Power for the Real World

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

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3M Company

June 8th, 2016

Project ID: FC104

Project Overview

Timeline

- Project start: 9/1/12
- Project end: 8/30/16*

* Project extended from 8/30/15 (no-cost).

Budget

- Total DOE Project Value: $4.606MM*
- Total Funding Spent: $4.346MM*
- Cost Share Percentage: 20%

* Includes DOE, contractor cost-share, and FFRDC funds, as of 2/28/16.

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. Produce Project Best of Class Components and CCMs (to be used for stack testing) via Continuous, Pilot Mfg. Processes	B. Cost C. Performance
2. Validate Performance and Operational Robustness of Project Best of Class MEAs in Short Stack.	B. Cost C. Performance
3. Evaluate Project Best of Class MEAs for Performance/Cost Modeling and Durability Under ASTs and Load Cycling.	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	$300 mA/cm^2$	3,4
Performance @ rated power	$1000 mW/cm^2$	3,4
PGM Content (both electrodes)	$0.125 g/kW_{RATED}$ $0.125 mg_{PGM}/cm^2$	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 (Mar. '16)
BUDGET PERIOD 2 (June '14-Aug. '16)			
1.2	15	**Comp. Cand. Meet Project Perf./Cost Goals.**	**98%**
2.2	15	**Comp. Cand. Meet Project Cold-Start Goals.**	**50% (2 of 4)**
5.2	15	**Comp. Cand. Meet Project Durability Goals.**	**91% (10 of 11)**
4.2	**15**	**Best of Class MEA Meets All Perf./Cost, Cold-Start, and Durability Project Goals**	**84%**
3.2	12	**Validation of Integrated GDL/MEA Model With ≥ 2 3M MEAs (Different Anode GDLs).**	**100%**
6.3	15	**BOC MEA: Short Stack Eval. Complete.**	**40%**
0	15	**Final Short Stack to DOE-Approved Location.**	**40%**

Status Against DOE 2020 Targets		
Characteristic	**2020 Targets**	**Status, '15 / '16**
Q/ΔT (kW / °C)	1.45 (@ 8kW/g)	1.45 (@ 6.5/6.8* kW/g)
Cost ($ / kW)	7	5 / 5* (PGM only @ $35/$g_{Pt}$; 0.692V)
Durability with cycling (hours)	5000	In progress
Performance @ 0.8V (mA/cm^2)	300	304 / 310*
Performance @ rated power (mW/cm^2)	1000	855 / 891* (0.692V, 1.45kW/°C)
PGM total content (g/kW (rated))	0.125	0.155 / 0.147* (0.692V, 1.45kW/°C)
PGM total loading (mg PGM / cm^2 electrode area)	0.125	0.133 / 0.131*

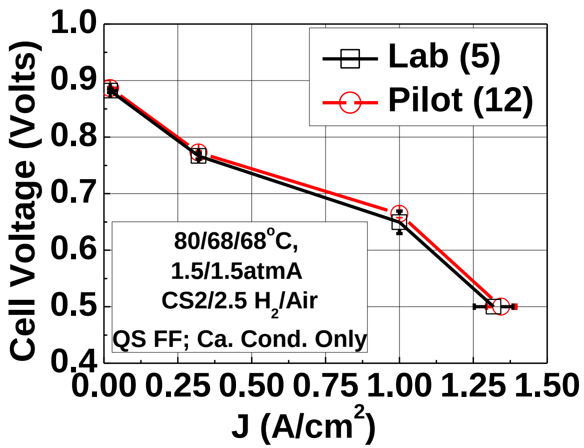
*: 2016 values from 2015(Sept.) Best of Class MEA, which include a cathode interlayer with 16µg-Pt/cm^2

Accomplishments and Progress

Best of Class Component Integration (Task 4.1):

Pilot Scale Component Fabrication

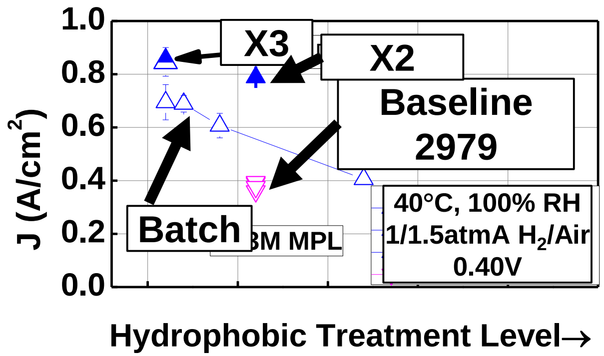
BOC CCM



- Pilot CCM improved vs. lab.
- ~30m of BOC CCM produced (two lots).
- Total CCM PGM loading (1st lot): $0.105 mg_{Pt}/cm^2$

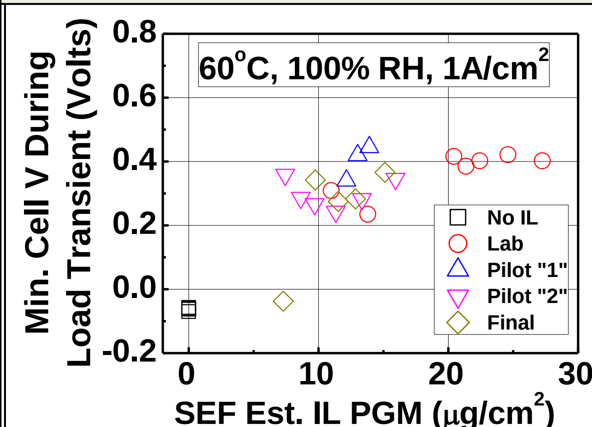
	Lab (5)	Pilot (12)
Mass Activity (A/mg_{PGM})	0.28 ± 0.03	0.33 ± 0.03
Specific Area (m^2/g_{PGM})	11.8 ± 1.4	14.5 ± 0.7

"X3" Anode GDL



- Last year, reported improved low T performance w/ reduced hydrophobic backing treatment.
- ~30m of "X3" produced.
- "X3" anode GDL yielded modest improvement over "X2" and > 2x gain over baseline GDL.

"B" Cathode Interlayer



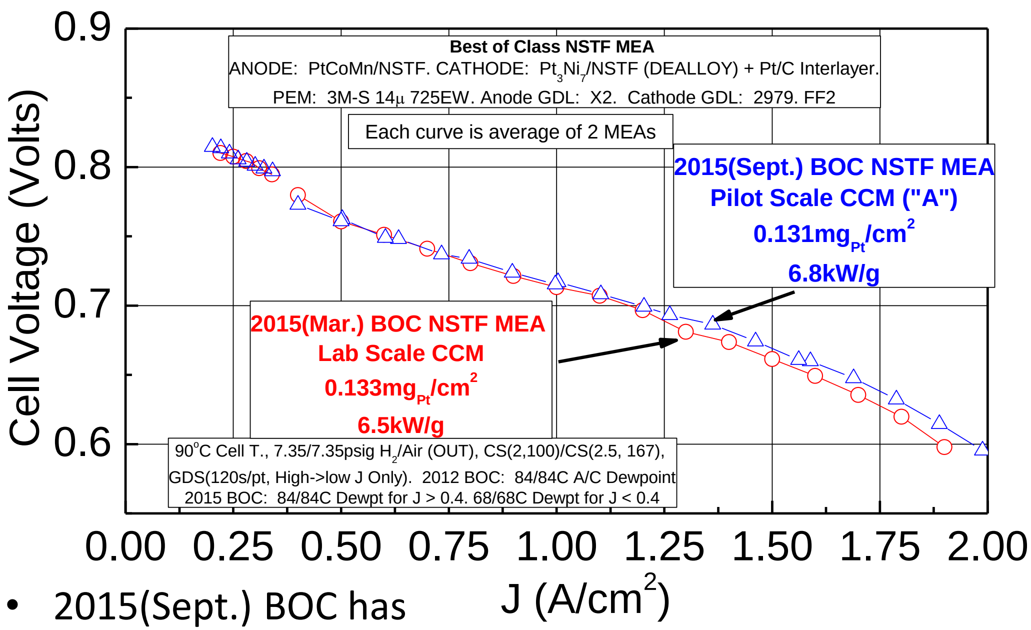
- Based on performance /durability assessment, downselected type "B" IL.
- ~50m of interlayer produced.
- Load transient performance largely in line with other pilot scale runs.
- Loading analysis: $16 \pm 3\ \mu g_{PGM}/cm^2$

Accomplishments and Progress

Best of Class Component Integration (Task 4.1):

2015(Sept.) 3M NSTF Best of Class MEA Performance, Robustness

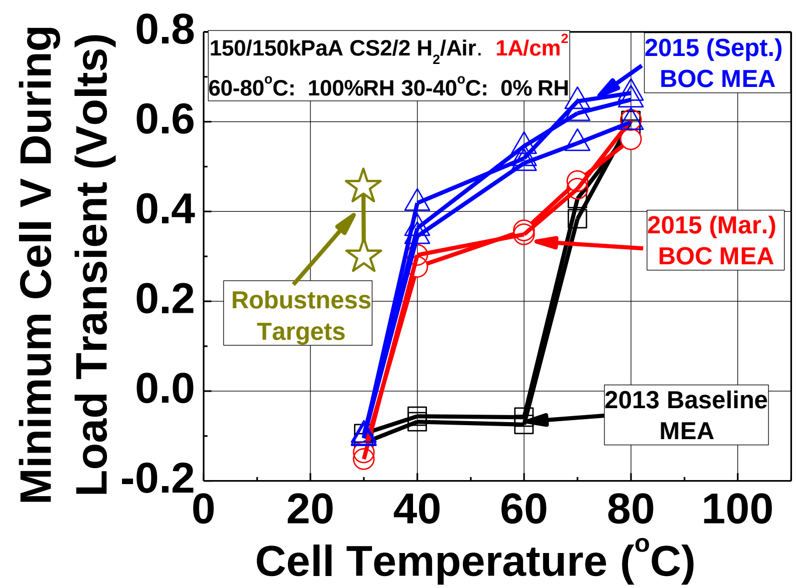
1.5atmA H_2/Air Performance



- 2015(Sept.) BOC has improved power and kinetic performance than 2015(Mar.) BOC MEA
  - Improved pilot CCM

MEA	Spec. Power (kW/g)	Rated Power (W/cm²)	1/4 Power (A/cm²)
Mar.	6.5	0.855	0.304
Sept.	6.8	0.891	0.310

Operational Robustness



- Sept. BOC MEA yields 0.1-0.2V gain in load transient robustness over Mar. BOC MEA.
  - Improved "X3" anode GDL, type "B" cathode IL

MEA	Anode Cat	PEM	Cathode Catalyst	CCM	Anode GDL/Cathode IL
2015(Mar.)	PtCoMn/NSTF, 15μg/cm²	3M-S 725EW	Dealloyed PtNi/NSTF, 0.103mg/cm²	Lab	"X2"/ 30% "A"(15μg/cm²)
2015(Sept.)	PtCoMn/NSTF, 19μg/cm²	14μ w/ add.	Dealloyed PtNi/NSTF, 0.096mg/cm²	Pilot	"X3"/ 30% "B"(16μg/cm²)

Accomplishments and Progress

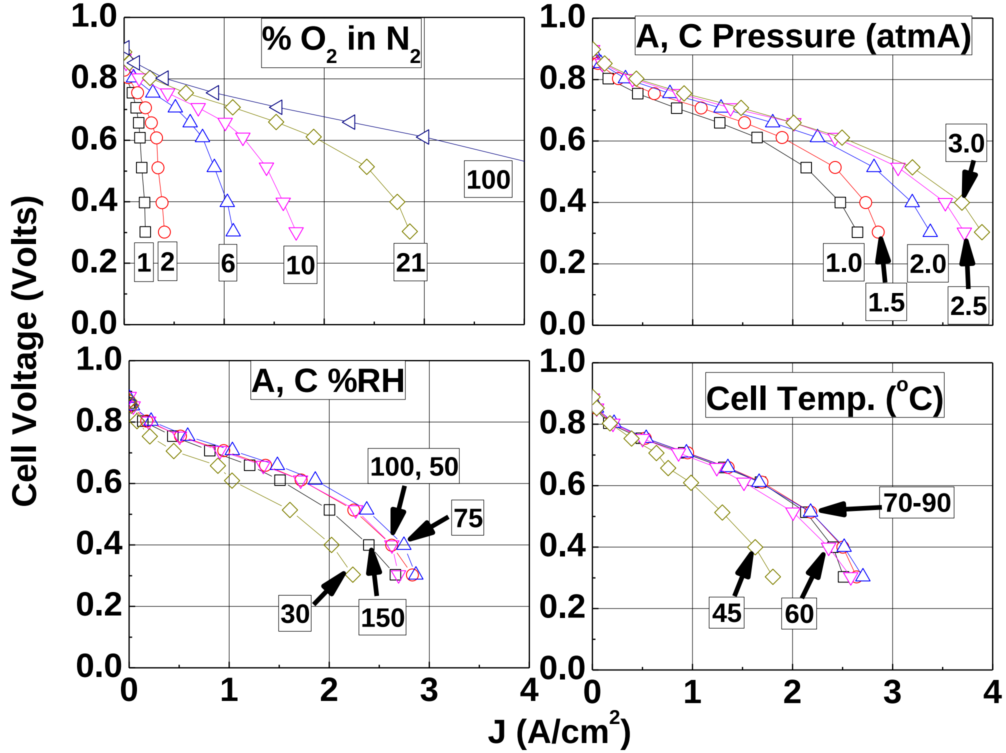
Best of Class Integration Diagnostics (Task 4.2):

2015(Sept.) BOC MEA Differential Cell Evaluation for ANL Model

pO_2, P, RH, Cell T Sensitivity Studies

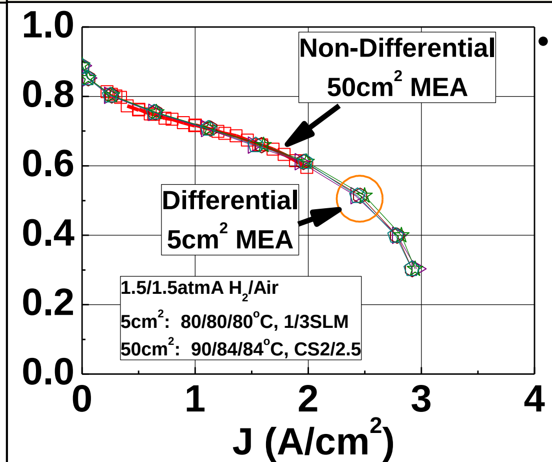
Base Conditions: 80°C, 100/100% RH, 1.5/1.5atmA H_2/Air (inlet), 1/3SLM

5cm² Active Area in 50cm² cell. Potential control, 5min/pt.



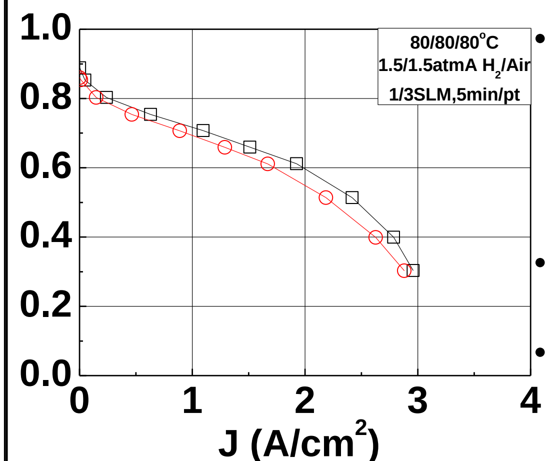
- High J's achieved, approaching 3A/cm2 under 1.5atmA H_2/Air.
- Little evidence of losses due to Ni^{2+} in PEM.
- Good RH and T sensitivity; modest loss at dry or low T operation.

Differential v. 50cm² Comparison



- Excellent agreement suggests differential cell data is representative.

Durability over Test

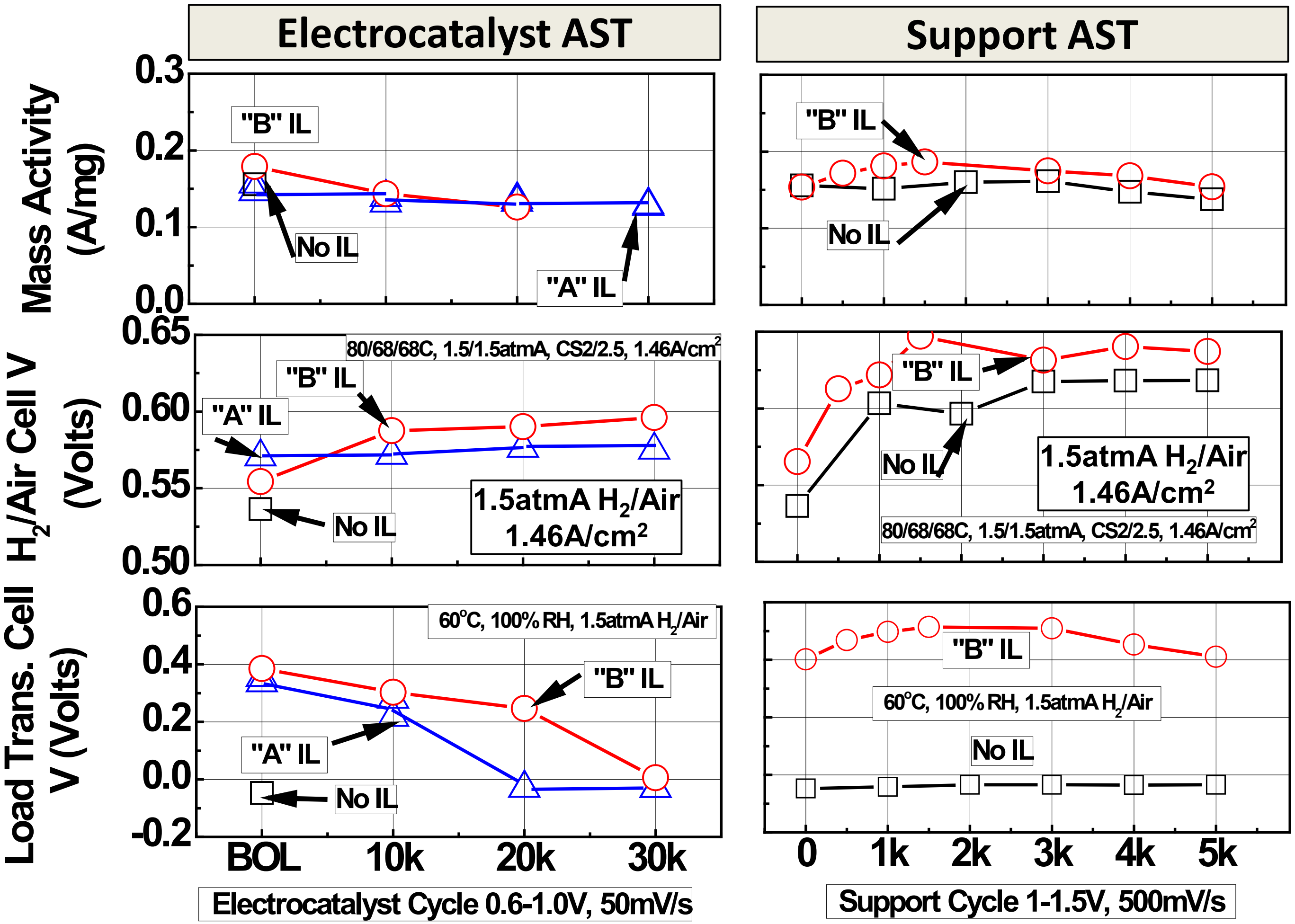


- ~20mV loss at 0.3A/cm² after ~800 additional testing hours.
- 25% ECSA loss.
- Minor loss of high J performance.

Accomplishments and Progress

Cathode Interlayer Durability (Task 5):

AST Durability Evaluations of “B” Interlayer



Baseline CCM: 0.05/0.15PtCoMn, 3M 825EW 20u. X2 Anode GDL

Electrocatalyst AST

- ‘15 AMR: “A” IL durability insufficient – load trans. failed after 10k cycles.
- **“B” improved,** load trans. fails after 20k cycles.
- **H_2/Air perf. improves**

Support AST

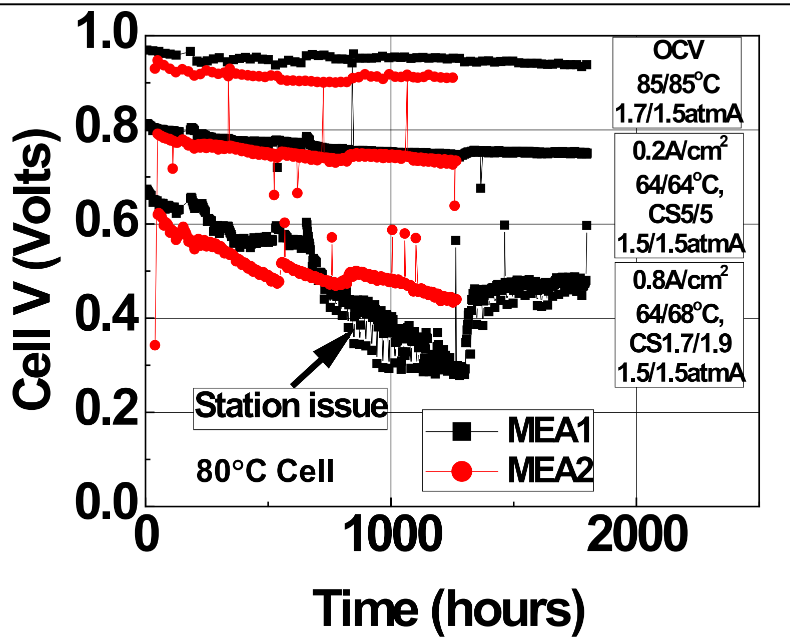
- **“B” passes support AST**
  - No net change in load transient after 5k cycles
- **H_2/Air performance increases 80mV at 1.46A/cm² w/ or w/o IL.**

- *“A” or “B” ILs w/ baseline NSTF CCM pass DOE durability (activity, H_2/Air) targets with either AST.*

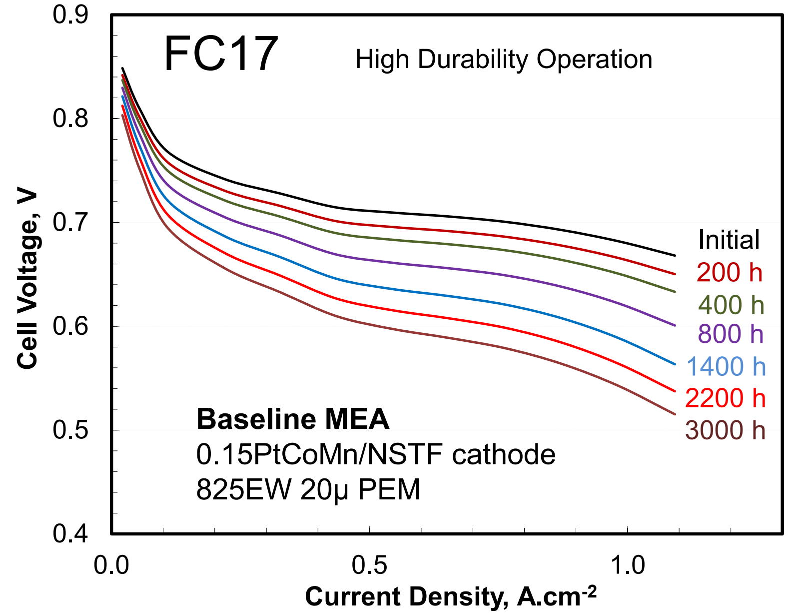
Accomplishments and Progress

MEA Rated Power Durability (Task 5): Load/RH Cycle Evaluation of 2015 (Sept.) BOC MEAs; ANL Durability Modeling of NSTF MEAs

Performance during 3M Load/RH Cycle	PtCoMn/NSTF MEA Durability Model (ANL)



- BOC MEAs have completed > 1200 hours of 3M load/RH cycle testing.
- Significant performance decay during cycling due to both reversible and irreversible factors.
- Steady OCV – no PEM breach.
- Tests ongoing and diagnostics conducted periodically.



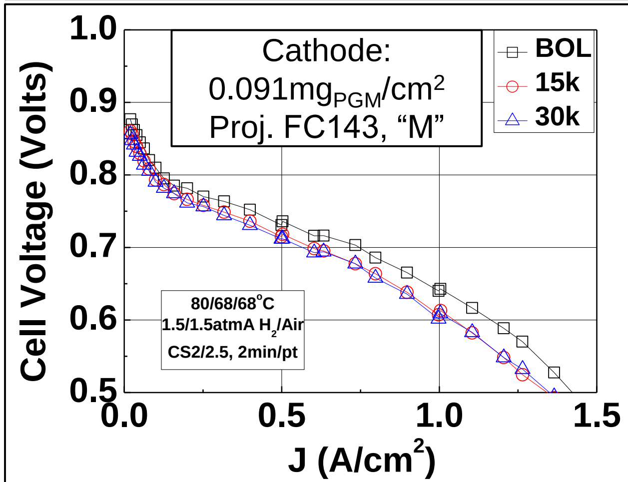
- NSTF rated power degradation correlates to PFSA decomposition extent ('15 AMR).
  - 800 hours to predicted 10% irreversible voltage loss; 2300 hours to 20% loss.
  - Critical requirement for 5000 hour durability (10% V loss): limit cathode F^- to $0.7 \mu g_{F-}/cm^2$ (80% FER reduction)
- **Path: Decrease MEA FER and increase cathode durable activity and surface area.**

Accomplishments and Progress

Best of Class Component Integration (Task 4.1):

New, Improved Durability NSTF "M" Cathode Integration

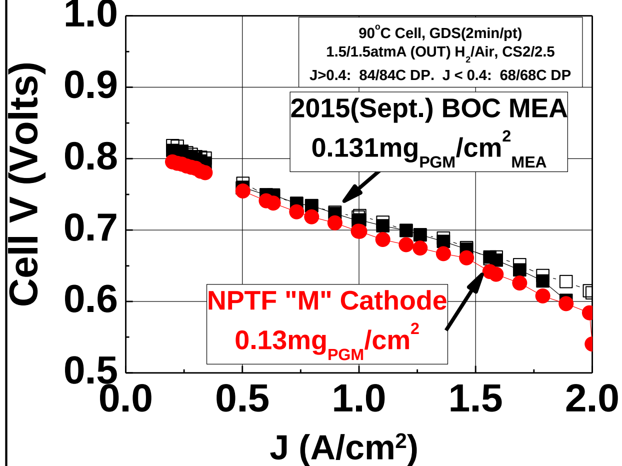
Durability (Baseline Format)	Performance (BOC Format)	Robustness (BOC Format)

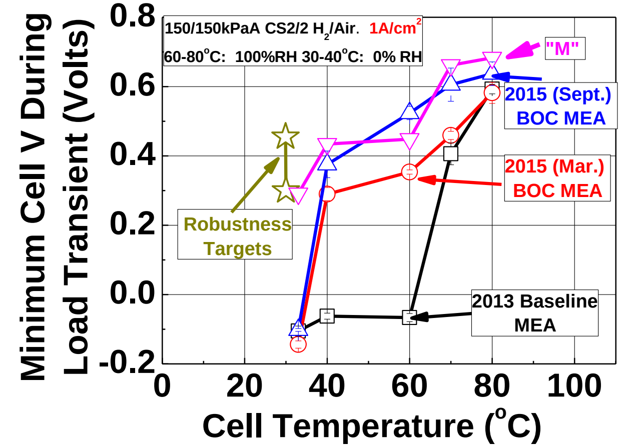


Metric	Change/DOE Tgt
Mass Activity (A/mg)	**-40±0.8 / -40%**
V @ 0.8A/cm²	**-28±1.4 /-30mV**
Surf. Area (m²/g)	**-14±0.15 / NA %**

- First durable "M" catalyst meets DOE electrocatalyst AST durability targets.
- BOC cathode: ~65% mass activity loss.

Both include "X3" anode GDL and "B" cathode interlayer (16µg/cm² Pt/C). Loadings are total MEA.





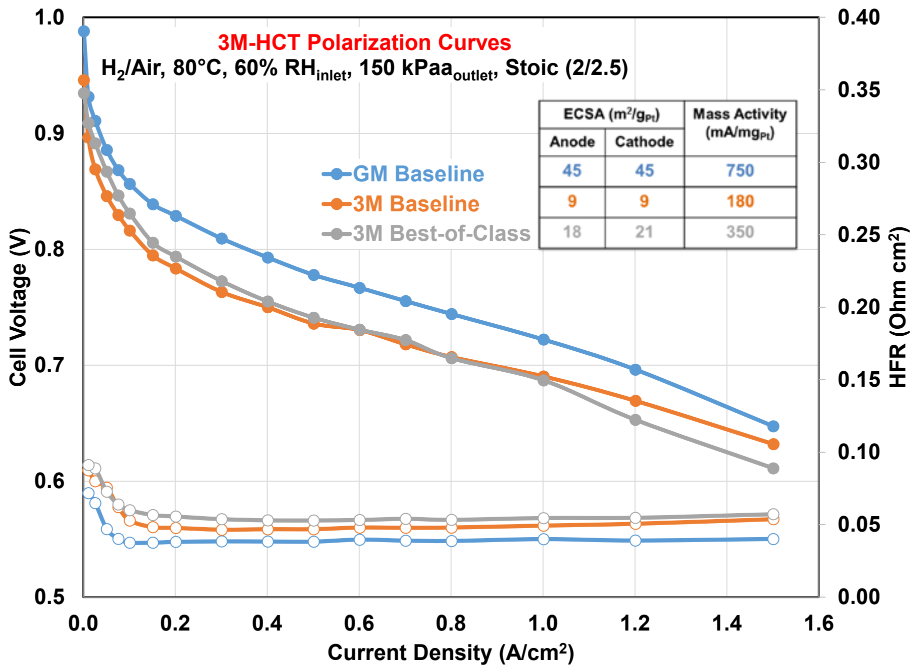
- "M" integrated into BOC MEA format with expected performance and operational robustness.
- As compared project BOC MEA, first "M" BOC MEA has:
  - Lower BOL mass activity (0.28 v. 0.39A/mg)
  - Lower rated and specific power (5.7 v. 6.8 kW/g)
  - Similar/improved operational robustness
- Additional durable catalysts w/ improved activity from project FC143 will be evaluated in BOC format as available.

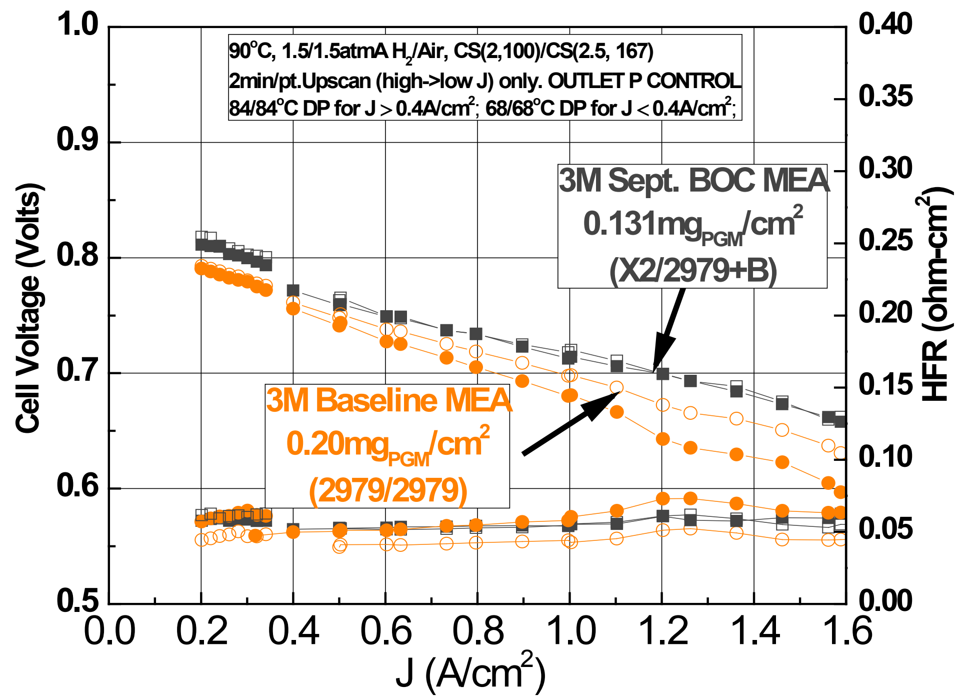
Accomplishments and Progress

BOC MEA Short Stack Evaluation (Task 6):

Single Cell Testing at 3M, GM – H_2/Air Performance

GM 80°C H_2/Air Performance	3M 90°C H_2/Air Performance





- At 1.5 A/cm^2, order of performance 3M Baseline > 3M March BOC
- BOC mass activity, specific areas largely in-line w/ 3M expectation.

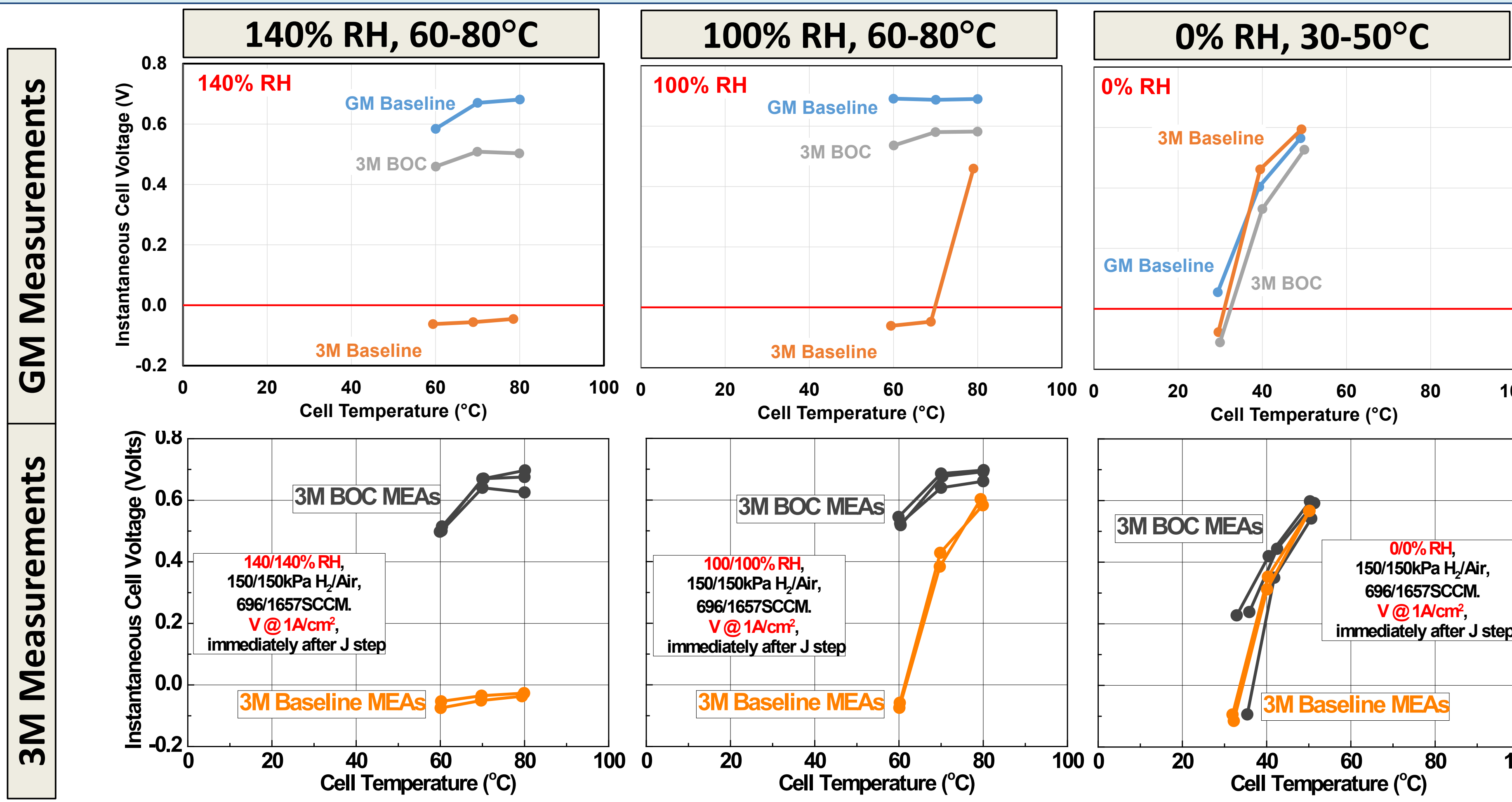
- 3M baseline MEA data consistent w/ GM
- BOC MEA data inconsistent at high current (GM: 60mV lower @ 1.5A/cm^2)

3M Baseline MEA: 0.05/0.15PtCoMn, 3M 825EW 20µ. 3M 2979/2979 GDL
3M BOC MEA: 0.019/0.096PtNi, 3M 725EW 14µ. 3M "X3"/2979+"B"IL GDL

Accomplishments and Progress

BOC MEA Short Stack Evaluation (Task 6):

Single Cell Testing at 3M, GM – Load Transients



- Load transient results for 3M baseline and BOC MEAs similar between sites.
- Robustness improvement of BOC MEA largely confirmed at single cell level

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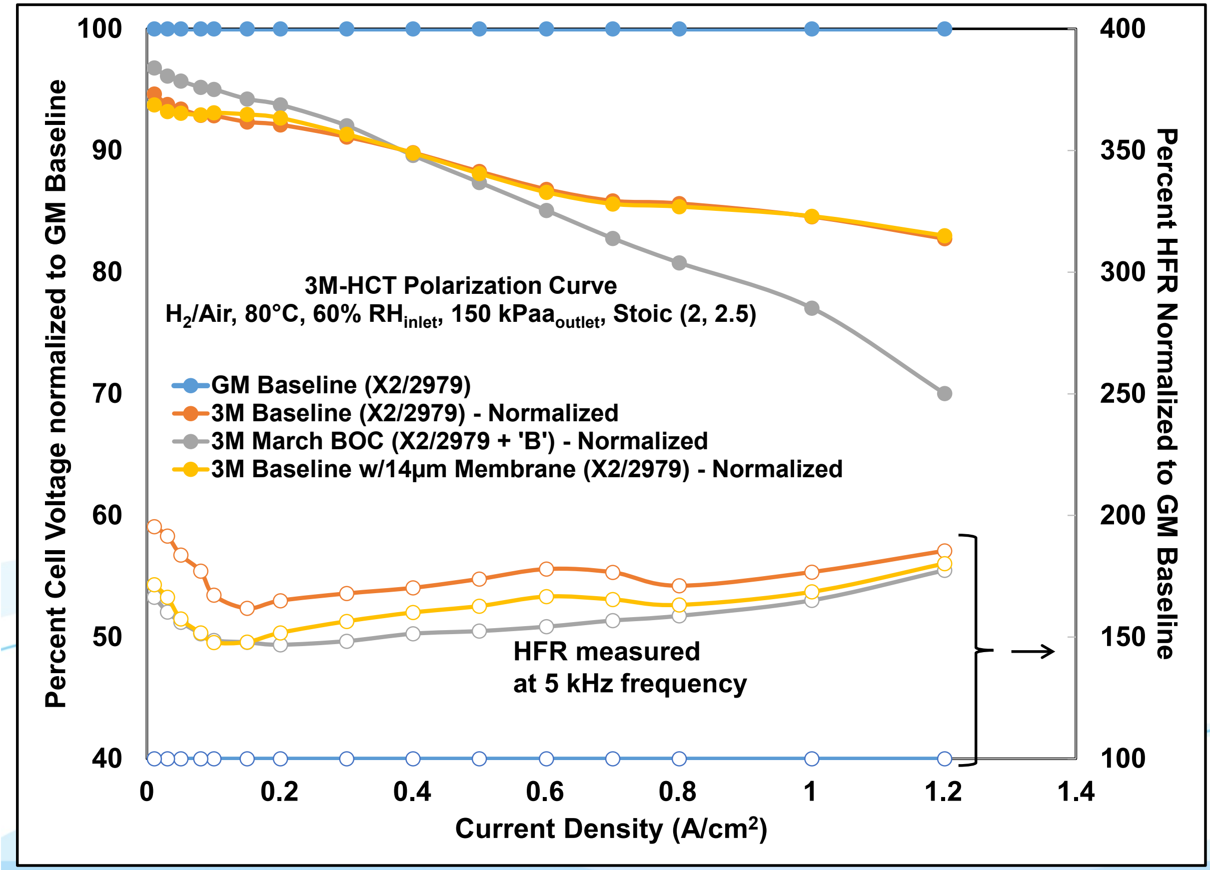
Accomplishments and Progress

BOC MEA Short Stack Evaluation (Task 6):

Stack H_2/Air Performance Much Lower than Expected

Short Stack – 3M-HCT Polarization Curve

H_2/Air, 80°C, 60% RH_{inlet}, 150 $kPaa_{inlet}$, Stoic (2/2.5)



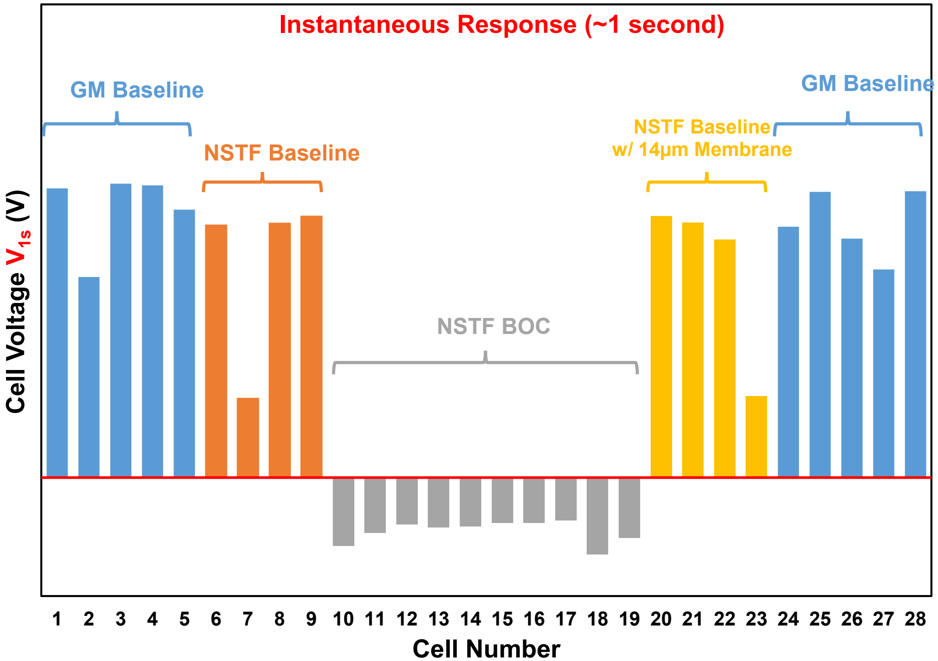
- Cell voltage of 3M CCMs from short stack testing have been normalized to the GM Baseline performance
- 3M BOC CCMs show a ~3% improvement in low current density performance over the 3M Baseline Cells
- At 1.2 A/cm^2, performance of 3M BOC CCMs are ~70% of that observed with GM Baseline Cells

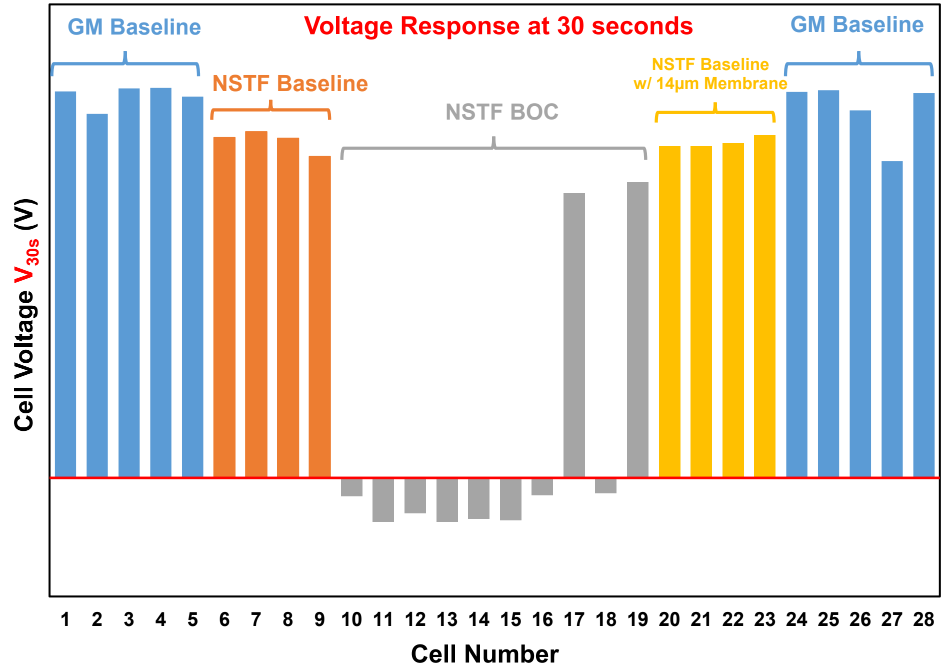
Accomplishments and Progress

BOC MEA Short Stack Evaluation (Task 6):

Stack Load Transient Performance Much Lower than Expected

100% RH_{inlet}, 70°C, H_2/Air, 150 $kPaa_{inlet}$, Transient from 0.02 to 1.0 A/cm^2



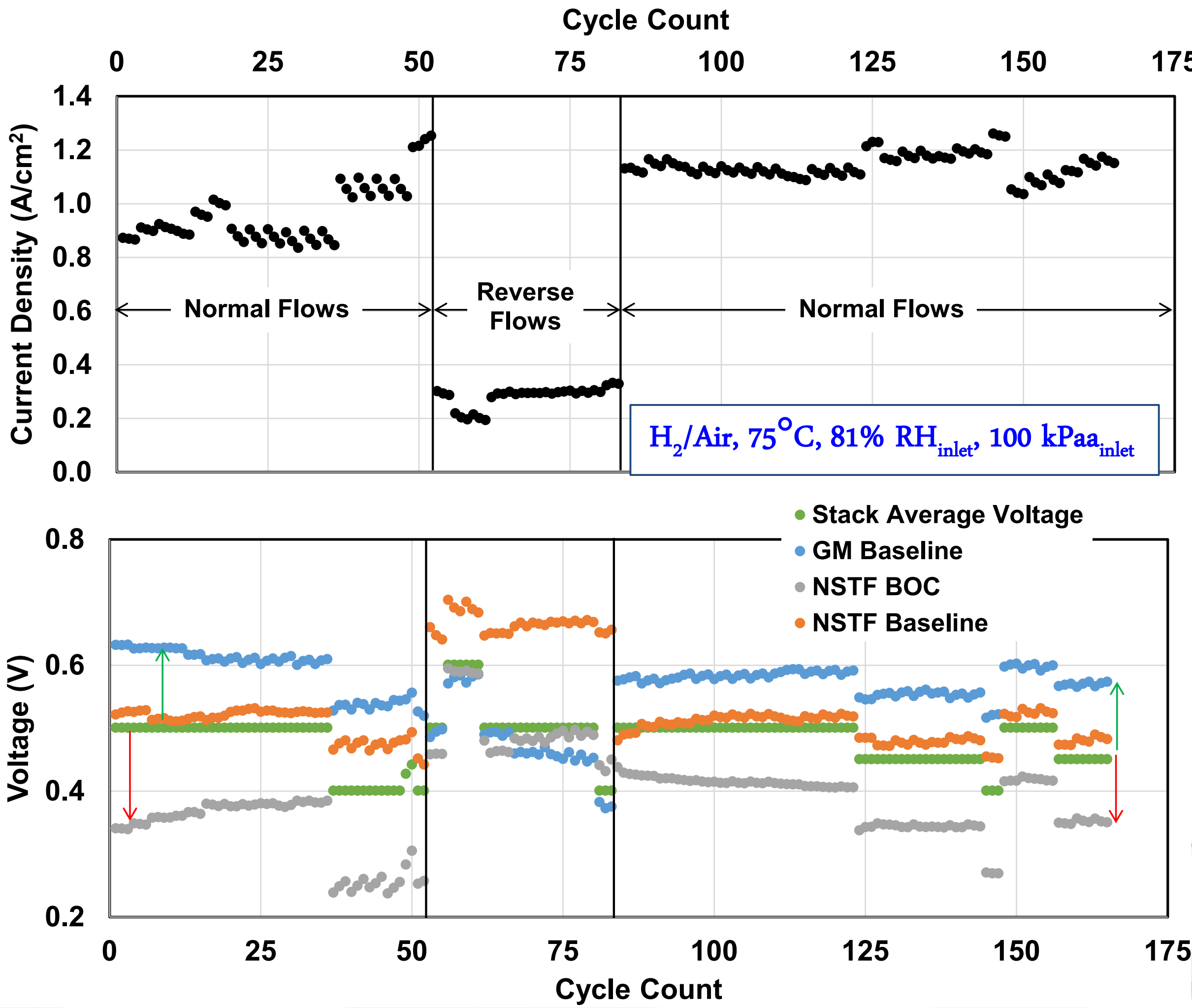


- At 70°C/100% RH, BOC MEA instantaneous voltage after load transient was negative (failed)
- Most BOC cells did not recover to positive cell voltages within 30 seconds.
- ***Unexpectedly, NSTF baseline CCMs (no cathode interlayer) pass***

More optimization of NSTF MEAs with the stack platform is needed to be competitive with conventional catalyst for steady state and load transient performance.

Accomplishments and Progress

BOC MEA Short Stack Evaluation (Task 6): Possible Cause for Low Stack Performance: Stack Conditioning Method May Not Be Effective

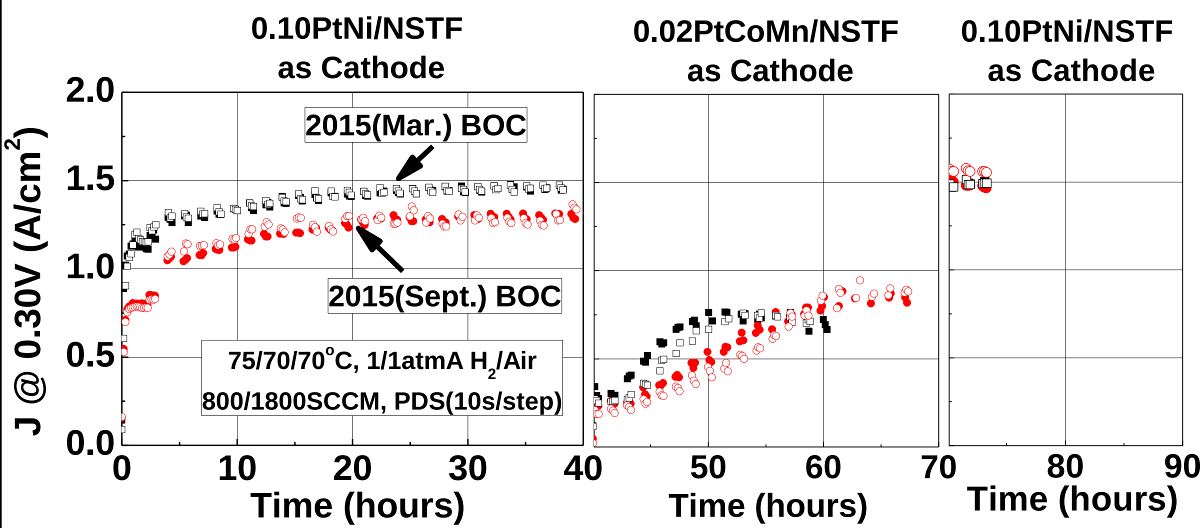


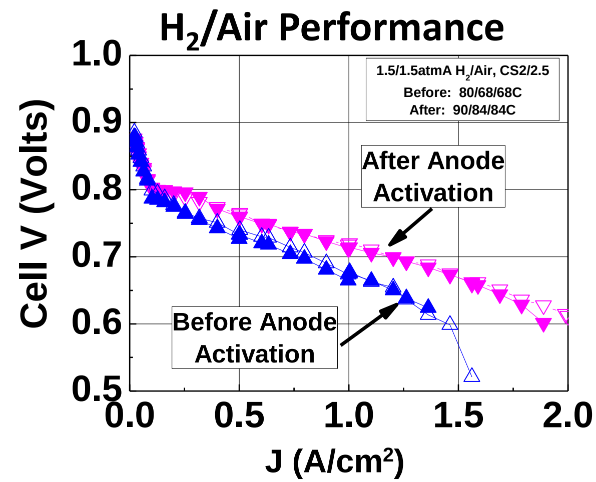
- For a given stack current density, NSTF BOC Cells show lower cell voltages than the Stack Average Voltage
- This scenario did not change during the entire stack test duration
- Not much improvement in performance observed after reverse flow conditioning
- Ineffective or a non-optimized thermal cycle break-in process at the stack level, likely prevents the effective conditioning and performance of the NSTF BOC Cells

Accomplishments and Progress

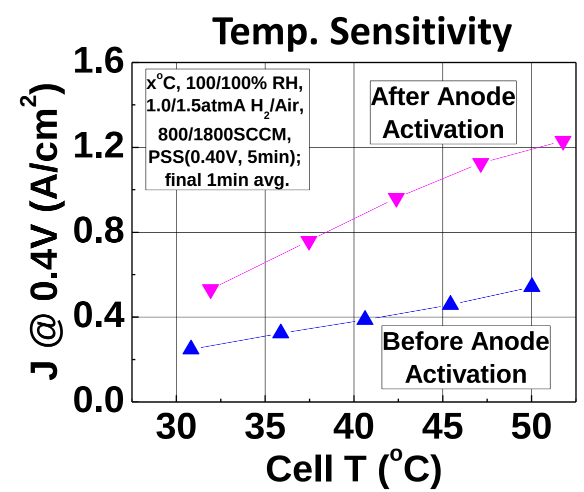
Best of Class Integration Diagnostics (Task 4.2): Best of Class MEA Activation Required for Entitlement Performance, Robustness

Cathode Activation	Anode Act.	Act. Complete	Impact of Anode Act (Sept.)





- Non-optimized "thermal cycle" protocol used to activate BOC MEAs.
  - Slow voltage and temperature cycles (1.5 hours per complete cycle).
  - Both electrodes are activated (operated as cell cathodes)
- After anode activation, substantial improvement in 80°C H_2/air performance and at low temperature.
  - ~60mV at 1.5A/cm^2, 2x J between 35-50°C



Likely contributors to poor stack performance to date:

1. "Thermal cycle" protocol not effective in GM stack.
2. Slower activation of Sept. BOC MEAs (cause under investigation)

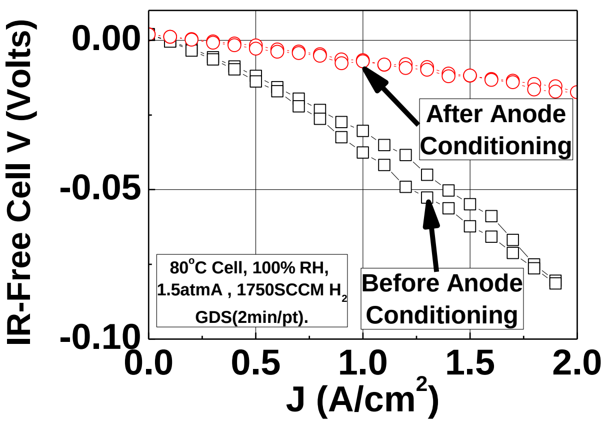
Accomplishments and Progress

Best of Class Integration Diagnostics (Task 4.2):

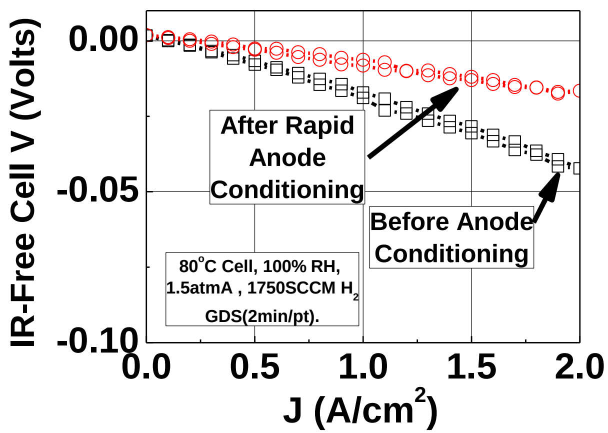
Rapid NSTF MEA Activation Development

Anode Activation

Thermal Cycle (15hrs)



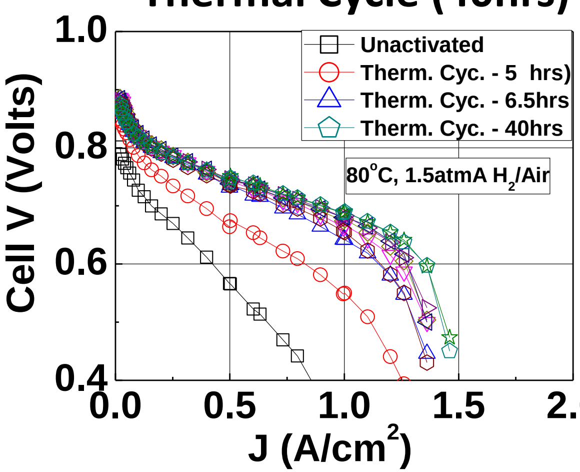
Rapid Activation (1hr)



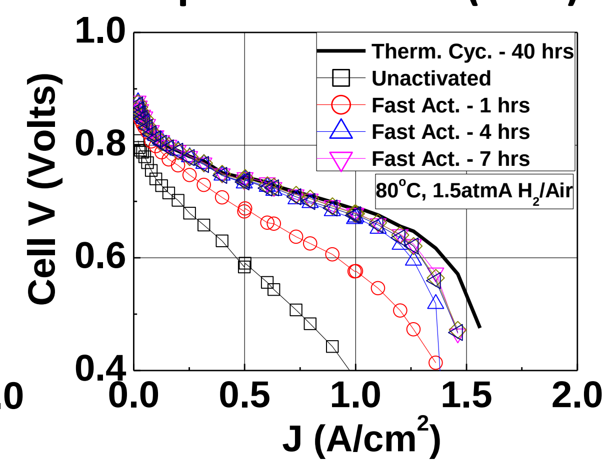
- BOC MEA anode HOR kinetics are highly deactivated prior to conditioning.
  - Challenge w/ very low SEF anode (~2.5cm^2_{Pt}/cm^2_{planar})
  - Actual BOC anode deactivation much larger than predicted.
- Rapid protocol has potential for activation in < 1 hour; simple.

Cathode Activation

Thermal Cycle (40hrs)



Rapid Activation (4hrs)



Cathode activation work under "FC Fundamentals at Low and Subzero Temp" (Weber)

- Dealloyed PtNi/NSTF (not BOC) can be substantially activated in ca. 4 hours.
  - Optimized T and V cycles
  - No water injection, no shutdowns (system friendly).
- To date, has not achieved entitlement performance.
- Method will be optimized for BOC MEA.

Rapid, stack friendly activation development is key remaining integration task

Response To Reviewers' Comments

- "**Very good progress and a good deal of work have been accomplished in the last year**. Key procedures to improve … apparently promise that, **in subsequent research efforts, most of the performances will be at 2020 levels**. However, **several problems … are not completely solved**: the necessity of using an **interlayer with the thickness of another catalytic layer**, **the dealloying procedure**, and the **problem with Ni leaching due to the Kirkendall effect**. The third point has not been considered at all."
  - *Agreed, additional materials (e.g. interlayer) and additional processing (e.g. dealloying) are undesirable from a cost/yield perspective. Tradeoff analysis for this approach vs. others, considering power density, durability, cost (material, process, yield), and end-use system requirements, is complex and not readily assessable.*
  - *Interlayer thickness is ca. 1-2 µm thick (low loading) and imposes little apparent transport loss (compare 2015(Jan.) to 2015 (Mar.) BOC in '15 AMR presentation for interlayer transport impact).*
  - *Transition metal stability in porous metal electrocatalyst has always been a key concern, but believed to be tractable. "M" is promising (see FC143).*

- "… **the key issues have still not been mitigated sufficiently** to enable this new catalyst to replace more conventional MEAs, primarily **because 3M has not been willing to make any significant changes to the original NSTF catalyst layer structure**. …"
  - *Our assessment remains that the project approach will achieve sufficient robustness in stack format.*
  - *Per the 2011 FOA, component development was not allowed; our work here was limited to modest modifications of existing components using known means. Development of a modified NSTF electrode structure was deemed out of scope.*
  - *An "advanced" NSTF electrode with improved intrinsic robustness is in early development (outside this project). Many factors not yet understood, but operational robustness is improved.*

Collaborations

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

- A. Steinbach, D. van der Vliet, C. Duru, D. Miller, I. Davy, M. Kuznia (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 –Kinetic, rated power durability, and performance modeling.

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

General Motors - Stack Testing

- B. Lakshmanan, N. Ramaswamy

Remaining Barriers

A. 2015(Sept.) Best of Class MEA does not achieve the DOE 2020 loading and specific power targets.

B. Operational robustness of enhanced durability “B” interlayer is not maintained after 30k Electrocatalyst AST cycles.

C. 2015(Sept.) BOC MEA is not sufficiently durable to achieve MEA load cycle durability targets (10% V loss after 5000 hours).
   1. Dealloyed Pt_3Ni_7/NSTF cyclic durability insufficient
   2. PFSA decomposition leading to cathode deactivation.

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

E. Rapid break-in conditioning method not yet implemented w/ BOC MEAs.

Key Future Work – FY16 (Through Aug. '16)

A. Complete short stack testing to evaluate operational robustness of project BOC MEAs in relevant architecture.
   1. Determine method to enable rapid break-in conditioning of BOC MEAs, compatible with stack testing.
   2. Evaluate stack towards performance, cold/freeze startup, load transient.

B. Complete evaluations of downselected Best of Class MEA:
   1. ANL performance model
   2. Load cycle durability and AST durability.

C. Improve load cycle durability by integration of higher durability NSTF cathodes and experimental PEMs with reduced degradation contaminant impact.

D. Complete assessment of relative cost savings of project Best of Class MEA to baseline.

E. Complete project final report.

Summary

Operational Robustness (Cold Start; Load Transient)

- Integrated new anode GDL and improved durability "B" cathode interlayer into 2015 (Sept.) BOC MEA, yielding 0.1-0.2V improvement at intermediate T over 2015(Mar.) BOC MEA.

Durability (MEA Load Cycling; Electrocatalyst/Support ASTs)

- New "B" interlayer maintains operational robustness after Support AST and after 20k Electrocatalyst AST cycles. H_2/Air performance near 1.5A/cm^2 *improves* after ASTs.
- Load cycle evaluation of BOC MEAs show significant reversible and irreversible performance losses after 1200+ hours; tests ongoing.
- New "M" NSTF cathode passes DOE Electrocatalyst AST, but improved activity needed.

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

- Substantial gains in specific power (55% kW/g v. pre-proj.) due to improved absolute performance and PGM reduction. DOE 2020 targets for loading, rated power approached.
- Pilot scale components successfully fabricated.

Short Stack Evaluation of BOC MEAs

- To date, BOC MEA evaluated in GM short stacks have not demonstrated expected performance and robustness benefit over baseline.
- Insufficient conditioning of ultra-low PGM anode suspected
- Development of stack-compatible, rapid conditioning methods are in progress.

Technical Back-Up Slides

Project Goal Table

Table 10. 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				
Goal ID	*Project Goals (units)*	*Target Value*	*Status (NEW since '15 AMR)*	*G/NG or Interim Goal Value*
1	Performance at 0.80V (A/cm²); single cell, ≥80ºC cell temperature, 50,100,150kPag, respectively.	0.300 NA NA	0.310 [A] NA NA	0.250 ≥0.300 ≥0.300
2	Performance at Rated Power, Q/ΔT : Cell voltage at 1.41A/cm² (Volts); single cell, ≥88ºC cell temperature, 50kPag*	0.709	0.679[A]	0.659
Cost Targets				
3	Anode, Cathode Electrode PGM Content (mg/cm²)	≤ 0.125	0.131[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)[A]	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/cm²)	≥ 0.8	0.7[A]	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	TBD[A]	2500
10	Table D-1 Electrocatalyst Cycle and Metrics (Mass activity % loss; mV loss at 0.8A/cm²; % initial area loss)	≤-40 ≤-30 ≤-40	-40±0.8 -28±1.4 -14±0.2 [F]	≤-40 ≤- 30 ≤-40
11	Table D-2 Catalyst Support Cycle and Metrics (Mass activity % loss; mV loss at 1.5A/cm²; % 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/cm²); OCV loss (% Volts); Shorting resistance (ohm-cm²))	≤2 ≤-20 >1000	PASS -4 PASS[B]	≤2 ≤-20 >1000
13	Table D-4 Membrane Mechanical Cycle: 20k Cycles (H_2 crossover (mA/cm²); Shorting resistance (ohm-cm²))	≤2 >1000	20.1k[A (PEM ONLY)]	≤3 >500

A: Mean values for duplicate 3M 2015(Sept.) Best of Class NSTF MEAs: Anode=0.02PtCoMn/NSTF, Cathode= 0.095Pt_3Ni_7/NSTF + 0.016Pt/C IL, (0.131m_{PGM}/cm² total), 3M-S 725EW 14µ PEM, X2/2979+IL Anode/Cathode, 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 value for duplicate 3M 2015(Mar.) Best of Class MEAs. Analogous result for 2015(Sept.) MEAs is expected.

C: OEM Stack testing results with 3M NSTF MEAs: Anode=0.10PtCoMn/NSTF, Cathode=0.15PtCoMn/NSTF, (0.25mg_{PGM}/cm² total), 3M ionomer in supported PEM, Baseline 2979/2979 GDLs. OEM-specific enabling technology.

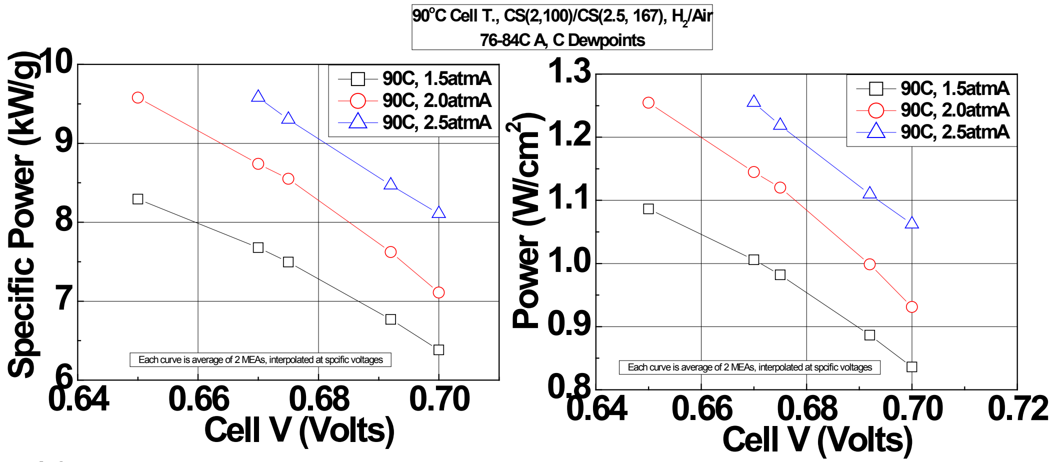
E: Value for Replicate 3M NSTF MEAs. Anode: 0.05PtCoMn/NSTF. Cathode=0.107 or 0.125 Pt_3Ni_7/ NSTF(Dealloy+SET), 3M 825EW 24µ PEM w/ or w/o additive, Baseline 2979/2979 GDLs, w/ or w/o Edge Protection, Quad Serpentine Flow Field.

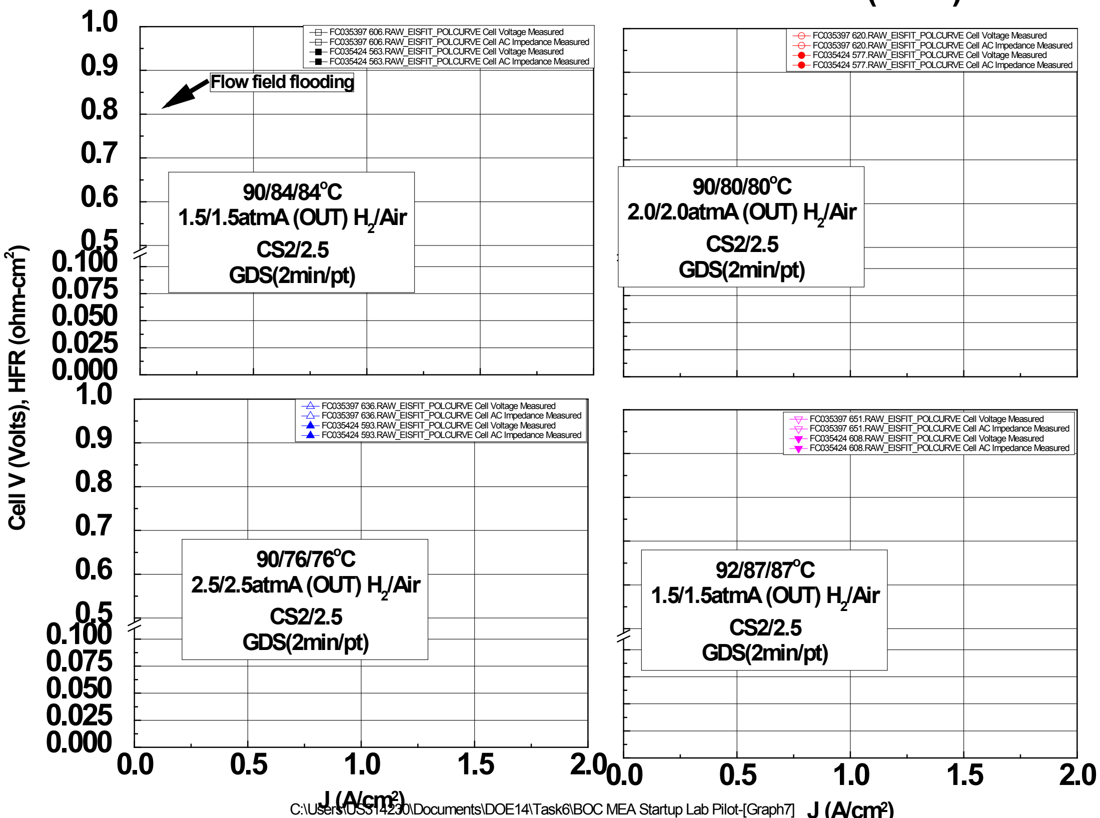
E: Value for Replicate 3M NSTF MEAs. Anode: 0.05PtCoMn/NSTF. Cathode: "M", 0.091mg_{PGM}/cm², 3M 825EW 24µ PEM w/ or w/o additive, Baseline 2979/2979 GDLs, w/ or w/o Edge Protection, Quad Serpentine Flow Field.

*: Cell performance of 0.709V at 1.41A/cm² with cell temperature of ≥88ºC simultaneously achieves the Q/ΔT and rated power targets of 1.45kW/ºC and 1000mW/cm², respectively.

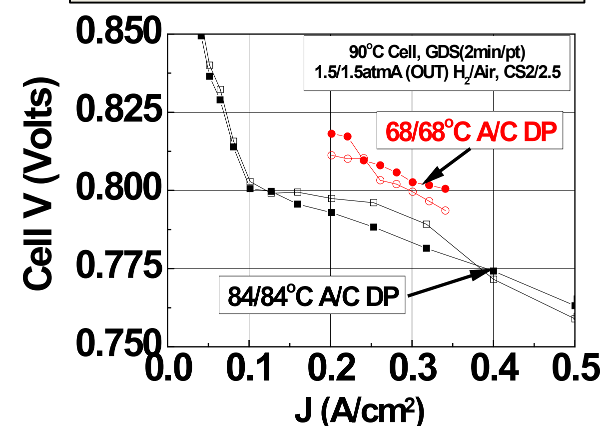
**: Single sample result. MEA failed prematurely due to experimental error.

2015 (Sept.) BOC MEA Performance v. Pressure

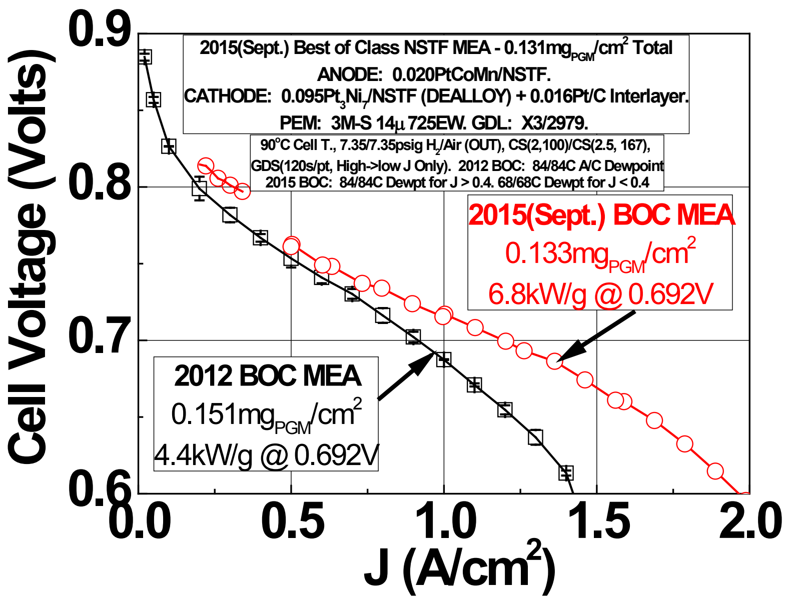


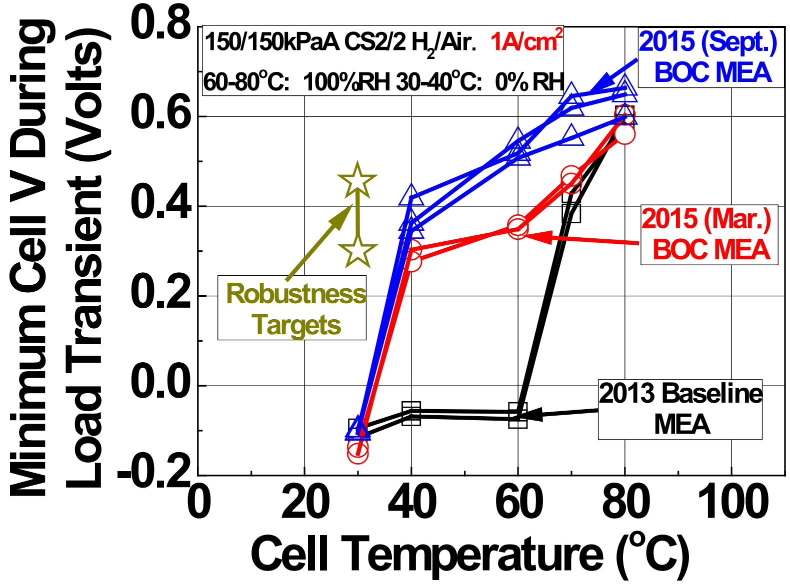


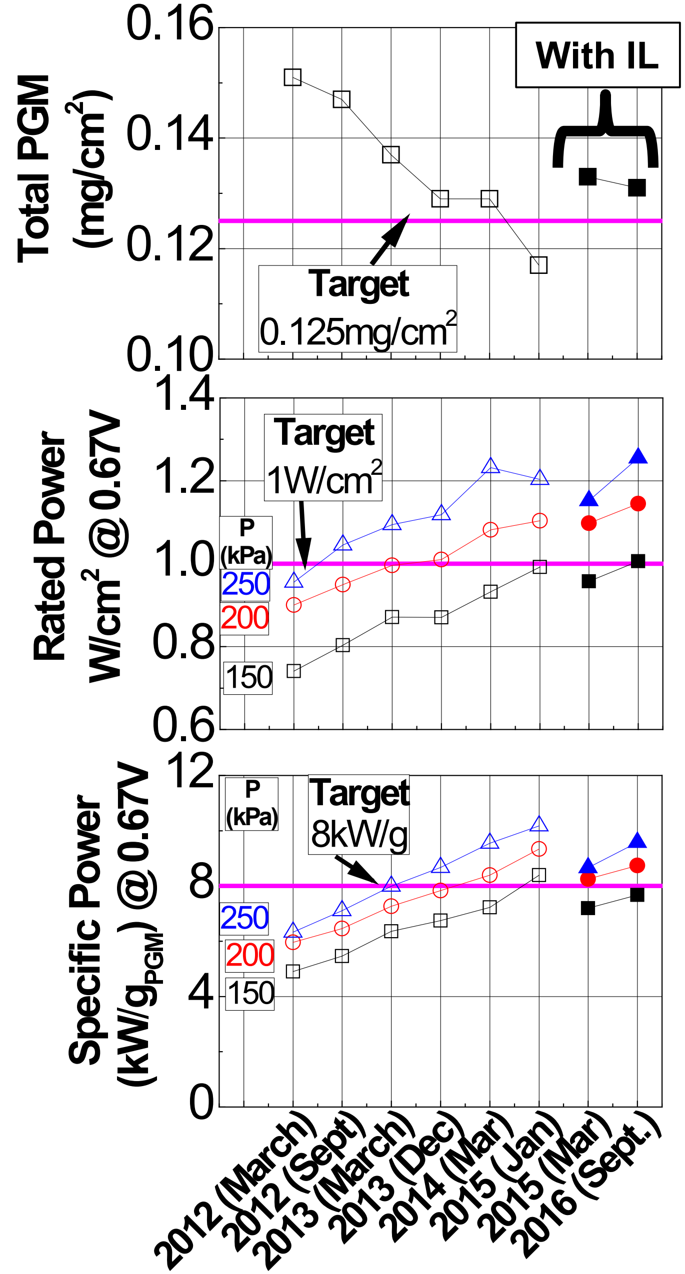
FF Flooding Mitigation By Reduced RH @ Low J



Technical Backup – Progression Over Project







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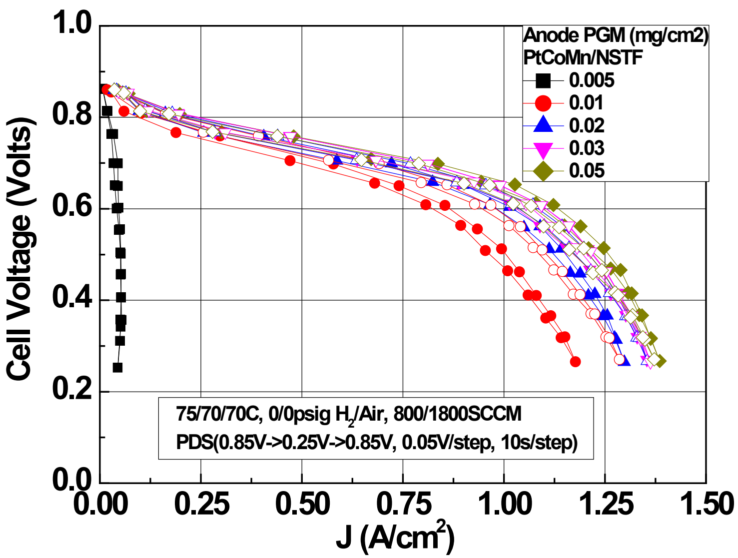
NSTF Anode Activation

1. Early project work: little apparent impact with $0.02 mg_{Pt}/cm^2$ PtCoMn/NSTF anode(all unactivated).

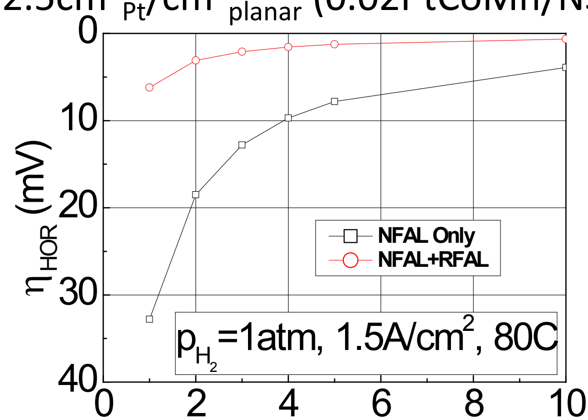


2. NSTF HOR kinetic study concluded that thermal cycle activation increased NSTF HOR specific activity > 5x over unactivated, and 1 order of magnitude over Pt/C.

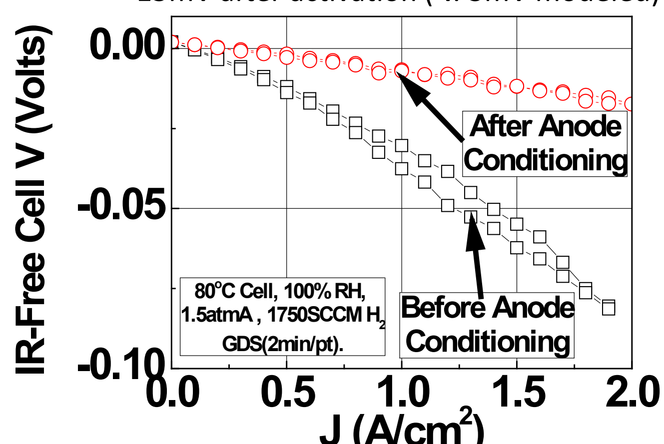
Wang et al., "Kinetics of Hydrogen Oxidation and Hydrogen Evolution Reactions…", *J. Electrochem. Soc.* **160**(3) F251 (2013)

Electrode	**E_{HOR} (kJ/mol)**	**i0 (mA/cm^2_{Pt})**
0.05PtCoMn/NSTF, Partially activated	38.9	489
0.05PtCoMn/NSTF, Fully activated	64.3	2727 ± 563
0.003Pt/C (5wt%)	NA	235-300

3. Model prediction of ~10mV excess loss due to poor activation at $2.5 cm^2_{Pt}/cm^2_{planar}$ (0.02PtCoMn/NSTF)



4. Actual HOR kinetics much lower than model prediction, or by early project FC tests (#1)
   - 60mV before activation (v. 15mV modeled)
   - 15mV after activation (v. 3mV modeled)



Short Stack Design

- Stack consisted of the following CCM MEAs

#	Type	Anode Description	Membrane	Cathode Description	No. of Cells
1	3M Baseline CCM	PtCoMn/NSTF 0.05 mg_{Pt}/cm^2	3M 825EW 20 µm	PtCoMn/NSTF 0.15 mg_{Pt}/cm^2	**4**
2	3M 'Baseline' CCM with 14 µm membrane	PtCoMn/NSTF 0.05 mg_{Pt}/cm^2	3M-S 725EW 14 µm w/ additive	PtCoMn/NSTF 0.15 mg_{Pt}/cm^2	**4**
3	3M March BOC CCM	PtCoMn/NSTF 0.019 mg_{Pt}/cm^2	3M-S 725EW 14 µm w/ additive	Dealloyed Pt_3Ni_7/NSTF 0.096 mg_{Pt}/cm^2 3M 2979 w/ "B" Interlayer IL Loading – 0.016 mg_{Pt}/cm^2	**10**
4	GM Baseline CCM	Dispersed Pt/C 800EW Ionomer	18 µm PFSA	Dispersed Pt-alloy/C 800EW Ionomer	**10**

- Following GDLs were used
  - Anode – 3M-X2 Low phobic GDL
  - Cathode – 3M 2979
- Short stack stands were equipped with DI Water Flush lines for thermal cycle break-in process