2013 Annual Merit Review
DOE Hydrogen and Fuel Cells and
Vehicle Technologies Programs

High Performance, Durable, Low Cost Membrane Electrode Assemblies for Transportation Applications

Andrew Steinbach
3M Company
May 15th, 2013

Project ID: FC104

Powered by 3M

DOE Hydrogen Program

Project Overview

Timeline

- Project start: 9/1/12
- Project duration: 3 years
- Percent Complete: 20%

Budget

- Total project funding **$4.307MM**
  - $3.445 MM DOE
  - $0.862 MM Contractor
- Funding Received FY12: $2.859MM
- Funding for FY13: $1.04MM
  (Est. non-FFRDC expend.; DOE share)

Partners

- Lawrence Berkeley Nat'l Lab.(A. Weber)
- Michigan Technological Univ. (J. Allen)
- Johns Hopkins Univ. (J. Erlebacher)
- Oak Ridge Nat'l Lab. (D. Cullen)
- Argonne Nat'l Lab. (R. Ahluwalia)

Barriers

A. MEA Durability

B. Stack Material & Mfg Cost

C. MEA Performance

DOE Technical Targets

Electrocatalyst ***(2017)***

- Mass Activity: 0.44A/mg
- Inv. Spec. Power: 0.125g/kW(rated)
- PGM Total Loading: 0.125mg/cm^2
- Electrocatalyst, Support Durability: < 40% Activity, ECSA Loss

MEA ***(2017)***

- Q/ΔT: 1.45kW/ºC
- Cost: $9/kW
- Durability w/cycling: 5000 hrs
- Performance @ 0.8V: 0.300A/cm^2
- Rated Power: 1W/cm^2

Relevance and Approach

Relevance (Objective): Development of a durable, low-cost, robust, and high performance membrane electrode assembly (MEA) for transportation applications, able to meet or exceed the 2017 DOE targets.

Approach:

Optimize integration of advanced anode and cathode catalysts, based on 3M's nanostructured thin film (NSTF) catalyst technology platform, with next generation PFSA PEMs, gas diffusion media, and flow fields for best overall MEA performance, durability, robustness, and cost.

Integration: Includes optimization of existing components and processes via reasonable and known means – **NO COMPONENT DEVELOPMENT**.

Primary Focus Topics:

- **NSTF Cathode Post-Processing Optimization (Dealloying, Annealing)**
- **NSTF Anode Catalyst Composition , PGM Content Sensitivity**
- **PEM-Electrode Integration Studies**
- **Anode GDL Characterization, Modeling for Cold-Startup Optimization**
- **Integration of 2012, 2013(March) Best of Class NSTF MEAs**
- Project Initiation at 3M and Partners
- MEA Integration Diagnostics (Segmented Cell; HOR Kinetic Studies; Water Balance)

Relevance and Approach – Project Tasks

- Tasks Address Barriers of Durability, Cost, and Performance
- Strong Emphasis on Cold-Startup, Load Transient (2,3), and Performance Durability (5).

Task	Task Description	Status/ Timing	A. Durability	B. Cost	C. Perform.
1	Component integration towards MEA ¼ power, rated power, and Q/ΔT targets.	In Progress/ On Target		●	●
2	GDL and interfacial layer integration towards cold start up and transient response targets.	Starting/ Delayed			●
3	Water management modeling for cold start	In Progress/ On Target			●
4	Overall Best of Class MEA Integration; component interaction mechanism studies.	In Progress/ On Target	●	●	●
5	Component/MEA durability evaluation; Rated-power performance loss mitigation.	Started/ Delayed	●	●	●
6	Short stack eval. of integrated MEAs for rated power, cold/freeze-start, transient response.	Not Started/ Delayed			●
7	Project management	In Progress/ On Target	●	●	●
8	Relative cost and manufacturing assessment	Not Started/ On Target		●	

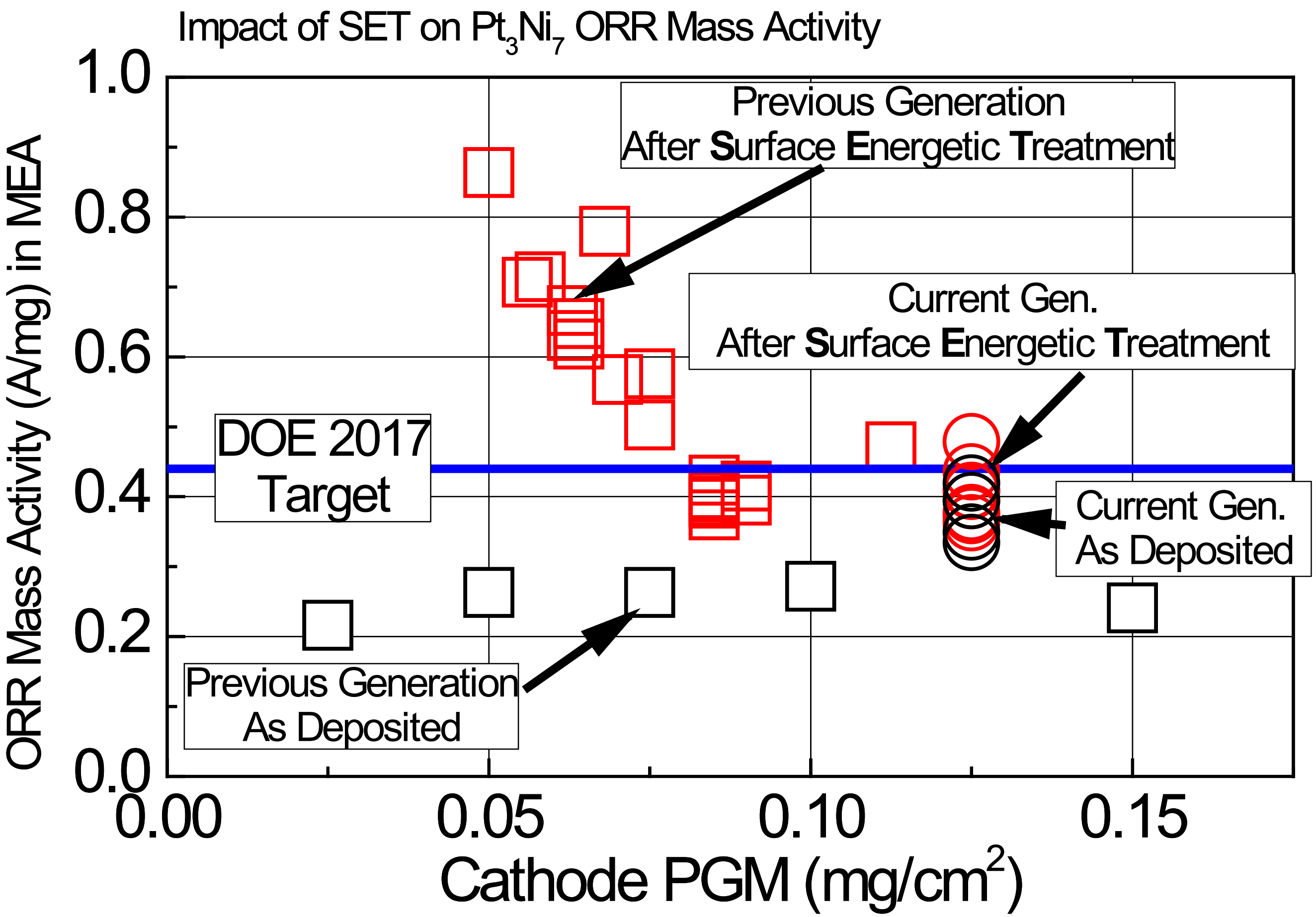
Milestone, Go/No-Go Goals and Status

Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13
Kick off							Go NG					End

Milestone ID	Project Quarter	Project Milestone	Mar. '13 Status / % Complete
BUDGET PERIOD 1 (Sept. '12-June '14)			
6.1	2	Baseline MEA: **Short Stack** Evaluation Complete.	25%
1.1	7	Component Candidates Meet **Interim Performance/Cost Goals**	33%
2.1	7	Component Candidates Meet **Interim Cold-Startup Goals**	5%
5.1	7	Component Candidates Meet **Interim Durability Goals**	20%
3.1	7	**GDL Model Validation** With 2 or More 3M Anode GDLs	20%
6.2	7	Interim Best of Class MEA: **Short Stack** Evaluation Complete.	0%
4.1 Go/No-Go	**7**	**Interim Best of Class MEA Meets Go/No-Go Goals:** **1) ≤ $0.135 mg_{PGM}/cm^2$ (Total)** **2) Rated Power, Q/ΔT: 0.659V@ $1.41 A/cm^2$, 90ºC, 1.5atm H_2/Air**	**99%** **$0.137 mg_{PGM}/cm^2$** **0.658V**
BUDGET PERIOD 2 (June '14 – Aug. '15)			
1.2	11	Component Candidates Meet **Project Performance/Cost Goals**	0%
2.2	11	Component Candidates Meet **Project Cold-Startup Goals**	0%
5.2	11	Component Candidates Meet **Project Durability** Goals	0%
4.2	11	**Best of Class MEA Meets All Project Goals**	0%
3.2	12	**MEA Cool Start Model Validation** with 2 or more 3M MEAs.	0%
6.3	12	Best of Class MEA: **Short Stack Evaluation** Complete.	0%
8.1	12	**Relative Cost Savings Report** – Final Best of Class MEA Relative to 2012 MEA.	0%
0 Deliverable	**12**	**Final Best of Class MEA Short Stack Delivered to Evaluation Site.**	**0%**

Accomplishments and Progress

Improved Activity, Rated-Power Capable ORR Catalysts (Task 1.1):
Post-Process Optimization (Surface Energetic Treatment (SET))



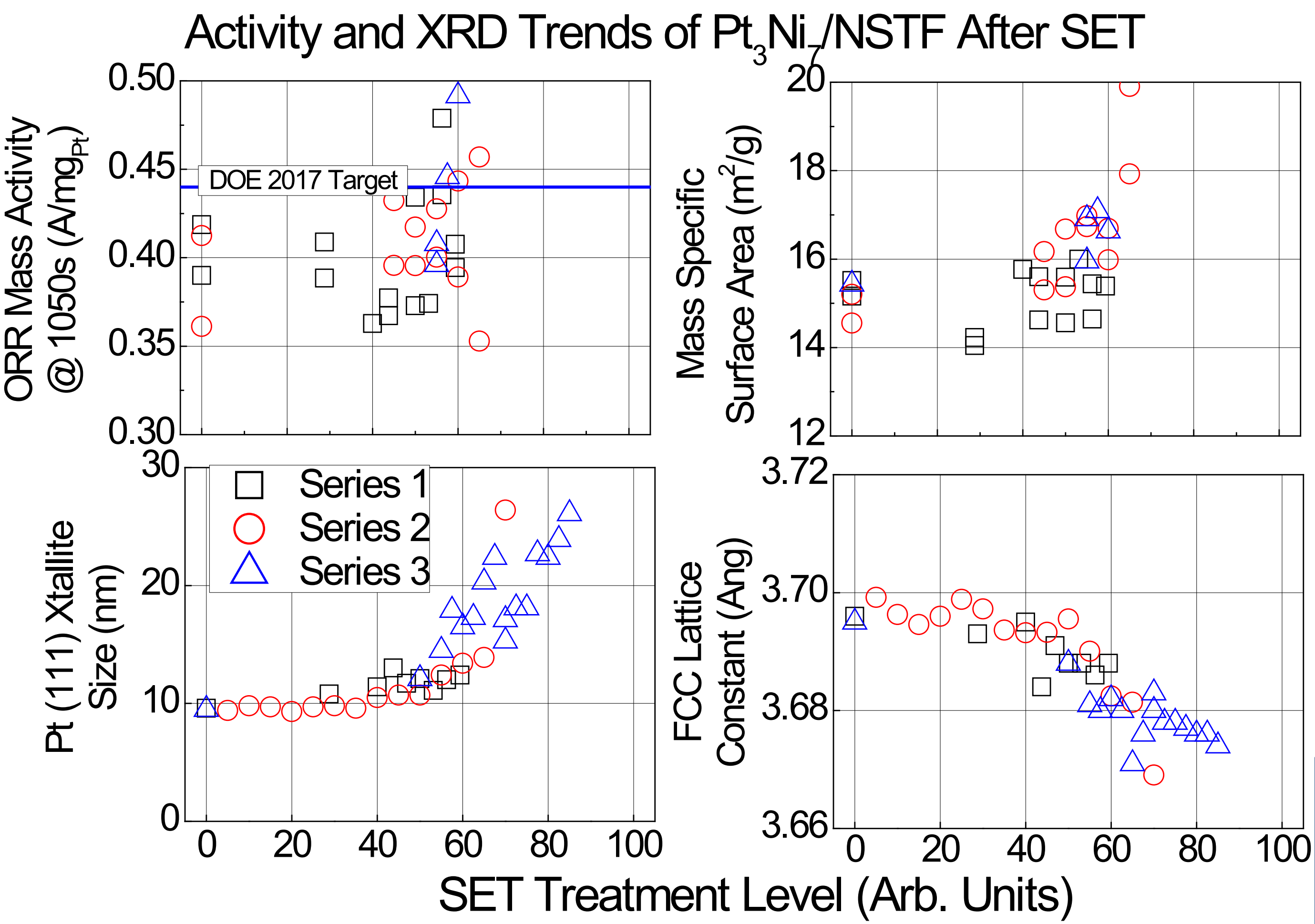
- Mass Activity of previous generation Pt_3Ni_7/NSTF increased significantly after SET.
  - SET: NSTF-compatible continuous annealing process.
  - **PREVIOUS WORK – DE-FG36-07GO17007.**
- Current generation Pt_3Ni_7/NSTF activity, as-deposited, higher than previous, but benefit of SET not yet demonstrated.

Focus of current work is determination of factors to achieve entitlement activity.

Accomplishments and Progress

Improved Activity, Rated-Power Capable ORR Catalysts (Task 1.1):

SET Induces Significant Structural Changes of Pt_3Ni_7/NSTF Cathodes

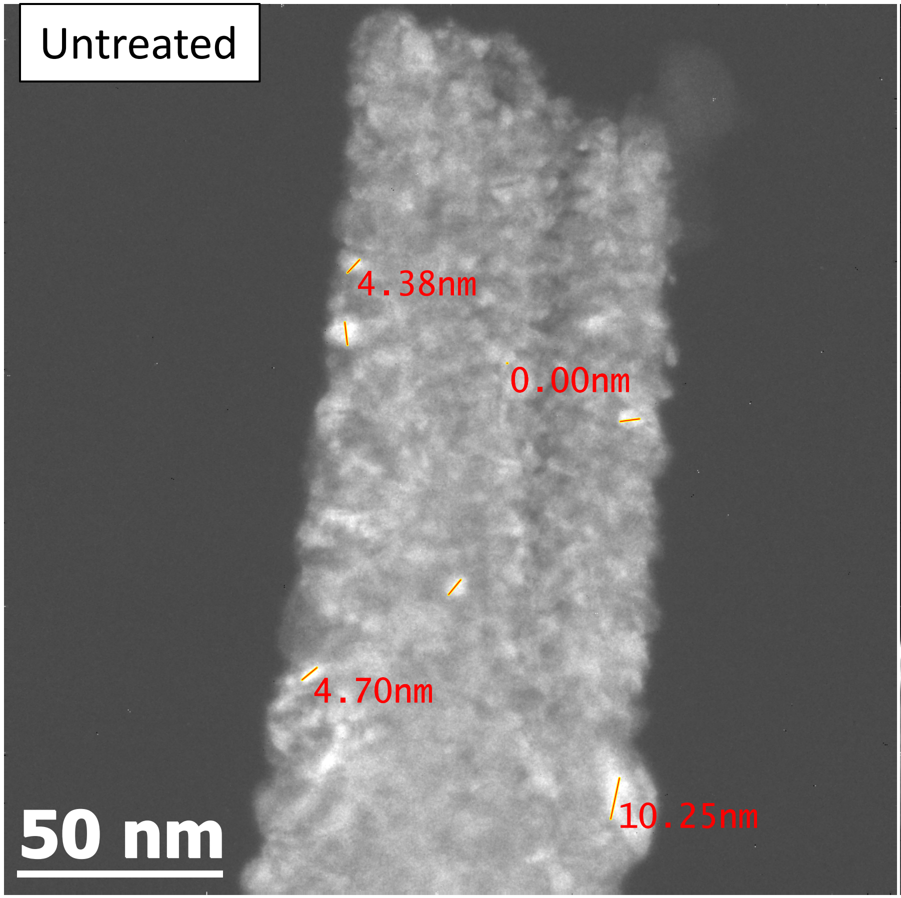


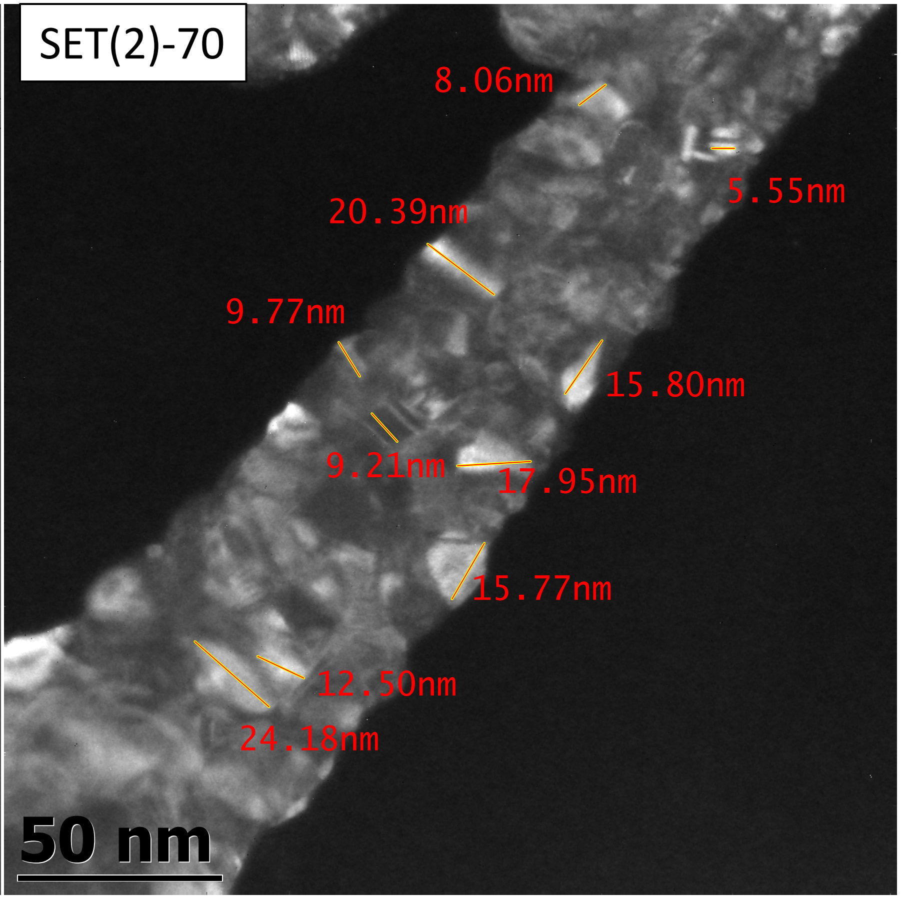
- To date, mass activity relatively unaffected by SET process parameters evaluated.
- Monotonic changes observed in specific area, crystallite size, and lattice constant.

MEA evaluation of larger grained materials in progress.

Accomplishments and Progress

Improved Activity, Rated-Power Capable ORR Catalysts (Task 1.1):
TEM Confirms Grain Growth After SET



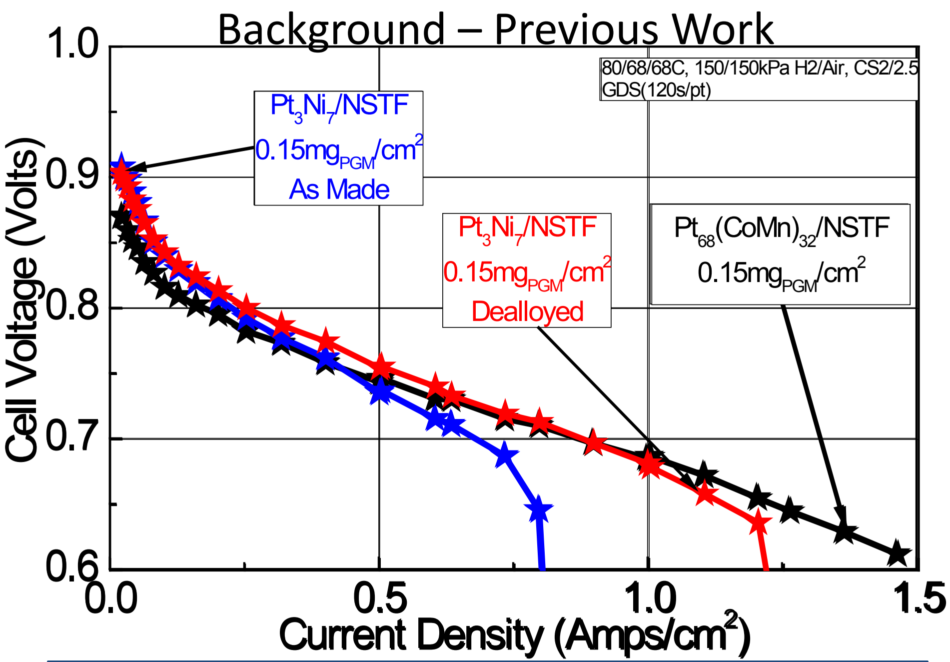


- Preliminary 3M TEM imaging confirms significant grain growth after SET.
- Analysis at ORNL in progress to quantify surface faceting and surface composition.

Accomplishments and Progress

Improved Activity, Rated-Power Capable ORR Catalysts (Task 1.1):
Post-Process Optimization (<u>Dealloying</u>) @ Johns Hopkins (J. Erlebacher)

Objective: Dealloying Optimization-Improve Peak Power, Maintain Activity, w/ <u>Scalable</u> Process.

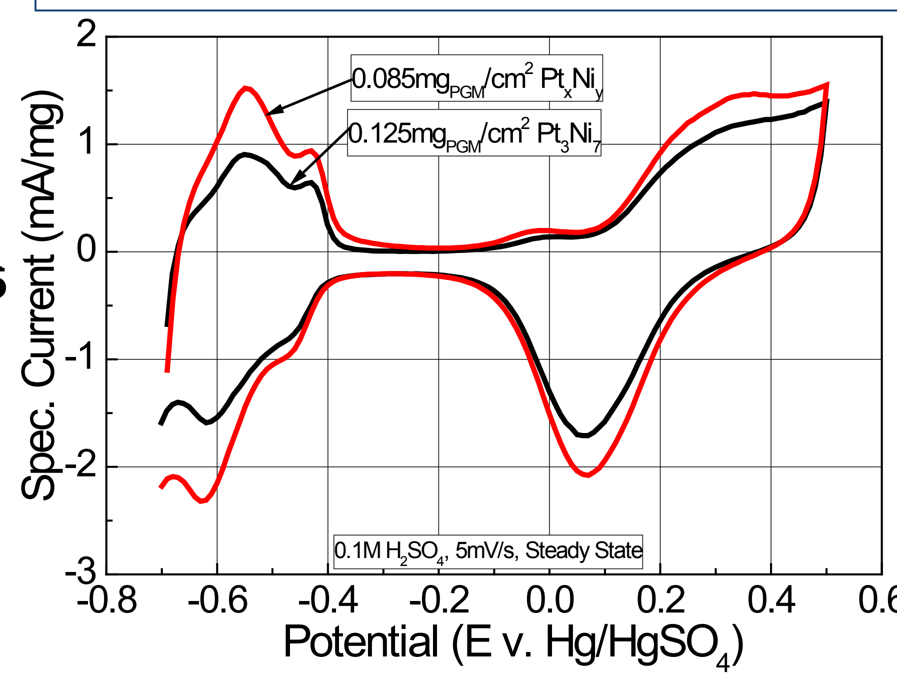


As-deposited, MEAs with Pt_3Ni_7/NSTF cathodes have higher activity but lower peak power than $Pt_{68}(CoMn)_{32}$ **<u>(Ni diss.)</u>**

Current practice dealloying improves peak power; still insufficient to achieve 1W/cm^2.

<u>Initial work @ JHU (start Feb. '13)</u>

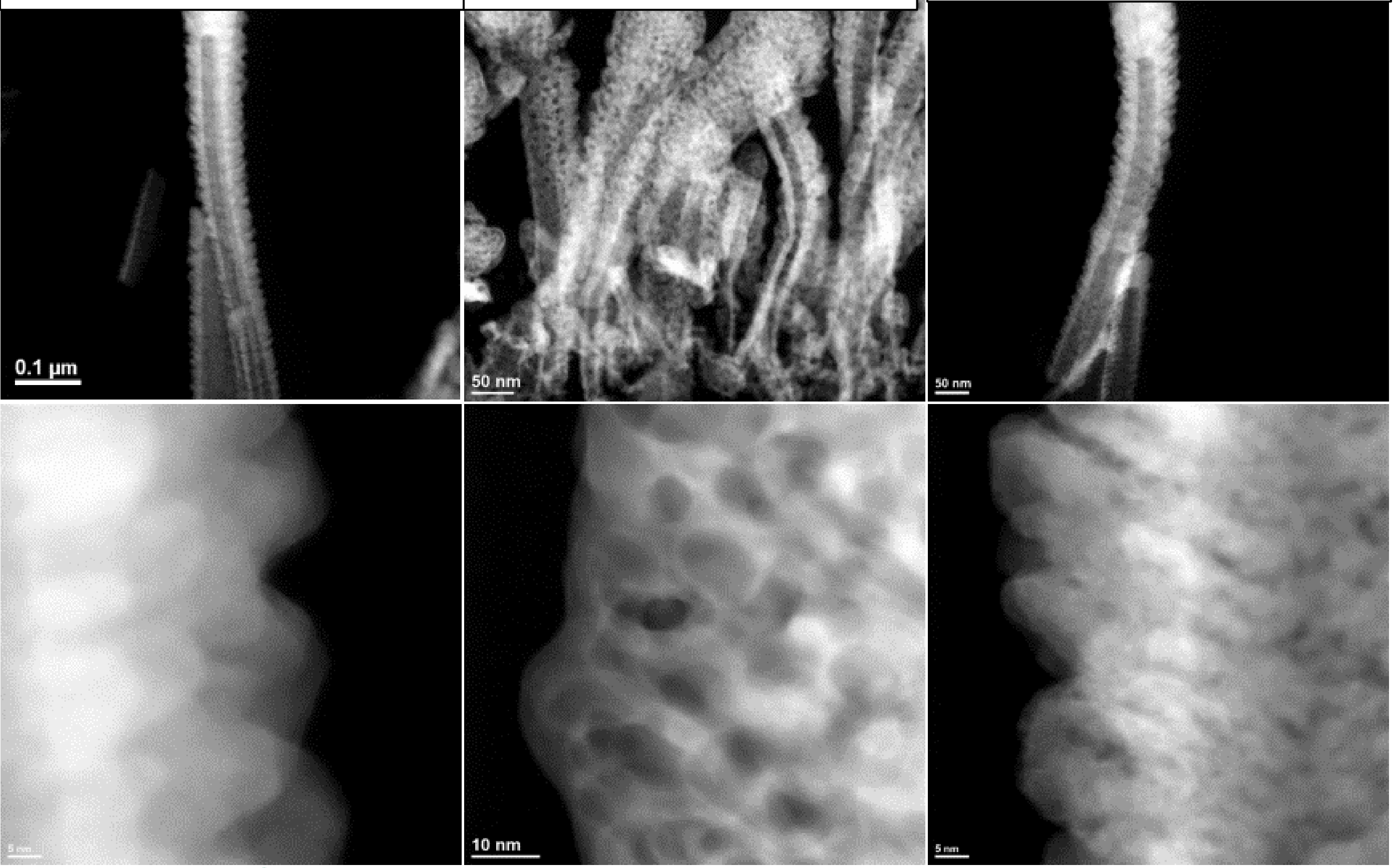
Electrochemical dealloying of Pt_xNi_y/NSTF to determine entitlement specific area, stable residual Ni content.



Improved Activity, Rated-Power Capable ORR Catalysts (Task 1.1):

Microscopy Reveals Structural Evolution of Pt_3Ni_7/NSTF (ORNL, D. Cullen)

As Dep. Pt_3Ni_7	**MEA Cond.** Pt_6Ni_4	**Dealloyed** Pt_4Ni_6



- Dramatic porosity increase, Ni loss after MEA conditioning.
- Current practice dealloying induces less porosity, Ni loss than MEA conditioning.

Dealloying Development Needed to Achieve MEA-Conditioned State, **Ex-Situ**

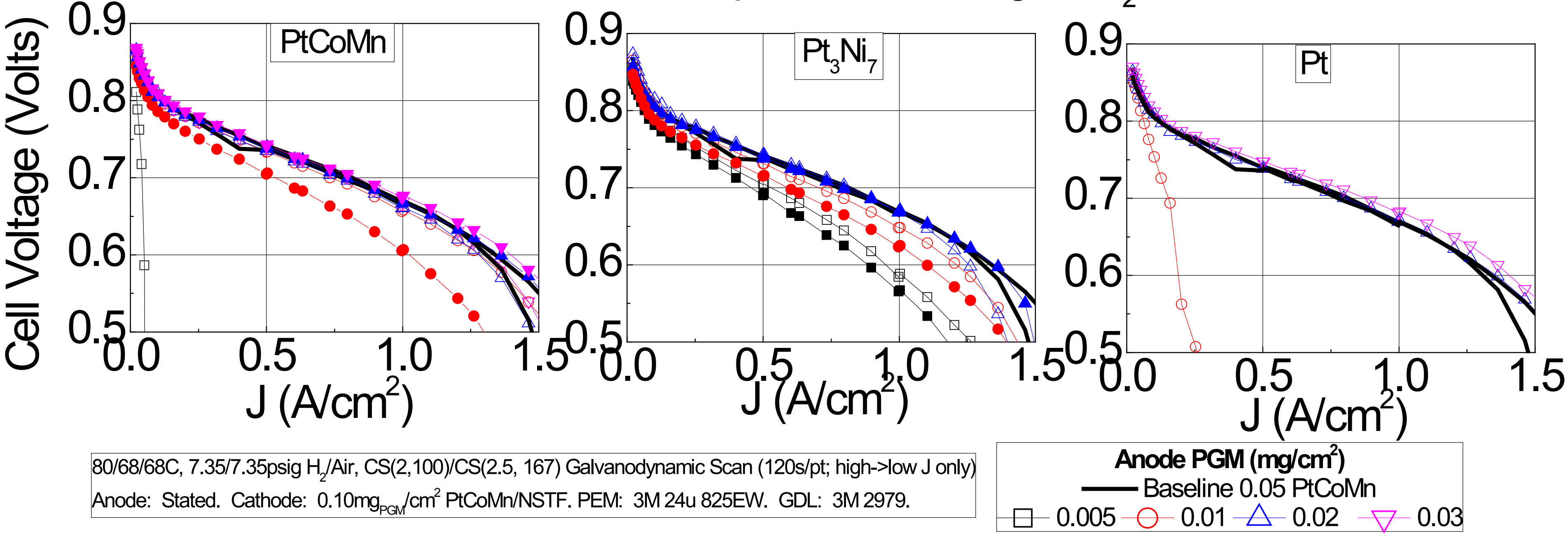
OAK RIDGE NATIONAL LABORATORY

Managed by UT-Battelle for the Department of Energy

Accomplishments and Progress

Durable, Ultra-Low PGM NSTF Anode Catalyst (Task 1.2):
PGM Content and Composition Sensitivity Study Completed

Influence of NSTF Anode Composition, Loading on H_2/Air Performance

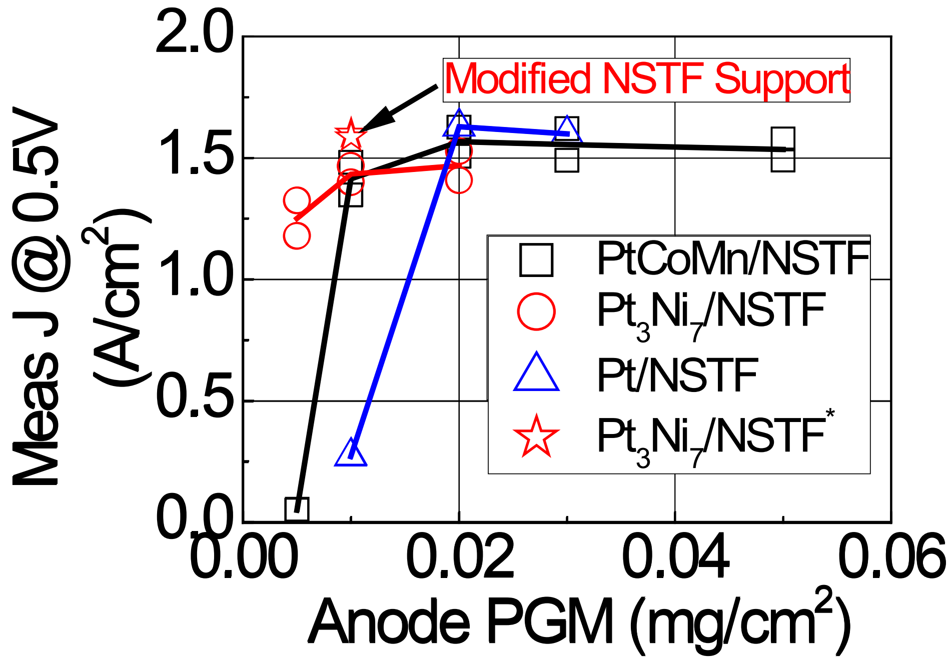


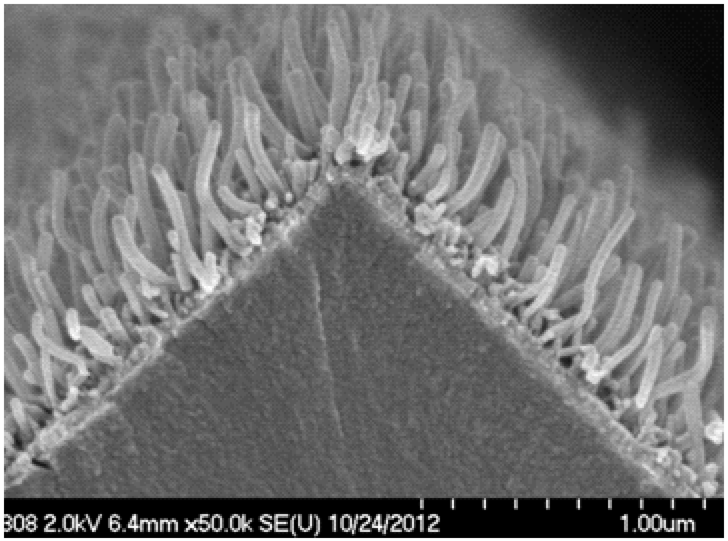
- Pt, PtCoMn, and Pt_3Ni_7 at $0.02mg_{PGM}/cm^2$ comparable to baseline $0.05mg_{PGM}/cm^2$ PtCoMn.
- **Project Goal of ≤ $0.02mg_{PGM}/cm^2$ Achieved.**
- At further reduced PGM, performance has significant loading, composition dependence.
  - $0.01mg_{PGM}/cm^2$: Pt_3Ni_7 , PtCoMn >> Pt
  - $0.005mg_{PGM}/cm^2$: Pt_3Ni_7 >> PtCoMn

Accomplishments and Progress

Durable, Ultra-Low PGM NSTF Anode Catalyst (Task 1.2):

Support Optimization Needed for Ultra-Low PGM NSTF Anodes





Large performance reduction below $0.02mg_{PGM}/cm^2$ is concern for robustness and performance durability.

Typically-used NSTF support not optimized for ultra-low PGM anodes.

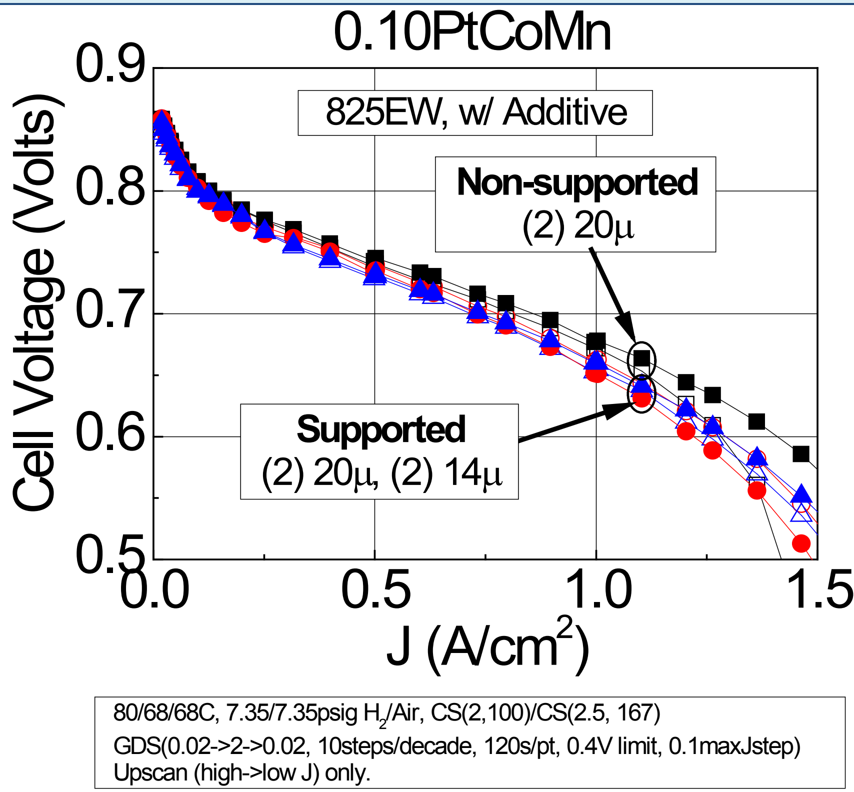
Modified NSTF generated.

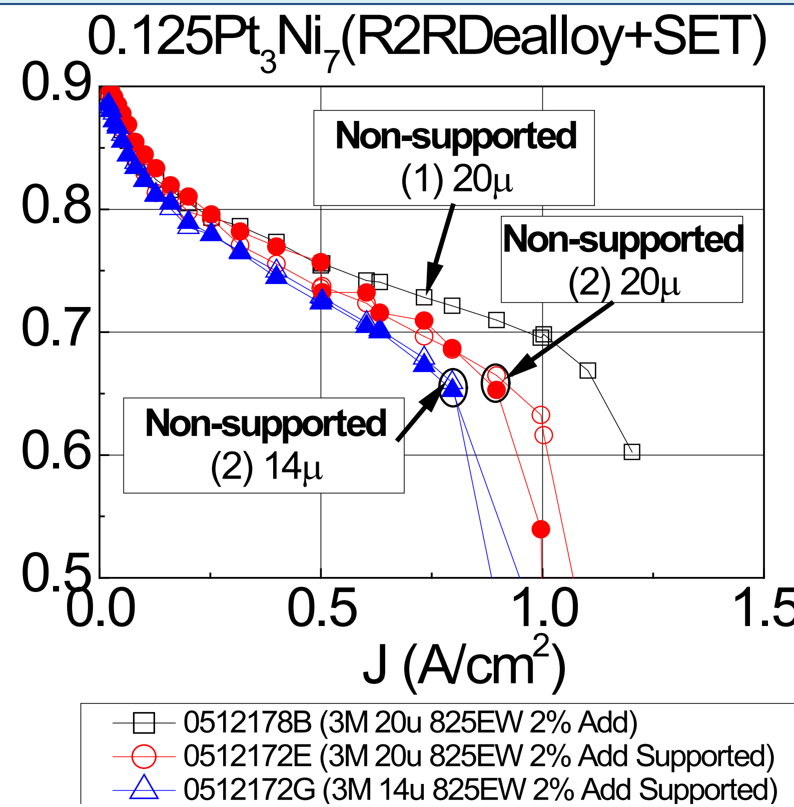
Performance Improvement with Modified Support – Further Gain Possible?

Accomplishments and Progress

Durable, Improved Conductivity PEMs (Task 1.3):

Multi-Factor Systematic PEM Variable Study Completed



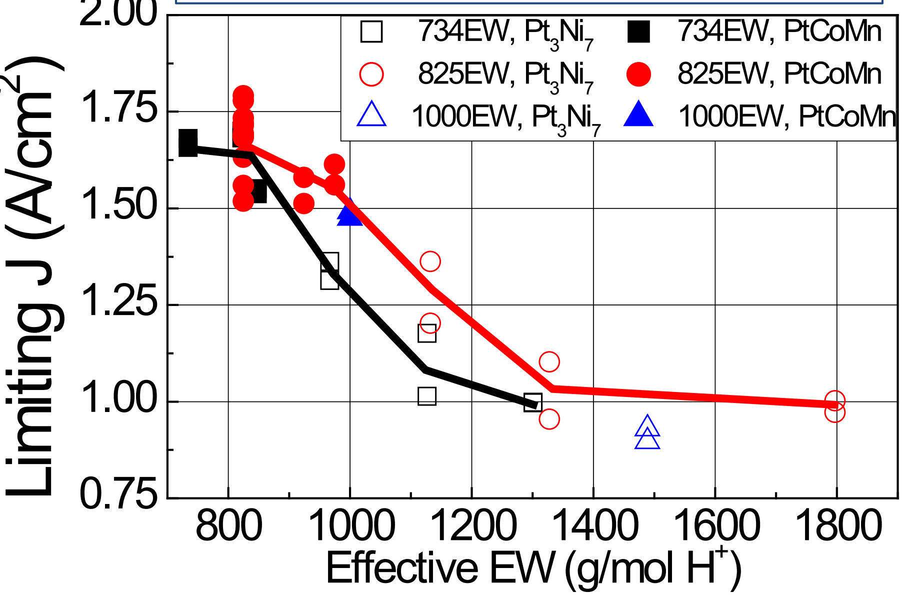


- Factors: PEM EW(3), additive(2), 3M support(2), thickness(3); cathode composition(2).
- Two Primary Observations
  1. **PtCoMn**: Performance Loss w/ Support and/or EW > 825 (Largely Non-Ohmic).
  2. **Pt_3Ni_7**: Most Trends Similar to PtCoMn, but More Accentuated.

Accomplishments and Progress

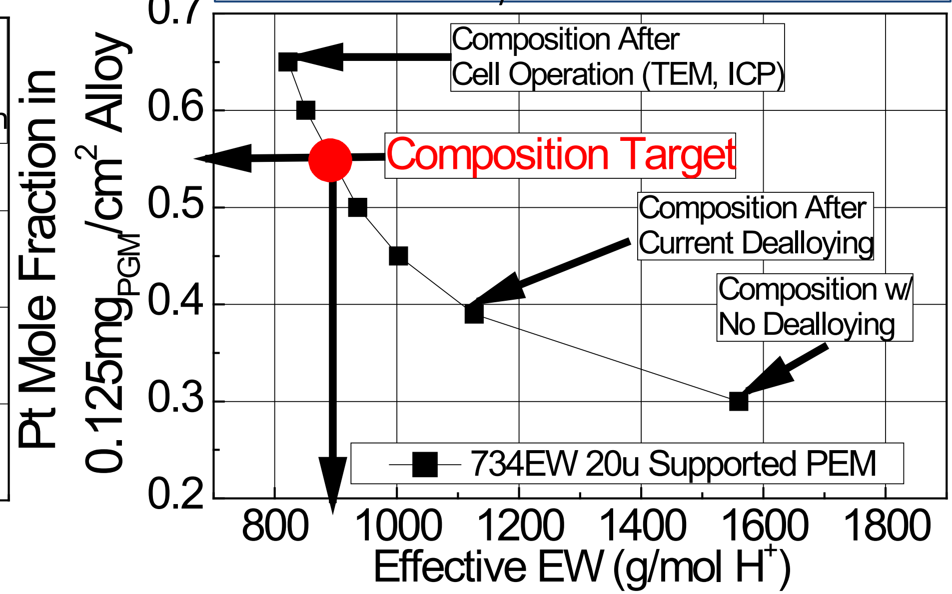
Durable, Improved Conductivity PEMs (Task 1.3): PEM "Effective" EW Correlation Identified; Dealloying Target Composition Identified

Pt_3Ni_7/NSTF Limiting J Correlates w/ "Effective" PEM Equivalent Weight



PEM Thickness, Support, Starting EW and Ni Dissolution (Pt_{39}->Pt_{65})

Calculated Effective PEM EW v. Pt_xNi_y Composition



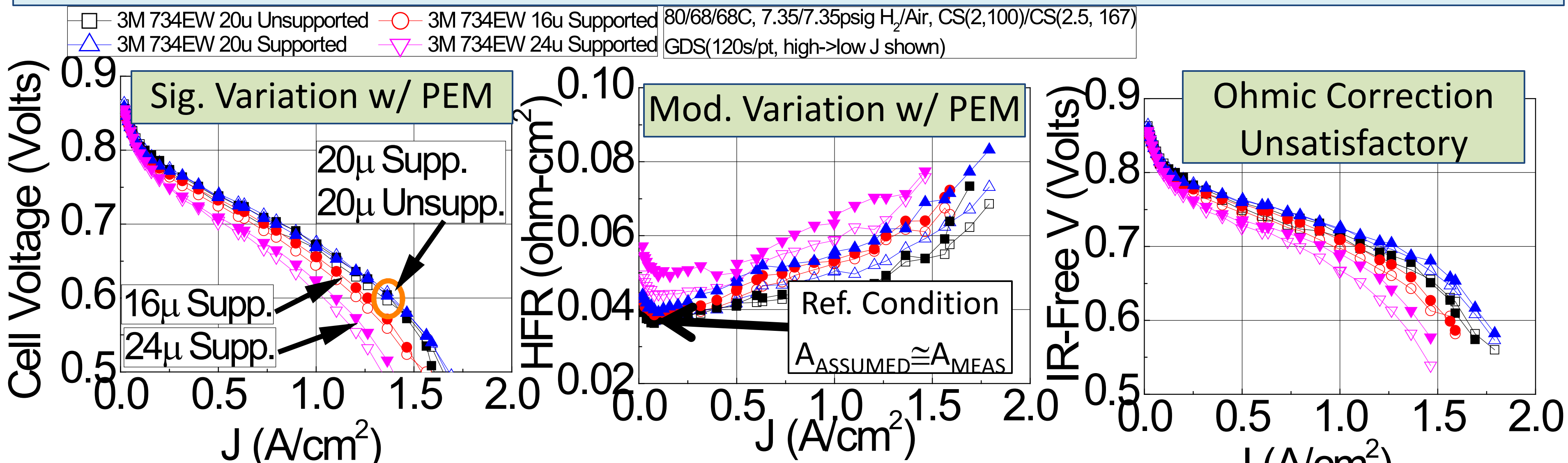
PEM Thickness, Support, Starting EW and Ni Dissolution (Pt_x->Pt_{65})

- Substantial cathode Ni dissolution greatly increases calculated PEM EW.
- Increase depends upon starting PEM EW, support, and thickness.

Correlation allows estimate of post-dealloying cathode composition needed to achieve rated power.

Accomplishments and Progress

Durable, Improved Conductivity PEMs (Task 1.3): Perf. Variation with PtCoMn/NSTF May Be Influenced by Active Area Utilization



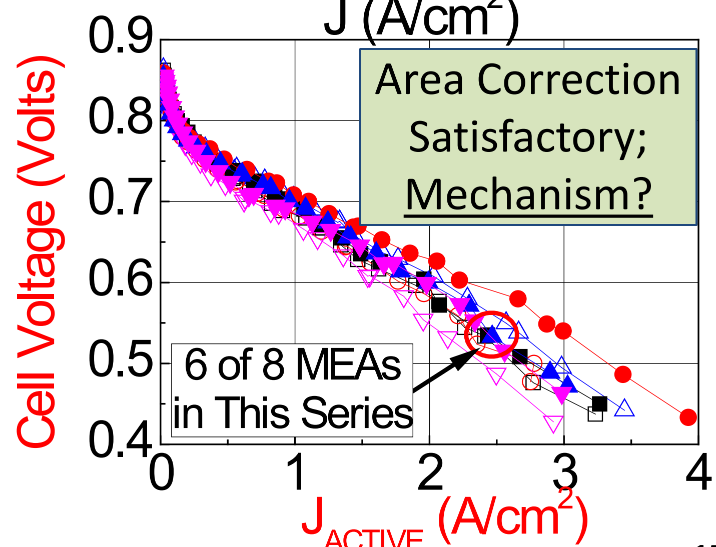
$$HFR(\Omega \cdot cm^2) = R_{MEAS} * A_{ASSUMED} = \left(\frac{\rho l}{A}\right)_{MEAS} * A_{ASSUMED}$$

(R_{MEAS}: FRA; $A_{ASSUMED}$: Cell Area)

Assume HFR variation is due to variation in MEA conductive ***AREA*** rather than bulk resistivity.

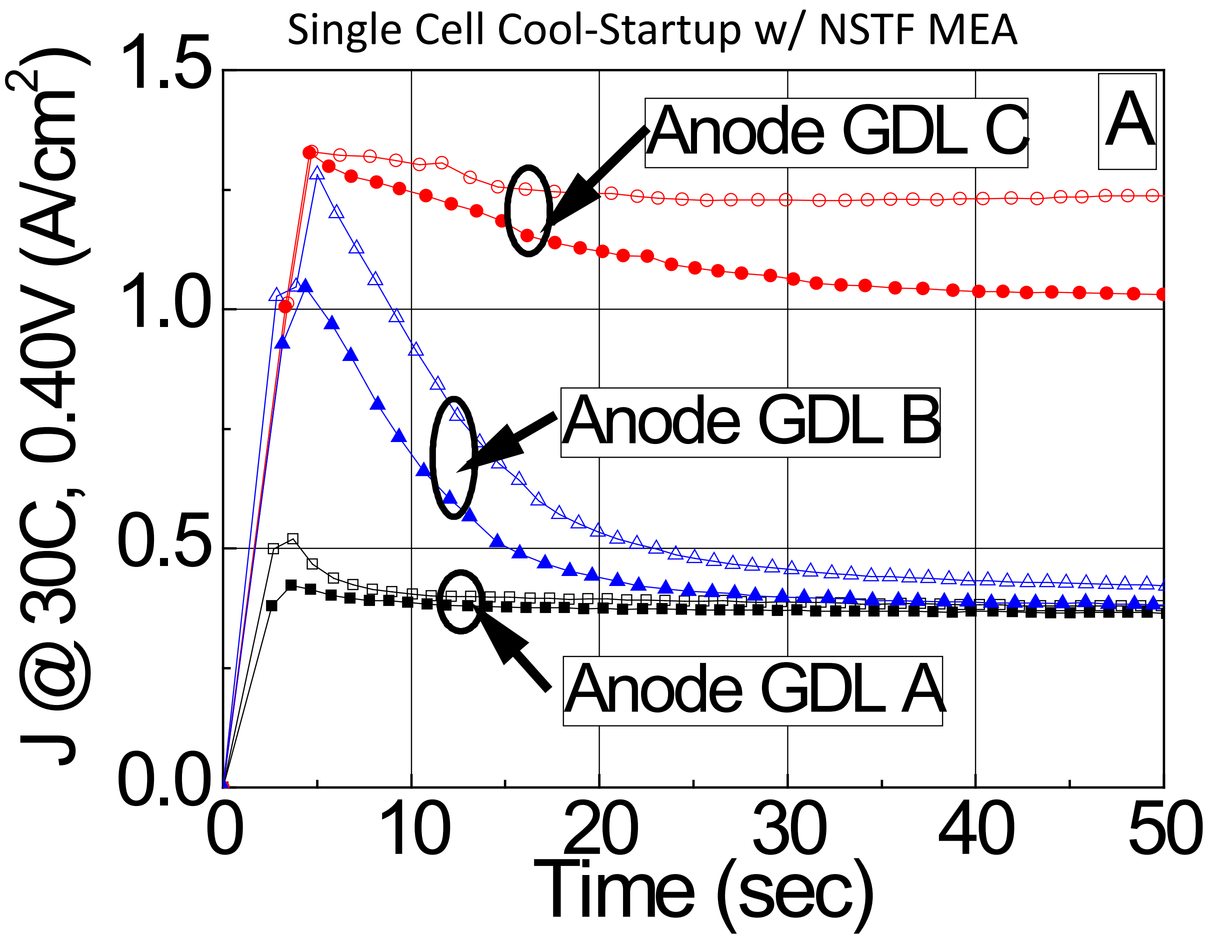
$$J_{ACTIVE} = \frac{I_{MEAS}}{A(I)_{MEAS}}$$

$$A(I)_{MEAS} = \frac{R(I)_{MEAS}}{R_{REF}} * A_{ASSUMED}$$



Accomplishments and Progress

Water Management Modeling for Cold Start (Task 3):
Understanding Influence of Anode Backing on NSTF MEA Cold-Startup



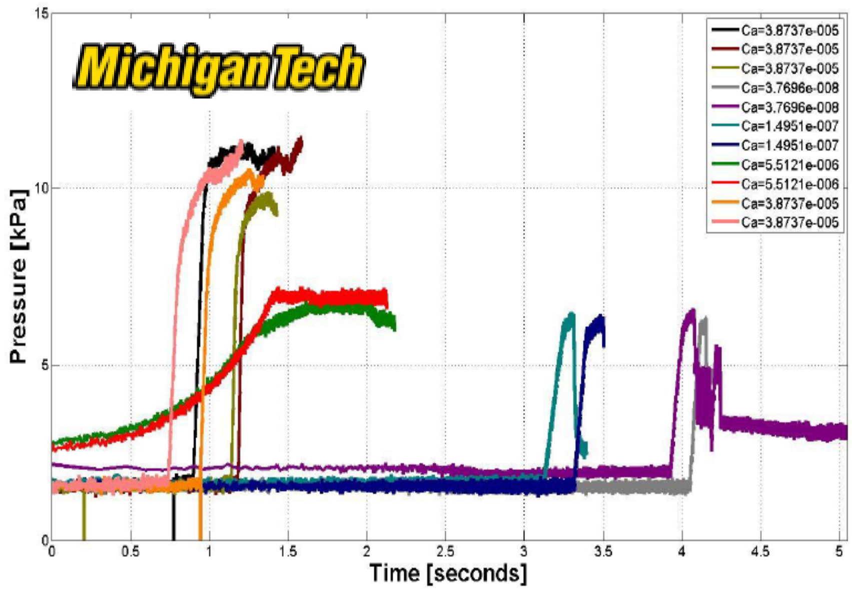
Significant influence of anode GDL backing on Cold-Startup with NSTF MEAs.

Task 3 Primary Objective:
Determine key material factors and mechanism(s).

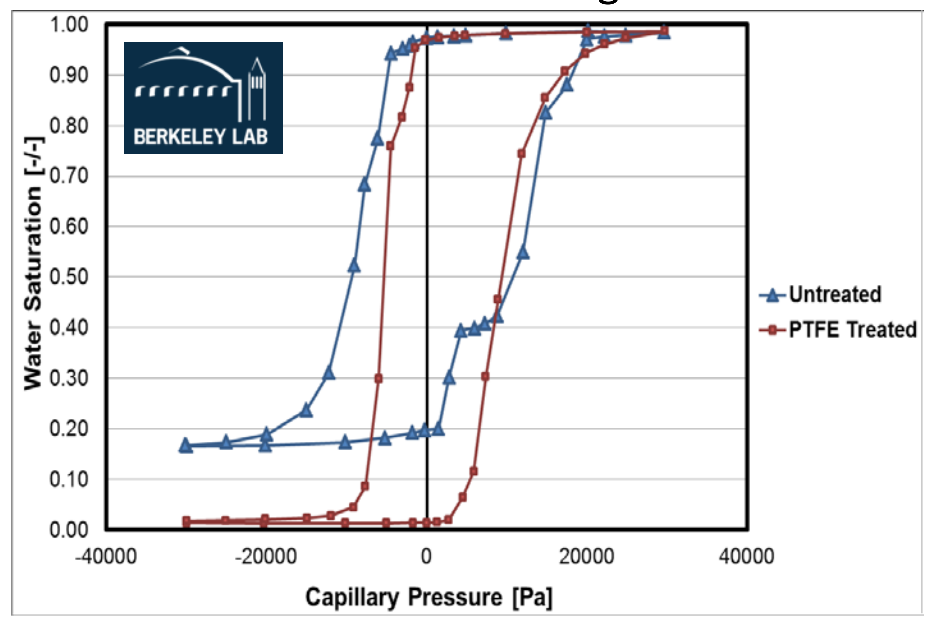
Accomplishments and Progress

Water Management Modeling for Cold Start (Task 3): Material Property Measurements Initiated at MTU(J. Allen), LBNL (A. Weber)

PTL Percolation Measurements
GDL C Backing



GDL Capillary Pressure/Saturation Measurements - GDL C Backing

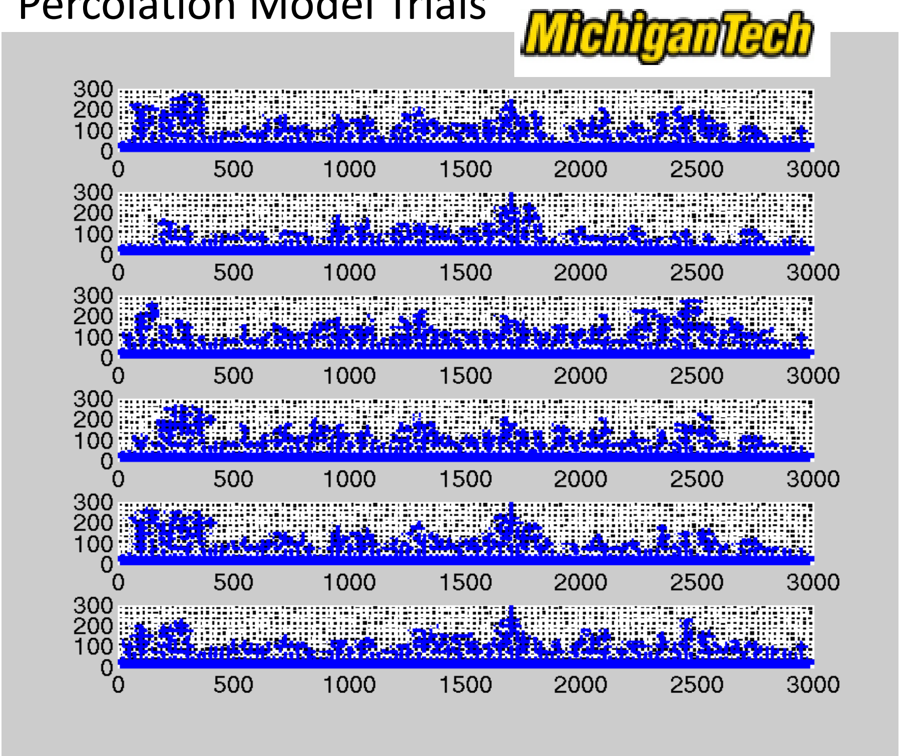


- Material property measurements in progress; results to be incorporated into existing MTU, LBNL models.
- Methods include: Liquid percolation, capillary pressure/saturation, contact angle, adhesion force, breakthrough pressure, tomography, thermal conductivity,…

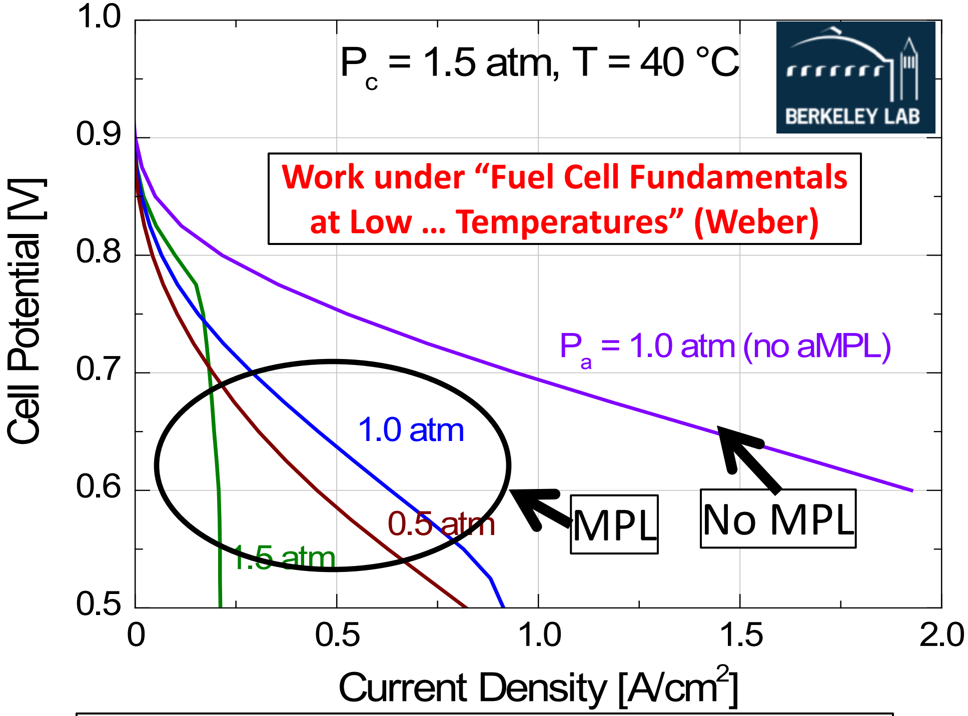
Accomplishments and Progress

Water Management Modeling for Cold Start (Task 3):
GDL, MEA Modeling Initiated at MTU(J. Allen), LBNL (A. Weber)

Percolation Model Trials



Influence of Anode Pressure, Anode MPL

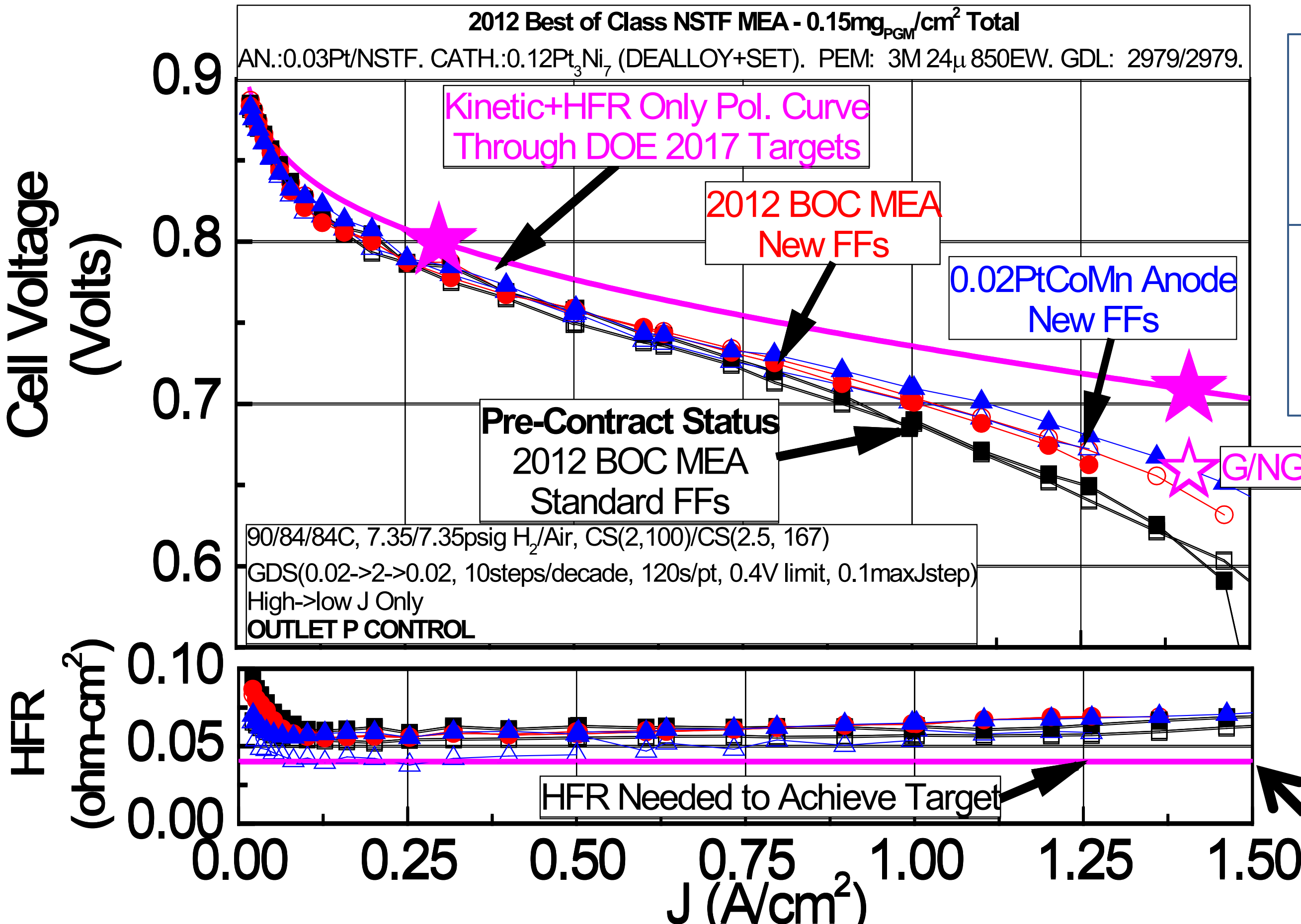


Parametric modeling study initiated on effect of backing solid phase distribution on thermal, water transport.

Current LBNL model captures many experimentally observed trends; incorporation of project materials/properties in progress.

Accomplishments and Progress

Best of Class Component Integration (Task 4.1): Go/No-Go Targets Approached - 2013 3M NSTF Best of Class MEA in Improved Flow Field



Significant gain in rated power, Q/ΔT with improved flow fields.

Anode PGM reduction - similar/improved performance.

Go/No Go Metric	Pre-Proj. Mar. '12	2012 BOC New FF Sept. '12	Red. Anode New FF Mar. '13
≤0.135 mg_{PGM}/cm^2	0.151	0.147	0.137
≥0.659V @1.41A/cm^2	0.609	0.644	0.658 1 MEA

High HFR - 50% of V gap to 2017 Power Target **Cathode Ni**

Path to Target: 1) **Reduce HFR** (Dealloying, Thinner Supp. PEM). 2) **Increase Activity** (SET)

Collaborations

Johns Hopkins University (Jonah Erlebacher) – Subcontractor

•Task 1 - Pt_3Ni_7/NSTF dealloying optimization for improved peak power.

Lawrence Berkeley National Laboratory (Adam Weber) – Subcontractor

•Task 3 - Cold startup MEA modeling.

•Task 3 - GDL characterization.

Michigan Technological University (Jeffrey Allen) – Subcontractor

•Task 3 - Integration of 3M anode GDLs into GDL network model.

•Task 3- GDL characterization.

Oak Ridge National Laboratory (David Cullen) – Subcontractor

•Task 1 - Characterization of dealloy/SET post-processed Pt_3Ni_7/NSTF cathodes.

Argonne National Laboratory (Rajesh Ahluwalia) – Collaborator

•Task 1 - NSTF HOR/HER kinetics characterization study.

•3M data provided in support of Fuel Cells Systems Analysis project

Key Future Work – FY13, FY14

Task 1 – Integration Activities Toward ¼ Power, Performance @ rated power…

- Dealloying, SET Optimization for Improved Peak Power, Activity w/ Pt_3Ni_7/NSTF.
- PEM Integration Towards Confirmation, Resolution of Area Under-utilization.
- Further Support Optimization for Ultra-Low PGM Anodes; Durable Anode Incorporation.
- Systematic Study of Flow Field Land, Channel Widths on Rated Power Response.

Task 2 - Integration …. Transient Response, Cold Start Up …

- Initiation of Anode GDL and Cathode Interlayer Optimization.

Task 3 - Water Management Modeling for Cold Start

- Finalize Material Property Measurements, Initiate Modeling with 3M-Specific Materials.

Task 4 - Best of Class MEA Integration Activities

- **Best of Class Component Integration Towards Interim BOC MEA, Go/No-Go Criteria: (≤ 0.135mg_{PGM}/cm^2; Rated Power, Q/ΔT: 0.659V @ 1.41A/cm^2).**
    - **Improvement in Dealloyed, SET Cathode Critical**

Task 5 - Durability Evaluation and Performance Degradation Mitigation

- Influence of Post-Processing on Pt_3Ni_7/NSTF Electrocatalyst Durability.
- Irreversible Peak Power Loss Mitigation Study Initiation (Material, Operational Factors).

Task 6 - Short Stack Performance, Power Transient, and Cold Start Evaluation

- Finalize Identification of Short Stack Testing Provider.
- Complete Short Stack Testing of Interim Best of Class MEA.

Summary

Performance, Cost, Durability Targets,Go/No-Go Criteria, March 2013 Status				
Performance @ ¼ Power, Rated power, and Q/ΔT Targets				
Goal ID	*Project Goals (units)*	*Target Value* ***DOE***	*2013 Status (Rep. MEA)* ***NEW***	***Go/No-Go*** *or Interim*
1	Performance @ 0.80V (A/cm^2); single cell, ≥80ºC cell temperature (50, 100, 150kPag Reactant Pressures)	0.300	0.292[A]	≥0.300
2	Performance at Rated Power, Q/ΔT : Cell voltage at 1.41 A/cm^2 (Volts); single cell, ≥88ºC cell temperature, 50kPag*	0.709	0.658[A]	0.659
Cost Targets				
3	Anode, Cathode Electrode PGM Content (mg/cm^2)	≤ 0.125	0.137[A]	0.135
4	PEM Ionomer Content (effective ion. thickness, microns)	≤ 16	24[A]	20
Cold/Freeze Startup, Power Transient Targets				
5	Transient response (time from 10% to 90% of rated power); single cell at 50°C, 100% RH (seconds)	≤ 1	TBD	5
6	Cold start up evaluated as single cell steady state J @ 30°C [to simulate cold start to 50% of rated power @ +20°C] (A/cm^2)	≥ 0.8	0.38[B]	0.6
7	Cold start up time … @ -20°C; short stack (seconds)	≤ 30	27[C]	30
8	Unassisted start from -40°C (pass/fail); short stack	Pass @ -40°C	Pass @ -20°C[C]	Pass @ -30°C
Durability Targets				
9	Cycling time under 80°C MEA/Stack Durability Protocol with ≤ 30mV Irreversible Performance Loss (hours)	≥ 5000	600[D,**]	2500
10	Table D-1 Electrocatalyst Cycle and Metrics (Mass activity % loss; mV loss @ $0.8A/cm^2$; % initial area loss)	≤-40 ≤-30 ≤-40	**-67** -24 -26[E]	≤-40 ≤- 30 ≤-40
11	Table D-2 Catalyst Support Cycle and Metrics (Mass activity % loss; mV loss @ $1.5A/cm^2$; % initial area loss)	≤-40 ≤-30 ≤-40	-10 -10 -10 [D]	≤-40 ≤-30 ≤-40
12	Table D-3 MEA Chemical Stability: 500 hours (H_2 crossover (mA/cm^2); OCV loss (% Volts); Shorting resistance ($ohm\text{-}cm^2$))	≤2 ≤-20 >1000	-13±4 -12±5 NA [D]	≤2 ≤-20 >1000
13	Table D-4 Membrane Mechanical Cycle: 20k Cycles (H_2 crossover (mA/cm^2); Shorting resistance ($ohm\text{-}cm^2$))	≤2 >1000	16k±0.3k NA[D]	≤3 >500

A: Mean or singular values for 3M 2013(March) Best of Class NSTF MEAs: Anode=0.02PtCoMn/NSTF, Cathode=0.117Pt_3Ni_7/ NSTF(Dealloy+SET), (0.137mg_{PGM}/cm^2 total), 3M 825EW 24µ PEM, Baseline 2979/2979 GDLs, "New" FF2 Flow Field, operated at 90ºC cell temperature with subsaturated inlet humidity and anode/cathode stoichs of 2.0/2.5 and at 50,100,150kPag anode/cathode reactant outlet pressures, respectively.

B: Mean values for duplicate 3M NSTF MEAs: Anode=0.05PtCoMn/NSTF, Cathode=0.10PtCoMn/NSTF, (0.15mg_{PGM}/cm^2 total), 3M 825EW 24µ PEM, Baseline 2979/2979 GDLs, Baseline Quad Serpentine Flow Field.

C: OEM Stack testing results with 3M NSTF MEAs: Anode=0.10PtCoMn/NSTF, Cathode=0.15PtCoMn/NSTF (0.25mg_{PGM}/cm^2 total), 3M ionomer in supported PEM, Baseline 2979/2979 GDLs. OEM-specific enabling technology.

D: Mean or singular values for 3M NSTF MEAs: Anode=0.05PtCoMn/NSTF, Cathode=0.15PtCoMn/NSTF, (0.20mg_{PGM}/cm^2 total), 3M supported 825EW PEM, Baseline 2979/2979 GDLs, Baseline Quad Serpentine Flow Field. Values with estimated standard deviation error tested in duplicate.

E: Value for Single 3M NSTF MEA. Anode: 0.05PtCoMn/NSTF. Cathode=0.107Pt_3Ni_7/ NSTF (Dealloy+SET), 3M 825EW 24µ PEM, Baseline 2979/2979 GDLs, Baseline Quad Serpentine Flow Field.

*: Cell performance of 0.709V @ $1.41A/cm^2$ with cell temperature of ≥88ºC simultaneously achieves the Q/ΔT and rated power targets of 1.45kW/ºC and $1000mW/cm^2$, respectively.

**: Single sample result. MEA failed prematurely due to experimental error.

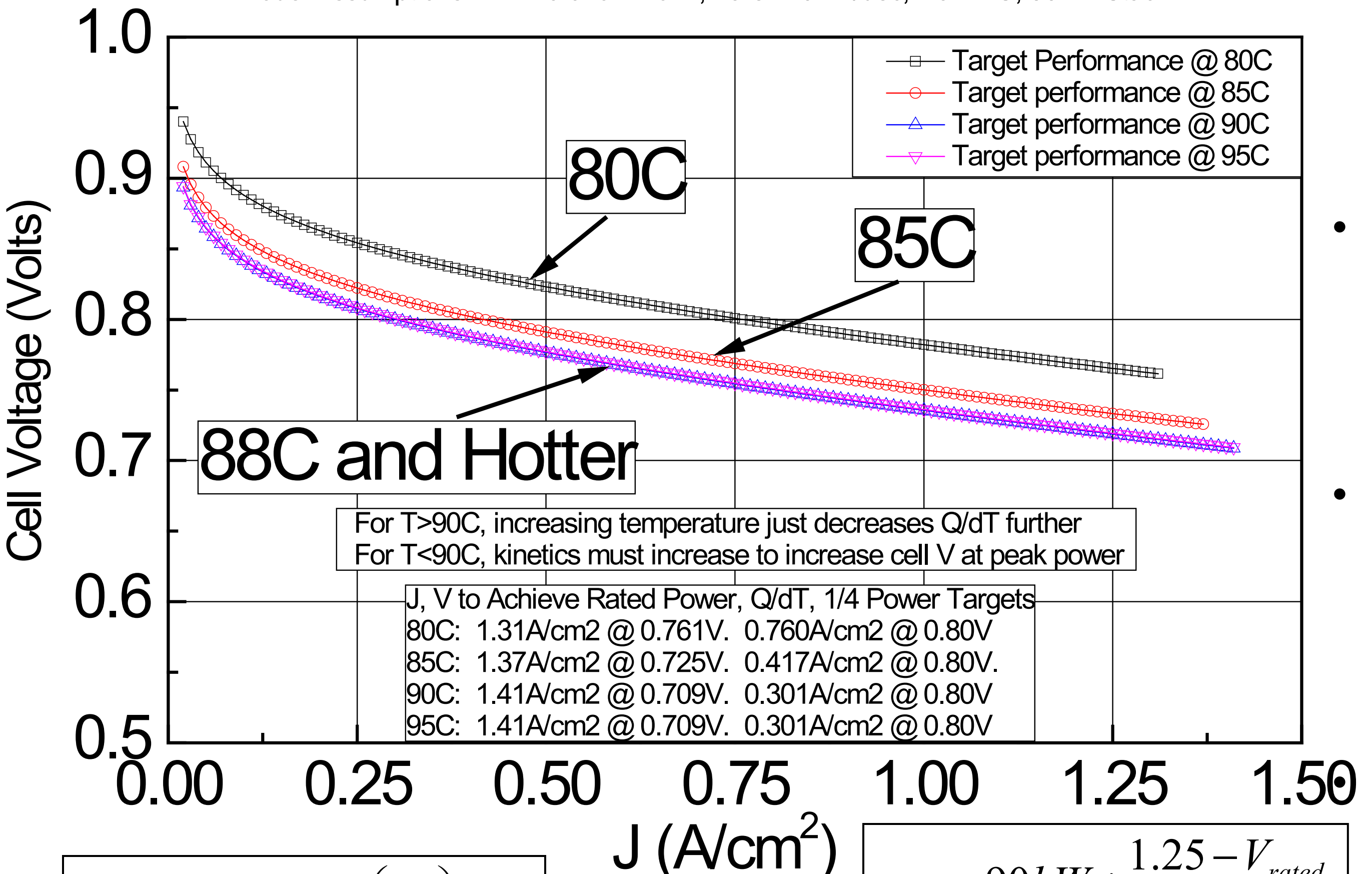
Technical Back-Up Slides

Target Polarization Curves Calculation

Performance Needed To Simultaneously Achieve DOE2017 MEA Targets At Various Cell Temperatures

Targets Addressed: J @ 1/4 Power (0.8V, 0.30A/cm^2), Rated Power (1W/cm^2), and Q/ΔT (1.45kW/degC)

Model Assumptions: HFR: 0.04ohm-cm^2, Tafel: 70mV/dec, No MTO, 90kW Stack



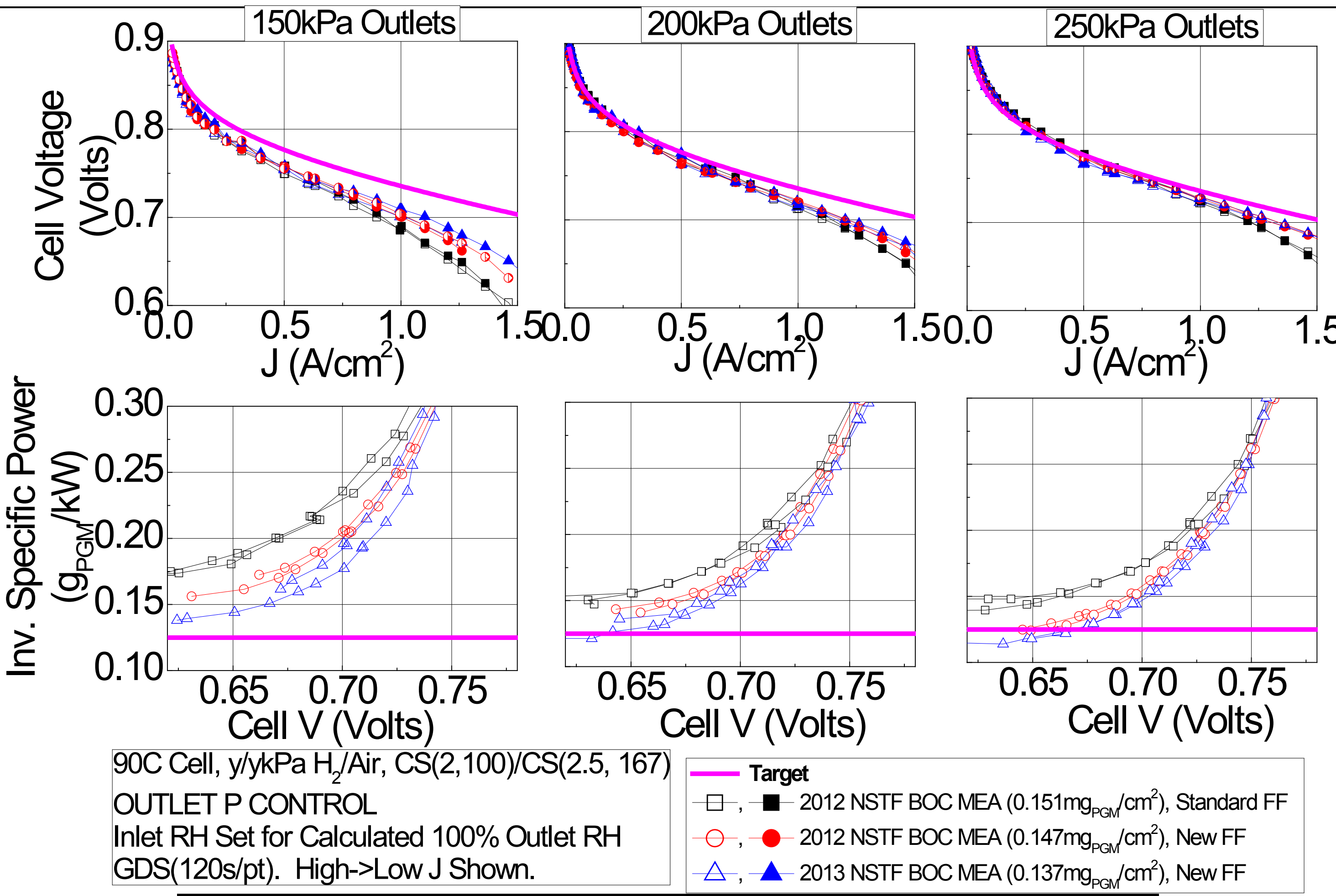
$$V = V_0 - 0.07LOG\left(\frac{J}{J_0}\right) - JR$$

$$\frac{Q}{\Delta T} = \frac{90kW * \frac{1.25 - V_{rated}}{V_{rated}}}{T_{rated} - 40C}$$

- Calculated polarization curves which simultaneously meet ¼ power, Q/ΔT, and rated power targets.
- Required performance *decreases* as cell temperature *increases* to 88°C (Q/**ΔT**)
- Q/ΔT target puts strict requirements on:
  - Cell T (≥88°C)
  - HFR (≤0.04ohm-cm^2)

Peak power (1W/cm^2) occurs at < 1.5A/cm^2 and >0.70V.

Performance Progression – March ‘12 to March ‘13



XRF Determined Pt Content for 2013 Best of Class MEA		
Measured on substrate prior to CCM fabrication.		
	Anode: PtCoMn	Cathode: Pt_3Ni_7, Dealloy+SET
Meas. #	Pt content (mg/cm^2)	Pt content (mg/cm^2)
AVG (#)	0.019 (2)	0.116 (8)
RSD (%)	1.5	2.5

Accomplishments and Progress

Water Management Modeling for Cold Start (Task 3):

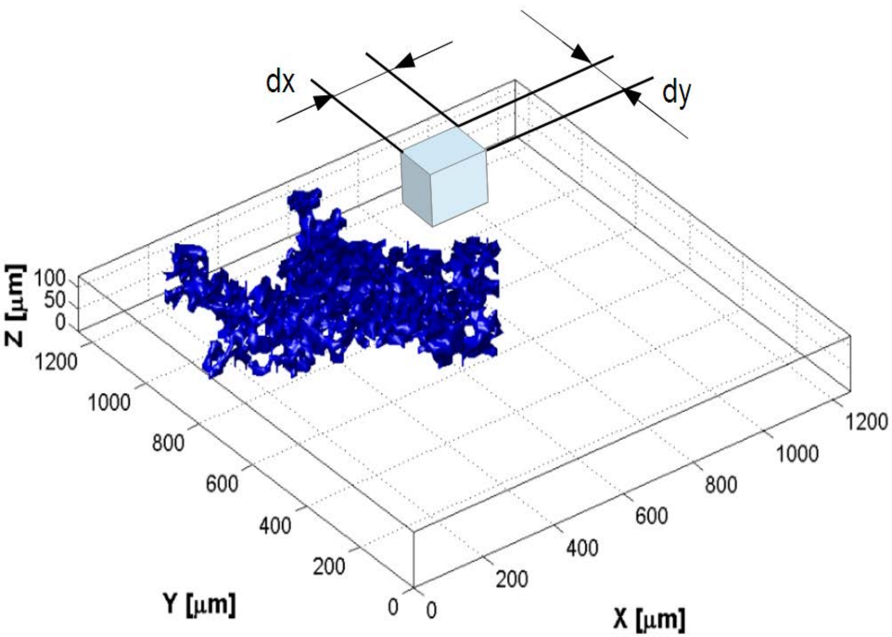
GDL – MEA Model Integration

Water Transport in MEA model (Macro Scale)

- Effective liquid permeability "k"
- Effective vapor diffusion coefficient "D"

Water Transport in GDL Model (Pore Scale)

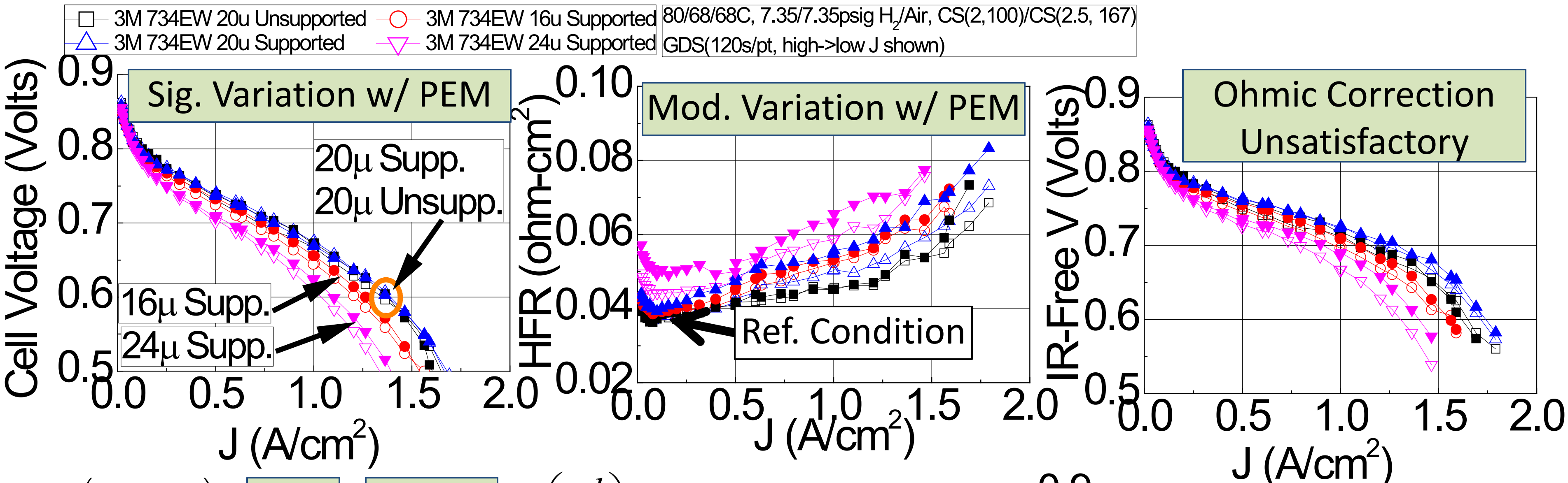
- Poiseuille flow liquid transport
- Concentration dispersion vapor transport



Proposed Integration Method

- MTU will generate lookup tables of "k" and "D" of discrete volumes from the GDL model, as function of:
  - Position
  - Local conditions (T, RH, P)
  - Pore morphology (size, distribution)
- LBNL will modify MEA model to utilize lookup tables.

Area Utilization Including Assumptions

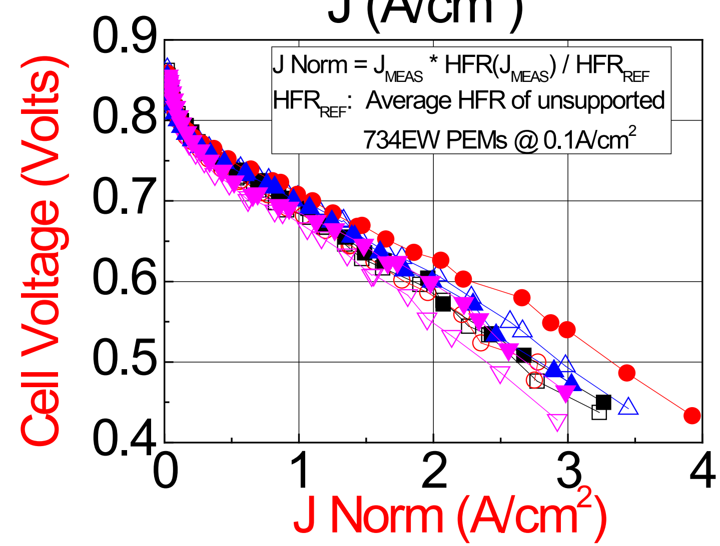


$$HFR(\Omega \cdot cm^2) = \underset{\text{FRA}}{R_{MEAS}} * \underset{\text{Cell Area}}{A_{ASSUMED}} = \left(\frac{\rho l}{A}\right)_{MEAS} * A_{ASSUMED}$$

THREE ASSUMPTIONS		
$A_{MEAS} \leq A_{ASSUMED}$ for all J	$\rho l \cong c$ for all J; meas at ref condition	$\frac{A_{MEAS}}{A_{ASSUMED}} \cong 1$ At ref cond.

$$U(J)_{ACTIVE} = \frac{R_{REF}}{R(J)_{MEAS}} = \frac{A(J)_{MEAS}}{A_{REF}}$$

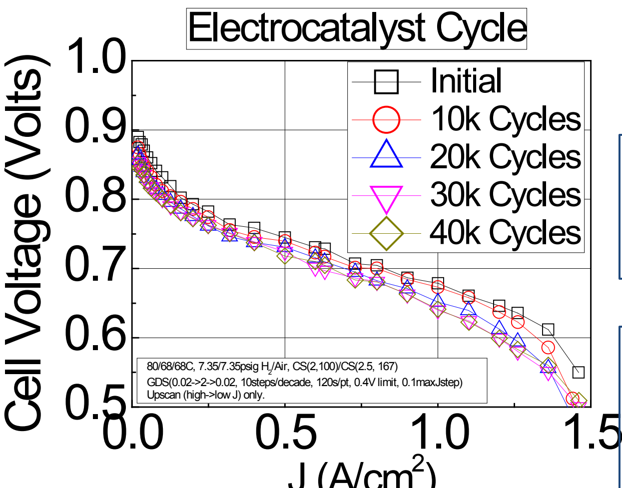
$$J_{NORM} = \frac{J_{MEAS}}{U(J_{MEAS})_{ACTIVE}}$$

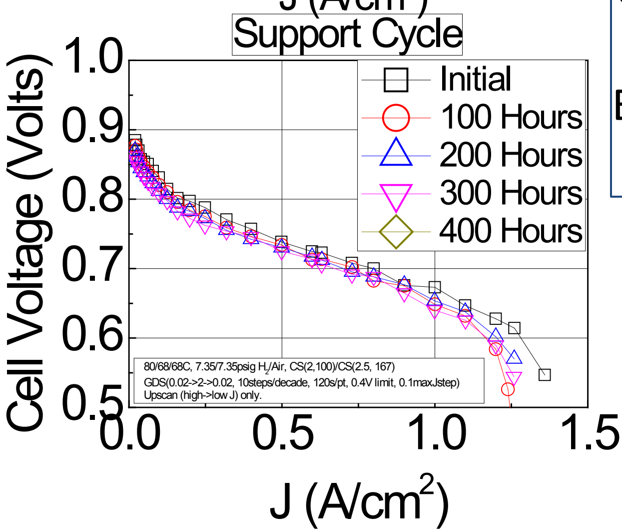


Accomplishments and Progress

Durability Evaluation and Perf. Degradation Mitigation (Task 5):

Support, Electrocatalyst Durability of 0.107mg_{PGM}/cm^2 Pt_3Ni_7/NSTF





Losses After Cycles Primarily Kinetic

Passes Specific Area, Cell V Loss Metrics; Mass Activity Loss Exceeds Acceptable Level

Improved M.A. durability to be addressed within and outside project.