Electrochemical Compression

2018 DOE Hydrogen & Fuel Cells Program

Annual Merit Review Meeting

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Project ID: PD136

Overview

Timeline

- **Project Start:** Oct. 1, 2016
- **Program Novation:** Apr.-Dec., 2017
- **Project End:** June 30, 2020
- **Percent Complete:** 21%

Budget

- **Total Project Budget: $3.52MM**
  - **Total Federal Share:** $2.81MM
  - **Total Recipient Share:** $0.71MM
  - **Total DOE Funds Spent*:** $0.46MM

* As of 3/31/18

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.** – 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 18 Objectives

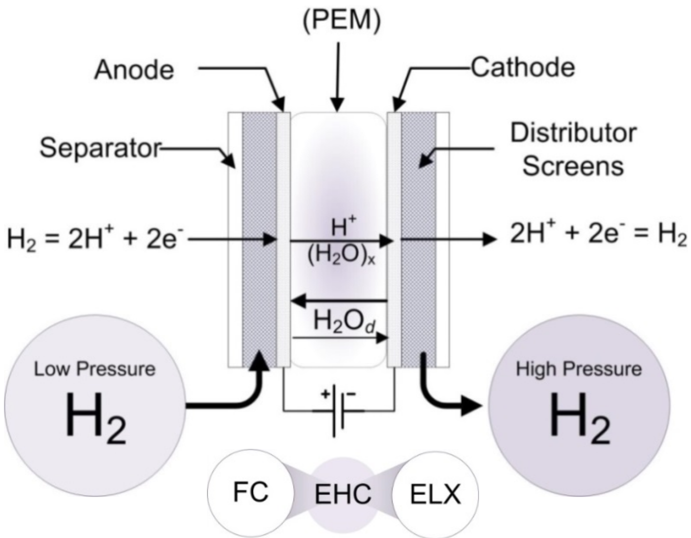
- Fabricate Aromatic membranes with enhanced properties for use in EHCs
  - Evaluate Aromatic membranes at 5,000 psi (350 bar)
- Improve EHC water and thermal management
  - Development of Water Management Membranes (WaMM) for use in EHCs
  - Engineer stack & cell components for high pressure operation
- **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 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

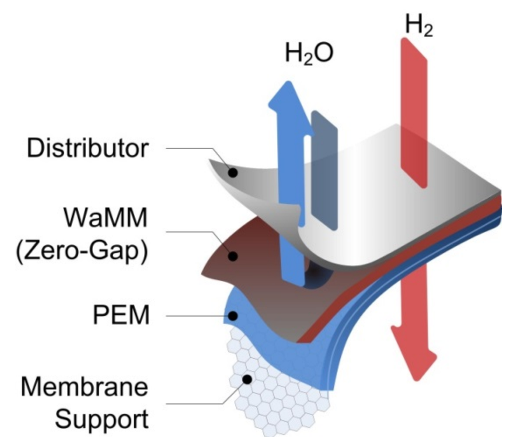


EHC: Benefits & Uses

- 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 (NG appl.)
  - Hydrogen Circulation (Pumps, Refrigeration)
  - H_2 Purity (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



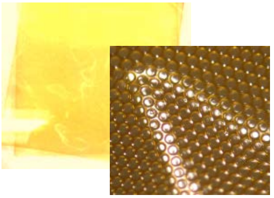
Advanced EHC Cell Design

Approach: Program Overview

Safety, Cost, Certification

Membrane

- Aromatic membranes: Synthesize membranes with:
  - Low Electroosmotic Drag & gas permeation
  - Compatible support structures
  - Improve cell voltage performance
- Water management membrane (WaMM) :
  - Provides passive water management

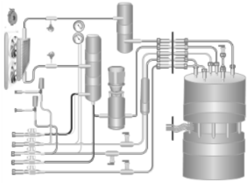


Stack

- 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 ✓
					75%

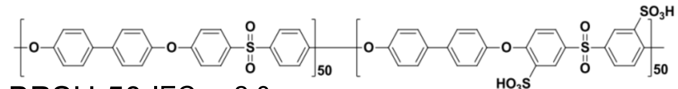
	Evaluate Cell Performance	M1.3	Voltage performance 250 mV @ ≥ 1,000 mA/cm^2 (combined Task 1, 2, & 3)	EHC cell voltage performance @ 1,000 mA/cm^2 (300 psig): ▪ 170 mV/cell (PFSA) ▪ 105 mV/cell (Aromatic), ▪ Initiated testing of Aromatic membranes at 5,000 psig	50%
3	Preliminary Stack Design	M1.4	Complete preliminary design of scaled-up stack (300 cm^2) for 875 bar operation	Initiated	15%
4	Desktop Review of EHC System	M1.5	Complete Desktop Review of EHC system	Intertek 1st review round complete. Report submitted	50%
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	✓

Progress- Aromatic Membrane/MEA Development

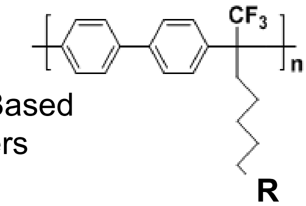
- **Hydrocarbon Membranes (BPSH)**
  - Inexpensive starting materials
  - Trade-off between conductivity and mechanical properties
  - Reduces gas permeation by 1 order of magnitude
  - Reduction in electro-osmotic drag transport

- **Biphenyl 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 can be added for increased mechanical stability

Polymer Synthesis



BPSH-50 IEC = 2.0



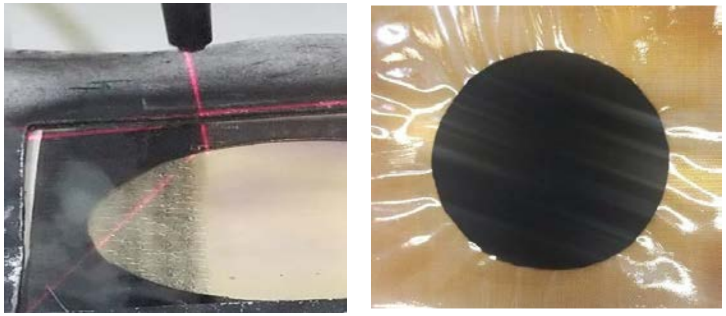
Biphenyl-Based Polymers

BP-ArF4 IEC = 1.4

BP-ArSA IEC = 2.0

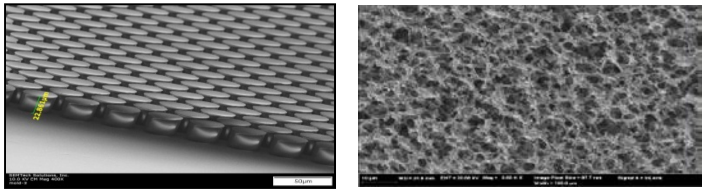
BP-SA IEC = 2.6

MEA Fabrication



MEA Fabrication & Catalyst Deposition at NREL

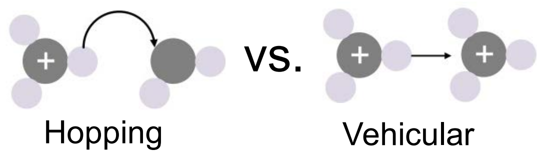
Supports



Addition of Membrane Supports

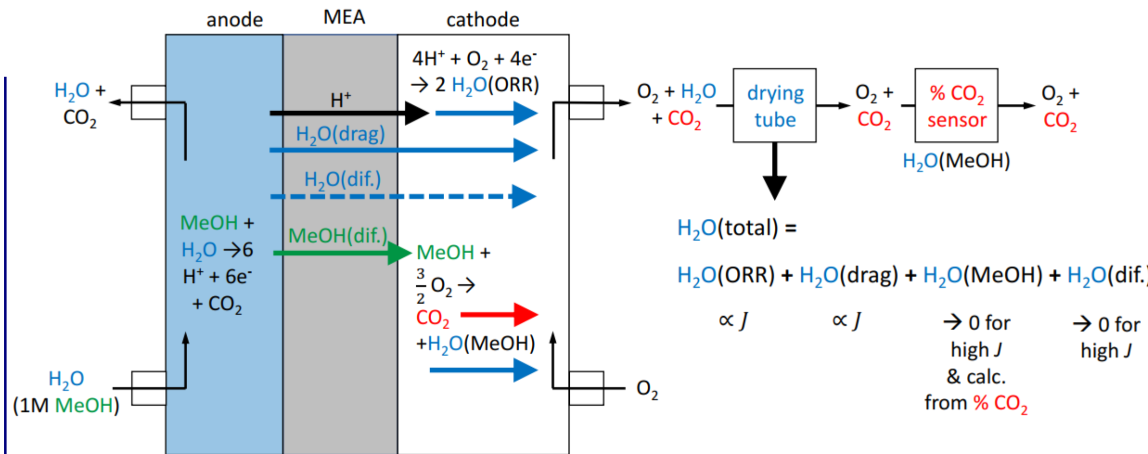
Progress- Electro-osmotic Drag (EOD)

Need to reduce EOD, maintain water in membrane for high current density operation

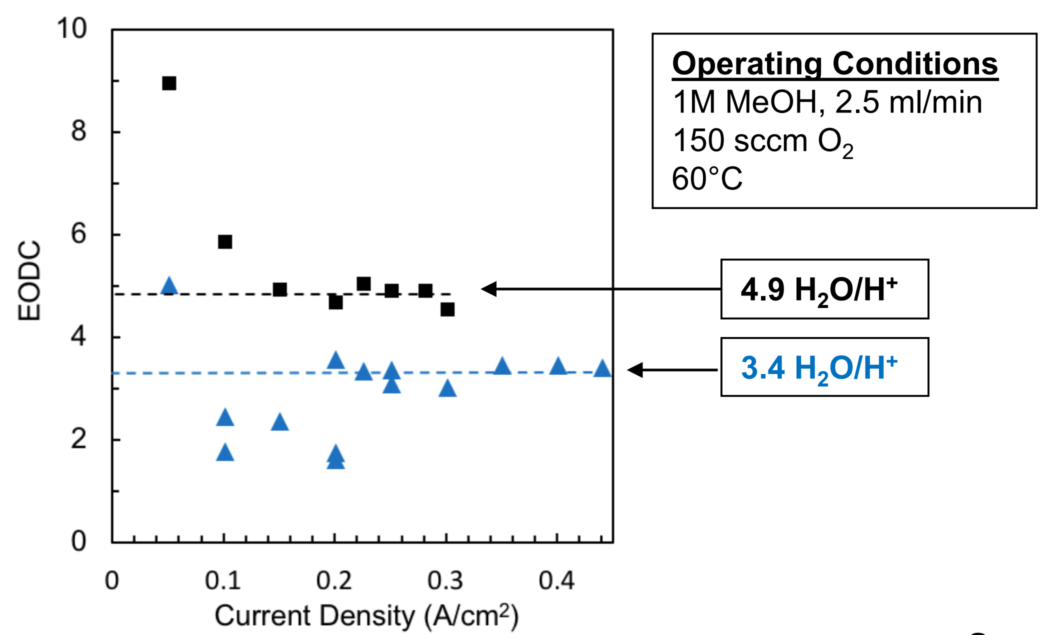


EOD Water Transport Mechanism

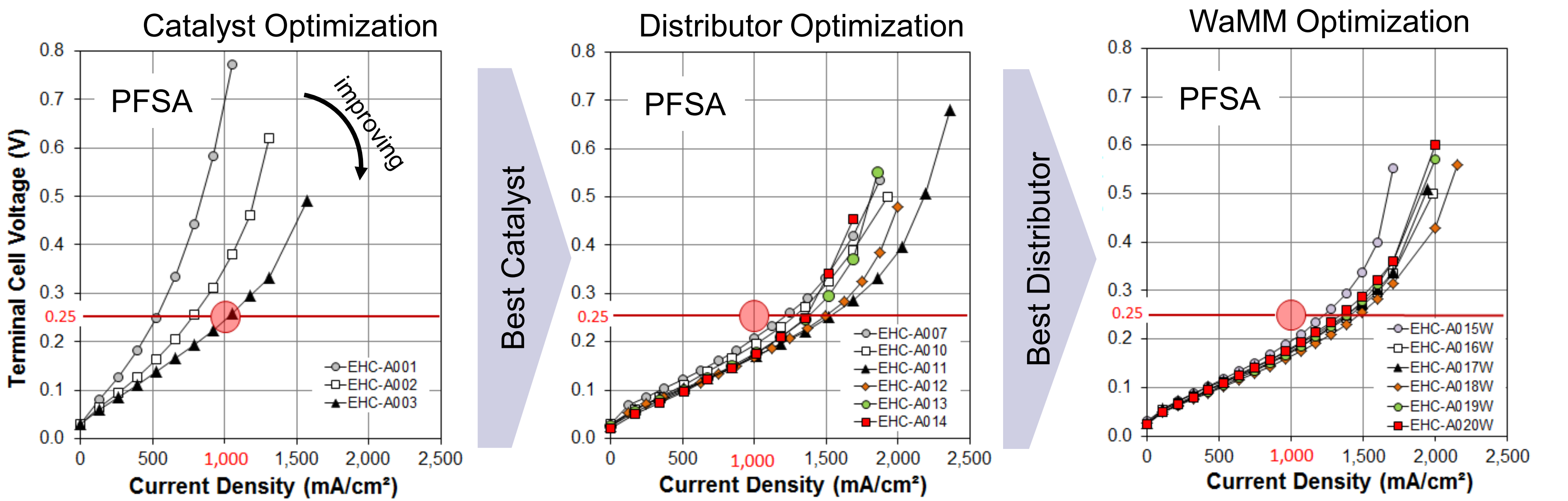
- EOD measured via DMFC (NREL):
  - PFSA: 4.9 H_2O/H^+
  - BP-Ar: ~ 3.4 H_2O/H^+
    - **30% lower compared to PFSA**
    - 1.0-1.5 H_2O/H^+ possible with membranes of lower IEC/higher selectivity
- EOD testing in EHC indicates 50% reduction
  - Low humidity evaluation

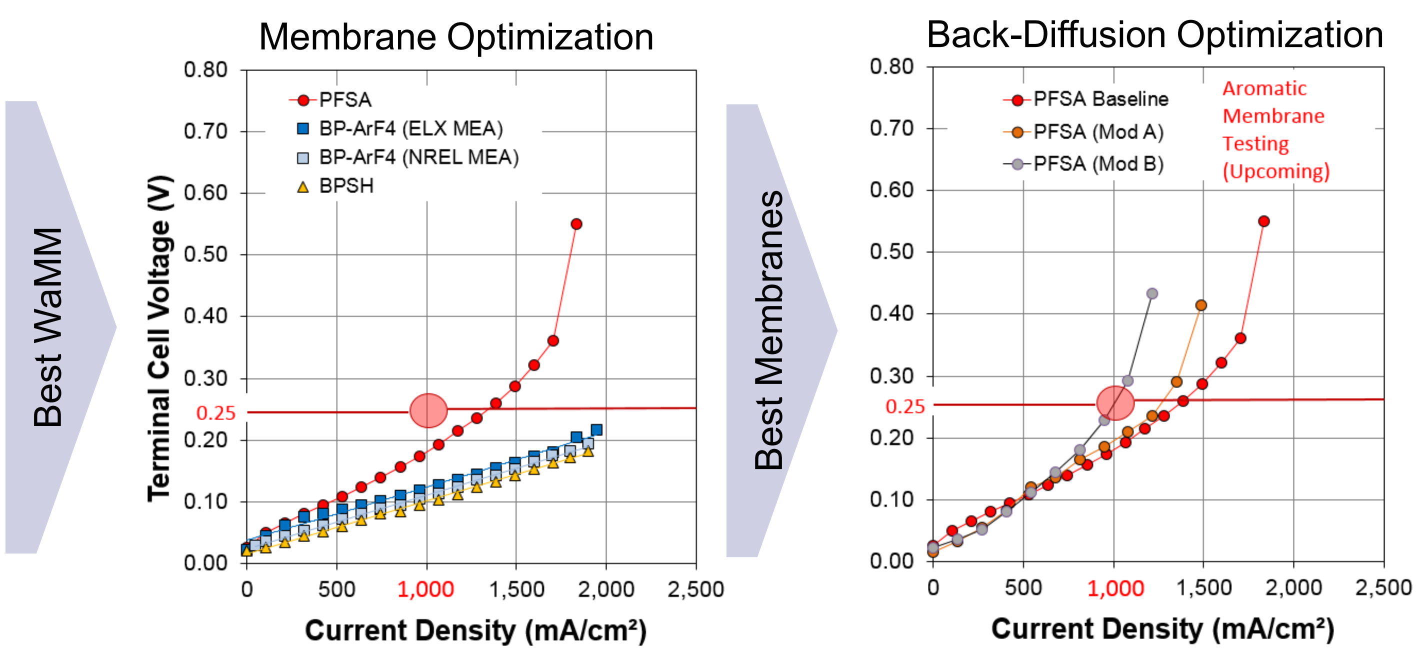


Ref: X. Ren, W. Henderson, S. Gottesfeld, *J. Electrochem. Soc.*, **144**, L267 (1997)



Progress- EHC Cell Performance & Optimization





Operating Conditions:

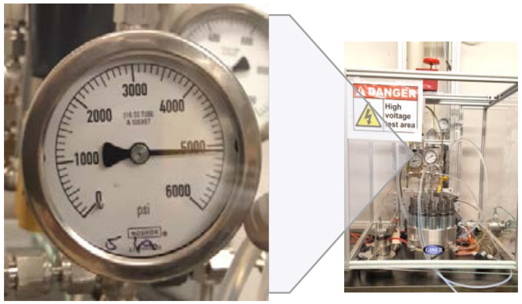
Outlet H_2 Pressure: 280 psi (~20 bar)

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

Active Area: 50 cm² HW
Temperature: 80°C

Progress- EHC Cell Performance @ 350 bar (5,000 psi)

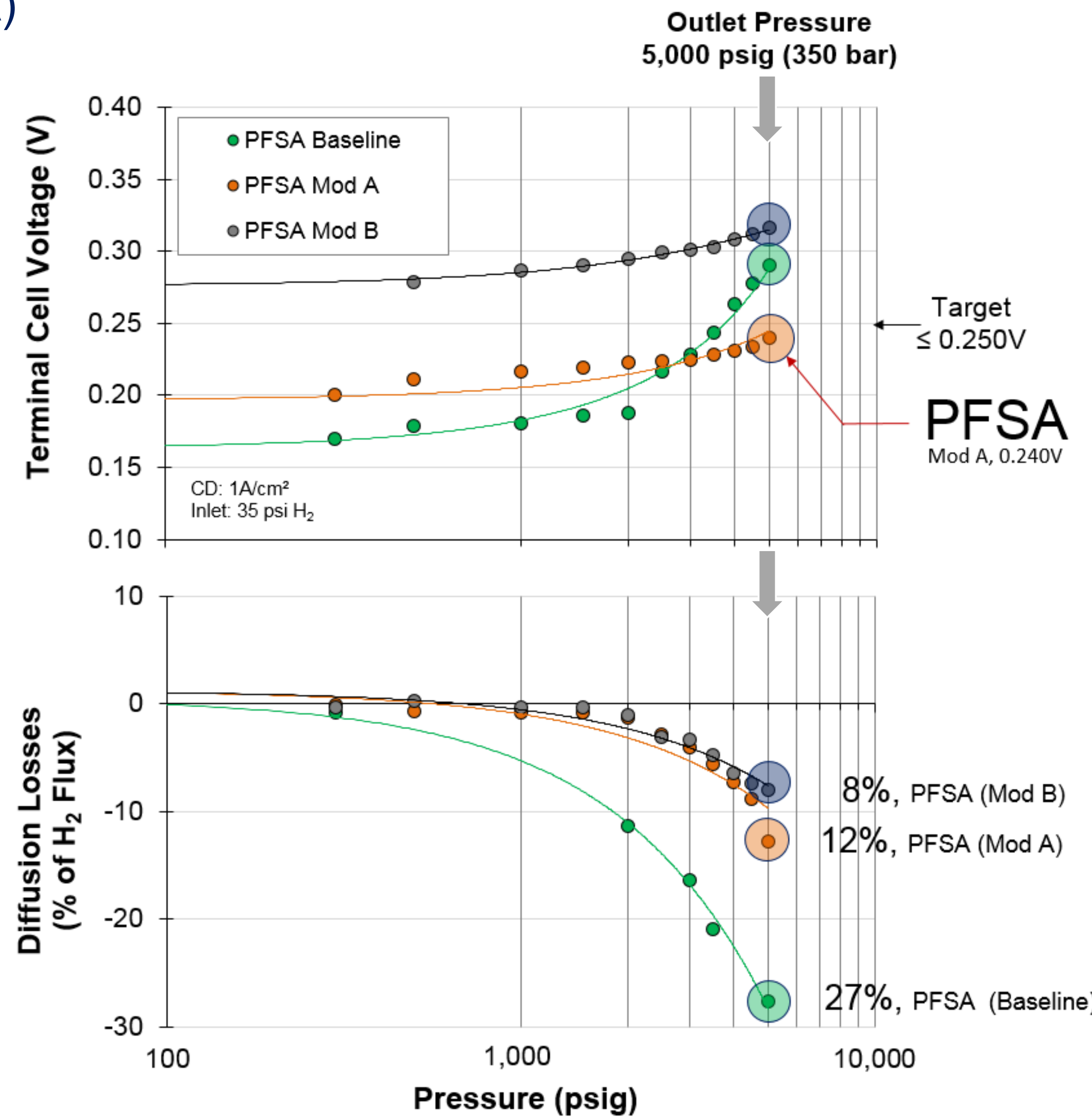
Reducing Back Diffusion (PFSA)



- Membranes modified to optimize (reduce) back diffusion
- H_2 Flux vs. pressure measured at maximum operating temperature (80°C)
- Losses due to back diffusion:
  - Baseline: 27% @ 80°C (8.3% @ 50°C)
  - Mod B: 8% @ 80°C (4.0% @ 50°C)

Gas diffusion in modified membranes reduced by > 50% compared to baseline

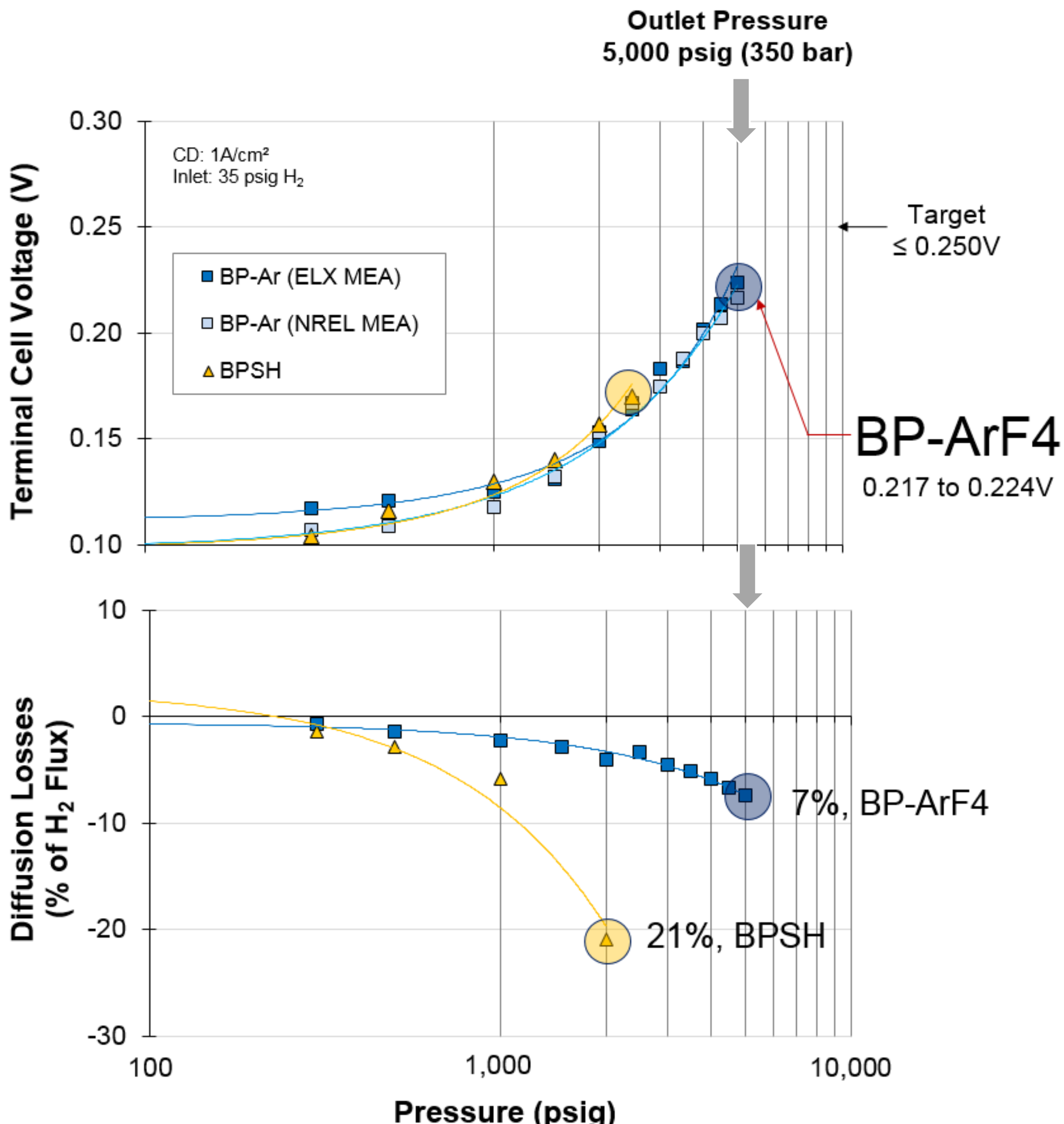
Applicable to Aromatic membranes



Progress- EHC Cell Performance @ 350 bar (5,000 psi)

Aromatic membrane

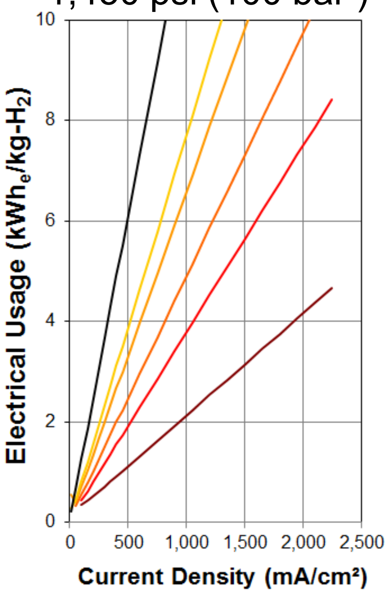
- Aromatic Membrane (BP-ArF4) meets Milestone target
  - Best performer: 0.217V @ 5,000 psi (350 bar) -NREL MEA
  - Diffusion losses
    - 7% @ 80°C (<3% @ 50°C)
    - Not optimized for diffusion!
- BPSH (50% di-sulfone) meets milestone for IEC target (~2.0 mmol/g)
  - MEA developed leak at ~2,500 psi (170 bar) , requires support
- Upcoming tests:
  - Optimization of aromatic membranes to further reduce back diffusion
  - Improving mechanical strength



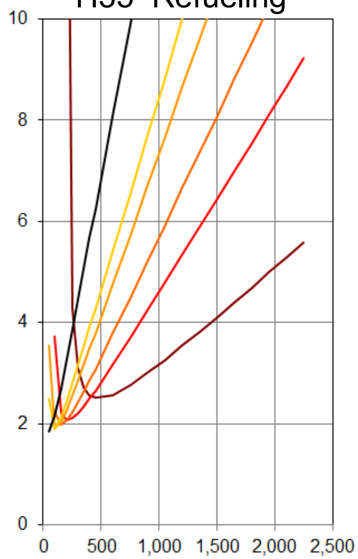
Progress – Modeling EHC Performance

- 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)

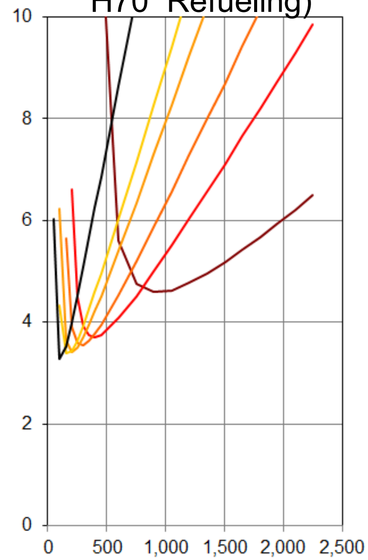


6,250 psi (430 bar),
H35 Refueling



+1.0
kWh/kg

12,688 psi (875 bar),
H70 Refueling)



+1.0
kWh/kg

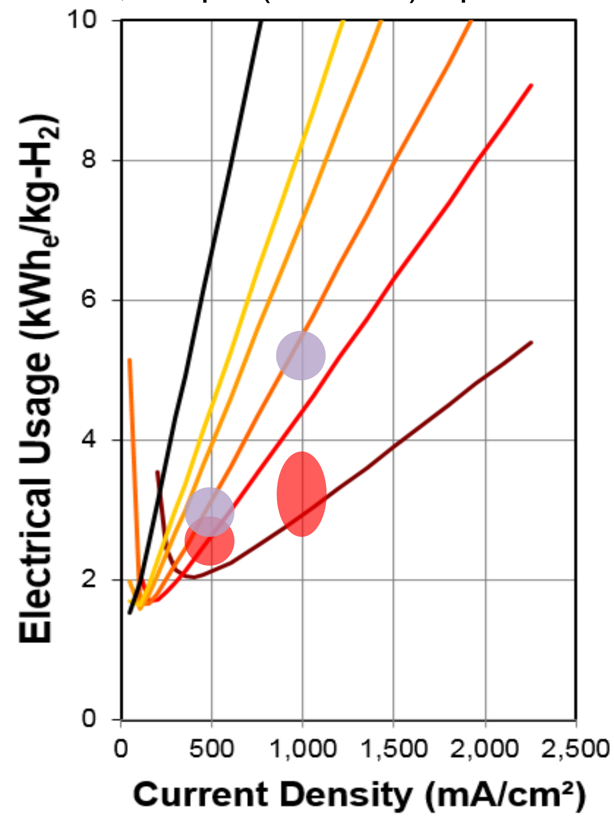
PFSA Membrane Thickness (mils)

2 5 7
10 12 20

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

Where are we?

5,000 psi (350 bar) Operation

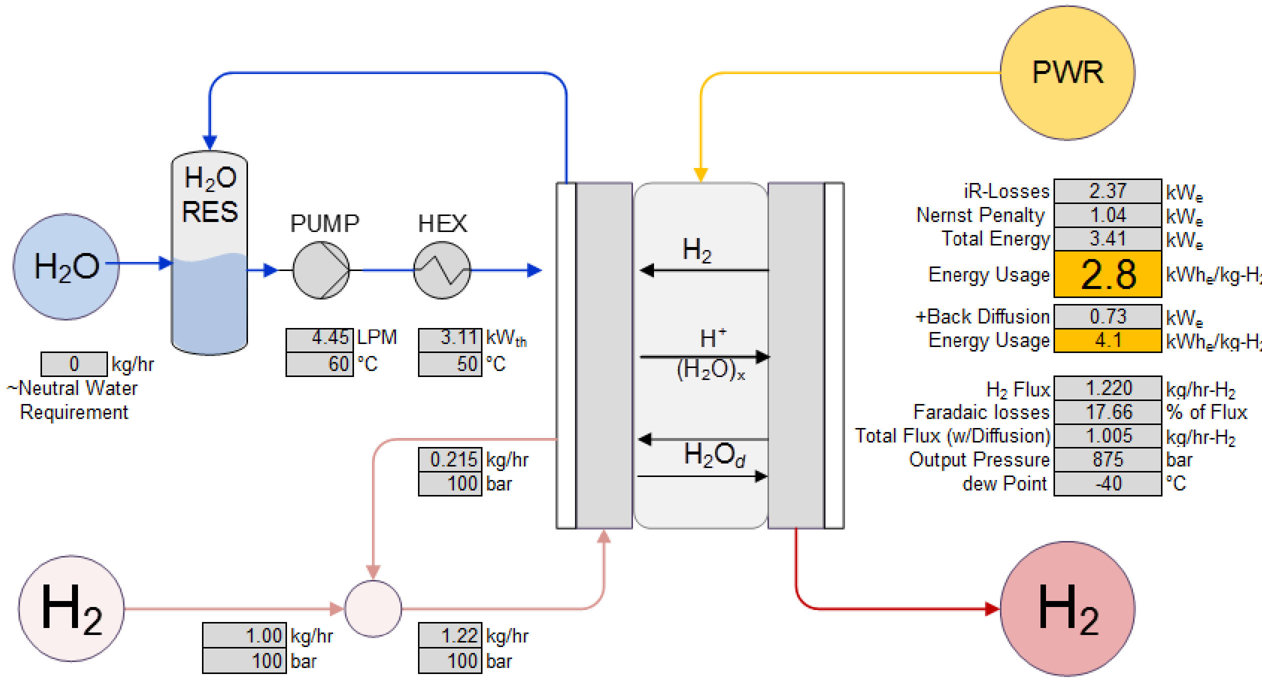


Efficiency (kWh$_e$/kg-H$_2$), 350 bar

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

Progress – Stack, EHC Mass & Energy Balance, 875 Bar

- Based on 1 kg/hr output @ 875 bar with best performing membrane
- Operating at highest efficiency point (< 1000 mA/cm²)
- Energy balance accounts for:
  - Nernstian penalty: ~1.0 $kW_e/kg\text{-}H_2$ @ 875 bar, 100 bar inlet
    - ~2 $kW_e/kg\text{-}H_2$ @ 350 bar, 2 bar inlet
  - Back diffusion: 0.73 $kW_e/kg\text{-}H_2$
- Cell voltage improvement at 875 bar, (100 bar feed)
- Water management @875 bar remains to be measured



Governing equations for EHC		350 Bar	875 Bar
Nernst Potential	$V_{Nernst} = V_o + \frac{RT}{2F} \ln \frac{Pc}{Pa}$	61 - 66mV (1 ⇨ 350 bar)	30 - 33mV (100 ⇨ 875bar)
iR Drop (0.5A/cm²)	$V_{iR} = I * R$	86 mV	86 mV
Activation Over Potential	$\eta = \eta_{anode} + \eta_{cathode}$	<1 mV	<1 mV
Total Voltage	$V_{cell} = V_{Nernst} + \eta + V_{iR}$	~0.152	~0.119

Progress - EHC Stack 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, membrane strength/rupture testing

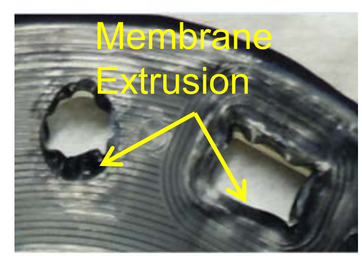
1,000-5000 psi (70-350 bar)

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: Ti, SS
  - Design incorporates use of distributor plates and WaMM
  - Enhanced bipolar plate design for 20 ksi capability, reduced part count
- Successfully evaluated cell components to 5,000 psi (350 bar)
  - 1400 bar testing upon completion of hardware
  - Initial evaluations will be conducted in 50cm² hardware, 875 bar
- Membrane supports for superior creep resistance; operation >2000 psi



Unsupported Membrane*

Supported Membrane*

*350 bar operation in an Electrolysis cell, 1000 hours

Progress- System Codes & Standards, Certification Review

- Conducted extensive review of EHC system with Intertek
  - System designed to be located in hazardous areas, zoned for Class 1, Div2, Grp B
  - Prior to system and process review, presented Intertek with design concept, layout, and BOP component selections
  - Completed ‘desktop review’ of ‘NEW’ H_2 compression technology w/Intertek
    - Determined appropriated standards, component classifications, and operating requirements
      - Over 20 standards* apply. Can Influences how system is designed
- **Program objective**: Increase TRL from 3 to 5. **Goal**: Certification & commercialization of the technology

System will meet all these standards

- **NFPA 2** Hydrogen Technologies Code
- **NFPA 55** Compressed Gases and Cryogenic Fluids Code
- **NFPA 69** Standard on Explosion Prevention Systems
- **NFPA 70** National Electric Code

- **ASME B31.3** Compliance to “Process Piping Guide”
- **ASME A13.1** Compliant with Piping marking

- **ISO 22734-1** - Hydrogen generators using water electrolysis process
- **ISO 12100** Safety of Machinery-General principles of design

- **UL 508A** Industrial Control Panels
- **UL 1203** Explosion-Proof and Dust-Ignition Proof Electrical Equipment for Use in Hazardous (Classified) Locations
- **UL 1995** Standard for Safety, Heating & Cooling Equipment

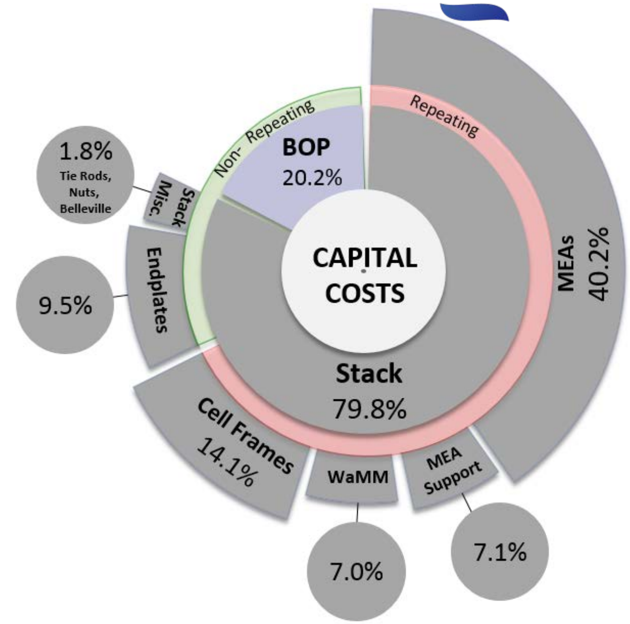
**Not all standards for EHC are shown*

Projected Compression Cost

H_2 Compression Cost Contribution	Current Status ($/kg)
Capital Costs[1]	0.196 ⇧[4]
Feedstock Costs[2]	0.302 (PFSA) ⇩[4]
Fixed O&M	0.004
Variable Costs	0.001
Total Cost ($/kg)[3]	**0.503**

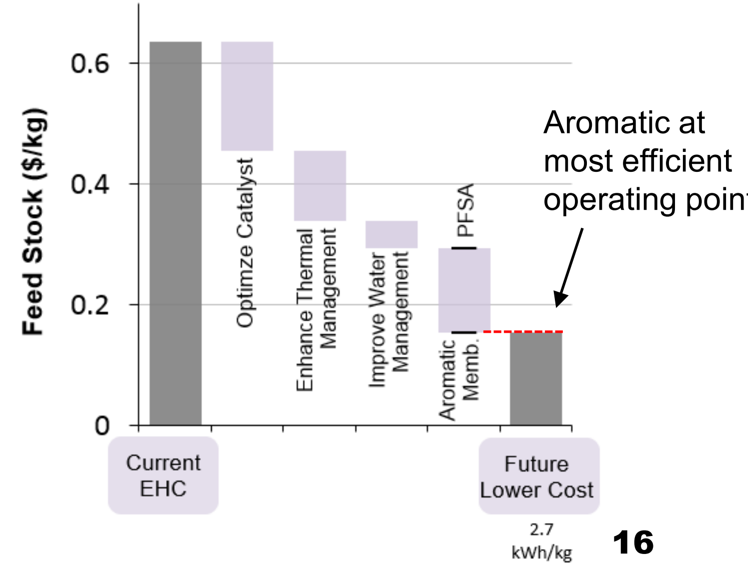
[1]10 year lifetime, [2]Based on electrical cost of $0.057/kWh & 5.3 kWh/kg, [3]Design Capacity: 100 kg-H_2/hr. Assumes large scale production. [4]Compared to previous year.

CapEx



- Based on 1 A/cm² Operation. Increasing Active Area & Operating Current Density reduces Capex repeating costs proportionally

OpEx



Cost Objectives

- $3.4k/year (O&M) and capital cost of $170k per compressor
- Economics: determined using PEM-based system cost models
  - Feed Stock, based on Efficiency Range @ 350 bar:
    - 2.7 to 3.7 kWh/kg (Aromatic MEA)
    - 3.1 to 5.3 kWh/kg (PFSA- Mod A)
    - Projected Operating Lifetime: 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 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

Summary

- **Program Novation (Giner, Inc → Giner ELX, Inc.)**
- **Yr1 Milestone Achieved:**
  - Successfully operated EHC at 5,000 psi (350 Bar) ≤ 0.250V @ ≥ 1,000 mA/cm²
  - Demonstrated Aromatic membrane operation at 0.217V @ 1000 mA/cm², 5,000 psi, 35 psi inlet
    - Yr1 Milestone also demonstrated for PFSA membrane
    - Demonstrated pressure ratio of 100, single stage
    - Highest Efficiency for EHC operating at 5,000 psi
- **Membrane**
  - Further optimization of membrane
    - Reduced back diffusion by > 50% in PFSA
      - Applicable to Aromatic membranes
    - Achieved further improvements in cell voltage
      - Aromatic membrane: Achieved significant improvement in membrane performance
        - Stack Efficiencies to 2.7 $kWh_e/kg\text{-}H_2$ (@ 1,000 mA/cm²)
    - WaMM: fabricated flexible WaMM compatible with high pressure operation
      - No loss in performance when operated at high pressure
      - Significantly improves water management, stabilizes cell voltage
- **Stack/System Hardware Development:**
  - Completed preliminary review of EHC System with Intertek
    - Established appropriated standards, component classifications, and operating requirements for certification
  - 875+ bar stack design, procurement of components initiated

Future Plans & Challenges (FY2018-19)

Future Plans*

- Membrane: Complete investigation on Aromatic membranes
  - Continue membrane optimization; reduce back diffusion
  - Conduct 1,000 hour duration testing
- Stack: Design, fabricate, and test high-pressure 12,688 psi (875 bar) stack hardware
  - Initiate 875+ bar testing: in 50 cm^2 hardware, then 300 cm^2 hardware
- System: Initiate assembly of prototype system design
  - Complete selection and procurement of system components

Future Challenges

- Increase stack active-area to 300 cm^2 or larger
  - Also requires scale-up for Aromatic membranes
- Increased operating pressure
  - Maintaining seals of stacks at operating pressure of >12,688 psi
- 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