Power for the Real World

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

Andrew Steinbach
3M Company
June 10th, 2015

Powered by 3M

Project ID: FC104

Project Overview

Timeline

- Project start: 9/1/12
- Project end: 8/30/15

Budget

- Total DOE Project Value: $4.606MM*
- Total Funding Spent: $3.691MM*
- Cost Share Percentage: 20%

* Includes DOE, contractor cost-share, and FFRDC funds, as of 2/28/15.

Barriers

A. MEA Durability
B. Stack Material & Mfg Cost
C. MEA Performance

Partners

- Johns Hopkins Univ. (J. Erlebacher)
- Oak Ridge Nat'l Lab. (D. Cullen)
- Lawrence Berkeley Nat'l Lab.(A. Weber)
- Michigan Technological Univ. (J. Allen)
- Freudenberg FCCT (V. Banhardt)
- Argonne Nat'l Lab. (R. Ahluwalia)
- Los Alamos Nat'l Lab. (R. Mukundan, R. Borup)
- General Motors (B. Lakshmanan)

Objective and Relevance

Overall Project Objective: Development of a durable, low-cost, robust, and high performance membrane electrode assembly (MEA) for transportation applications, able to meet or exceed the DOE 2020 MEA targets.

Primary Objectives and Approaches This Year	Barriers Addressed
1. Improve MEA Robustness for Cold Startup and Load Transient via Materials Optimization, Characterization and Modeling.	B. Cost C. Performance
2. Evaluate Candidate MEA and Component Durability to Identify Gaps; Improve Durability Through Material Optimization and Diagnostic Studies.	A. Durability
3. Improve Activity, Durability, and Rated Power Capability of Pt_3Ni_7/NSTF Cathodes via Post-Process Optimization and Characterization.	A. Durability B. Cost C. Performance
4. Integrate MEAs with High Activity, Rated Power, and Durability with Reduced Cost.	A. Durability B. Cost C. Performance

MEA, Catalyst Targets Addressed		
2020 Target	**Target Values**	**Obj.**
$Q/\Delta T$	1.45kW / °C	3,4
Cost	$7 / kW	3,4
Durability with cycling	5000 hours w/ < 10% V loss	2,3,4
Performance @ 0.8V	0.300A/cm^2	3,4
Performance @ rated power	1W/cm^2	3,4
PGM Content (both electrodes)	0.125g/kW$_{RATED}$ 0.125mg$_{PGM}$/cm^2	3,4

Approach, Milestones, and Status v. 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, cathode interfacial layers, and flow fields for best overall MEA performance, durability, robustness, and cost.

1. Place appropriate emphasis on key commercialization and DOE barriers.
2. Through advanced diagnostics, identify mechanisms of unanticipated component interactions resulting from integration of low surface area, low PGM, high specific activity electrodes into MEAs.

MS ID	QTR	Project Milestone MS 1.2, 2.2, 4.2, and 5.2 based on Achievement of Multiple Project Goals (See Backup Slides)	% Complete (Apr. '15)
BUDGET PERIOD 2 (June '14-Aug. '15)			
1.2	11	**Comp. Cand. Meet Project Perf./Cost Goals.**	**97%**
2.2	11	**Comp. Cand. Meet Project Cold-Start Goals.**	**50% (2 of 4)**
5.2	11	**Comp. Cand. Meet Project Durability Goals.**	**82% (9 of 11)**
4.2	**11**	**Best of Class MEA Meets All Perf./Cost, Cold-Start, and Durability Project Goals**	**80%**
3.2	12	**Validation of Integrated GDL/MEA Model With ≥ 2 3M MEAs (Different Anode GDLs).**	**30%**
6.3	12	**BOC MEA: Short Stack Eval. Complete.***	**10%**
0	12	**Final Short Stack to DOE. ***	**0%**

*: Work contingent upon achievement of 3 operational robustness metrics (US DRIVE FC Tech Team draft protocol).

Status Against DOE 2020 Targets		
Characteristic	**2020 Targets**	**Status, '14 / '15**
Q/ΔT (kW / °C)	1.45 (@ 8kW/g)	1.45 (@ 6.2/6.5* kW/g)
Cost ($ / kW)	7	6 / 5* (PGM only @ $35/$g_{Pt}$; 0.692V)
Durability with cycling (hours)	5000	NA (In progress)
Performance @ 0.8V (mA/cm²)	300	125 / 304*
Performance @ rated power (mW/cm²)	1000	796 / 855* (0.692V, 1.45kW/°C)
PGM total content (g/kW (rated))	0.125	0.162 / 0.155* (0.692V, 1.45kW/°C)
PGM total loading (mg PGM / cm² electrode area)	0.125	0.129 / 0.133*

*: 2015 values from 2015(Mar.) Best of Class MEA, which includes a cathode interlayer with 15μg-Pt/cm²

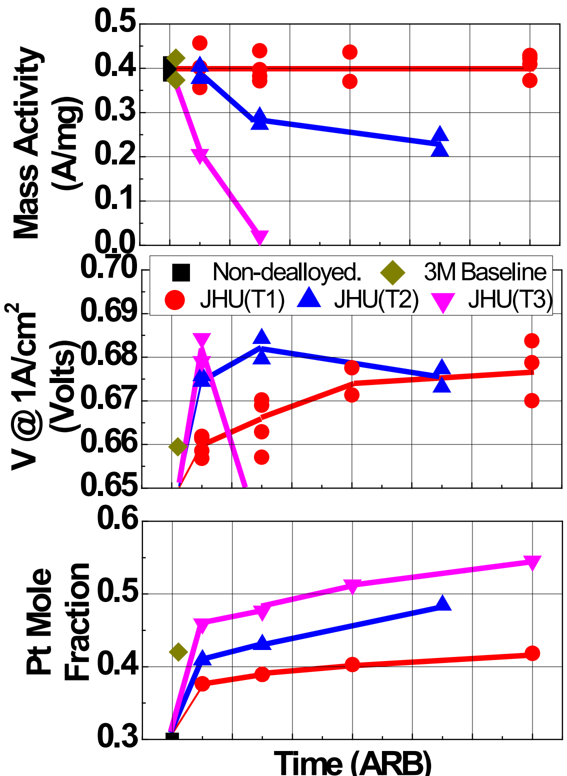
3M

Accomplishments and Progress

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

JHU Chemical Dealloying Process Development for Pt_3Ni_7/NSTF

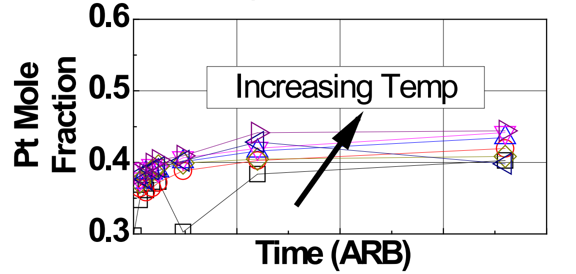
Dealloy Factor Study



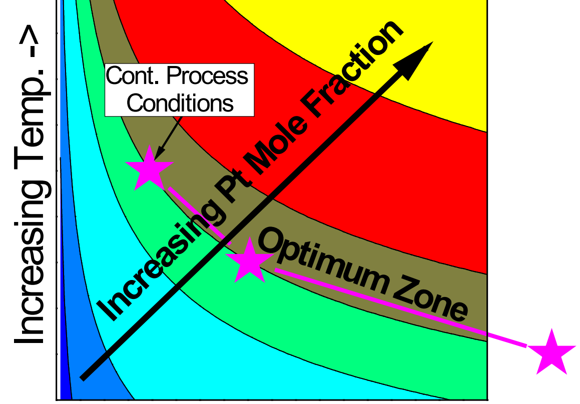
- Pt mole fraction and H_2/Air V increase with dealloy time and temp., but activity suffers if dealloying is too aggressive.
- Optimum: 40-42 at% Pt.

Process Map Development

Composition Sens. to Time, Temp. 7 Temps, 7 Times. Batch



JHU Dealloy Process Map

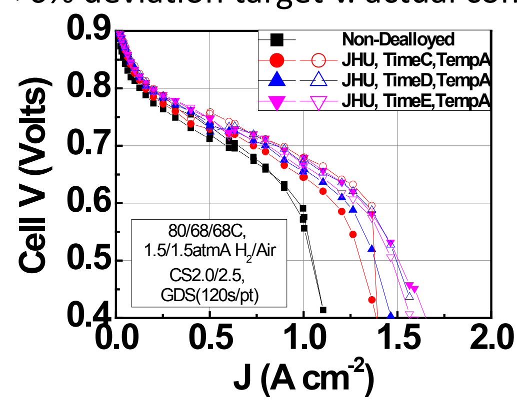


- Composition response functionalized (time, temp).

Continuous Dealloy Trials

Coded Time	Coded Temp	Target Pt at%	Actual Pt at%	MEA Mass Activity (A/mg)
C	A	39	40±0	0.33±0.05
D	A	40	42±0	0.39±0.00
E	A	42	44±1	0.34±0.00
D	B	41	43±0	TBD
B	C	41	41±0	TBD
A	D	41	41±0	TBD

Process in control (< 6% deviation target v. actual comp.)



Substantially improved limiting current density v. non-dealloyed

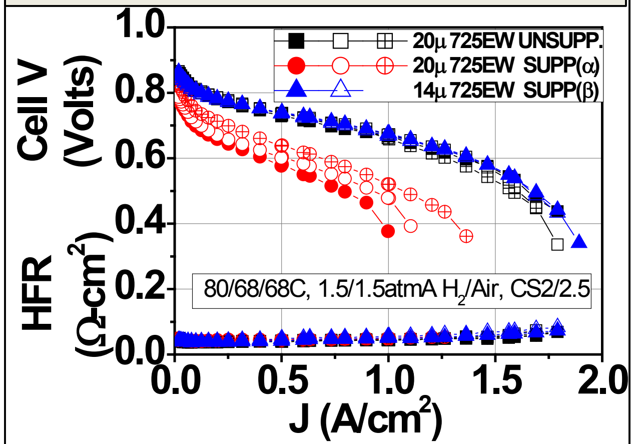
High Activity and High J Downselect: Time D, Temp A

Accomplishments and Progress

Durable, Improved Conductivity PEMs (Task 1.3):

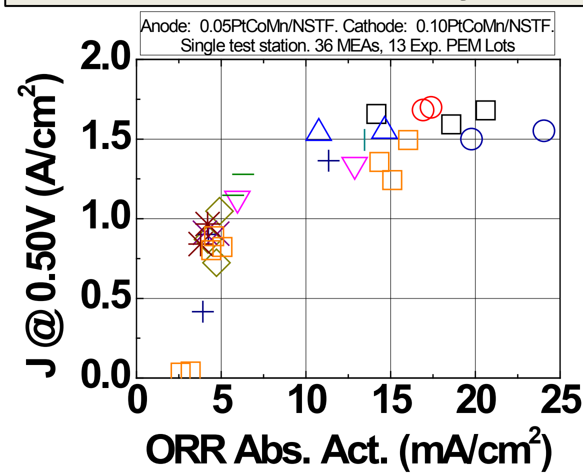
3M-S Integration with NSTF Electrodes – Major Challenge Resolved

Impact of PEM Variable (w/ 0.10PtCoMn/NSTF cathode)

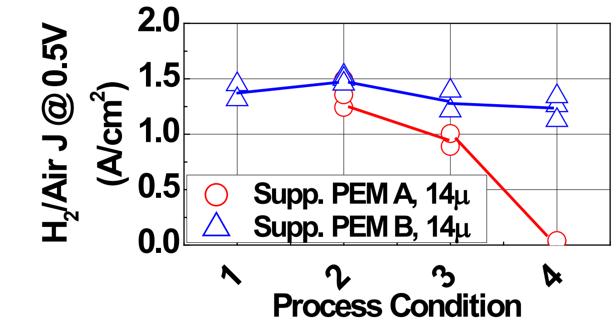


- As 3M-S PEM was varied, H_2/Air performance varied unexpectedly; observed with multiple experimental lots.
- **Key issue preventing integration of durable, conductive 3M-S PEM.**

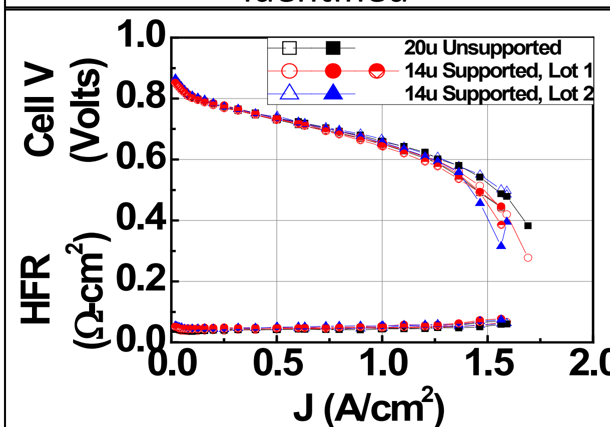
PEM Impact on Cathode Activity



- Key result – MEAs with severe H_2/Air loss also have suppressed ORR
  - ***Suppression induced by PEM.***
  - **Strong effect only observed w/ ultra-low PGM PtCoMn/NSTF cathode.**



Key material and process factors identified



Solution validated in 2 lots

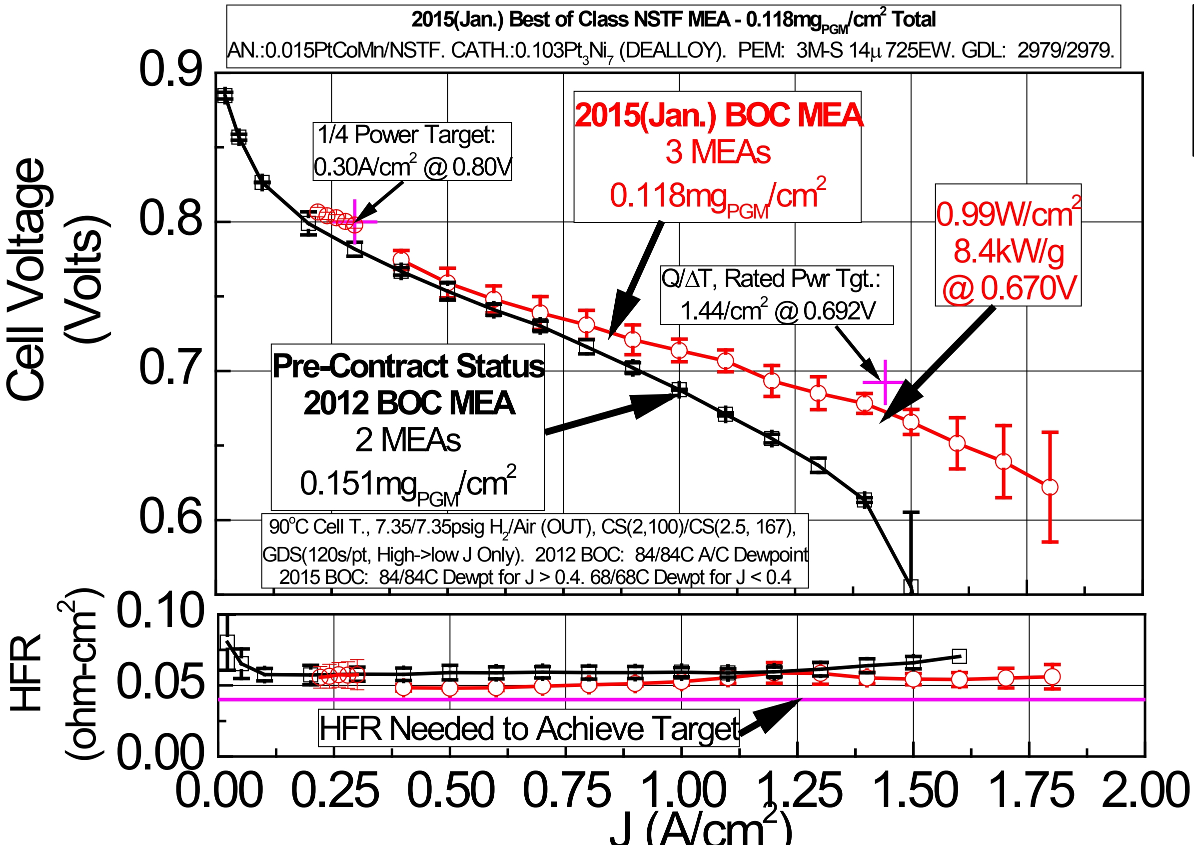
ISSUE RESOLVED

Downselect: 3M-S 725EW 14μ w/ additive, Type [B,2]

Accomplishments and Progress

Best of Class Component Integration (Task 4.1):

2015(Jan.) 3M NSTF Best of Class MEA



- PGM content and Q/ΔT targets achieved.
- Within 10-15% of rated and specific power (@ 0.692V) and 0.80V targets.
- Rated and specific power achieved @ 0.67V.

Characteristic	Unit	Target	Value
Performance @ 0.80V	mA/cm^2	≥300	280
Q/ΔT	kW/°C	≤ 1.45	1.45 (@ 7.3kW/g, 90°C)
Performance @ rated power	mW/cm^2	≥ 1000	861 (@0.692V)
Specific Power	g/kW	≤ 0.125	0.137 (@0.692V)
PGM Content	mg/cm^2	≤ 0.125	0.118

Key Improvements Over 2012

1. **Improved dealloyed Pt_3Ni_7/NSTF – high J, 0.39A/mg mass activity (MEA), and reduced loading ($0.103mg_{Pt}/cm^2$).**
2. **725 EW PFSA, 3M-S 14μ PEM – ORR suppression minimized.**
3. **Improved H_2/Air kinetics - *FF* flooding** minimized via low RH.
4. **Minimized anode Pt ($0.015mg/cm^2$).**
5. Narrower flow field land/channels.

Path to 2020 MEA Performance/Cost Targets:

1) Increase 0.80V H_2/Air Activity (+10% Absolute Activity)
2) Reduce HFR 14mohm-cm² (Reduce interface R and Ni leaching)

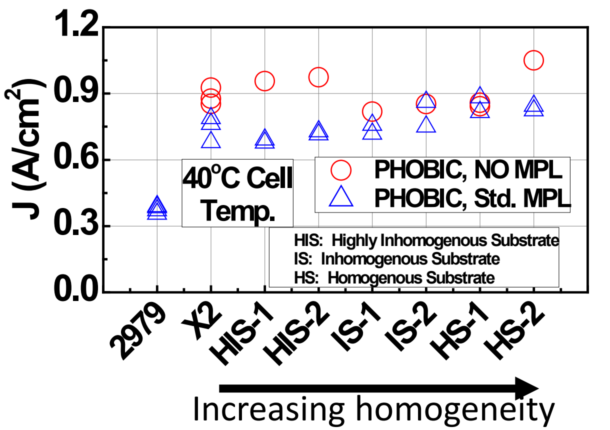
Accomplishments and Progress

Anode GDL for Improved Operational Robustness (Task 2.1):

Structured Freudenberg Papers; Thickness; Hydrophobic Treatment

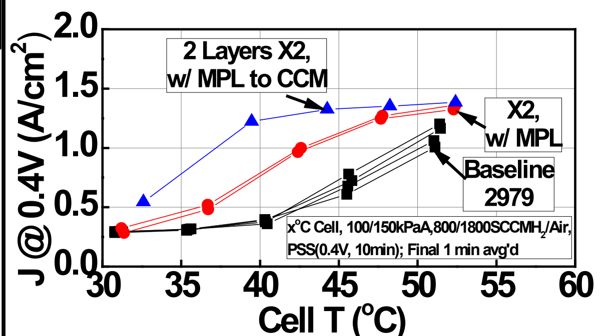
0.05/0.15PtCoMn/NSTF, 3M 20µ 825EW; 3M 2979 Cathode GDL. Anode GDL variable.

Structure-Controlled Freudenberg Backings

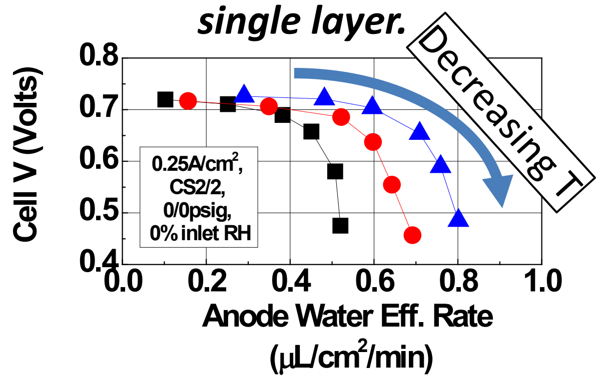


- Without MPL, response generally highest w/ highly inhomogenous (HIS) backings.
  - However, best overall was 1 of 2 homogenous backings (HS-2) (?)
- Std. 3M MPL quenches improved performance of HIS design.
- *All yield >2x higher J than baseline 2979.*

Backing Thickness (Layers)

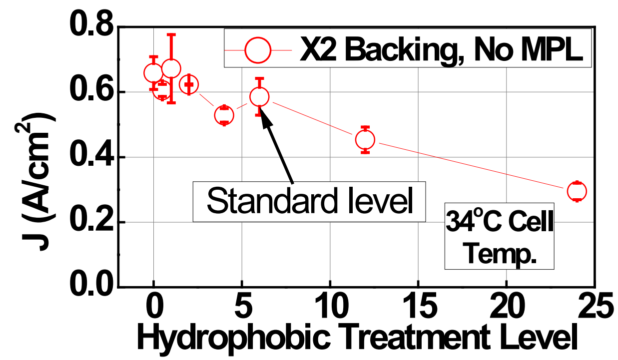


Unexpected result – ***2 X2 layers yields 50% gain in J @ 40 ℃ vs. single layer.***



Two layers of X2 increases anode water removal over single layer.

Hydrophobic Treatment



Performance improves w/ lower hydrophobic level.

Interim Downselect:

X2, std. phobic and std. MPL

Work in Progress

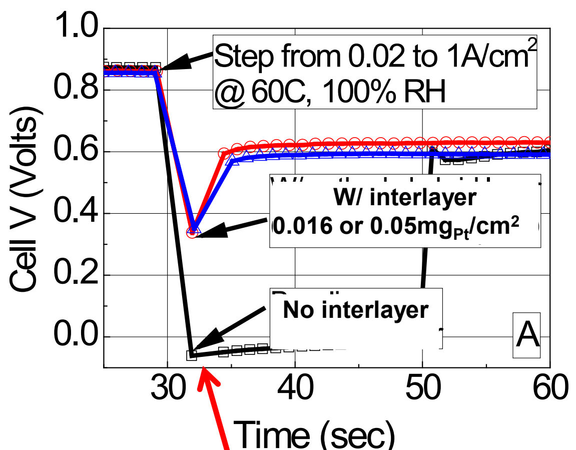
- 3M and Fruedenberg MPL optimization on "low" phobic X2.
- Assessment of two layer approach.

3M

Accomplishments and Progress

Interlayer for Improved Operational Robustness (Task 2.2): Cathode Interlayer Design Factors (Pt wt%; Scale-up; carbon type; HT)

Background

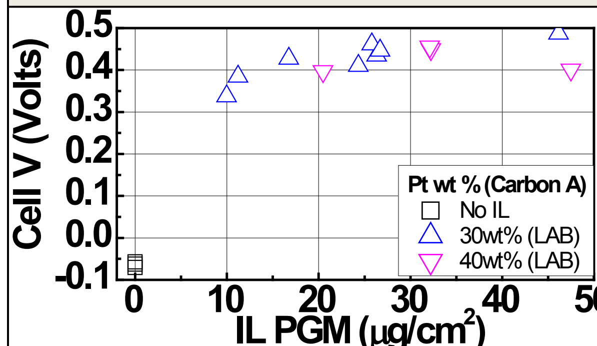


Metric: V @ 1A/cm², immediately after J transient, 60°C, 100% RH, CS2/2, 1.5/1.5atmA

Low PGM interlayer (dispersed electrode between NSTF cathode and GDL) improves NSTF MEAs' ability to rapidly transition from low to high J under condensing conditions.

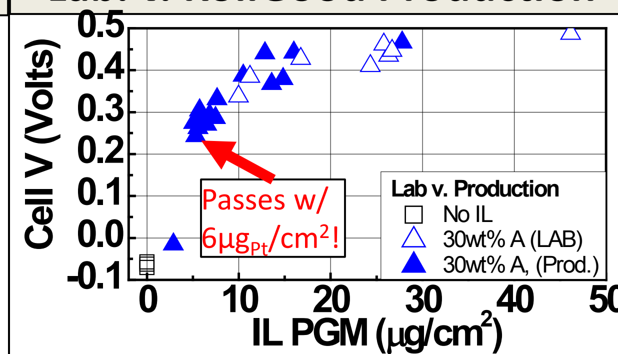
0.05/0.15PtCoMn/NSTF, 3M 20µ 825EW; X2 Anode GDL

Pt wt% on Carbon



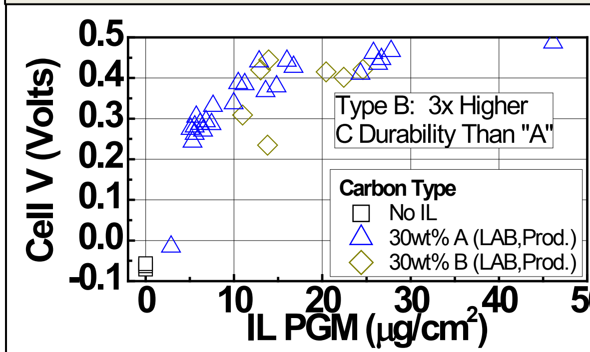
Little impact of IL thickness

Lab. v. RollGood Production



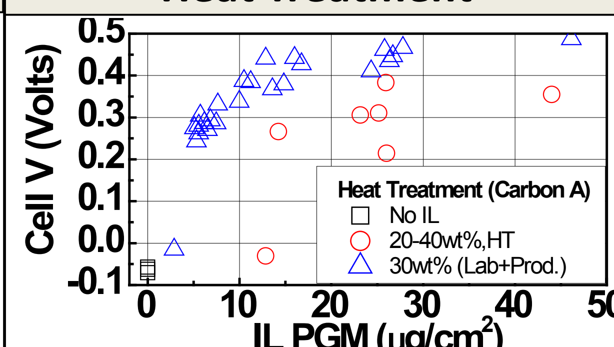
Good Overlap - *Scalable*

Carbon Type



3x Higher Durability "B" similar to "A"

Heat Treatment



HT of "A" induces strong, negative effect

***Interim* Downselect:** **30wt% Carbon A, no HT @ 15µg$_{Pt}$/cm²**

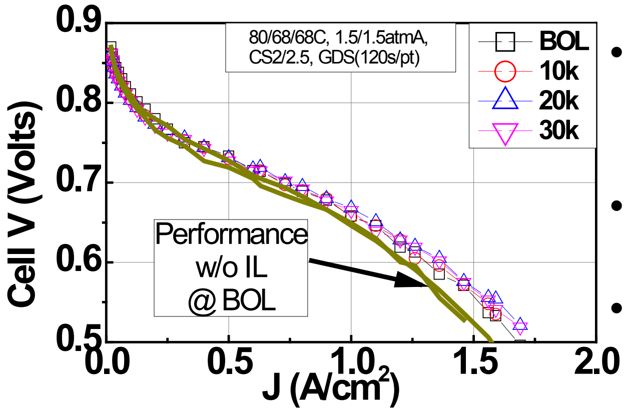
Accomplishments and Progress

Interlayer for Improved Operational Robustness (Task 2.2):

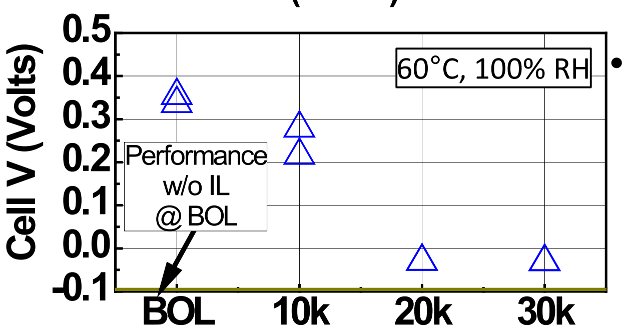
Electrocatalyst and Support Cycle Durability Evaluation

0.05/0.15PtCoMn/NSTF, 3M 20μ 825EW; X2 Anode GDL; Interim DS Cathode IL @ 25μg/cm²

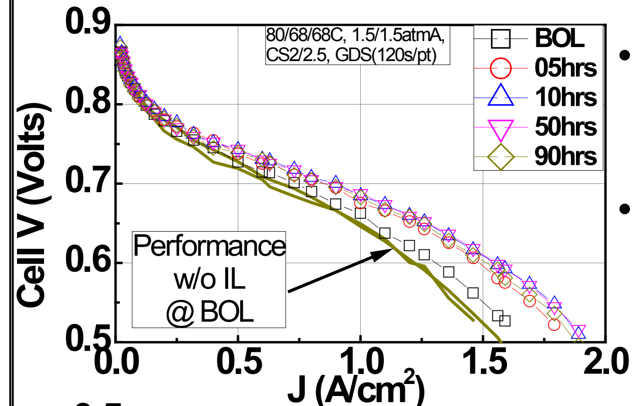
DOE Electrocatalyst Cycle 80°C, 30k Cycles (0.6-1.0V, 50mV/s)	DOE Support Cycle 80°C, 1.2V, 400 Hours (Previous)



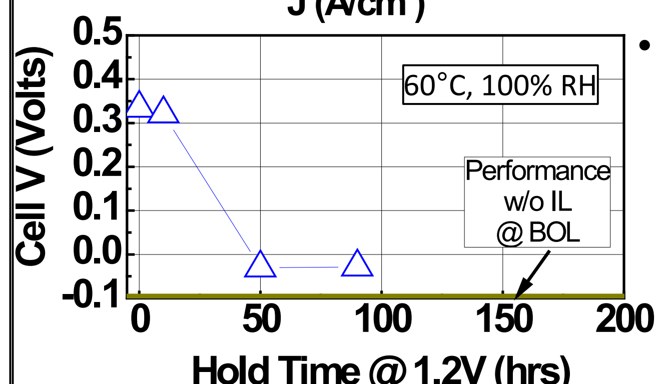
- Slight H_2/Air perf. *increase* w/ cycling.
- 15% mass activity loss
- *Passes DOE tgts*



- Load transient failure after 10k cycles, but still higher than no IL.



- *50mV gain @ 1.5A/cm²* after 5 hours
- 10% mass activity loss after 90 hours

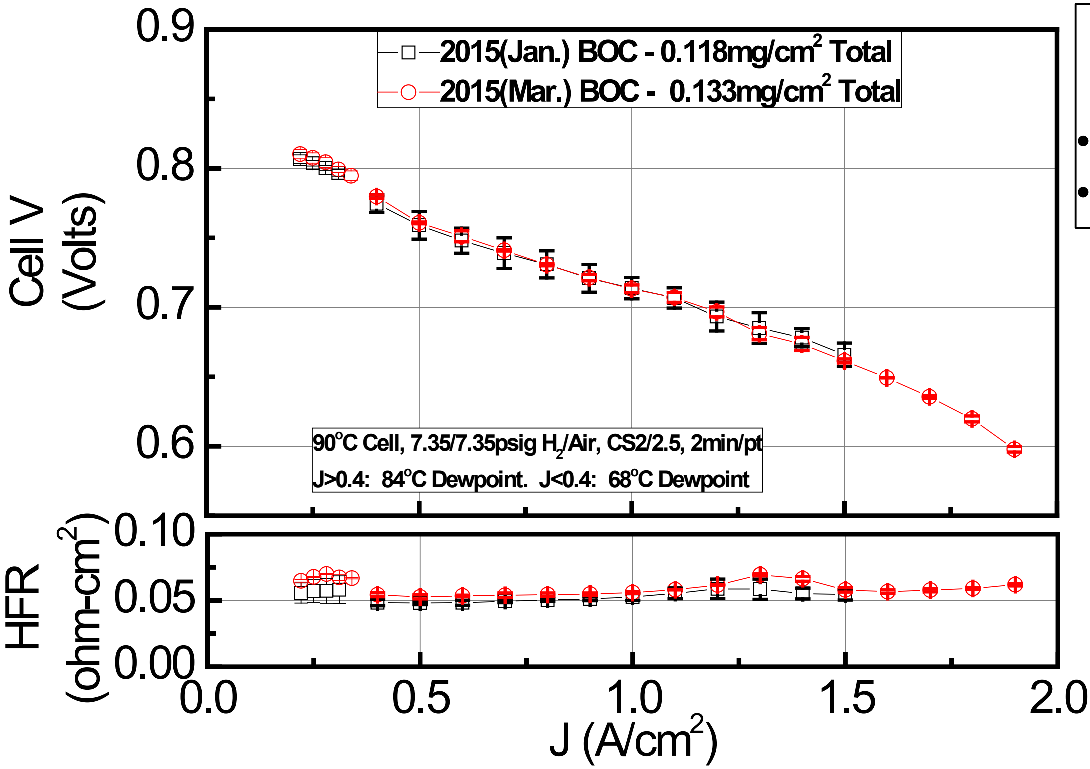


- Load transient failure after 10 hours.

Durability of Interim Downselect IL Likely Sufficient to Achieve DOE Targets, but Insufficient to Maintain Operational Robustness – Development Continues w/ Higher Durability IL (type B).

Accomplishments and Progress

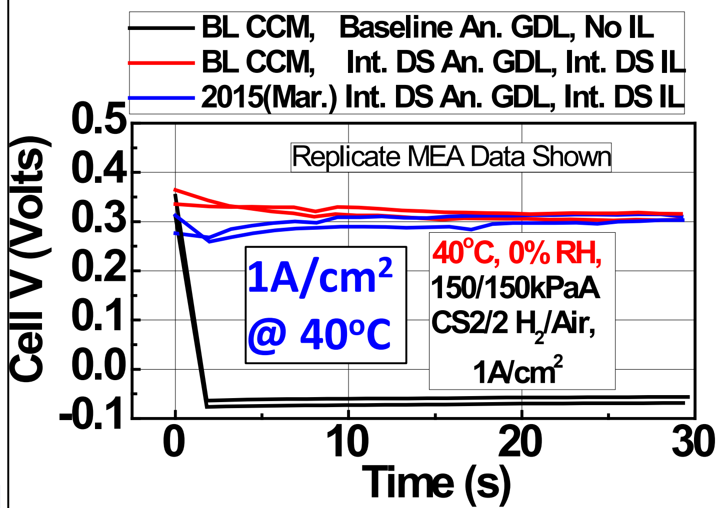
Best of Class Component Integration (Task 4.1): Integration of Improved Anode GDL, Cathode Interlayer w/ Best of Class CCM



Mar. BOC MEA: Jan. BOC CCM w/ X2 anode GDL and cathode IL (15$\mu g_{Pt}/cm^2$).

- ¼ Power target achieved.
- Rated power similar, but spec. power reduced.

Improved Operational Robustness



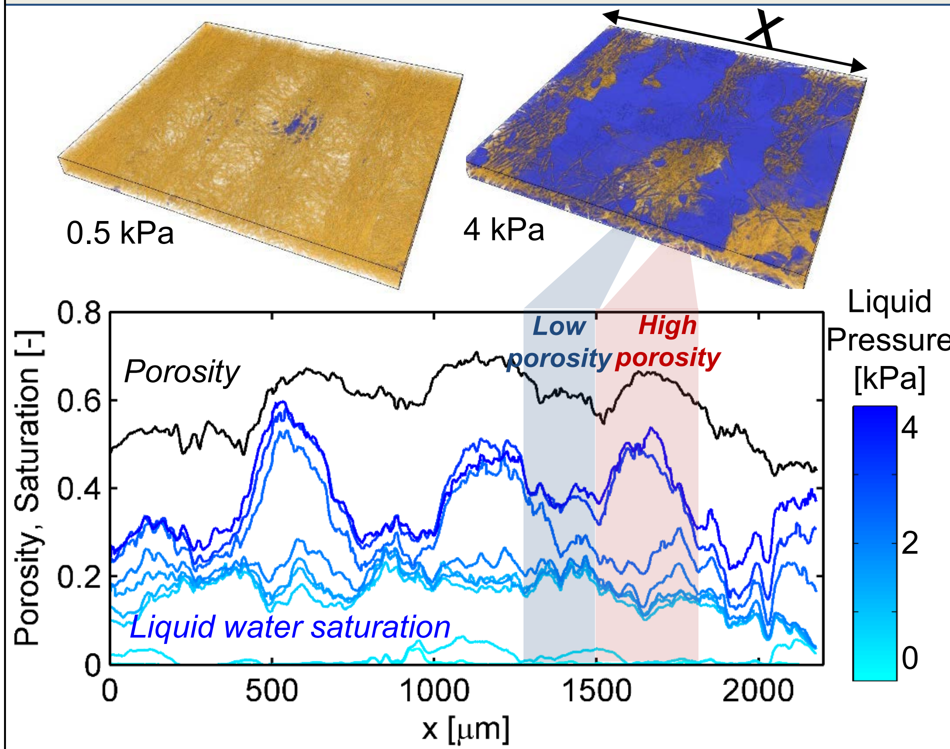
MEA	Total PGM (mg/cm^2)	Cathode	Anode GDL/ Cathode IL	J @ 0.80V (A/cm^2)	Spec. Power @ 0.692V (kW/g)
2015(Jan.) BOC	0.118	0.103 Pt_3Ni_7/NSTF (JHU Dealloyed)	Baseline/ None	0.280	7.3
2015(Mar.) BOC	0.133	0.103 Pt_3Ni_7/NSTF (JHU Dealloyed)	X2/ 30%,A(0.015)	0.304	6.5

+ 30°C improvement in $1A/cm^2$ load transient over baseline MEA (70→40°C)
– $15\mu g/cm^2$ additional PGM.
– Insufficient robustness durability.

Accomplishments and Progress

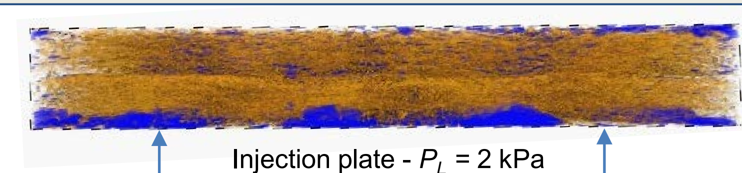
Cold Start Modeling (Task 3): X-Ray CT Provides Unique Insight of Liquid Water Transport within Anode Backings (LBNL, I. Zenyuk)

X2 Single Layer (Hydrophobic, no MPL)

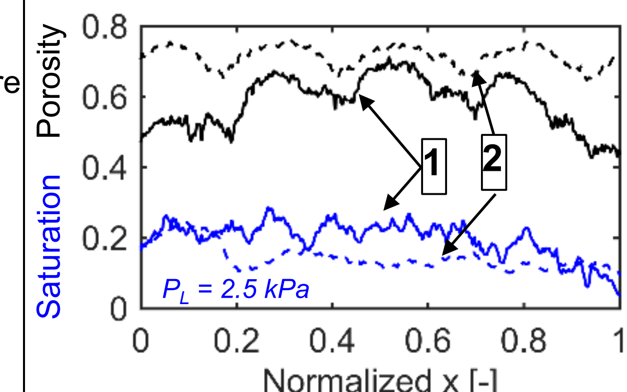


- Density modulation evident.
- Water preferentially fills high porosity bands w/ relatively low liquid pressure.
  - Low density regions provides low R pathway.

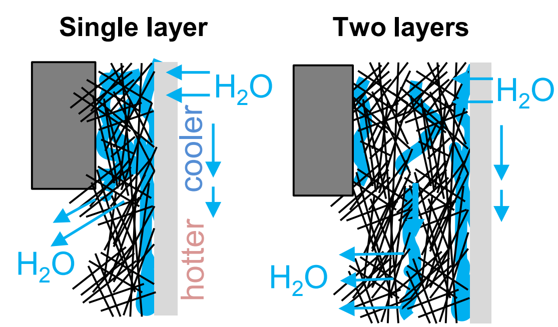
X2 Two Layers (Hydrophobic, no MPL)



Stacking generates complex 3D porosity profile



2x has higher porosity (interface) and lower saturation



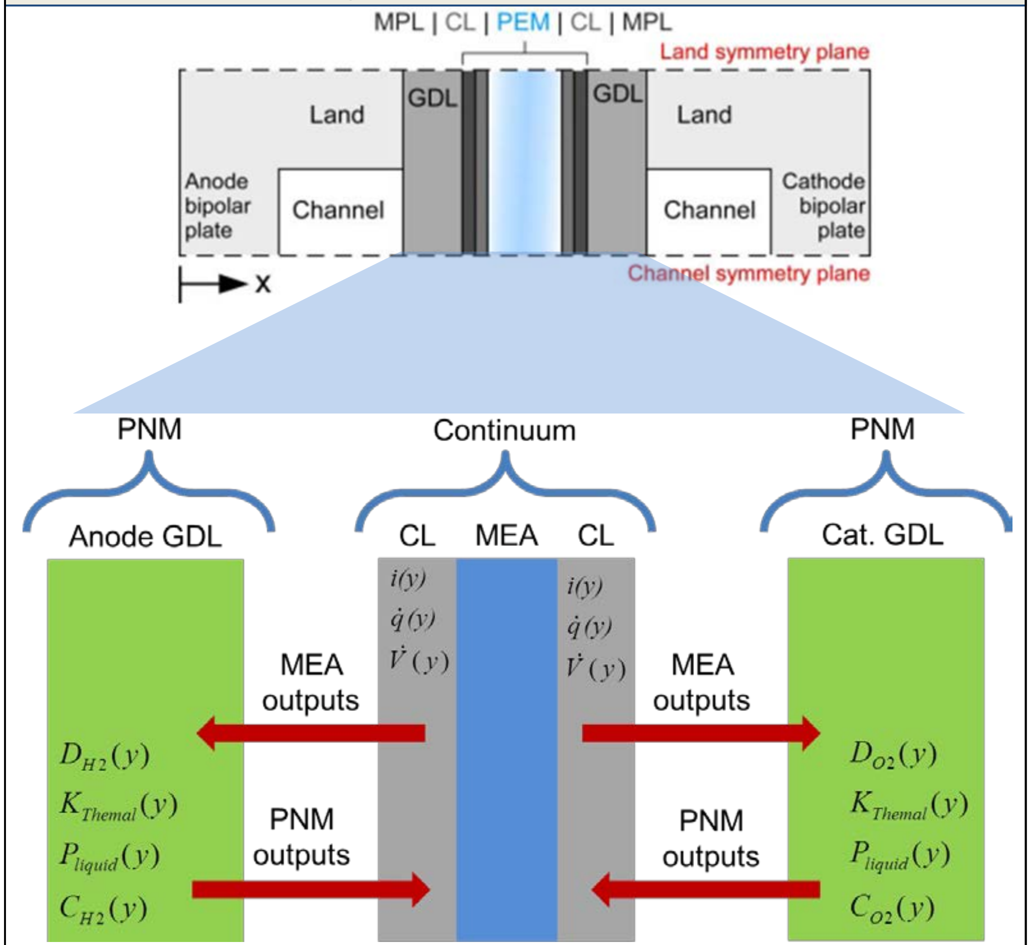
Hypothesis

Interface provides low R pathway for liq. water removal from cooler land area.

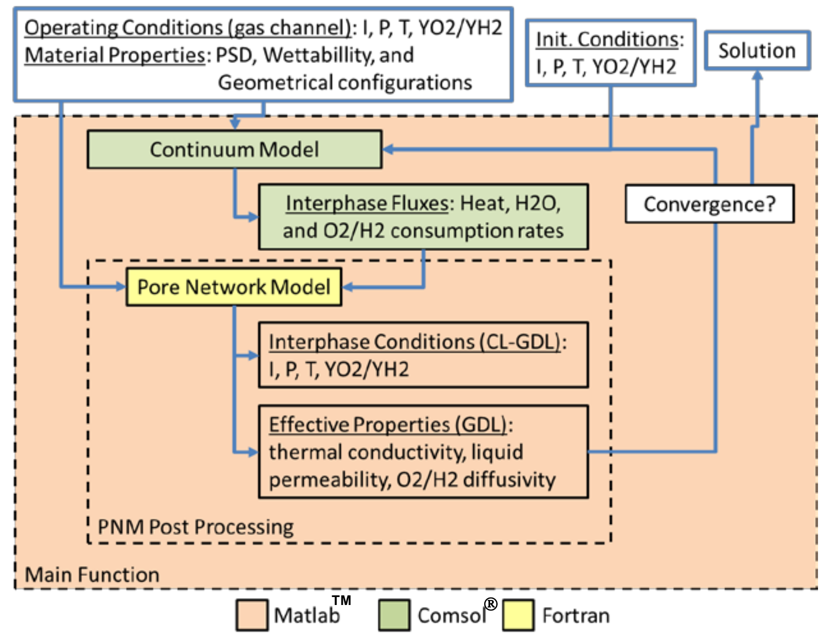
Accomplishments and Progress

Cold Start Modeling (Task 3): Integration of Michigan Technological University GDL Pore Network Model and LBNL MEA Model

Half-land half-channel coupled continuum-pore network fuel cell model



Coupling Algorithm

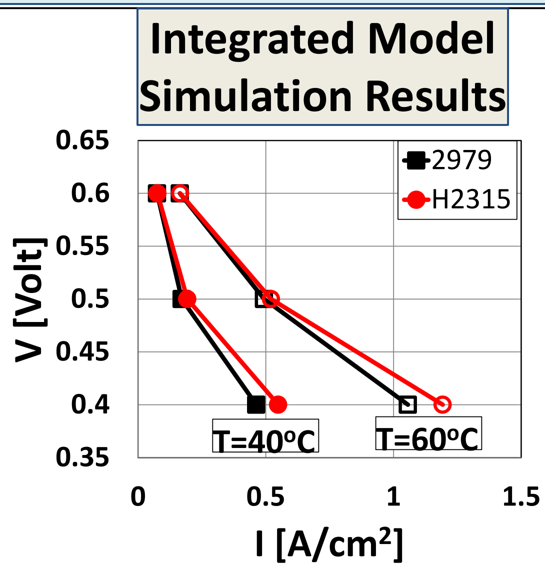


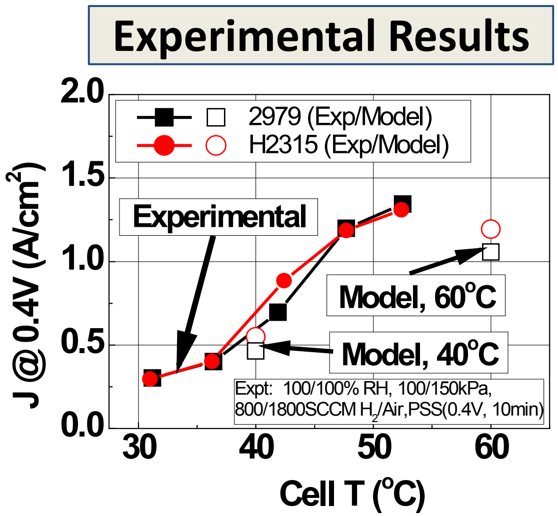
Coupling done through spatially-dependent effective parameters:

- Diffusivity (D)
- Thermal Conductivity (K)
- Liquid Permeability (P)
- Reactant Concentration (C)

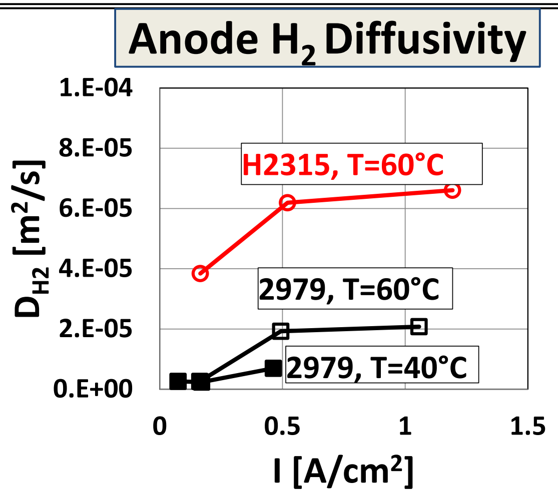
Accomplishments and Progress

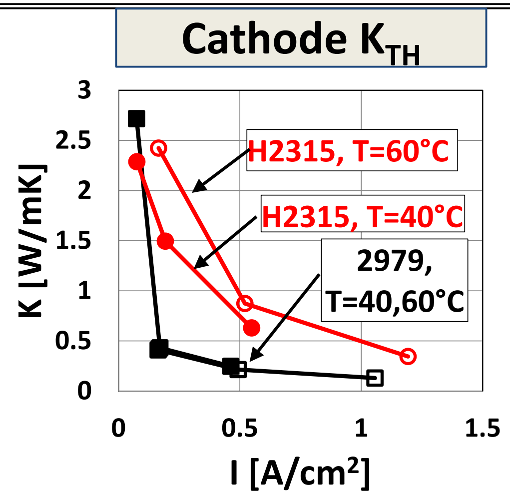
Cold Start Modeling (Task 3): Integration of MTU GDL Pore Network Model and LBL MEA Model





- Integrated continuum-PNM converges and agrees well with experiments at V = 0.4 V and 40°C.
  - Model predicts improved low T performance of H2315
  - Captures performance sensitivity to temperature.
- Two material sets validated: 2979 and H2315. Task 30% completed.





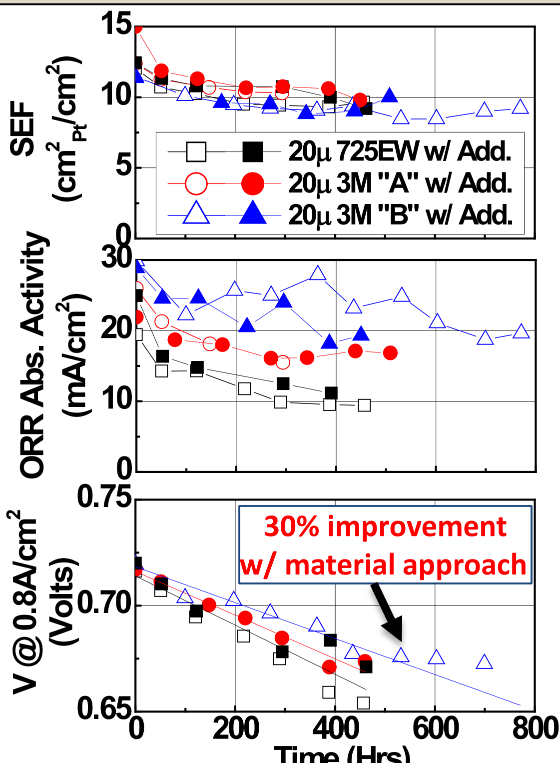
- Effective properties as predicted by PNM.
- H2315 has higher hydrogen diffusivity due to less flooding.
- Thermal conductivity is non-uniform due to thermo-osmosis and phase-change-induced flow

Accomplishments and Progress

MEA Rated Power Durability (Task 5): Improved PEM; Impact of Cell V

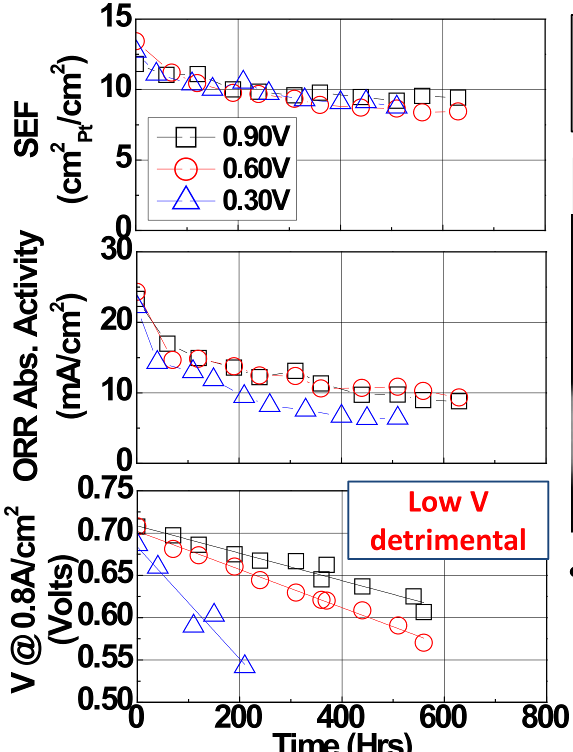
Baseline: 0.05/0.15PtCoMn/NSTF, 825EW 20µ PEM, Mod. Tech Team Load Cycle (90°C)

PEM Type



PEM Type	V @ 0.8A/cm² Accel. Factor
3M 725EW	**1**
3M "A"	**0.9**
3M "B"	**0.7**

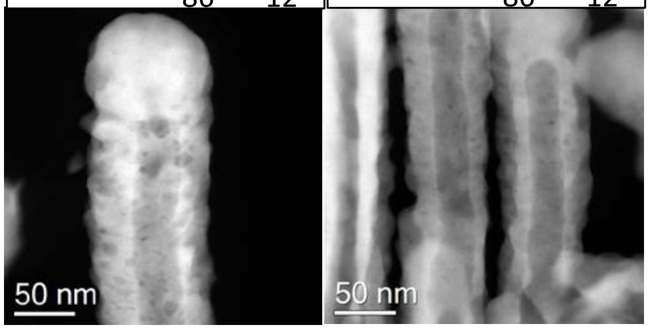
Cell Voltage (Potentiostatic Holds)



Cell V (Volts)	V @ 0.8A/cm² Accel. Factor
0.90	**0.7**
0.60	**1**
0.30	**2.3**

Post-Test Cathode Analysis
TEM/EDS (ORNL, D. Cullen)

0.9V – $Pt_{86}Co_{12}$ | 0.3V – $Pt_{86}Co_{12}$



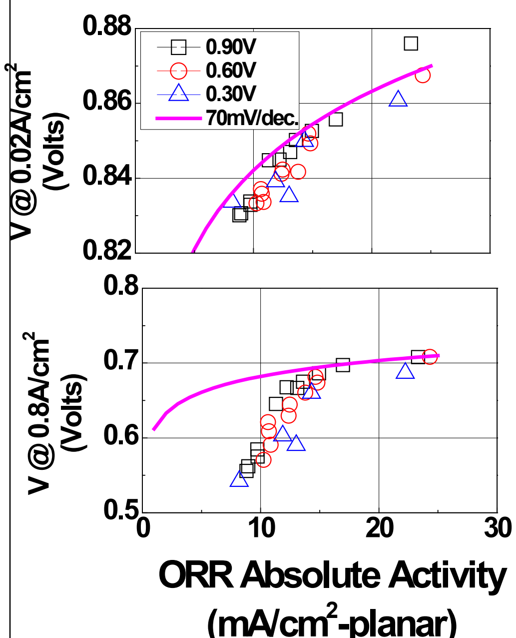
- Little apparent difference between low and high degraded MEA cathodes.
  - Similar whiskerrette smoothening (same SEF)
  - Identical final composition (initial: $Pt_{68}Co_{29}Mn_3$) – likely similar *intrinsic* specific activity
- More analysis in progress…

3M

Accomplishments and Progress

MEA Rated Power Durability (Task 5): Rated Power Loss Due to ORR Activity Loss; ORR Activity Loss Due to Two Factors (Cathode ECSA, PEM Decomposition)

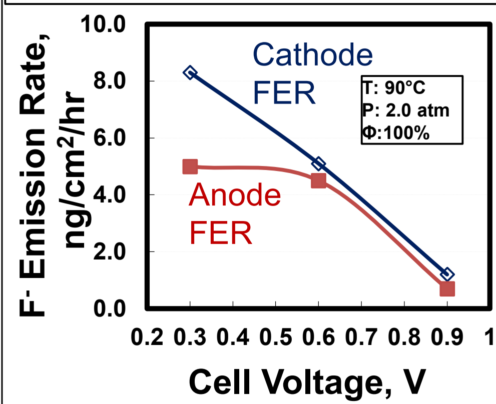
H_2/Air V v. ORR Activity



- **H_2/Air performance function of ORR activity, independent of hold V.**
- Not simple 70mV/dec relationship at high J

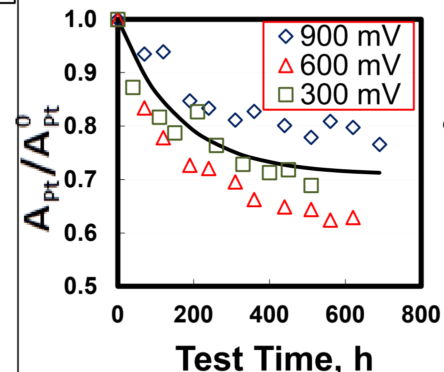
Factor Analysis by ANL (R. Ahluwalia and J-K Peng)

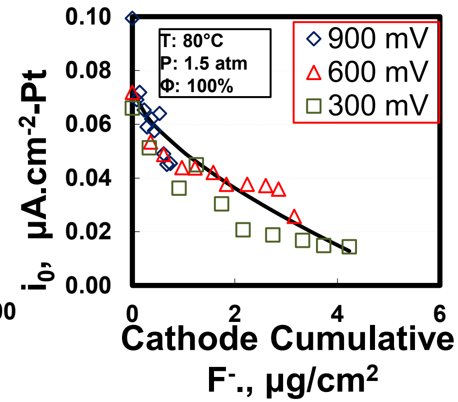
F^- Gen. During Holds



- Cathode FER increases w/ decreasing V, consistent with RRDE literature
  - $\%H_2O_2$ ↑ as E ↓
- Anode FER increases as V decreases from 0.9 to 0.6, then stabilizes.

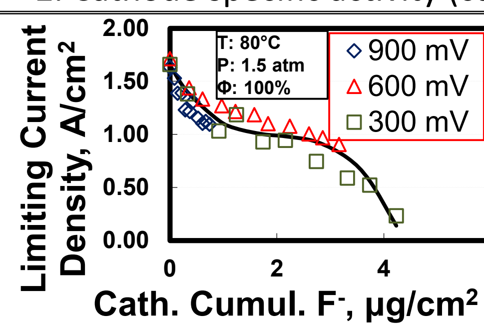
Loss Factor Breakdown





Loss is due to two independent(?) factors

1. Cathode Pt surface area (test time).
2. Cathode specific activity (cumulative F^- gen.).



Rated power loss correlates with PEM ionomer decomposition

Mitigation Path: 1) Develop Ionomers to Minimize Contaminant Generation 2) Maintain ORR > ~15mA/cm² (Active, Durable Cathodes). 3) Recovery Method Development

Response To Reviewers' Comments

Addressing NSTF MEA Operating Condition Sensitivity and Project Approach

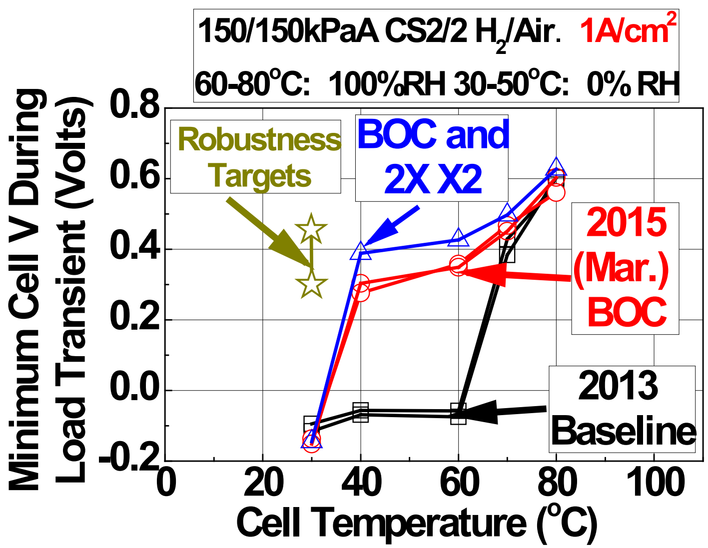
- "The **Pt/C interlayer** is of **limited value** because there are **additional process costs and durability issues** with inclusion of such a layer. … Although the … **anode** … **(GDL) designs have demonstrated improvements**, MEA temperature performance is still significant and … **difficult to incorporate "as-is" in an automotive application**.
- "**NSTF has serious issues** that must be addressed … **difficulty to break in, high sensitivity to contaminants, extreme sensitivity to low temperatures, and durability**. **The only way to address … is to make some serious changes to the electrode configuration**. **Instead**, this project is focused on **minor changes** that are having only a **minor impact**"

•***The anode GDL and cathode interlayer approach has****:*

- ***more than doubled the stable operating temperature range*** *in high heat capacity single cells; stack testing is needed to determine if sufficient.*
- ***demonstrated high durability*** *(rated power performance, mass activity)* ***in ASTs****, similar to NSTF MEAs w/o ILs. Enhanced operational robustness durability is being actively addressed.*

•***Changes to electrode configuration could feasibly resolve operating condition sensitivity, but raises host of other issues*** *(e.g. O_2 transport through ionomer film issue which limits min. PGM with traditional dispersed electrodes).* ***Large project well beyond 2011 FOA scope.***

1A/cm² Load Transient Capable Operational Temperature Range *Doubled* w/ Project Approach



Collaborations

3M – Project management; Materials and process optimization; MEA integration

- A. Steinbach, D. van der Vliet, C. Duru, D. Miller, I. Davy (Core)
  - Cathode Integration: A. Hester, D. Lentz, S. Luopa, D. Tarnowski, B. Smithson, C. Studiner IV, A. Armstrong, M. Stephens, J. Bender, M. Brostrom
  - PEM Integration: M. Yandrasits, D. Peppin, G. Haugen, R. Rossiter
  - Anode GDL/Cathode IL: M. Pejsa, A. Haug, J. Abulu, J. Sieracki
  - Durability: A. Komlev

Michigan Technological University – GDL char. and PNM modeling; model integration

- J. Allen, E. Medici, V. Konduru, C. DeGroot

Johns Hopkins University - Pt_3Ni_7/NSTF dealloying method studies

- J. Erlebacher

Lawrence Berkeley National Laboratory – GDL char. and MEA modeling; model integration

- A. Weber, J. MacDonald, I. Zenyuk, A. Kusoglu, S. Shi

Oak Ridge National Laboratory – Materials characterization (TEM, XPS)

- D. Cullen, H. Meyer III

Los Alamos National Laboratory – Accelerated Load Cycle Durability Testing

- R. Borup, R. Lujan, R. Mukundan

Argonne National Laboratory – NSTF HOR/ORR kinetic modeling, ORR activity/perf. modeling

- R. Ahluwalia, X. Wang, J-K Peng

General Motors - Stack Testing

- B. Lakshmanan

Remaining Barriers

A. 2015(Mar.) Best of Class MEA does not achieve the DOE 2020 total loading and specific power targets, in part due to cathode interlayer PGM content.

B. Enhanced robustness achieved w/ cathode interlayer is insufficiently stable under ASTs.

C. 2015(Mar.) BOC MEA is likely not sufficiently durable to achieve MEA load cycle durability targets (maintain >15mA/cm^2 ORR act. after 5k hours).
   1. Pt_3Ni_7/NSTF cyclic durability insufficient
      1. Specific activity, rated power loss due to Ni leaching
      2. Specific area loss - nanoporosity coarsening.
   2. PEM factors influencing rated power durability not yet fully eliminated.

D. Operational robustness of 2015(Mar.) BOC MEA has not been demonstrated to be acceptable for automotive traction applications.

Key Future Work – FY15 (Through Aug. ‘15)

A. Integrate experimental NSTF cathodes with higher mass activity (developed outside this project) to allow requisite 15µg/cm^2 PGM reduction to achieve total PGM target and approach specific power targets.

B. Improve operational robustness durability by
   1. Integrate higher durability “type B” interlayers to maintain operational robustness through ASTs (AST evaluation in progress).
   2. Incorporate new anode GDLs w/ X2 backing and improved MPL (evaluation in progress)

C. Improve load cycle durability by integration of higher durability NSTF cathodes and experimental PEMs with reduced degradation contaminant impact.
   1. Experimental NSTF nanoporous electrode with ~50% lower specific area loss through 30k cycles developed (outside project). Dealloying optimization in progress, then integrate into BOC.
   2. Experimental PEMs which have demonstrated 30% lower rated power degradation rate will be integrated into BOC format.

D. Conduct short stack testing to evaluate operational robustness of project BOC MEAs (under consideration by project team).

Summary

Operational Robustness (Cold Start; Load Transient)

- Integrated new anode GDL and cathode interlayer (@ $15\mu g_{Pt}/cm^2$) w/ Best of Class CCM, resulting in high rated power performance and $1A/cm^2$ operation at 40°C.
- Modeling and characterization confirms banded anode GDL structure approach; PNM/MEA model integration in progress and is consistent with experiment.

Durability (MEA Load Cycling; Electrocatalyst/Support ASTs)

- Rated power loss mechanism confirmed and a material approach has shown 30% improvement in V loss rate.
- NSTF MEAs w/ interlayer (likely) pass DOE Electrocatalyst, Support durability ASTs but operational robustness diminished. High durability IL integration in progress.

Power, Cost (Cathode Post Processing; Best of Class MEA Integration)

- Dealloying scale-up feasibility complete – process in control, factors understood.
- 3M-S integration complete - key material, process factors identified and validated.
- MEA integration –
  - substantial gains in specific power (up to 70% kW/g v. pre-proj.) due to improved absolute performance and PGM reduction.
  - DOE 2020 targets for loading, rated power approached

Technical Back-Up Slides

Project Goal Table

Goal ID	Project Goals (units)	Target Value	Status (NEW)	G/NG or Interim Goal Value
Table 11. Performance, Cost, Durability Targets, Current Project Status, and Go/No-Go and Goal Criteria				
Performance at ¼ Power, Performance at rated power, and Q/ΔT Targets				
1	Performance at 0.80V (A/cm^2); single cell, ≥80ºC cell temperature, 50,100,150kPag, respectively.	0.300 NA NA	0.304[A] NA NA	0.250 ≥0.300 ≥0.300
2	Performance at Rated Power, Q/ΔT : Cell voltage at 1.41A/cm^2 (Volts); single cell, ≥88ºC cell temperature, 50kPag*	0.709	0.672[A]	0.659
Cost Targets				
3	Anode, Cathode Electrode PGM Content (mg/cm^2)	≤ 0.125	0.133[A]	0.135
4	PEM Ionomer Content (effective ion. thickness, microns)	≤ 16	12[A]	20
Transient response (time from 10% to 90% of rated power), Cold start up time to 50% of rated power at -20°C, +20°C), and Unassisted start.				
5	Transient response (time from 10% to 90% of rated power); single cell at 50°C, 100% RH (seconds)	≤ 1	PASS (0%RH)[F]	5
6	Cold start up time to 50% of rated power at +20°C; evaluated as single cell steady state J at 30°C (A/cm^2)	≥ 0.8	0.7[B]	0.6
7	Cold start up time … at -20°C; short stack (seconds)	≤ 30	27[C]	30
8	Unassisted start from -40°C (pass/fail); short stack	Pass at -40°C	Pass at -20°C[C]	Pass at -30°C
MEA Durability with cycling, Electrocatalyst Cycle, Catalyst Support Cycle, MEA Chemical Stability, and Membrane Mechanical 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 at 0.8A/cm^2; % initial area loss)	≤-40 ≤-30 ≤-40	-66±4 -13±15 -28±4 [E]	≤-40 ≤- 30 ≤-40
11	Table D-2 Catalyst Support Cycle and Metrics (Mass activity % loss; mV loss at 1.5A/cm^2; % initial area loss)	≤-40 ≤-30 ≤-40	-40±7 -11±3 (0.8) -19±3[E]	≤-40 ≤-30 ≤-40
12	Table D-3 MEA Chemical Stability: 500 hours (H_2 crossover (mA/cm^2); OCV loss (% Volts); Shorting resistance (ohm-cm^2))	≤2 ≤-20 >1000	3.7±0.3 -2 971±98 [E]	≤2 ≤-20 >1000
13	Table D-4 Membrane Mechanical Cycle: 20k Cycles (H_2 crossover (mA/cm^2); Shorting resistance (ohm-cm^2))	≤2 >1000	20.1k cycles[G]	≤3 >500

A: Mean values for duplicate or singular 3M 2015(Mar.) Best of Class NSTF MEAs: Anode=0.015PtCoMn/NSTF, Cathode= 0.103Pt_3Ni_7/NSTF + 0.015Pt/C Interlayer, (0.133m_{PGM}/cm^2 total), 3M-S 725EW 14µ PEM, Baseline 2979/2979 GDLs, 3M "FF2" flow fields, operated at 90ºC cell temperature with subsaturated inlet humidity and anode/cathode stoichs of 2.0/2.5 and at stated anode/cathode reactant outlet pressures, respectively.

B: Mean values for duplicate 3M NSTF MEAs: Anode=0.05PtCoMn/NSTF, Cathode=0.15PtCoMn/NSTF, (0.15mg_{PGM}/cm^2 total), 3M 825EW 24µ PEM, "X2"/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 Replicate 3M NSTF MEAs. Anode: 0.05PtCoMn/NSTF. Cathode=0.107 or 0.125 Pt_3Ni_7/ NSTF(Dealloy+SET), 3M 825EW 24µ PEM w/ or w/o additive, Baseline 2979/2979 GDLs, w/ or w/o Edge Protection, Quad Serpentine Flow Field.

F: Mean values for duplicate 3M NSTF MEAs: Anode=0.05PtCoMn/NSTF, Cathode=0.15PtCoMn/NSTF, (0.15mg_{PGM}/cm^2 total), 3M 825EW 24µ PEM, "X2"/2979 GDLs, Baseline Quad Serpentine Flow Field. 0.03mgPt/cm^2 Cathode Interlayer.

G: 2015(Jan). Best of Class PEM and GDLs Only.

*: Cell performance of 0.709V at 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.

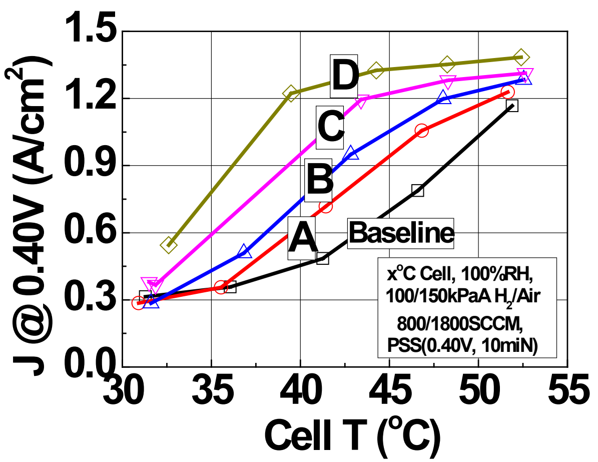
Notes

- Goal 9 is addressed in Task 5. Currently using higher T accelerated testing prior to evaluating at 80C.
- Goal 8 requires stack testing to achieve – contingent upon passing robustness criteria.
- Goal 10 requires cathode w/ improved durability – out of proj. scope but is in progress at 3M.

Accomplishments and Progress

Cold Start Modeling (Task 3): MTU PNM Predicts Improved Low J Response of Banded Anode Papers – Maintains Higher Permeability

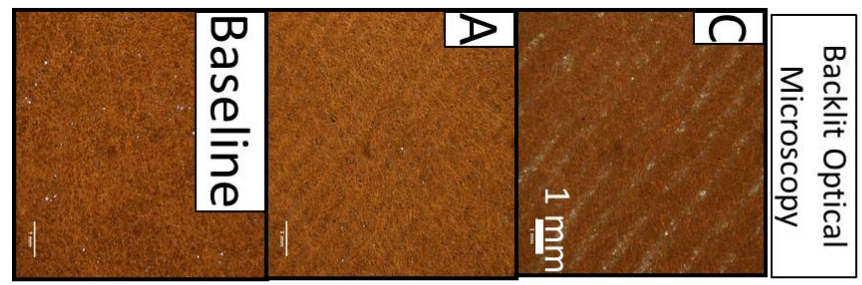
Experimental	MEA Limiting J Based on PNM Permeability Evolution

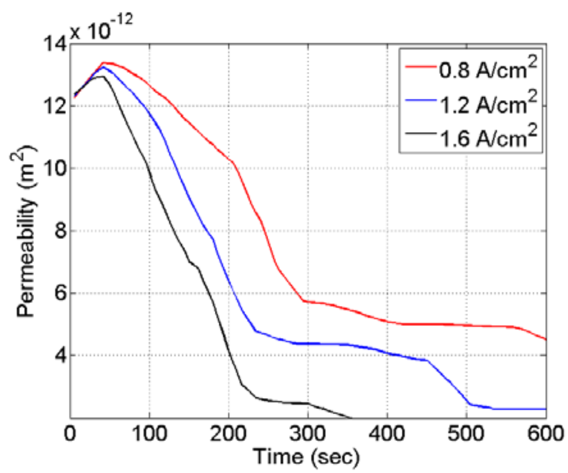


Baseline – 2979

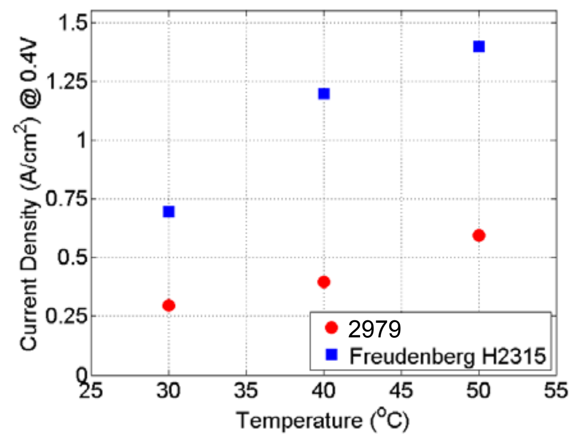
H2315 – hydrophobic, + MPL

Increasing Density Modulation





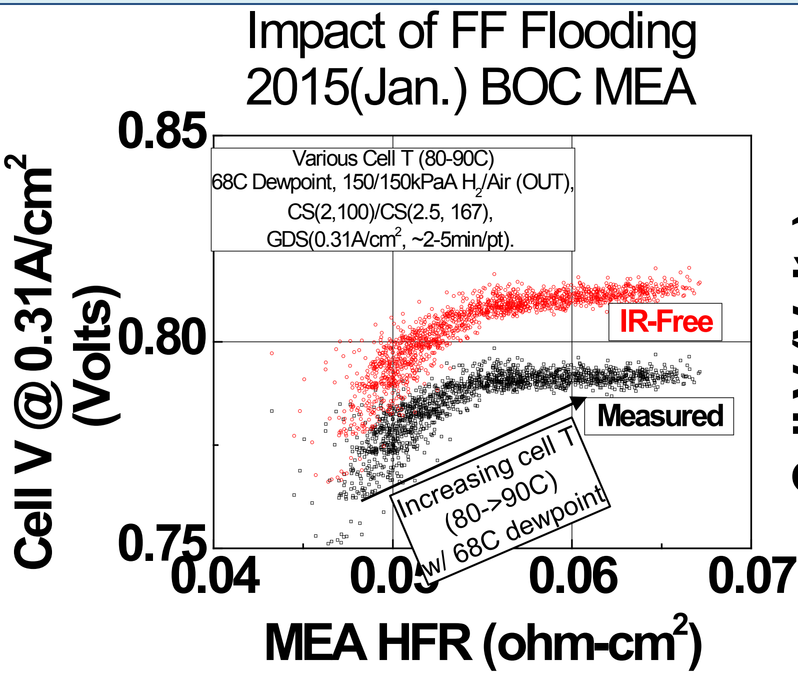
Permeability for Freudenberg H2315 at 40°C @0.4V

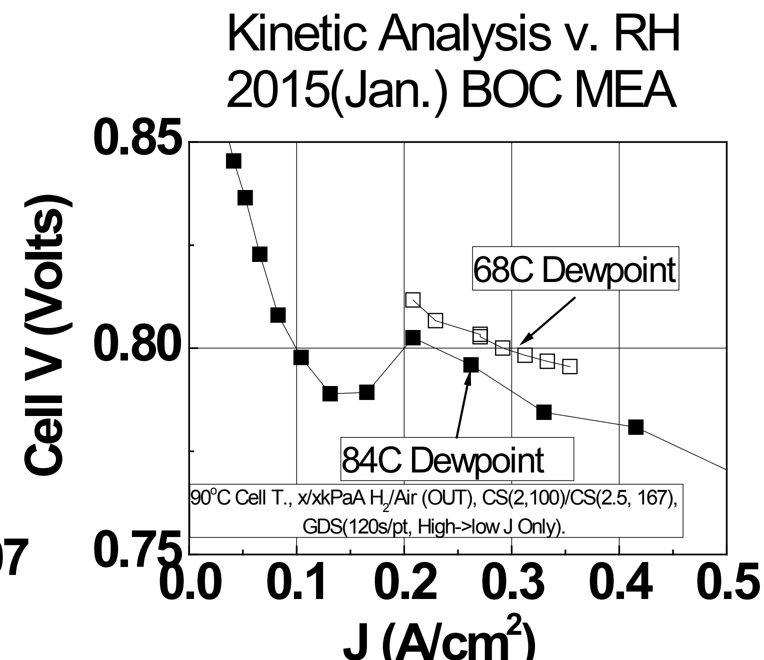


Limiting Current Density based on Gas Permeability

Accomplishments and Progress

Best of Class Component Integration (Task 4.1): Strong Kinetic Response to Low RH – Due to FF Flooding (FF2, highly parallel)



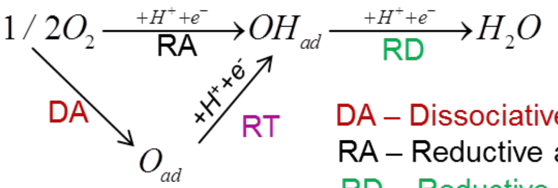


- Determined that flooding of BOC flow field was cause of unexpectedly low kinetic performance in last year's BOC MEA
  - Unsteady, depressed performance at relatively higher RH)
- With 2015 BOC, performance maximized and stabilized with substantial RH reduction
  - 68°C inlet dewpoint at low J v. 84°C at high J.

- Low J pol curves with reduced RH used to determine kinetic response of BOC MEAs in FF2.

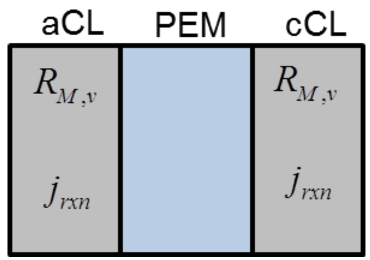
MTU – LBL models

Double-trap kinetic model based on Wang and Adzic [1] formulation:



DA – Dissociative adsorption
RA – Reductive adsorption
RD – Reductive desorption
RT – Reductive transition

Membrane model based on Weber and Newman [2] with updated transport parameters:



	Associated Gradient	
Flux	**Ionic Potential** $\nabla\Phi_2$	**Chemical Potential** $\nabla\mu_0$
Current	κ_α (Ohm)	$\kappa_\alpha \xi_\alpha / F$
Water	$M_w \kappa_\alpha \xi_\alpha / F$	$M_w\left(\alpha_{M_w} + \kappa_\alpha \xi_\alpha^2 / F^2\right)$ (Fick)

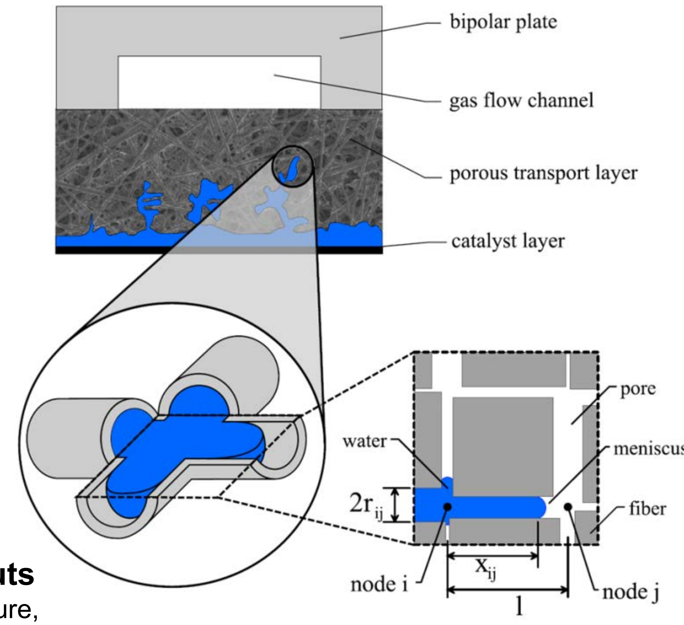
Transport
Concentrated species theory for diffusion Darcy's law for liquid and gas (convection) Ohm's law for ionic and electric currents Electro-osmosis and back-diffusion for membrane

Thermodynamics
Standard cell potential
Equilibrium H_2O content membrane, liquid, vapor

[1] J. X. Wang, J. Zhang and R.R. Adzic, J. Phys. Chem. A (2007)
[2] A.Z. Weber and J. Newman, JES 151 (2004)

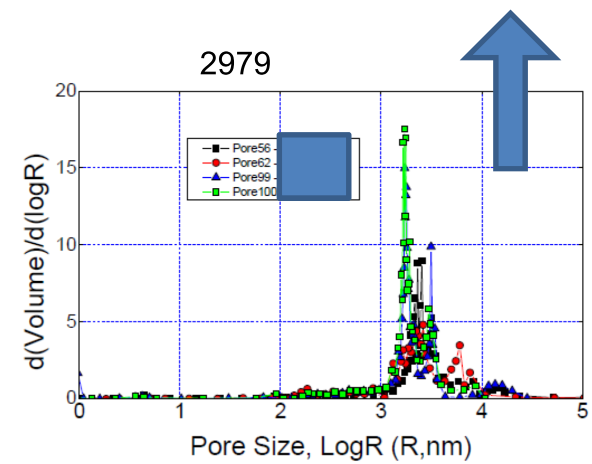
Pore Network model of GDL [3]:

Transport
2-dimensional liquid water, vapor, heat, and reactants transport for Cathode and Anode GDLs with diffusive phase change model.



GDL Model Inputs
- Porosimetry
- Contact angle
- Thickness
- Porosity

PNM Model Outputs
- Pressure, temperature, liquid water, vapor and reactants concentrations destructions inside the GDL
- Effective transport properties: thermal conductivity, permeability, vapor and reactant diffusivities, reactant permeabilities.



[3] E. F. Medici, and J. S, Allen, IJHMT (2013)

3M

Robustness Metric Testing

Table 3. Robustness Criteria Needed for Stack Testing at GM				
Demonstration of the three robustness criteria to occur in subscale (e.g. 50cm^2) hardware with stack candidate materials. Evaluation to occur at 3M.				
Criteria name	Description	Target Value	**Status** (1x X2 GDL, Int. DS Cathode IL(0.03mg/cm2))	**Status** (2x X2 GDL, Int. DS Cathode IL (0.015mg/cm2))
Cold Operation	Stack voltage at 30°C as a fraction of the stack voltage at 80°C operation at 1.0 A/cm^2, measured using the protocol for a polarization curve found in Table 3. A 25°C dew point is used only for 30°C operation.	> 0.3	~ 0 (w/ 150kPa anode) 0.29 w/ 100kPa	0.38
Hot Operation	Stack voltage at 90°C as a fraction of the stack voltage at 80°C operation at 1.0 A/cm^2, measured using the protocol for a polarization curve found in Table 3. A 59°C dew point is used for both 90°C and 80°C operations.	> 0.3	1.0 (performance increased)	0.9
Cold Transient	Stack voltage at 30°C transient as a fraction of the stack voltage at 80°C steady-state operation at 1.0 A/cm^2, measured using the protocol for a polarization curve found in Table 3. A 25°C dew point is used only for 30°C operation. 30°C transient operation is at 1 A/cm^2 for at least 15 minutes then lowered to 0.1 A/cm^2 for 3 minutes without changing operating conditions. After 3 minutes, the current density is returned to 1 A/cm^2. The voltage is measured 5 seconds after returning to 1 A/cm^2.	> 0.3	~0 w/ 150kPa anode "almost" achieved @ 100kPa anode	0.38

CCM: 0.05PtCoMn/0.15PtCoMn, 3M 20u 825EW
Anode GDL: 1 or 2 X2 w/ 3M Hydrophobic Treatment+ MPL (interim DS).
Cathode IL: 2979 + "B" IL (interim DS)