Electrochemical Compression

2017 DOE Hydrogen & Fuel Cells Program

Annual Merit Review Meeting

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Project ID: PD136

Overview

Timeline

- **Project Start:** Oct. 1, 2016
- **Project End:** Sep. 30, 2019
- **Percent Complete:** 12%

Budget

- **Total Project Budget: $3.52MM**
  - **Total Federal Share:** $2.81MM
  - **Total Recipient Share:** $0.71MM
  - **Total DOE Funds Spent*:** $0.3MM

* As of 3/31/17

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	Giner Status (2017)
Availability	%	70-90	85	--
Compressor Specific Energy	kWh/kg	1.62[2]	1.62[2]	2.72[3]
Uninstalled Cap. Cost[2]	$	275k	170k	>450k
Annual Maintenance	% of Capital Cost	8	4	--
Lifetime	Years	--	10	--
Outlet Pressure Capability	bar	950	950	350

[1] FCTO Multi-Year Research, Development, and Demonstration Plan (2011-2020). [2] 100-bar delivery/Commercial mechanical compressors are >6-8 kWh/kg (@7-bar delivery). [3] 2-bar delivery (100-bar expected to reduce to 1.16 kWh/kg)

Partners

- **National Renewable Energy Laboratory (National Lab)** – Membrane/System Validation
- **Rensselaer Polytechnic Institute (Academic)** – Membrane Development
- **Gaia Energy Research Institute (Private)** – Techno-Economic Analysis

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 2016-17 Objectives

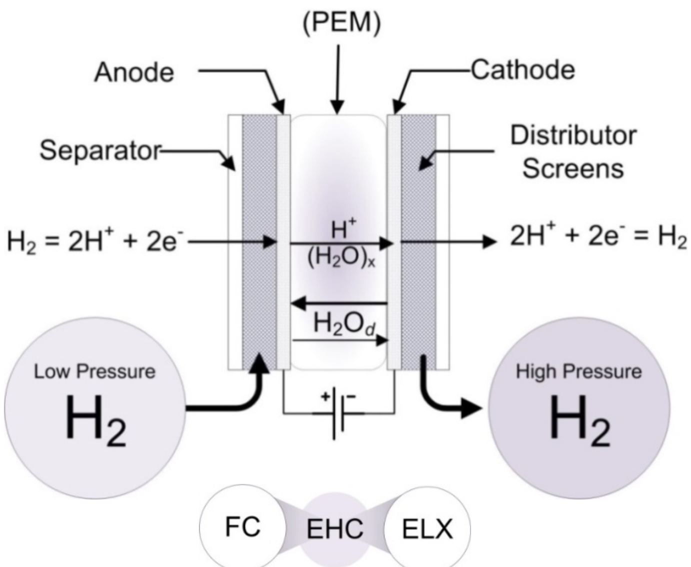
- Fabricate hydrocarbon (HC) membranes with enhanced properties for use in EHCs
- Improve EHC water and thermal management
  - Development of Water Management Membranes (WaMM) for use in EHCs
  - Engineer flow distributors for high pressure operation
- Optimize stack hardware and demonstrate cell performance ≤ 0.250 V/cell at current densities ≥1,000 mA/cm²

Impact

- Low cost, reliable, high pressure hydrogen to help enable 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

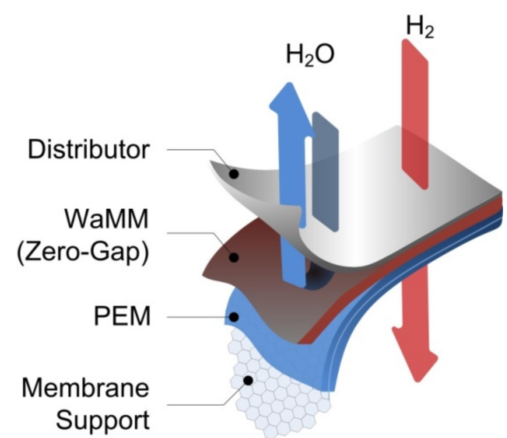


EHC: Benefits & Uses

- Solid State, No moving parts
  - Improves downtime
- No membrane degradation (no O_2)
  - Enables use of low-cost HC membranes
- Cross-cutting technology
  - Fuel Cells, Electrolyzers
- Alternative applications:
  - Hydrogen Purification
  - Hydrogen Circulation (Pump)
  - Power Generation (Reversible)
  - H_2 Purity (Sensor Applications)

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

- Hydrocarbon (HC) membranes: Synthesize membranes with:
  - Low EOD (& gas permeation)
  - Optimize ionomer composition to achieve cell voltage of 0.25 V/cell (1,000 mA/cm²)
- Water management membrane (WaMM) :
  - Provides passive water management

Stack

- Design of flow distributor cell plate
  - Provides heat removal of each individual cell
  - Enables variable H_2 Feed (1-100 bar)
- Scale-up active area of stack (& membranes)
- Build/Demonstrate 875 bar stack operation (Yr. 2)

System

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

Approach: 2016-17 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%

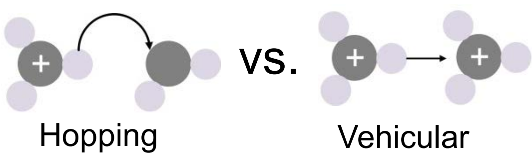
2	Hydrocarbon Membrane Fabrication,
	
	WaMM Fabrication
		M1.2	Synthesis HC membranes with IECs in the range of 1.8–2.6 mmol/g, protonic conductivity >0.1 S/cm, and electro-osmotic requirement <50-80% than conventional PFSA PEMs
			
			Synthesize WaMM with water flux of ≥0.039 g/min-cm^2 and conductivity ≥ 1.0 S/cm membrane
				▪ Partially fluorinated HC membranes synthesized (on-going):
				  ▪ Conductivity: 0.106 S/cm
				  ▪ EOD: 50% of PFSA
				  ▪ IEC: 1.4 / 2.0 mmol/g
				
				▪ WaMM synthesized:
				  ▪ Water flux: ≥0.1 g/min-cm^2
				  ▪ Through-plane conductivity: > 1.0 S/cm
					60%

	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) ▪ 120 mV/cell (HC)	30%
3	Preliminary Stack Design	M1.4	Complete preliminary design of scaled-up stack (300 cm^2) for 875 bar operation	Initiated	5%

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 an advanced membrane**	**On track to successfully operate EHC at 350 Bar ≤ 0.250V @ ≥ 1,000 mA/cm^2**	--

Progress- HC Membrane Development

- **Hydrocarbon Membranes (BPSH)**
  - Inexpensive starting materials
  - Trade-off between conductivity and mechanical properties
  - Reduces gas permeation by 1 order of magnitude
  - Reduction in electro-osmotic drag transport

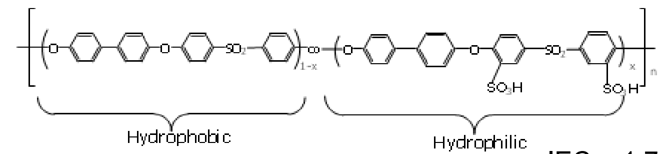


- **Biphenyl-based Membranes, Partially Fluorinated Hydrocarbons (BP-Ar, F4FBP-S, PBPA-S)**
  - Similar benefits as BPSH, but include:
    - Mechanical stability
      - Membrane support structures can be added for increased stability
    - Higher IEC , protonic conductivity

Comparison among hydrocarbon PEMs: BPSH-40, BP-Ar, F4FBP-S, and PBPA-S				
	BPSH-40	**BP-Ar**	**F4FBP-S**	**PBPA-S**
IEC (mmol/g)	1.7	1.4-2.0	up to 2.2[a]	2.6
Water Uptake (wt%)	56[b]	32	Not available	76[b] (87[c])
M_n (kg/mol)	40–50	60–80[d]	69.1[d]	70.8[d]
Viscosity (dL/g)[e]	0.9	Not available	2.03[d]	2.18[d]

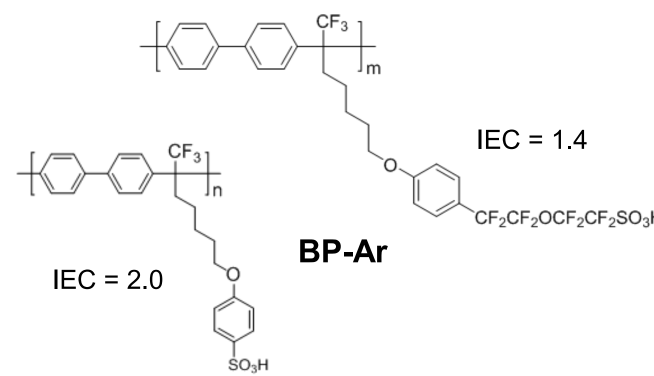
[a] IEC calculated based on repeating structure containing two alkyl-sulfonate chains. [b] Measured at 30 °C. [c]. Measured at 80 °C. [d] Molecular weight data from non-ionic precursor polymers, F4FBP and PBPA-Br. [e] Intrinsic viscosity.

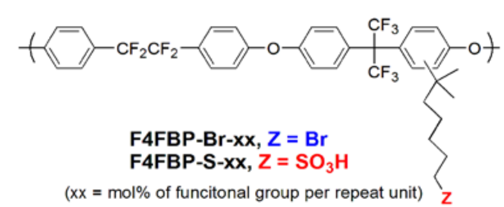
Bi-Phenyl Sulfone, H form (BPSH)

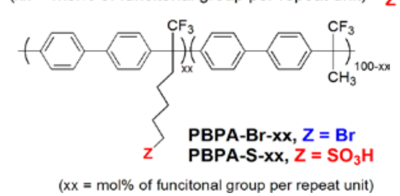


IEC = 1.7

Biphenyl-based Perfluoroalkylsulfonate & Bromoalkyl-tethered Aromatic Polymers (BP-Ar & F4FBP-S/PBPA-S)

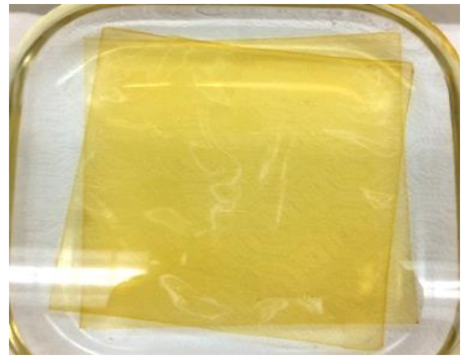




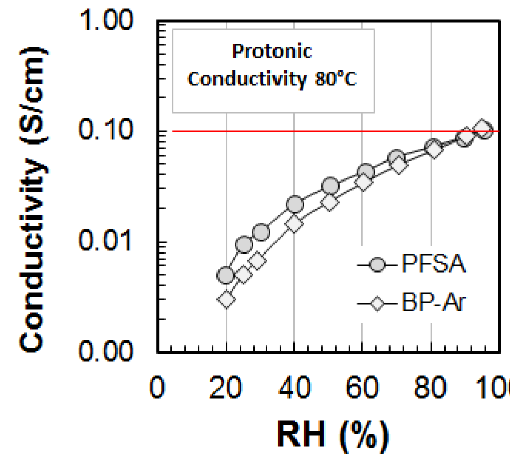


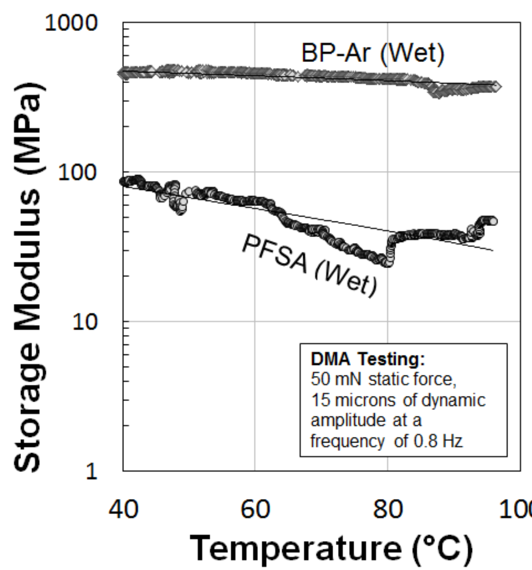
Progress- HC Membrane Development (BP-Ar)

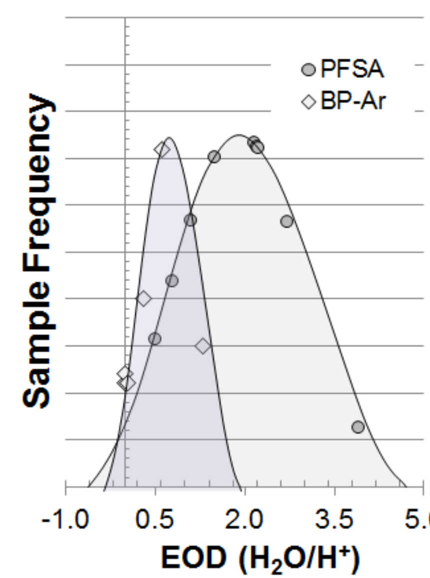
- Conductivity: 0.106 S/cm, (met *target >0.100 @ 80°C)*
- Dynamic mechanical analysis **(**DMA): High storage modulus, indicating high strength and resistance to swelling
- Electro-osmotic Drag (EOD):
  - **PFSA:** ranged from 0.5 to 3.9 H_2O/H^+
  - **BP-Ar:** ~ 1.0 H_2O/H^+ *WaMM requirement? (see Slide 11)*
- IEC: 1.45 mmol/g
  - Exploring increasing IEC for improved properties



BP-Ar Membrane (H^+ form)
Membrane size: 5.5” x 5.5”

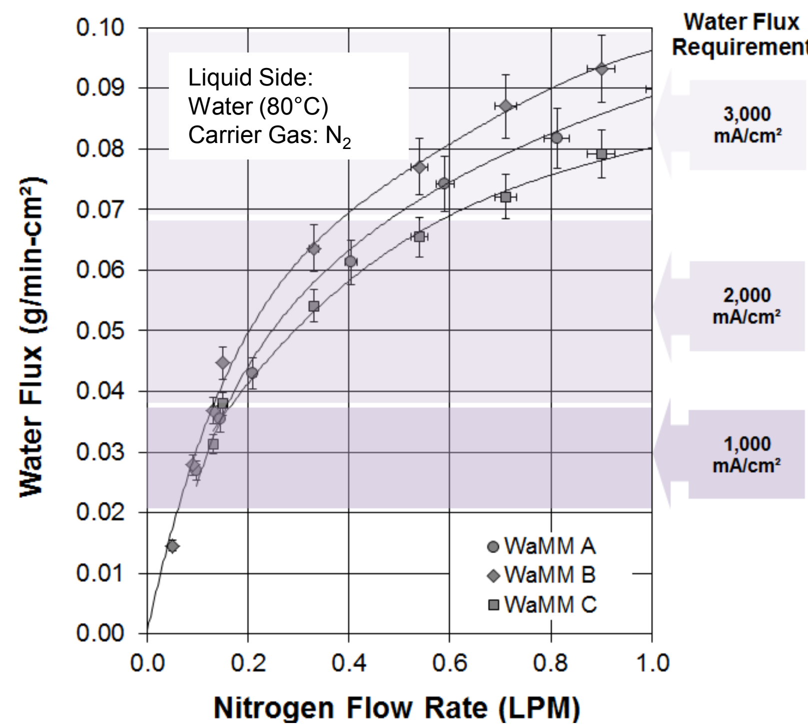


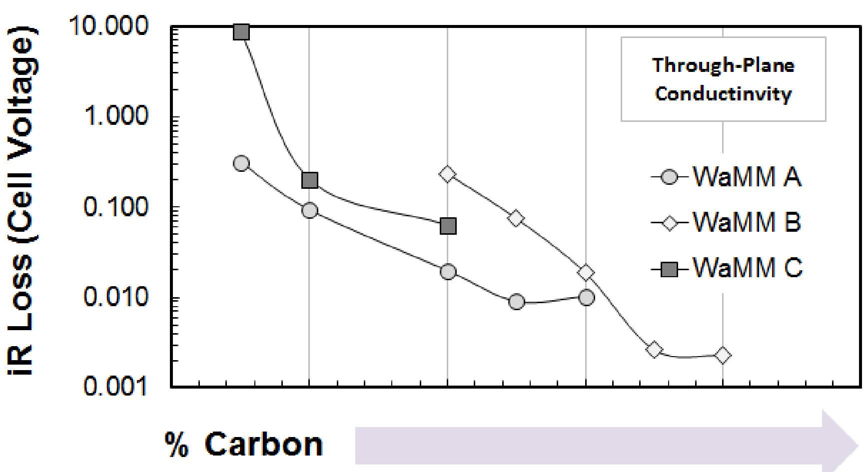




Progress-WaMM Development

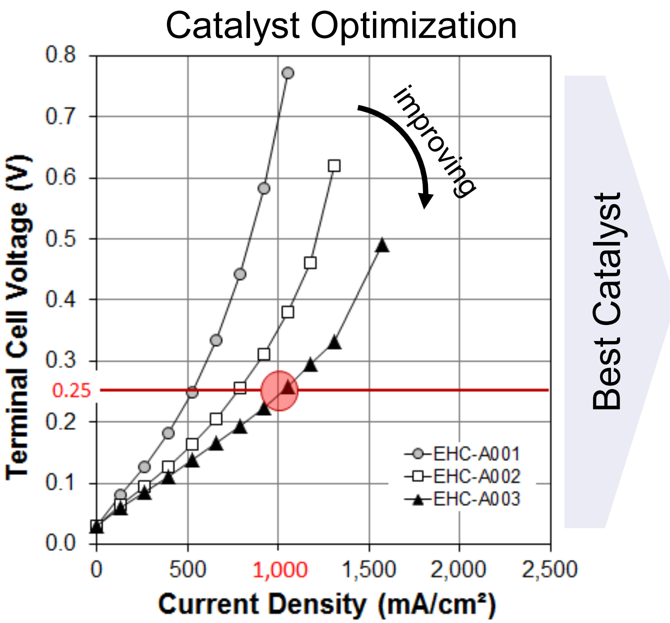
- WaMM successfully fabricated (active areas >200 in²)
  - Exhibits high mechanical integrity & flexibility
  - Thickness:1.25 mil (32 µm)
- Through-plane conductivity of select composite WaMMs > 1 S/cm
  - WaMM is anisotropic , high In-plane conductivity
  - Supports bipolar stack configurations
- Water flux: > 0.09 g/min-cm² (*target > 0.039g/min-cm²*)
  - Additional improvements feasible by casting thinner WaMMs

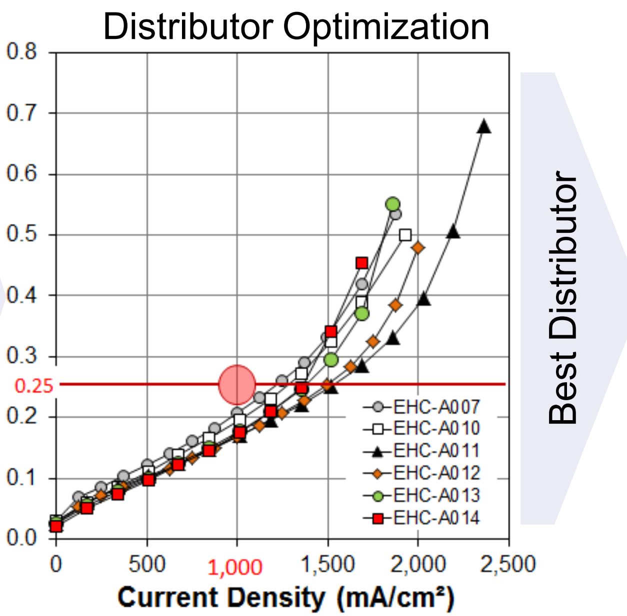


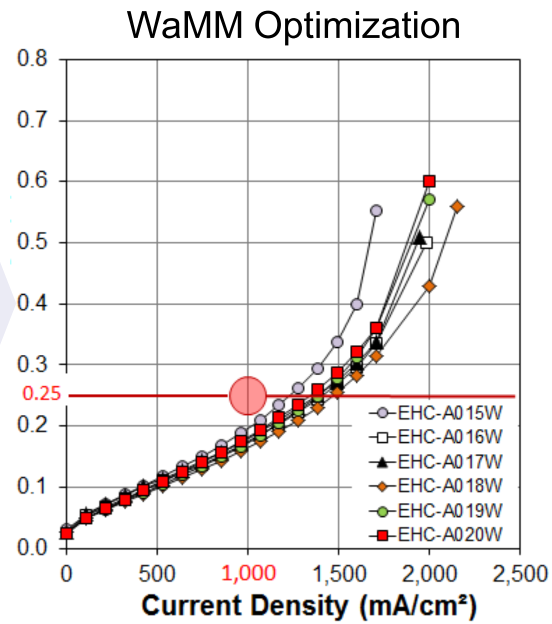


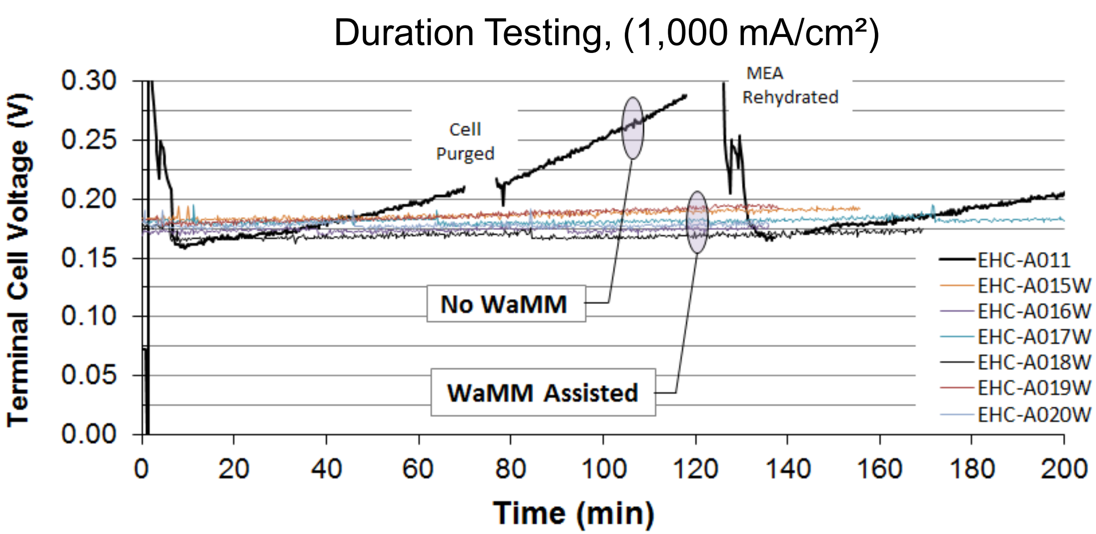
WaMM Membrane

Progress- EHC Cell Performance (PFSA)





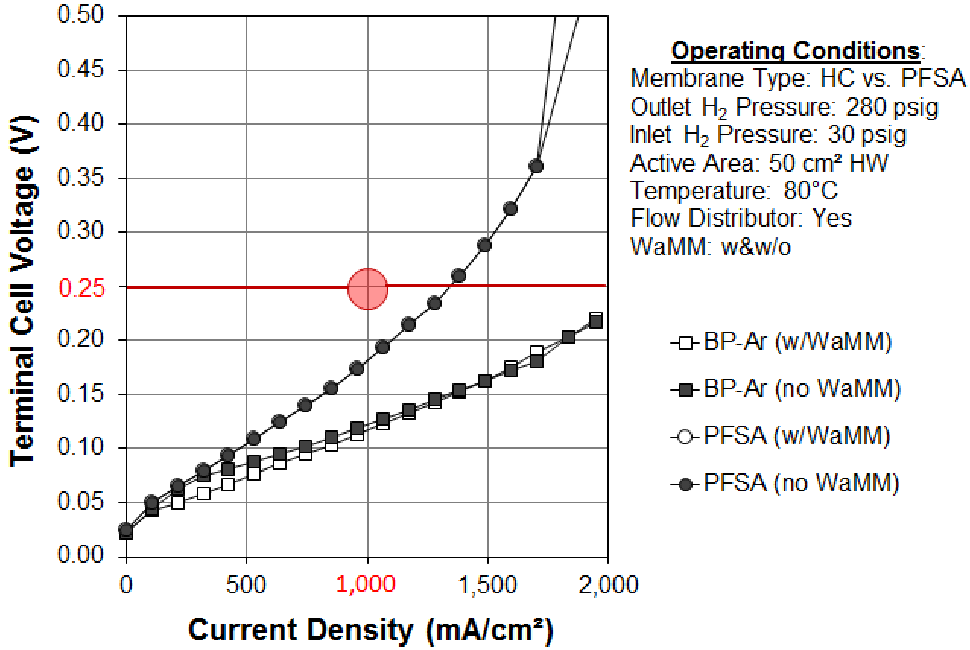




- Combined optimization of Catalyst, Flow Distributor, & WaMM significantly improves EHC performance: 0.7V→0.17V/Cell (@1,000 mA/cm²)
- WaMM maintains water equilibrium in MEA and prevents drying/flooding

Operating Conditions:
All Membranes: PFSA (5 mil)
Outlet H_2 Pressure: 280 psig
Inlet H_2 Pressure: 30 psig (dry/dead-ended)
Active Area: 50 cm² HW
Temperature: 80°C

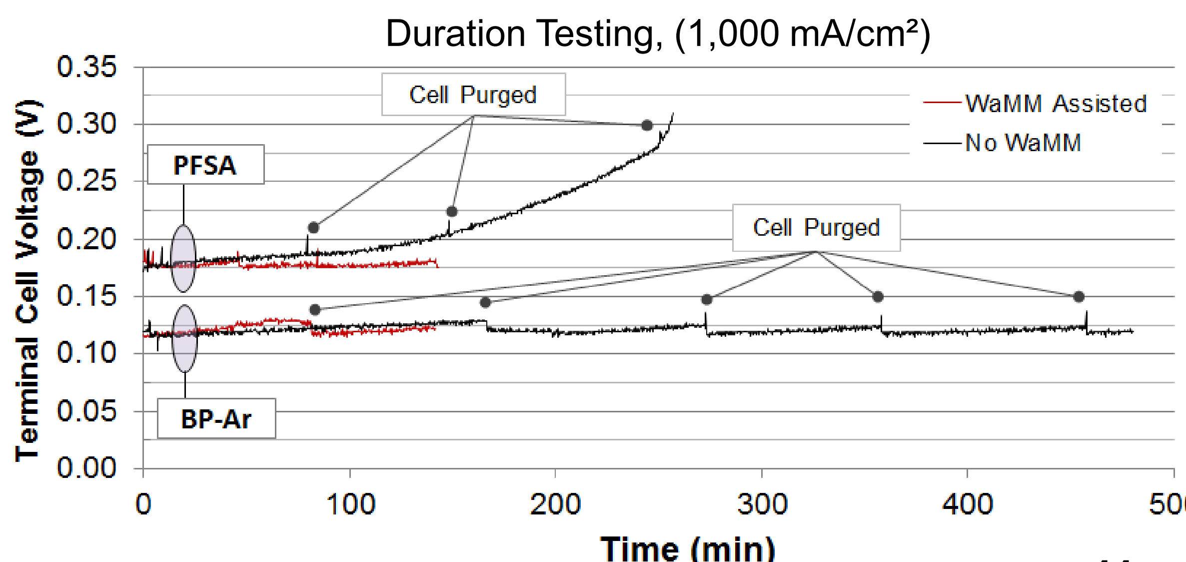
Progress- EHC Cell Performance (HC vs. PFSA)



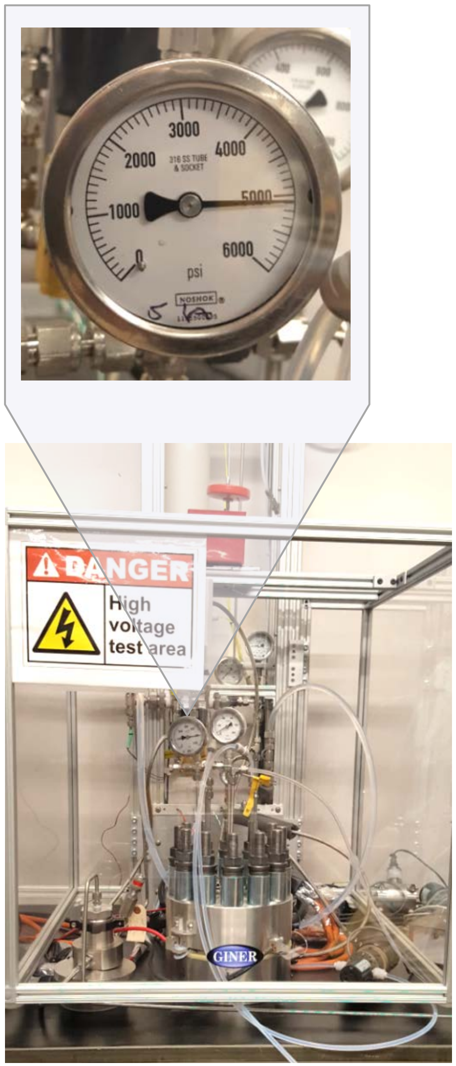
- EHC Performance @ 1,000 mA/cm²
  - PFSA : 0.170V
  - HC (BP-Ar) : **0.110V**
- Anode purge required to remove inert gases every ~100 min
  - H_2 fed from tank-cylinder with purity of 99.95%

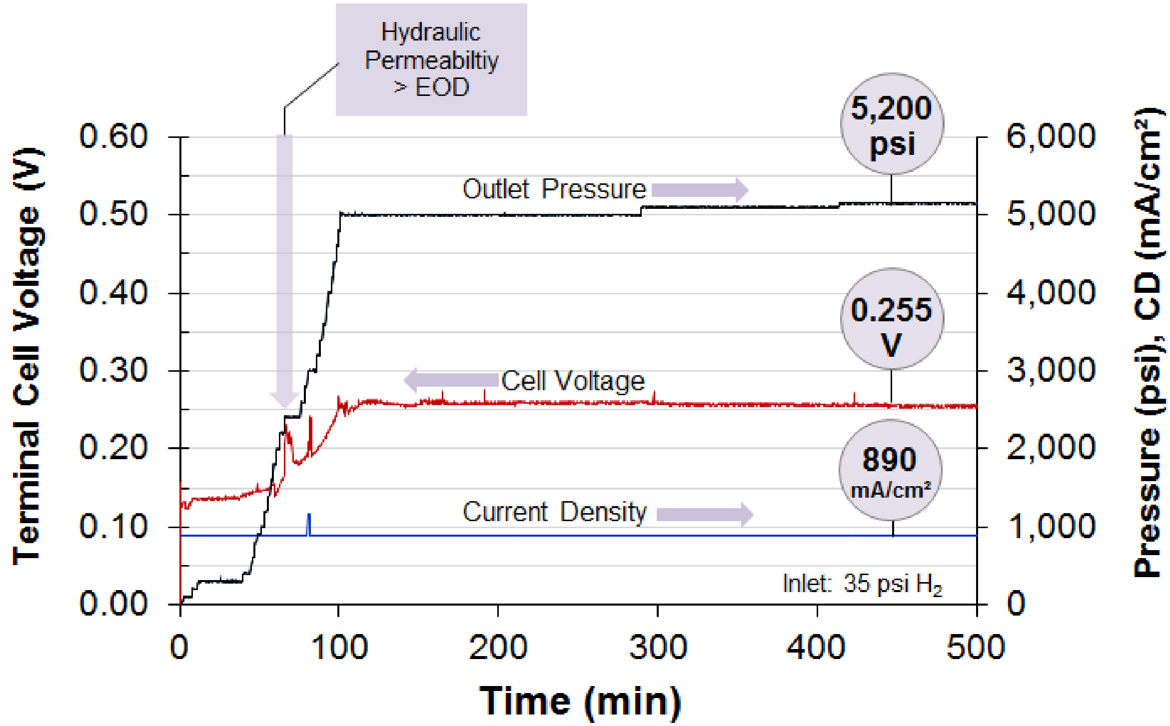
HC membrane (with low EOD) and/or WaMM can significantly improve water management in EHC.

We have multiple choices!



Progress- EHC Cell Performance
(350 bar Operation)



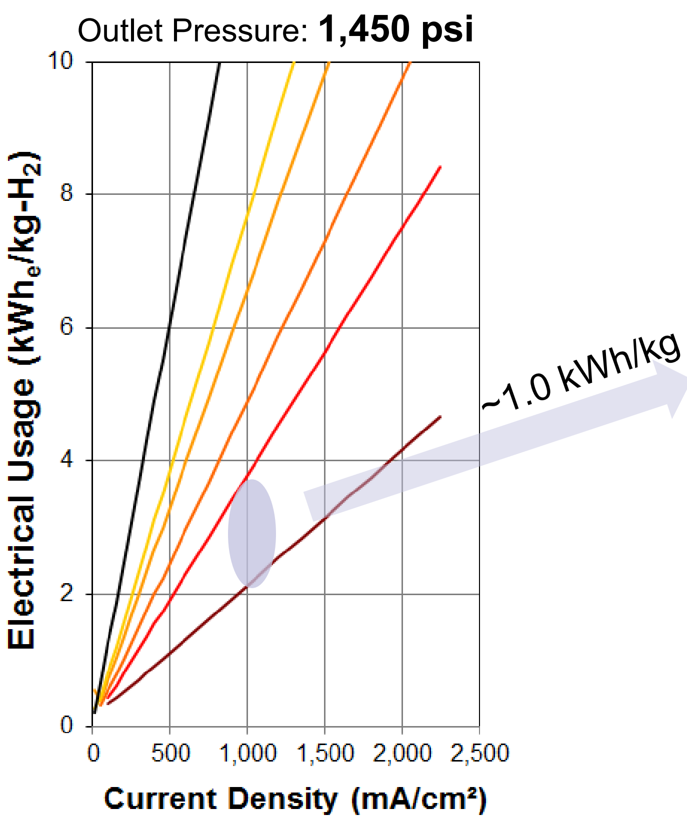


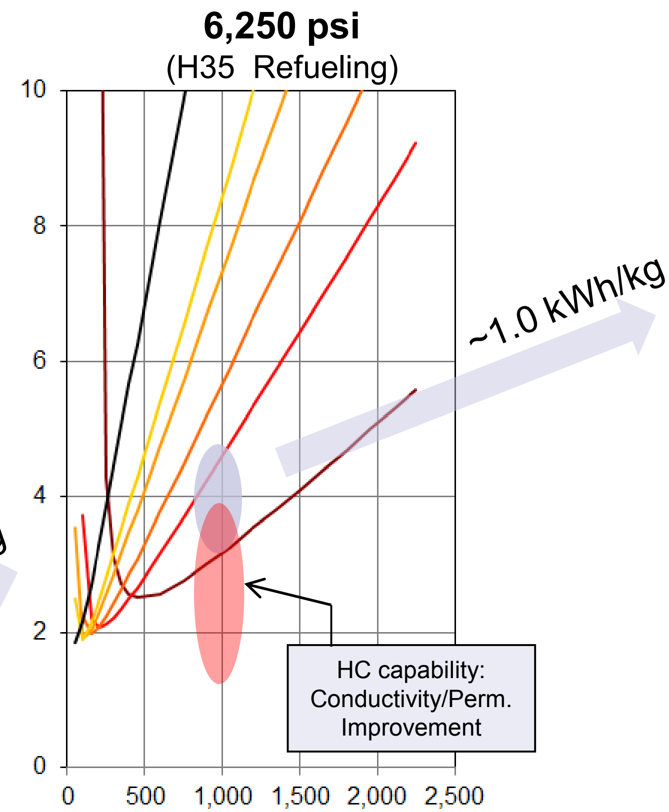
- 350 bar stack hardware modified for EHC operation
- Initial run operated at >5,000 psi (350 bar) w/PFSA & WaMM
  - Performance 0.25V @ ~890 mA/cm²
- Further improvements:
  - HC membranes expected to improve performance significantly with lower EOD
  - Further optimization of WaMM to provide additional water
  - Increasing inlet pressure to 100 bar will reduce Nernst losses

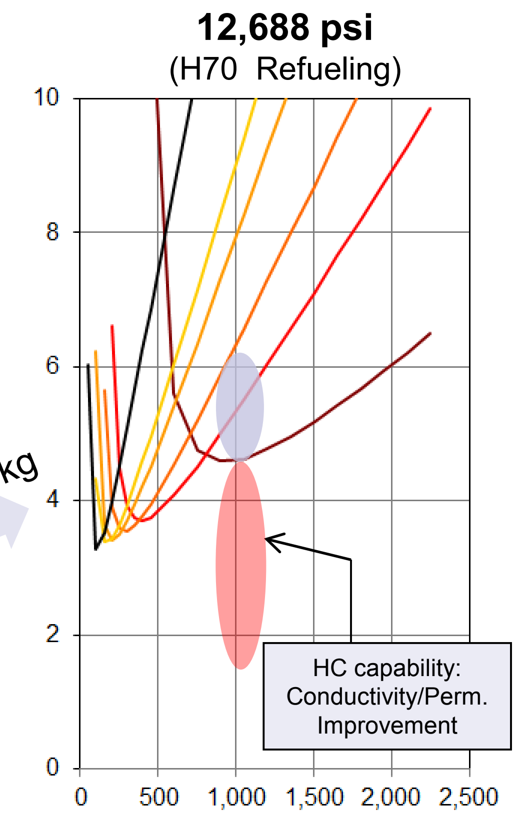
Progress - EHC Performance Projections

PFSA vs. HC Membrane

- Combined effect of iR-losses, Nernstian Penalty, Catalytic Activity, Ionic conductivity, and Back diffusion
- Increased power consumption at high operating pressure (back diffusion)







HC PEM - 1 order magnitude lower diffusion rate

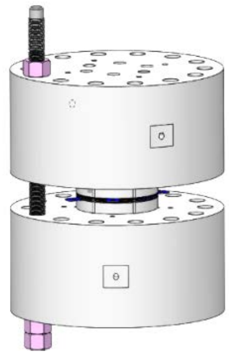
50°C, 100 bar Feed. Assumes optimal water management

PFSA Membrane Thickness (mils)

2, 5, 7, 10, 12, 20

Progress-EHC Stack & System Design & Fabrication

12,688 psi
(875 bar)



5,000 psi
(350 bar)

Modified stack to accommodate Distributor and WaMM. Supported membranes required

Evaluation of high pressure components, Flow distributors & internal cell components

1,000 psi
(70 bar)

300 psi
(20 bar)

Catalyst, Membrane & Cell-Component, Testing & Validation

875 bar Stack

- Stack Design Initiated
- Designed for proof pressure of 20,000 psi (~1,400 bar) - required for approval
- Incorporates new distributor plates and WaMM
- Evaluate at 350 bar, followed by 875 bar operation
- Scale-up hardware to larger active areas

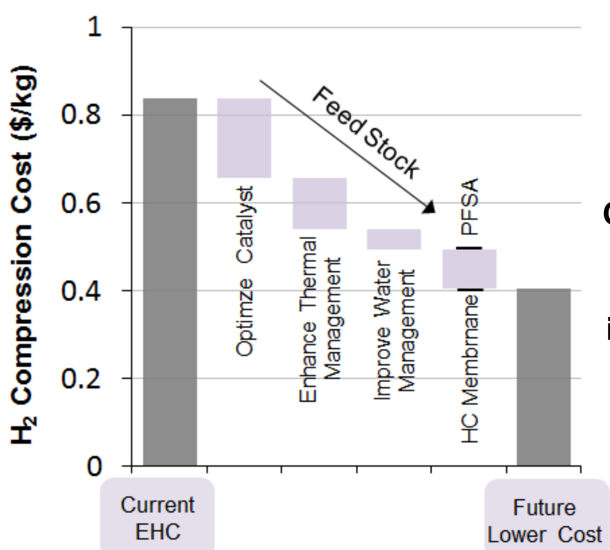
System

- Increase TRL from 3 to 5 (goal is commercialization of the technology)
  - Certification Intertek
    - CDR & HazOp/Stack & System
- Designing system to meet Safety & Regulatory Codes
  - Design based on mobile refueling applications, designed to meet safety and regulatory codes as listed by UL, NFPA(2 &70), SAE, ASME, and NHA
  - System design includes multiple compartments to separate hazard zones – simplifies certification

Projected Compression Cost

H_2 Compression Cost Contribution	Current Status ($/kg)
Capital Costs[1]	0.176
Feedstock Costs[2]	0.313 (PFSA)
Fixed O&M	0.004
Variable Costs	0.001
Total Cost ($/kg)[3]	0.494

[1]10 year lifetime, [2]Based on electrical cost of $0.057/kWh, [3]Design Capacity: 100 kg-H_2/hr. Assumes large scale production.



Cost reduction related to efficiency improvements

Targets: $3.4k/year (O&M) and capital cost of $170k per compressor

- **System Economics:** determined using current Giner PEM-based electrolyzer system cost models
  - **Feedstock:**
    - Efficiency Range (kWh_e/kg-H_2):
      - 2.7 ± 1.2 (HC)
      - 5.5 ± 1.2 (PFSA)
  - **Capital Cost:** Increasing Active Area & Operating Current Density reduces CapEx significantly
  - **Projected Operating Life:** The unit will be designed to operate for a term of 10 years or more (> 20 years expected)
    - Membranes are not expected to degrade due to lack of O_2 in system

Collaborations

Giner, Inc. -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 -Subcontractor	National Lab	Coordinate stack testing and optimization studies of membranes, cell components & materials. Membrane and cell component validation. Operation of EHC stacks and scaled-up EHCs systems at high hydrogen pressure that are key to performing system diagnostics and validation.
Rensselaer Polytechnic Institute -Subcontractor	Academia	Development of mechanically-stable hydrocarbon-based PEMs which serve as a key material in this project.
Gaia Energy Research Institute LLC -Subcontractor	Private Business	EHC stack cost analysis and system-level analysis. Developing EHC cost estimates, techno-economic analysis (TEA), and life cycle assessment (LCA).

Summary

- **Membrane**
  - WaMM: Successfully developed/fabricated flexible WaMM compatible with high pressure operation
    - Significantly improves water management, stabilizes cell voltage
  - HC membrane: Achieved significant improvement in membrane performance
    - Cell voltage improvement to 0.110V/cell
      - Stack Efficiencies to 2.7 $kWh_e/kg\text{-}H_2$ (@ 1,000 mA/cm^2, 2 bar feed)
        - 100 bar feed expected to reduce to <1.6 $kWh_e/kg\text{-}H_2$
        - Highest Efficiency for EHC operating at 5,000 psi

- **Stack Hardware Development:**
  - Fabrication of test hardware (for validation of membrane and cell components) completed
  - Developed Flow Distributor to maintain temperature in each individual cell
  - Combined WaMM and Flow Distributor enables significant:
    - Cell voltage improvement: 0.7V/cell → 0.110V/cell
    - Stable EHC operation at elevated current density operation
  - Initiated operation at 5,000 psi (350 bar), demonstrated stable performance
  - 875 bar stack design initiated

Future Plans & Challenges (FY2017-18)

Future Plans*

- Membrane: Complete investigation on HC membranes
  - Conduct HC membrane evaluations at 5,000 psi (350 bar)
    - Conduct 1,000 hour duration test
- Stack: Design, fabricate, and test high-pressure 12,688 psi (875 bar) stack hardware
- System: Initiate assembly of porotype system design
  - Selection and procurement of Class 1, Div. 2, Group B components

Future Challenges

- Increase stack active-area to 300 cm^2 or larger
  - Also requires scale-up for HC membranes
- Increased operating pressure
  - Maintaining seals of stacks at operating pressure of 12,688 psi or higher
- Reduce Stack Costs
  - Unitize cell components (reducing parts/cell)
    - Combine cell components at the production level
      - Combine Flow-Distributor and WaMM compartment into single component
    - Investigate techniques to reduce fabrication costs
      - Chemical etching and machining is current solution. Possibility of stamping components
- Embrittlement of cell components
- Effect of H_2 impurities

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