AURORA Program

Transport Studies Enabling Efficiency Optimization of Cost-Competitive Fuel Cell Stacks

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Principal Investigator: Amedeo Conti

Nuvera Fuel Cells

May 16, 2013

Project ID #
FC028

Program Overview

Timeline

- Started: Sept. 2009
- Completed: Nov. 2012

Barriers

- Barriers addressed
  - (B) Cost
  - (C) Performance
  - (E) System thermal & water management

Budget

- Total project funding
  - $4.46 M (DOE, includes $375K to LBNL)
  - $1.57 M (Cost Share)

Partners

- Johnson Matthey Fuel Cells
- Penn State University / University of Tennessee
- Lawrence Berkeley Lab

Relevance

*The **objective** of this program is to optimize the efficiency of a stack technology meeting DOE 2015 cost targets.*

Table 3.4.4 Technical Targets: 80-kW_e (net) Transportation Fuel Cell Stacks Operating on Direct Hydrogen[a]				
Characteristic	**Units**	**2011 Status**	**2017 Targets**	**2020 Targets**
Stack power density[b]	W / L	2,200[c]	2,250	2,500
Stack specific power	W / kg	1,200[c]	2,000	2,000
Stack efficiency[d] @ 25% of rated power	%	65	65	65
Cost[e]	$ / kW_e	22[f]	15	15
Durability with cycling	hours	2,500[g]	5,000[h]	5,000[h]
$Q/\Delta T_i$[i]	kW/ºC	–	1.45	1.45

[e] Based on 2002 dollars and cost projected to high-volume production (500,000 stacks per year).

<u>Program has been successfully completed</u>

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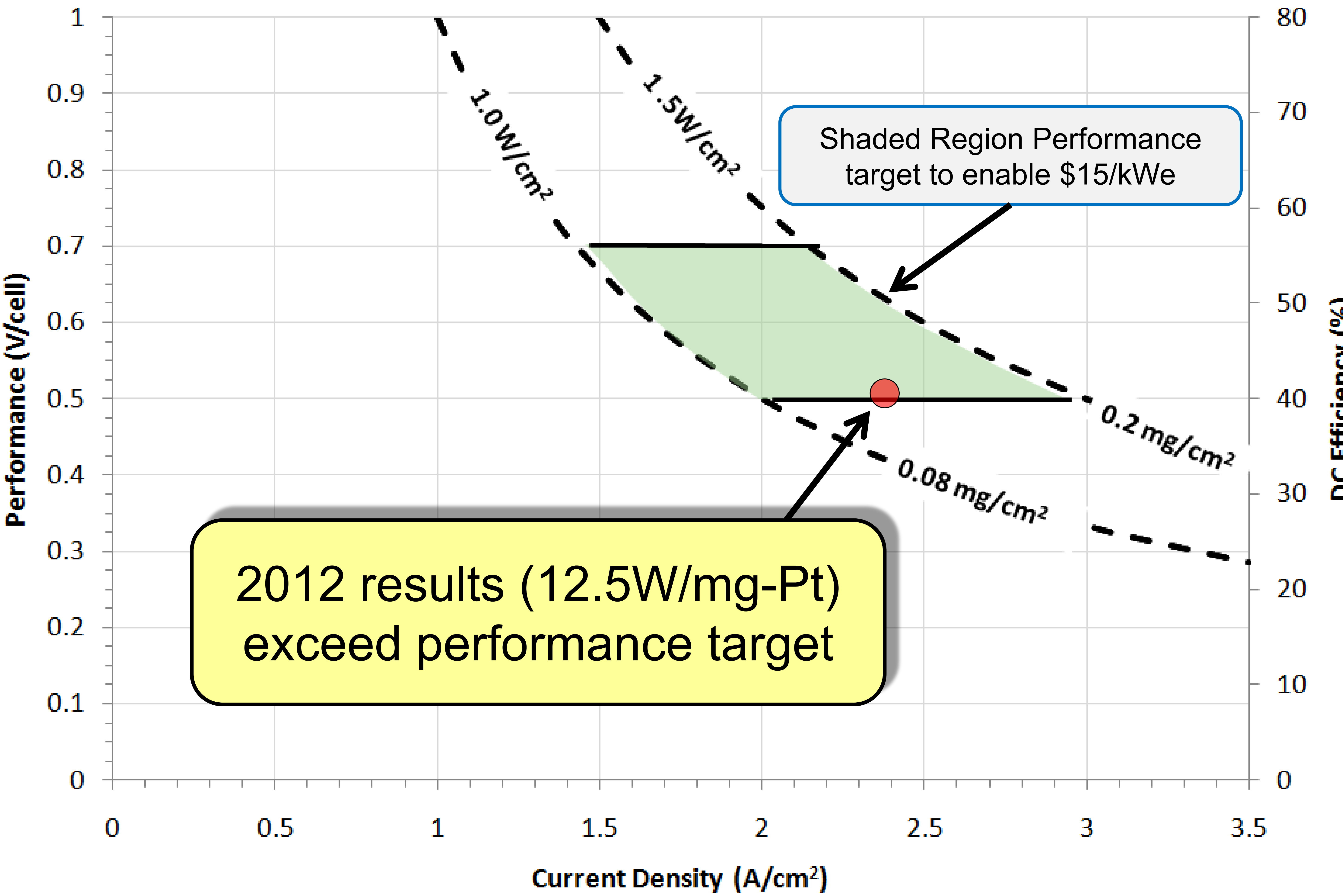
Technical Target - Approach

Target: *Demonstrate stable and repeatable high power performance on a full format fuel cell stack: 7.5 W/mg-Pt @ 500mV.*



AMR 2011
5.6 W/mg-Pt
0.548 V @ 2.03 A/cm2
0.2 mg-Pt/cm^2

AMR 2012
7.98 W/mg-Pt
0.521 V @ 2.0 A/cm2
0.13 mg-Pt/cm^2

November 2012
12.5 W/mg-Pt
0.501V @ 2.4 A/cm2
0.096 mg-Pt/cm^2

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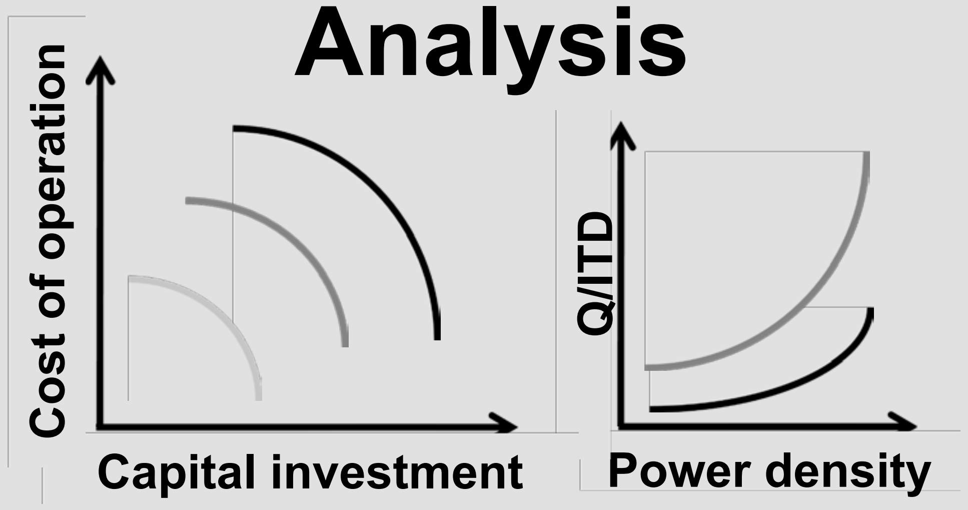
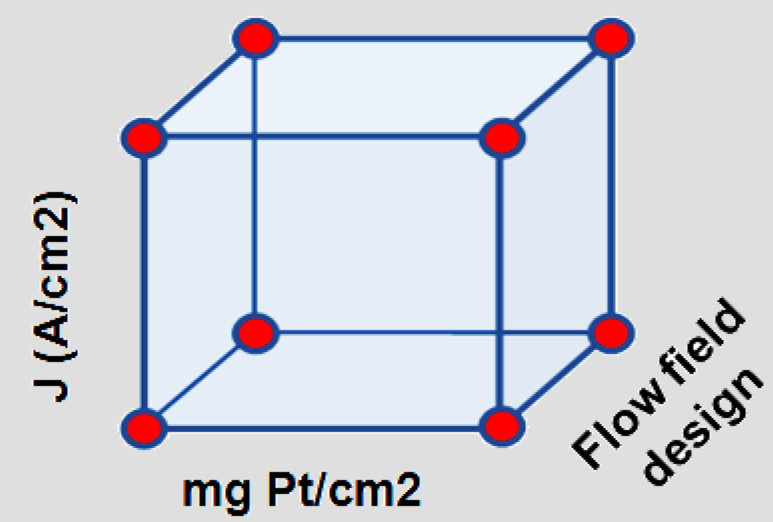
Program Approach

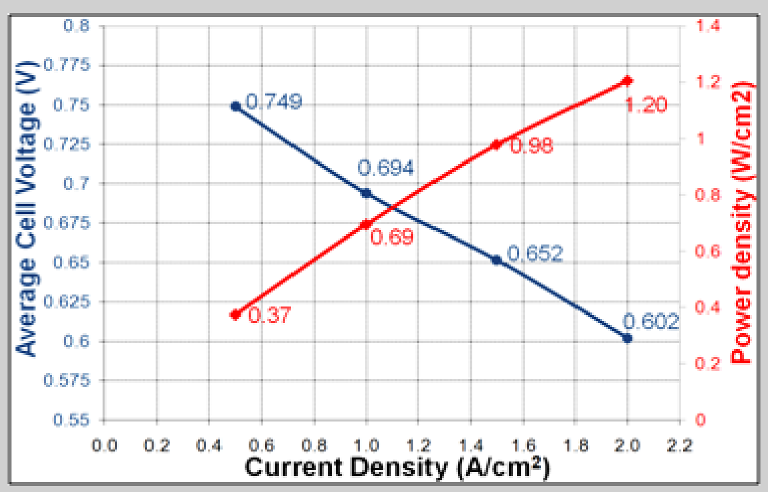
Cost & System Analysis



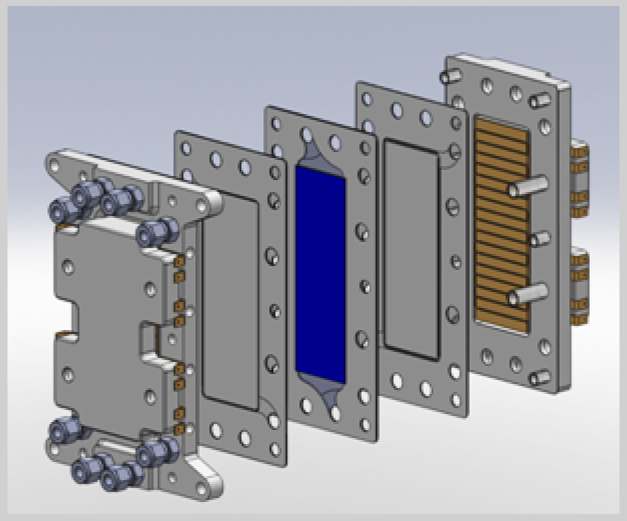
Parameter Space



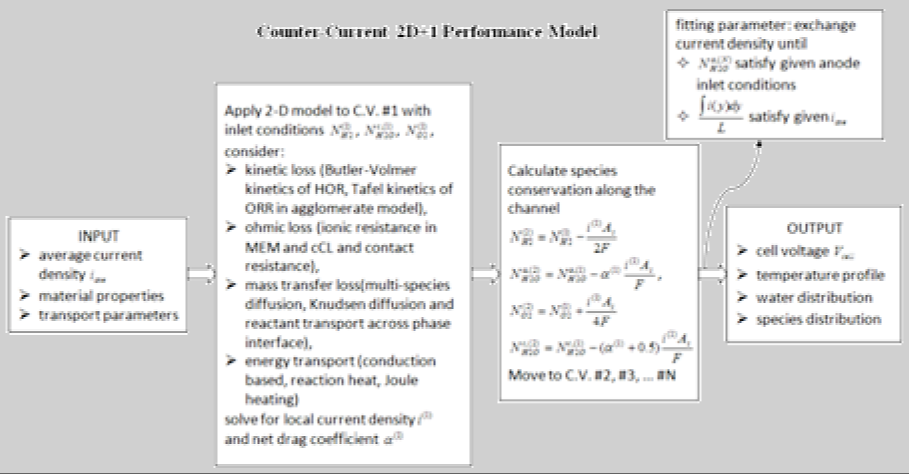
Stack Verification



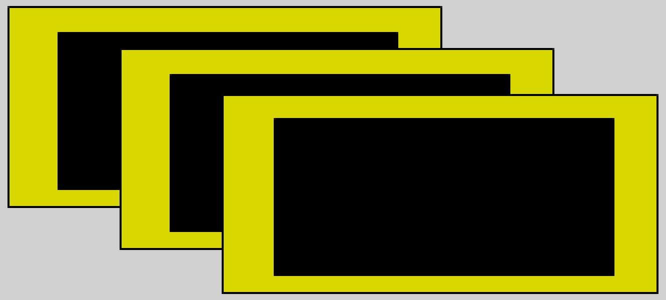
Single Cell Testing



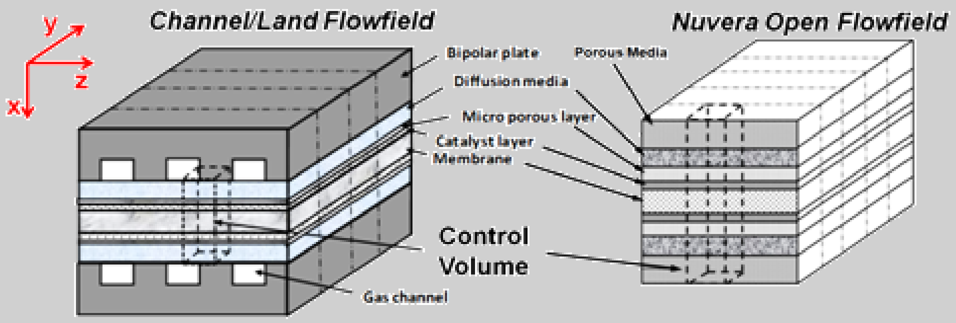
Published Model



Material Development

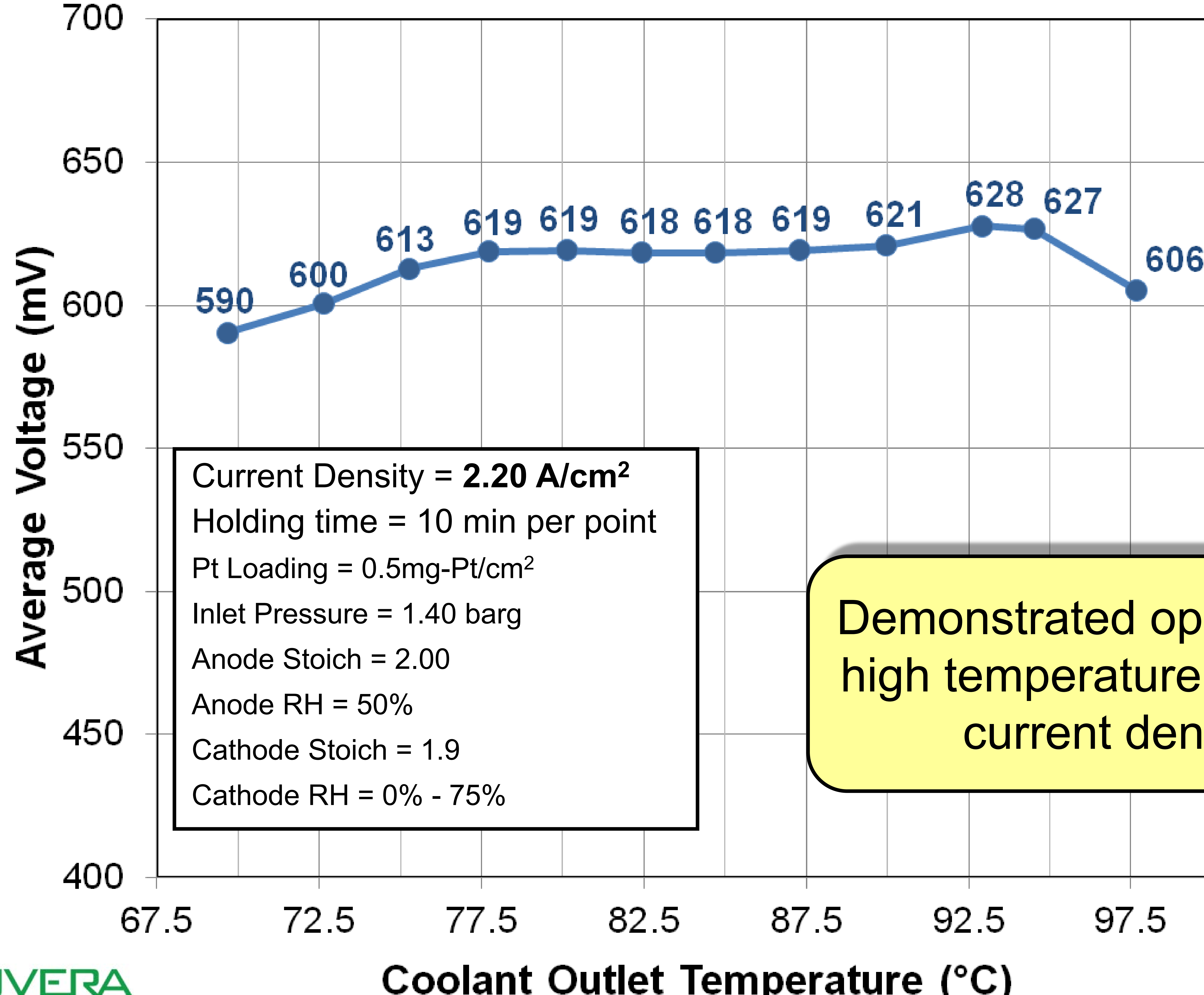


Model Development



Stack Testing

Stable performance at 95°C on full format, 10 cell stack running at high current density



Demonstrated operation at high temperature and high current density

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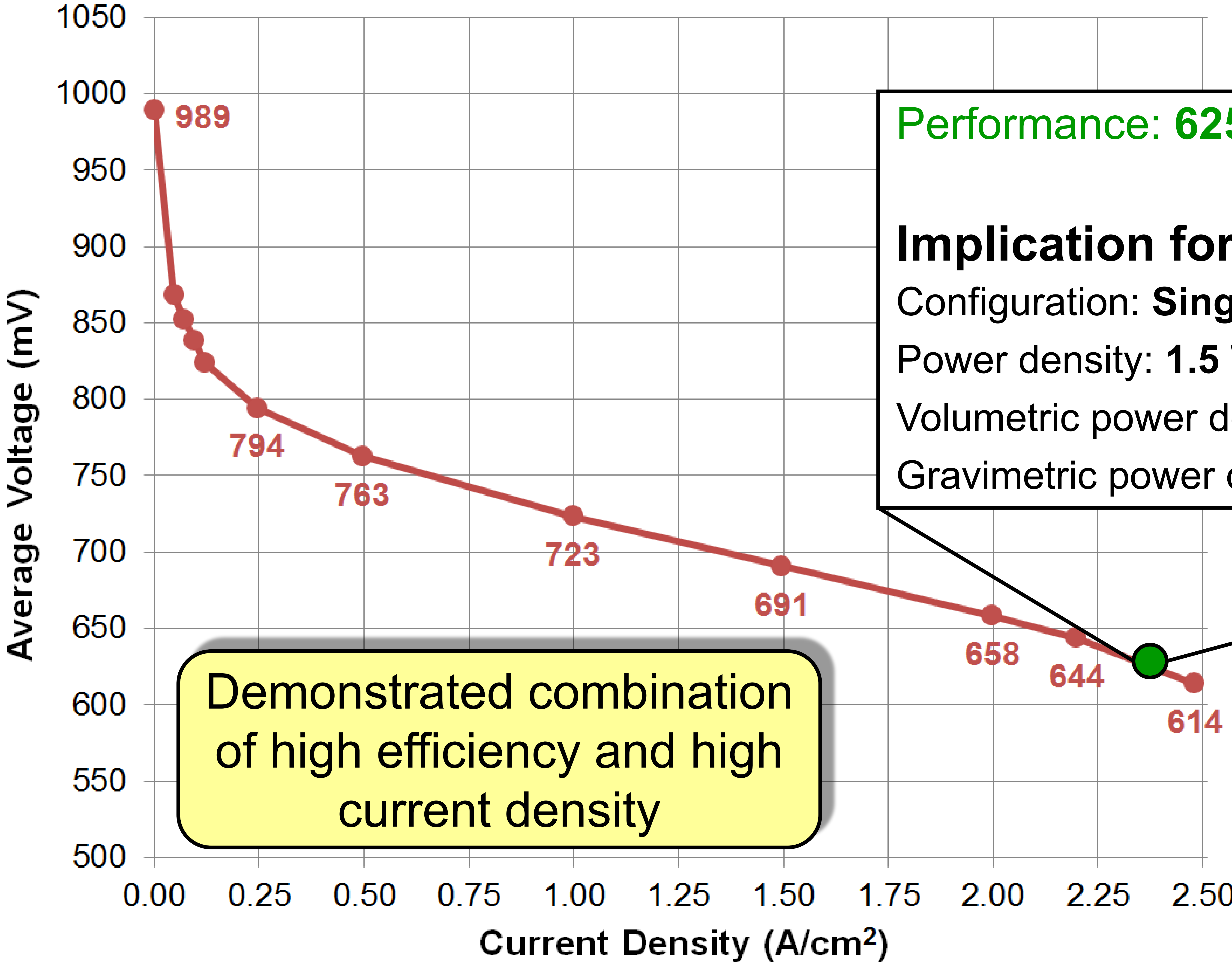
Stack Testing

High efficiency at high current density on full format, 4 cell stack



Performance: **625 mV @ 2.40 A/cm^2**

Implication for 80 kW$_{Net}$ FC System

Configuration: **Single stack**

Power density: **1.5 W/cm^2**

Volumetric power density: **3.4 kW/l**

Gravimetric power density: **2.0 kW/kg**

$T_{cell} \leq 85^oC$, An 50% RH, Ca 75% RH, P_{In} ~1.2 - 2.4 bara

0.5 mg Pt/cm^2 Total Loading

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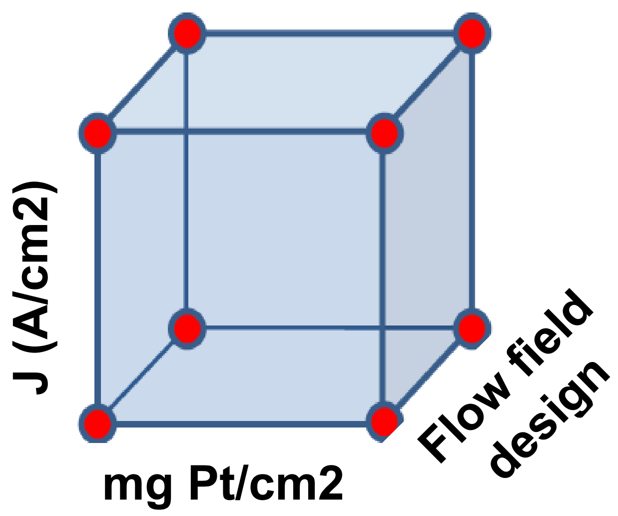
Model Roadmap

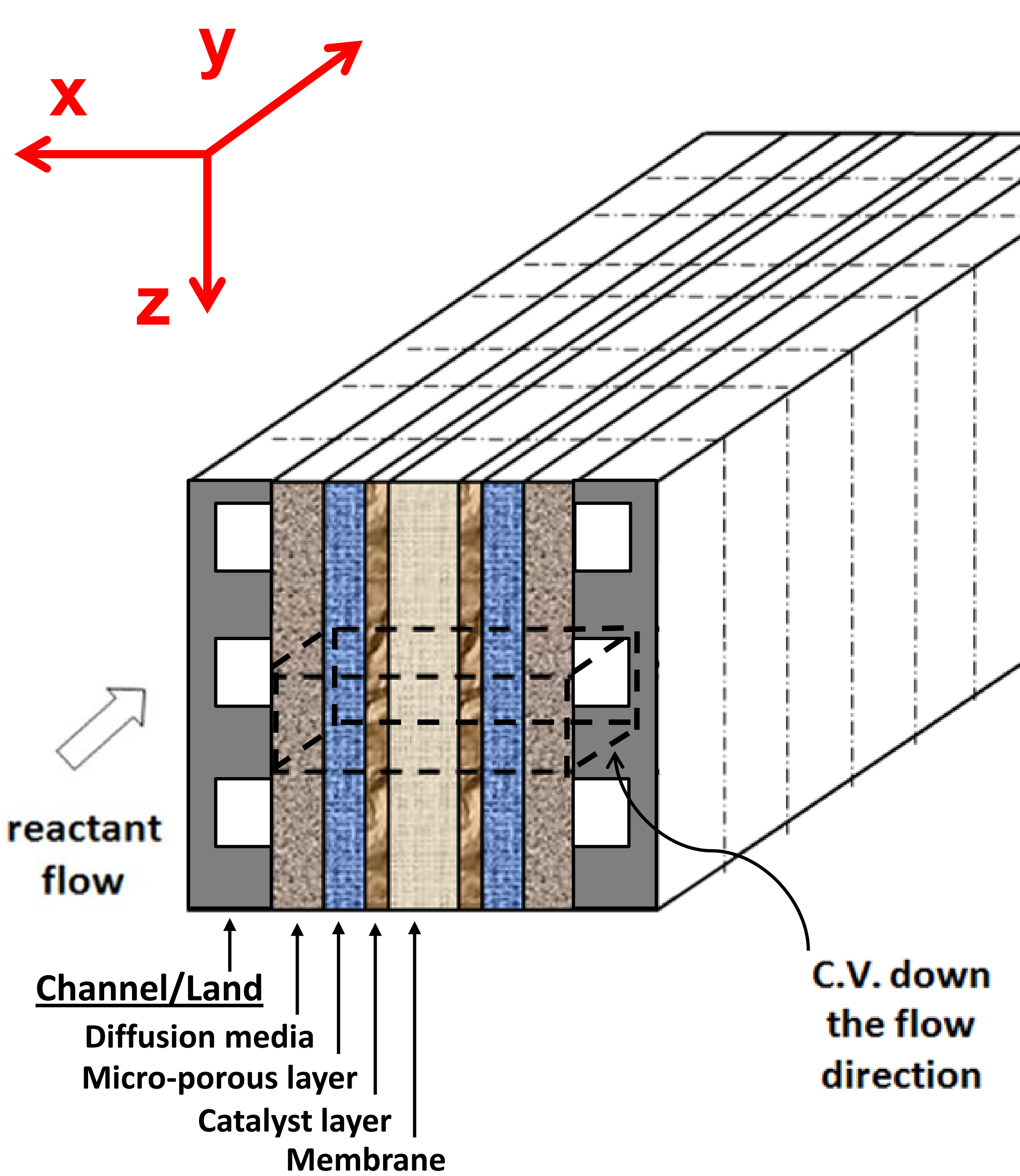
A model capable of predicting high current density operation in different architectures is the central deliverable of the program

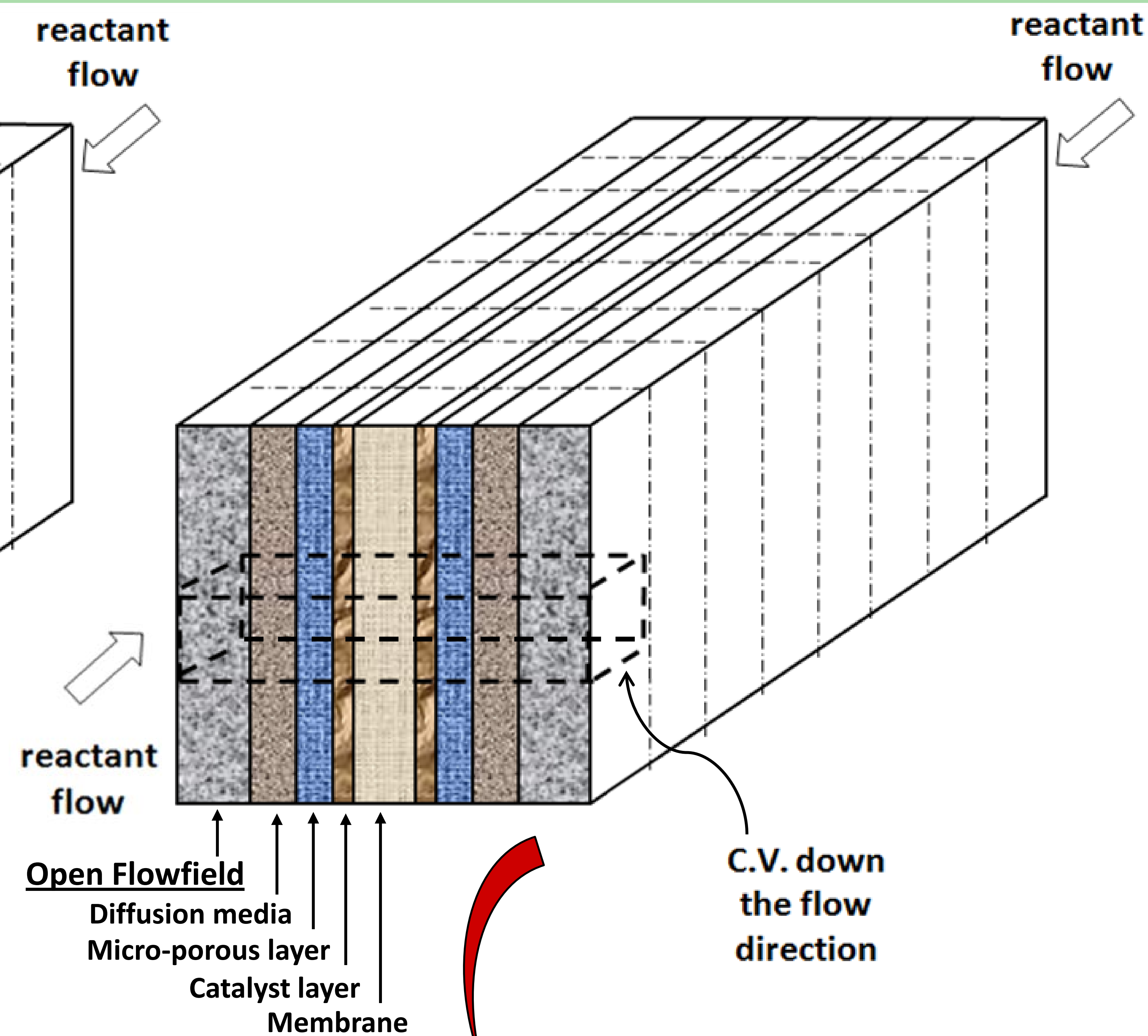
- **Single phase model generation** from PSU 2D channel/land model – **Q2 2010** Completed
  - 2D +1, counter flow reactants, compatible with multiple architectures
- **Initial validation with empirical Nuvera model – Q3 2010** Completed
- **Initial performance verification** – **Q4 2010** Completed
- **Multi-phase physics implementation** – **Q1 2011** Completed
  - Verification with empirical Nuvera model
  - Initial performance verification
- **Agglomerate electrode model implementation (LBNL)** – **Q1 2011** Completed
- **Tune model parameters and collect dataset – Q3 2011** Completed
- **Model Validation**: Demonstrate predictive capability – **Q4 2011** Completed
- **Additional Model Validation– Q3 2012** Completed in Q4 2012
  - Validate: High Temperature, Channel Land Architecture, Low Pt Loading
- **Model Publication** – **Q3 2012** Completed in Q2 2013



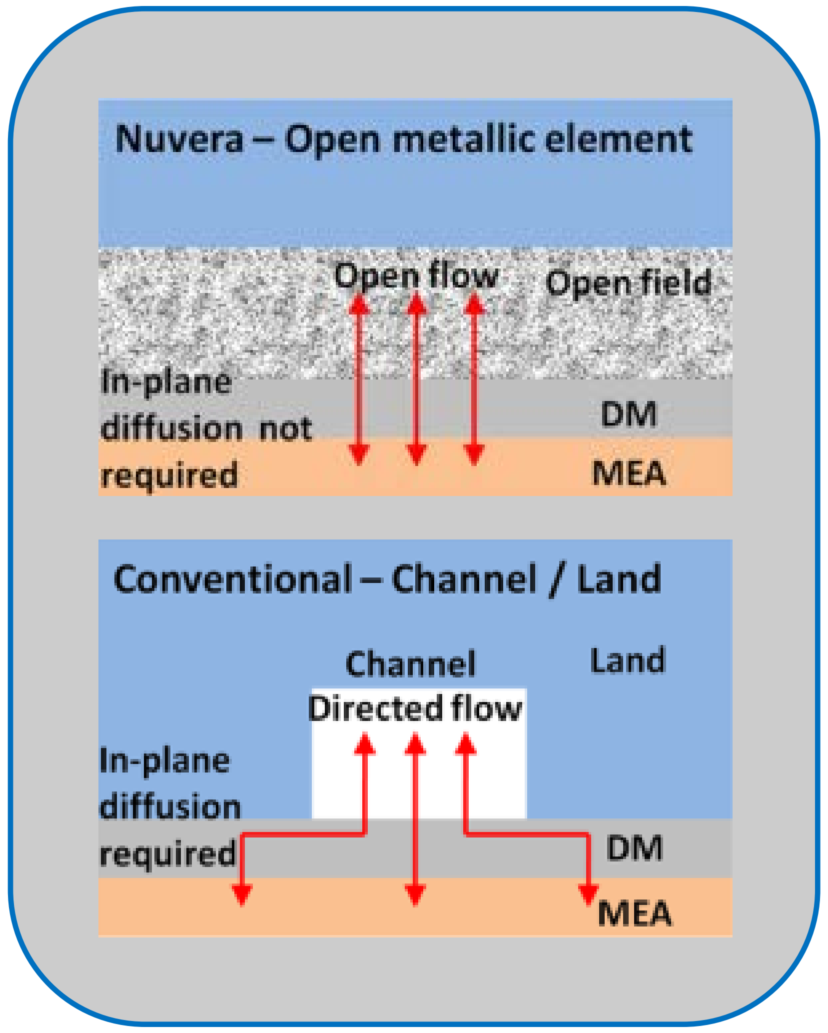
FC Modeling - Approach

The physics of the quasi-3D, multi-architecture model is as similar as possible between channel/land and open flowfields.

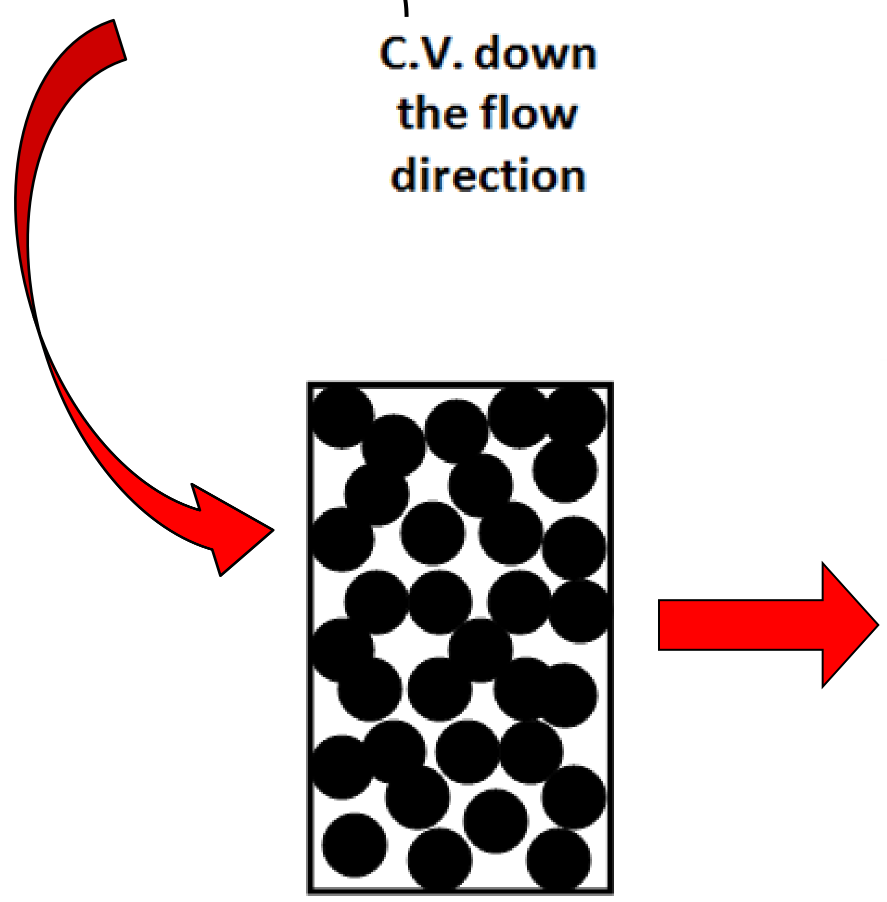




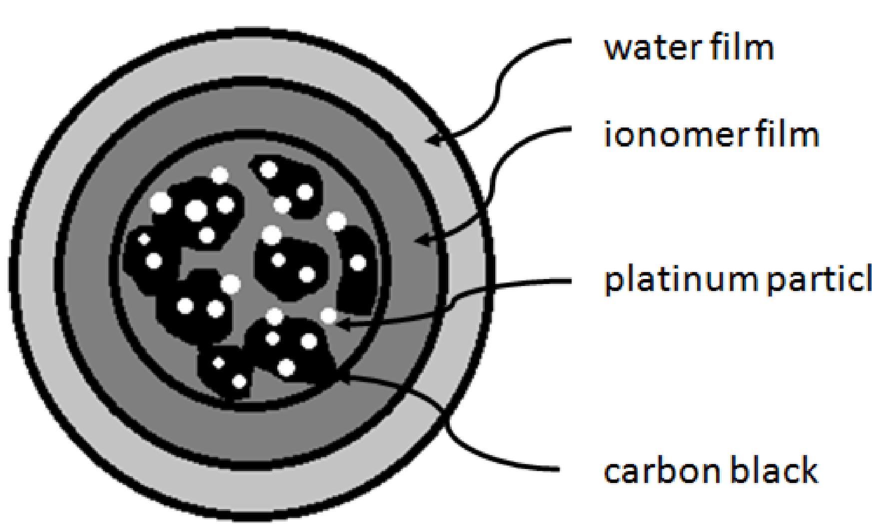
2D+1 domain, Multi-architecture capable



- 2D+1 domain reduces computational efforts
- No parameters vary in Y direction inside control volume (C.V.).
- Species concentrations and T vary in Y direction along different control volumes.
- 2D model (XZ) is inferred by variations along Y and uses a fine mesh to predict local conditions accurately.
- Multi-physics decribes phenomena in each layer
- Agglomerate model describes catalytic behavior



Multi-physics model



Agglomerate model

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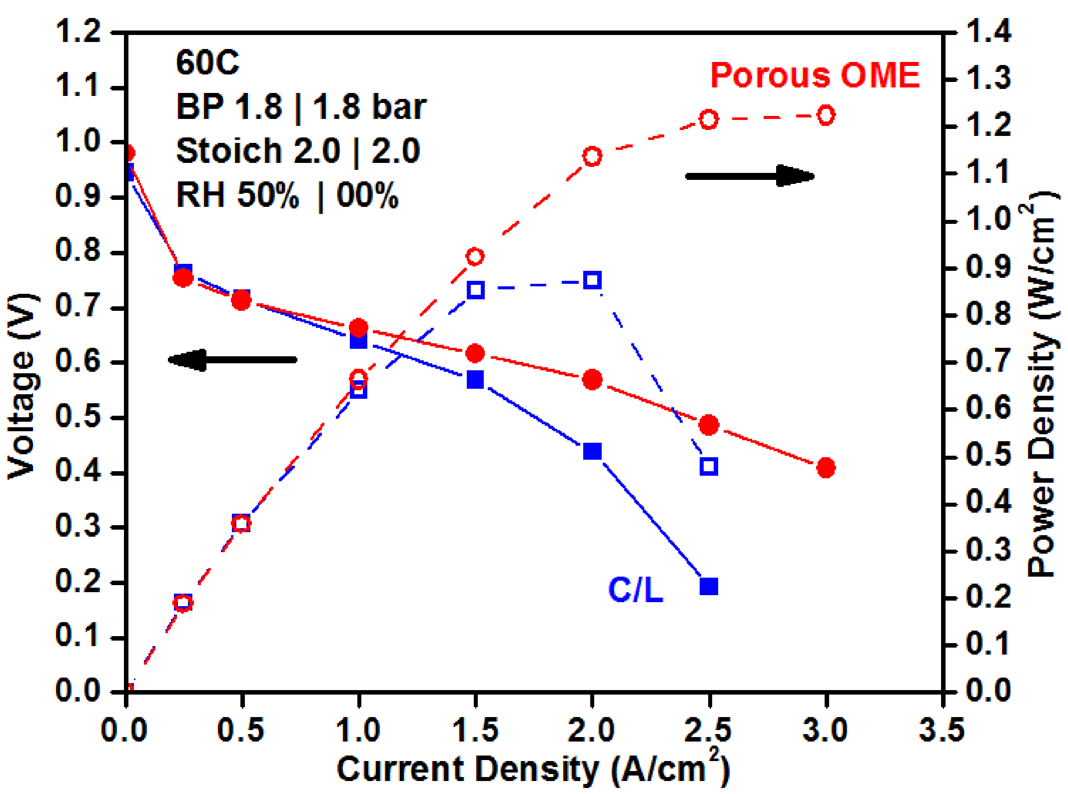
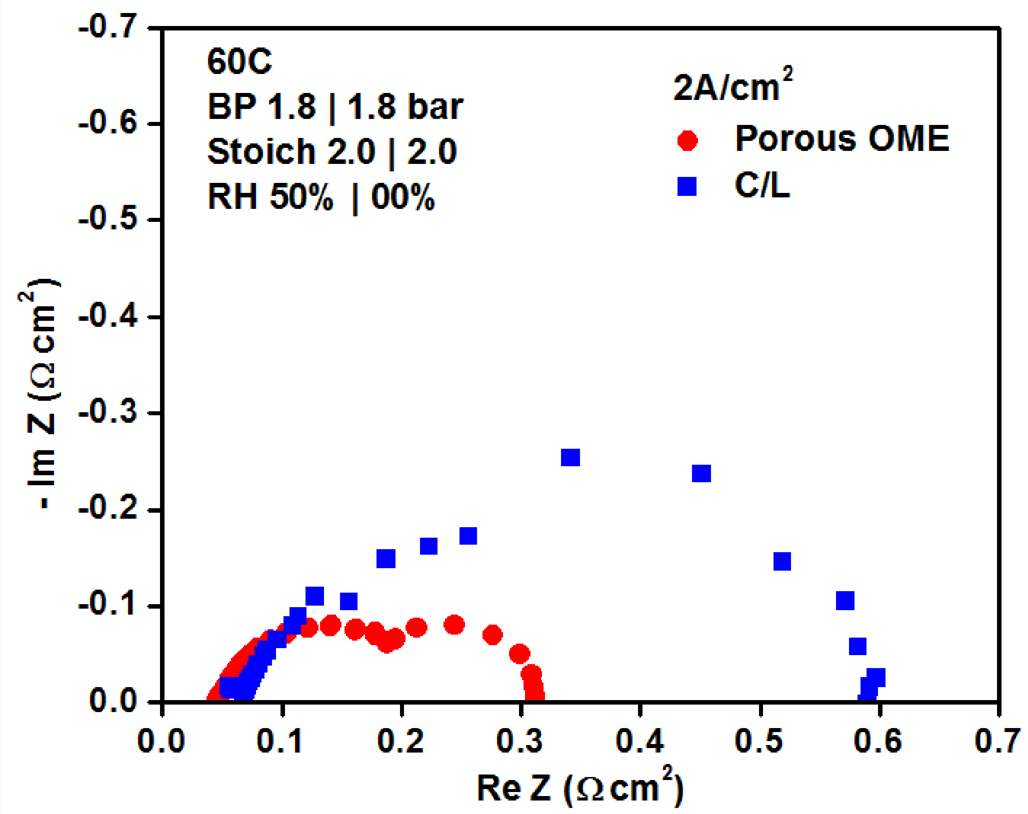
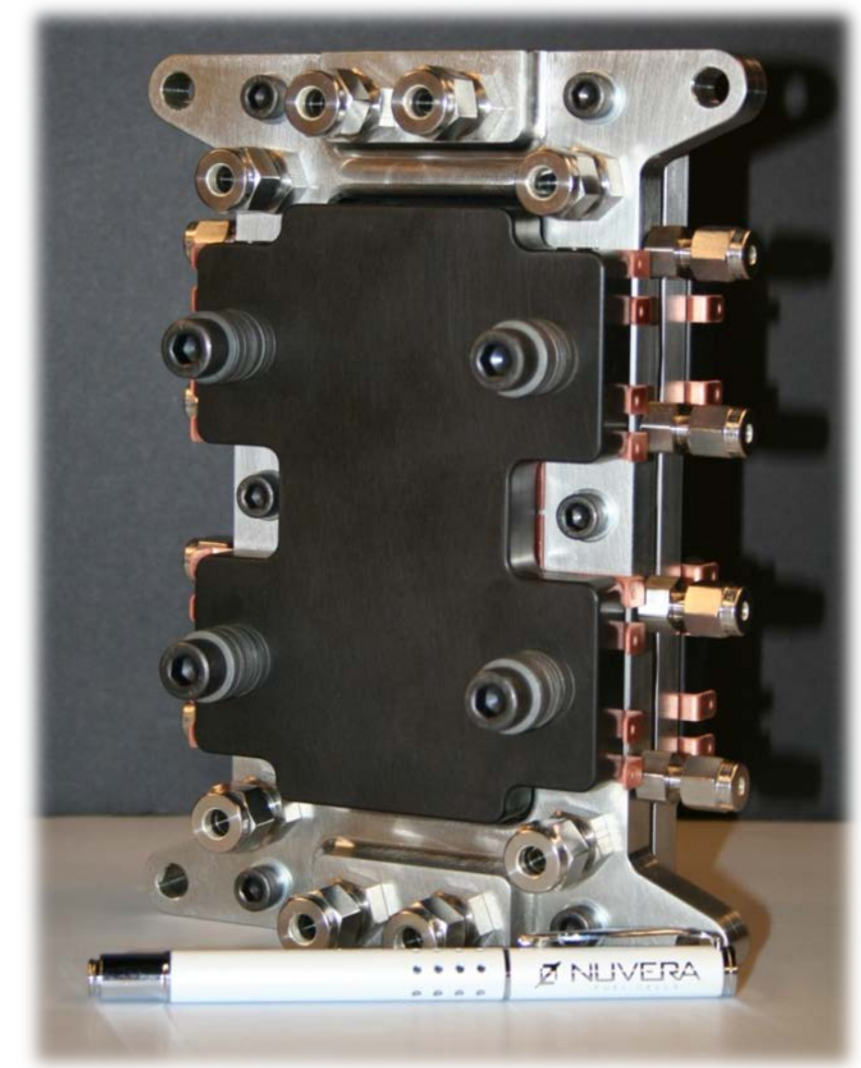
FC Modeling - Status

Single Cell Testing to Support Model Development

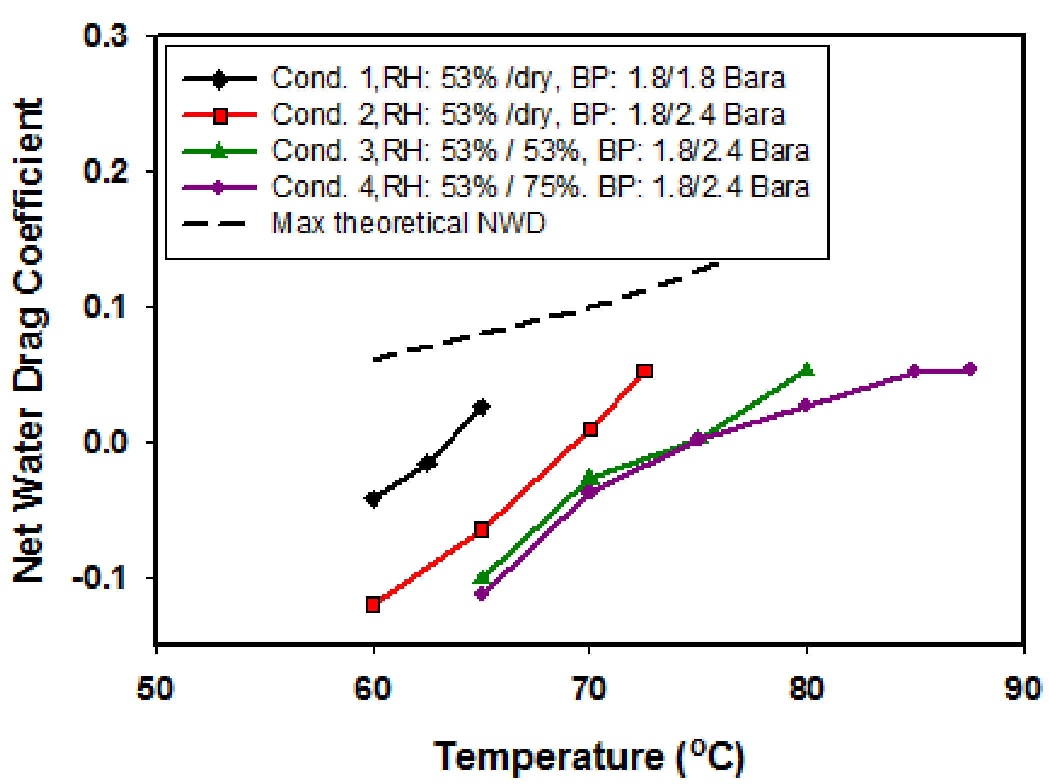
Evaluation of high current density operation



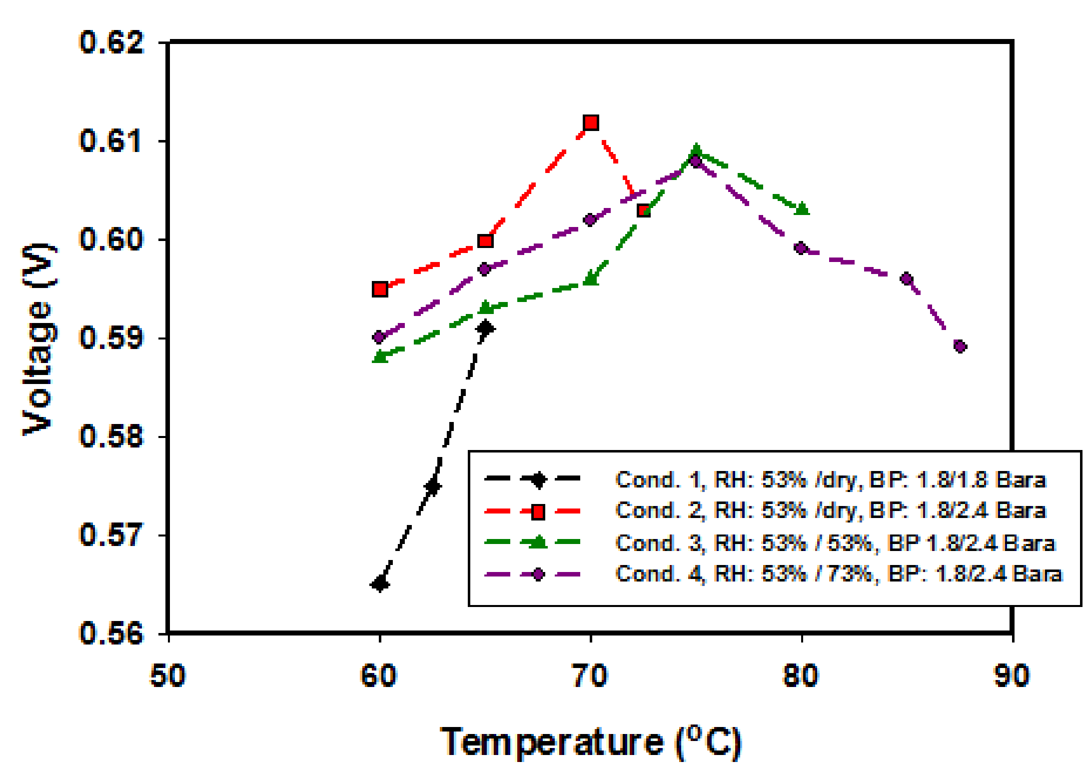




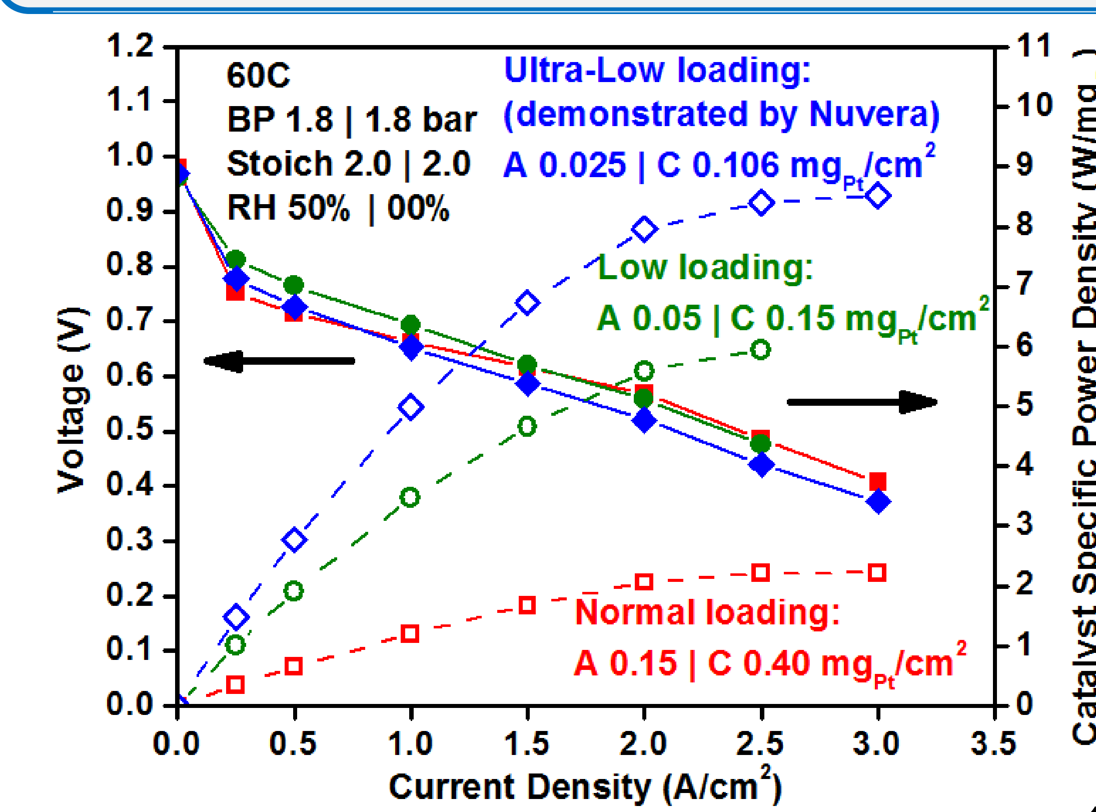
Transport characterization



High temperature
High current operation



Ultra-Low Pt loading High current operation **(exceeds DOE target of 5.5 W/mgPt)**



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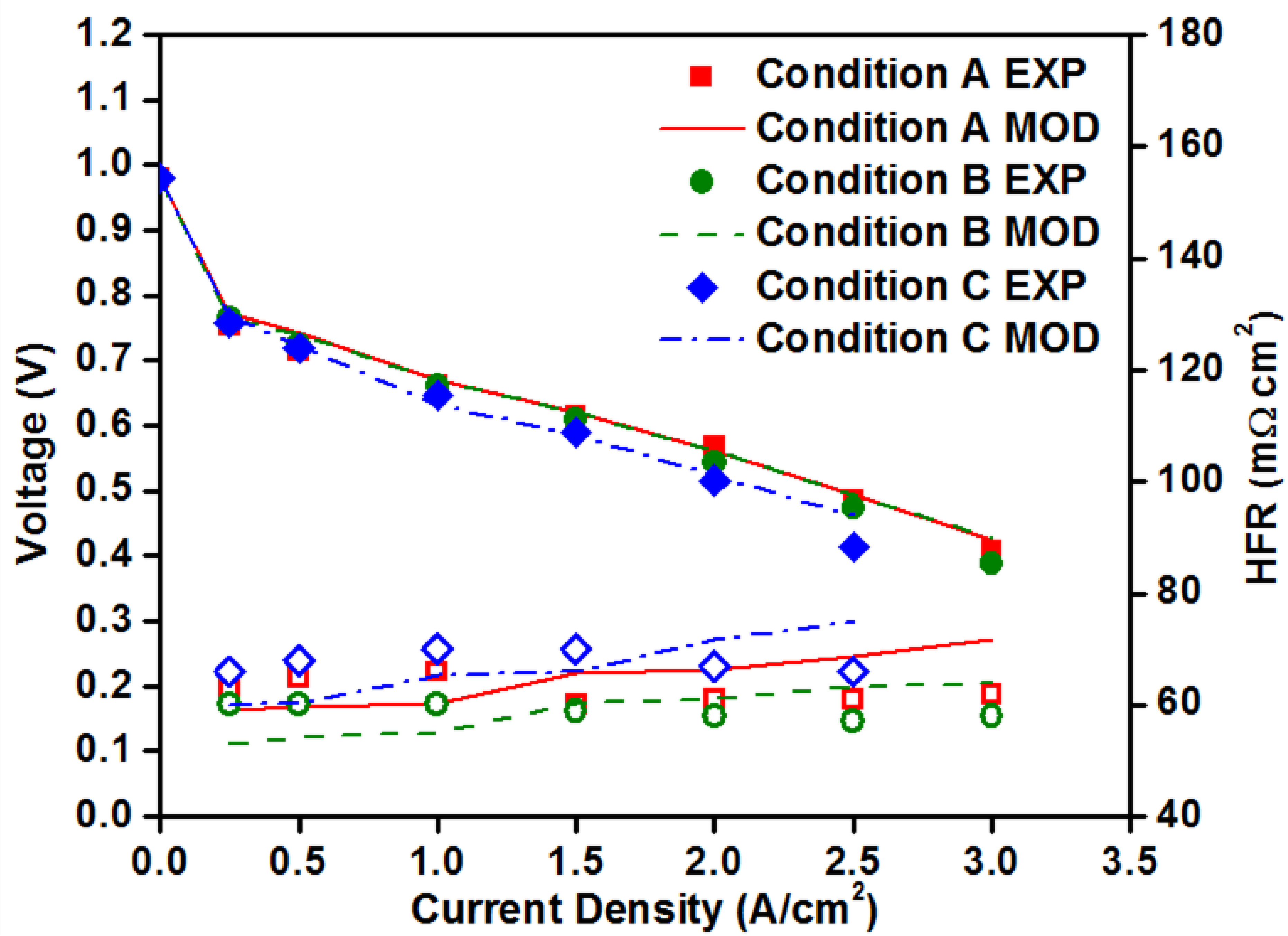
FC Modeling - Status

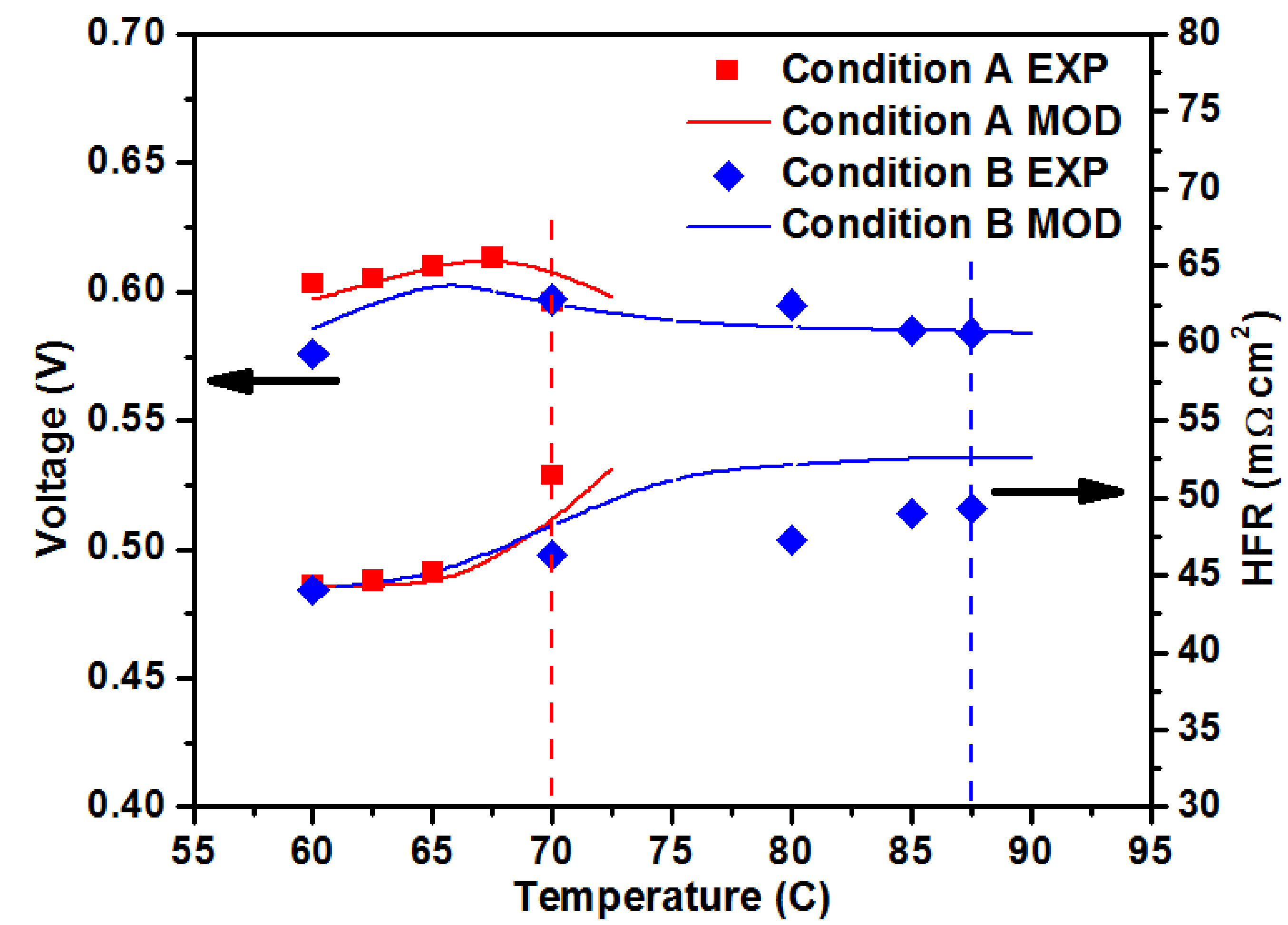
Development of Transport Model

Validation under wide range of operating conditions

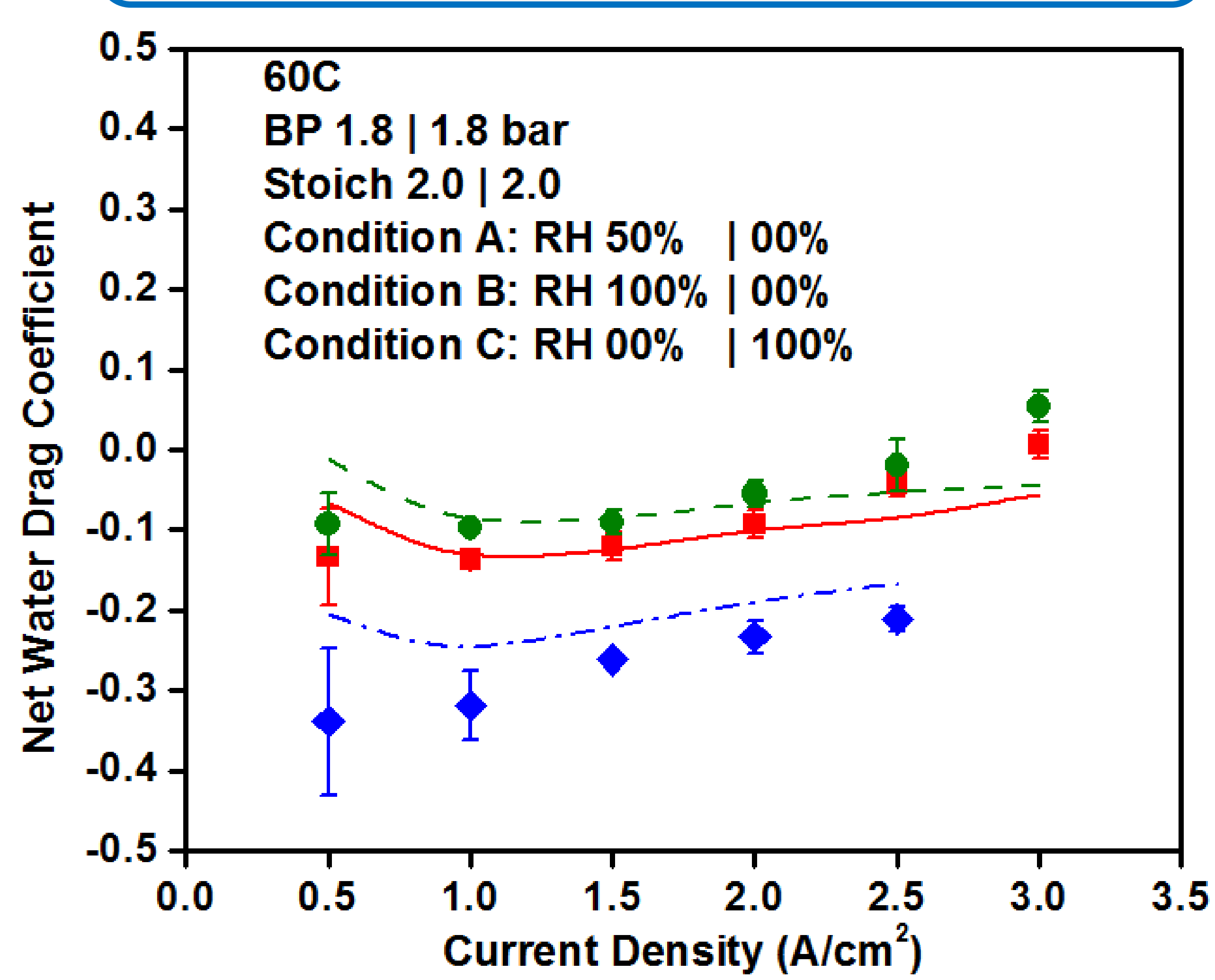


Executable model and manual published and publicly available!

Model tuned to identify dry-out limitations



Performance, cell resistance, net water drag simulation and validation



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FC Modeling - Status

Model Validation Summary

Reactant Humidification

Condition	Catalyst Loading [1]	Cell Structure [2]	BP (bar)	Stoich	Humidification An / Ca	Coolant Flow Rate [3]	i (Acm^{-2})	T (°C)	Cell V (V) Exp	Mod	error
1	normal	OME	1.8/1.8	2.0/2.0	50% / 0%	high	1	60	0.662	0.670	1.2%
							2		0.568	0.560	1.4%
2	normal	OME	1.8/1.8	2.0/2.0	100% / 0%	high	1	60	0.661	0.670	1.4%
							2		0.544	0.561	3.1%
3	normal	OME	1.8/1.8	2.0/2.0	0% / 100%	high	1	60	0.646	0.632	2.2%
							2		0.516	0.523	1.4%
4	normal	OME	1.8/1.8	2.0/2.0 heliox	50% / 0%	high	1	60	0.666	0.680	2.1%
							2		0.541	0.571	5.5%

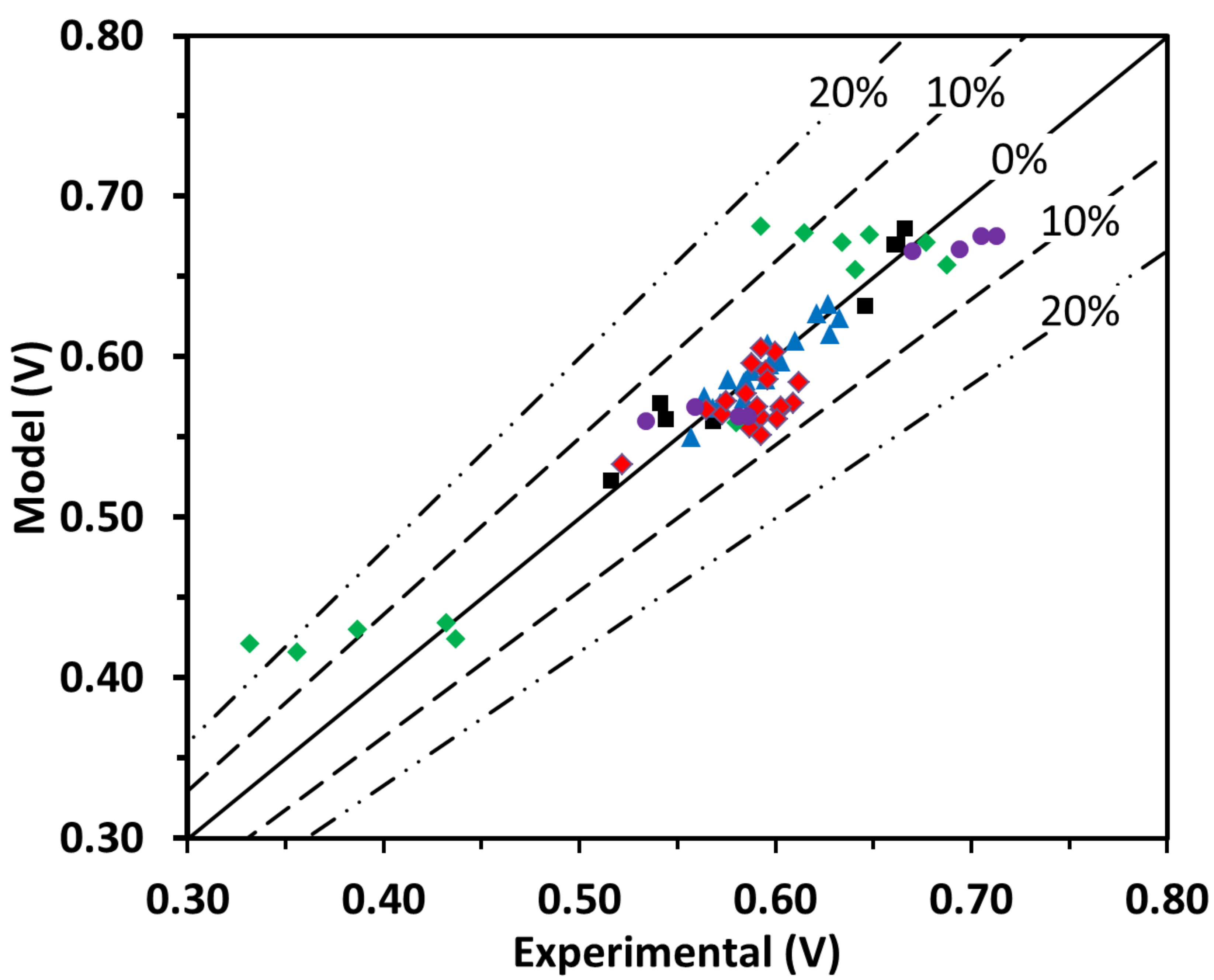
Low Pt Loading

Condition	Catalyst Loading [1]	Cell Structure [2]	BP (bar)	Stoich	Humidification An / Ca	Coolant Flow Rate [3]	i (Acm^{-2})	T (°C)	Cell V (V) Exp	Mod	error
21	low	OME	1.8/1.8	2.0/2.0	50% / 0%	high	1	60	0.694	0.667	3.9%
							2		0.559	0.569	1.8%
22	low	OME	1.8/1.8	2.0/2.0	50% / 0%	high	1	70	0.670	0.666	0.6%
							2		0.534	0.560	4.9%
23	low	OME	1.8/2.4	2.0/2.0	50% / 50%	high	1	90	0.705	0.675	4.3%
							2		0.581	0.563	3.1%
24	low	OME	1.8/2.4	2.0/2.0	50% / 75%	high	1	90	0.713	0.675	5.3%
							2		0.586	0.563	3.9%

Channel Land Architecture

Condition	Catalyst Loading [1]	Cell Structure [2]	BP (bar)	Stoich	Humidification An / Ca	Coolant Flow Rate [3]	i (Acm^{-2})	T (°C)	Cell V (V) Exp	Mod	error
14	normal	CL	1.8/1.8	2.0/2.0	50% / 0%	low	1	60	0.641	0.654	2.0%
							2		0.437	0.424	3.0%
15	normal	CL	1.8/1.8	2.0/2.0 heliox	50% / 0%	low	1	60	0.688	0.657	4.5%
							2		0.580	0.559	3.6%
16	normal	CL	1.8/1.8	2.0/2.0	50% / 0%	low	1	70	0.648	0.676	4.3%
							2		0.432	0.434	0.5%
17	normal	CL	1.8/1.8	2.0/2.0	50% / 50%	low	1	70	0.634	0.671	5.8%
							2		0.387	0.430	11.1%
18	normal	CL	1.8/1.8	2.0/2.0	50% / 0%	low	1	80	0.615	0.677	10.1%
							2		0.356	0.416	16.9%
19	normal	CL	1.8/1.8	2.0/2.0	50% / 50%	low	1	80	0.593	0.681	14.8%
							2		0.332	0.421	26.8%
20	normal	CL	1.8/2.4	2.0/2.0	50% / 75%	low	1	90	0.677	0.671	0.9%

Successfully validated under a wide range of conditions



Temperature Sensitivity High DT

Condition	Catalyst Loading [1]	Cell Structure [2]	BP (bar)	Stoich	Humidification An / Ca	Coolant Flow Rate [3]	i (Acm^{-2})	T (°C)	Cell V (V) Exp	Mod	error
10	normal	OME	1.8/1.8	2.0/2.0	50% / 0%	high	2	60	0.573	0.564	1.6%
								65	0.585	0.577	1.4%
								70	0.593	0.562	5.2%
								72.5	0.593	0.551	7.1%
								75	0.522	0.533	2.1%
11	normal	OME	1.8/1.8	2.0/2.0	50% / 0%	low	2	60	0.565	0.567	0.4%
								62.5	0.575	0.572	0.5%
								65	0.591	0.569	3.7%
12	normal	OME	1.8/2.4	2.0/2.0	50% / 0%	low	2	60	0.595	0.591	0.7%
								65	0.600	0.603	0.5%
								70	0.612	0.584	4.6%
								72.5	0.603	0.567	6.0%
13	normal	OME	1.8/2.4	2.0/2.0	50% / 50%	low	2	60	0.588	0.596	1.4%
								65	0.593	0.605	2.0%
								70	0.596	0.586	1.7%
								75	0.609	0.571	6.2%
								80	0.603	0.569	5.6%
								82.5	0.601	0.561	6.7%
								85	0.587	0.556	5.3%

Temperature Sensitivity Low DT

Condition	Catalyst Loading [1]	Cell Structure [2]	BP (bar)	Stoich	Humidification An / Ca	Coolant Flow Rate [3]	i (Acm^{-2})	T (°C)	Cell V (V) Exp	Mod	error
5	normal	OME	1.8/1.8	2.0/2.0	60°C / 0%	high	2	60	0.603	0.597	1.0%
								65	0.610	0.610	0.0%
								70	0.596	0.608	2.0%
6	normal	OME	1.8/2.4	2.0/2.0	60°C / 0%	high	2	60	0.621	0.627	1.0%
								65	0.627	0.633	1.0%
								70	0.633	0.624	1.4%
								75	0.628	0.614	2.2%
7	normal	OME	1.8/1.8	2.0/1.5	60°C / 0%	high	2	60	0.557	0.550	1.3%
								65	0.564	0.575	2.0%
								70	0.572	0.571	0.2%
								72.5	0.568	0.568	0.0%
8	normal	OME	1.8/1.8	2.0/2.0	60°C / 60°C	high	2	60	0.584	0.574	1.7%
								65	0.598	0.597	0.2%
								70	0.588	0.591	0.5%
9	normal	OME	1.8/2.4	2.0/1.5	50% / 50%	high	2	60	0.576	0.586	1.7%
								70	0.597	0.595	0.3%
								80	0.595	0.586	1.5%
								85	0.585	0.585	0.0%
								87.5	0.584	0.584	0.0%

FC Modeling - Status

Validation with varied Reactant Humidification

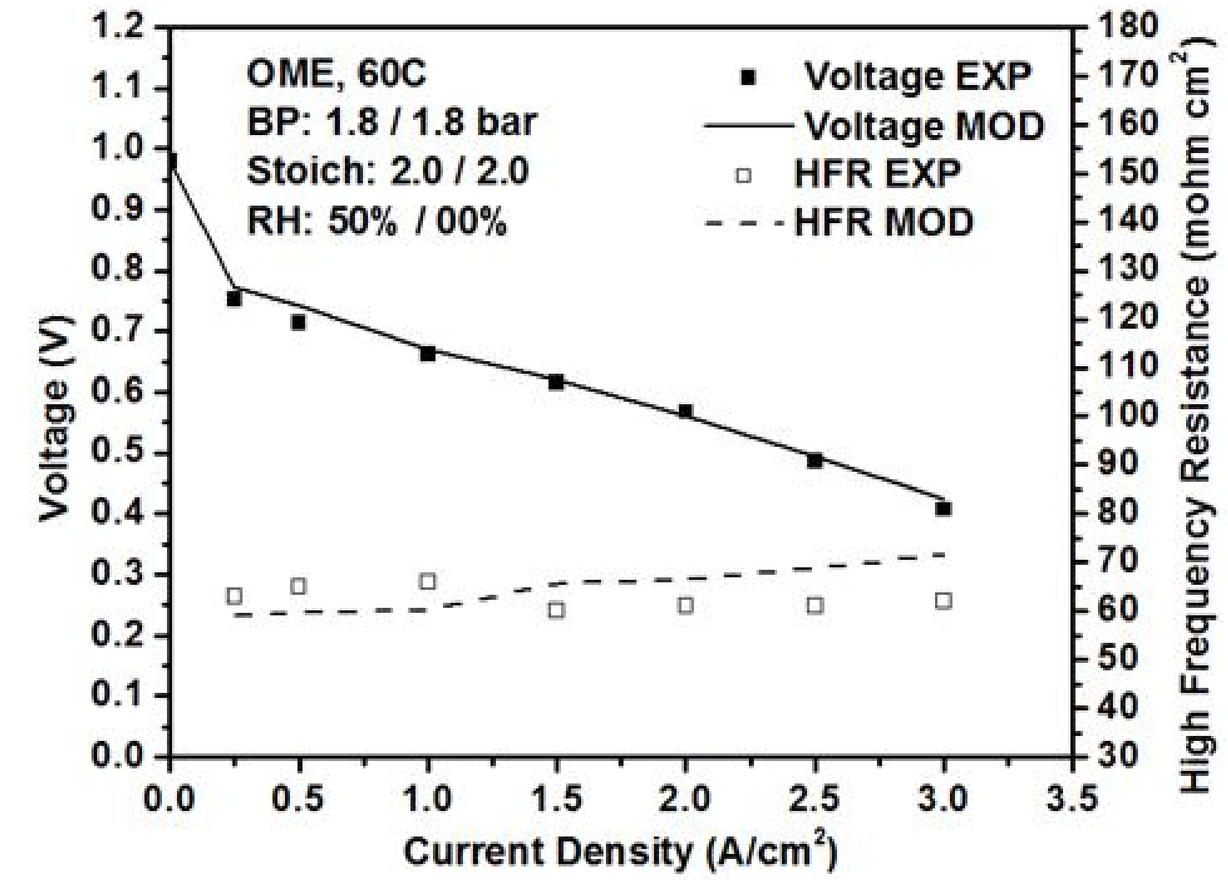
Condition	Catalyst Loading [1]	Cell Structure [2]	BP (bar)	Stoich	Humidification An / Ca	Coolant Flow Rate [3]	i (Acm^{-2})	T (°C)	Cell V (V) Exp	Cell V (V) Mod	Cell V (V) error
1	normal	OME	1.8/1.8	2.0/2.0	50% / 0%	high	1	60	0.662	0.670	1.2%
							2		0.568	0.560	1.4%
2	normal	OME	1.8/1.8	2.0/2.0	100% / 0%	high	1	60	0.661	0.670	1.4%
							2		0.544	0.561	3.1%
3	normal	OME	1.8/1.8	2.0 / 2.0	0% / 100%	high	1	60	0.646	0.632	2.2%
							2		0.516	0.523	1.4%
4	normal	OME	1.8/1.8	2.0/2.0 heliox	50% / 0%	high	1	60	0.666	0.680	2.1%
							2		0.541	0.571	5.5%

[1] MEA with "normal" loading is Anode 0.15 / Cathode 0.40 mg_{Pt}/cm^2. MEA with "low" loading is Anode 0.05 / Cathode 0.15 mg_{Pt}/cm^2.

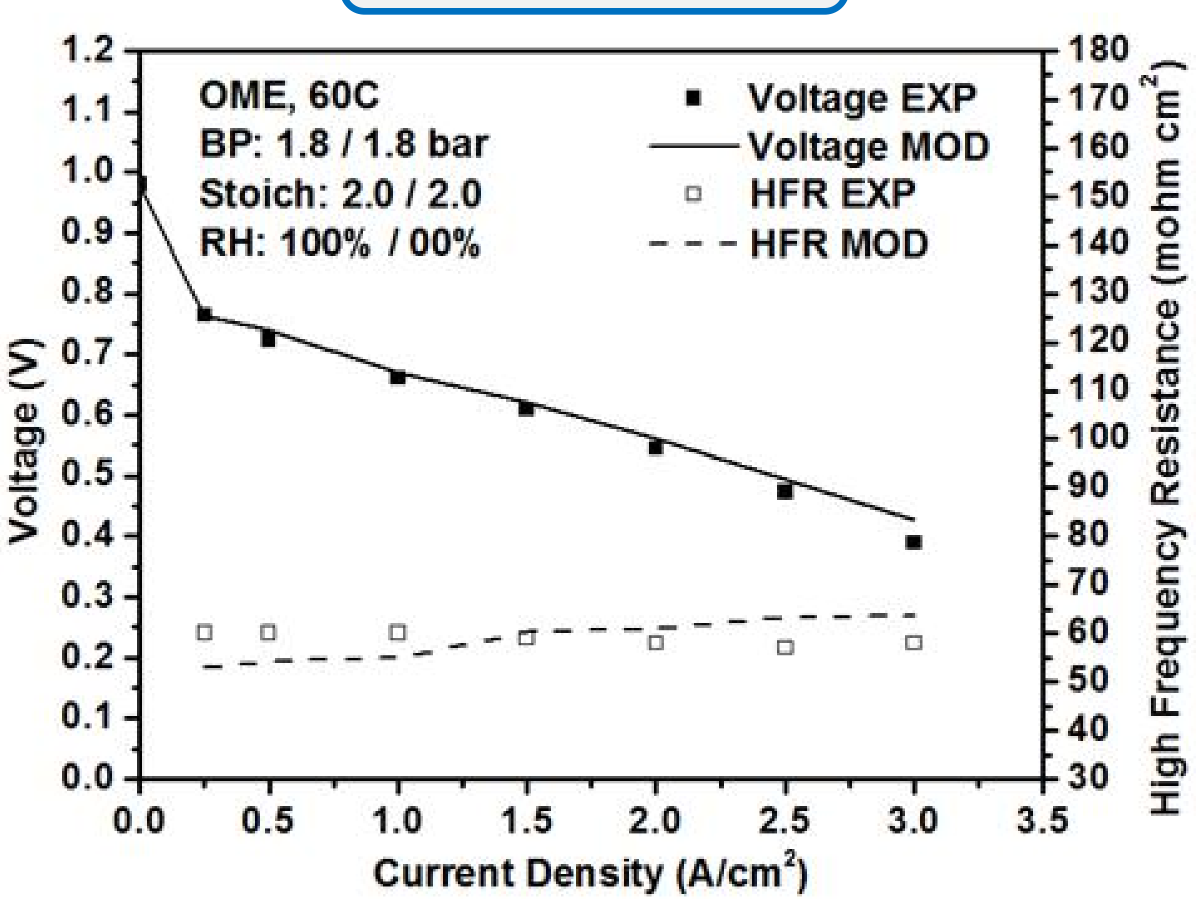
[2] "CL" is the straight channel / land flow field, "OME" is the open metallic element flow field by Nuvera Fuel Cells Inc.

[3] "low" means DT ≈ 5°C. "high" means DT ≈1°C

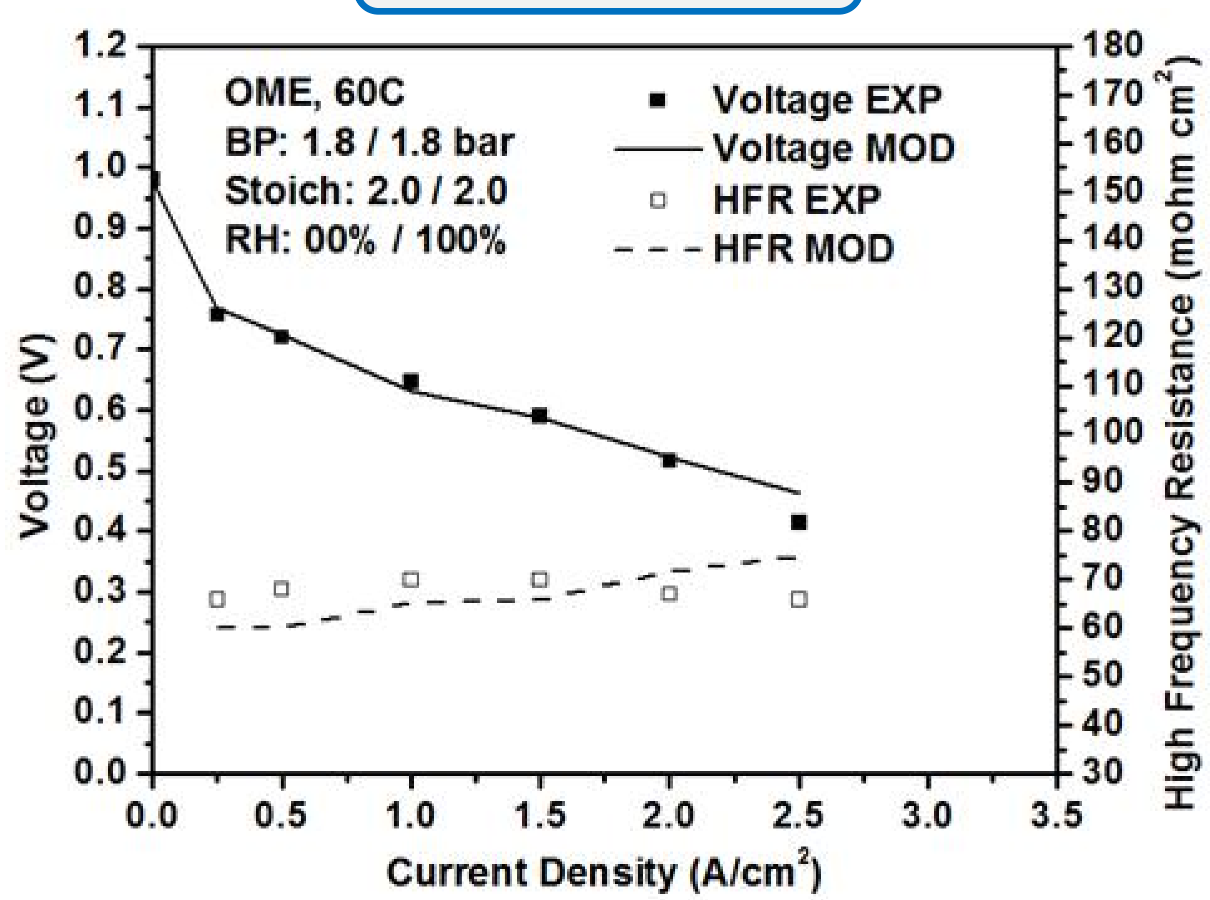
Condition 1



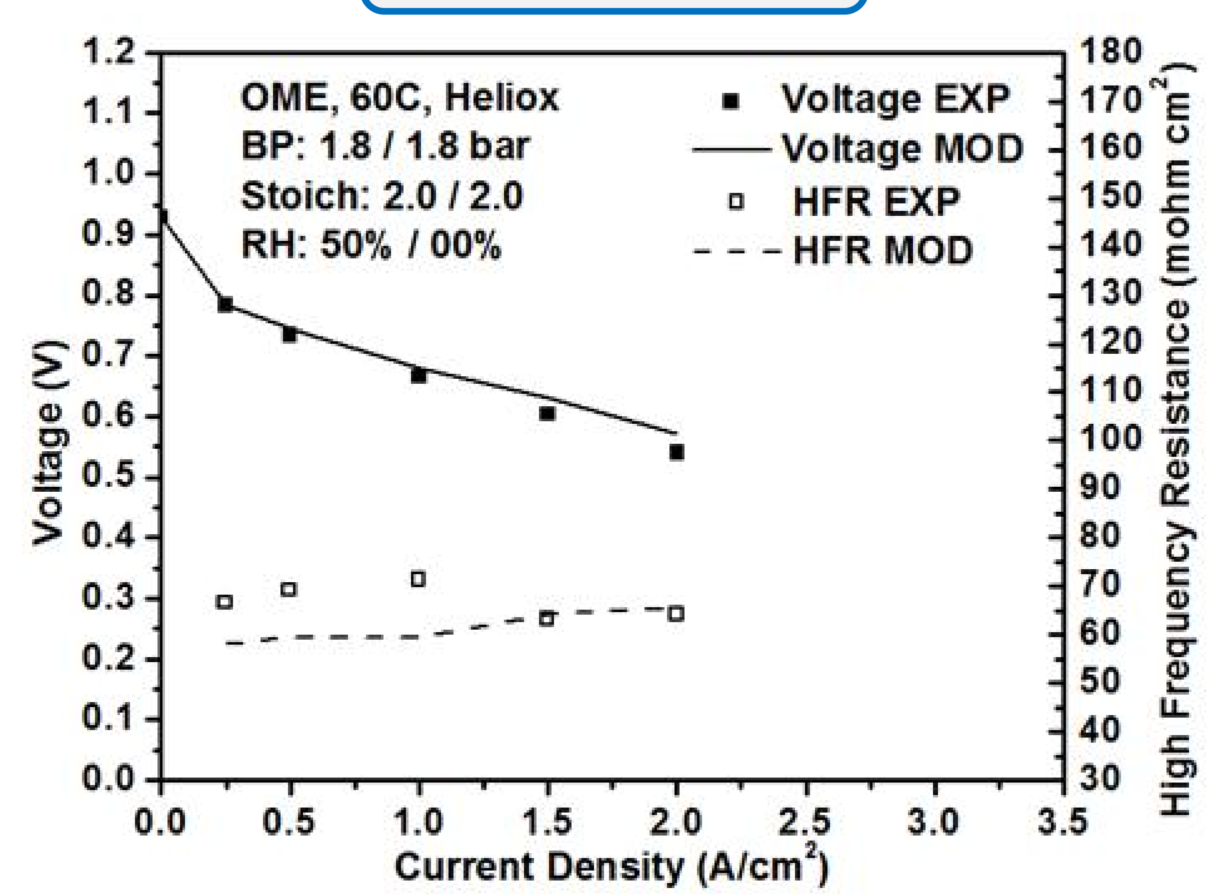
Condition 2



Condition 3



Condition 4



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FC Modeling - Status

Temperature Sensitivity Validation at Low DT

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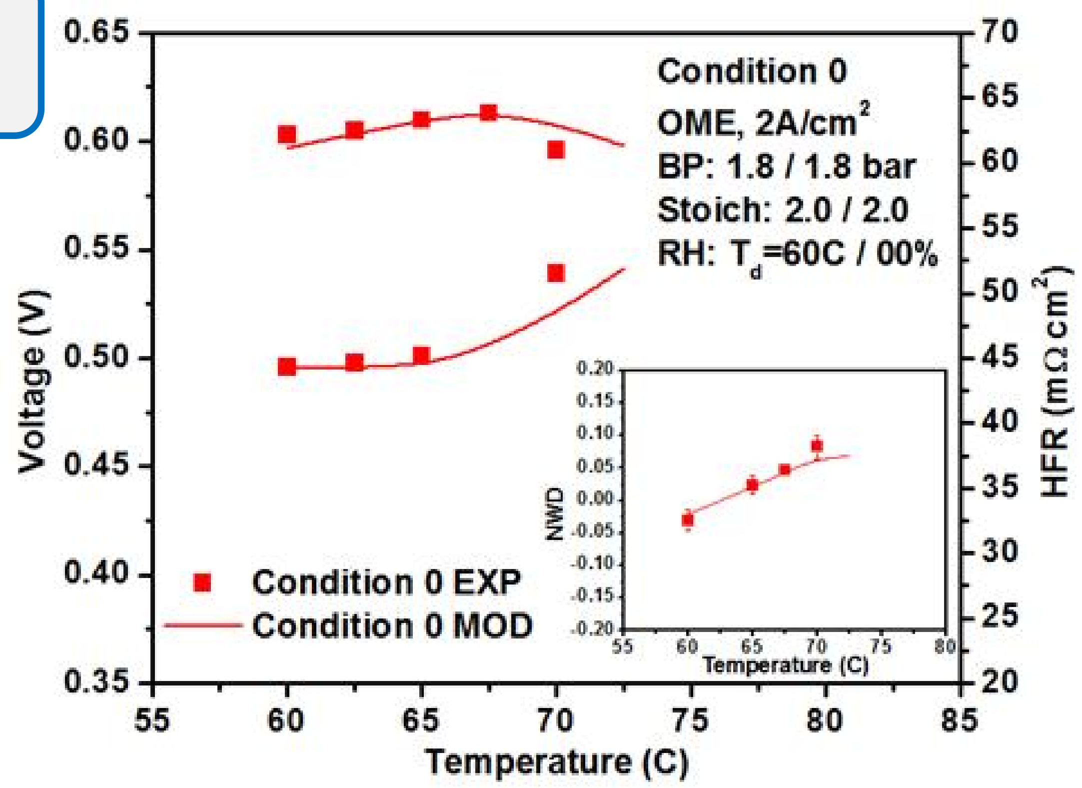

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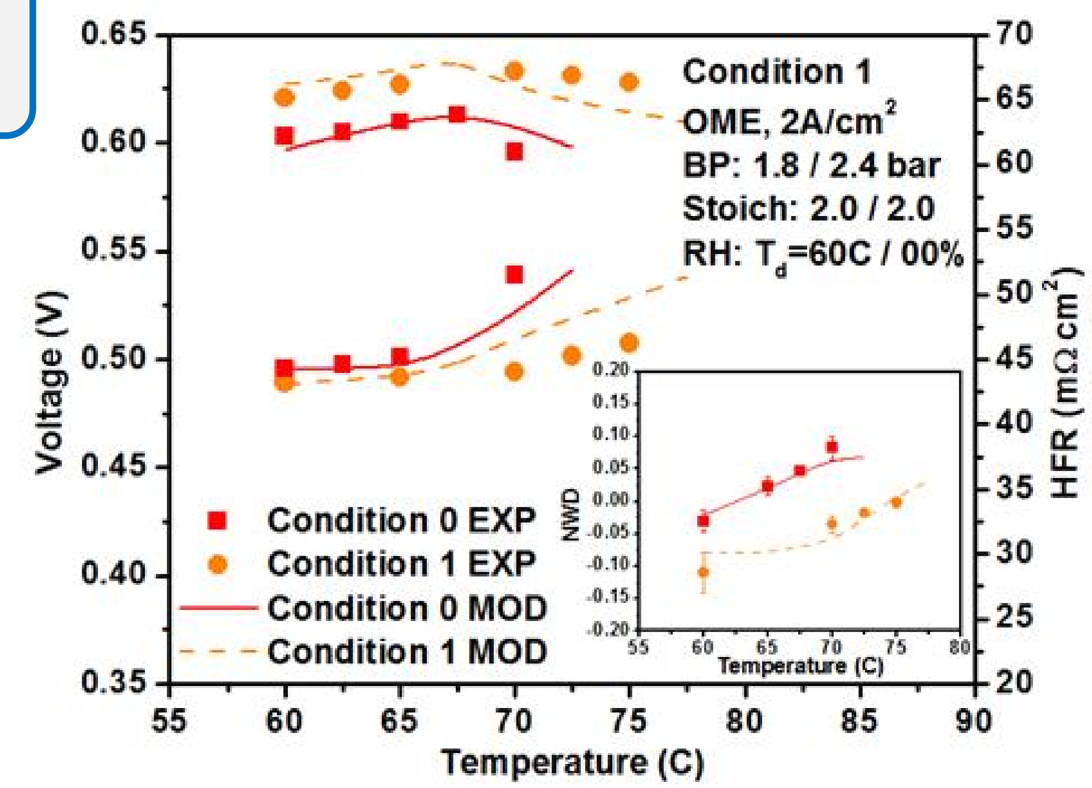

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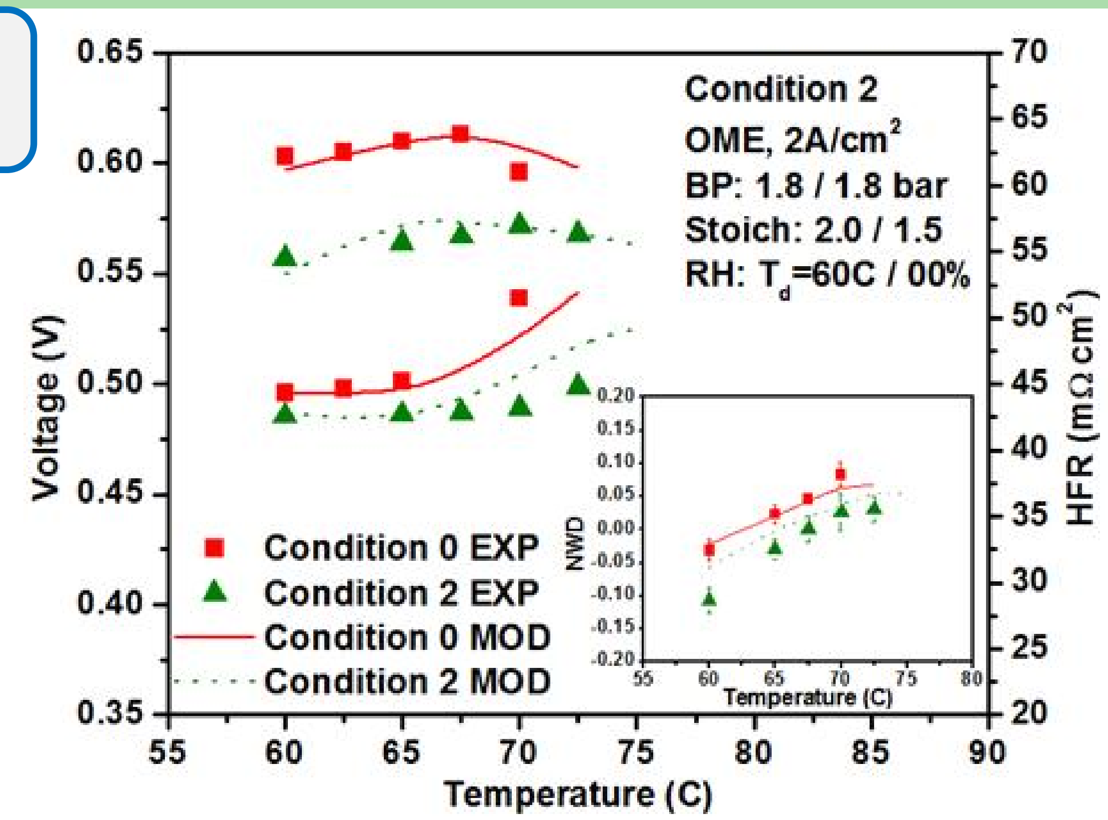


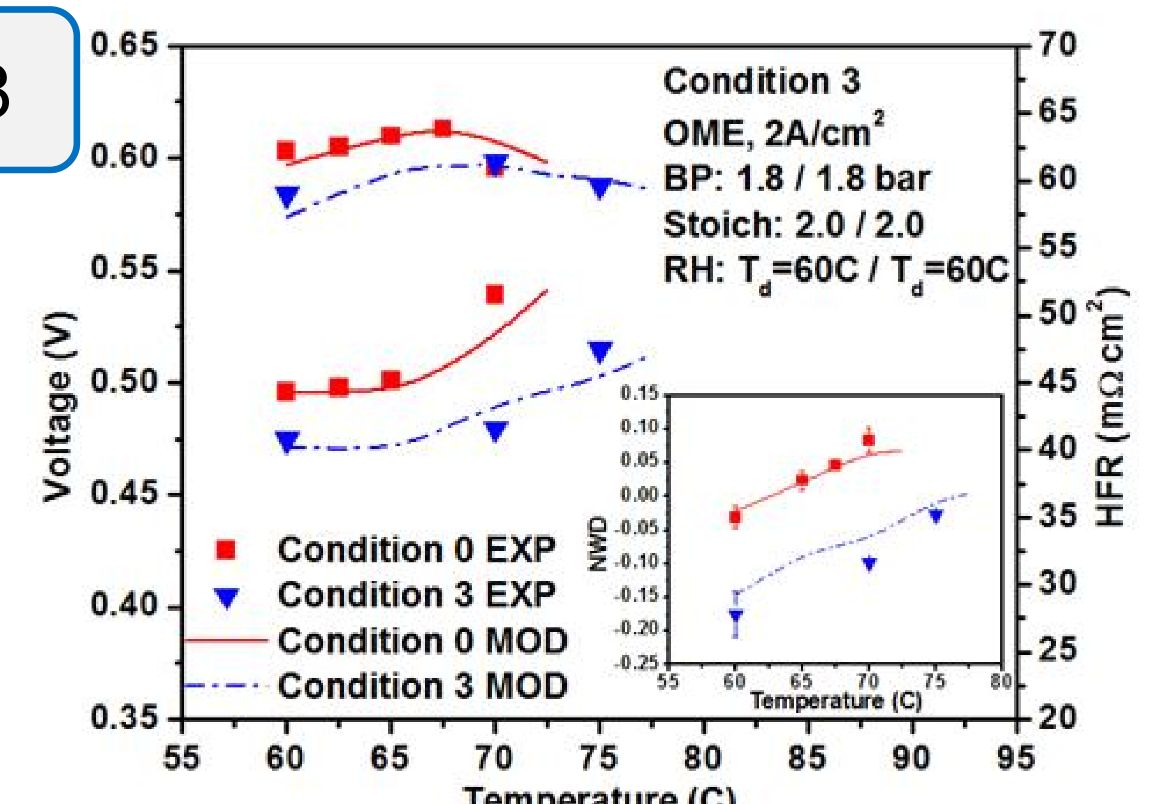
Condition	Catalyst Loading [1]	Cell Structure [2]	BP (bar)	Stoich	Humidification An / Ca	Coolant Flow Rate [3]	i (Acm^{-2})	T (°C)	Cell V (V) Exp	Mod	error
5	normal	OME	1.8/1.8	2.0/2.0	60°C / 0%	high	2	60	0.603	0.597	1.0%
								65	0.610	0.610	0.0%
								70	0.596	0.608	2.0%
6	normal	OME	1.8/2.4	2.0/2.0	60°C / 0%	high	2	60	0.621	0.627	1.0%
								65	0.627	0.633	1.0%
								70	0.633	0.624	1.4%
								75	0.628	0.614	2.2%
7	normal	OME	1.8/1.8	2.0/1.5	60°C / 0%	high	2	60	0.557	0.550	1.3%
								65	0.564	0.575	2.0%
								70	0.572	0.571	0.2%
								72.5	0.568	0.568	0.0%
8	normal	OME	1.8/1.8	2.0/2.0	60°C / 60°C	high	2	60	0.584	0.574	1.7%
								65	0.598	0.597	0.2%
								70	0.588	0.591	0.5%
9	normal	OME	1.8/2.4	2.0/1.5	50% / 50%	high	2	60	0.576	0.586	1.7%
								70	0.597	0.595	0.3%
								80	0.595	0.586	1.5%
								85	0.585	0.585	0.0%
								87.5	0.584	0.584	0.0%

[1] MEA with "normal" loading is Anode 0.15 / Cathode 0.40 mg_{Pt}/cm^2. MEA with "low" loading is Anode 0.05 / Cathode 0.15 mg_{Pt}/cm^2.

[2] "CL" is the straight channel / land flow field, "OME" is the open metallic element flow field by Nuvera Fuel Cells Inc.

[3] "low" means DT ≈ 5°C. "high" means DT ≈1°C

8



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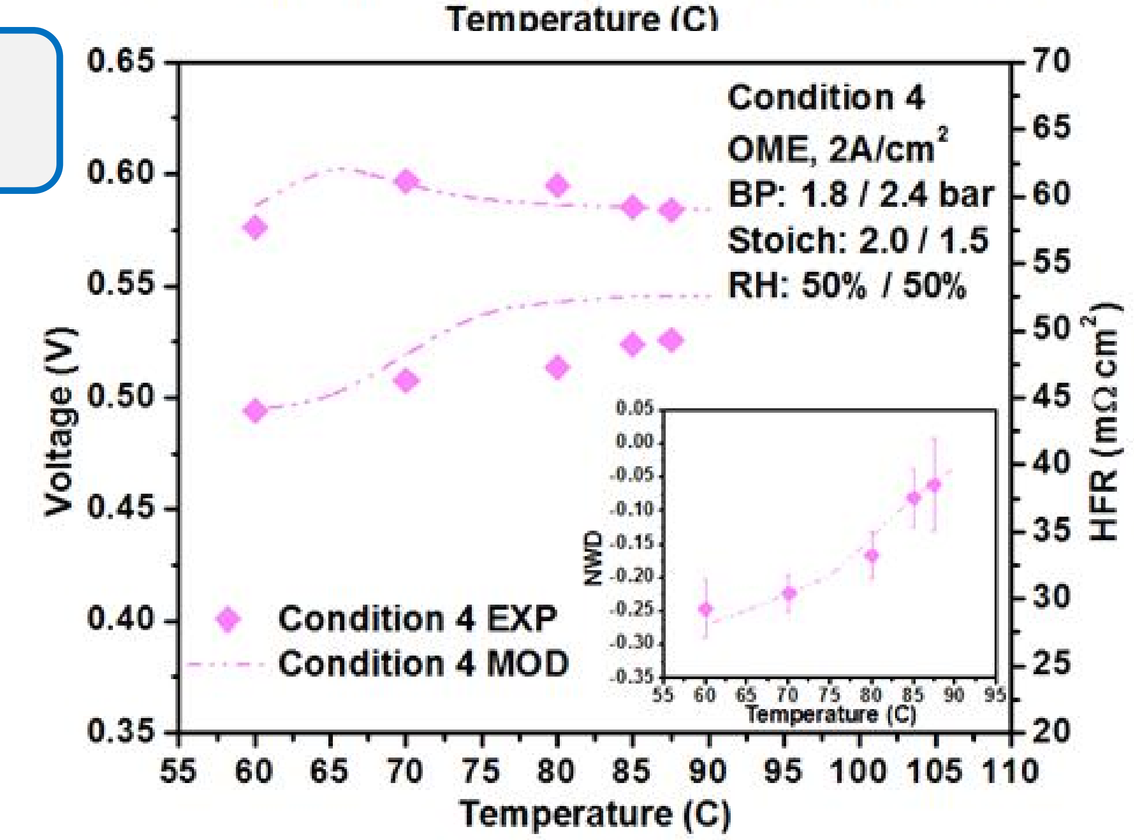
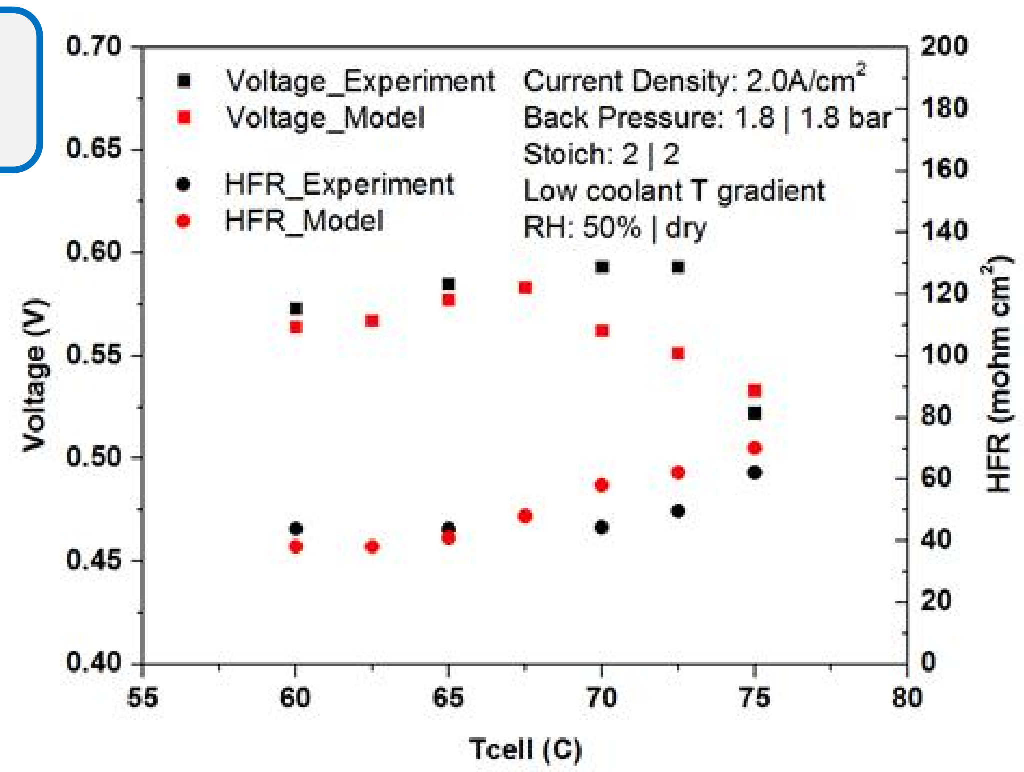


FC Modeling - Status

Temperature Sensitivity Validation at high DT

10



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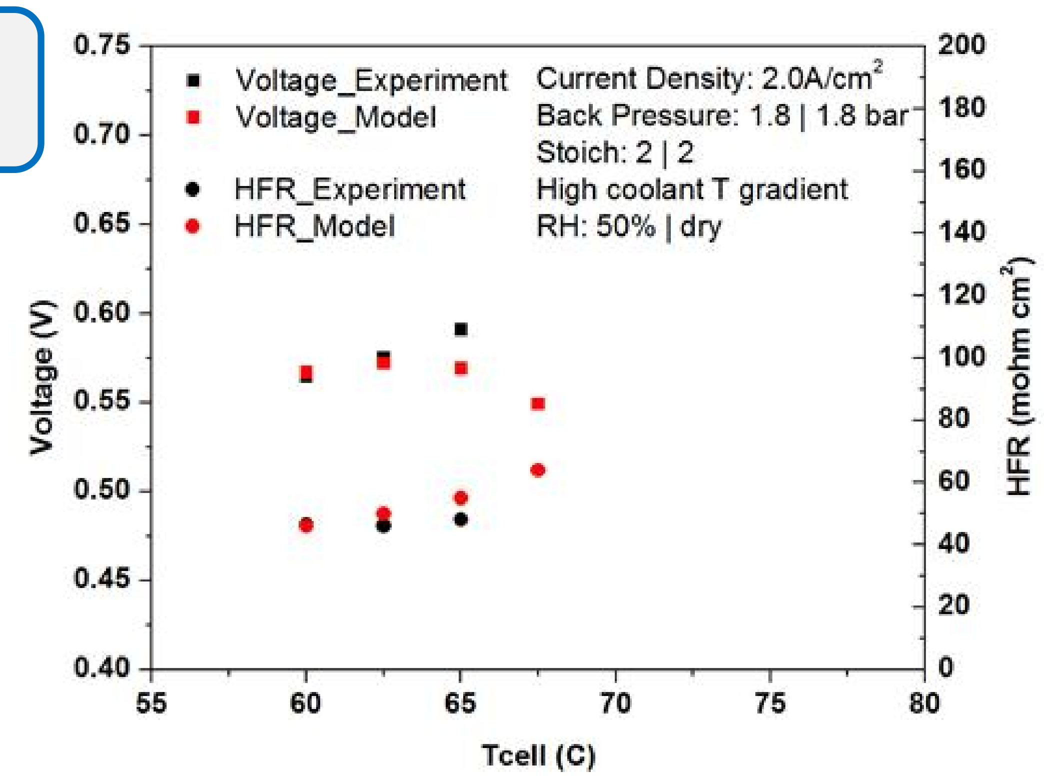
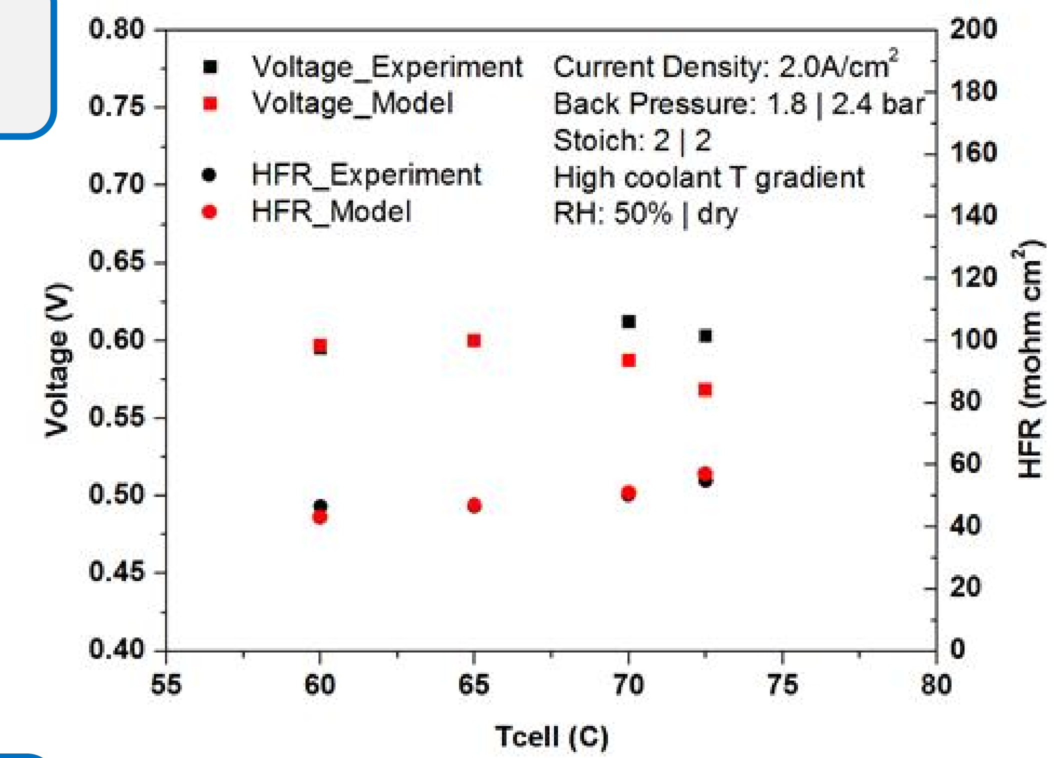
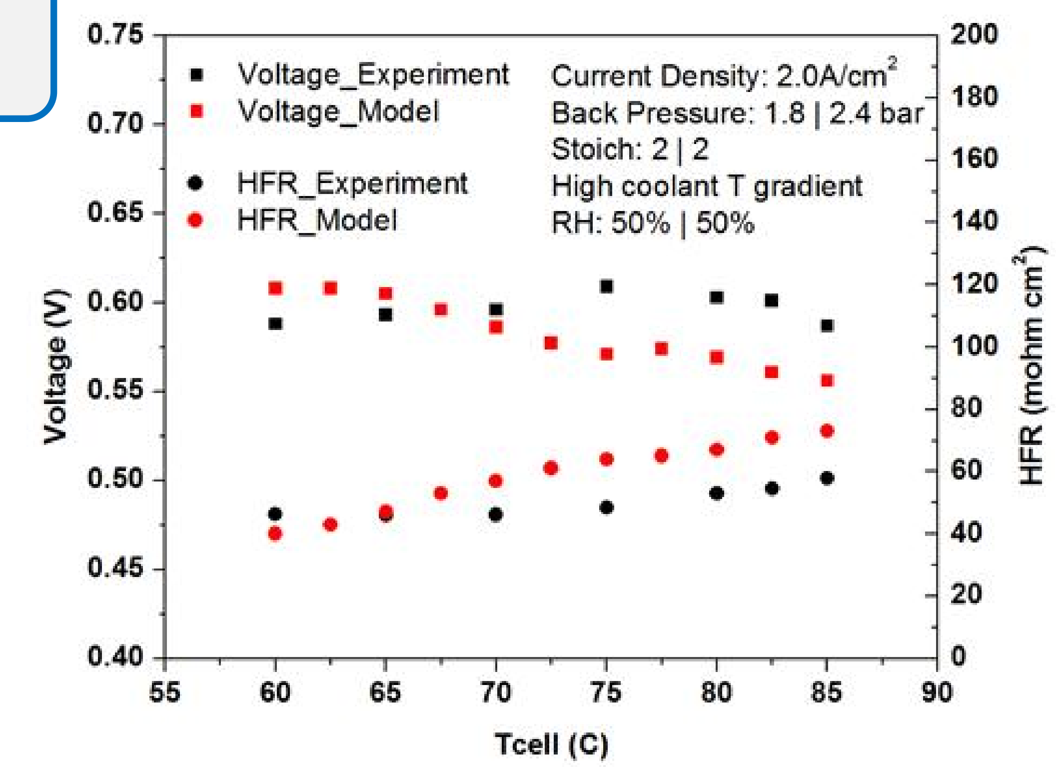


12



Condition	Catalyst Loading [1]	Cell Structure [2]	BP (bar)	Stoich	Humidification An / Ca	Coolant Flow Rate [3]	i (Acm^{-2})	T (°C)	Cell V (V) Exp	Cell V (V) Mod	Cell V (V) error
10	normal	OME	1.8/1.8	2.0/2.0	50% / 0%	high	2	60	0.573	0.564	1.6%
								65	0.585	0.577	1.4%
								70	0.593	0.562	5.2%
								72.5	0.593	0.551	7.1%
								75	0.522	0.533	2.1%
11	normal	OME	1.8/1.8	2.0/2.0	50% / 0%	low	2	60	0.565	0.567	0.4%
								62.5	0.575	0.572	0.5%
								65	0.591	0.569	3.7%
12	normal	OME	1.8/2.4	2.0/2.0	50% / 0%	low	2	60	0.595	0.591	0.7%
								65	0.600	0.603	0.5%
								70	0.612	0.584	4.6%
								72.5	0.603	0.567	6.0%
13	normal	OME	1.8/2.4	2.0/2.0	50% / 50%	low	2	60	0.588	0.596	1.4%
								65	0.593	0.605	2.0%
								70	0.596	0.586	1.7%
								75	0.609	0.571	6.2%
								80	0.603	0.569	5.6%
								82.5	0.601	0.561	6.7%
								85	0.587	0.556	5.3%

13



Completed High Temperature Validation

[1] MEA with "normal" loading is Anode 0.15 / Cathode 0.40 mg_{Pt}/cm^2. MEA with "low" loading is Anode 0.05 / Cathode 0.15 mg_{Pt}/cm^2.

[2] "CL" is the straight channel / land flow field, "OME" is the open metallic element flow field by Nuvera Fuel Cells Inc.

[3] "low" means DT ≈ 5°C. "high" means DT ≈1°C

FC Modeling - Status

Channel Land Architecture Validation

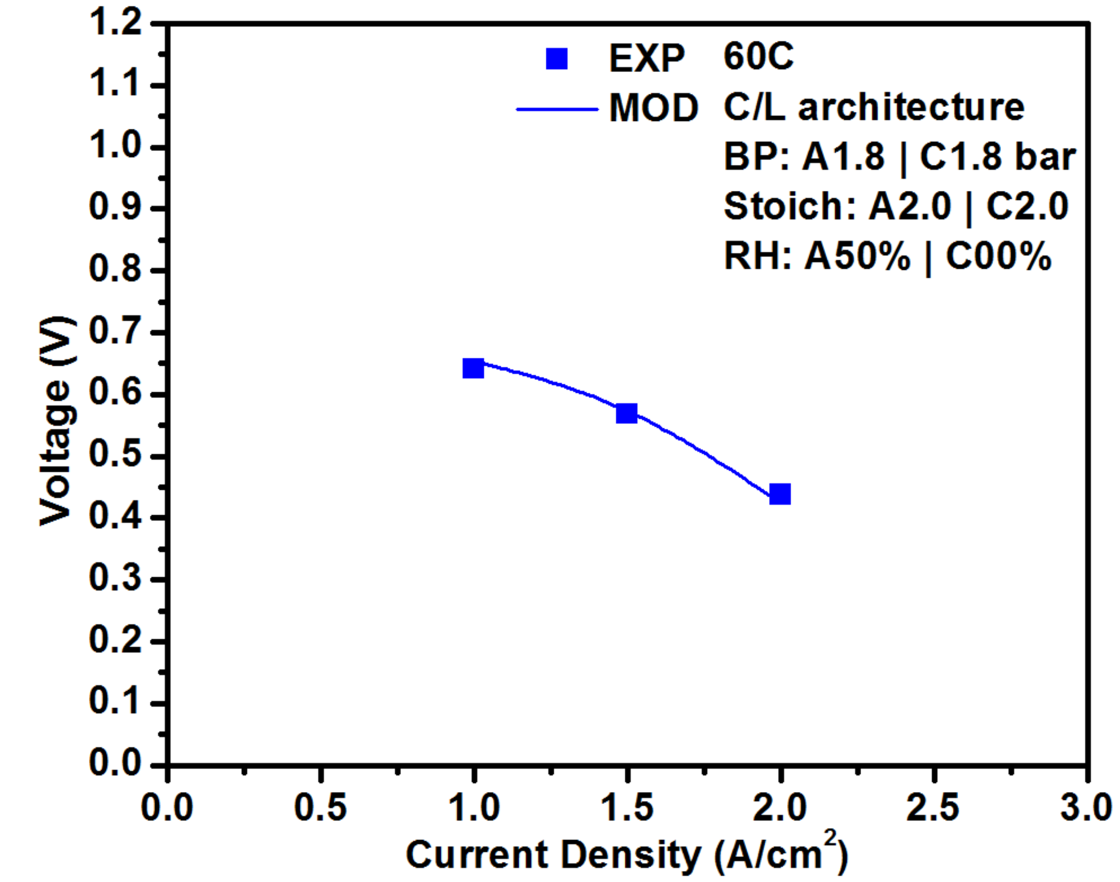
Condition	Catalyst Loading [1]	Cell Structure [2]	BP (bar)	Stoich	Humidification An / Ca	Coolant Flow Rate [3]	i (Acm^{-2})	T ($^{\circ}$C)	Cell V (V) Exp	Mod	error
14	normal	CL	1.8/1.8	2.0/2.0	50% / 0%	low	1	60	0.641	0.654	2.0%
							2		0.437	0.424	3.0%
15	normal	CL	1.8/1.8	2.0/2.0 heliox	50% / 0%	low	1	60	0.688	0.657	4.5%
							2		0.580	0.559	3.6%
16	normal	CL	1.8/1.8	2.0/2.0	50% / 0%	low	1	70	0.648	0.676	4.3%
							2		0.432	0.434	0.5%
17	normal	CL	1.8/1.8	2.0/2.0	50% / 50%	low	1	70	0.634	0.671	5.8%
							2		0.387	0.430	11.1%
18	normal	CL	1.8/1.8	2.0/2.0	50% / 0%	low	1	80	0.615	0.677	10.1%
							2		0.356	0.416	16.9%
19	normal	CL	1.8/1.8	2.0/2.0	50% / 50%	low	1	80	0.593	0.681	14.8%
							2		0.332	0.421	26.8%
20	normal	CL	1.8/2.4	2.0/2.0	50% / 75%	low	1	90	0.677	0.671	0.9%

[1] MEA with "normal" loading is Anode 0.15 / Cathode 0.40 mg_{Pt}/cm^2. MEA with "low" loading is Anode 0.05 / Cathode 0.15 mg_{Pt}/cm^2.

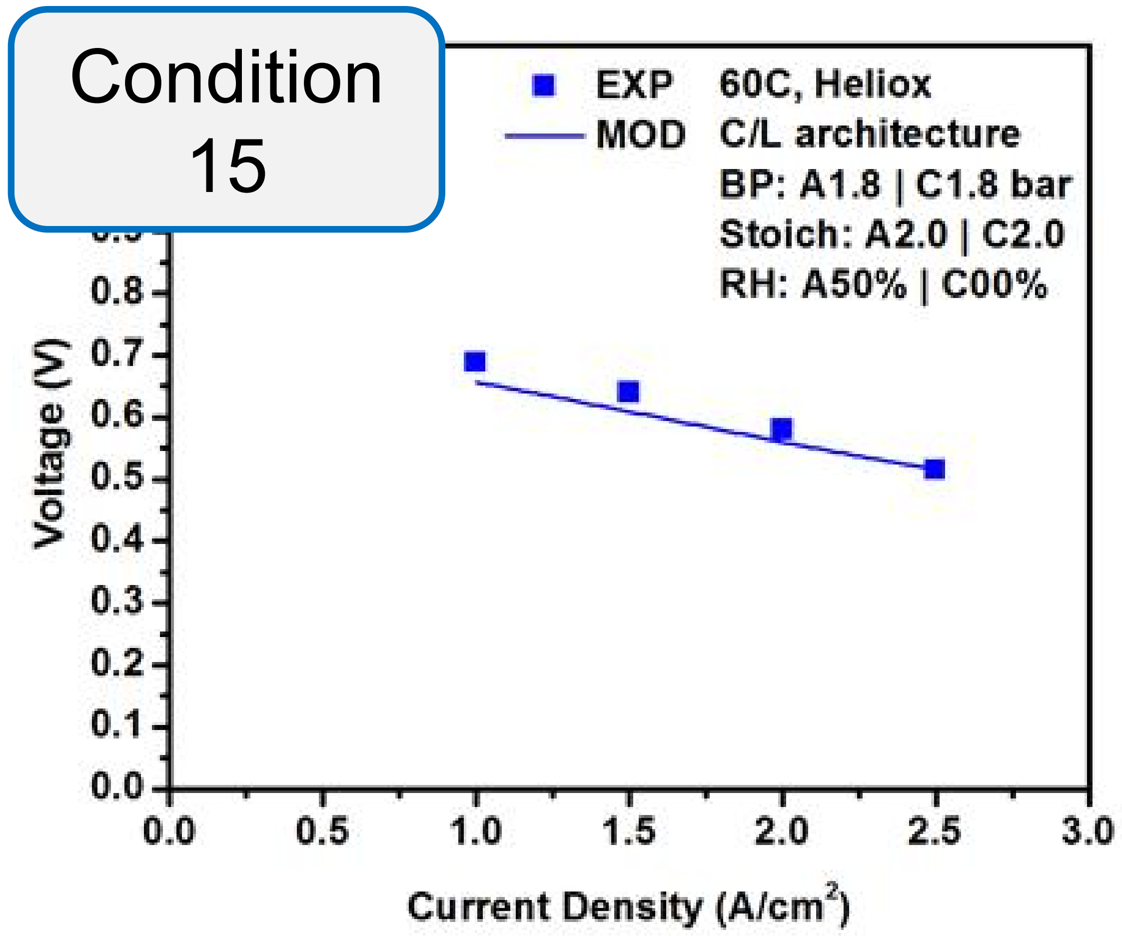
[2] "CL" is the straight channel / land flow field, "OME" is the open metallic element flow field by Nuvera Fuel Cells Inc.

[3] "low" means DT ≈ 5°C. "high" means DT ≈1°C

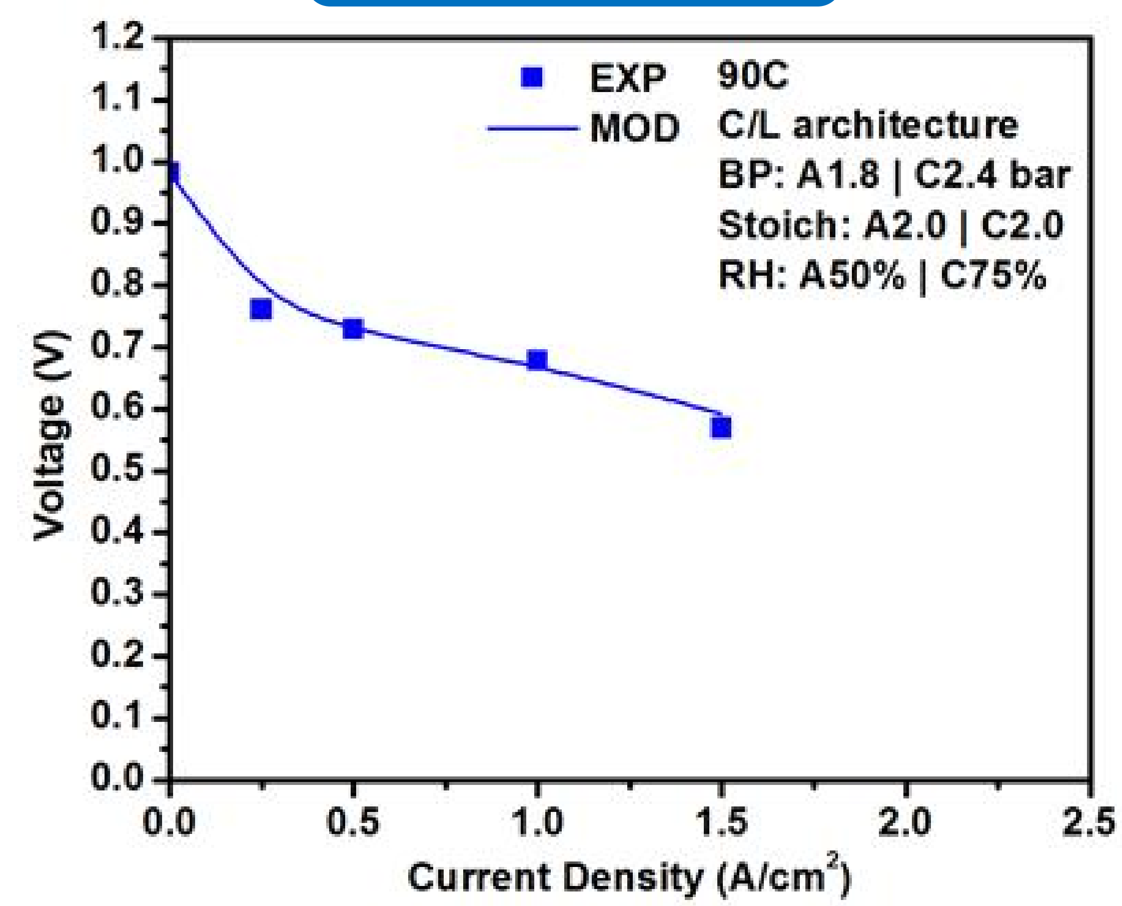
Condition 14



Condition 15



Condition 20



Channel/Land Architecture Validated

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FC Modeling - Status

Low Pt Loading Validation

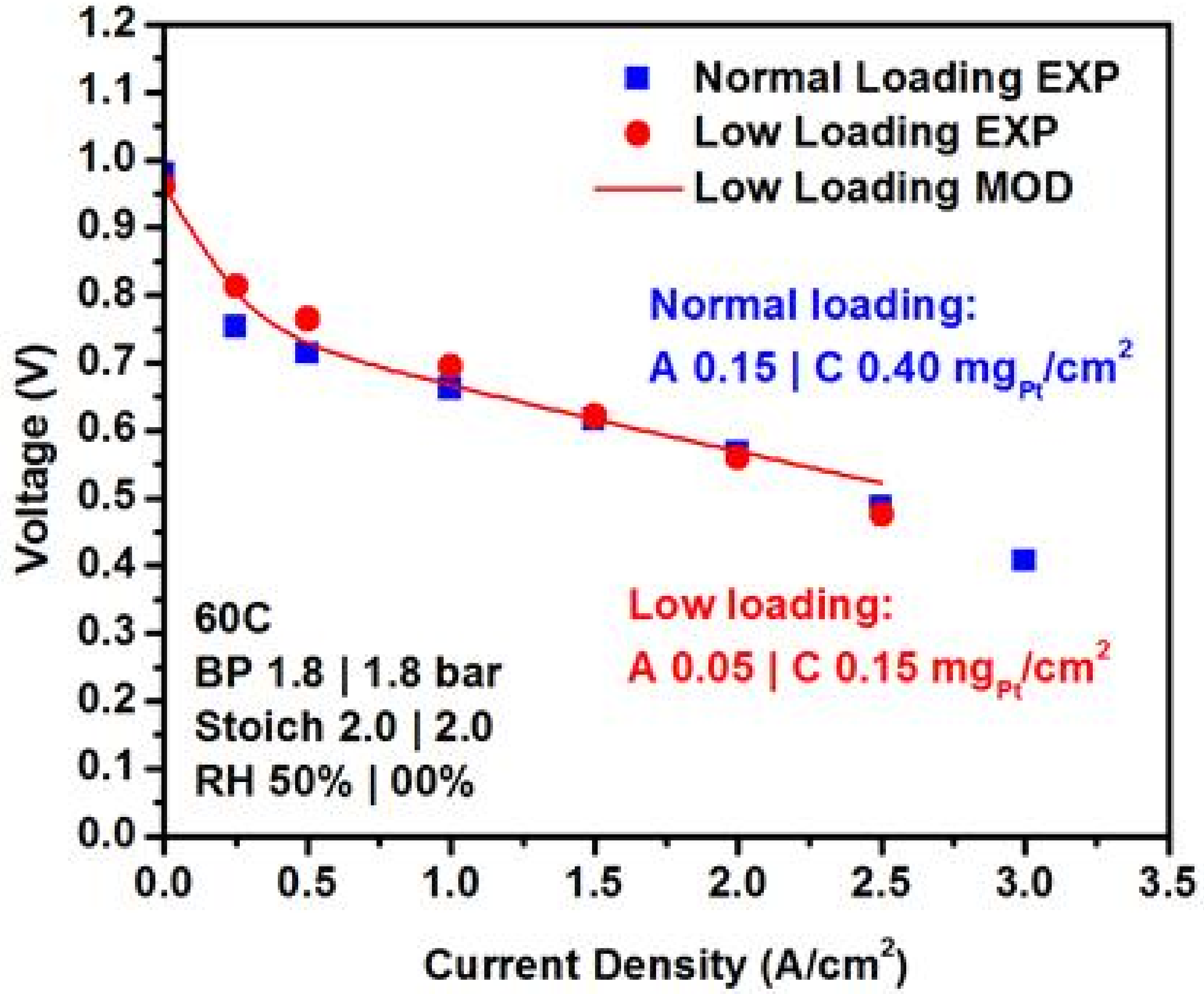
Condition	Catalyst Loading [1]	Cell Structure [2]	BP (bar)	Stoich	Humidification An / Ca	Coolant Flow Rate [3]	i (Acm^{-2})	T (°C)	Cell V (V) Exp	Mod	error
21	low	OME	1.8/1.8	2.0/2.0	50% / 0%	high	1	60	0.694	0.667	3.9%
							2		0.559	0.569	1.8%
22	low	OME	1.8/1.8	2.0/2.0	50% / 0%	high	1	70	0.670	0.666	0.6%
							2		0.534	0.560	4.9%
23	low	OME	1.8/2.4	2.0/2.0	50% / 50%	high	1	90	0.705	0.675	4.3%
							2		0.581	0.563	3.1%
24	low	OME	1.8/2.4	2.0/2.0	50% / 75%	high	1	90	0.713	0.675	5.3%
							2		0.586	0.563	3.9%

[1] MEA with "normal" loading is Anode 0.15 / Cathode 0.40 mg_{Pt}/cm^2. MEA with "low" loading is Anode 0.05 / Cathode 0.15 mg_{Pt}/cm^2.

[2] "CL" is the straight channel / land flow field, "OME" is the open metallic element flow field by Nuvera Fuel Cells Inc.

[3] "low" means DT ≈ 5°C. "high" means DT ≈1°C

Model Validated with Low Pt Loading Electrode



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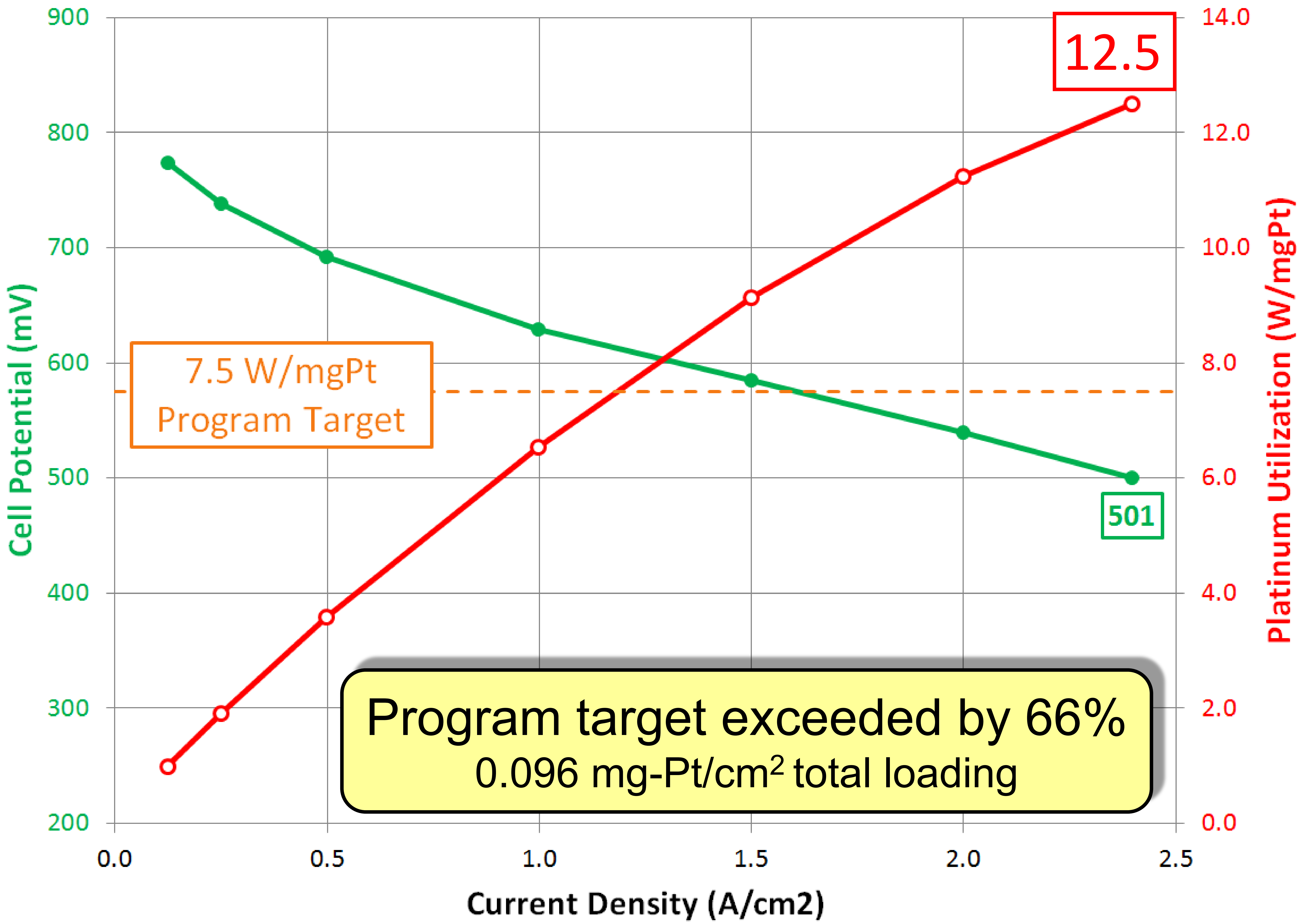
Materials Roadmap - Completed

Material development aimed at reducing Pt loading and optimizing performance at high current densities is the key to the success of the program

Strategy	2010				2011				2012		
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3
Pt Reduction on Standard Electrodes	■	■	■	■							
New Electrode Structures						■	■				
~~Graded Pt Loading Electrodes~~ Further reduction in Pt Loading							■	■	■		
Thinner Membranes			■	■	■	■	■				
Low Equivalent Weight Ionomer in Electrode				■	■	■					
~~Novel MEA Architectures~~ Improved Resistivity Membranes									■	■	

Materials Development Status

Demonstrated 12.5 W/mg-Pt at 501 mV on a 4 Cell Orion® Stack



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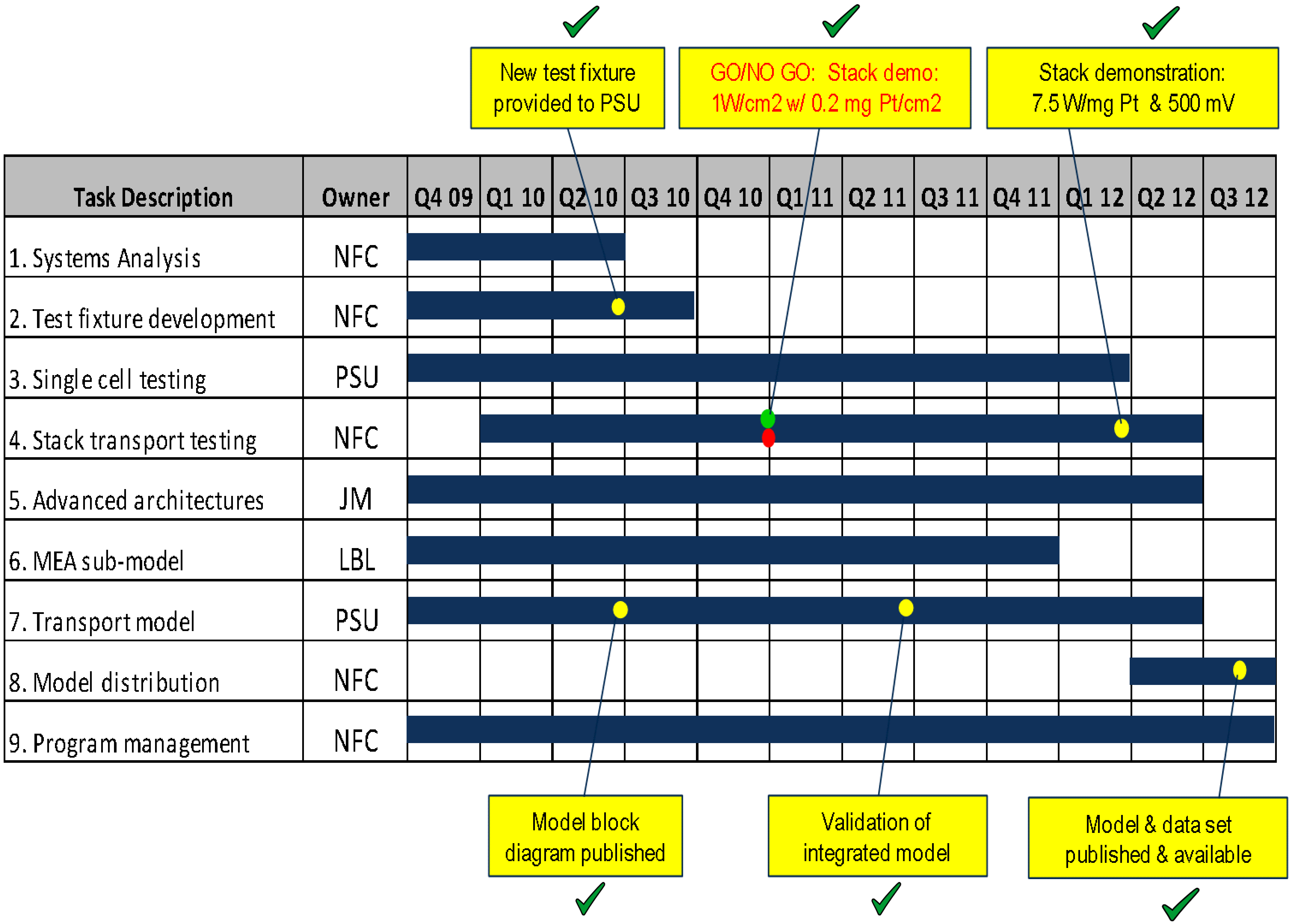
Johnson Matthey Fuel Cells — the power within

T_{cell} = 60 °C, An 50% RH, Ca 0% RH, Press ~1.1 to 2.4 bara

0.027 mg Pt/cm² An, 0.069 mg Pt/cm² Ca GDL: SGL 25BC

Program Milestones - Approach

The program has been completed, all the milestones have been met



NUVERA FUEL CELLS

Future work

The program has been successfully completed. Here are reported the opportunities for further studies based on the program findings

Existing gaps and needs:

- Water transport and management for low Pt loading electrodes
- GDL water transport physics and aging phenomena
- Transport processes during start-up and shut down and their link to performance and durability
- Transport between and across interfaces and components

Future ideas:

- Continue pursuing optimization of standard carbon supported electrodes as effective cost reduction strategy with the quickest path to production.
- Integrate existing performance and durability models together
- Optimize GDL design for water transport to improve performance and durability at high current density
- Pursue innovative GDL design as a way to implement a simpler architecture with higher performance in order to minimize cost.

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Summary

- The AURORA program main goal was to achieve DOE cost targets by using a combination of high current density with low Pt loadings.
  - Program target was to demonstrate Platinum Utilization ≥ 7.5W/mg-Pt
- A model capable of predicting high current density operation in different architectures was the central deliverable of the program.
  - Model predictions have been thoroughly validated with experiments in both open flow field and land-channel architectures
  - Model has been published and it is available to the FC Community
- Material development aimed at reducing Pt loading and optimizing performance at high current densities yielded to demonstration of Platinum Utilization = 12.5W/mg-Pt on full active area stack.
  - Result obtained exceeds Program Target by 66%
- High temperature operation has been further explored and stable operation at ≥ 95°C has been demonstrated in full format stack testing

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