FY2015 – FY2020

FY2021 – FY2025

Durability Developments from FC-PAD to M2FCT

Rod Borup and Rangachary Mukundan

Biden Administration Targets CO2 Emissions

FACT SHEET: President Biden Sets 2030 Greenhouse Gas Pollution Reduction Target Aimed at Creating Good-Paying Union Jobs and Securing U.S. Leadership on Clean Energy Technologies

Building on Past U.S. Leadership, including Efforts by States, Cities, Tribes, and Territories, the New Target Aims at 50-52 Percent Reduction in U.S. Greenhouse Gas Pollution from 2005 Levels in 2030

On Day One, President Biden fulfilled his promise to rejoin the Paris Agreement and set a course for the United States to tackle the climate crisis at home and abroad, reaching net zero emissions economy-wide by no later than 2050. As part of re-entering the Paris Agreement, he

- $1 Trillion Infrastructure Bill Passed Senate (69-30) Nov House (228-206), signed by President Biden Nov 15
- Department of Energy has 180 days to issue proposal calls for:
  - > 4 Hydrogen regional HUBs - $8B over 5 years
  - $1B for Electrolysis
  - $500M for Clean Hydrogen Manufacturing and Recycling

Transition from FC-PAD to M2FCT
Target Comparison between Light- and Heavy-Duty

Condition	Traditional	M2FCT Focus
Operating temperature	60 - 80 °C	~ 90 °C
Catalyst	Random alloy $Pt_{90}Co_{10}$	Tailored and ordered alloys, annealed Pt
Membrane	Ultra-thin, reinforced with mobile Ce	Stabilized, durable, high selectivity (H+ conductance/H_2 permeance)
Operating voltage	0.6 – 0.9 V	>0.7 V
Durability	5,000 hrs	25,000 hrs
Pressure	150 kPa	250 kPa
Catalyst loading	0.15 g_{Pt}/cm^2	0.3 g_{Pt}/cm^2

Table 1. Technical Targets for Automotive-Scale (80 kW_e net Fuel Cell System Operating on Hydrogen[a]

Characteristic	Units	Status	2020 Target	2025 Target
Peak Energy Efficiency [b]	%	60 [c]	65	65
Specific power	W/kg	659 [d]	650	900
Cost [f]	$/$kW_e$	45 [e]	40	35
Cold start-up time to 50% of rated power				
@ -20°C ambient temp	sec	20 [f]	30	30
@ +20°C ambient temp	sec	<10 [f]	5	5
Durability in automotive load cycle	hours	4130 [g]	5,000	8,000
Unassisted start from [h]	°C	-30 [i]	-30	-30

Table 1. Technical System Targets: Class 8 Long-Haul Tractor-Trailers (updated 10/31/19)

Characteristic	Units	Targets for Class 8 Tractor-Trailers	
		Interim (2030)	Ultimate[9]
Fuel Cell System Lifetime[1,2]	hours	25,000	30,000
Fuel Cell System Cost[1,3,4]	$/kW	80	60
Fuel Cell Efficiency (peak)	%	68	72
Hydrogen Fill Rate	kg H_2/min	8	10
Storage System Cycle Life[5]	cycles	5,000	5,000
Pressurized Storage System Cycle Life[6]	cycles	11,000	11,000
Hydrogen Storage System Cost[4,7,8]	$/kWh ($/kg H_2 stored)	9 (300)	8 (266)

M2FCT Consortium - Overview

Timeline

- Project start date: 10/01/2020
- Project end date: 09/30/2025

Budget

- FY20 project funding: $10M
  - Planned $1M external partners
  - $1.5M Effort to Support FOAs
  - 5-year consortium with yearly milestones & Go/No-Go

Partners/Collaborations

- DOE DE-FOA-0002044:
  - GM, Nikola, Carnegie Mellon
- DOE DE-FOA-EE0009244:
  - 3M, Lubrizol, Nikola, UT Knoxville
  - Cummins, Plug Power
- No-cost collaborations

Heavy-Duty Transportation (2025)

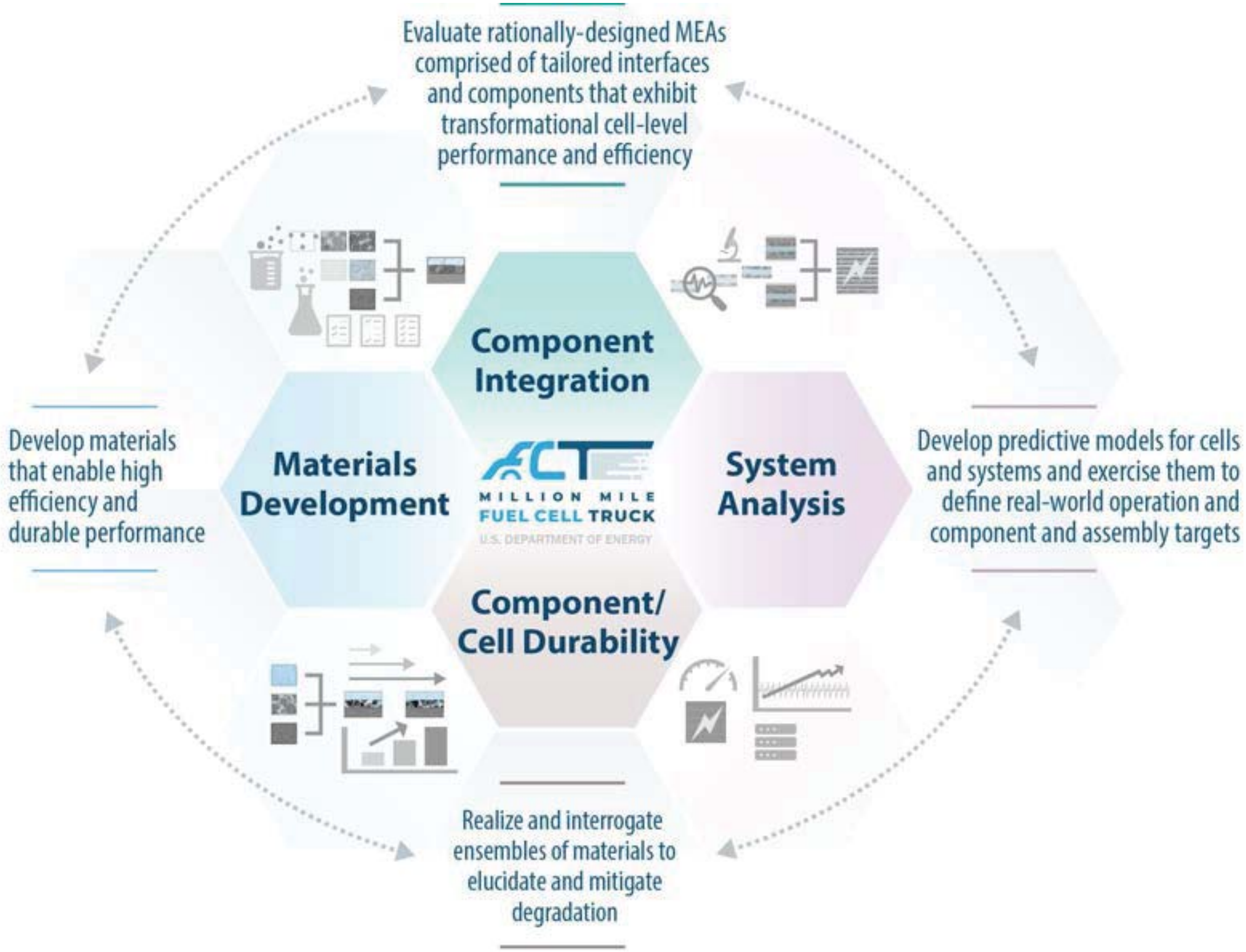
- Durability: 25,000 hour lifetime
- 68% peak efficiency
- $80/kW fuel cell system cost
- **Overall Target:** 2.5 kW/g_{PGM} power (1.07 A/cm^2 current density) at 0.7 V after 25,000 hour-equivalent accelerated durability test

Heavy-Duty Transportation (2030)

- Durability: 30,000 hour lifetime
- 72% peak efficiency
- $60/kW fuel cell system cost

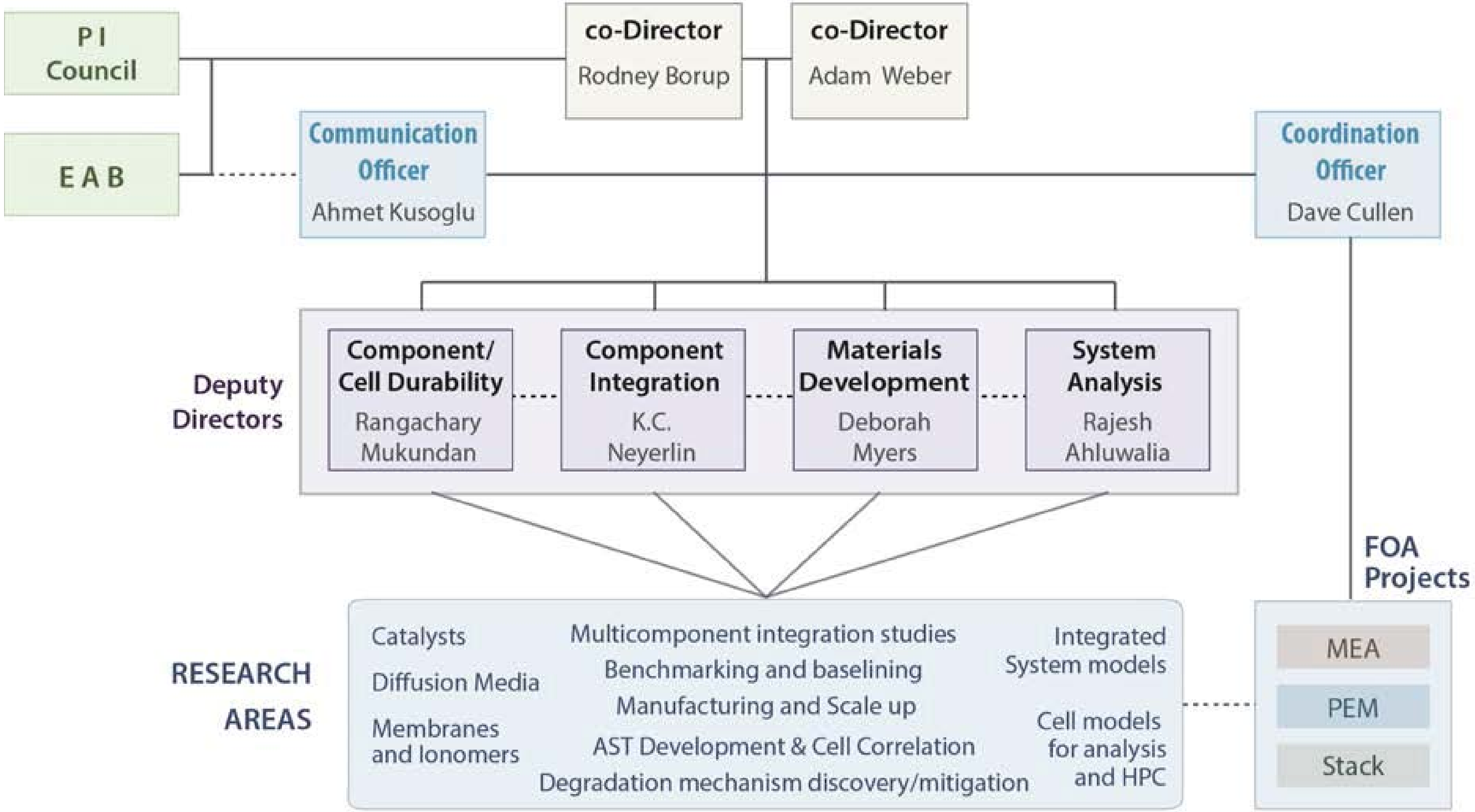
M2FCT Approach

Million Mile Fuel Cell Truck (M2FCT) will tackle these challenges through a “team-of-teams” approach featuring main teams in analysis, durability, integration, and materials development. By coming together as sets of dynamic teams, the integrated consortium will provide rapid feedback, idea development, and information exchange, resulting in an effort that is more than the sum of its parts.



2.5 kW/g_{PGM} power (1.07 A/cm^2 current density) at 0.7 V after 25,000 hour-equivalent accelerated durability test

Organization Chart



EAB: External Advisory Board

Amy M. Adams – Cummins
Christian Appel – Nikola
Simon Cleghorn – W.L. Gore
Ken Howden – DOE (21st Cent. Truck)
JoAnn Miliken – Retired DOE
Mike Perry – Retired UTRC
Gary Robb - Hyzon

M2FCT: National Labs in Partnership with Universities and Industry

MILLION MILE FUEL CELL TRUCK
U.S. DEPARTMENT OF ENERGY

"Team-of-teams" approach that allows for rapid feedback, idea development, and information exchange

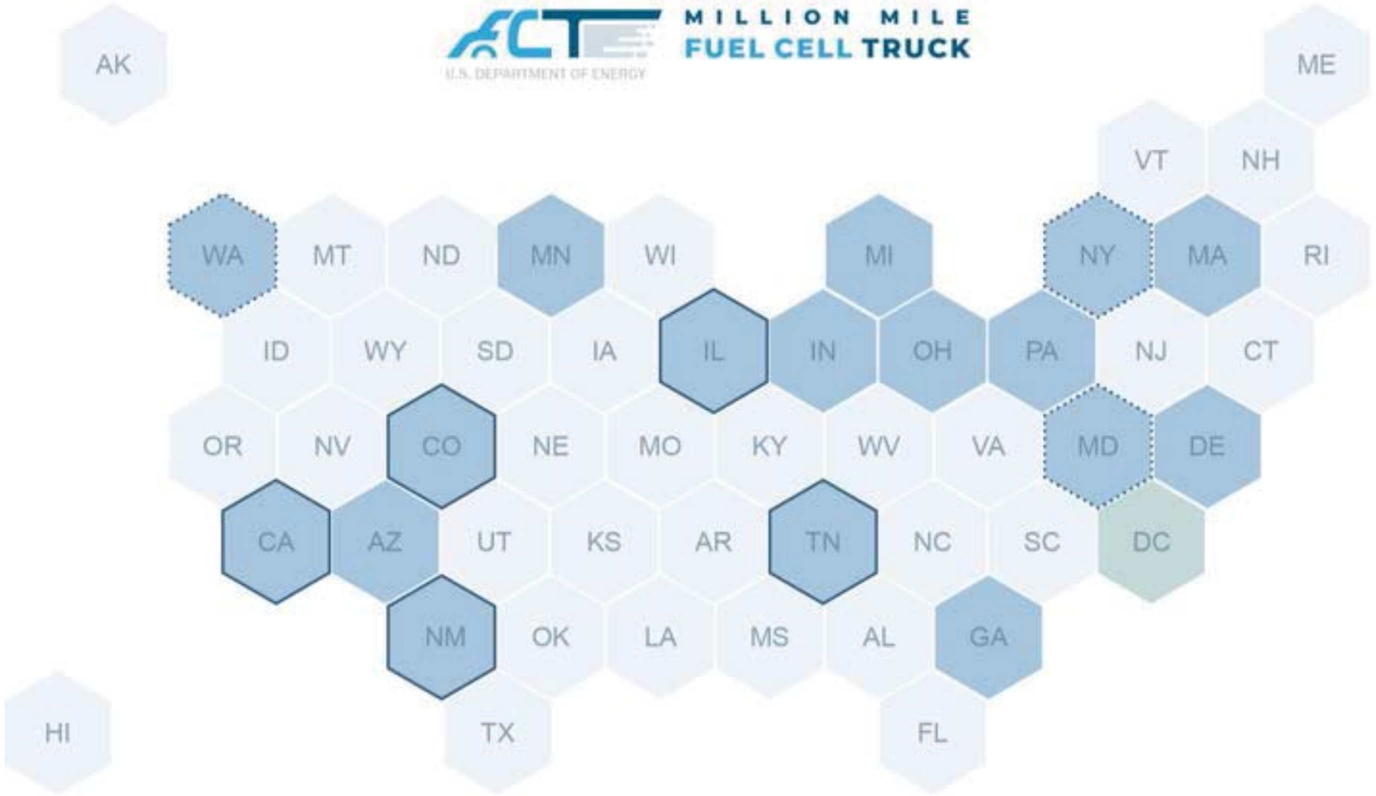
MEA Projects
Carnegie Mellon University · gm · NIKOLA

Membrane Projects
Lubrizol · 3M

Stack Projects
Cummins · PLUG POWER

Bipolar Plate Projects
gm · Raytheon Technologies · TreadStone Technologies, Inc. · NEOGRAF SOLUTIONS

Air Management Projects
CAT · MAHLE · EATON · R&D Dynamics Corporation



Discretionary Funding: Recently Announced

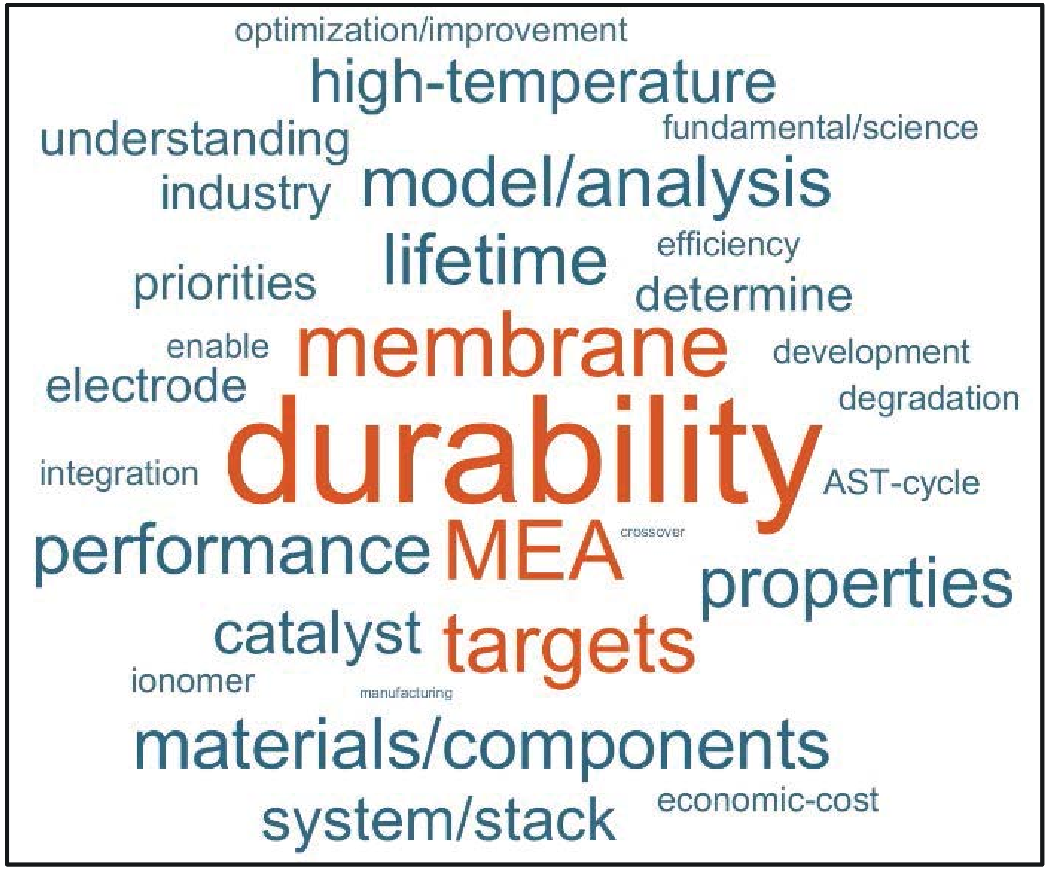
- **State University of New York Buffalo**, $200,000: *Integrating Highly Durable Carbon Supports and Intermetallic PtCo Catalysts for Heavy-Duty MEAs*
- **UC Irvine**, $175,000: *Materials and Design Solutions for PEMFC Durability*
- **Drexel University**, $200,000: *Advanced PILBCP Ionomer Composites for Durable Heavy Duty PEMFCs*
- **UC Merced**, $150,000: *Characterization and Simulation of Interfacial Transport Phenomena in the Membrane-Electrode Assemblies using Rheo-impedance and Imaging Diagnostic Tools*
- **Florida International University**, $200,000: *Real-Time Continuous Monitoring of Ionomer Degradation with Ion-Sensitive Field-Effect Transistor (ISFET) Microsensors*

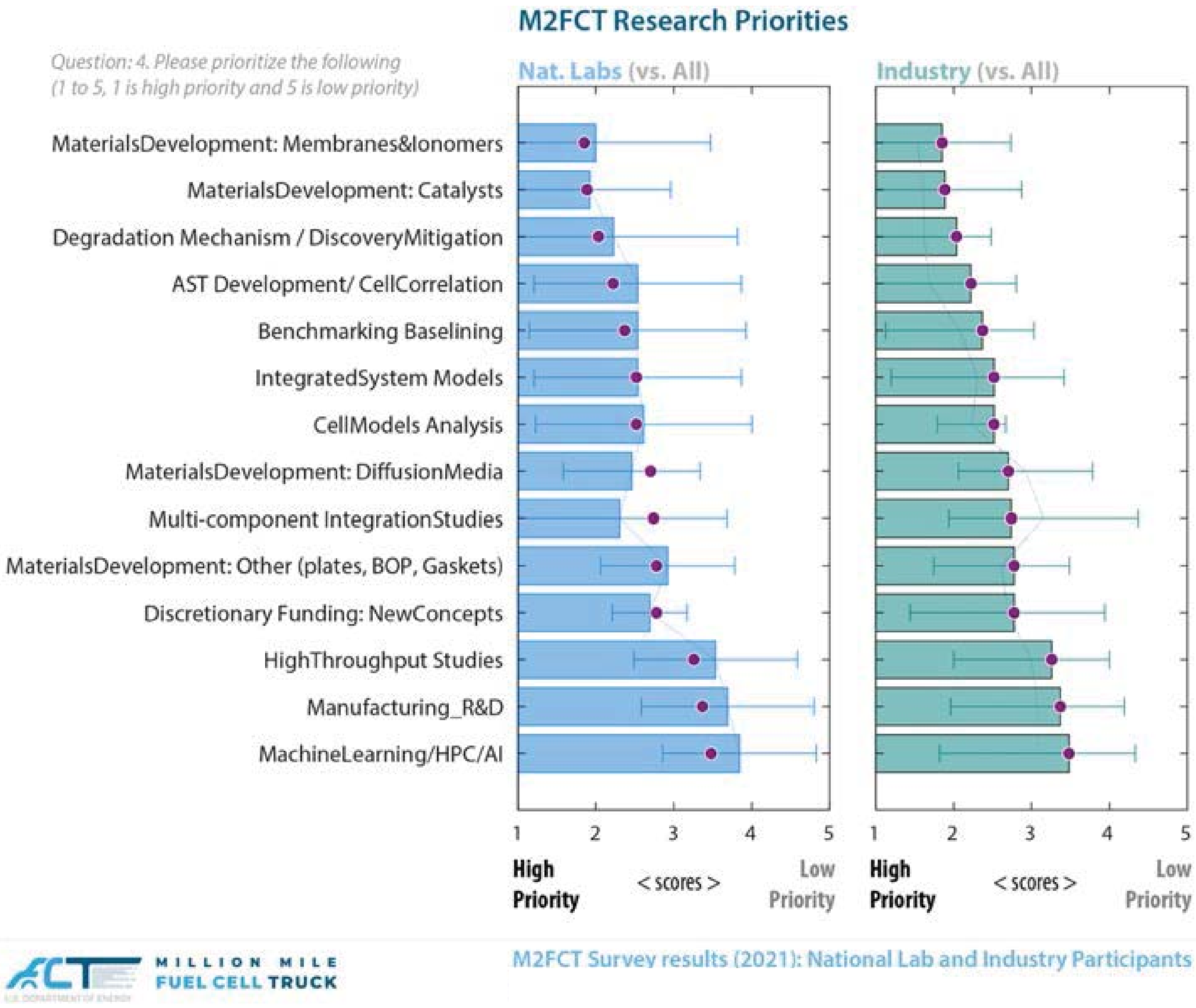
Main Laboratories
Los Alamos NATIONAL LABORATORY
BERKELEY LAB
OAK RIDGE National Laboratory
NREL NATIONAL RENEWABLE ENERGY LABORATORY
Argonne NATIONAL LABORATORY

Affiliate Laboratories
Pacific Northwest NATIONAL LABORATORY
BROOKHAVEN NATIONAL LABORATORY
NIST National Institute of Standards and Technology

M2FCT: R&D Priorities

Word Cloud





1 is highest priority

International Durability Working Group (iDWG)

8 Countries
from America, Europe, and Asia

30 Institutions
participants representing governments, universities, industry and labs

80 Researchers
facilitating data sharing, exchanging materials, promoting AST development

MILLION MILE FUEL CELL TRUCK — U.S. DEPARTMENT OF ENERGY · IMMORTAL · NEDO New Energy and Industrial Technology Development Organization · FC-Platform · cea

Heavy-Duty Stressors
- Thermal Stressors
- Chemical Stressors
- Mechanical Stressors
- Chemical-Mechanical

Material Characterization
- Degradation Durability
- Ex-situ Operando
- Multi-Modal
- Multi-Scale

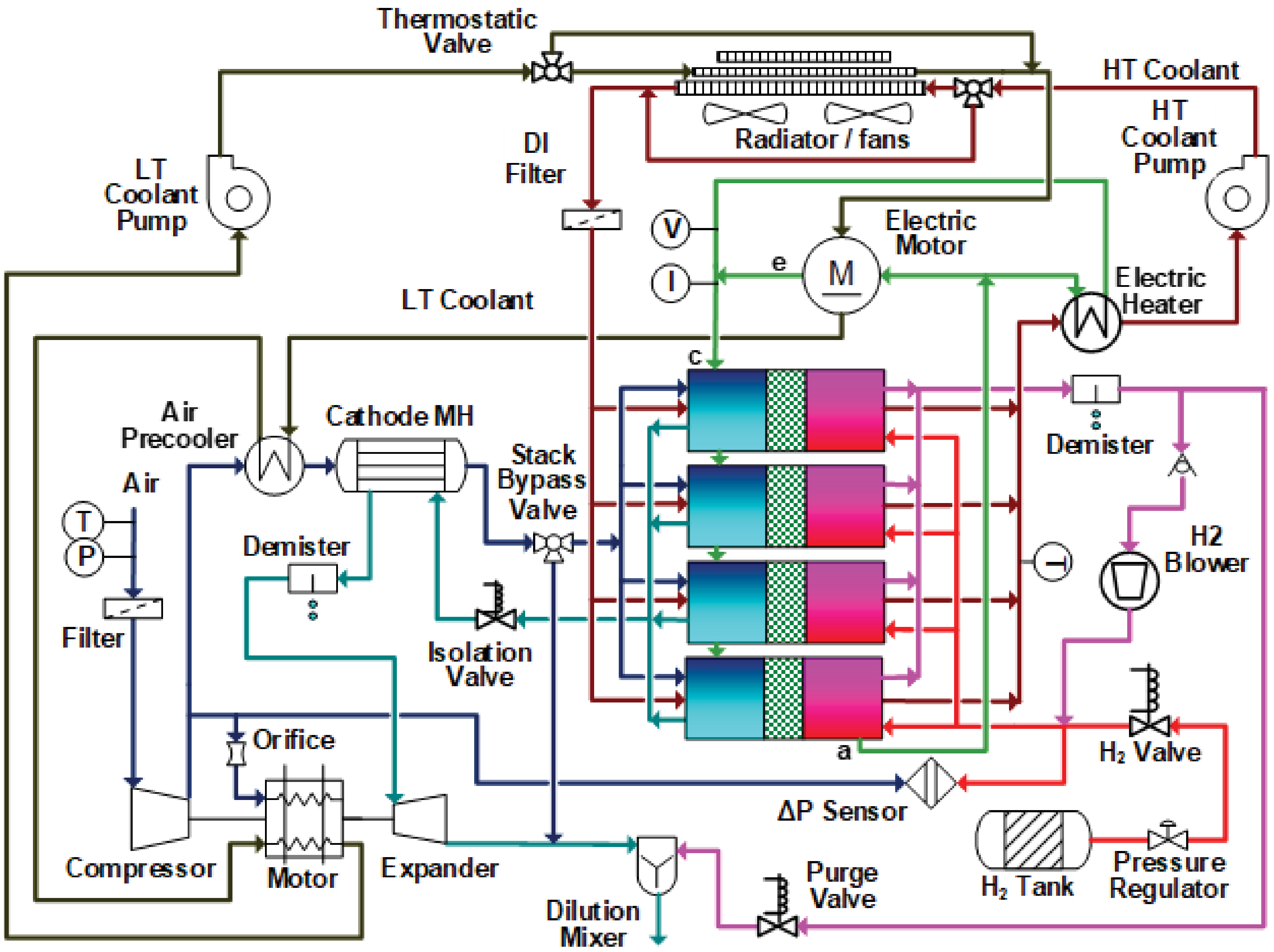
Benchmarking and Protocols
- Benchmarking Baselining
- Testing & Protocols
- Durability Performance
- Various Cell Sizes

Stressors related to Heavy Duty

Characterization

Benchmarking and Protocols

M2FCT System Modeling



Salient Features

- 275 kW net (70-kWh ESS) at EOL
- Multiple stacks: 4
- Electrodes
  Cathode: a-Pt/C, 0.25 mg_{Pt}/cm^2, 50 wt.% Pt
  Anode: Pt/C w IrO_2 (TBD), 0.05 mg_{Pt}/cm2
- Membrane: 14 mm, chemically stabilized, mechanically reinforced
- Single air system with expander
- Single anode system with recirculation blower
- Cathode humidifier: No (TBD)
- Rated power conditions at EOL: 2.5 atm, 87-95ºC, 660-700 mV
- Control valves for startup and shutdown, cold start and OCV

Determining typical HDV relevant condition

Autonomy simulation results provided by Vincent Nicolas Freyermuth, Argonne National Laboratory

Real World Drive Cycle

- Gross Vehicle Weight (GVW): 36.3 MT (80,000 lbs)
- 10.5-h drive segment, 3 extended idles with engine off
- Truck speed around 65 mph

Motor Power

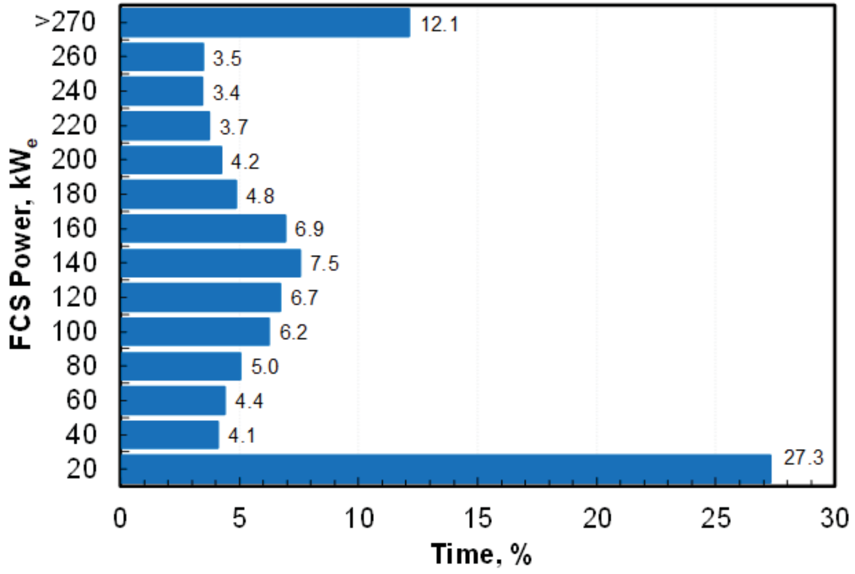
- Maximum power on drive cycle: 500 kW_e
- Motor input power on 6% grade at 30 mph, 36.3-MT GVW: 400 kW
- Motor input power at 65-mph, 0% grade: 160 kW

Jason Lustbader and Kenneth Kelly: HD/MD duty cycles from NREL

Real World Fleet Data

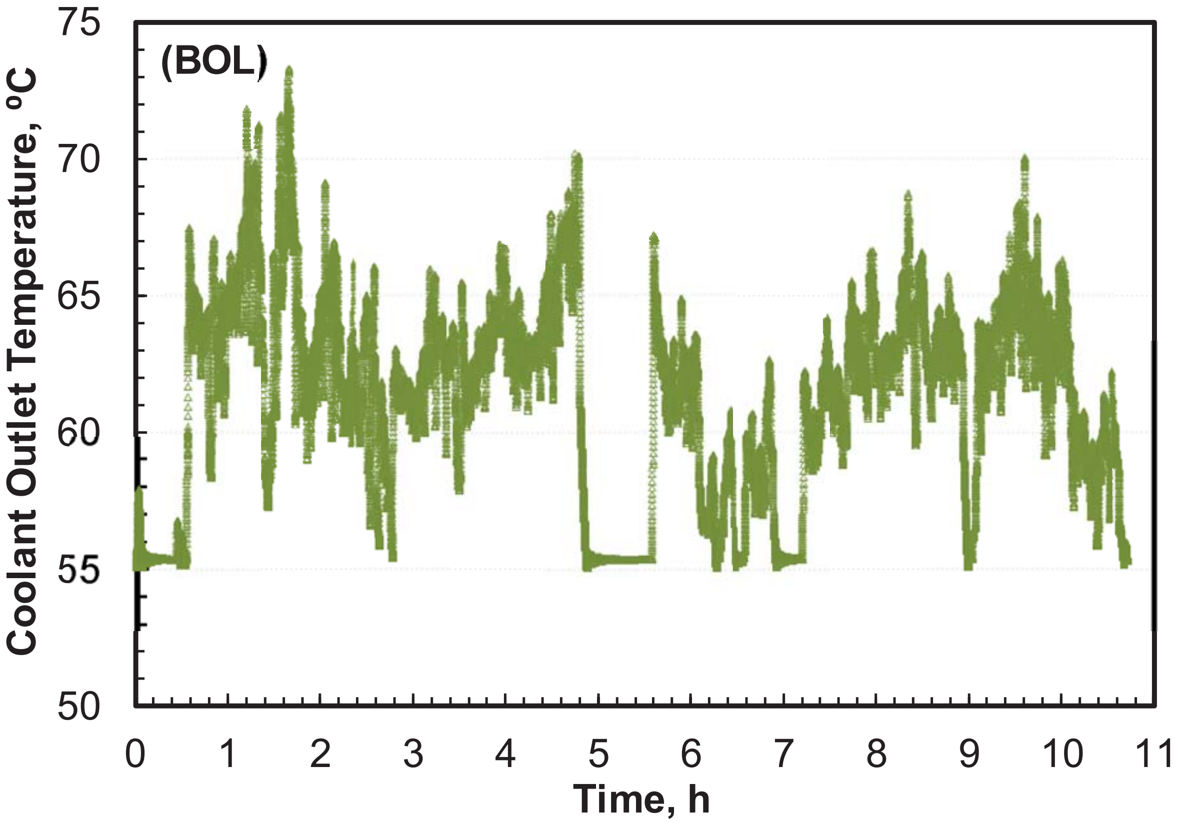
- NREL has millions of miles of Fleet data (From demo project) at 1Hz resolution
- Will analyze data and provide
  - ✓ Typical driving conditions for numerous applications
  - ✓ Start/Stops
  - ✓ High temperature excursion (grade at lower speeds)
  - ✓ Power cycling
  - ✓ External temperature extremes

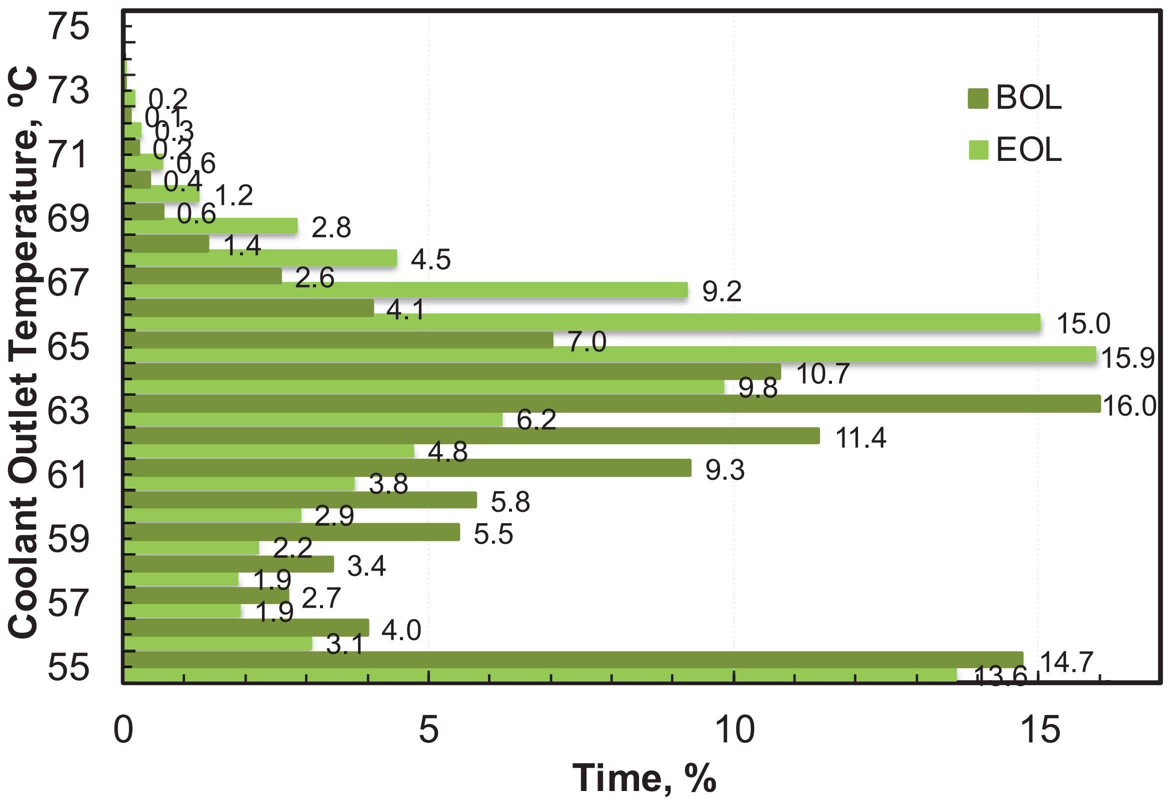
ANL converts real world truck data to FC-power and operating conditions



Operating Temperatures Statistics

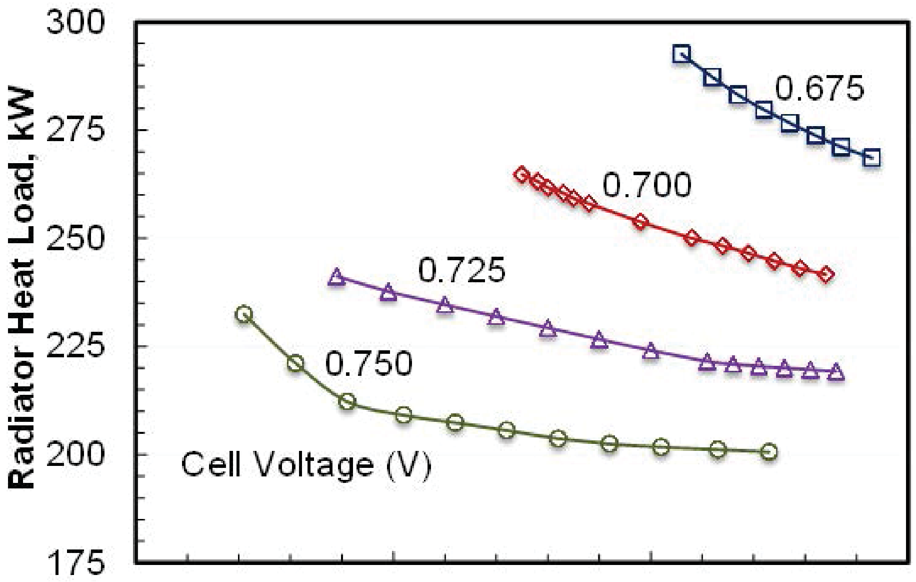
- Stack temperature remains below 75°C throughout the drive cycle
- Median stack temperature maintained within 65±1 °C for 34.3% time. Can be further adjusted by controlling the fan power and/or the thermostatic valve.
- Stack temperature below 70°C for >98% time.





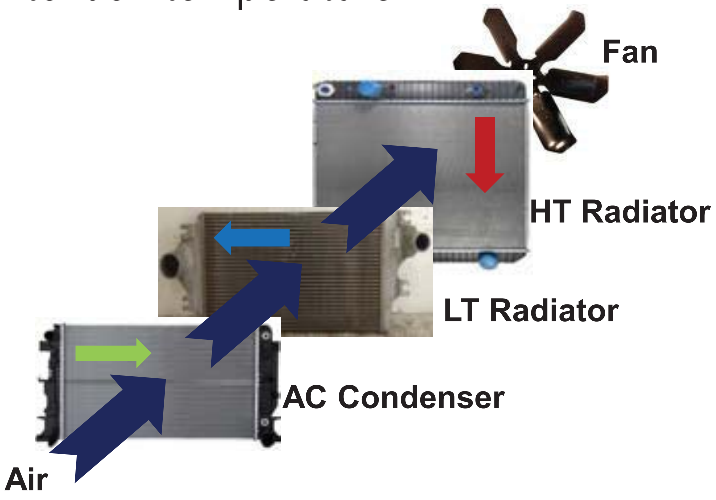
FCS Heat Rejection

- Fuel cell dominant propulsion system rated at 275-kW_e net, 35-kWh ESS
  - Hill climb at 35 mph, 6% grade, 20-min duration
  - Battery supplies balance of propulsion power and operates in a charge depleting mode
  - 25°C ambient temperature
- FCS heat load and fan power
  - Heat load (Q) is mainly a function of cell voltage
  - Lower coolant temperature (T_c), higher fan power, higher Q
  - Higher cell voltage, smaller fan power
  - Need cell voltage > 0.75 V at rated power for stacks that operate below 80°C
  - Sample result at 0.7 V: 87°C, 265 kW radiator heat load, 30 kW fan power



FCS Heat Rejection on Hill Climb

Modeled system equivalent to radiator fan for 450-hp diesel engine, 52°C air-to-boil temperature

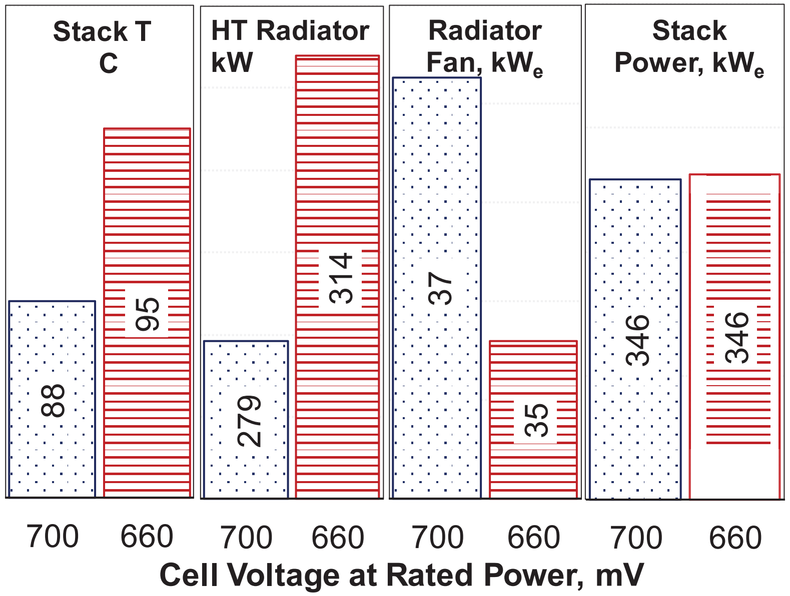


Study Conclusions

Study parameters: Hill climb at 30 mph, 6% grade, 20-min duration, 25°C ambient temperature

1. Largest FCS for which waste heat can be rejected using radiators in a 450-hp diesel trucks: 275 kW_e net
2. Smallest battery operated in charge depleting mode during hill climb: 35 kWh
3. Lowest cell voltage at EOL for exit coolant temperature below 95°C: 660 mV

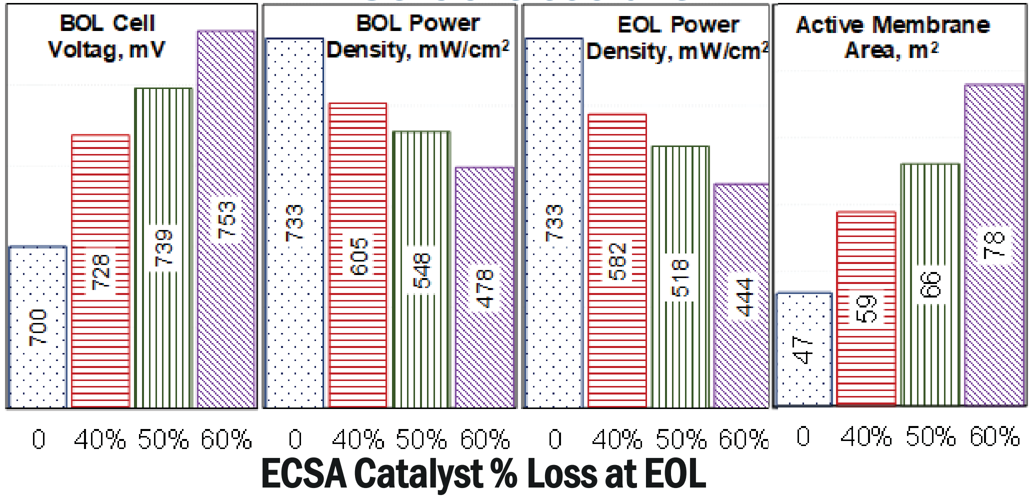
Heat Exchangers	Dimensions and Details	Heat Loads	Radiator Fan 37 kW
HT Radiator	40″ (W) x 42″(H) x 2″ (D) Fins: louvered, 12-fpi, 10-mm height Tubes: 2-mm height	280 kW	Vehicle Speed: 30 mph
LT Radiator	40″ (W) x 35″ (H) x 2.5″ (D) Fins: louvered, 8-fpi, 20-mm height Tubes: 10-mm height	49 kW	Ambient T: 25°C
AC Condenser	40″ (W) x 28″ (H) x 0.75″ (D) Fins: plain, 12-fpi, 10-mm height Tubes: 2-mm height	12 kW	Air Flow Rate: 9.3 kg/s



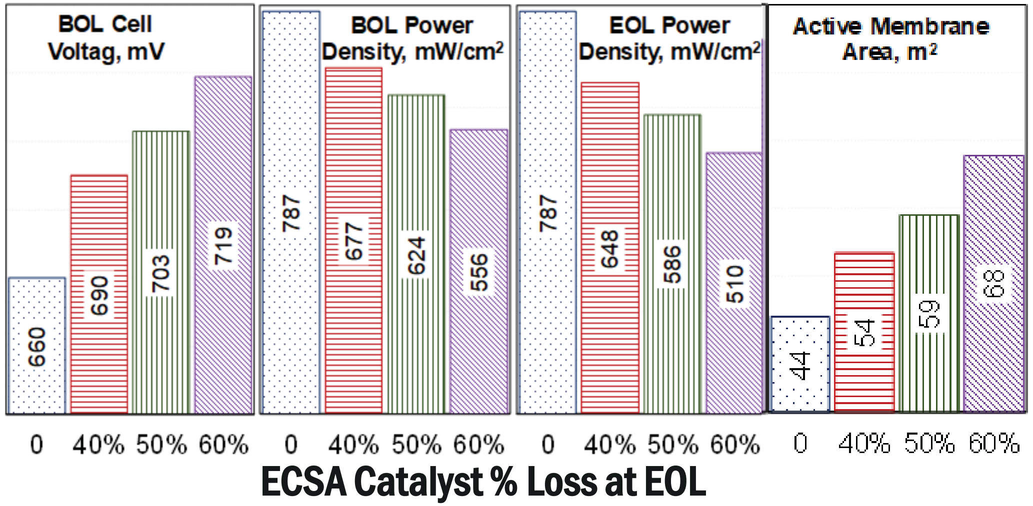
FCS-HDV Degradation Adjusted Stack Size

Lifetime defined by ECSA loss as marker of aging (275 kW_e at EOL)

85-90°C coolant



90-95°C coolant



- Stack size defined by efficiency target
  - Stack coolant exit temperature at peak power
- Stack active area defined for various catalyst degradation for 700 mV (EOL cell voltage)

Modeled Electrode Degradation Mechanisms

- ECSA loss due to Pt dissolution and growth in particle size
- Degradation in ORR kinetics
- Increase in oxygen transport resistance
- Change in Pt accessibility

- Relaxing EOL cell voltage to 660 mV decreases the initial stack active area by 10-15%
  - Stack coolant exit temperature at peak power, ~ 50°C higher

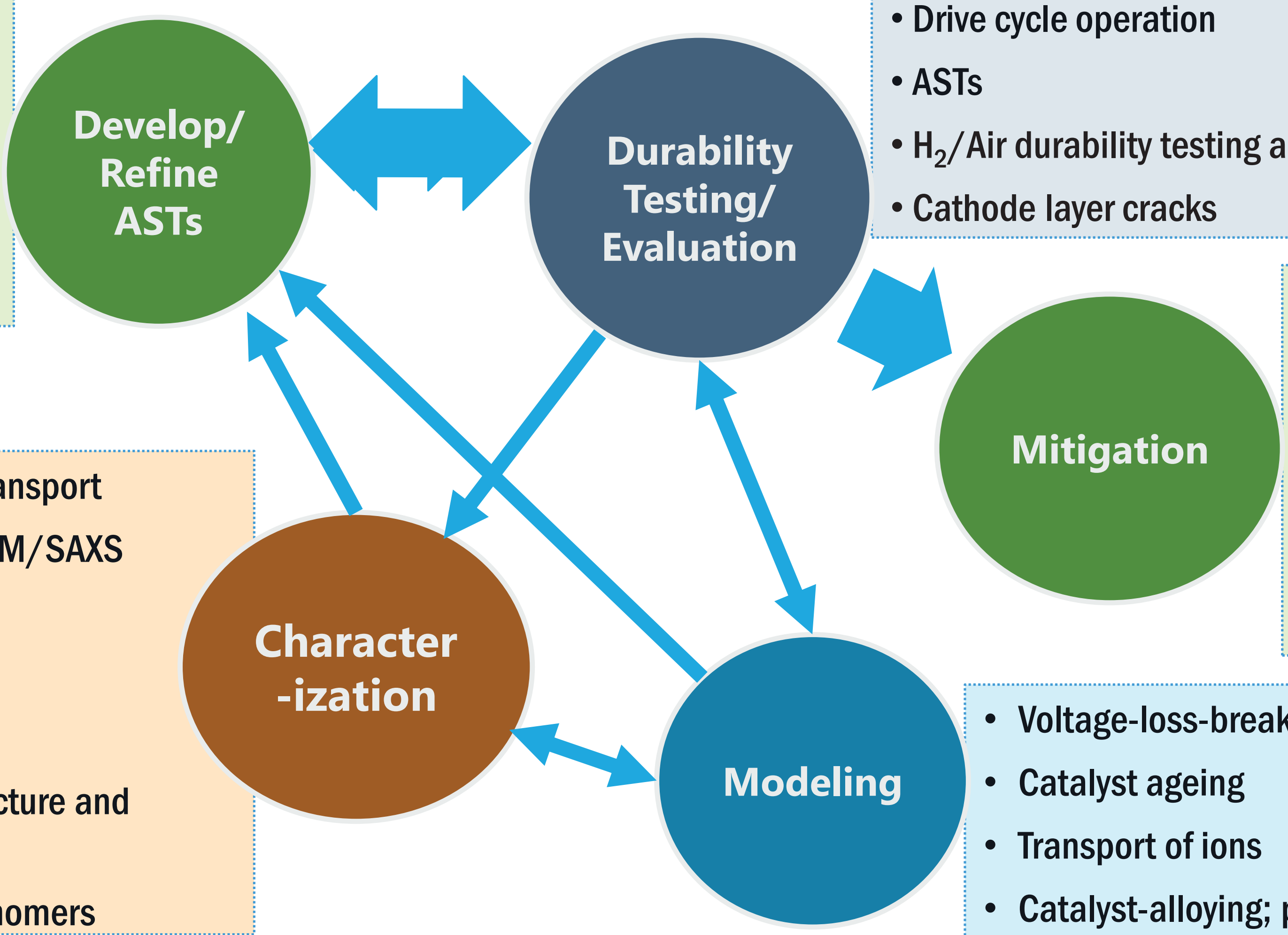
2.5 atm, 1.5 SR(c), 0.3 mg/cm² Pt, a-Pt/HSC cathode catalyst

Durability

Understanding, evaluating, and mitigating durability concerns with materials-based solutions

- Mechanistic based ASTs
- Single/multi-mechanism (MEA) ASTs
- Simulate drive cycle

- Drive cycle operation
- ASTs
- H_2/Air durability testing and anode reversal
- Cathode layer cracks

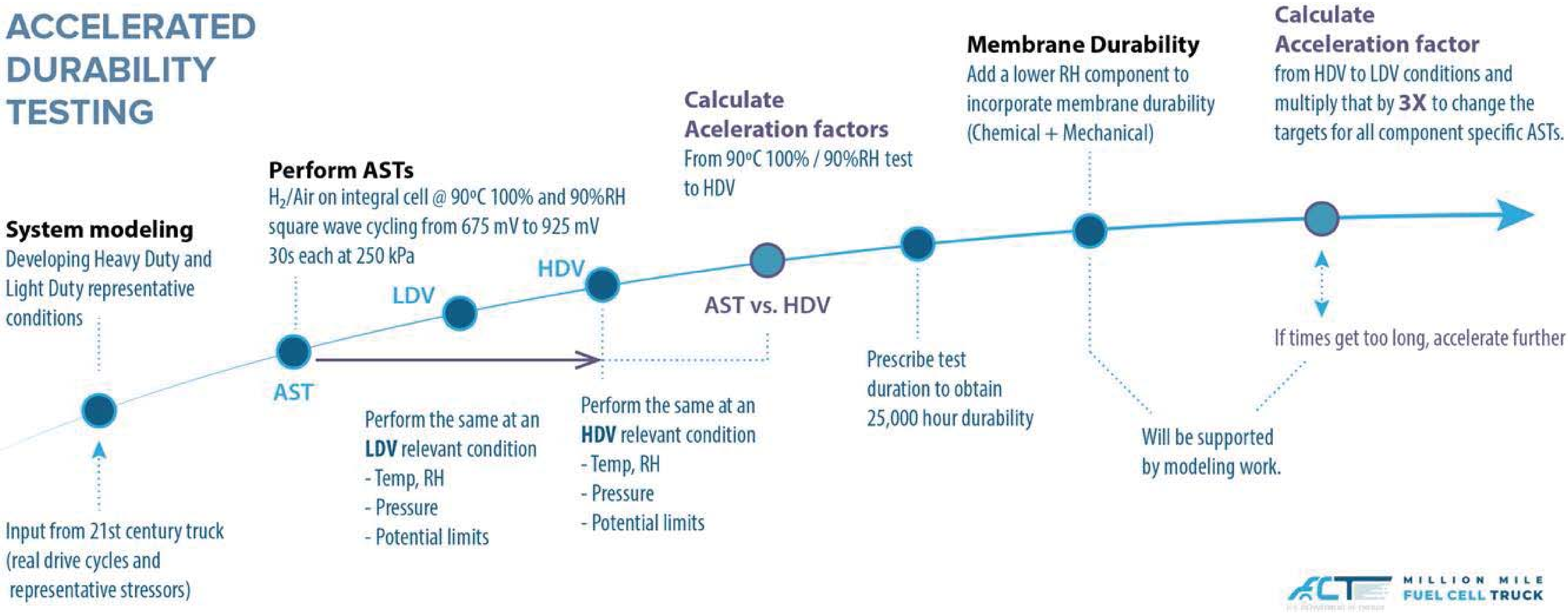


- Catalyst-alloying; particle growth, kinetics losses with leaching
- Catalyst-support corrosion
- Membrane Ce stabilizers
- New materials and integration schemes

- Metal dissolution and transport
- Catalyst ripening with TEM/SAXS
- Catalysts
- Membranes
- GDL/MPL cracks
- Catalyst Layer microstructure and stability
- Cation partitioning in ionomers

- Voltage-loss-breakdown
- Catalyst ageing
- Transport of ions
- Catalyst-alloying; particle growth, kinetics losses with leaching

Flowchart

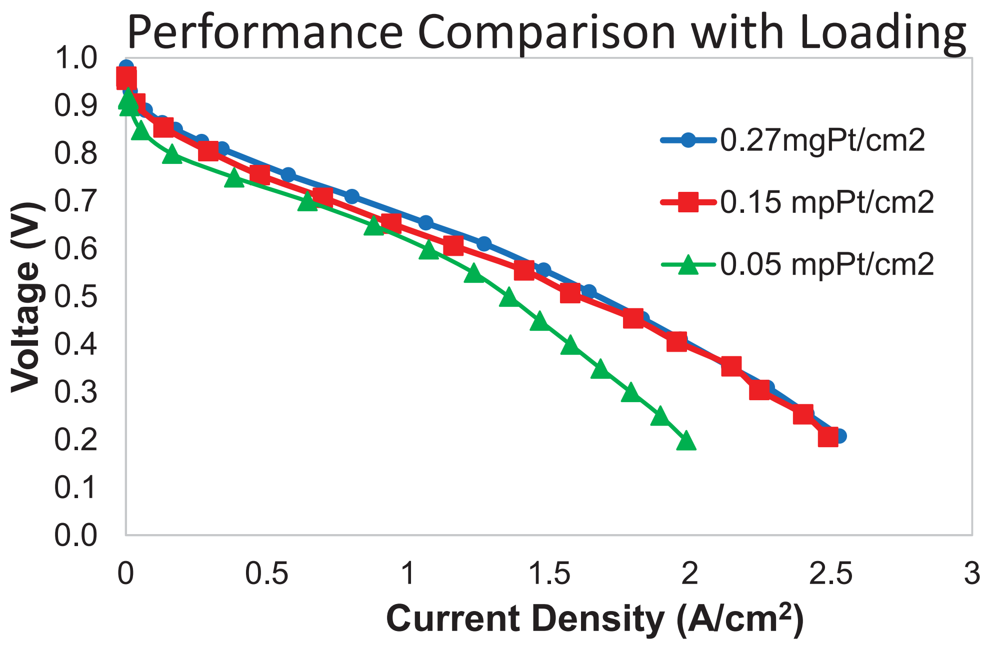


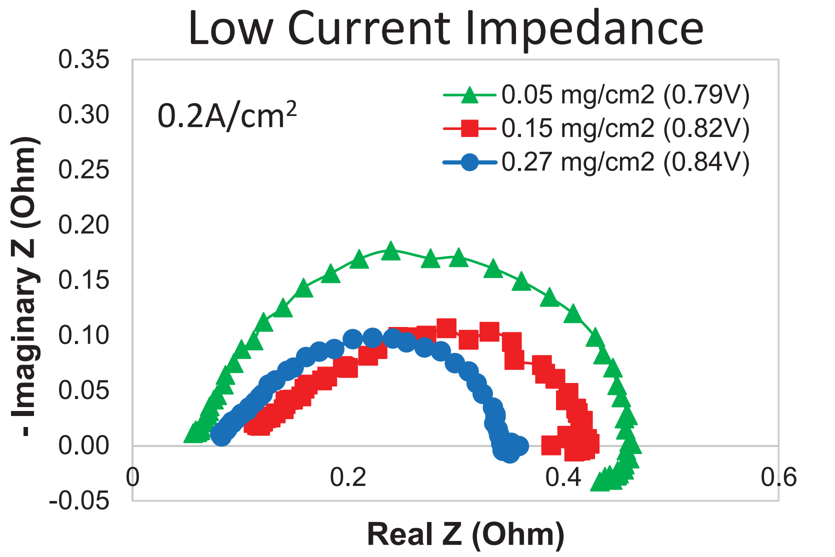
ACCELERATED DURABILITY TESTING
System modeling
Developing Heavy Duty and Light Duty representative conditions
Input from 21st century truck (real drive cycles and representative stressors)
Perform ASTs
H2/Air on integral cell @ 90ºC 100% and 90%RH square wave cycling from 675 mV to 925 mV 30s each at 250 kPa
AST
LDV
HDV
Perform the same at an LDV relevant condition
- Temp, RH
- Pressure
- Potential limits
Perform the same at an HDV relevant condition
- Temp, RH
- Pressure
- Potential limits
Calculate Aceleration factors
From 90ºC 100% / 90%RH test to HDV
AST vs. HDV
Prescribe test duration to obtain 25,000 hour durability
Membrane Durability
Add a lower RH component to incorporate membrane durability (Chemical + Mechanical)
Will be supported by modeling work.
Calculate Acceleration factor
from HDV to LDV conditions and multiply that by 3X to change the targets for all component specific ASTs.
If times get too long, accelerate further
MILLION MILE FUEL CELL TRUCK

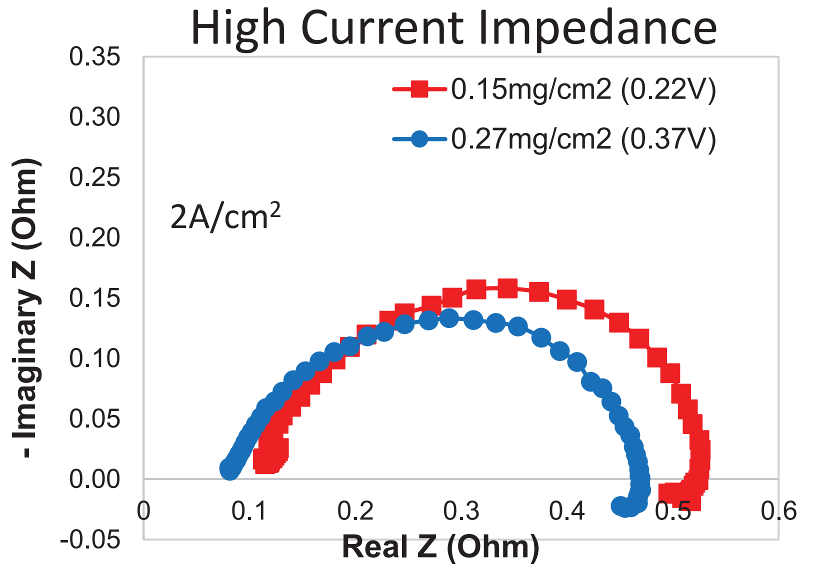
Plan for ASTs: Catalyst followed by Membrane and MEA

- Currently performing ASTs in H_2/Air on integral cell @ 90 ºC, 100%RH with square wave cycling from 675 mV to 925 mV 30s each at 250 kPa
- Perform ASTs in H_2/Air on integral cell @ 90 ºC, 90%RH with square wave cycling from 675 mV to 925 mV 30s each at 250 kPa
- Perform the same at an LDV relevant condition (Temp, pressure, RH, potential limits)
- Perform the same at an HDV relevant condition (Temp, pressure, RH, potential limits)
- Calculate acceleration factors from 90 ºC, 100% RH, 90%RH test to HDV conditions and prescribe test duration to obtain 25,000 hour durability.
  - Introduce RH switching and a drier condition to accelerate membrane durability
  - Timeline Sept 2021
- Calculate acceleration factor from HDV to LDV conditions and multiply that by 3X to change the targets for all component specific ASTs. If times get too long, then we can further accelerate it. Will be supported by modeling work.
  - 2 years +
- Refine HDV cycle by including other stressors like high temp, high voltage, dry operation.

Durability Performance: High Loading - Effect of Loading



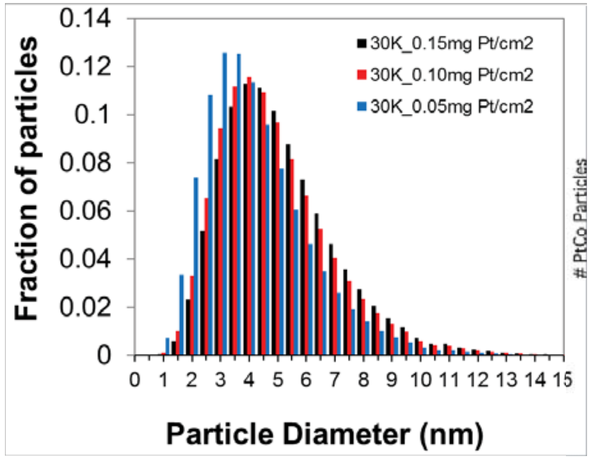


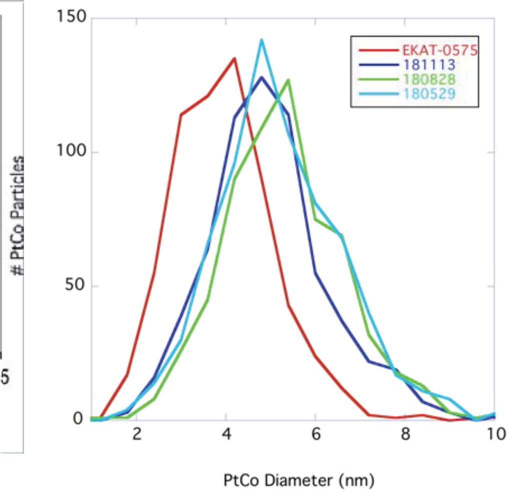


- Loading improves kinetic performance but Mass activity decreases (worse utilization of Pt) from 977mA/mg @ 0.05mg/cm² 0.495mA/mg @ 0.27 mg/cm². Diminishing returns
- Mass transport does not improve at high loadings and thicker electrodes lose any benefit at high current densities

80C, 100% RH, 150 kPa

Durability Characterization: Effect of loading
(0.05 to 0.15 mg_{Pt}/cm^2)





Mean diameter after AST (SAXS)

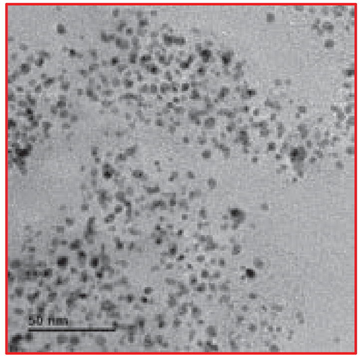
0.05 mg/cm^2: 4.5 nm
0.10 mg/cm^2: 5.2 nm
0.15 mg/cm^2: 5.5 nm

Pt:Co at% in electrode (EDS)

BOL : Pt:Co = 75:25
30K (0.05) : Pt:Co = 80:20
30K (0.10) : Pt:Co = 85:15
30K (0.15) : Pt:Co = 87:13

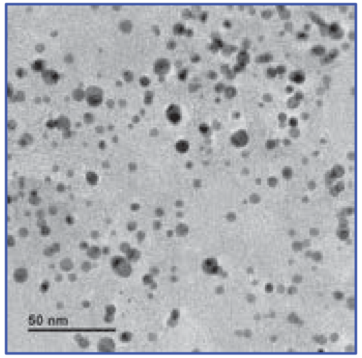
- Higher loading results in slightly larger growth in Pt particle size (both SAXS and TEM)
- On average Co is retained better in the lower loaded electrode
- Larger lattice contraction loss for lower loading (EXAFS data, not shown) coupled with smaller particle growth indicate larger particles retain Co better than smaller particles

BOL (EKAT 0574)



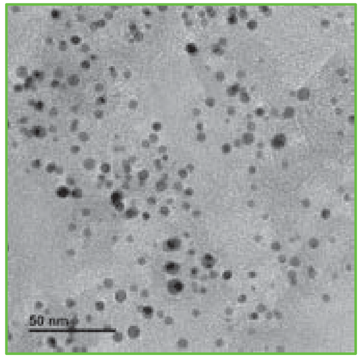
PtCo particle size = 4.2 nm

$0.05 mg_{Pt}/cm^2$
30,000 cycles



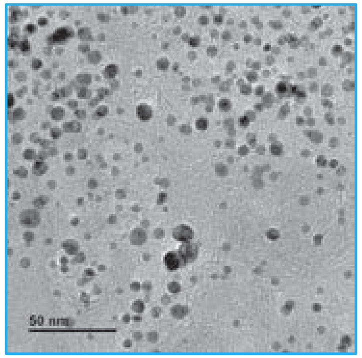
PtCo particle size = 5.1 nm

$0.10 mg_{Pt}/cm^2$
30,000 cycles



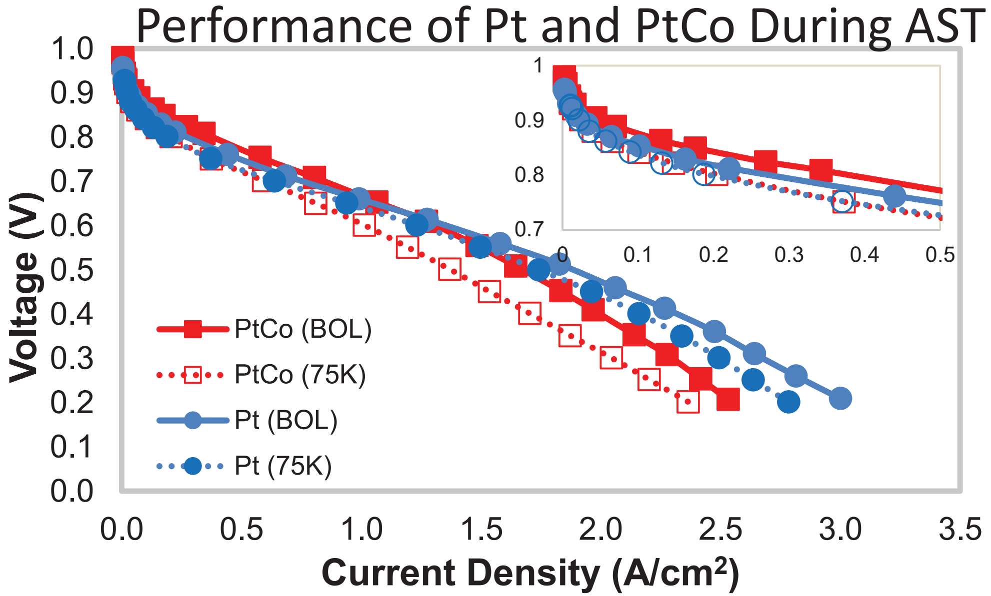
PtCo particle size = 5.5 nm

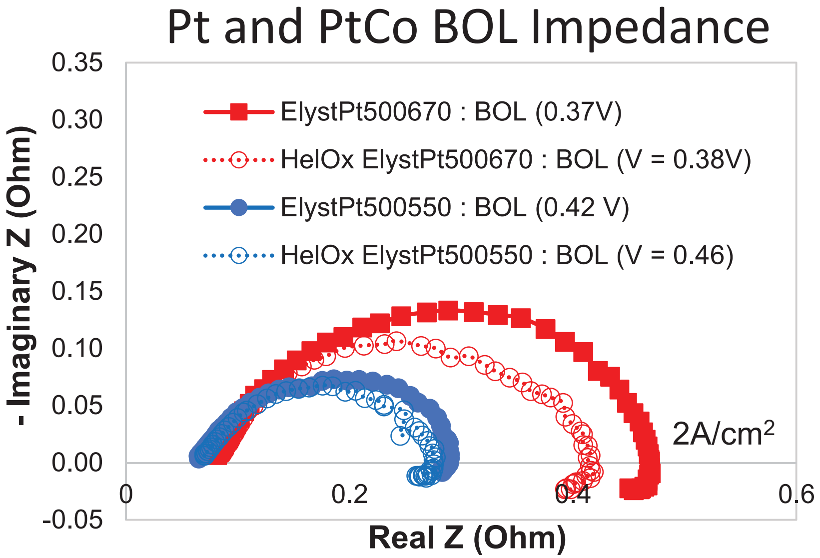
$0.15 mg_{Pt}/cm^2$
30,000 cycles

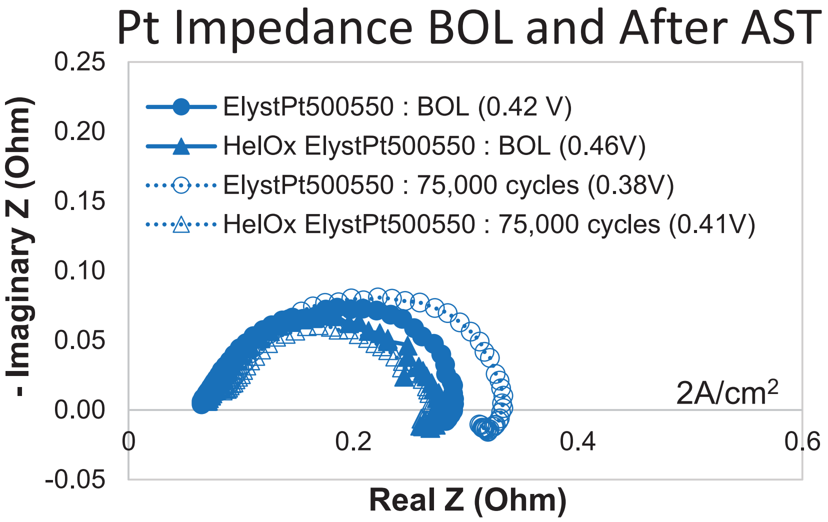


PtCo particle size = 5.6 nm

Durability Performance: High Loading - Effect of Alloying







- Kinetic performance of PtCo is better than that of Pt at BOL: higher alloy mass activity
- No kinetic advantage at EOL of using alloy catalyst: significant loss in kinetic performance of alloy catalyst
- Transport resistance of PtCo alloys higher than Pt

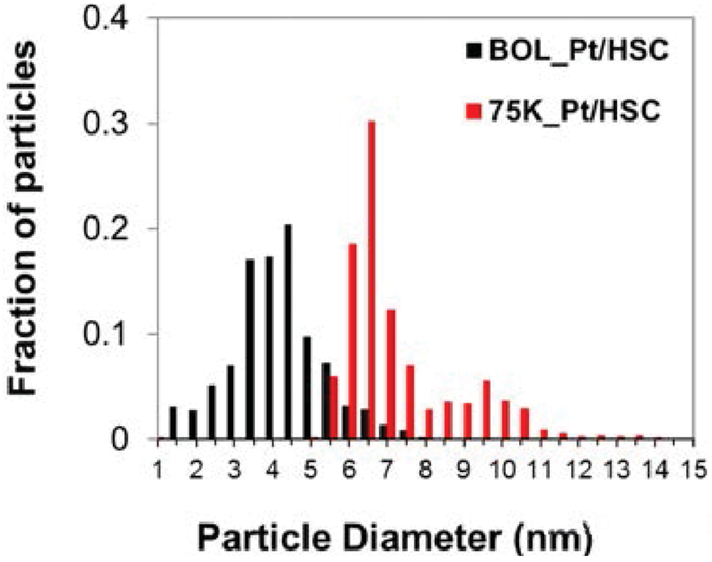
ElystPt500550 (Pt) and
ElystPt500670 (PtCo)

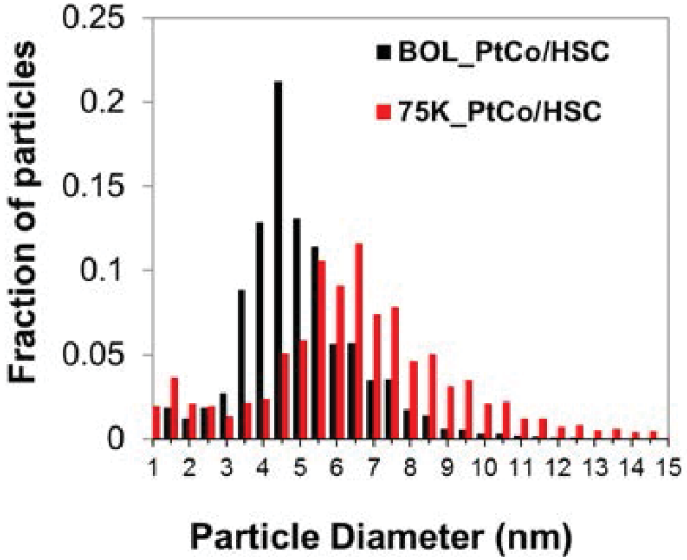
80C, 100% RH, 150 kPa   Loading = 0.25mg/cm²

FCPAD FUEL CELL PERFORMANCE AND DURABILITY

SW AST = Square Wave Catalyst AST (0.6 – 0.95V)

Durability Characterization: High Loading - Effect of Alloying





- PtCo has a larger initial particle diameter and grows less
- Pt has a smaller initial particle diameter and grows more (Pt has larger particle size than PtCo after 75,000 cycles)
- Particle size increase does not have an effect on high current performance at high loadings

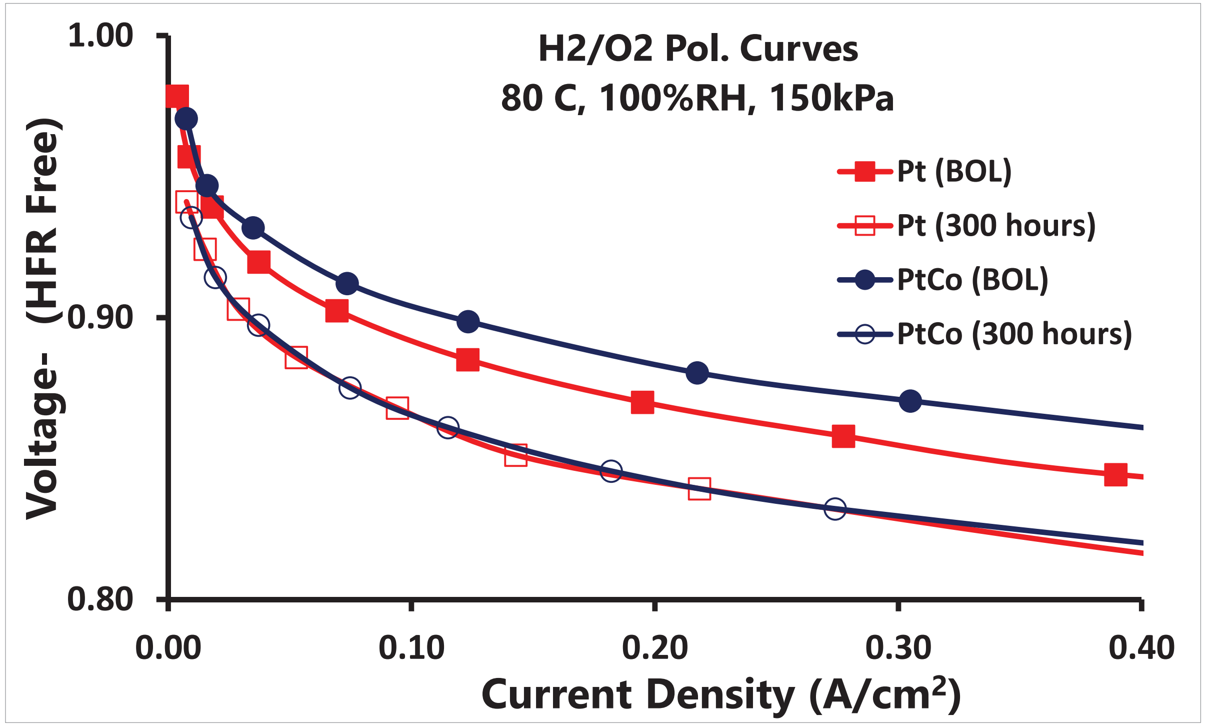
	Mean diameter (nm)		
Sample	**BOL**	**EOT**	**Δd (nm)**
Pt/HSC 0.25mgPt/cm^2	4.3	7.5	3.2
PtCo/HSC 0.27mgPt/cm^2	5.2	6.8	1.6

TEM shows 6.8 nm Pt and 6.4 nm PtCo particles after 75,000 cycles

SW AST = Square Wave Catalyst AST (0.6 – 0.95V)

ASTWG: Catalyst Durability Protocol

- Develop H_2/Air tests to measure degradation rates under accelerated conditions
- Operate cell @ 90°C to accelerate all degradation mechanisms for the longer life time
  - Potential cycling between 0.65V and 0.925V under 100%RH to accelerate catalyst degradation
  - Introduce RH cycling and dry operation to accelerate membrane degradation
- Degradation rates under accelerated conditions will be compared with rates at typical LDV and HDV operating conditions to determine duration of AST to yield 25,000 hours equivalent durability



Pt

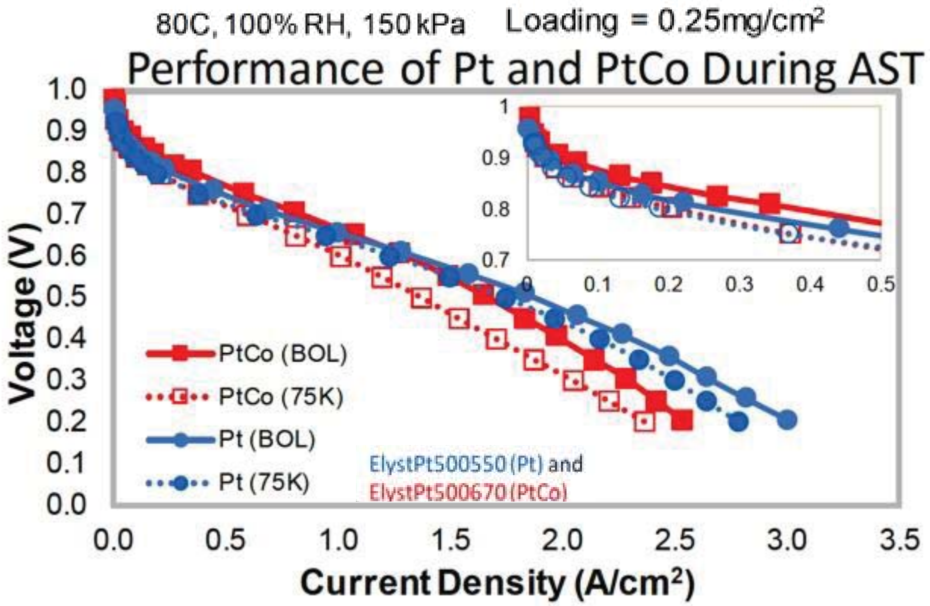
Hours	A/mg-Pt
0	0.31
50	0.23
100	0.21
200	0.17
300	0.13

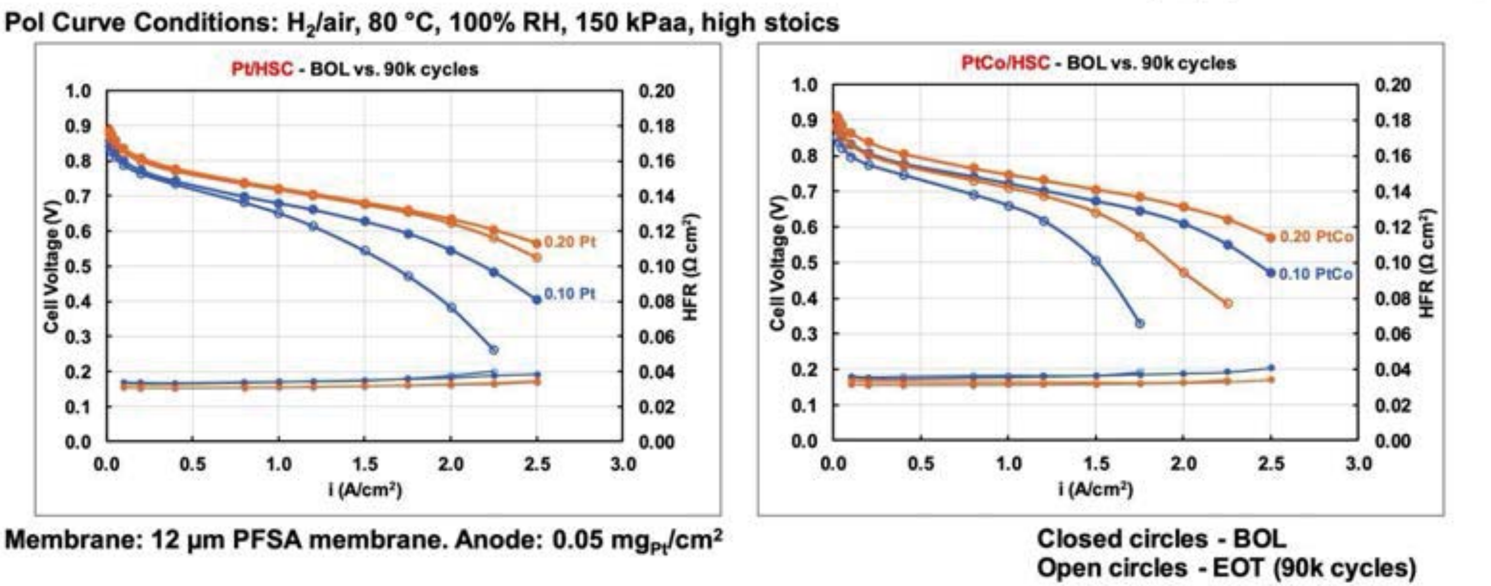
PtCo

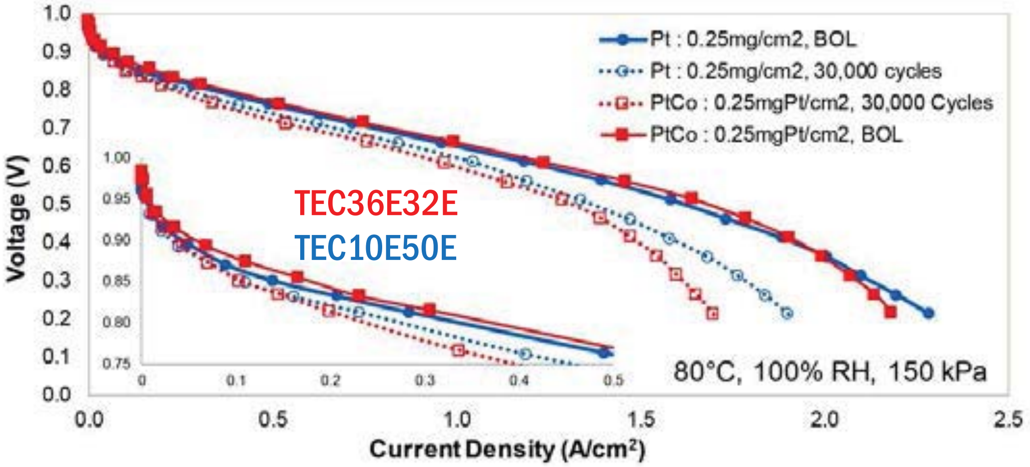
Hours	A/mg-Pt
0	0.47
50	0.33
100	0.23
200	0.18
300	0.14

- PtCo has mass activity = 0.47 A/mg_{Pt} at BOL while Pt = 0.31 A/mg_{Pt}
- At 300 hours both have almost the same mass activity of 0.135 A/mg_{Pt}

Catalyst ASTs (90,000 cycles)

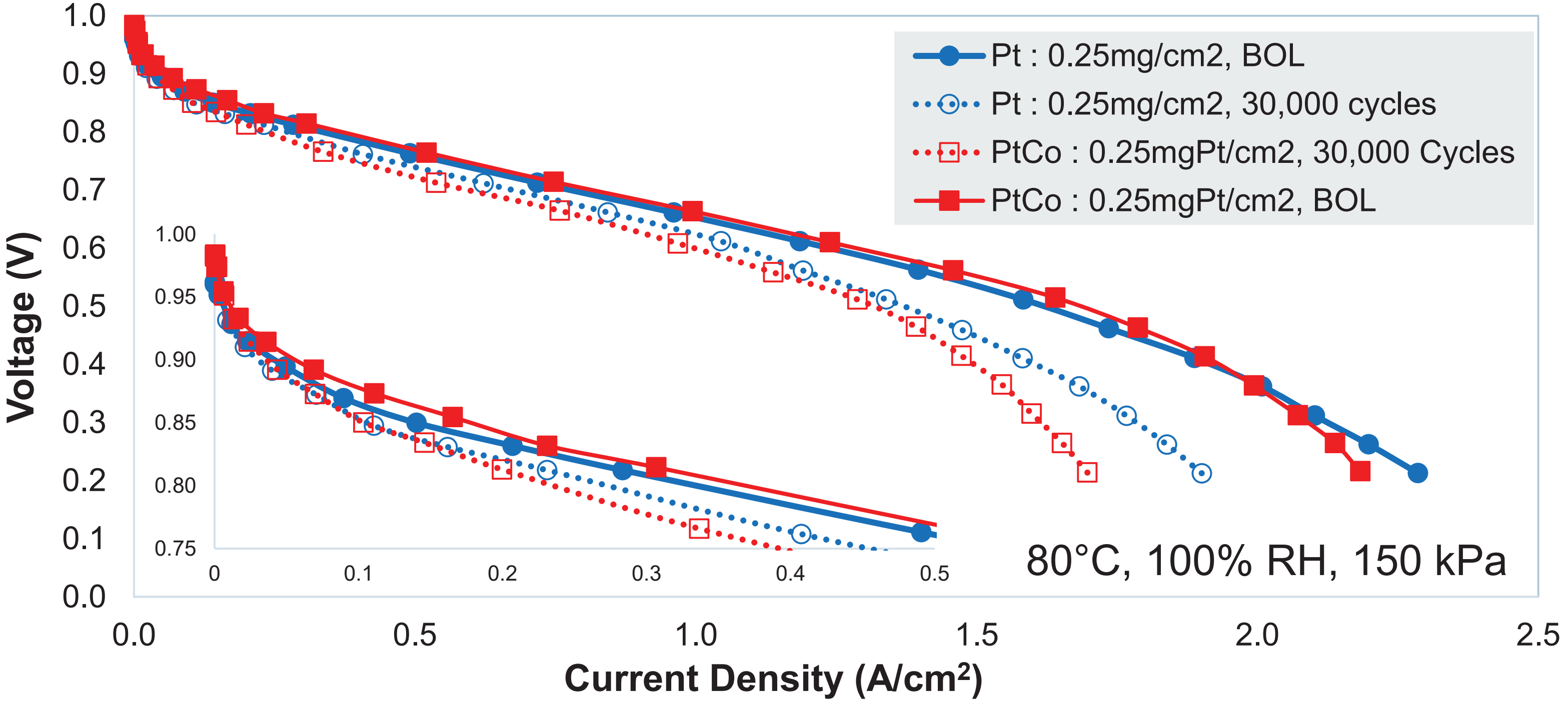


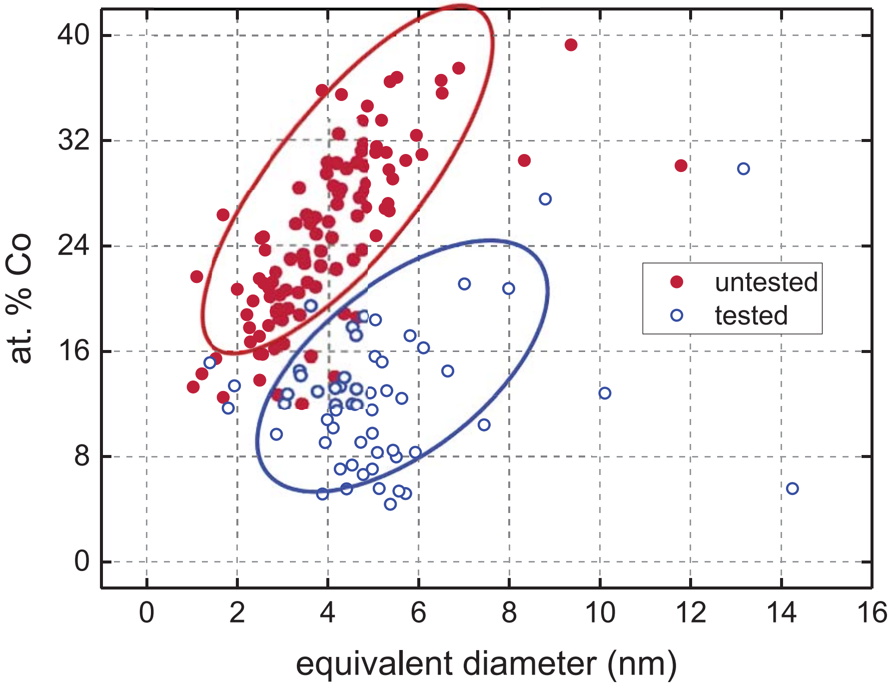




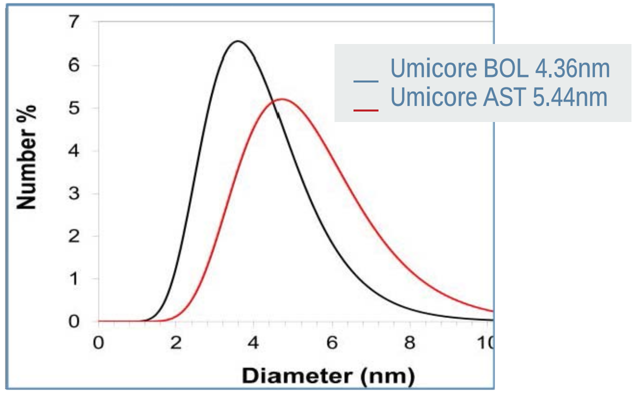
- Increasing the current trapezoidal AST from 30K to either 75K or 90K cycles seems to serve the purpose
- Maybe decrease UPL to 0.925V instead of 0.95V to prevent elimination of potentially viable catalysts

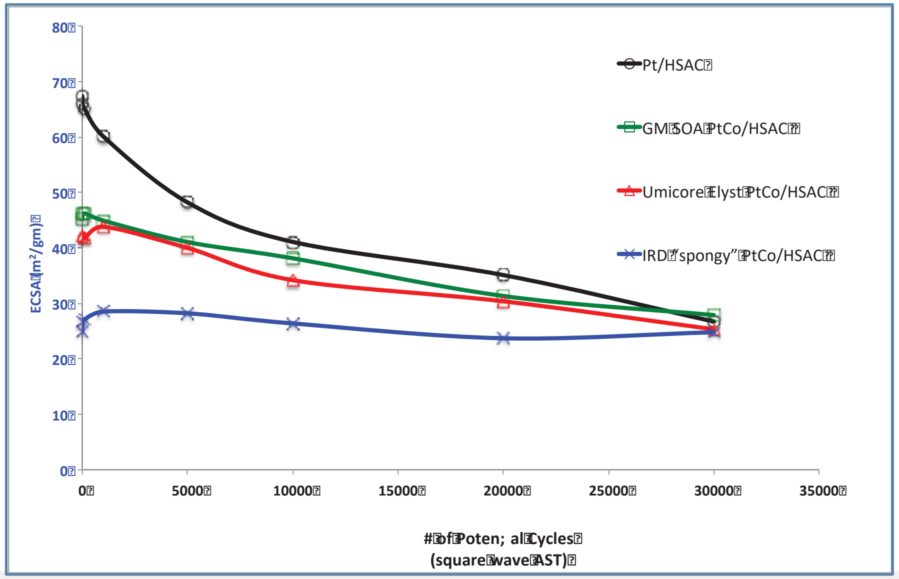
Durability Performance : High Loading: Effect of Alloying



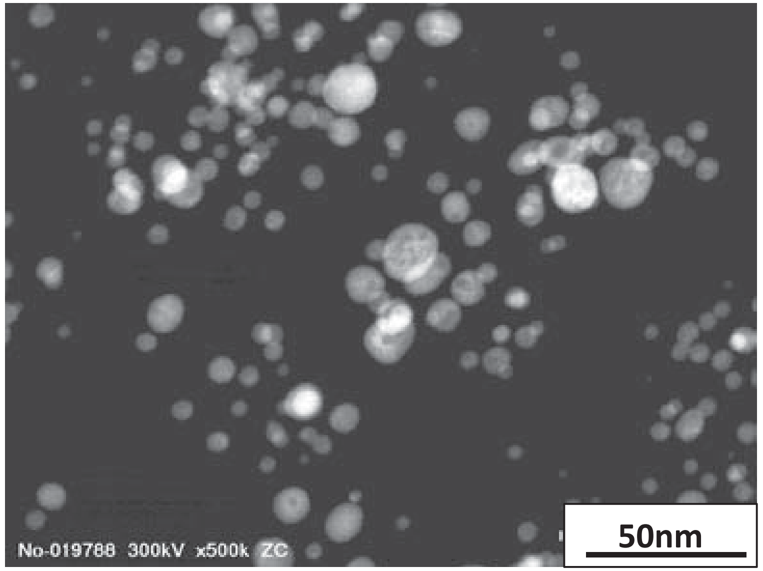


- PtCo alloy catalysts lose kinetic advantage after durability cycles
- Mass transport in Pt catalysts better during all stages of the AST

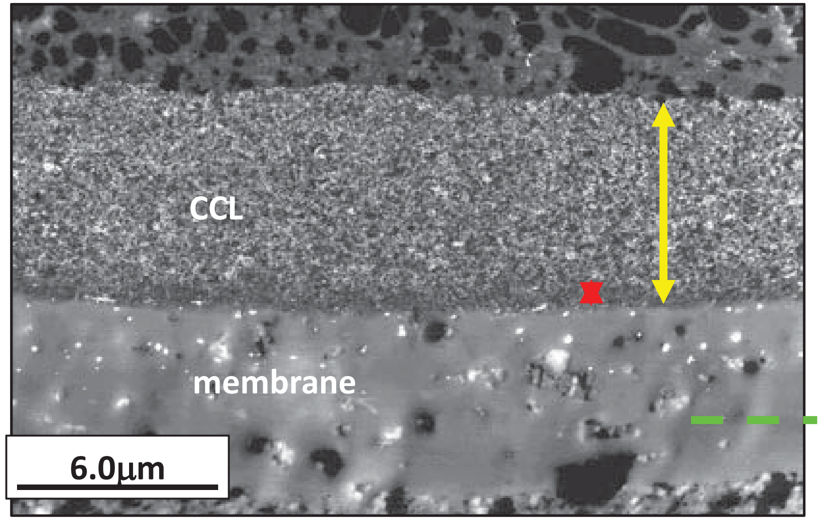




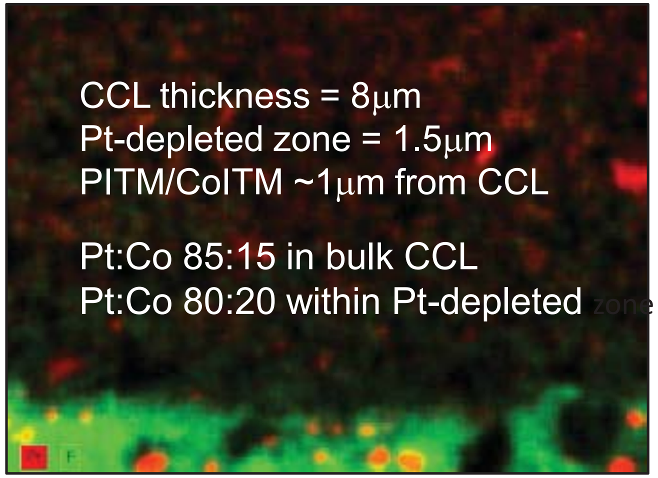
Durability Characterization: High Loading - Effect of Alloying



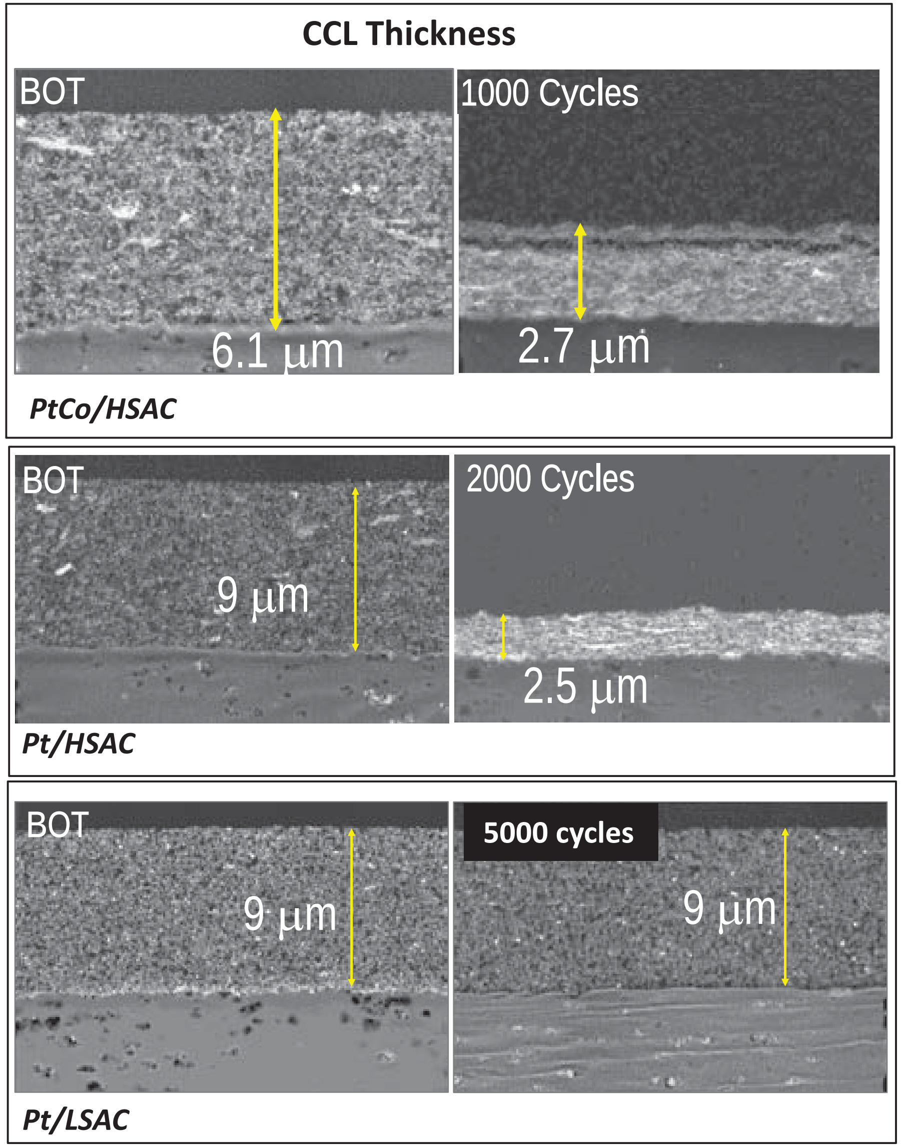
- Larger PtCo particles exhibit a “spongy” or “core-shell” morphology
- Large PtCo particles (Core shell)
- CCL porosity is similar
- Ionomer more aggregated in PtCo than Pt (I/C 0.95 in PtCo and 0.83 in Pt)
- Both Pt and Co measured ITM (In The Membrane)

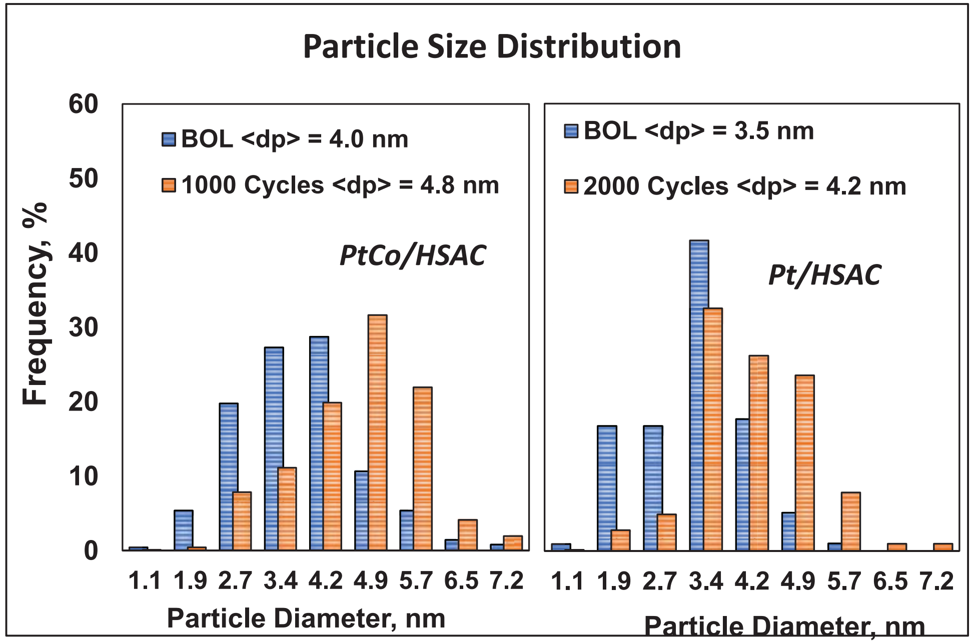


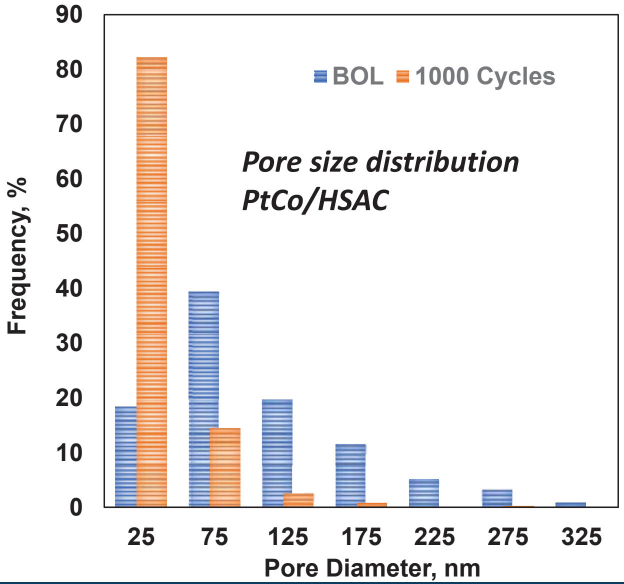
CCL thickness = 7μm
Pt-depleted zone = 1μm
PITM ~4μm from CCL



Changes in Electrode Microstructure (AST)





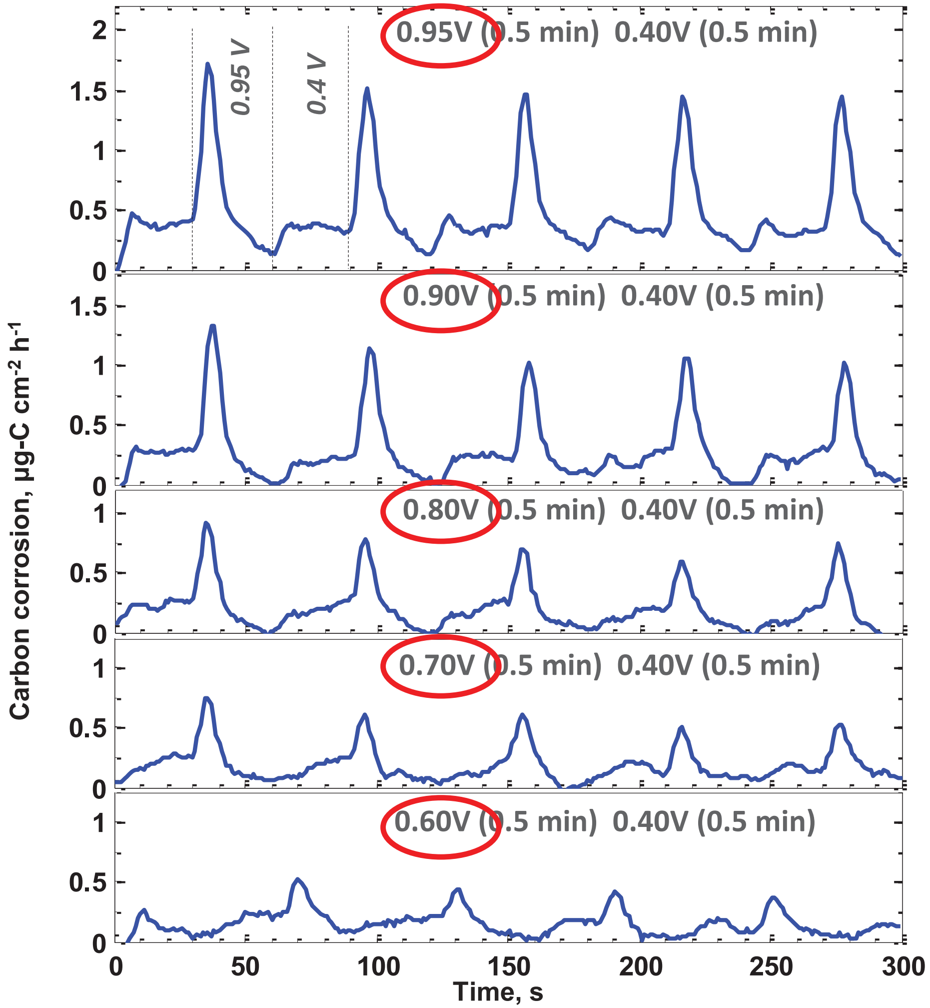


Moderate growth in catalyst particle size in HSAC electrode after 1000 cycles, but larger secondary pores have collapsed

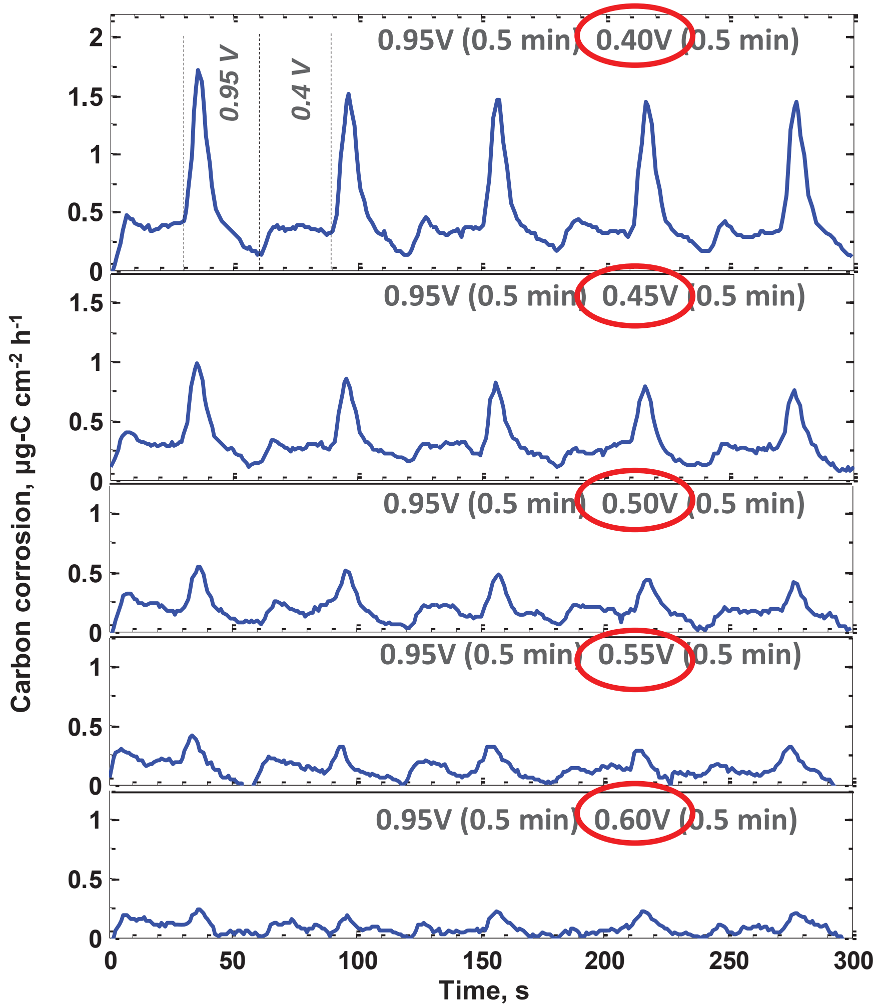
FCPAD FUEL CELL PERFORMANCE AND DURABILITY

Carbon Corrosion During Drive Cycle –
Corrosion Rate Depends upon Changing Potential Amplitude

Vary Upper Potential



Vary Lower Potential

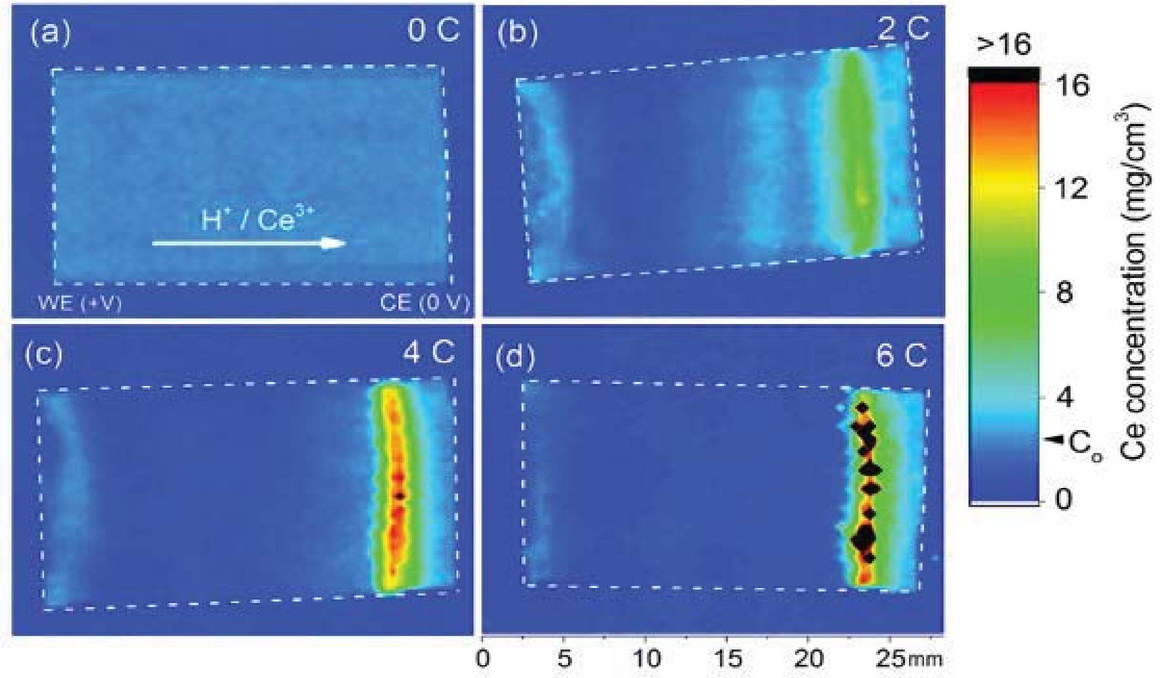


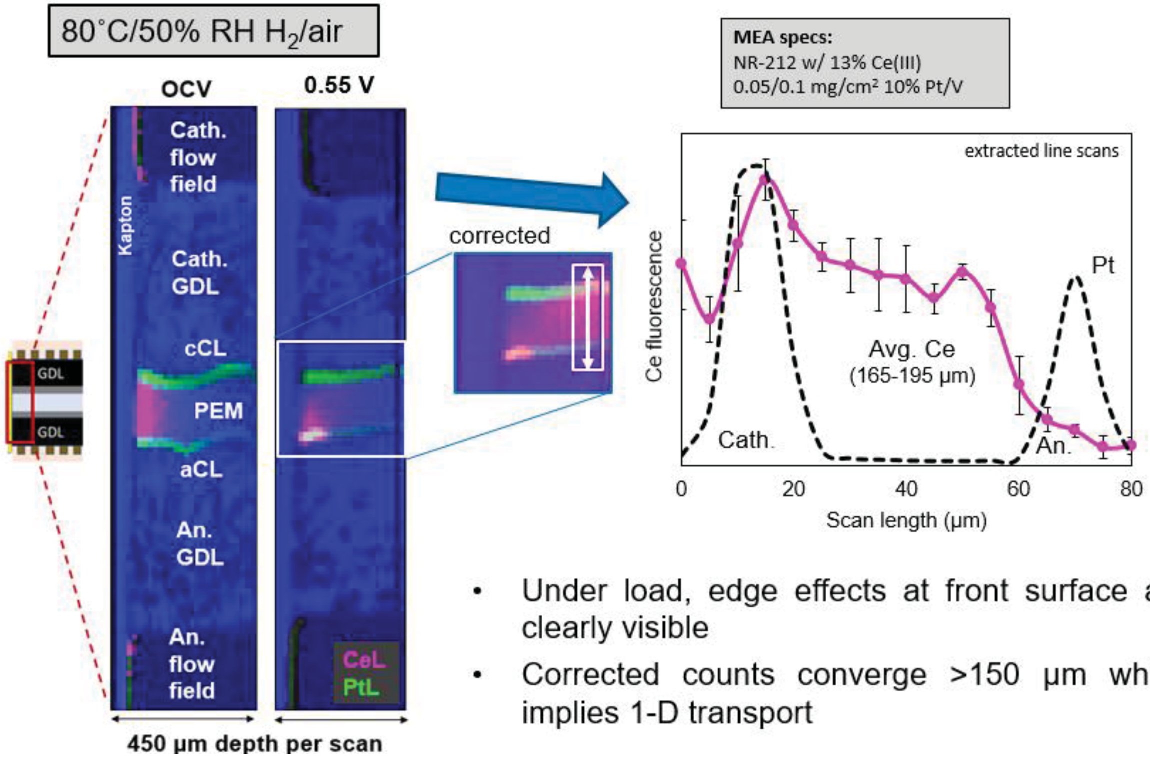
- CO2 Corrosion rate depends on the amplitude of the square potential cycle

FCPAD FUEL CELL PERFORMANCE AND DURABILITY

Membrane Durability – Radical Scavenger Migration

Migration of cerium under 4V, 80C, 100% RH at different charge transfer





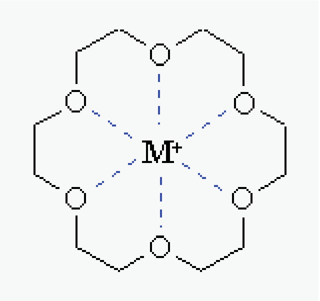
- Under load, edge effects at front surface are clearly visible
- Corrected counts converge >150 µm which implies 1-D transport

Stabilization of Cerium

Crown ethers

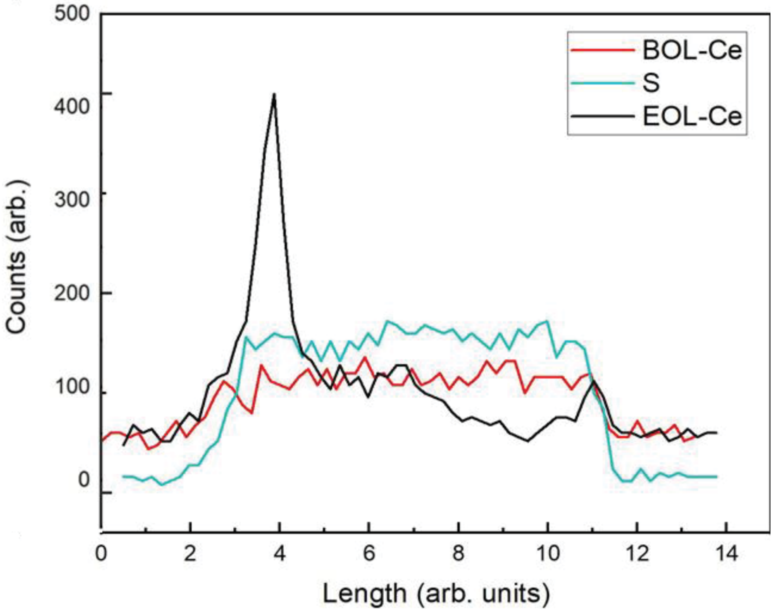
Strong complexing agents for cerium

Strong complexing agents for metal ions,
Principle: Size selectivity

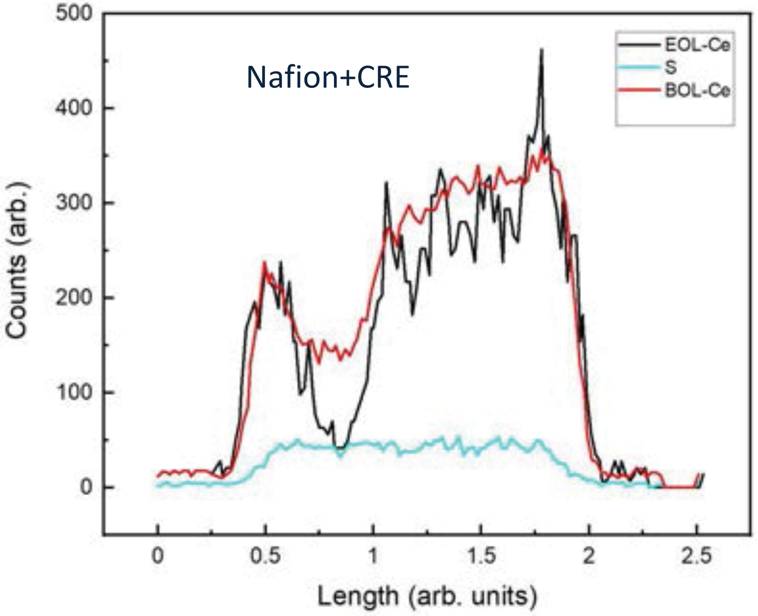


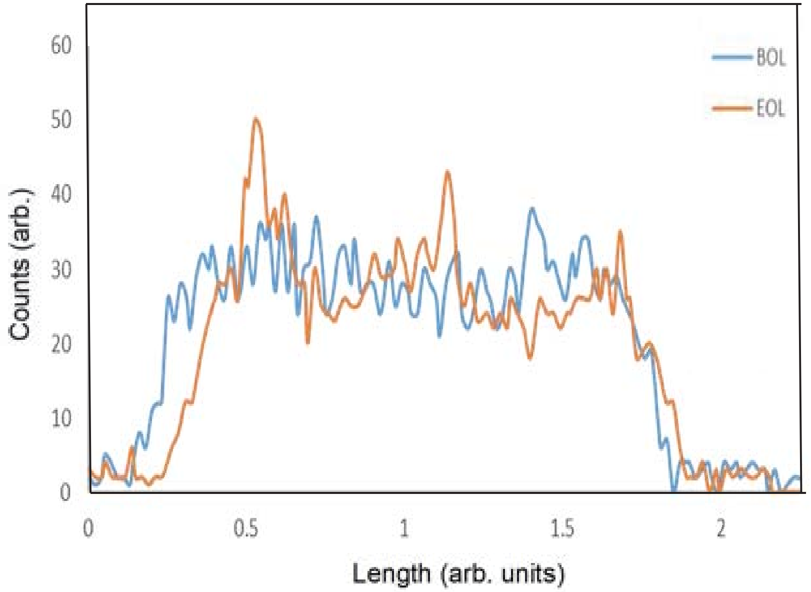
A stronger basicity anion than the counter ion in Nafion side chain, and which can assemble around cerium.

Nafion XL



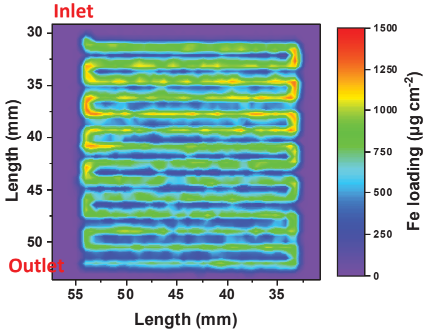
Nafion+CRE

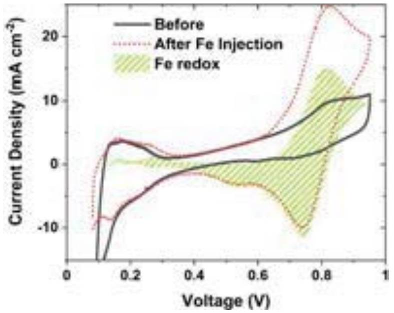




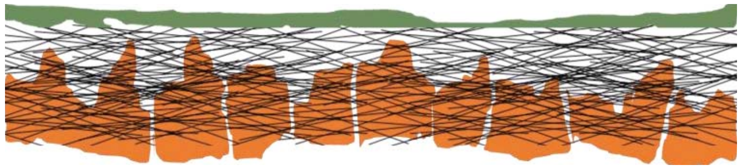
Transport of Cation Contaminant into the Fuel Cell

1. Understanding Cation Transport Mechanism



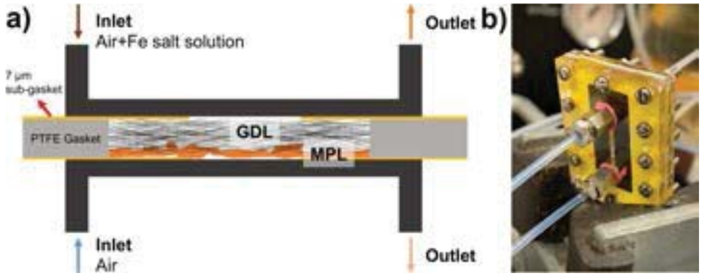


2. Development of GDL to suppress the Cation Transport



Babu, S.K., et al. Journal of The Electrochemical Society 168.2 (2021): 024501.

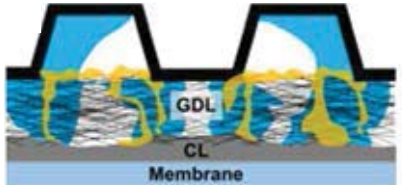
3. Estimation of Cation Transport Rates



GDLs for Cation Transport Suppression

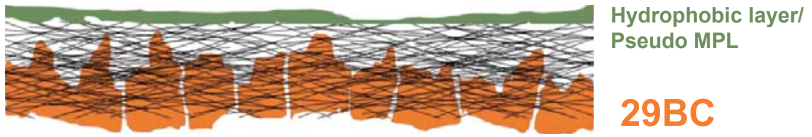
- Cations are present in PFSAs as radical scavengers (Ce and Mn), contaminants (Ca), byproducts of catalyst dissolution (Co and Ni), and from corrosion of BOP components (Fe)
  - Fe transport through GDL (from BPP corrosion or BOP components) problematic for membrane durability

Studied GDL/MPL morphology effect on cation transport



MPLs with cracks and hydrophilic GDLs show enhanced cation transport

GDL modification to suppress the Cation transport rates

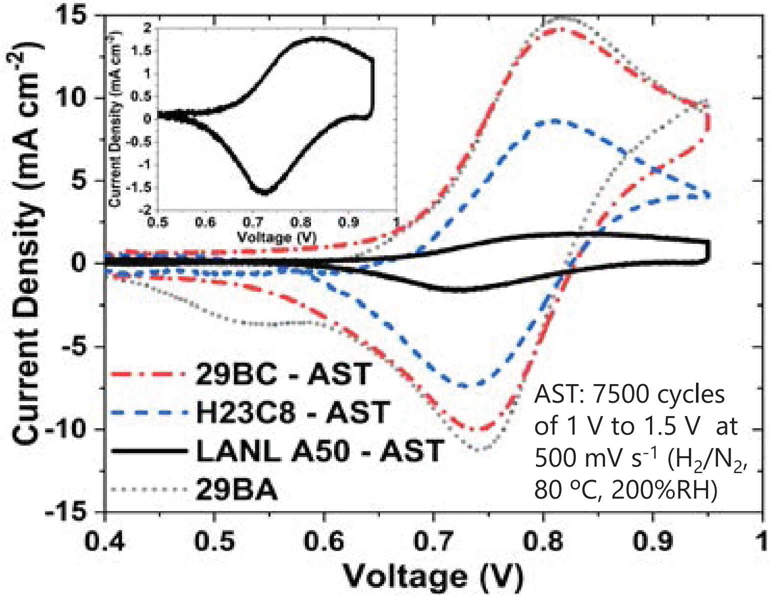


Addition of hydrophobic layer

- Novel GDLs suppress cation transport from the flow field
  - Smaller Fe^{2+}/Fe^{3+} redox couple post- flowfield injection of Fe
  - AST corrodes the 29BC and H23C8 MPL significantly and increases the Fe transport rates

Flowfield injection of Fe to study cation transport

Fe^{2+}/Fe^{3+} redox couple obtained from CV

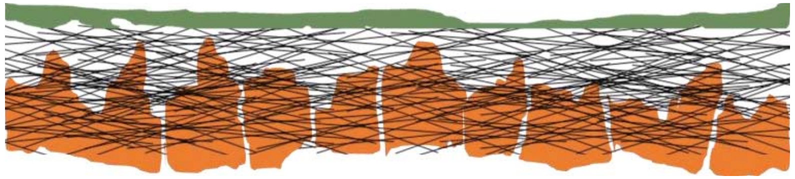


- Subtracting the after curve from the before curve to obtain the Fe redox curve
- Peak current used to calculate the Fe loading in the catalyst layer
- Modified 29BC shows significant suppression of Fe transport even after AST

- Babu, S.K., et al. Journal of the Electrochemical Society 168.2 (2021) 024501.

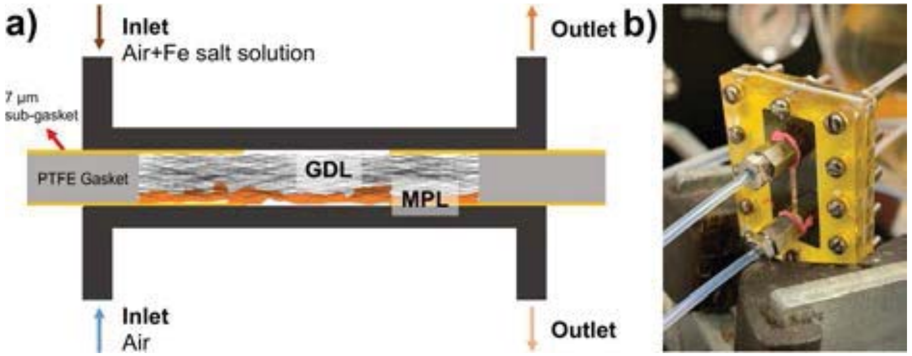
Effect of GDLs on Fe Transport

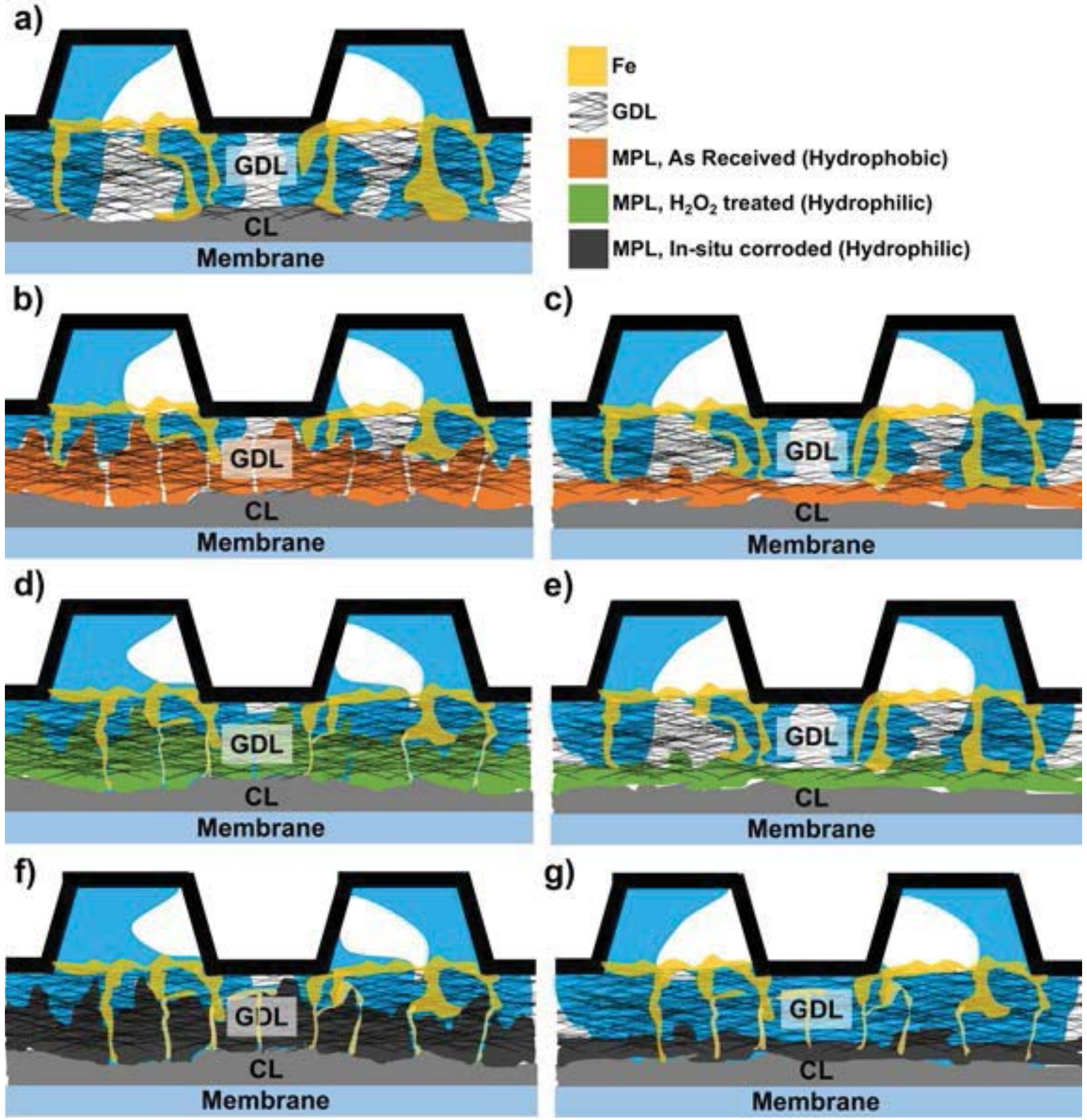
- GDL/MPL morphology effect on Fe transport mechanism
- GDL modification to suppress the Fe transport rates
- Ex-situ experiment for Fe transport rates estimation



Hydrophobic layer/
Pseudo MPL

29BC





Future Work

- **M2FCT consortium** aimed at delivering MEAs and components that meet 2.5 kW/gPGM power (1.07 A/cm^2 current density) at 0.7 V
  - Targets are end-of-life performance
  - Greater efficiency (68-72%)
  - High durability (1,000,000 miles; 25,000-30,000 hrs)
  - Material down-selects ~ year 3
    - Catalyst areas Go/No-Go at Q6
- **Analysis**
  - Refine models, characterization, and diagnostics for heavy-duty operating conditions
  - Define operating conditions efficiency and durability trade-offs
  - Coordinate and harmonize truck platforms and duty cycles
  - Compare systems with different ratios of fuel cell power and battery energy storage
  - Sensitivity of performance, durability and cost to cell voltage target at EOL
  - Incorporate membrane durability in system analysis
- **Machine learning / Data analysis**
  - Correlations of metadata for material and integration studies
- **High-Performance Computing**
  - Unsteady FCS simulations on truck drive cycles
  - Electrode and agglomerate structure
  - Upscaling physics-based micro- and nano-scale models to cell models and optimization
- **Durability**
  - Develop refined ASTs for life-time prediction with heavy-duty materials and operating conditions
    - Refine existing LDV ASTs
    - Develop new ASTs/protocols specific for HDV
  - Propose new protocols in collaboration with ASTWG by end of FY21
  - Electrode stability
  - Membrane and ionomer durability with additives
  - High-temperature operating time effect on durability
    - Membrane
    - Catalyst
  - Understand long-term durability effects on other components (GDL, contamination, reversible degradation, carbon corrosion at operating potentials)

Future Work

- **Integration**
  - Baseline SOA
    - Establish benchmark performance and cost of state-of-art MEA
  - Incorporate advance catalyst ink understanding into R2R manufacturing
  - Integrate newly developed materials into optimized MEA structures
    - Membranes
    - Ionomers
    - Catalysts
    - Catalyst supports
    - GDLs
  - Catalyst layer studies
    - Understand cation migration effects on catalyst layer performance
    - Catalyst layer porosity
    - Catalyst ink to structure formation models
  - Transport Properties (Gas phase, water, cations)
    - Catalyst Layer
    - GDL

- **Material Development**
  - Catalysts & Catalyst supports
    - Pt-Co Intermetallics
    - Metal oxide-metal-carbon junction to stabilize PtM NPs catalysts
    - Nitrogen-Doped PtMN Catalysts and Supports
    - Tailored Pt-nanomaterials, supports, and interfaces
  - Membranes & Ionomers
    - High-conductivity Novel Perfluorinated Ionomers
    - Low Molecular Weight Oligomeric Electrode and Membrane Ionomers
    - Composite PFSA Membranes and Ionomer EW and Side-Chain Chemistry
  - Other components (GDLs, Bipolar plates…)
  - Material and characterization studies

Planned activities include discretionary funding for additional collaborators on identified gaps and needs

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Berkeley Lab

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Shawn Reeves
Alexey Serov
Haoran Yu
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Pacific Northwest National Laboratory

Yang Qiu
Yuyan Shao

Brookhaven National Laboratory

Kotaro Sasaki

Acknowledgements

DOE EERE Hydrogen and Fuel Cell Technologies Office

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U.S. DEPARTMENT OF ENERGY

http://millionmilefuelcelltruck.org

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NREL NATIONAL RENEWABLE ENERGY LABORATORY

Argonne NATIONAL LABORATORY

OAK RIDGE National Laboratory

BROOKHAVEN NATIONAL LABORATORY

Pacific Northwest NATIONAL LABORATORY

NIST

User Facilities

DOE Office of Science: SLAC, LBNL-Advanced Light Source, LBNL-Molecular Foundry, ANL-Advanced Photon Source, LBNL-Molecular Foundry, ORNL-Center for Nanophase Materials Sciences, ANL-Center for Nanostructured Materials, NIST: BT-2