Electrochemical Compression

2019 DOE Hydrogen & Fuel Cells Program

Annual Merit Review Meeting

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April 30th, 2019
Project ID: in0005

Overview

Timeline

- **Project Start:** Oct. 1, 2016
- **Program Novation:** Apr.-Dec., 2017
- **Project End:** June 30, 2020
- **Percent Complete:** 40%

Budget

- **Total Project Budget: $3.52MM**
  - **Total Federal Share:** $2.81MM
  - **Total Recipient Share:** $0.71MM
  - **Total DOE Funds Spent*:** $1.36 MM

* As of 12/31/2018

Technical Barriers (Advanced Compression)

- B. Reliability and Costs of Gaseous Hydrogen Compression

Technical Targets: Small Compressors: Fueling Sites (~100 kg H_2/hr)[1]

Characteristics	Units	2015 Status	2020 Target
Availability	%	70-90	85
Compressor Specific Energy	kWh/kg	1.60[2]	1.60[2]
Uninstalled Cap. Cost[2]	$	275k	170k
Annual Maintenance	% of Capital Cost	8	4
Lifetime	Years	--	10
Outlet Pressure Capability	bar	950	950

[1] FCTO Multi-Year Research, Development, and Demonstration Plan (2015). [2] 100-bar delivery/Commercial mechanical compressors are >6-8 kWh/kg (@7-bar delivery).

Partners

- **National Renewable Energy Laboratory (National Lab)** – Membrane/System Validation
- **Rensselaer Polytechnic Institute (Academic)** – Membrane Development
- **Gaia Energy Research Institute (Private)** – Techno-Economic Analysis
- **Giner, Inc. (R&D/Private)** – System Development & Assy

Collaborations

- **TÜV SÜD America** – Codes/Stack Certification
- **Intertek** – Codes/System Certification

Relevance

Overall Project Objectives

- Develop/demonstrate electrochemical hydrogen compressor (EHC) to address critical needs of lower-cost, higher efficiency, and improved durability

FY 19 Objectives

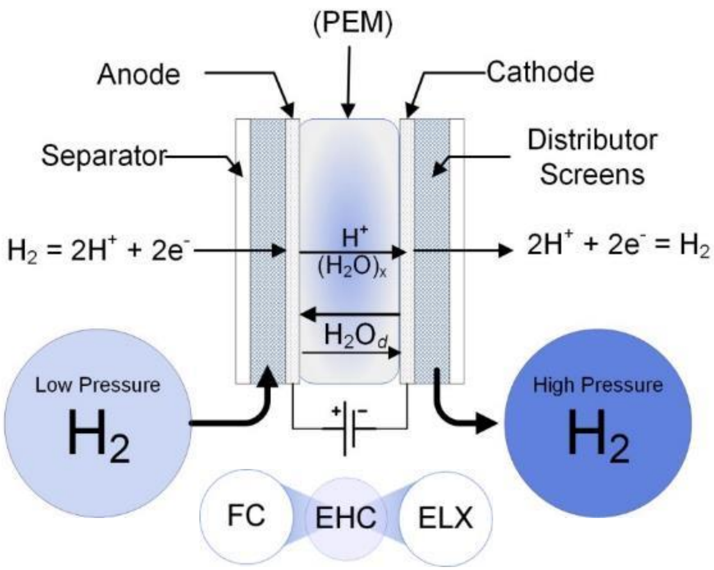
- Engineer stack & cell components for 12,688 psi (875 bar) operation
- Scale-up membranes, MEA, Stack hardware
  - Assemble EHC Stack and verify EHC stack operation at a pressure of 875 bar.
- Initiate design of EHC prototype unit
- **Optimize stack hardware and demonstrate cell performance $\leq$ 0.250 V/cell at current densities $\geq$1,000 mA/cm^2**

Impact

- Low cost, reliable, high pressure hydrogen to support FCEV penetration
  - Compressor reliability is a major concern for enhanced use of high pressure hydrogen systems and threatens the deployment of a hydrogen infrastructure

High Pressure Stack

EHC Background

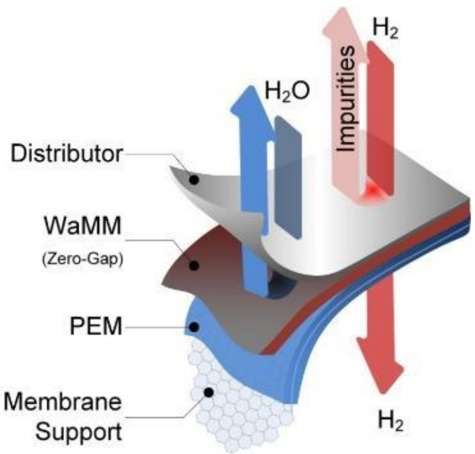


EHC: Benefits & Uses

- Solid State, No moving parts
  - Improves downtime
- No membrane degradation (no O_2)
  - Enables use of low-cost Aromatic membranes
- Cross-cutting technology
  - Fuel Cells, Electrolyzers
- Alternative applications:
  - Home/Roadside-Refuelers
  - Hydrogen Purification/Separation (eg. Storage/Natural Gas appl.)
  - Hydrogen Circulation (Refrigeration)
  - H_2 Sensor Applications
  - Power Generation (Reversible)

Efficient, stable, high pressure, & high current EHC operation requires:

- **Water Management**
  - Difficult under varying operating parameters (P_i, P_o, T_i, Current, H_2O_d)
    - Leads to catalyst flooding or membrane dehydration
  - High electro-osmotic drag (EOD) in conventional membranes; 6X higher than can be supplied by humidification
- **Thermal Management**
  - Limits to operating current density
  - Individual cell cooling required
- **Mechanical Strength**
  - Stack hardware, membranes, sealing



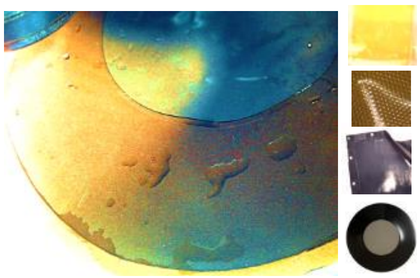
Advanced EHC Cell Design

Approach: Program Overview

Safety, Cost, Certification

Membrane

- Aromatic membranes: Synthesize membranes with:
  - Low Electroosmotic Drag & gas permeation
  - Compatible support structures
  - Improve cell voltage performance
  - Demonstrate 0.25V/cell @ 1A/cm², 5000+ psi
- Water management membrane (WaMM) :
  - Provides passive water management



Stack

- Design high pressure stack & cell components
- Engineered flow distributor plates
  - Provides heat removal of each individual cell
  - Enables variable H_2 Feed (1-100 bar)
  - Enables dead-ended feed
- Scale-up active area of stack (& membranes)
- Build/Demonstrate 875+ bar stack operation

System

- Build 0.5 kg-H_2/hr prototype system
- Lab-scale demonstration of the technology
- Increase TRL level from 3 to 5

Approach: YR1 Tasks & Milestone Progress

Task No.	Task Title	Mile-stone	Milestone Description (Go/No-Go Decision Criteria)	Progress Notes	Percent Complete
1	Test Hardware Development	M1.1	Fabricate 50cm^2 test hardware for evaluation of HC and WaMM membranes	▪ Designed & fabricated test hardware to accommodate distributor plate and WaMM ▪ 3 sets of hardware delivered to NREL for testing & validation of membrane samples	100%

2	Hydrocarbon Membrane Fabrication,
	
	WaMM Fabrication
		M1.2	Synthesis Aromatic membranes with IECs in the range of 1.8–2.6 mmol/g, protonic conductivity >0.1 S/cm, and electro-osmotic requirement <50-80% than conventional PFSA PEMs
			
			Synthesize WaMM with water flux of ≥0.039 g/min-cm^2 and conductivity ≥ 1.0 S/cm membrane
				▪ Partially fluorinated Aromatic membranes synthesized (on-going):
				  ▪ Conductivity: 0.106 S/cm ✓
				  ▪ EOD: 50% of PFSA ✓
				  ▪ IEC: 1.4 / 2.0 mmol/g demonstrated ✓
				  ▪ Optimize/reduce back diffusion (on-going)
				▪ WaMM synthesized:
				  ▪ Water flux: ≥0.1 g/min-cm^2 ✓
				  ▪ Through-plane conductivity: > 1.0 S/cm ✓
					100%
					
					But continue investigation at 900 bar

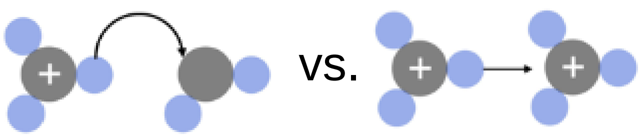
	Evaluate Cell Performance	M1.3	Voltage performance 250 mV @ ≥ 1,000 mA/cm^2 (combined Task 1, 2, & 3)	EHC cell voltage performance @ 1,000 mA/cm^2 (300 psig): ▪ 170 mV/cell (PFSA) ▪ 105 mV/cell (Aromatic),	100%
3	Preliminary Stack Design	M1.4	Complete preliminary design of scaled-up stack (300 cm^2) for 875 bar operation	Complete (May require fine tuning based on results from 50 cm^2 testing at 875 bar)	100%
4	Desktop Review of EHC System	M1.5	Complete Desktop Review of EHC system	Intertek 1st review round complete. Report submitted	100%
Go/No-Go Decision Y1			**Demonstrate EHC voltage performance of ≤ 250 mV/cell @ ≥ 1000 mA/cm^2 in a 50 cm^2 stack platform utilizing advanced 'Aromatic' membranes**	**Successfully operated EHC at 350 Bar ≤ 0.250V @ ≥ 1,000 mA/cm^2** Demonstrated Aromatic membrane operation at 0.217V @ 1000 mA/cm^2, 350 bar	✓

Approach: YR2 Tasks & Milestone Progress

Task No.	Task Title	Mile-stone	Milestone Description (Go/No-Go Decision Criteria)	Progress Notes	Percent Complete
5	Cell Components Scale-up Stack / Cell Components	M2.1	Scale-up HC membrane in Task 1 to 300 cm^2	Developed new membrane architecture and sealing technique • 20,000 psi (1,400 bar) seal demonstrated • Sealing under high clamping loads (not effected by thermal or pressure cycling) • Demonstrated scale-up to 300 cm^2 • Complete, but additional optimization on HC membranes required • Bubble-tight seal for 875 bar stack developed & demonstrated	50%
		M2.2	Fabricate scaled-up stack hardware including internal components (flow distributor plates). Stack will be designed to accommodate 300 cm2 hydrocarbon membranes and WaMM.	Demonstrated method to scale-up unitized cell architecture • Issues with stack component delivery times	10%
	Preliminary Stack Design	M2.3	Assemble EHC Stack and verify EHC stack operation at a pressure of 875 bar	Fabricated components for a 50 cm^2 high pressure (875 bar) stack that will be used to fine tune the design of the 300 cm^2 • Modification in distributor plate required. New parts received. On test. 1st run at 875 bar✓	20%
6	Prototype System Design	M2.4	Complete preliminary design of lab-scale prototype unit. This includes delivery of P&ID and PFD diagrams	Initiated. P&ID, PFD, Layout, Component Selection, and HazOp Study under review by Intertek	65%
Go/No-Go Decision Y1			**Scale-up stack, membranes, and distributor plates to an active area of 300 cm. Demonstrate EHC operation at 875 bar and EHC cell voltage performance of ≤ 250 mV/cell @ ≥ 1000 mA/cm^2**	---	---

Progress- Aromatic Membrane/MEA Development

- **Hydrocarbon Membranes (BPSH)**
  - Inexpensive starting materials
  - Reduces gas permeation by 1 order of magnitude
  - Reduction in electro-osmotic drag transport

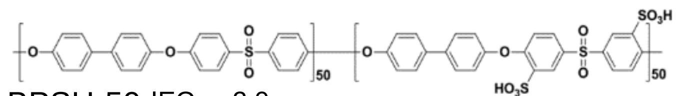


Hopping

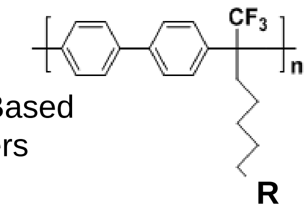
Vehicular

- **Biphenyl Series Membranes (BP-ArF4, BP-ArSA, BP-SA)**
  - Similar benefits as BPSH, but include:
    - Higher protonic conductivity at lower IEC with lower swelling in water
    - Improved mechanical stability
      - Membrane support structures added for increased mechanical stability

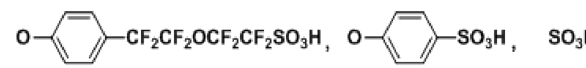
Polymer Synthesis



BPSH-50 IEC = 2.0



Biphenyl-Based Polymers



BP-ArF4 IEC = 1.4

BP-ArSA IEC = 2.0

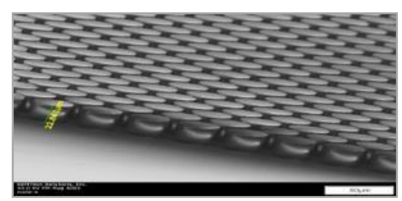
BP-SA IEC = 2.6

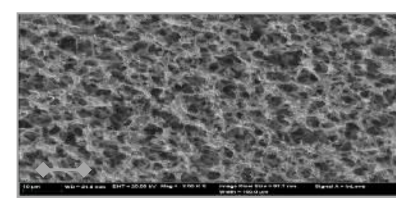
MEA Fabrication

MEA Fabrication & Catalyst Deposition at NREL

External Support

Supports





Addition of Internal Membrane Supports

Progress-Latest MEA Developments

Development of High-Pressure Seals

- Membrane supports required for superior creep resistance; when operating pressure >2000 psi
- Difficult to maintain seal above 7000 psi with ‘Traditional’ membrane supports
  - High operating pressures require large clamping loads and a ‘Solid’ membrane surface to seal against
- Developed & demonstrated NEW membrane sealing technology for 875-bar EHC operation
  - Thermoplastic extension of membrane
  - Demonstrated sealing to 20,000 psi (1,400 bar)
  - NREL support in characterization and optimization of new support

Demonstrated Sealing Pressures

2,000 psi
(140 bar)

Non-Supported Membrane

7,000 psi
(480 bar)

Traditional Dimensionally Supported Membrane (DSM)

20,000 psi
(1,400 bar)

‘Solid’ Supported Membrane (SSM)

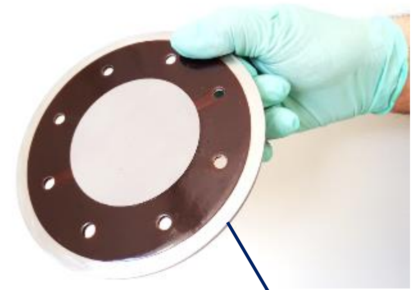
Progress-Latest MEA developments

Scale-up of EHC Membrane

50 cm^2 300 cm^2

Membrane extends only ⅛” beyond active area

Unitized Cell Structures



Enables dry-build and single-piece cell structures

- SSM bonds directly to polymer membranes (while in the acid form). Demonstrated:
  - Sealing under high clamping loads
  - Resistance to pressure and thermal cycling
  - Dry assemblies (with Dry membranes)
  - Unitized Cell structures (1 piece/cell). Ease of assembly/cost reduction
- Non-contaminating
- Process applicable to PFSA & Aromatic membranes
- **Demonstrated scale-up of MEA and SSM to 300 cm^2**

Progress - EHC MEA Performance & Optimization

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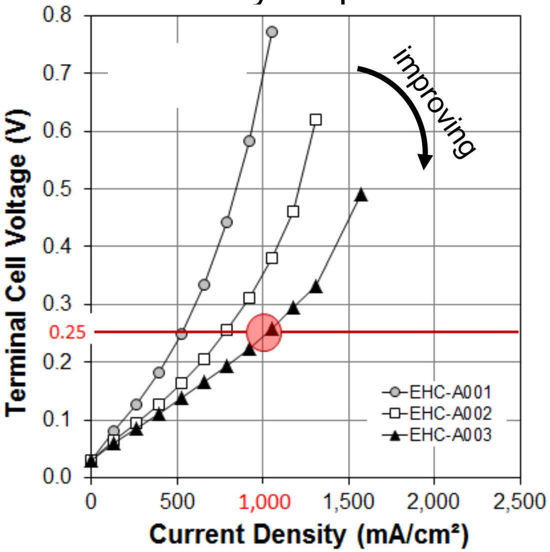
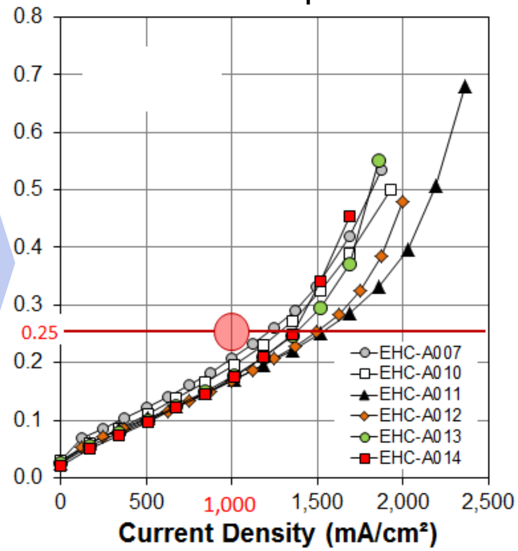
Catalyst Optimization



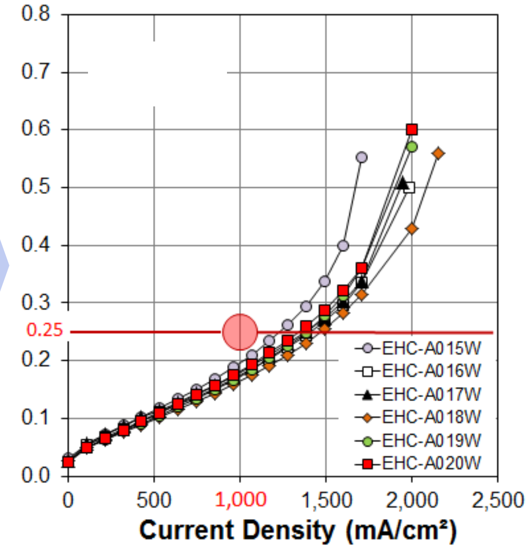
Best Catalyst

Distributor Optimization



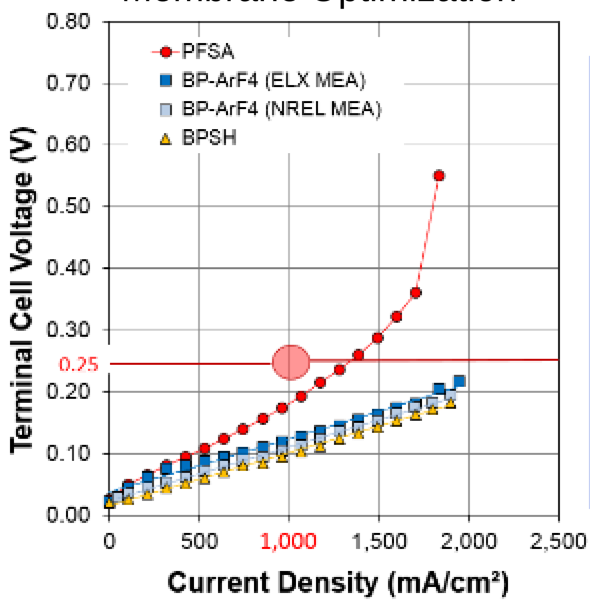
Best Distributor

WaMM Optimization



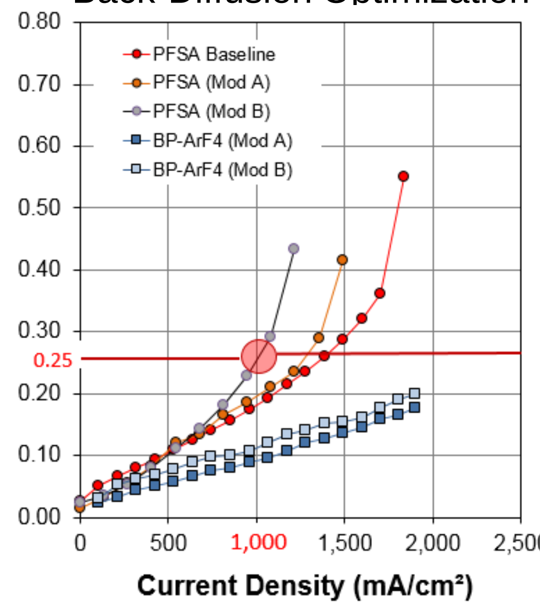
Best WaMM

Membrane Optimization



Best Membranes

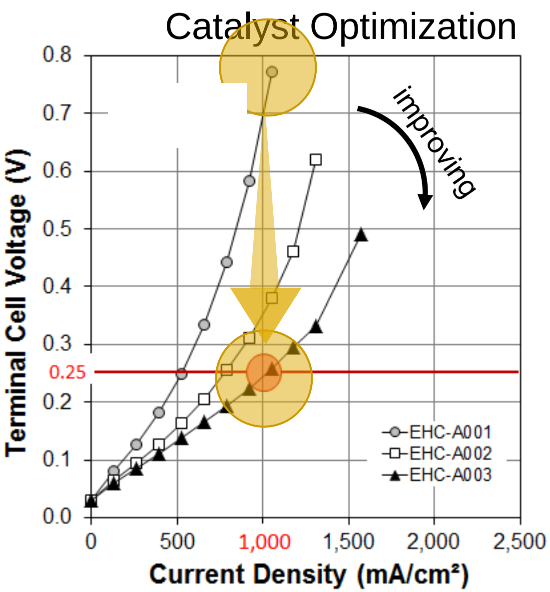
Back-Diffusion Optimization



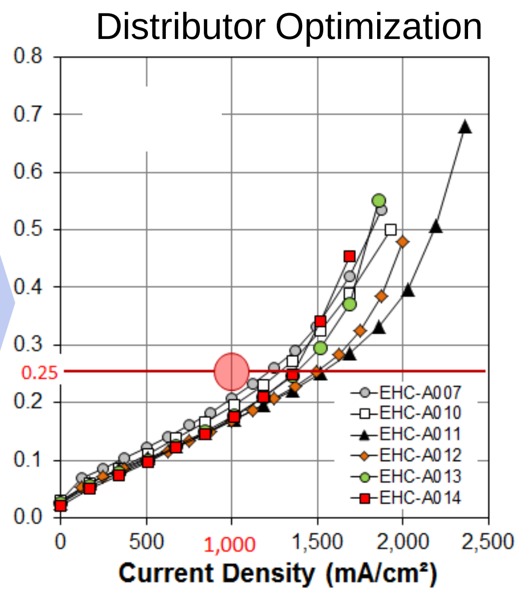
Operating Conditions:
Outlet H_2 Pressure:
280 psi (~20 bar)

Inlet H_2 Pressure:
30 psig (~2 bar),
dry/dead-ended flow

Progress - EHC MEA Performance & Optimization



Best Catalyst



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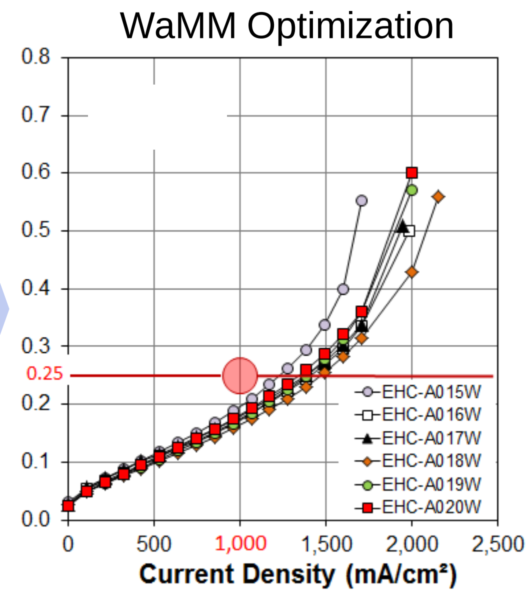
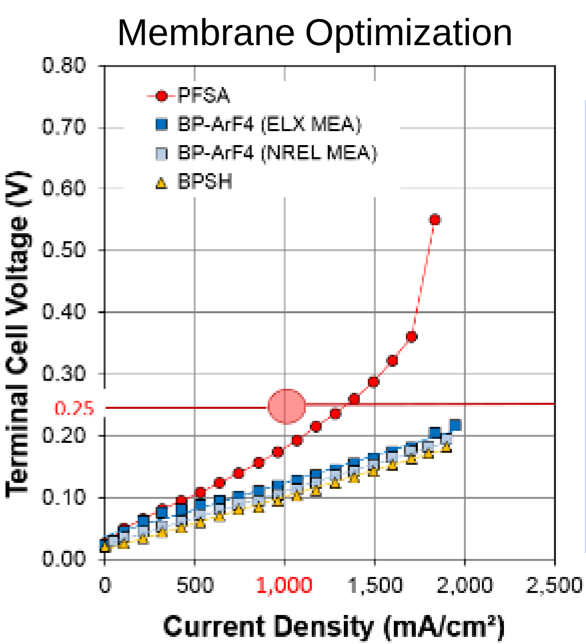
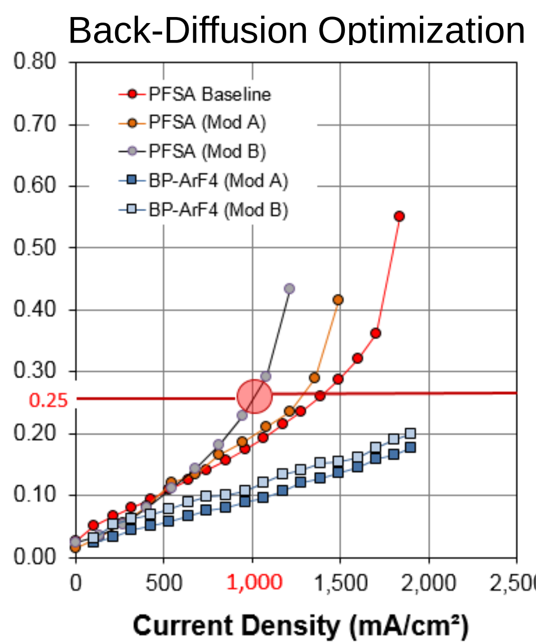


Best WaMM



Best Membranes

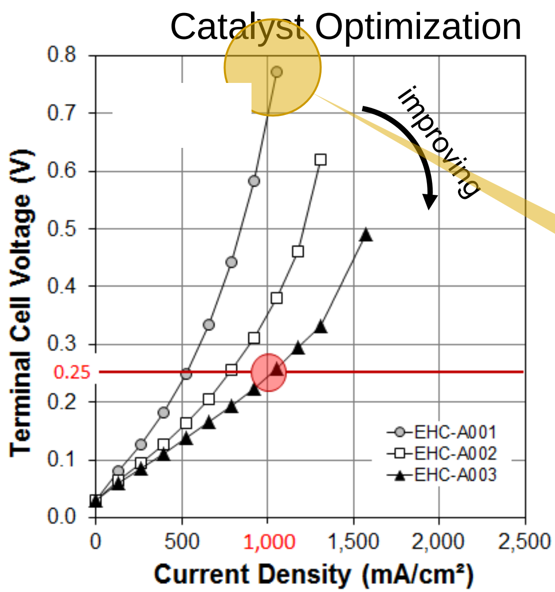


3X

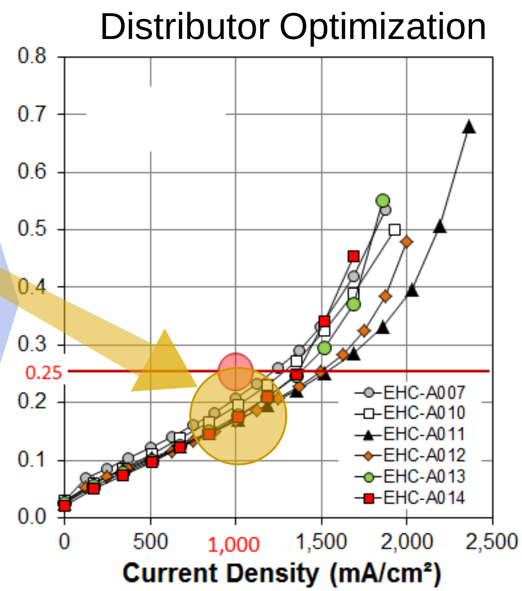
Voltage Improvement!

Catalyst optimization provided highest voltage improvements

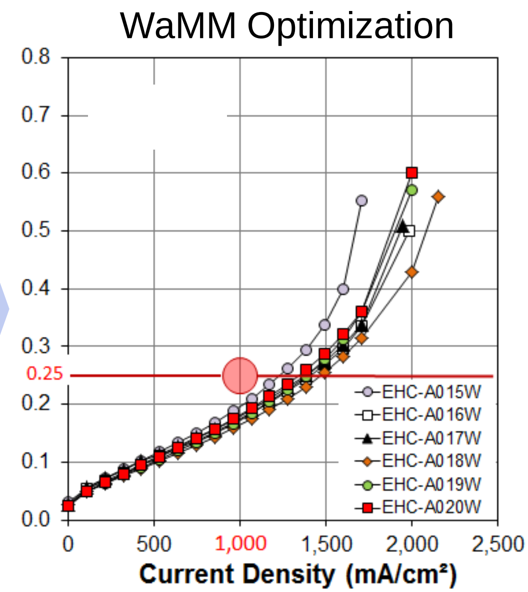
Progress - EHC MEA Performance & Optimization



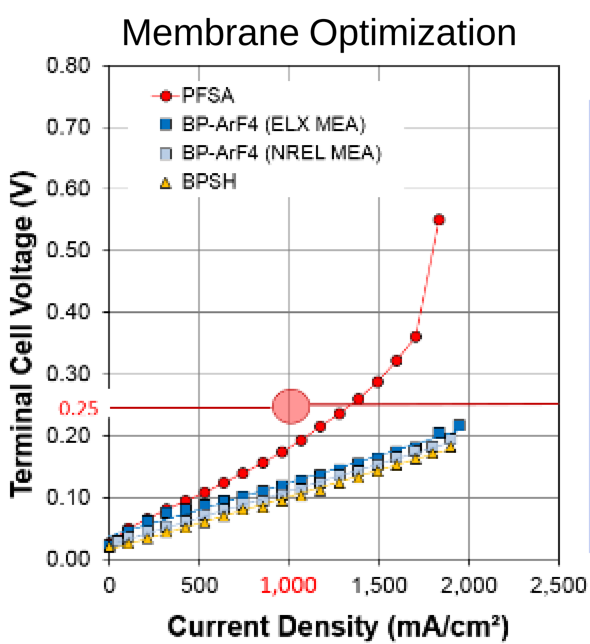
Best Catalyst



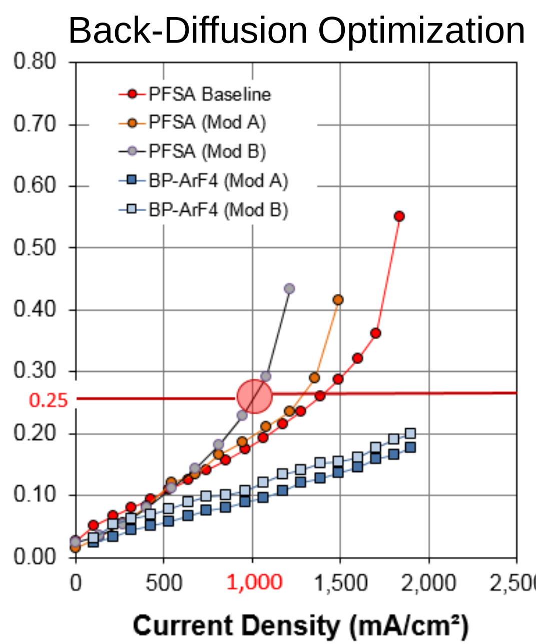
Best Distributor



Best WaMM



Best Membranes

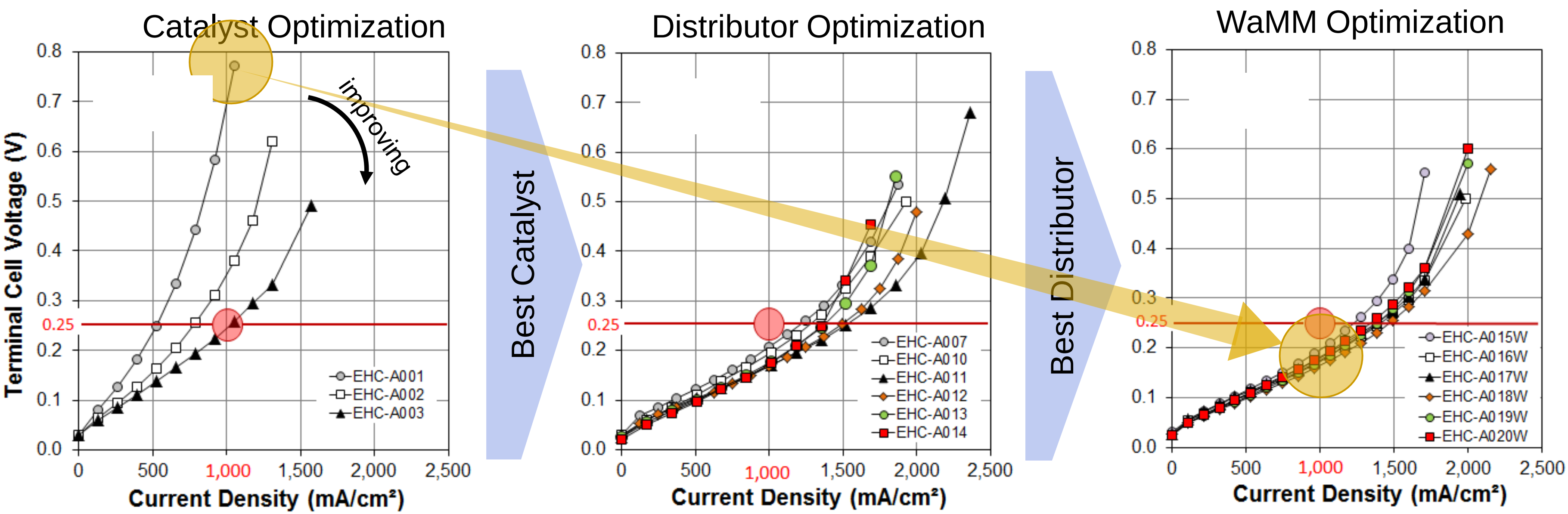


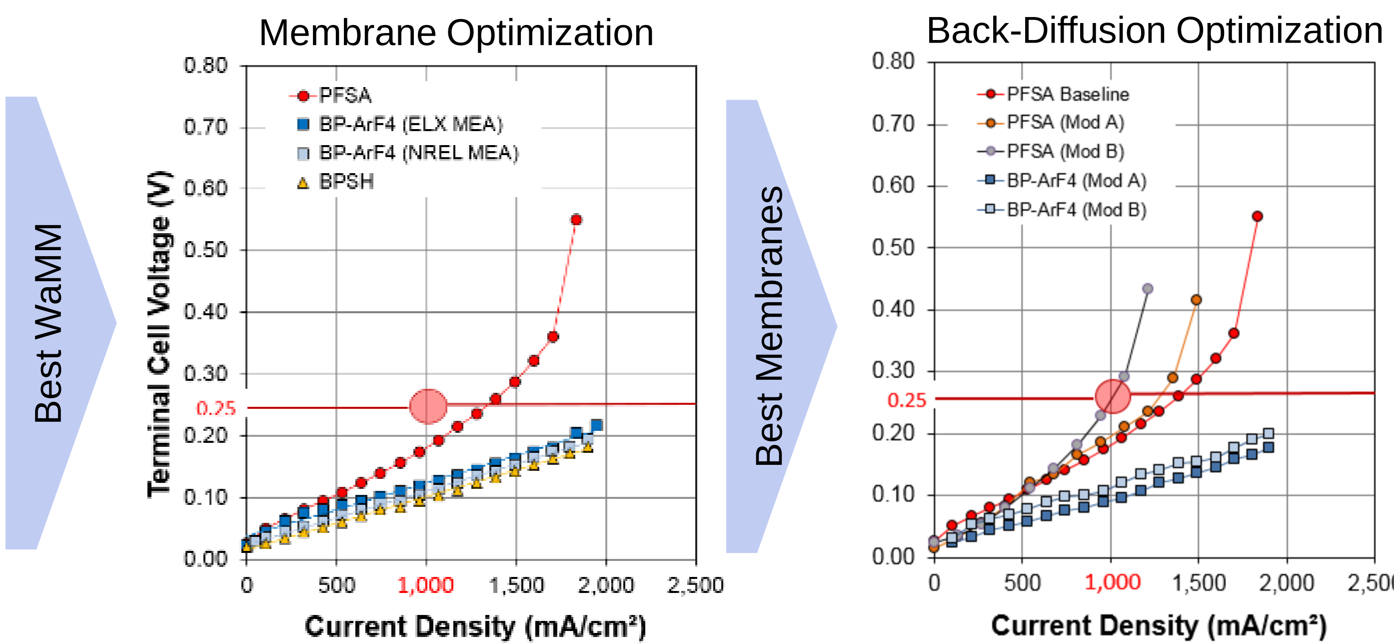
4.5X

Voltage Improvement!

Improved Gas Distribution

Progress - EHC MEA Performance & Optimization



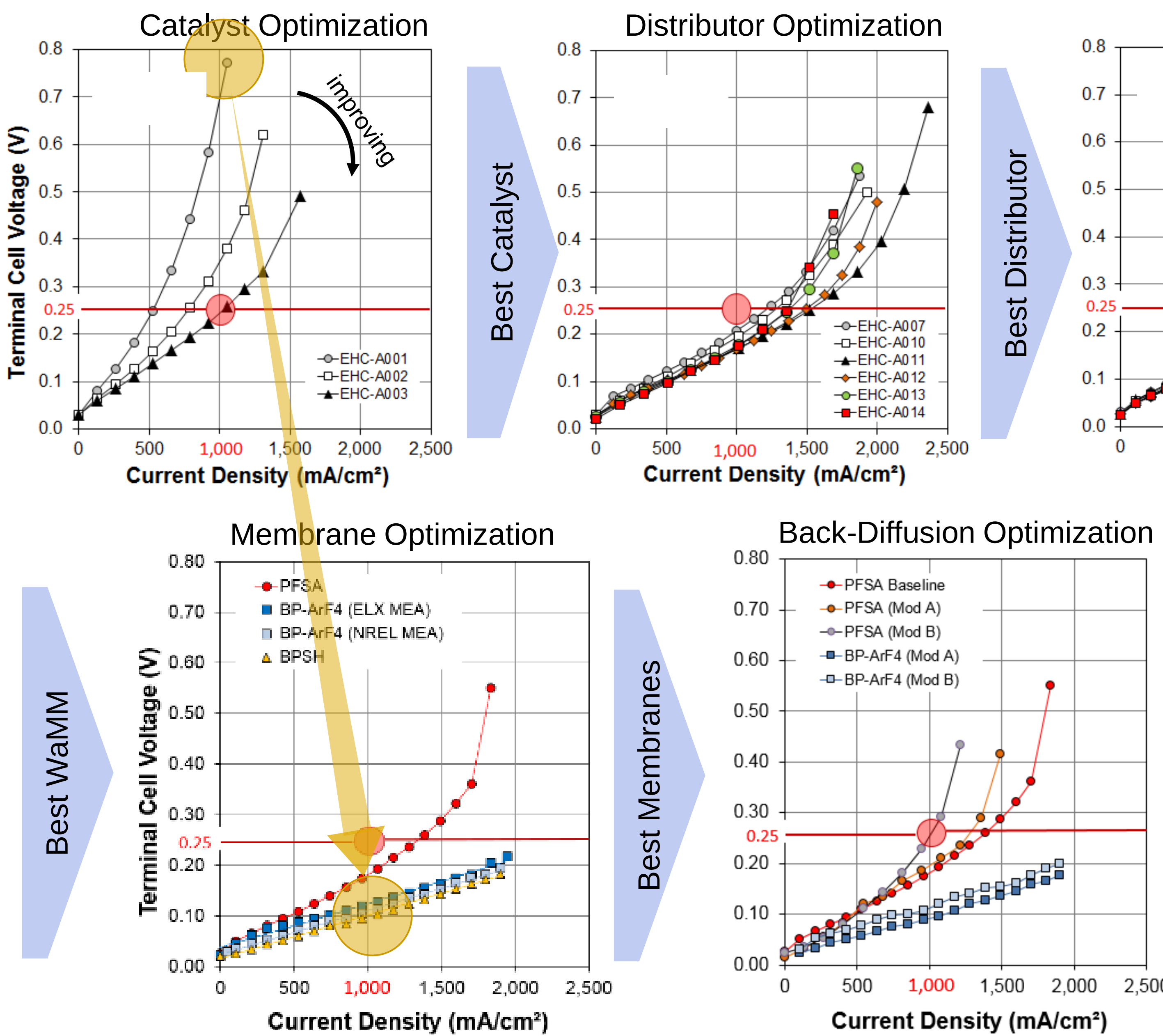


4.6X

Voltage Improvement!

Slight voltage improvement, Maintains membrane hydration, stabilizes cell voltage

Progress - EHC MEA Performance & Optimization



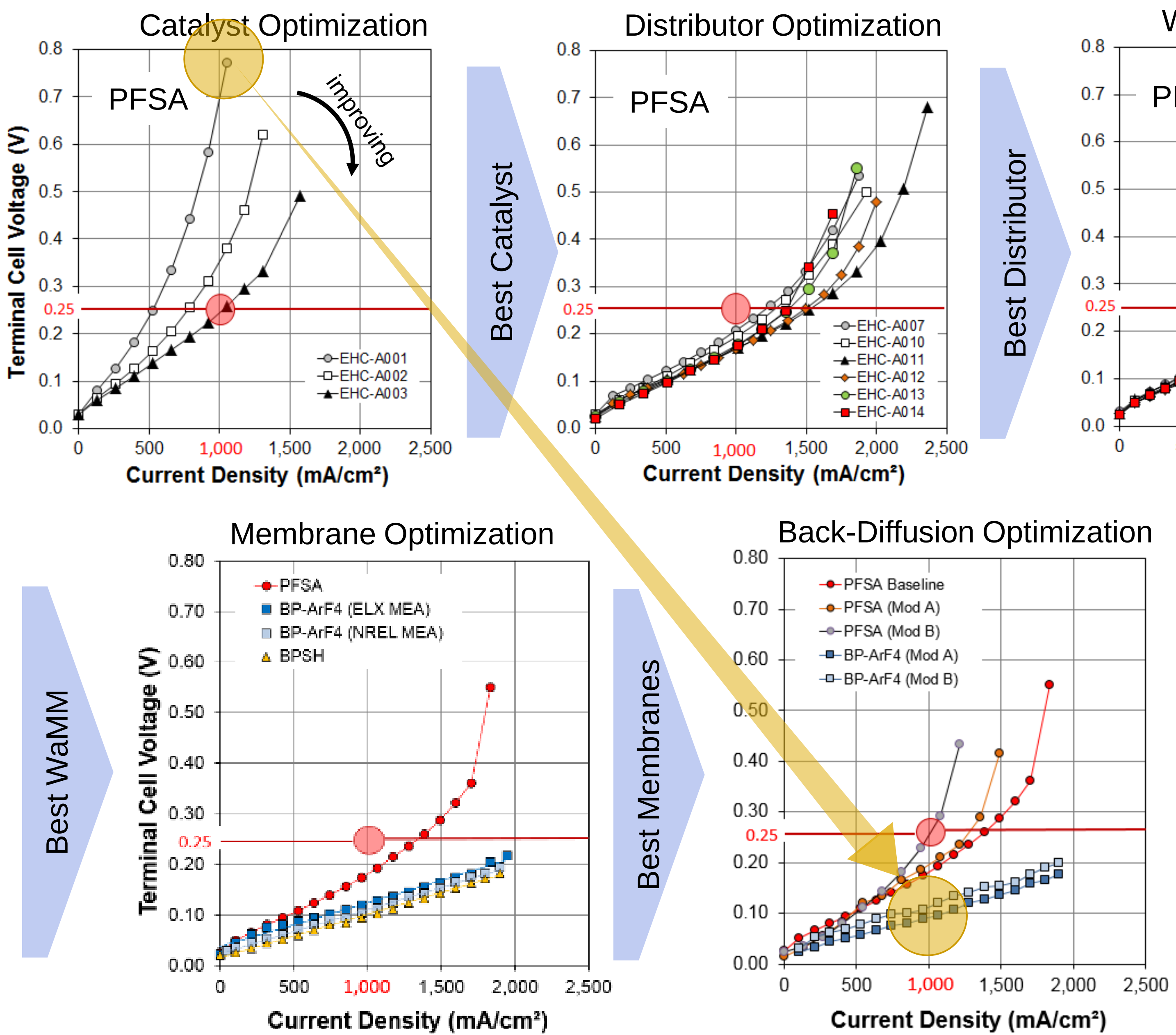
7.7X

Voltage Improvement!

Use of Aromatic membranes with high water content

Largest Improvements related to Catalyst & Membrane Optimization

Progress - EHC MEA Performance & Optimization



7.6X

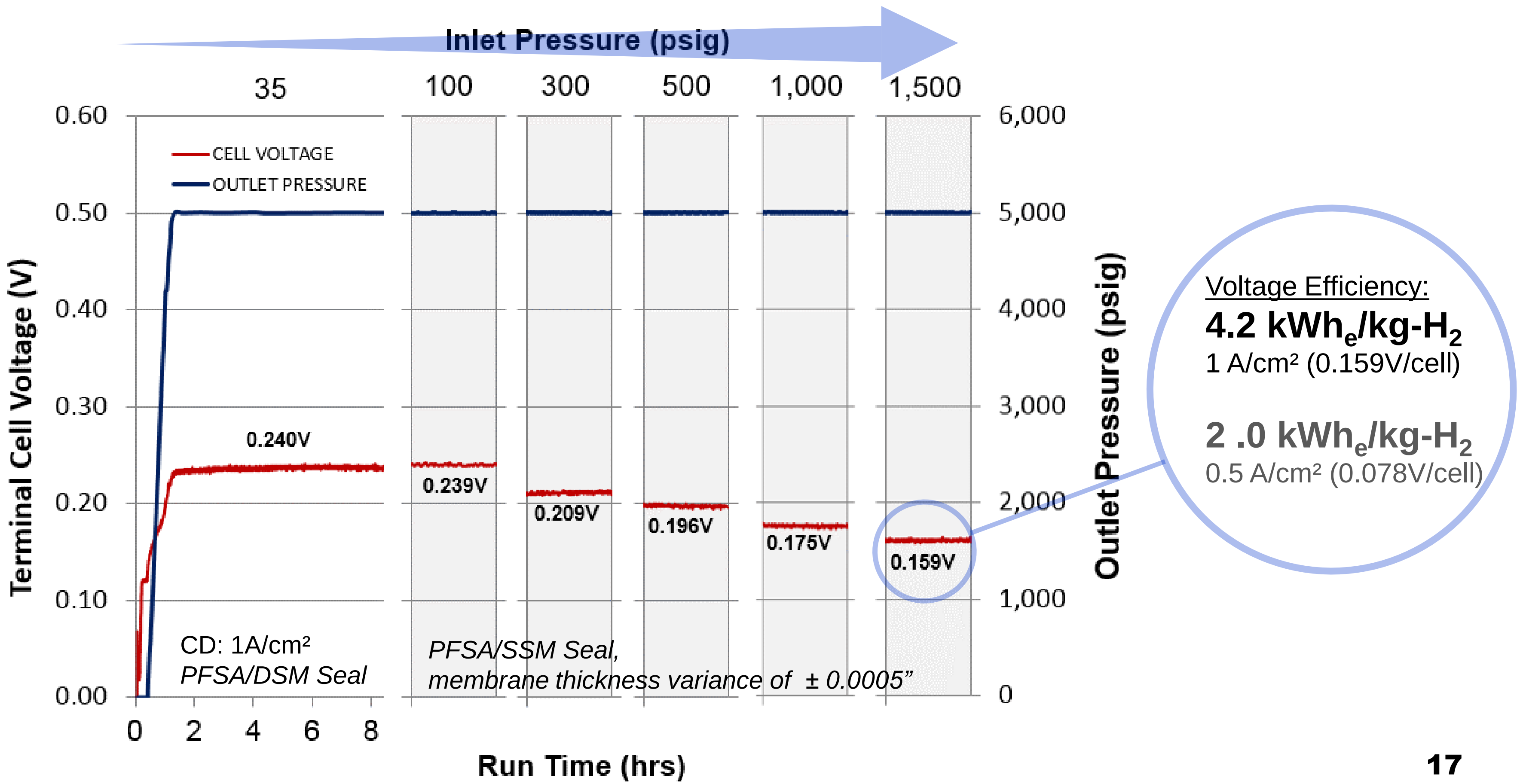
Voltage Improvement!

No further voltage improvement, but diffusion reduced.
PFSA (Mod): 50%
BP-ArF4 (Mod): 32%

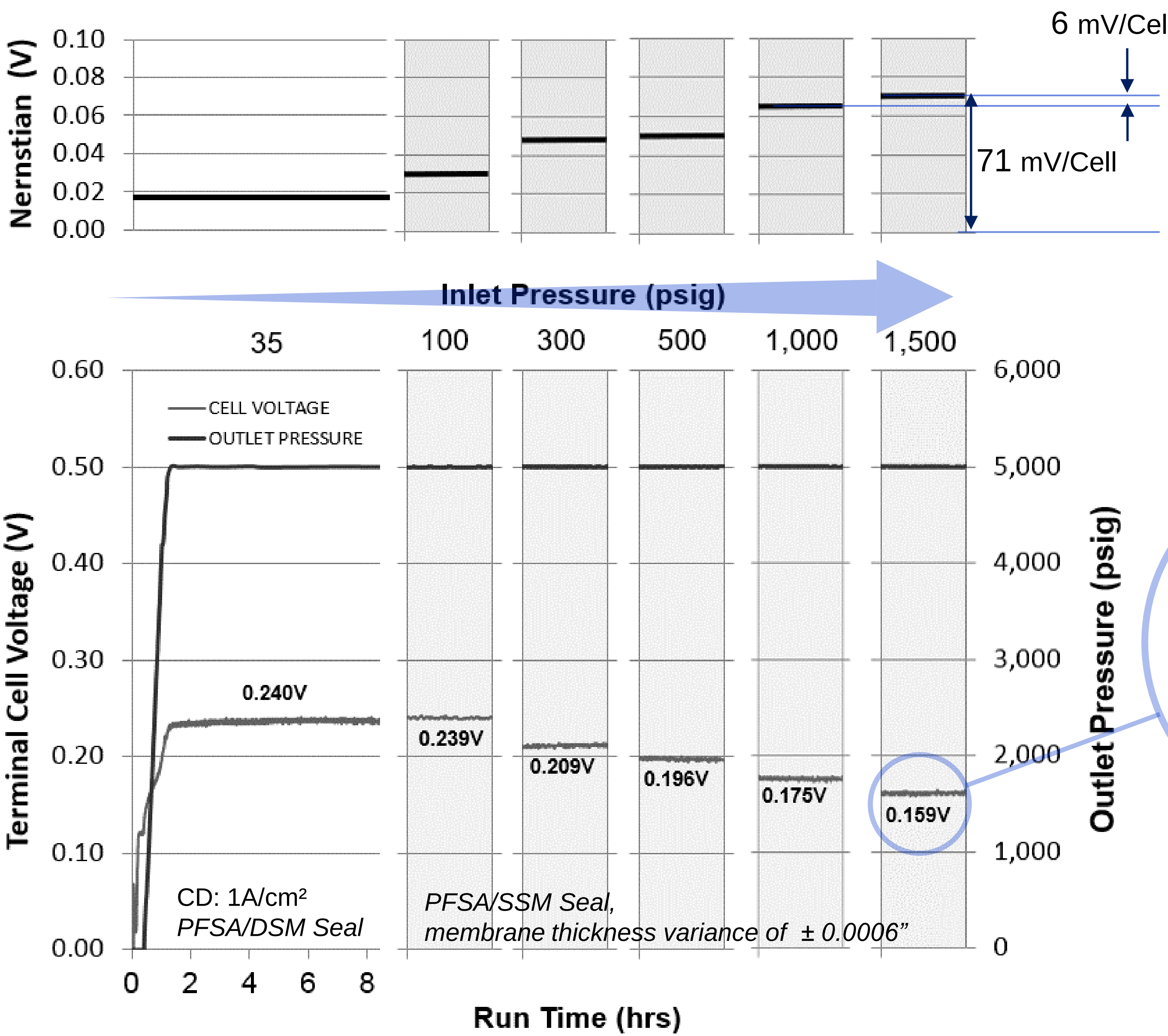
MEA Performance (5,000 psig) as a function of Inlet pressure

Demonstrated Capabilities of EHC

- Dead-ended H_2 Inlet feed
  - Simplifies system: no H_2 flow thru, No external humidification, and No H_2 recovery required
- Dry H_2 Inlet feed (humidified H_2 ok, will not improve performance)
- Variable inlet feed pressure up to 1,500 psi (100 bar), & Stable Cell Voltage at each inlet pressure
- High Voltage Efficiency to 2 kWh/kg-H_2!



MEA Performance (5,000 psig) as a function of Inlet pressure



$$E_{Nernst} = \frac{RT}{2F} \ln \frac{P_C}{P_A}$$

71 mV/cell Improvement

at 1,500 psi (100 bar) inlet

Reduced voltage gain with increasing inlet pressure

Voltage Efficiency:

4.2 kWh$_e$/kg-H$_2$

1 A/cm² (0.159V/cell)

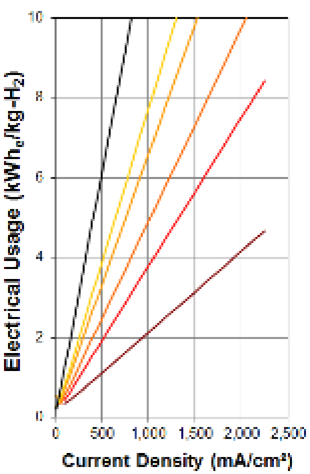
2 .0 kWh$_e$/kg-H$_2$

0.5 A/cm² (0.078V/cell)

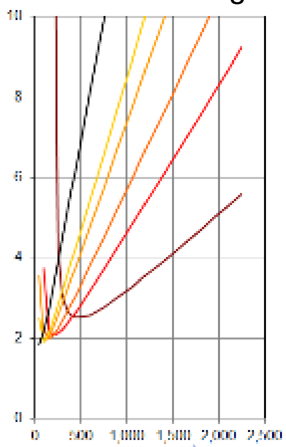
Progress – Modeling EHC Performance

- Combined effect of iR-losses, Nernstian Penalty, Catalytic Activity, Ionic conductivity, and Back diffusion
- Increased power consumption at high operating pressure (back diffusion)
- Max efficiency at ~500 mA/cm²

Outlet Pressure:
1,450 psi (100 bar)

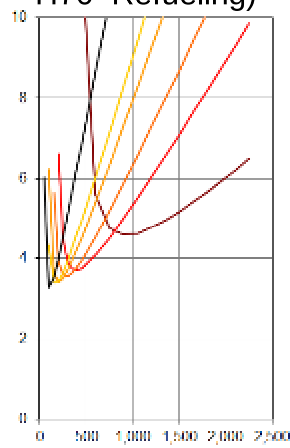


6,250 psi (430 bar)
H35 Refueling



+1.0
kWh/kg

12,688 psi (875 bar)
H70 Refueling)



+1.0
kWh/kg

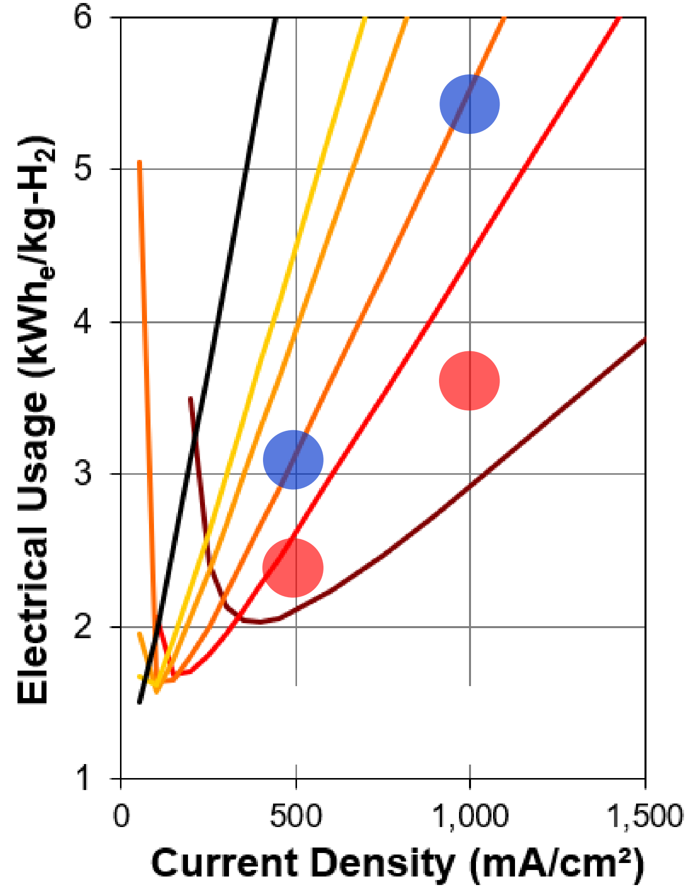
PFSA Membrane Thickness (mils)

2, 5, 7, 10, 12, 20

50°C. 100 bar Feed. Assumes optimal water management

Where are we?

5,000 psi (350 bar)



Efficiency (kWh$_e$/kg-H$_2$), 350 bar

	0.5 A/cm²	1 A/cm2
PFSA	3.1	5.3
BP-ArF4	2.7	3.7

Progress – Modeling EHC Performance

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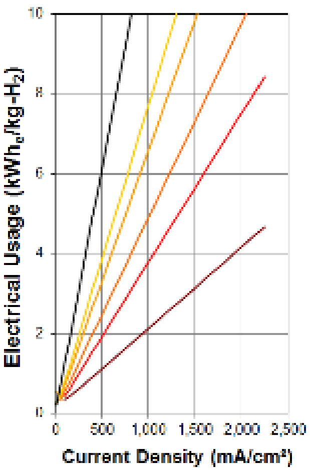

6,250 psi (430 bar)
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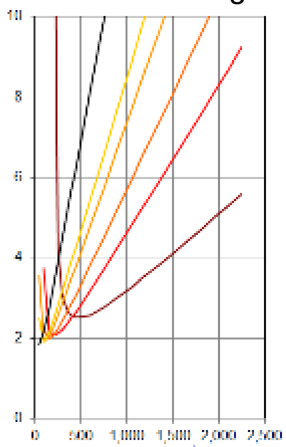
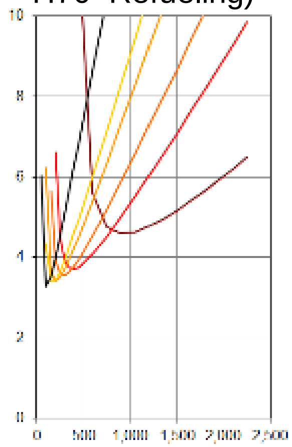


+1.0
kWh/kg

12,688 psi (875 bar)
H70 Refueling)



+1.0
kWh/kg

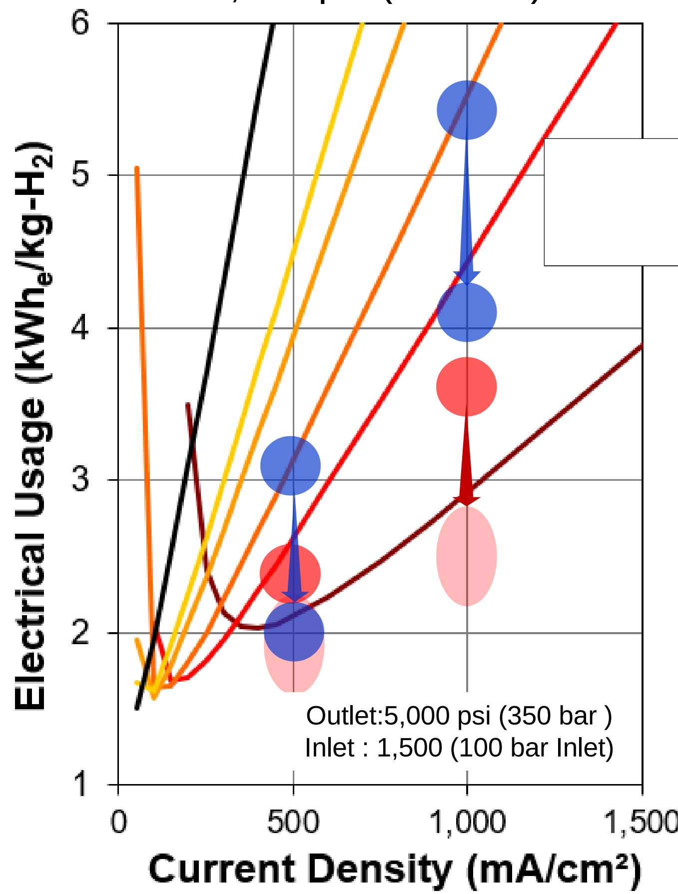
PFSA Membrane Thickness (mils)

2, 5, 7, 10, 12, 20

50°C. 100 bar Feed. Assumes optimal water management

Where are we?

5,000 psi (350 bar)



Efficiency ($kWh_e/kg\text{-}H_2$), 350 bar

	0.5 A/cm²	1 A/cm2
PFSA	2.0	4.2
BP-ArF4	2.7→ 1.7est.	3.7 → 2.7est.

Progress - EHC Stack Design & Fabrication

12,688 psi
(875 bar)

12,688 psi
(875 bar)

12,688 psi stack (SSM membranes required)

5,000 psi
(350 bar)

5,000 psi stack with Distributor and WaMM. (DSM membranes req'd)

1,000-5000 psi
(70-350 bar)

Evaluation of high pressure components, Flow distributors & internal cell components, membrane strength/rupture testing

300 psi
(20 bar)

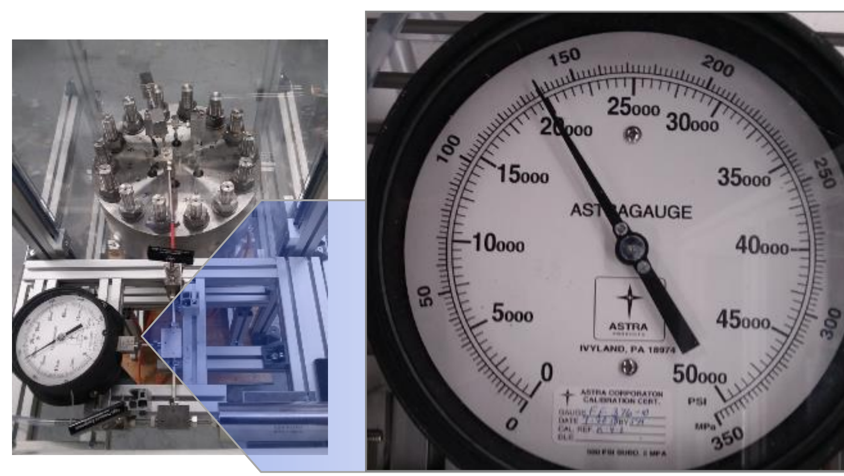
Catalyst, Membrane & Cell-Component, Testing & Validation

875 bar Stack Novel Design Features

- Proof pressure design: 20,000 psi (1,400 bar)
  - Scale-up active area to 300 cm²
  - Utilizing low cost materials: SS
  - Design incorporates use of integrated distributor plate and WaMM, reduced part count
  - Enhanced bipolar plate design for 20 ksi capability

Proof-Pressure Testing

- Hydraulic pressure assembly rated to 50,000 psi
- Test enclosure assembled - Measures deflection of endplate
- Stack successfully pressure tested to **20,000 psi** (1,400 bar) with new 'SSM' MEA



Progress- 875 bar EHC Operation

875 bar Operation!

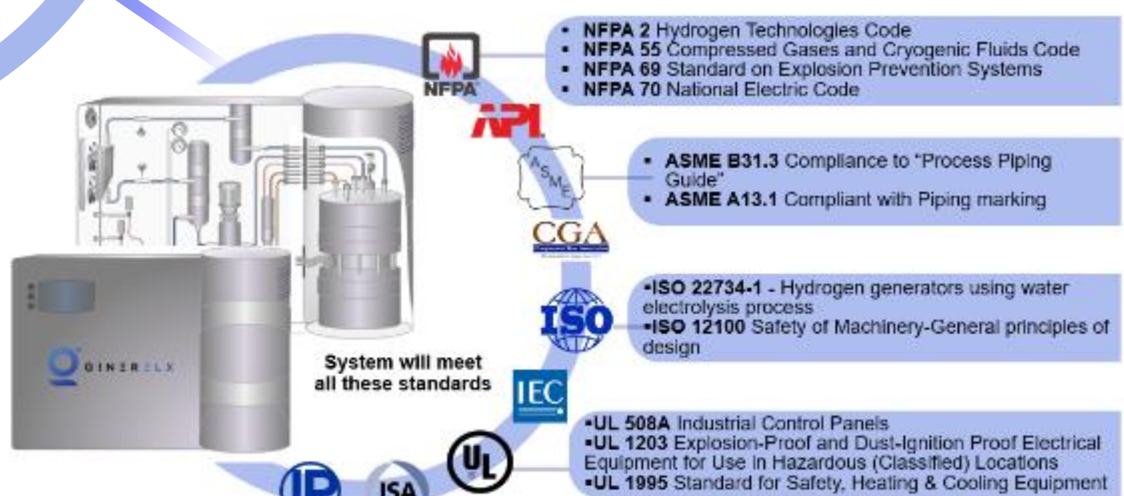
- Stack designed with SS internal components
- Operates at inlet pressures ranging from 1 to 100 bar
  - Single stage compression to 875 bar
  - Can be operated above 875 bar based on proof pressure ratings
- Optimization of 875 bar hardware followed by scale-up

Progress- System Design

- Initiated procurement of system components/System assembly
- Design Specs:
  - H_2 Flux Rate: 0.5 kg/hr
  - H_2 Inlet Pressure: 1-100 bar
  - H_2 Outlet pressure: 875 bar
  - Dimensions: 4’x4’x1’
- System reviewed by Intertek. Over 20 standards* apply. Influences how system is designed

Program objective:
Increase TRL from 3 to 5

Goal: Certification & commercialization of the technology



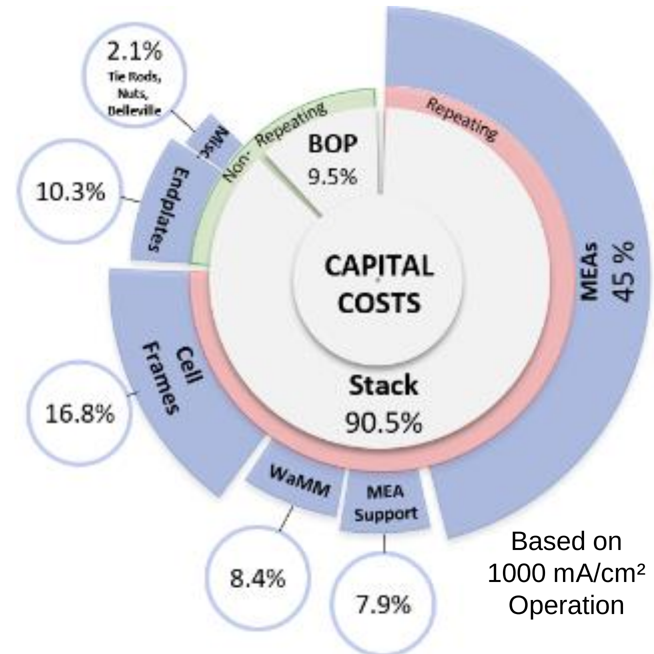
*Not all standards for EHC are shown

Projected Compression Cost

H_2 Compression Cost Contribution	Current Status ($/kg)
Capital Costs[1]	0.175 ⇩[4]
Feedstock Costs[2]	0.239 (1000 mA/cm²) ⇩[4] 0.114 (500 mA/cm²)
Fixed O&M	0.004
Variable Costs	0.001
Total Cost ($/kg)[3]	**0.419**

[1]10 year lifetime, [2]Based on electrical cost of $0.057/kWh kWh_e/kg, [3]Design Capacity: 100 kg-H_2/hr, 1,000mA/cm² EHC Operation. Assumes large scale production. [4]Compared to previous year: CapEX & OpEx previously 0.196 & 0.305 $/kg, respectively.

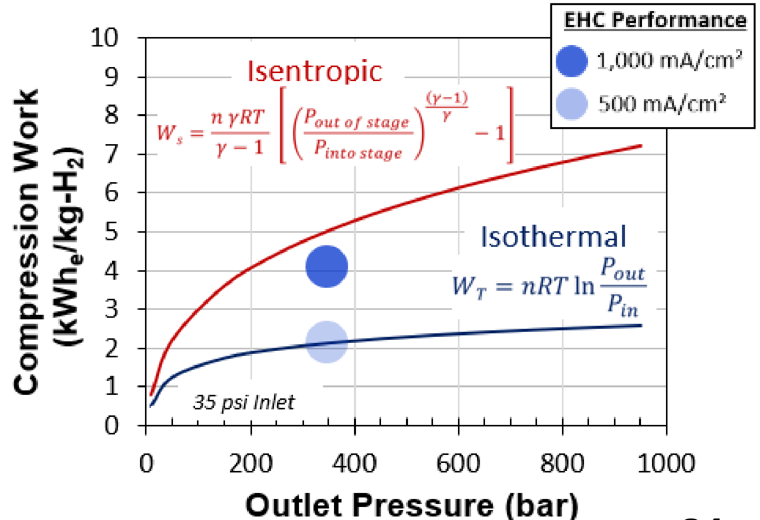
CapEx



Based on 1000 mA/cm² Operation

- Economics: determined using PEM-based system cost models
  - Feed Stock, based on Efficiency Range @ 350 bar:
    - 2.0 to 4.2 kWh_e/kg-H_2
    - Projected Operating Lifetime: designed to operate for a term of 10 years or more (> 20 years expected)
    - Use of SS components vs. Ti
- 10 year lifetime: Membranes are not expected to degrade due to lack of O_2 in system

OpEx



Collaborations/Acknowledgements

Giner ELX, Inc. -Monjid Hamdan -Prime	Industry	Stack and system engineering, development, and operation. Fabrication and optimization of catalyst and membrane electrode assemblies. WaMM development and optimization. Testing & validation
National Renewable Energy Laboratory (NREL) -Bryan Pivovar -Subcontractor	National Lab	Membrane and cell component validation. Coordinate stack testing and optimization studies of membranes, cell components & materials. Testing of high-pressure EHC stack and system
Rensselaer Polytechnic Institute (RPI) -Chulsung Bae -Subcontractor	Academia	Development of mechanically-stable Aromatic PEMs which serve as a key material in this project.
Gaia Energy Research Institute LLC (Gaia) -Whitney Colella -Subcontractor	Small Business	EHC stack cost analysis and system-level analysis. Developing EHC cost estimates, techno-economic analysis (TEA), and life cycle assessment (LCA)
Intertek/TUV -Subcontractor	Nationally Recognized Testing Laboratory	Certification for System & Stack
Giner, Inc. -Subcontractor	R&D	System assembly, sub-component fabrication, PLC controls. Includes documentation for certification process

Department of Energy, DOE Fuel Cell Technologies Office (FCTO),
Ms. Neha Rustagi, Dr. Dave Peterson, Dr. Eric Miller
Dr. Sunita Satyapal

Summary

- **Demonstrated EHC operation to a pressure of 875 bar**
  - Demonstrated compression ratio of 875:1, single stage

- **Membrane Development:**
  - Designed MEA with new sealing properties;
    - Enables bubble-tight seal to 20,000 psi (1,400 bar) & Stack operation to 12,688 psi (875 bar)
      - Resistant to thermal & pressure cycling
    - Demonstrated scalability of MEA & seal to 300 cm², unitized cells, & dry build
  - Reduced membrane back diffusion by > 50% in PFSA, 32%; Aromatic membranes
  - Optimization: Demonstrated further improvements in cell voltage:
    - 0.159V/cell (100 bar inlet); Stack efficiencies to 2.0 $kWh_e/kg\text{-}H_2$ at 5,000 psi (350 bar)
    - Highest Efficiency for EHC operating at 5,000 psi (350 bar)
      - Further improvements expected in next round of aromatic membrane tests

- **Stack Development:**
  - Successfully designed, assembled, and operated a 875 bar EHC stack (50 cm² platform)
  - Demonstrate proof pressure of 20,000 psi (1,400 bar)
    - Operates at an inlet pressure range of 1-100 bar, dead-ended feed, & dry H_2
  - Reduced Stack Cost
    - Unitization of cell components (reduced part count/cell)
      - Combined Flow-Distributor and WaMM compartment into single component
      - Use of SS cell components

- **System Development:**
    - Initiated procurement and assembly of 875 EHC system

Future Plans & Challenges (FY2019-20)

Future Plans*

- **Membrane**: Fabricate aromatic membranes using SSM seal, integrate into 875 bar stack and evaluate
- **Stack**: Optimize internal cell components to replicate performance achieved in 350 bar stack, Scale up to 300 cm^2
- **System**: Complete assembly of prototype system design
  - Initiate operation and system studies

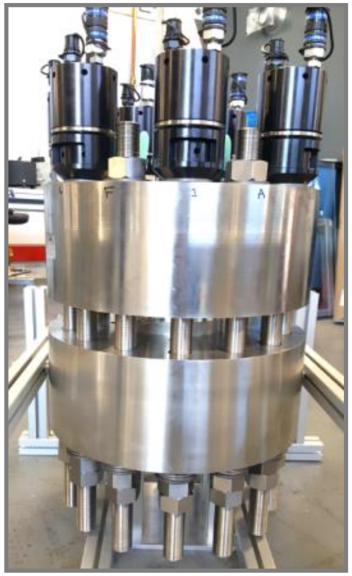
Future Challenges

- Increase stack active-area to 300 cm^2
  - Scale-up for aromatic membranes
- Further reduce stack costs
  - Endplate thickness & cost
    - Investigate techniques to reduce cell component fabrication costs
      - Possibility of stamping components
- Investigate embrittlement of cell components
- Determine effect of H_2 impurities
  - Giner ELX will conduct additional studies with impure H_2 sources
    - e.g. Removal, and compression, of hydrogen from NG source containing 5% H_2

*Any proposed future work is subject to change based on funding levels

Technical Back-Up Slides

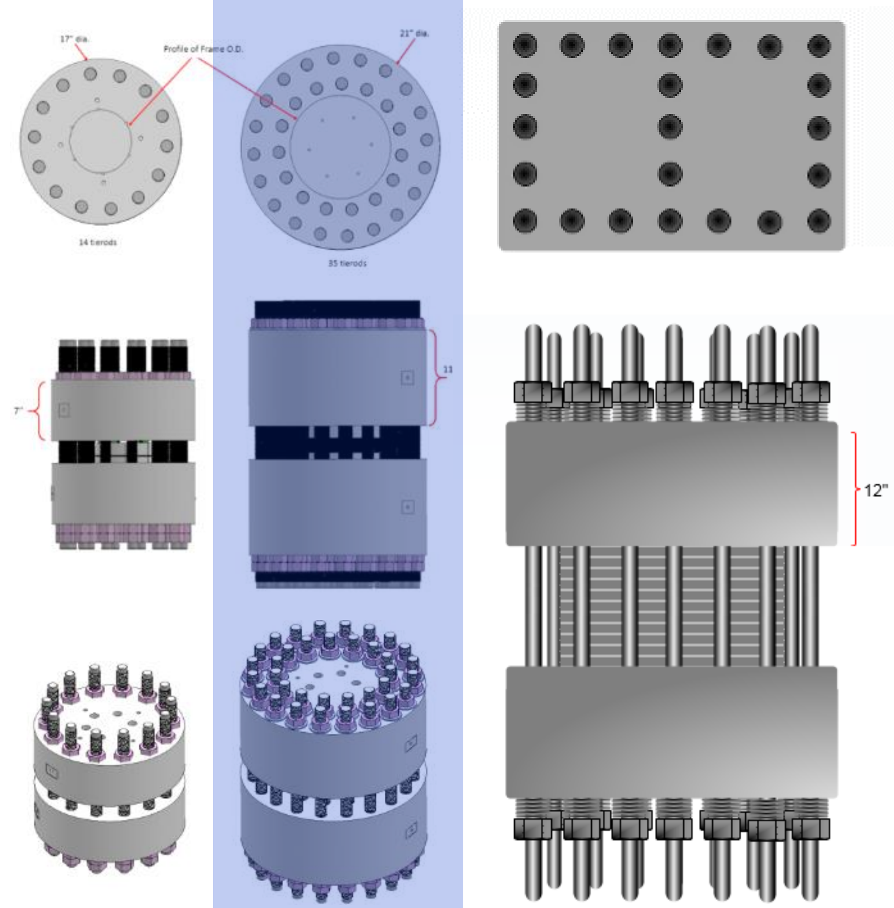
Progress – 875 bar Stack Design – Endplate Scale-up



900 bar stack endplate (50 cm²)

Large End-Plate due to Nuts/Bolts

Stack Active Area	Endplate	
	Thickness (in.)	Dia. (in.)
50 cm²	7	17
300 cm² *Program Target*	11	21
1,000 cm²	12	-



50 cm² → 300 cm² → >1000 cm²

Dual-bolt circle design

Minimize Endplate thickness with Bolt pattern