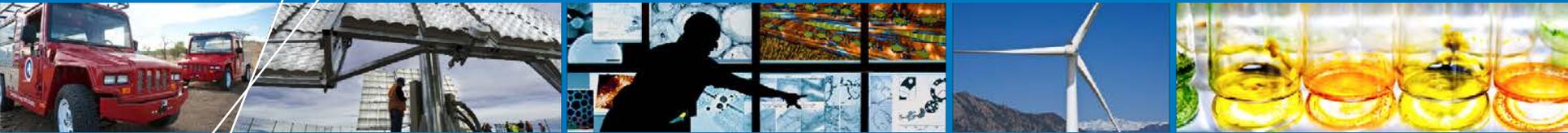# Extended, Continuous Pt Nanostructures in Thick, Dispersed Electrodes

2015 DOE Hydrogen and Fuel Cells Program Review

Bryan Pivovar (PI)

June 9, 2015

FC007

Overview

Timeline
- Start: July 2009
- End: September 2015
- % complete: ~95%

Budget ($K)

DOE Cost Share	Recipient Cost Share	TOTAL
9,816	868	10,684

Budget ($K)	
FY 2014	782
FY 2015	650

Barriers

A. Durability
B. Cost
C. Performance

Partners – Principle Investigators

Oak Ridge National Laboratory (ORNL) – Dave Cullen

University of Delaware (Delaware) – Yushan Yan

Colorado School of Mines (CSM) – Dave Diercks, Svitlana Pylypenko

Tanaka Kikinzoku Kogyo (TKK) – Fumiaki Ogura

GM – Anusorn Kongkanand

Past project collaboration denoted in gray – not included in FY 15 work scope to date.
Current (year) collaboration denoted in black

Relevance
ETFECS/Dispersed Electrodes

<u>Review Period Objectives:</u>

- **Pt catalysis remains a primary limitation for fuel cells. We have pursued synthesis of novel <u>e</u>xtended <u>t</u>hin <u>f</u>ilm <u>e</u>lectro<u>c</u>atalyst <u>s</u>tructures (ETFECS) for improved cost, performance, and durability.**

- **Incorporation of ETFECS to meet DOE MEAs targets for fuel cell performance and durability.**

Table 3.4.13 Technical Targets: Electrocatalysts for Transportation Applications				
Characteristic	**Units**	**2011 Status**	**Targets**	
			2017	**2020**
Platinum group metal total content (both electrodes)[a]	g / kW (rated)	0.19[b]	0.125	0.125
Platinum group metal (pgm) total loading[a]	mg PGM / cm^2 electrode area	0.15[b]	0.125	0.125
Loss in initial catalytic activity[c]	% mass activity loss	48[b]	<40	<40
Electro catalyst support stability[d]	% mass activity loss	<10[b]	<10	<10
Mass activity[e]	A / mg Pt @ 900 $mV_{iR\text{-free}}$	0.24[b]	0.44	0.44

[a] PGM content and loading targets may have to be lower to achieve system cost targets.

[b] M. Debe, U.S. Department of Energy Hydrogen and Fuel Cells Program 2011 Annual Merit Review Proceedings, May, 2011, (http://www.hydrogen.energy.gov/pdfs/review11/fc001_debe_2011_o.pdf)

[c] Durability measured in a 25-50 cm^2 MEA during triangle sweep cycles at 50 mV/s between 0.6 V and 1.0 V at 80°C, atmospheric pressure, 100% relative humidity, H_2 at 200 sccm and N_2 at 75 sccm for a 50 cm^2 cell. Based on U.S. DRIVE Fuel Cell Tech Team Cell Component Accelerated Stress Test and Polarization Curve Protocols (http://www.uscar.org/commands/files_download.php?files_id=267), Electrocatalyst Cycle and Metrics (Table 1). Activity loss is based on loss of mass activity, using initial catalyst mass, at end of test.

[d] Durability measured in a 25-50 cm^2 MEA during a hold at 1.2 V in H_2/N_2 at 80°C, 150 kPa absolute, 100% relative humidity. Based on U.S. DRIVE Fuel Cell Tech Team Cell Component Accelerated Stress Test and Polarization Curve Protocols (http://www.uscar.org/commands/files_download.php?files_id=267), Catalyst Support Cycle and Metrics (Table 2). Activity loss is based on loss of mass activity, using initial catalyst mass, at end of test.

[e] Test at 80°C H_2/O_2 in MEA; fully humidified with total outlet pressure of 150 KPa; anode stoichiometry 2; cathode stoichiometry 9.5 (as per Gasteiger et al. Applied Catalysis B: Environmental, 56 (2005) 9-35).

Approach
Extended Thin Film Electrocatalyst Structures (ETFECS)/ Electrodes

Extended surface catalyst as most promising approach to meeting catalyst targets.

Current focus is on Pt/Co and Pt/Ni nanowires, due to demonstrated performance. Focus on post-processing (annealing and acid leaching) and ALD synthesis.
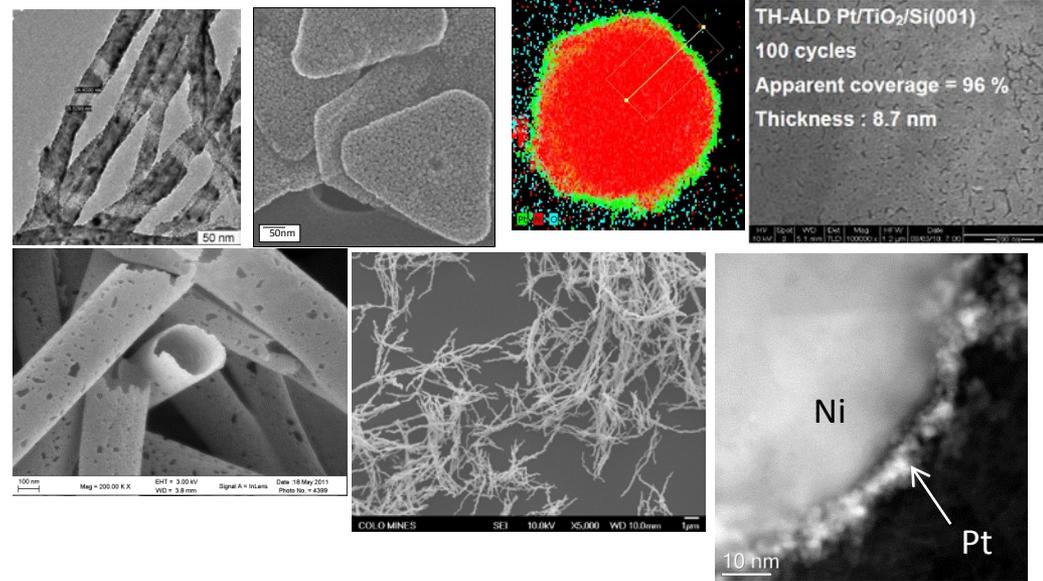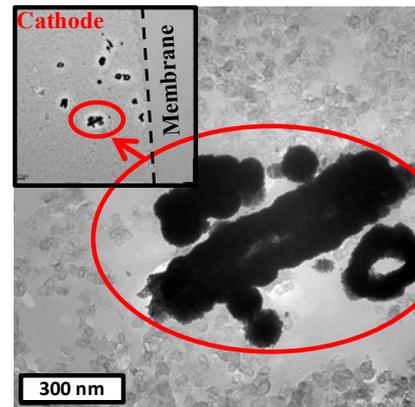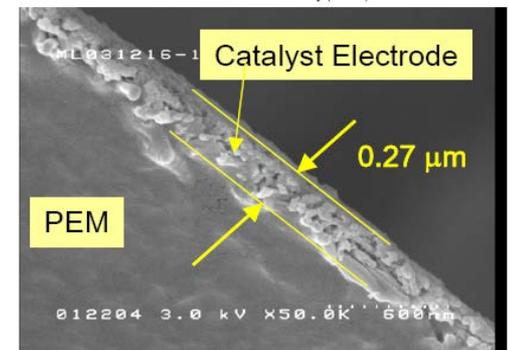

Efforts to translate catalytic improvements demonstrated in RDE studies over to fuel cells.

Multiple catalysts tested in MEAs.
Multiple fabrication techniques, operating conditions, and compositions investigated. (optimization studies)

NREL ETFECS

3M NSTF

http://www.hydrogen.energy.gov/pdfs/review04/fc_4_debe.pdf

Approach
Project Milestones

Qtr	Due Date	Type	Milestones, Deliverables, or Go/No-Go Decision	Status
Q3	6/30/2014	Go/No-Go	Validate annealing as a potential route for improved mass activity and/or durability (No go if mass activity gain is less than 10% of unannealed samples and durability gain is less than 25% compared to unannealled samples.)	**Go Decision**
Q4	9/30/2014	Stretch	Demonstrate fuel cell performance using novel electrocatalysts of 0.44 A/mg Pt @900 mV (IR free) (DOE 2020 Target).	**Unmet (stretch milestone)**

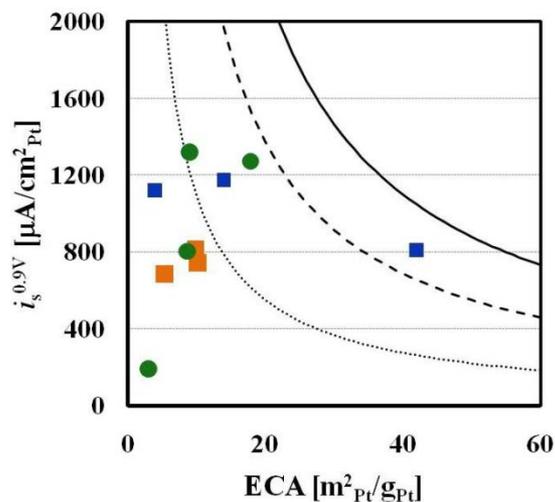| Qtr	Due Date	Type	Milestones, Deliverables, or Go/No-Go Decision	Status
Q2	3/31/2015	Annual Milestone (Regular)	Using pre-leaching on top performing novel electrocatalysts to reduce transition metal dissolution impact on durability, demonstrate a mass activity of 880 mA mgPt^{-1} at 0.9V (2x DOE 2020 Target) and less than a 5% loss after durability testing (30k cycles, mass activity) in RDE tests with a total transition metal dissolution of less than 1% of initial catalyst mass (current high performance materials experience dissolution rates up to 7 mass% under these conditions).	**Complete**
Q3	6/30/2015	Annual Milestone (Stretch)	Aligned with DOE's 2020 targets, 1,000 mW/cm^2 at rated power and less than 40% loss in catalytic activity, develop MEAs with 100% improvement in initial mass activity when compared to baseline Pt/C catalysts at rated power (5 A/mgPt at 0.75V IR corrected) using novel electrocatalysts. Demonstrate less than 40% loss of mass activity at rated power (0.75 V IR free) 80°C, 100% RH after 30,000 potential cycles between 0.6 and 1.0V at 500mV/s.	**On track**

Accomplishments and Progress
Responses to Previous Year (2014 AMR) Reviewer's Comments

- **Reviewer Comment:** It is still unclear if it is real to make both durable and highly active Pt-coated Ni nanowires. Ni nanowires are not stable when partially coated with Pt, and they are not very durable while fully coated with Pt.

- **Reviewer Comment:** The study on the oxide layer does provide good insights into the effect of oxidation of the catalyst. However, this was not the best area on which to focus the resources of last year. The effects of oxide layers on catalysts are relatively well known in the literature. They do provide protection for the non-oxidized part of the catalyst, but they are temporary layers that get dissolved again during low potentials.

- **Response:** Multiple comments addressed our prior year's work investigating an oxide layer and the value of this effort, and concerns about obtaining durable catalysts with high mass activity. This year's presentation contains current year results where both highly active and highly durable materials have been demonstrated. For our current, best of class materials, an O_2 annealing step, has been a critical post-processing step to increase durability and activity. It is unlikely we would have gained the insight of the potential importance and benefit of such a step without these past oxide studies.

- **Reviewer Comment:** The approach certainly has its merits, because it focuses on increasing available active sites on the catalyst. However, it is not clear how this would help reduce degradation, which is currently the main problem with catalysts…does not provide certainty that the catalyst will be durable in an MEA under automotive conditions (e.g., including start-up/shutdown cycles).

- **Response:** This comment suggests an activity connection only between ECA and durability, where extended surface materials can also have significant deviation from nanoparticle based materials even at high ECA due to a reduction in low coordination sites, and to the potentially reduced impact of dissolution/re-precipitation and agglomeration in extended surface catalysts. We have investigated durability for both Pt/dissolution and start/stop conditions and found advantages of our extended surface catalysts in both cases.

- **Reviewer Comment:** One critical point is that progress toward developing high-activity MEA electrodes is not nearly as advanced and remains a key barrier.

- **Response:** Agreed. Materials demonstrated/developed prior to this year didn't have intrinsic properties of both high activity and high durability. This made studying this area and progress more difficult. It remains a key challenge for taking advantage of these highly promising materials.
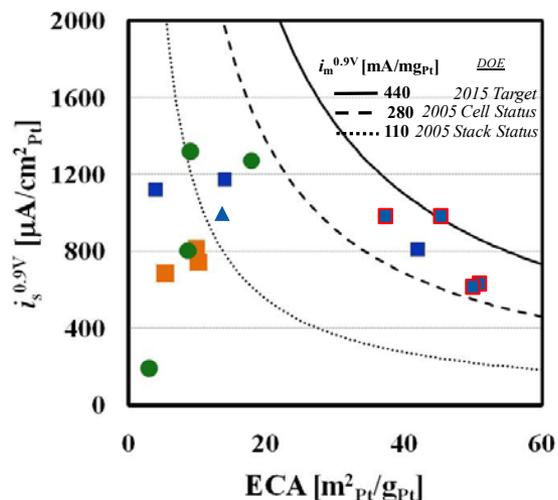
Accomplishments and Progress
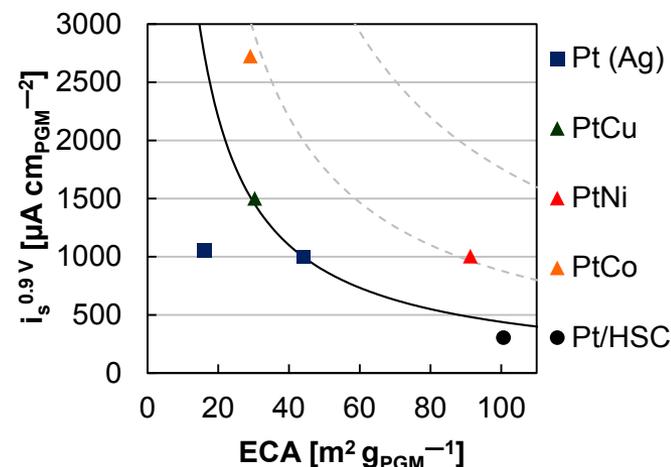## Achieving high mass activity – Galvanic displacement (2014 AMR)

2011

2012

DOE legend:
$i_m^{0.9V}$ [mA/mg$_{Pt}$]
- 440 — *2015 Target*
- 280 --- *2005 Cell Status*
- 110 ···· *2005 Stack Status*

2013

Legend: ■ Pt (Ag), ▲ PtCu, ▲ PtNi, ▲ PtCo, ● Pt/HSC

2014

Legend: ■ Pt (Ag), ▲ PtCu, ▲ PtNi, ▲ PtCo, ▲ NG PtNW, ● Pt/HSC

DOE Target; 4x; 2x

Electrochemically available surface area (ECA) has been limited in extended surface materials to low values (~10m²/g Pt), we have reach (~90m²/gPt comparable to Pt/C)

Our efforts have seen consistent increases in both ECA and specific activity (i$_s$).

We have recently achieved both high ECA and i$_s$ (resulting in exceptionally high mass activity, ~5x DOE 2020 MEA target in RDE test). 2014 materials exhibited durability concerns related to transition metal ion leaching.
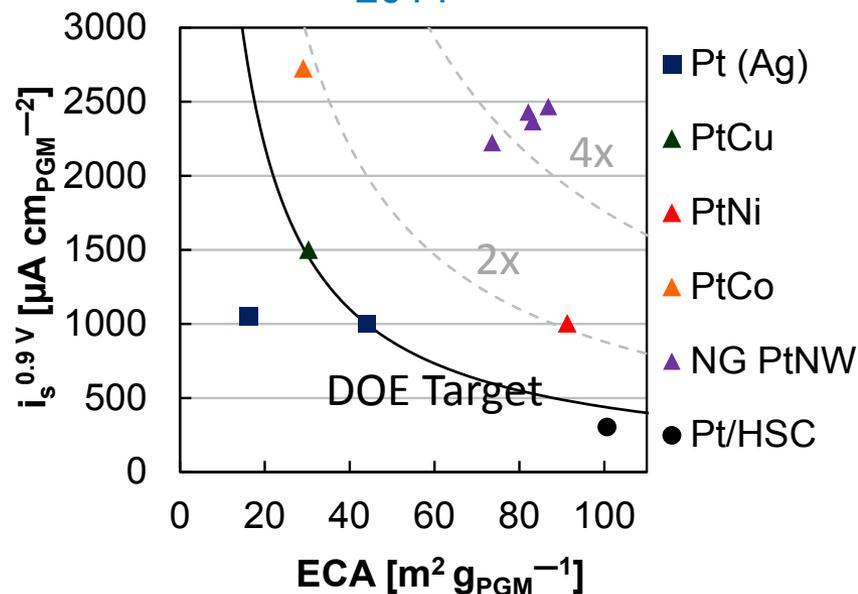
Accomplishments and Progress

Optimizing H$_2$ annealing for mass activity
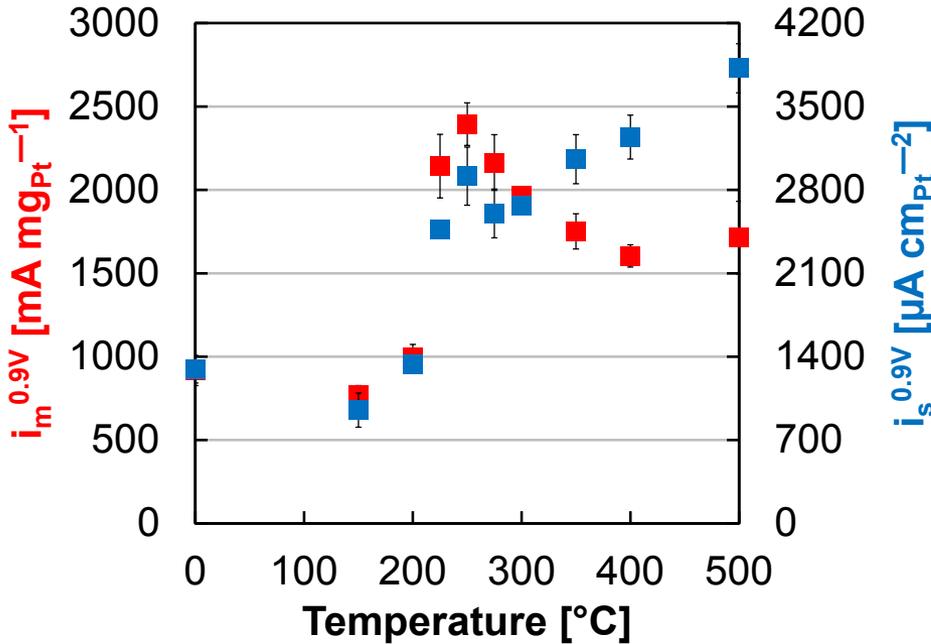
Annealing in a reducing atmosphere (H$_2$) was investigated/optimized to promote alloying thereby increasing activity.

Specific activity increased with increasing temperature. Mass activity peaked at 250°C, as Pt surface area (ECA) dropped above 250°C.
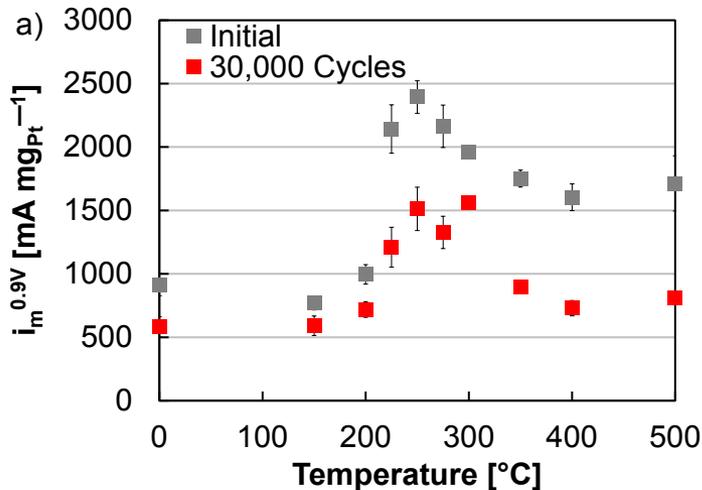
Highly performing samples showed durability losses following potential cycling (RDE, 30k cycles, 0.6-1.0V, 500 mV s^{-1}).
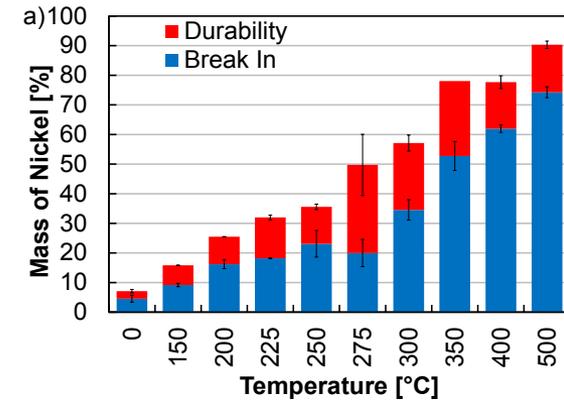
Ni dissolution rates increased with increasing annealing temperatures.

Highly active samples show poor durability, durable samples show lower activity.

Accomplishments and Progress

Addressing durability concerns of transition metal ion contamination

250°C H$_2$ anneal followed by O$_2$ anneal
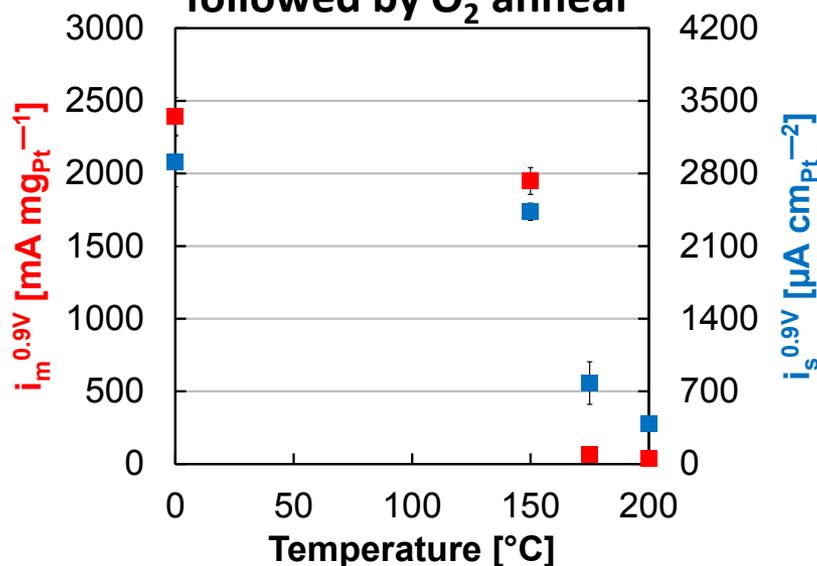
Multiple approaches/steps investigated, focus on annealing (oxidizing and/or reducing conditions) and acid leaching, efforts build on work presented previously.

O$_2$ anneal resulted in major losses in performance when applied above 150°C.
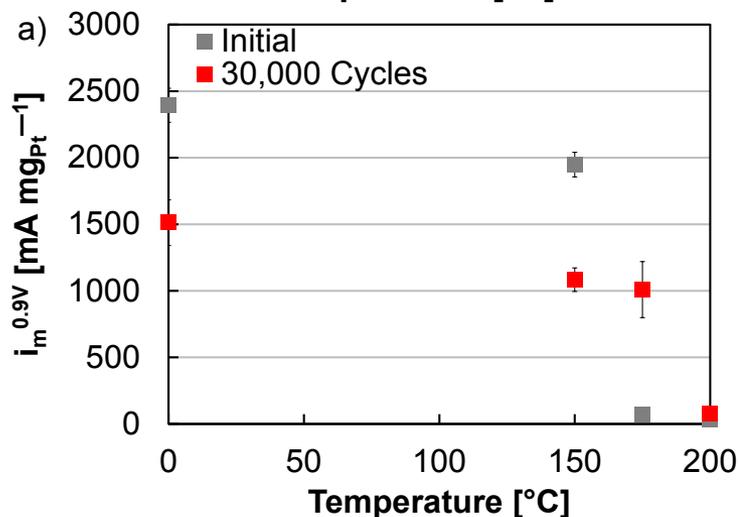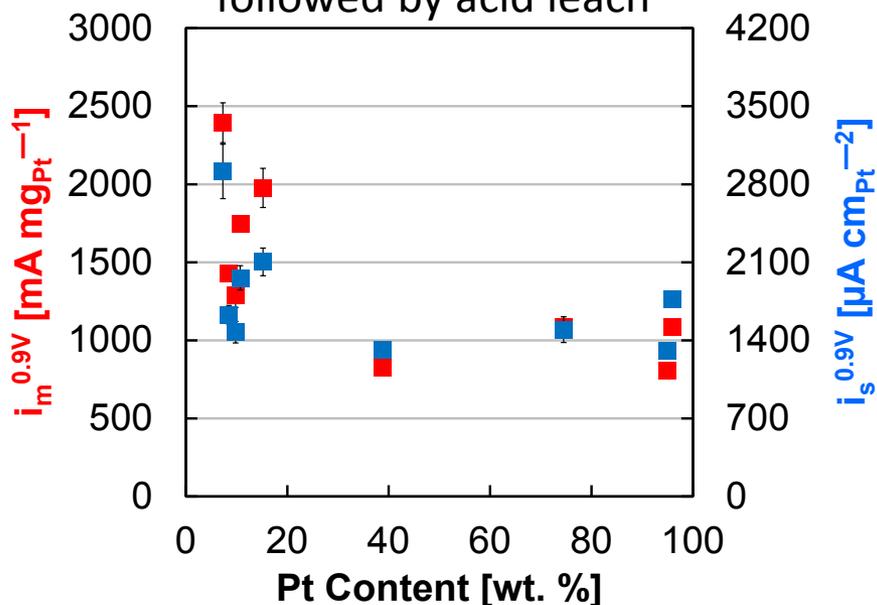
At 175°C performance improved significantly post cycling.
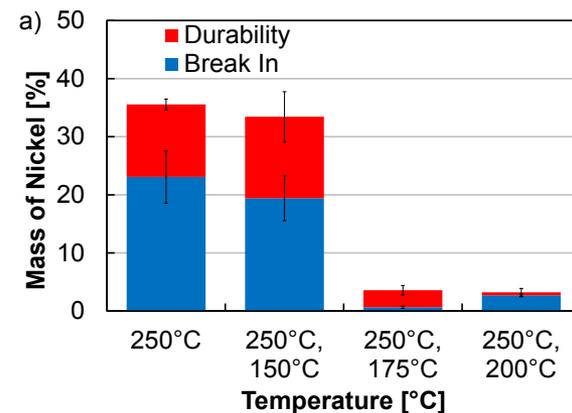
Ni dissolution rates decreased substantially above 150°C.

Highly active samples show poor durability, durable samples show lower activity.

Accomplishments and Progress

Addressing (Improving) durability concerns of transition metal ion contamination

250°C H_2 anneal followed by acid leach

Acids of different types, concentrations, and exposure times were used to pre-leach transition metal (Ni^+) ions from catalysts.

Decreasing performance (primarily due to specific activity loss) found as increasing leaching strength (increased Pt wt%)
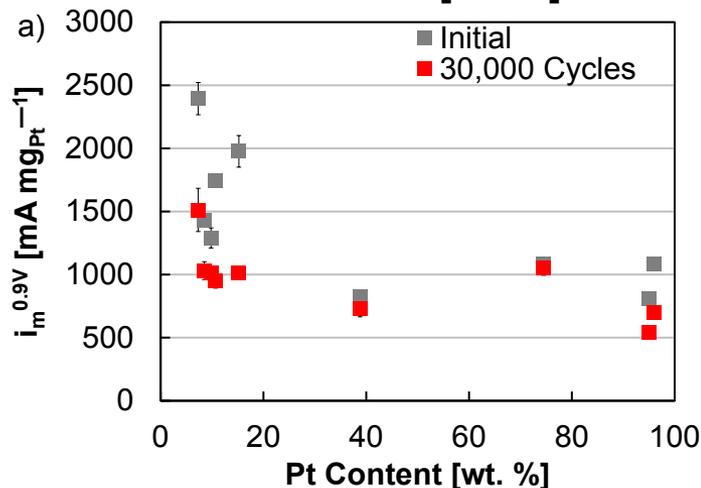
Durability improved for samples with increased Pt wt%.

a) Initial / 30,000 Cycles
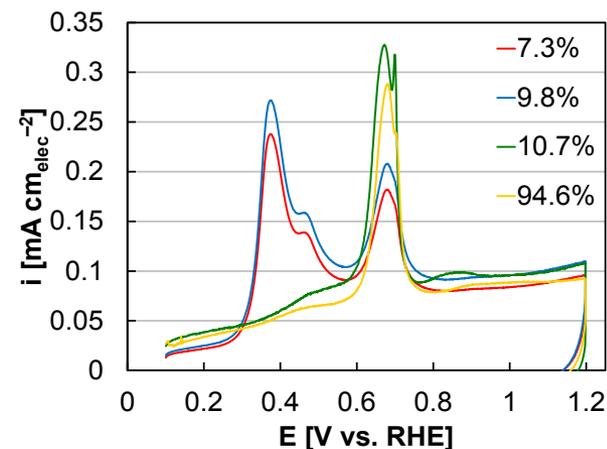
Below 10 wt% Pt, CO stripping shows presence of surface Ni.

Highly active samples show poor durability, durable samples show lower activity.

Accomplishments and Progress
Addressing (Improving) durability concerns of transition metal ion contamination

H$_2$ anneal, acid leach followed by O$_2$ anneal

a)
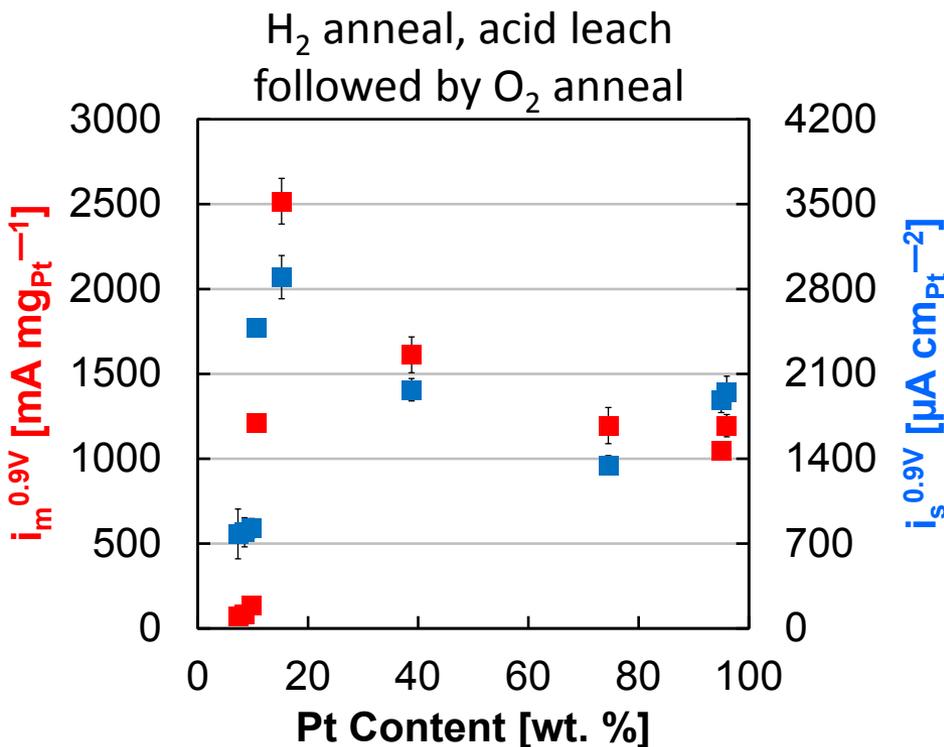
O$_2$ annealing was applied to acid leached samples to explore durability improvements.

O$_2$ annealing post-acid leaching resulted in high mass activity samples at higher Pt wt%. Ni contamination reduced at higher Pt content.
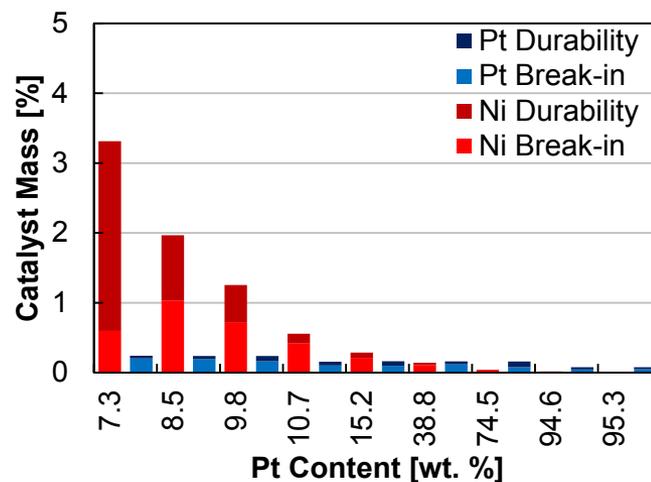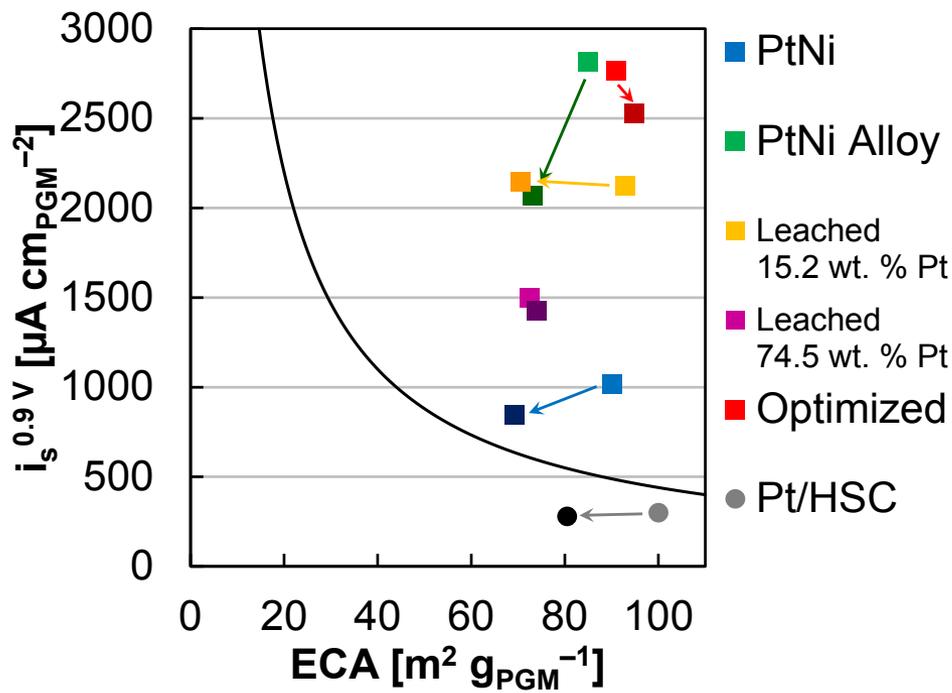
Exceptional durability demonstrated for potential cycling.

Above 10 wt% Pt, metal dissolution rates are very low.
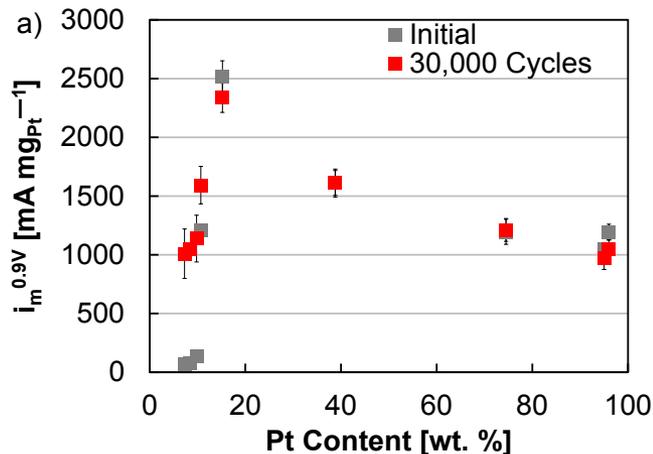
Highly active samples also show high durability !!!

Accomplishments and Progress
Galvanic displacement PtNiNW performance summary/comparison

Initial performance and performance after cycling shown for a series of different PtNiNW catalysts. Current generation materials show improved performance and durability.

Leached and optimized samples also show low losses of Pt and Ni through electrochemical tests and enabling MEA fabrication without transition metal leaching concerns.
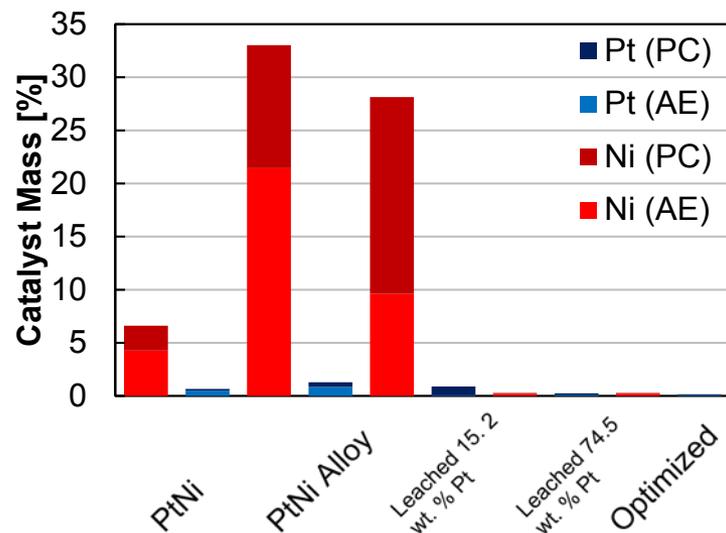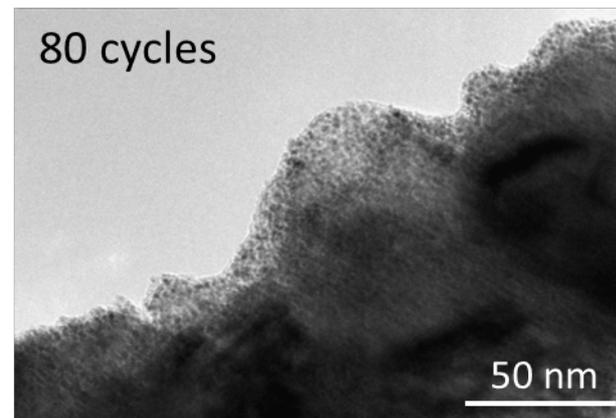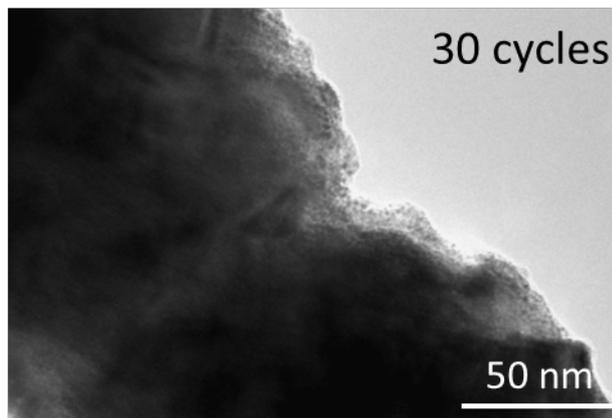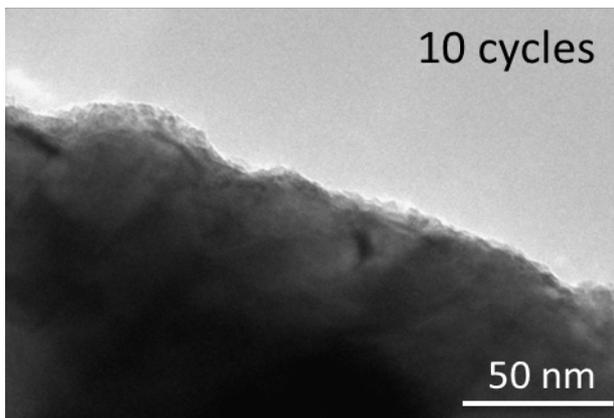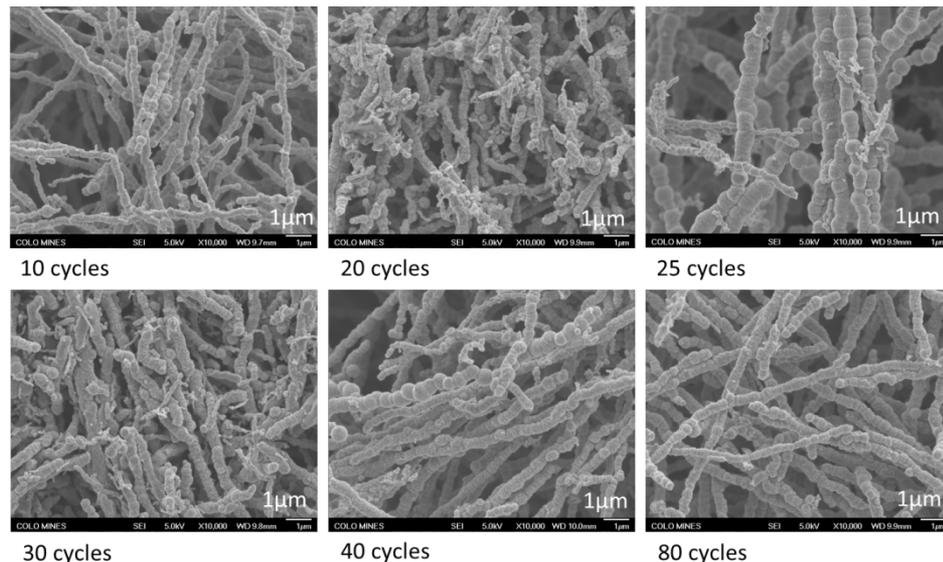
Accomplishments and Progress

Investigation of Atomic Layer Deposition (ALD) for Pt alloy NW synthesis

- **Batch sizes of several (perhaps 100's of) grams synthesized easily with our equipment**

- **Synthesis much quicker and easier**

- **Higher reproducibility expected**

- **Target structures and processing steps already optimized by galvanic displacement**

- **Have investigated ALD reaction conditions for O_2 exposure and subsequent H_2 annealing of materials.**

Morphologies and structures obtained similar to galvanic displacement and uncoated Ni NWs.

10 cycles   20 cycles   25 cycles

30 cycles   40 cycles   80 cycles

10 cycles   30 cycles   80 cycles
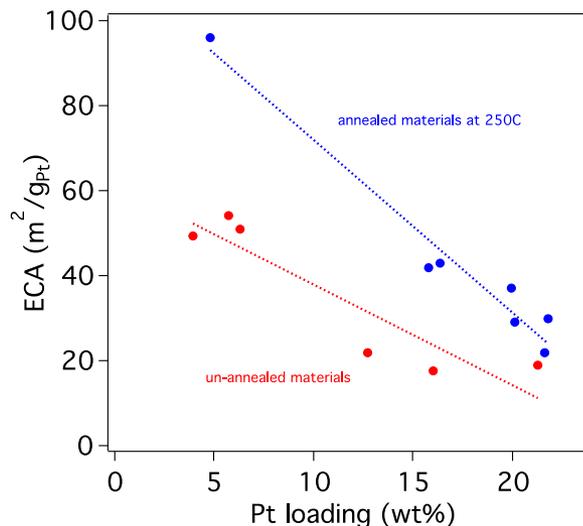
50 nm   50 nm   50 nm

Accomplishments and Progress
Investigation of Atomic Layer Deposition (ALD) for Pt alloy NW synthesis
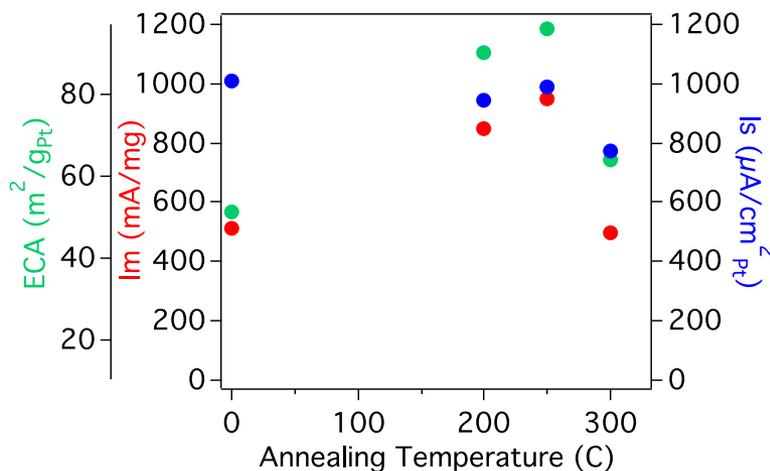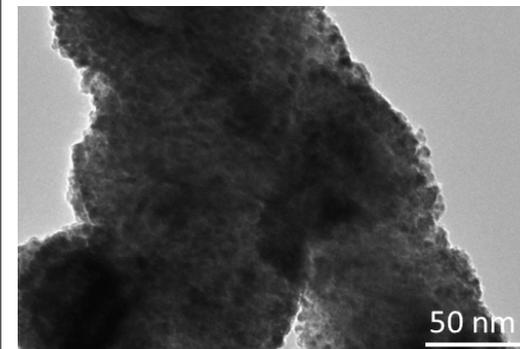

Annealing temperature of 250°C found to be optimal in limited temperature study, consistent with galvanically displaced samples.
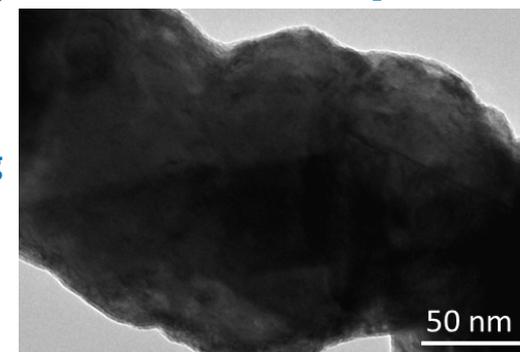

H₂ annealing found to dramatically increase surface area (ECA), >90 m²/g Pt achieved.

Pt on Ni – 60 ALD cycles

Pt on Ni – 60 ALD cycles H₂ annealed

Current approach (non-agitated samples) has resulted in intra- and inter-batch heterogeneity.
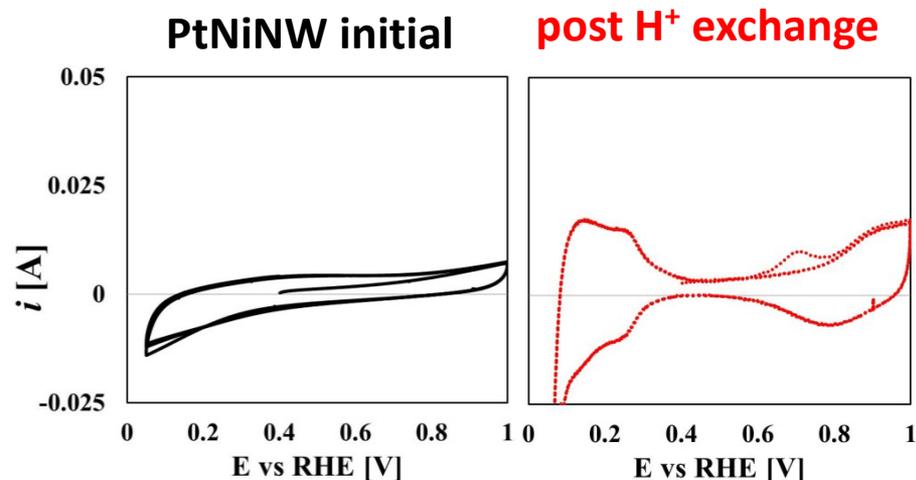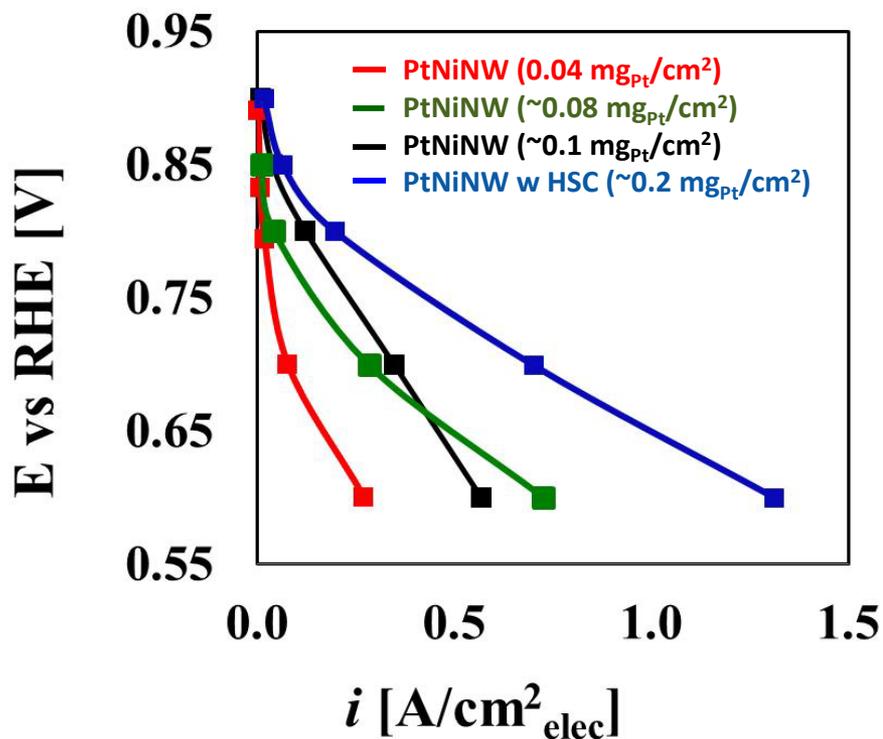
80 cycles -4 different batches

Is ($\mu A/cm^2_{Pt}$)	Im (mA/mg_{Pt})	ECA (m^2/g_{Pt})
2134	879	41
1921	426	22
1549	444	29
1814	663	37

Annealing found to smoothen surface (decrease roughness), but also resulted in increased Pt ECA.

High ECAs obtained, specific activity still lower than galvanic displacement.

PtNiNW initial   **post H⁺ exchange**

Legend:
- PtNiNW (0.04 mg_{Pt}/cm^2)
- PtNiNW (~0.08 mg_{Pt}/cm^2)
- PtNiNW (~0.1 mg_{Pt}/cm^2)
- PtNiNW w HSC (~0.2 mg_{Pt}/cm^2)

Transition metal ion leaching was a problem for this generation of materials and required an acid wash step after MEA fabrication to remove nickel ion contamination from the MEA.

Successive tests of related materials yielded continuous improvements in performance as we have improved our MEA fabrication techniques and optimized compositions.
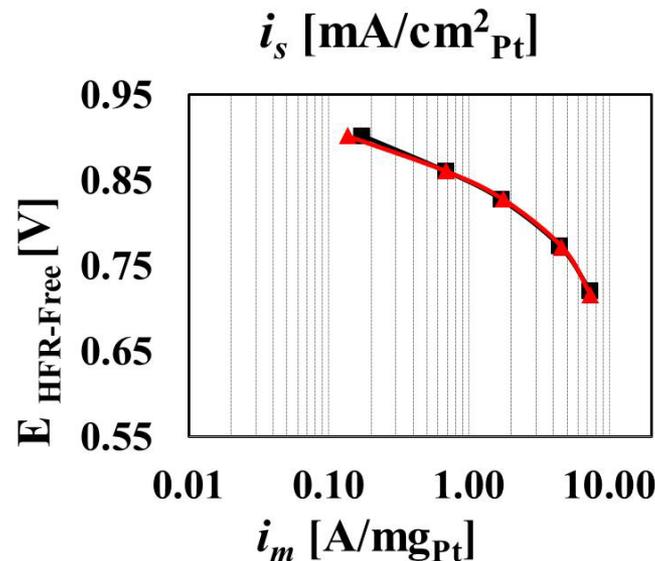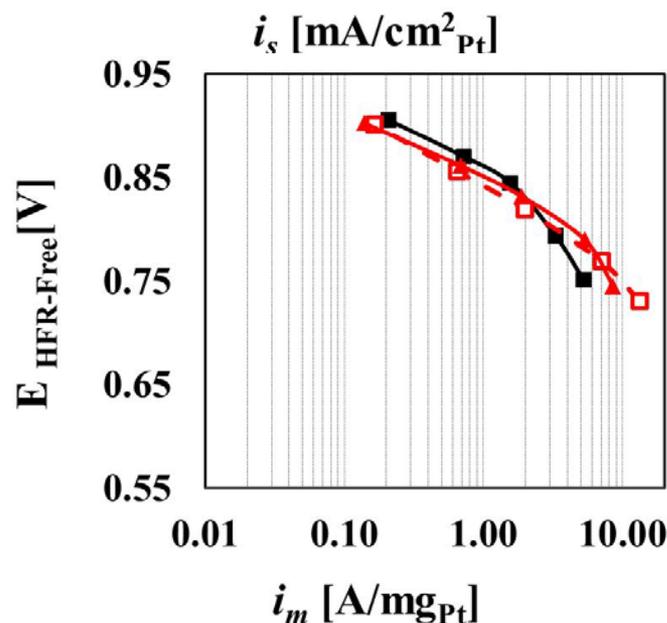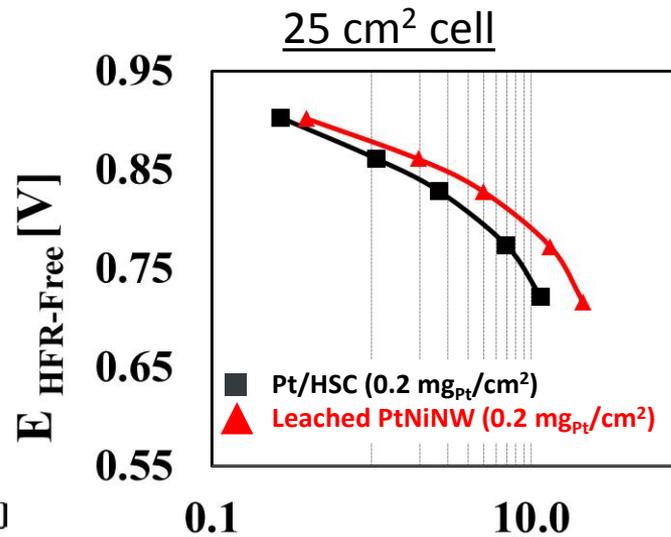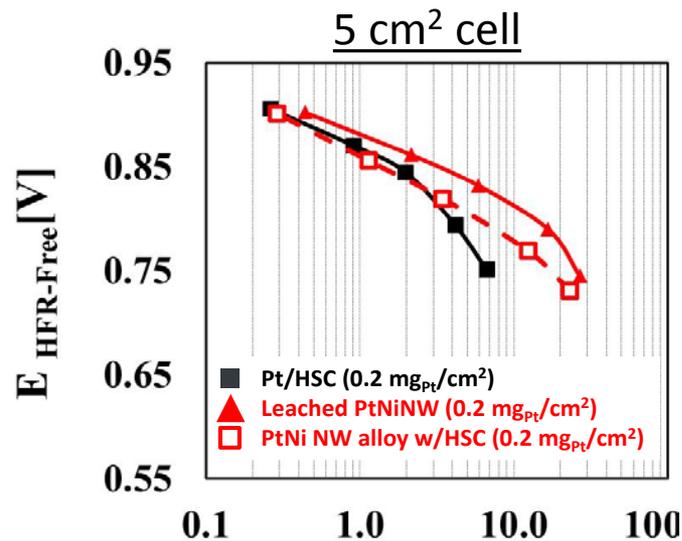
Accomplishments and Progress

ETFECS fuel cell performance

5 cm² cell

Pt/HSC (0.2 mg$_{Pt}$/cm²)
Leached PtNiNW (0.2 mg$_{Pt}$/cm²)
PtNi NW alloy w/HSC (0.2 mg$_{Pt}$/cm²)

25 cm² cell

Pt/HSC (0.2 mg$_{Pt}$/cm²)
Leached PtNiNW (0.2 mg$_{Pt}$/cm²)

MEA performance of PtNiNWs showed similar performance and higher specific activity when compared to Pt/C baseline MEAs. Leached PtNiNWs did not require an acid wash step and was demonstrated in 5 and 25 cm² cells.
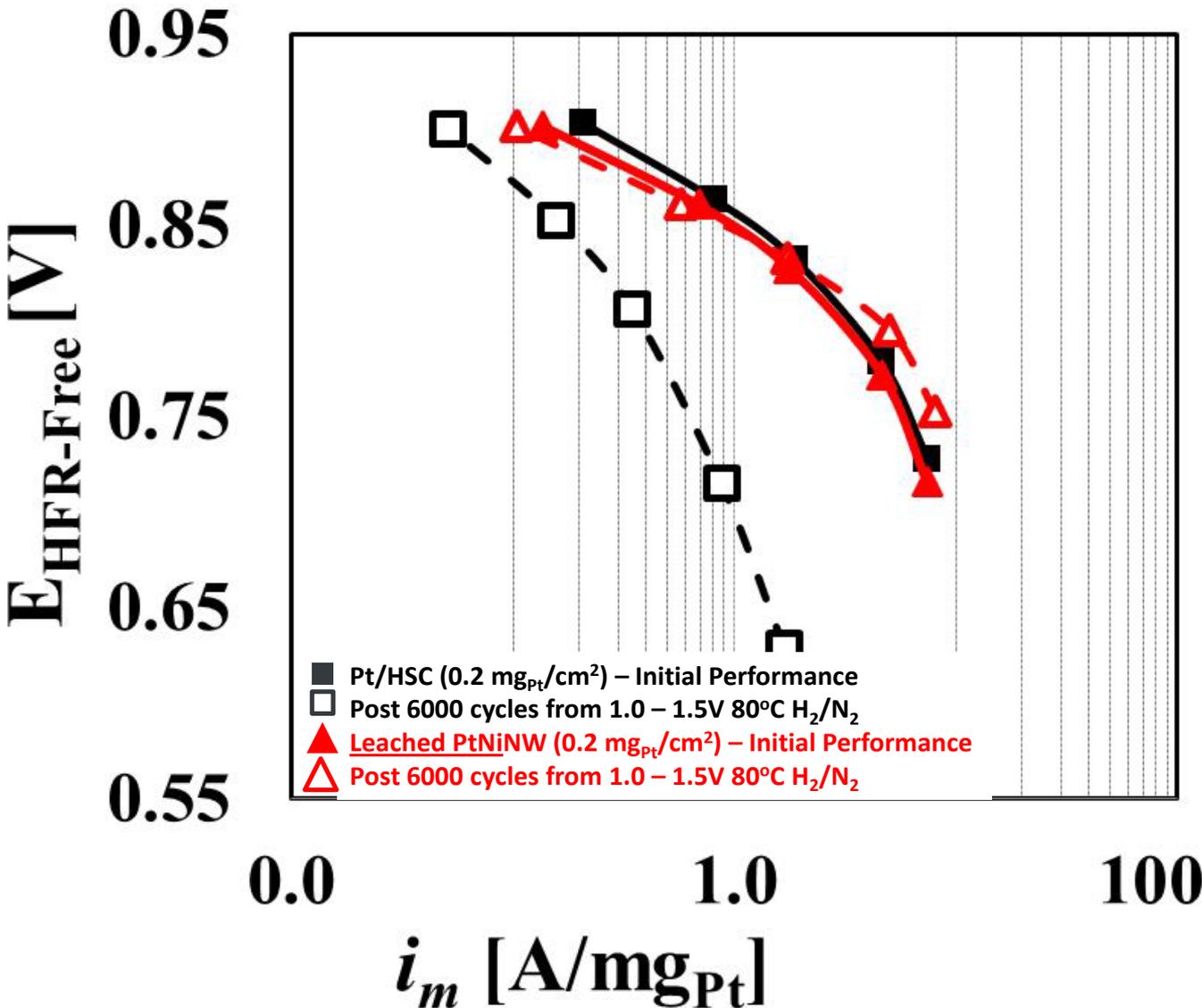
Determination of optimum synthesis conditions had limited MEA tests. Optimized catalyst scaled up and focus of current tests.

5 cm² single serp. 80°C 100% RH 150 kPa H$_2$/O$_2$ Constant E, 15 min per point
25 cm² triple serp. 80°C 100% RH 150 kPa H$_2$/O$_2$ constant E, 15 min per point

Accomplishments and Progress
ETFECS fuel cell durability

Pt/HSC (0.2 mg_{Pt}/cm^2) – Initial Performance
Post 6000 cycles from 1.0 – 1.5V 80°C H_2/N_2
Leached PtNiNW (0.2 mg_{Pt}/cm^2) – Initial Performance
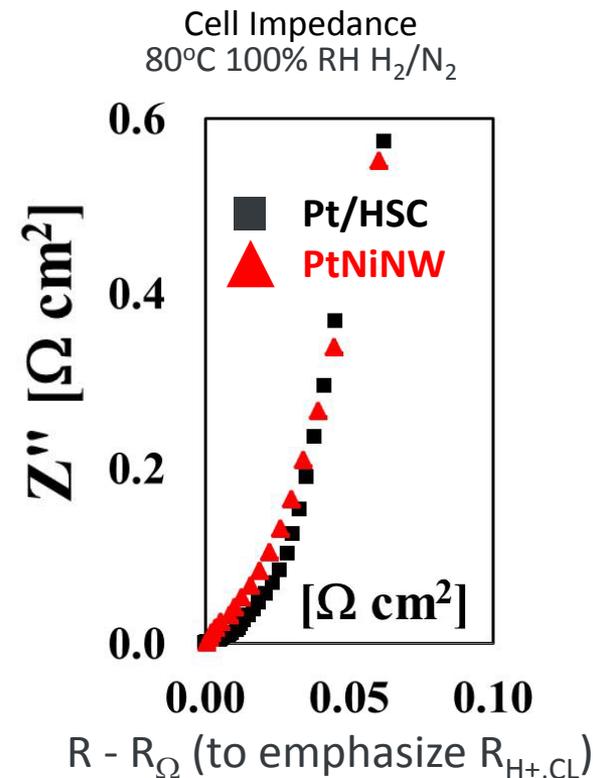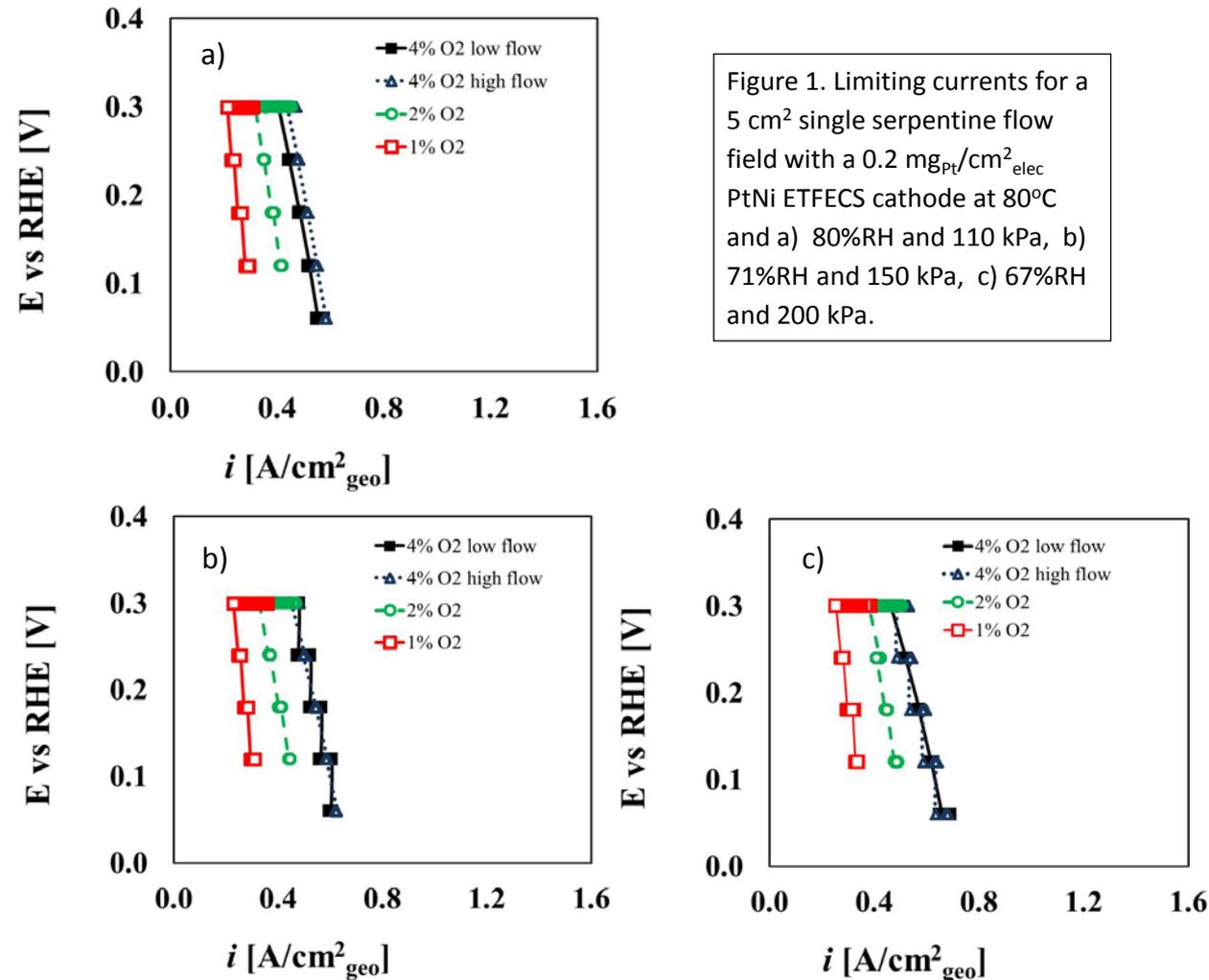**Post 6000 cycles from 1.0 – 1.5V 80°C H_2/N_2**

PtNiNWs show greatly improved stability compared to Pt/C when studied with potential cycling between 1-1.5V.

Results not particularly surprising due to the absence of carbon in the PtNiNW samples.

25 cm_2 triple serp. 80°C 100% RH 150 kPa H_2/O_2 constant E, 15 min per point

Fuel cell diagnostics oxygen limiting current experiments and impedance

a)

- 4% O2 low flow
- 4% O2 high flow
- 2% O2
- 1% O2

Figure 1. Limiting currents for a 5 cm² single serpentine flow field with a 0.2 mg_{Pt}/cm^2_{elec} PtNi ETFECS cathode at 80°C and a) 80%RH and 110 kPa, b) 71%RH and 150 kPa, c) 67%RH and 200 kPa.

Cell Impedance
80°C 100% RH H_2/N_2

Pt/HSC
PtNiNW

$[\Omega \, cm^2]$

R - R_Ω (to emphasize $R_{H+,CL}$)

b)

- 4% O2 low flow
- 4% O2 high flow
- 2% O2
- 1% O2

c)

- 4% O2 low flow
- 4% O2 high flow
- 2% O2
- 1% O2

Cell impedance has been used to determine H^+ resistance of the catalyst layer ($R_{H+,CL}$) inside of PtNiNW electrodes and compare this to Pt/C electrodes. For the cases shown 12 μm Pt/C electrodes (30 wt% Nafion) shows similar $R_{H+,CL}$ to 2 μm PtNiNW electrodes (10 wt% Nafion). , tradeoff between thickness and ionomer content. Further PtNiNW studies are underway.

Oxygen limiting current measurements have been made on PtNiNWs. This data will be used to elucidate oxygen transport resistance local to the Pt surface. It will be investigated as a function of electrode fabrication conditions (ionomer/catalyst ratio, loading, carbon loading), and compared to Pt/C results to understand and minimize transport resistance.

Accomplishments and Progress
Summary of MEA vs RDE results

Catalyst	MEA			RDE		
	ECA	$i_s^{0.9V}$	$i_m^{0.9V}$	ECA	$i_s^{0.9V}$	$i_m^{0.9V}$
	$[m^2_{Pt}/g_{Pt}]$	$[\mu A/cm^2_{Pt}]$	$[mA/mg_{Pt}]$	$[m^2_{Pt}/g_{Pt}]$	$[\mu A/cm^2_{Pt}]$	$[mA/mg_{Pt}]$
47 wt% Pt/HSC	83	263	216	100	275	275
Pt Black (decal)	21	270	56	22	800	176
PtCo [co-deposited]	14	1050	150	17	2200	370
PtCrCo [co-deposited]	21	550	115	26	1800	470
Pt-AAO template (Decal)	10	340	34	8	1250	100
Pt-AAO template (Filter)	7	400	28			
PtNi (Filter)	55	76	41	56	1200	660
NGPtNW	57	290	165	69	2600	1800
NGPtNW (pre-leached)	45	440	200	69	1900	1300

MEA data versus RDE data show reasonable agreement between ECA values for all except NGPtNW (this electrode is much thicker than others 60 μm vs 10 μm). Specific activity values at 0.9V for transition metal containing samples show greater decreases in MEA values versus RDE than Pt only samples.

Collaborations

Institutions	Role
National Renewable Energy Laboratory (NREL): Bryan Pivovar (PI), Shaun Alia, KC Neyerlin, Katie Hurst, Jason Zack, Clay Macomber, Shyam Kocha	**Prime, Oversees the project, lead catalyst synthesis and characterization; lead electrode fabrication and fuel cell testing**
University of Delaware (Delaware): Yushan Yan, Jarrid Wittkopf	**Sub; Support work in catalyst synthesis by galvanic displacement**
Colorado School of Mines (CSM): Svitlana Pylypenko, Dave Diercks, Ami Neyerlin, Jeremy Leong	**Sub; Materials characterization using XPS and microscopy, electrospinning of polymers.**
General Motors LLC (GM): Anusorn Kongkanand	**In-kind partner; Consultation on transition metal impacts, fuel cell performance, and MEA fabrication**

Interactions: Related collaborative work with SLAC (Mike Toney) and Colorado University (Will Medlin)
Participation in the DOE catalysis working group
Past year(s) project participants have included LANL, CNSE, Stanford, Tennessee, NTCNA, Cabot.

Future Work/Remaining Challenges

Electrocatalyst synthesis:
- Focus on reproducibility/increased batch size.
  - Galvanic displacement to produce materials of target performance in increased quantity.
  - Further post-processing studies of ALD synthesized materials, use of rotary to improve intra- and inter- batch reproducibility.

Electrode structure/fuel cell studies:
- Optimization of electrode structure/fuel cell performance using ETFECS with a focus on catalyst ink dispersions and composition.
- Isolation of overpotential losses in MEA electrodes made with ETFECS materials (separation of mass transfer, ohmic, and kinetic losses).
- Durability studies to quantify performance loss with specific emphasis on transition metal leaching.

Summary

- **Relevance:** Focused on overcoming the cost, performance and durability barriers for fuel cell commercialization by increasing Pt mass activity and durability.

- **Approach:** Developing durable, high mass activity extended surface Pt catalysts , and optimize MEA performance/durability for these materials.

- **Accomplishments and Progress:** The project has demonstrated extended surface catalysts with remarkably high surface area and specific activity that offer the potential to dramatically decrease required Pt loadings through exceptionally high mass activities (**>2500 mA/mg Pt**). These materials have also demonstrated good durability under select (potential cycling, both RDE and MEA) conditions, including dramatically reduced transition metal dissolution rates. The project has advanced the performance of these materials in MEAs and demonstrated the need for further understanding and development in these areas.

- **Collaborations:** We have a diverse team of researchers including 2 universities, and 1 industrial participant.

- **Proposed Future Research:** Fuel cell efforts are focused on optimized electrode structures of complex catalysts.

Technical Backup Slides

Accomplishments and Progress

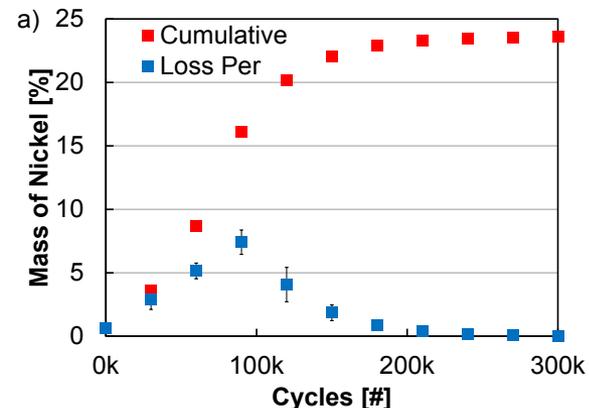**Addressing durability concerns of transition metal ion contamination**

250°C H_2 anneal followed by 175°C O_2 anneal

a)

b)
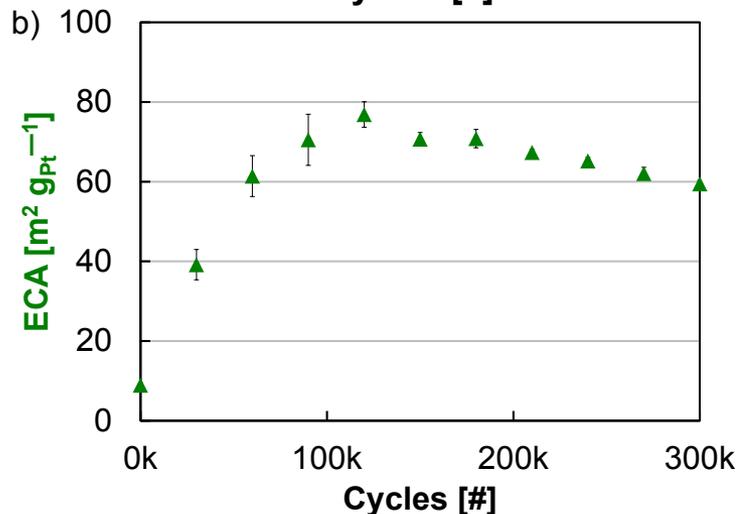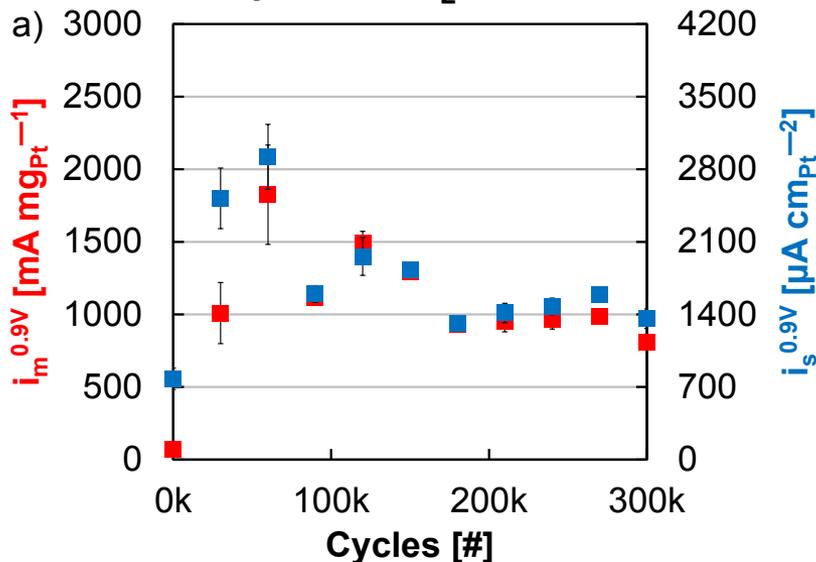
Extended durability (RDE) investigated to study recovery of previous high activity.

Specific activity and mass activity improve for this highly oxidized sample, presumably due to removal of Ni oxide species from the surface, up to 100k cycles.

a)

ECA shows initial increase with cycle number as well (RDE, 30k cycle experiments, 300k cycles in total, 0.6-1.0V, 500 mV s⁻¹).

Ni dissolution levels off after several successive durability tests.

Material reaches peak activity following 60k cycles, and is fairly stable above 200k cycles.

Accomplishments and Progress

Addressing durability concerns of transition metal ion contamination

Acid leach
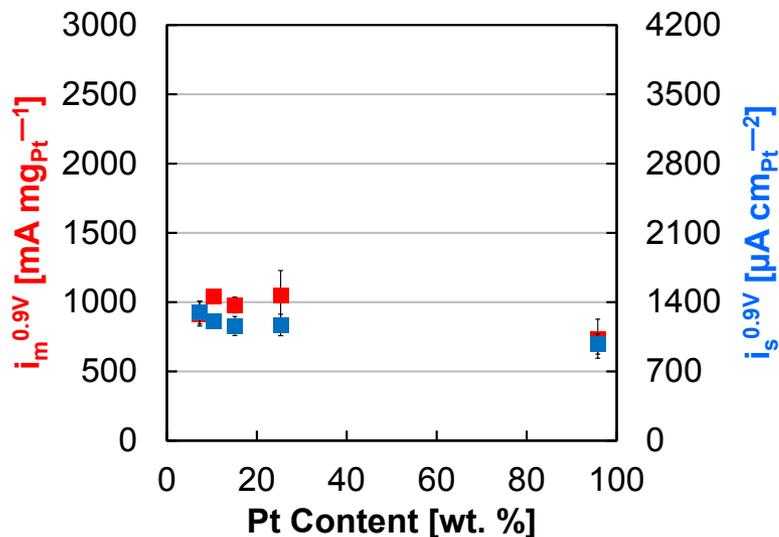
Acids of different types, concentrations, and exposure times were used to pre-leach transition metal (Ni^+) ions from catalysts.

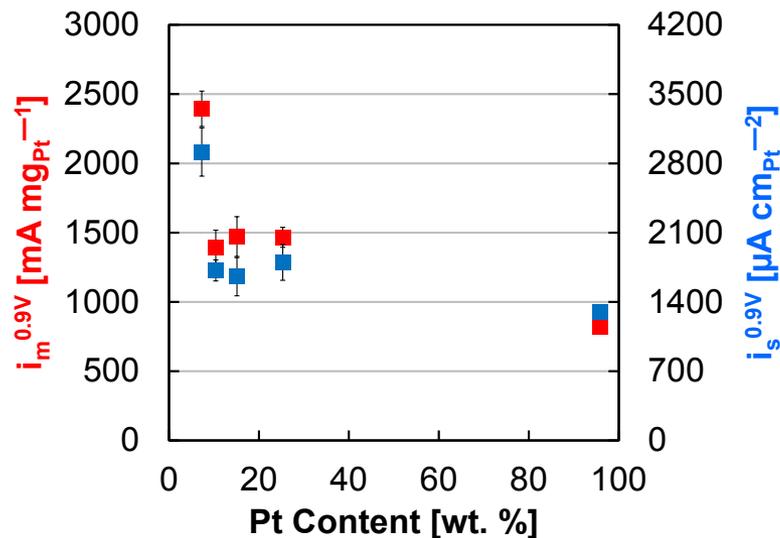Modest performance changes witnessed when only acid leaching was performed.
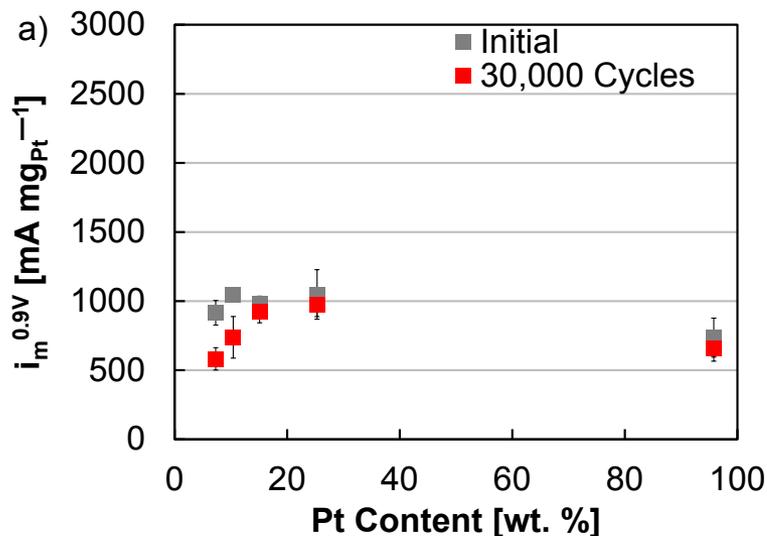
Low leaching levels showed slightly decreased durability results.

Sample activities consistent regardless of Ni content. Durability improved with Ni leaching.

Optimizing H$_2$ annealing for mass activity

Acid leach followed by 250°C H$_2$ anneal

Annealing in a reducing atmosphere (H$_2$) was investigated/optimized to promote alloying thereby increasing activity.
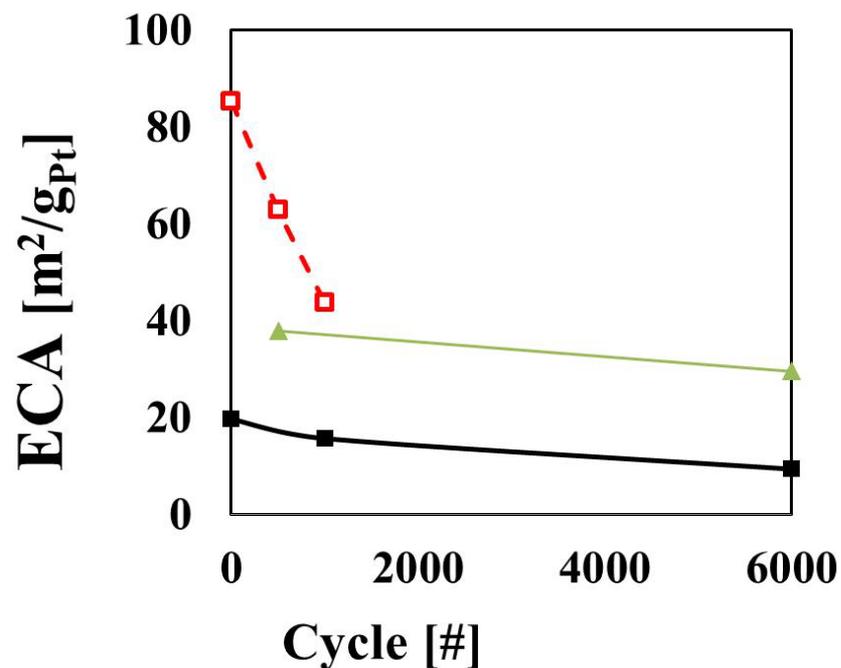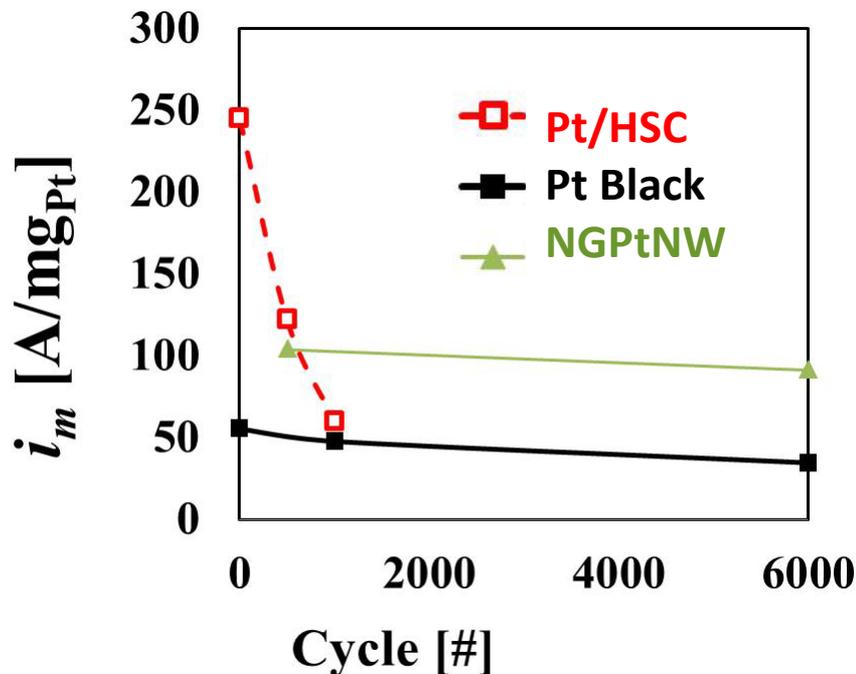

Pt lattice compression less severe at higher Pt content.
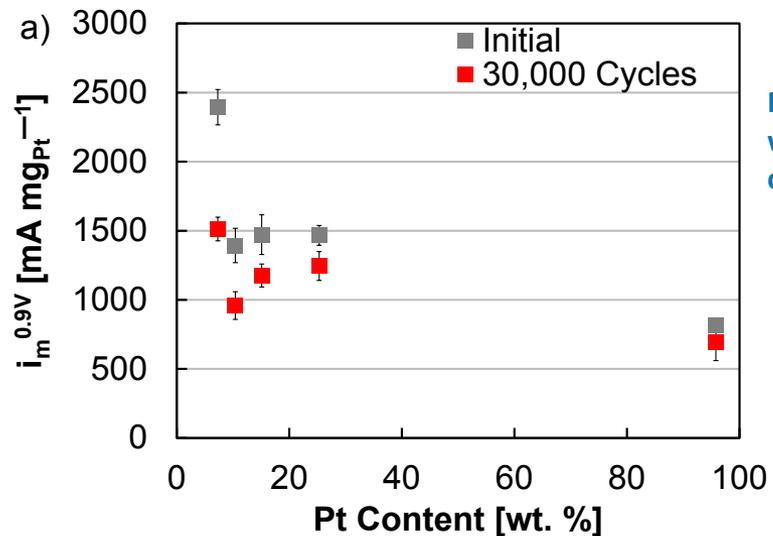
Durability decreased with increasing Ni content.
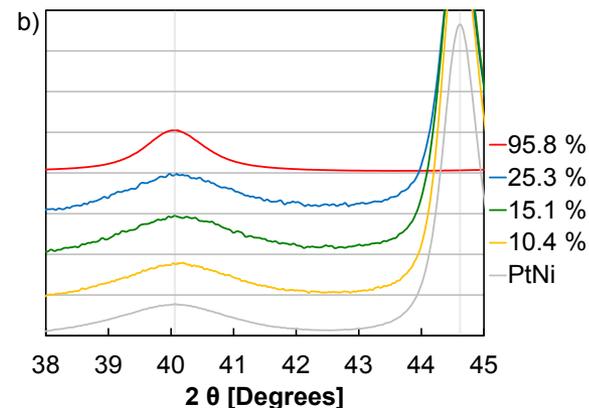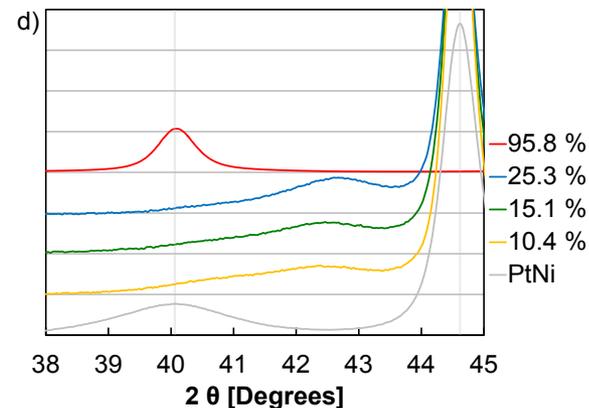
Increasing Ni removal resulted in lower activity following H$_2$ anneal, improved durability.

1-1.5V @ 500 mV/sec, 80°C, 100%RH, H_2/N_2

Conditions for all fuel cell data reported: 80°C, 150 kPa, 100 %RH – (47 kPa P_w, 100 kPa gas pressure) – 0.2 mg_{Pt}/cm^2

15 min per point (0.6, 0.7, 0.8, 0.85, 0.9V)

ECA @ 35°C 150 kPa, 100 %RH, 150/100 sccm H_2/N_2 (100mV/sec)

High potential, support corrosion cycling experiments (for start-stop conditions) showed promising results in terms of retained performance compared to Pt/C. Our most advanced catalyst showed higher performance and improved durability compared to Pt black under identical conditions.

Present Year Accomplishments and Progress

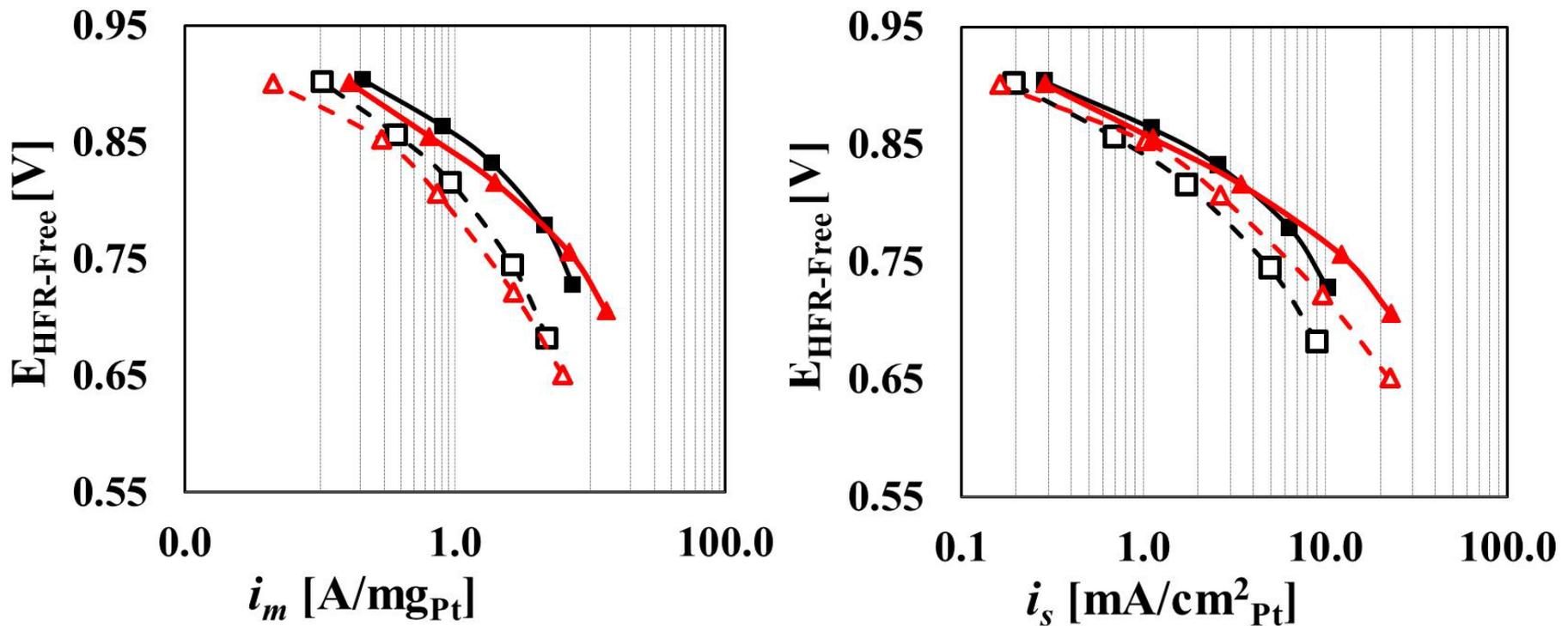**Optimization of ETFECS fuel cell uncorrected performance - (5 cm^2)**
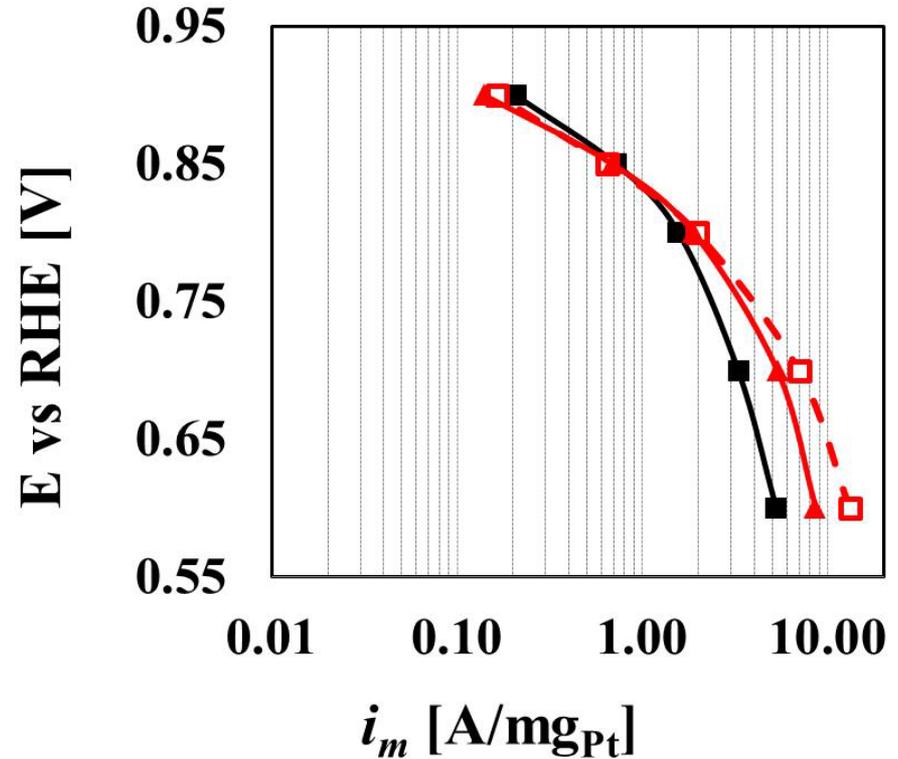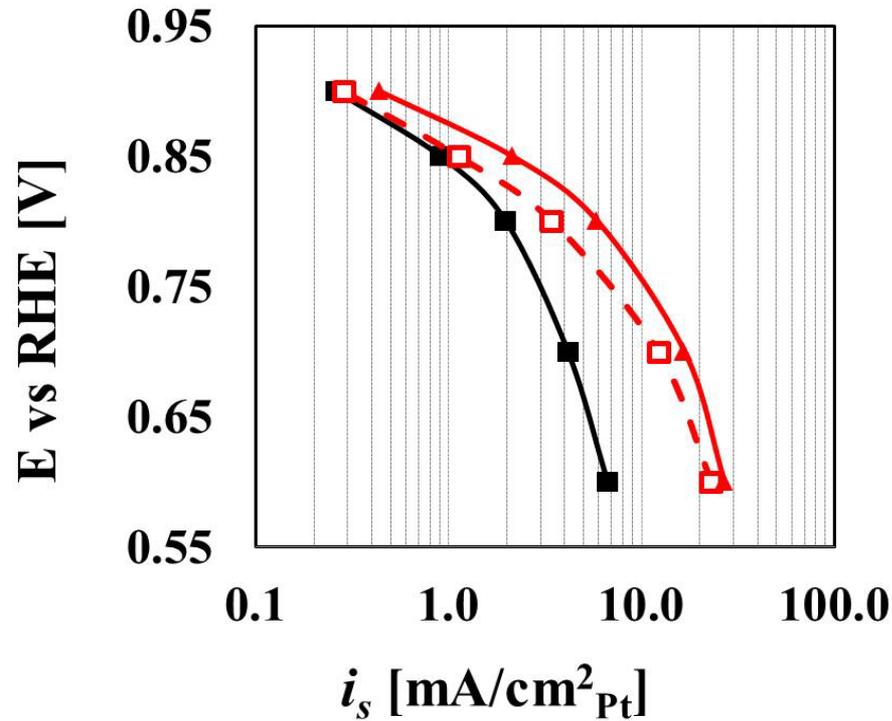
Pt/HSC (0.2 mg$_{Pt}$/cm^2)
Pre-treated PtNi (0.2 mg$_{Pt}$/cm^2)
PtNi w/HSC (0.2 mg$_{Pt}$/cm^2)

5 cm$_2$ single serp. 80°C 100% RH 150 kPa H$_2$/O$_2$
Constant E, 15 min per point

## ETFECS fuel cell durability – effect of carbon incorporation

■ Pt/HSC (0.2 mg$_{Pt}$/cm²) – Initial Performance
□ Post 1000 cycles from 1.0 – 1.5V 80°C H$_2$/N$_2$
▲ <u>PtNi w HSC</u> (0.2 mg$_{Pt}$/cm²) – Initial Performance
△ Post 1000 cycles from 1.0 – 1.5V 80°C H$_2$/N$_2$

25 cm$_2$ triple serp. 80°C 100% RH 150 kPa
H$_2$/O$_2$ constant E, 15 min per point

Accomplishments and Progress

## Electrospinning of polymer nanowires for electrode incorporation

| Samples	Electric Field (kV/cm)	Observation	Diameter (nm)
Nafion (20 wt PAA)	10/15	Fiber mat	340 ± 4
Fractured Nafion[a]	10/15	Fiber mat	466 ± 38
Fractured Nafion after dispersed in solution[b]	10/15	Partially dissolved	-
PFSA (2 wt PEO)	10/15	Fiber mat	173
Fractured PFSA[a]	10/15	Fiber mat	316
Fractured PFSA after dispersed in solution[b]	10/15	Partially dissolved	-
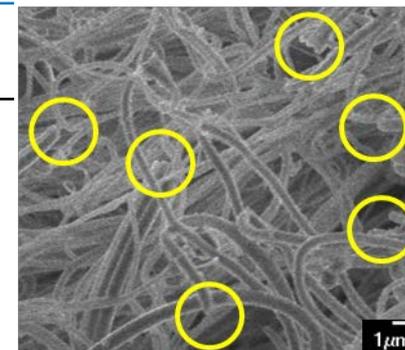
Fractured Nafion

Electrospinning of Nafion has been undertaken in order to provide ionic pathways through electrodes without requiring complete catalyst coverage of Pt sites (looking to take advantage of conduction properties of extended surface electrocatalysts). Fibers have been spun and fractured at liquid N_2 temperatures. Annealing has been employed to improve solvent tolerance.
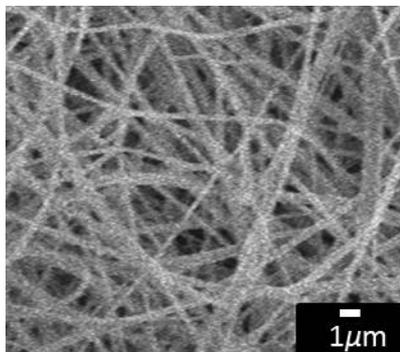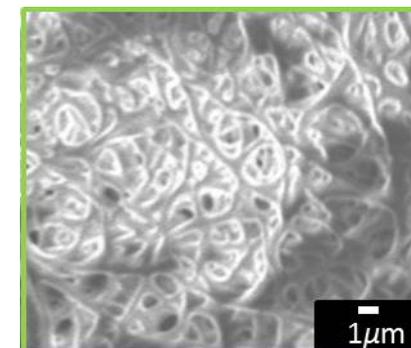

PFSA
(2 wt PEO)
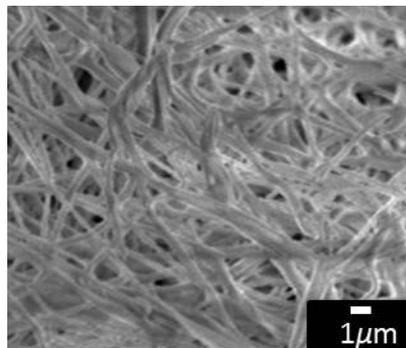
No thermal treatment before dispersing in H_2O
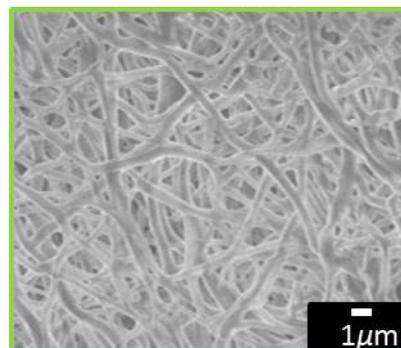
Annealing at 110°C before dispersing in H_2O

Annealing at 140°C before dispersing in H_2O

* Structure is altered at 140°C