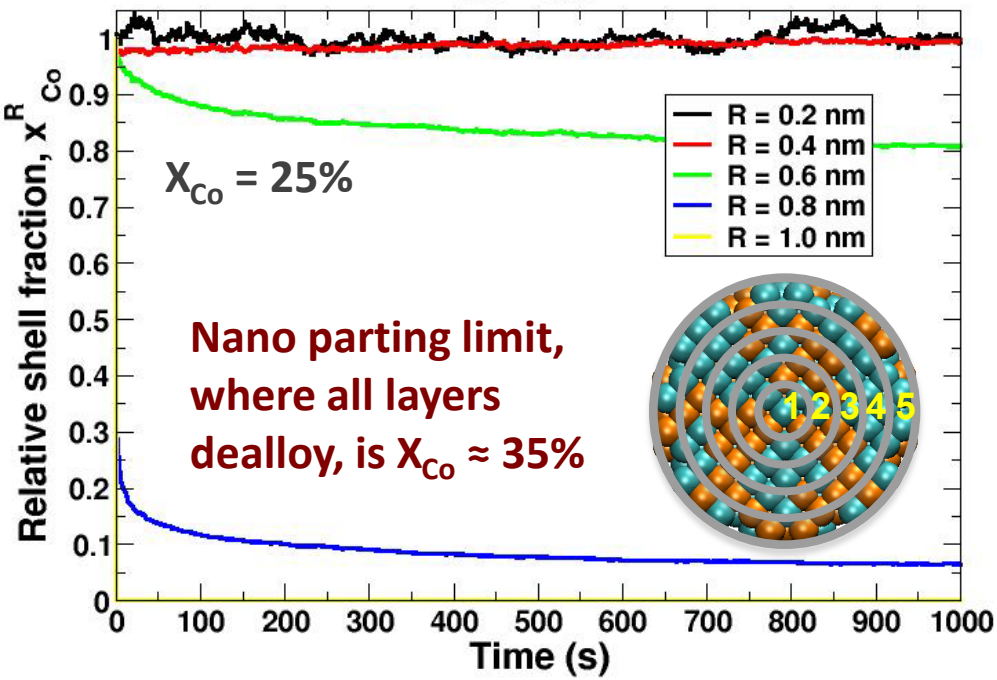


- Basic KMC model completed (~20min, 1000 particles)
- Can simulate Pt-Co evolution vs. time, X_{Co}, size, temp, pH, V, …

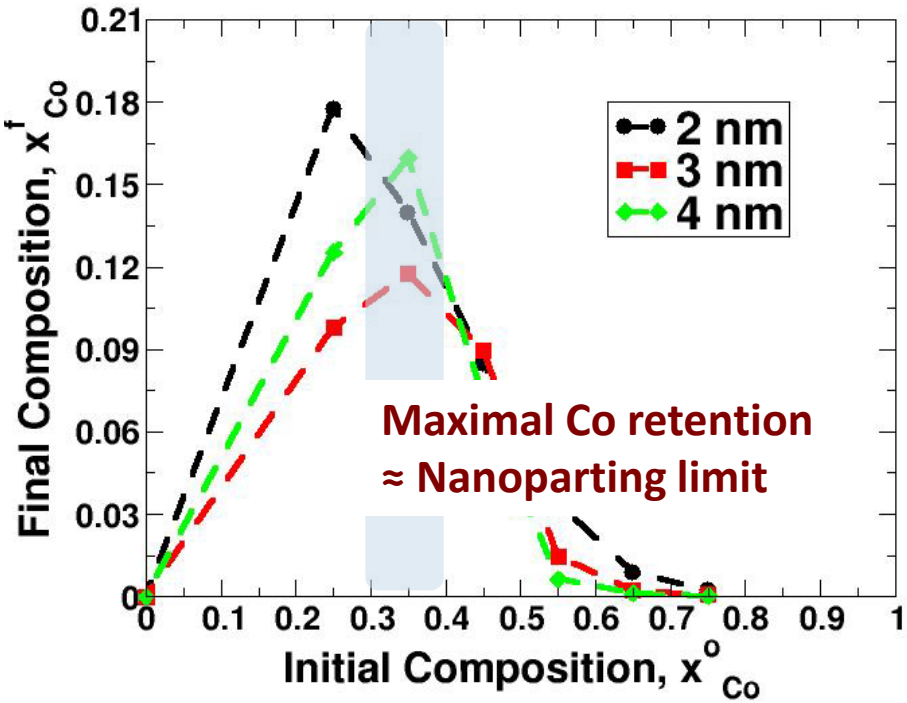
Technical Progress (Task 5.1)

Kinetic Monte Carlo (KMC) Model of Pt Alloy Nanoparticles: Structural Evolution and Dissolution

Understanding Dealloying



Maintaining Co Concentration



- Identified how particles dealloy and nanoparticle dealloying limit at X_{Co} ≈ 35%
- Retained Co peaks near nanoparting limit

Summary

Relevance:

- Mitigate catalyst-related PEMFC performance loss and enable PEMFC systems to achieve lifetime targets by defining catalyst properties and operating conditions that will enhance catalyst lifetimes.

Approach:

- Identify catalyst degradation modes and factors contributing to degradation using a variety of in-cell and out-of-cell techniques and systematic variation of catalyst physicochemical properties.

Accomplishments:

- Prepared Pt/alternative carbons, Pt/C different levels of Cl impurities. Fabricated and tested MEAs of $Pt_xCo_{(1-x)}$, acid-leached, Pt_3Sc, and various Pt/C
- Established relationship between loss of ECA, mass activity, and particle size: dominating factor in ECA and MA loss is initial particle size
- Determined that the operating parameters of upper potential limit and anodic sweep rate have the most significant impact on cell degradation
- Established most significant factors governing cycling-induced change in PSD and ECA loss: competition between Pt dissolution and oxide formation and coalescence of particles via re-deposition

Collaboration:

- Project team of JMFC, UTRC, MIT, UT-Austin, and UW-Madison
- LANL, Nuvera, and 3M; co-chairing "Durability Working Group"

Future Work:

- Preparation, characterization and MEA testing of Pt-Ni; characterization and MEA testing of Pt/alternative carbons, Pt/C with Cl impurities
- Complete analysis of ASAXS and XAFS data for Pt and Pt_3Co MEAs
- Study effect of temperature on oxide structure and dissolution
- Complete cathode performance degradation model

Collaborations and acknowledgments

- Project team (subs) within DOE H_2 Program
  - Johnson Matthey Fuel Cells
  - United Technologies Research Center
  - Massachusetts Institute of Technology
  - University of Texas at Austin (Ferreira and Meyers)
  - University of Wisconsin – Madison
- Los Alamos National Laboratory, Nuvera, and 3M
- Co-chairing "Durability Working Group"

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- DOE, Office of Energy Efficiency and Renewable Energy, Fuel Cell Technologies Program – Nancy Garland (Technology Development Manager)
- DOE, Office of Science, Basic Energy Sciences
  - Argonne National Laboratory Advanced Photon Source
  - Argonne National Laboratory's Electron Microscopy Center

Technical Back-Up Slides

Technical Progress: Catalyst and MEA fabrication (Task 1)

Pt/C - Ketjen EC300J and corrosion resistant carbons (A and B)

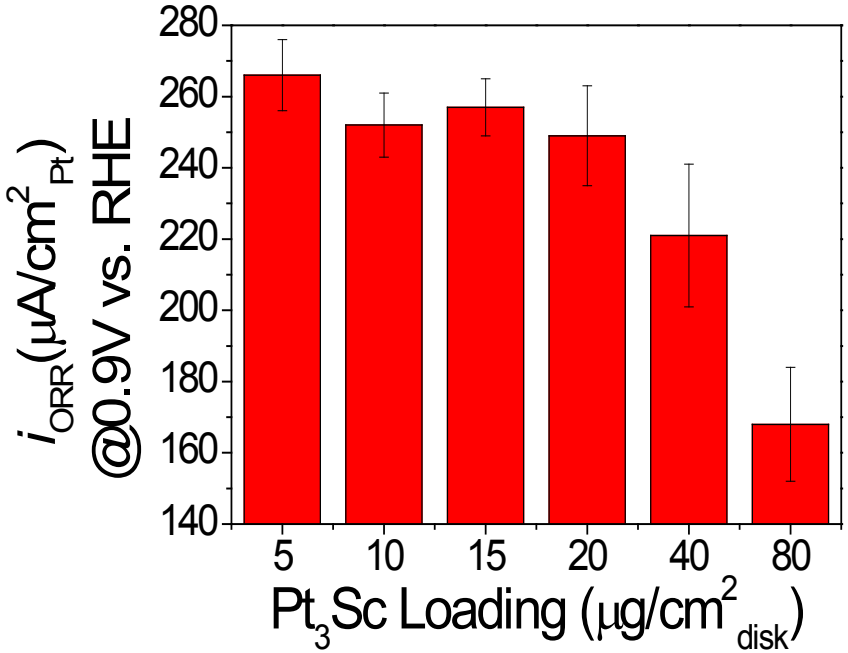
Catalyst identifier	Carbon surface area (m^2/gC)	Calculated Wt% carbon loss 24hr 1.2V hold 80C*	Annealing conditions	Pt (%)	CO area ($m^2\ g^{-1}$-Pt)	XRD C.S. (nm)	TEM Mean particle size (nm)	ECA CO stripping (1M H_2SO_4, 80ºC)
Pt/Ketjen (1.9 nm)	831	32	none	35.6	96	<2 nm	1.9	94
Pt/Ketjen (3.2 nm)	831	32	T_1	40.7	63	Non-gaussian peaks – crystallite size not determined	3.2	60
Pt/Ketjen (4.9 nm)	831	32	$T_{1.5}$	40.7	35	~4.9 (non gaussian peaks)	tbd	tbd
Pt/Ketjen (7.1 nm)	831	32	T_2	40.2	26	5.8	7.1	22
Pt/Carbon A	136	1	T_1	29.6	32	4.6	tbd	32
Pt/Carbon B	232	12	tbd	35 (nom)	tbd	tbd	tbd	tbd

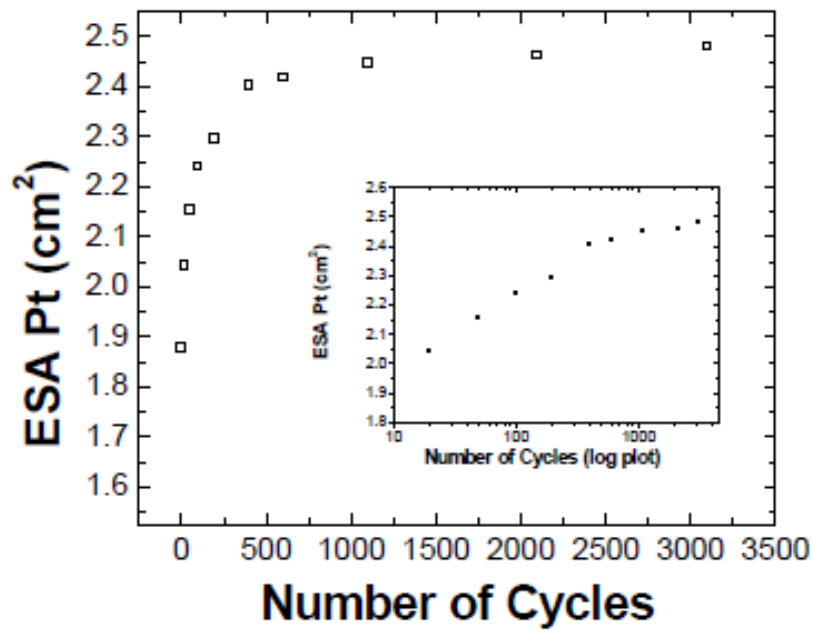
Pt/Carbon A (low corrosion rate carbon) and similar particle size and gas phase metal area to Pt/Ketjen 4.9 nm
Pt/Carbon B (intermediate corrosion rate carbon) to be annealed to target similar particle size

* wt % carbon calculated for carbon only electrode by integration of charge as described in JPS 171, 2007, 18.

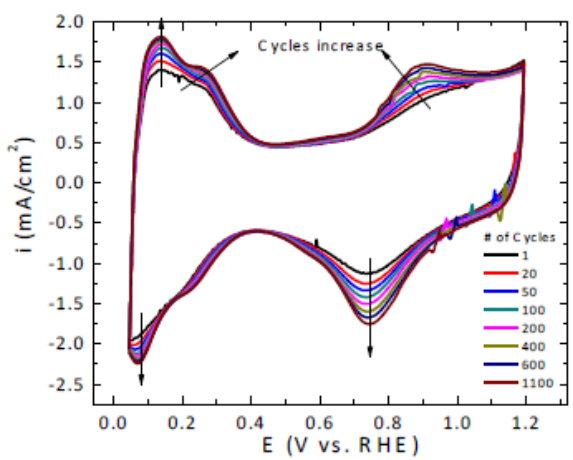
Technical Progress (Task 3)

Rotating-disk electrode measurements of Pt_3Sc/C ORR activity and stability





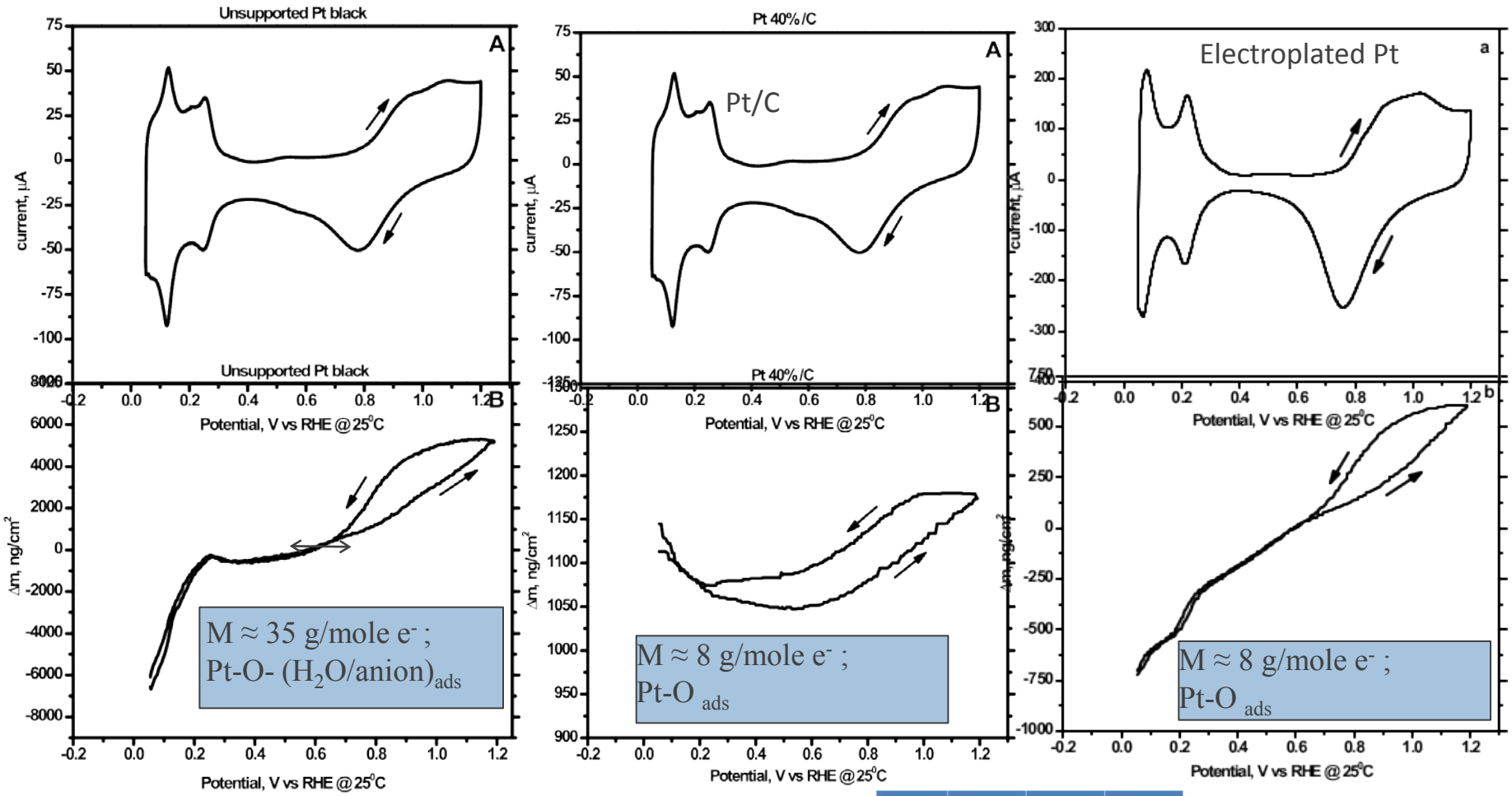
1600 rpm, 0.1 M $HClO_4$, room temp., 10 mV/s



Cycling protocol:
0.06 to 1.19 V,
0.1 M $HClO_4$,
room temp.,
40 ug Pt_3Sc/cm^2

Technical Progress (Task 3)

Electrochemical quartz crystal microbalance studies of Pt oxidation/dissolution



0.5 M H_2SO_4; 50 mV/s

species	g/mole	e-	g/e- mol
O	16	2	8
O2	32	1	32
OH	17	1 or 2	17 or 8.5
$(OH)_2$	34	2	17 or 8.5
(O_2H)	33	1	33
OH_2	18	1 or 2	18/9

MEYERS research group

Technical Progress (Task 5)

Components of mathematical model at UT-Austin

	Model	Model components
i	Anodic film formation-direct deposition	Charge transfer, chemical reaction
ii	Anodic film formation-direct deposition	Charge transfer, chemical reaction
iii	Anodic film formation-dissolution precipitation	Charge transfer, chemical reaction (precipitation), film resistivity, diffusion
iv	Film growth – solid state diffusion	Charge transfer, chemical reaction, solid state diffusion
v	Film growth – place exchange	Charge transfer, place exchange
vi	Film growth – surface roughening	Charge transfer, irreversible place exchange
vii	Film growth – ionic migration	High field growth

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