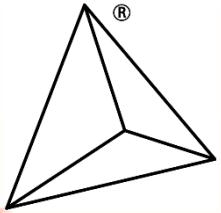
New Approaches to Improved PEM Electrolyzer Ion Exchange Membranes



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Tetramer Technologies, L.L.C.

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Project ID # PD151

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Overview of Current Project

Timeline

- Start: April 10, 2017
- End: April 9, 2019
- Phase IIB Effort Complete: 50%

Budget

- Total Phase IIB project funding
  - $1,000,000
- Funding received in FY 17
  - $184,272
- Total funding planned for FY18
  - $653,520

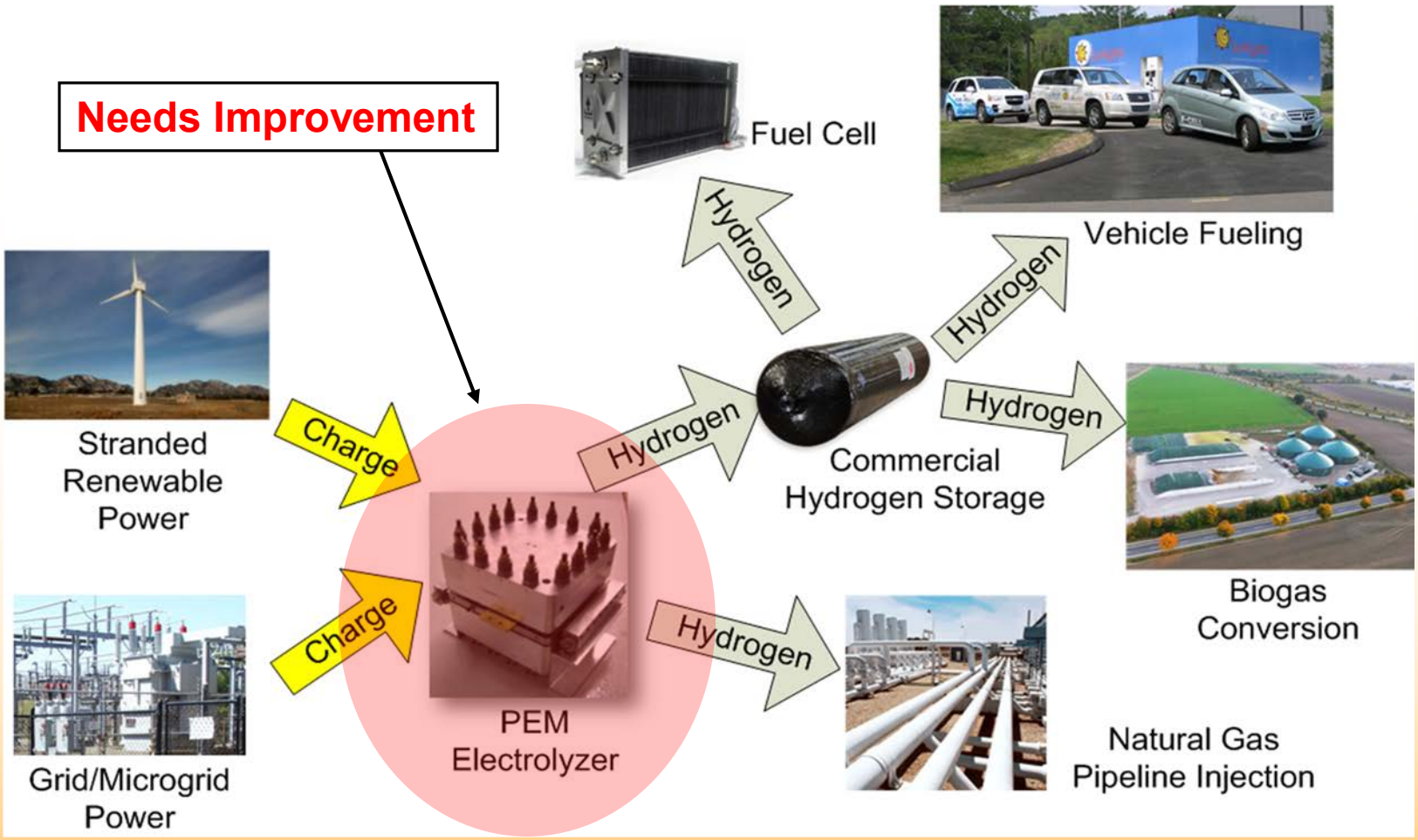
Barriers

- Performance
- Mechanical Durability
- Cost

Partner

- Proton OnSite (Wallingford, CT)

Relevance to DOE



Hydrogen Production for Grid Stabilization and Energy Storage

Approach – Tetramer Ionomers

Polymer Design Elements

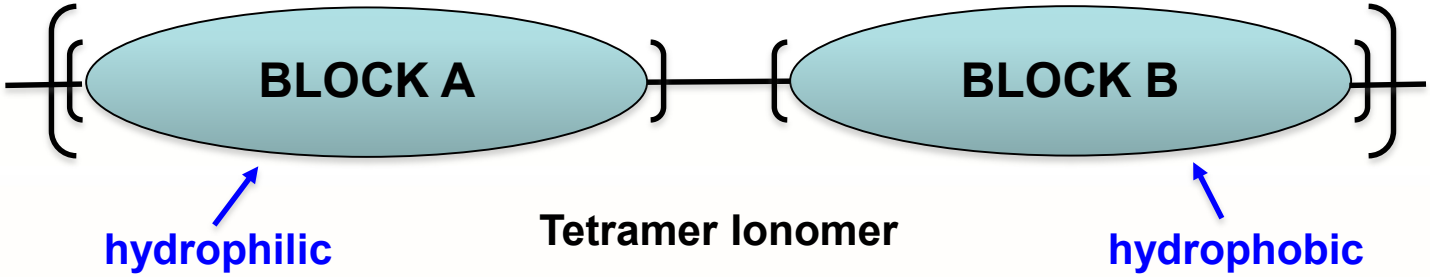
Design proprietary conductive polymer molecular architectures to enable cost efficient hydrogen generation while minimizing physical and chemical degradation.

Performance	***Mechanical Strength***	***Processability***	***Stability***
Conductive Ionic Groups & Morphology	Rigid Structures & Hydrophobic Linkages	Stereoisomeric & Solubilizing Groups	Chemical Resistance Crosslinking & Mw

Goals

- Optimize ionomer molecular architecture and membrane configuration to enhance performance and durability.
- Further develop synthetic procedures and scale-up.
- Work closely with Proton OnSite to build a prototype electrolyzer unit and assess performance over time in customer trials.

Approach – Tetramer Ionomers



Molecular Architecture
[Backbone structure]

Hydrophilic : hydrophobic ratio
Block lengths of A and B

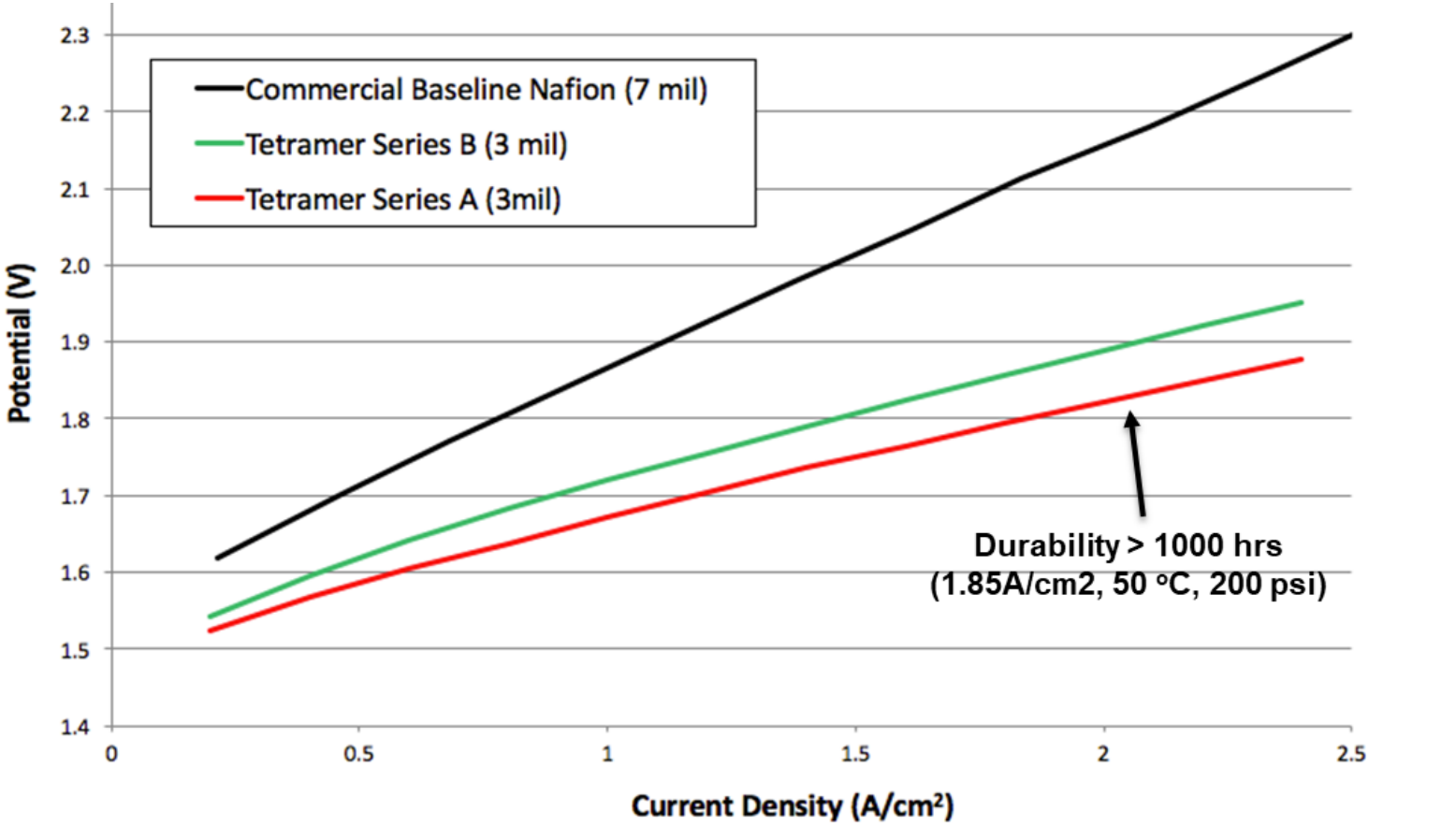
IEC
[Degree of functionalization]

Conductivity

Distribution of IEC
[Selective Functionalization]

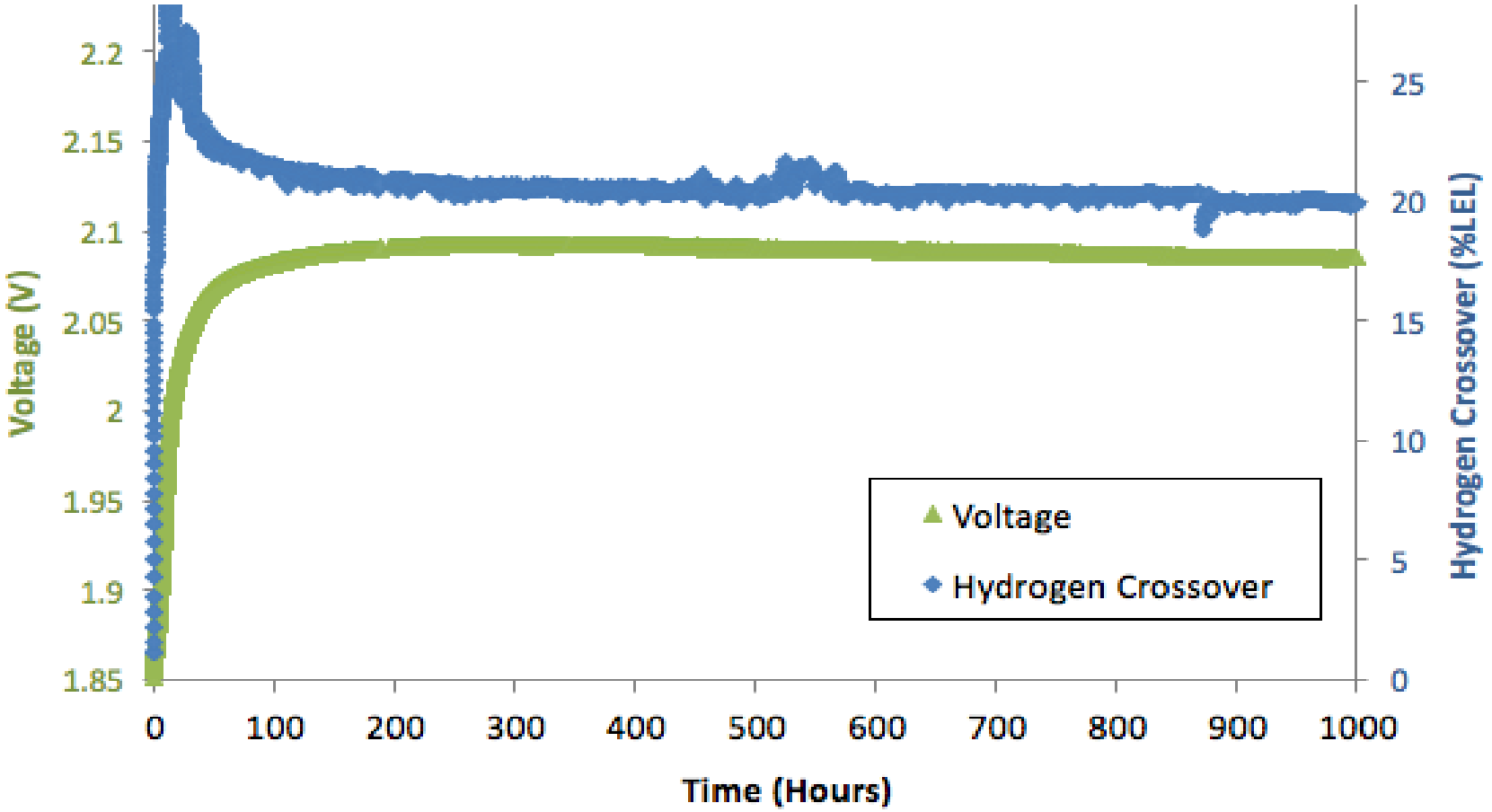
Effective conductivity & backbone stability
Performance and Durability

Phase IIB Baseline



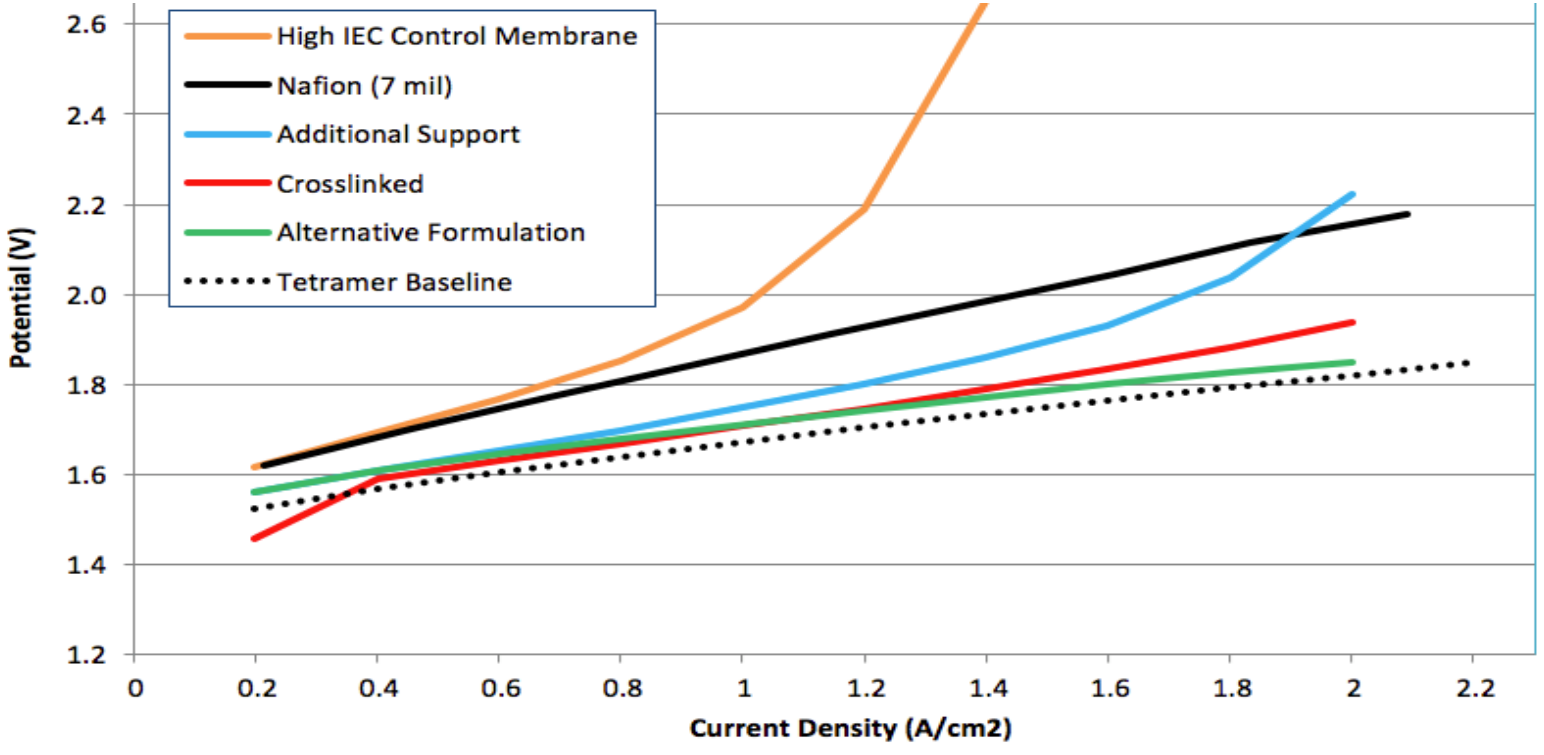
Phase II down-selected ionomers
(based on performance and durability)

Series A Membrane – Durability Test



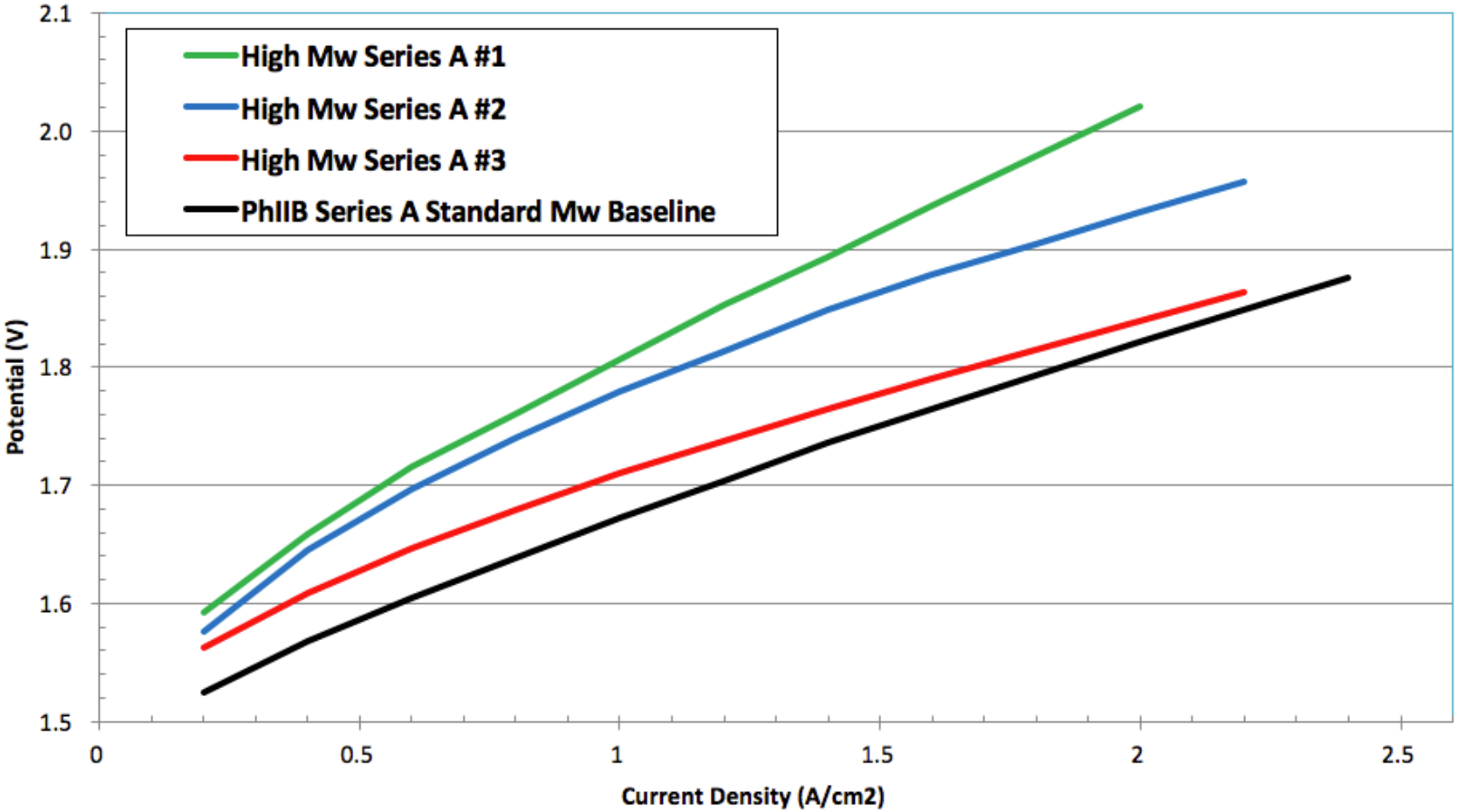
1000 hrs durability with acceptable hydrogen crossover (1.85A/cm^2, 50 ^{o}C, 200 psi)

Increased IEC and Swell Control



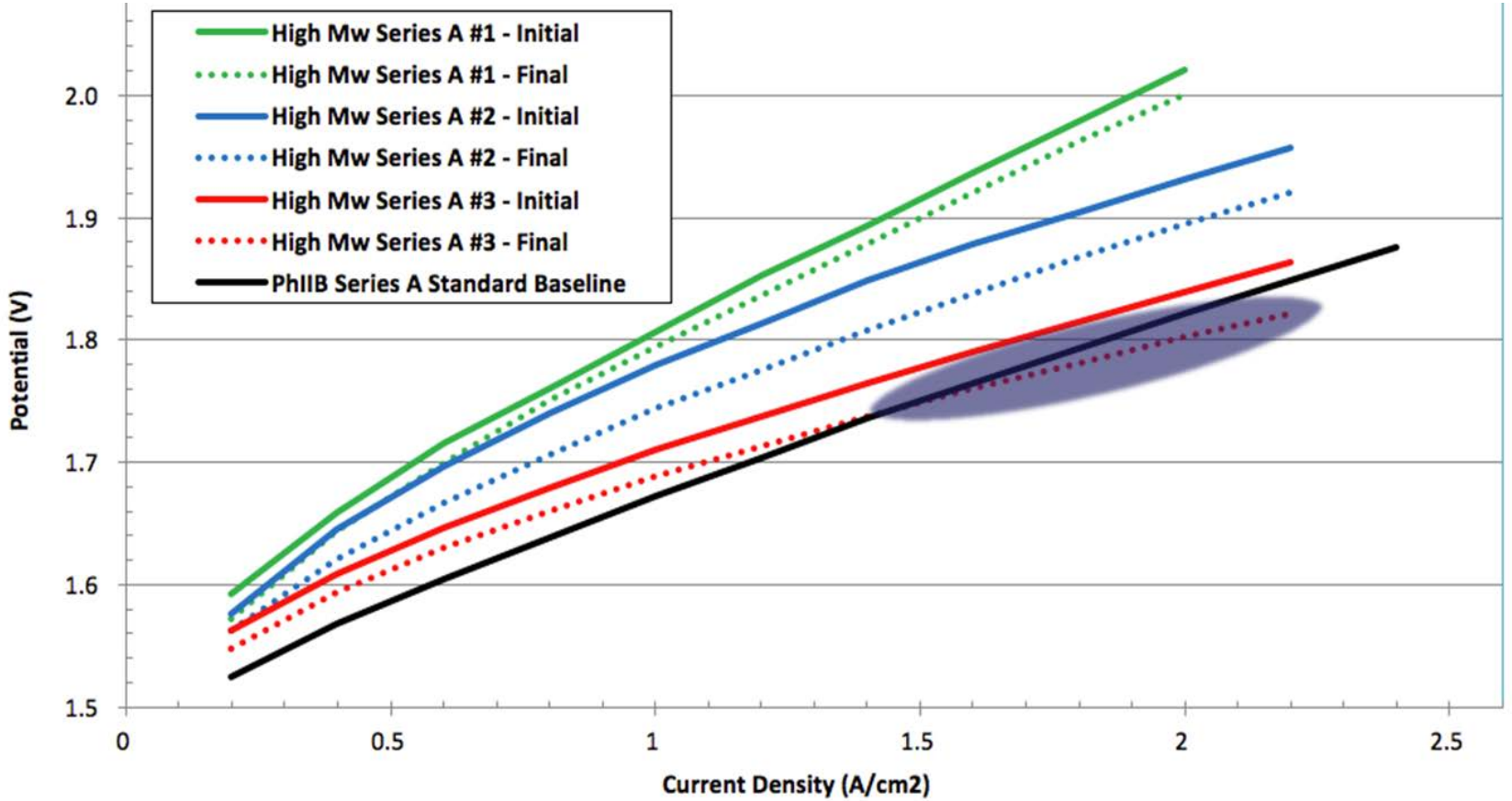
1) Process changes → increased IEC Series A ionomers ✓
2) High IEC membranes failed initial performance test due to excessive swell
3) Demonstrated 3 approaches to control swell:
   i. Additional support incorporated into membrane ✓
   ii. Crosslinking ✓✓
   iii. Alternative formulation of casting solution ✓✓✓

Additional Approach to Control Swell



Series of high molecular weight ionomers synthesized with varying IEC
Synthetic parameters optimized and reproducibility demonstrated

Conditioning Improves Performance



Initial = Cycle 1, Final = Cycle 5
Performance improves with conditioning and exceeds Series A baseline

Synthesis - Process Developments

Monomers

- Refined synthetic processes
- Increased purity
- Reproducible at 5L reactor scale
- SOP's in place
- High purity monomers prepared for polymer scale-up

Polymers

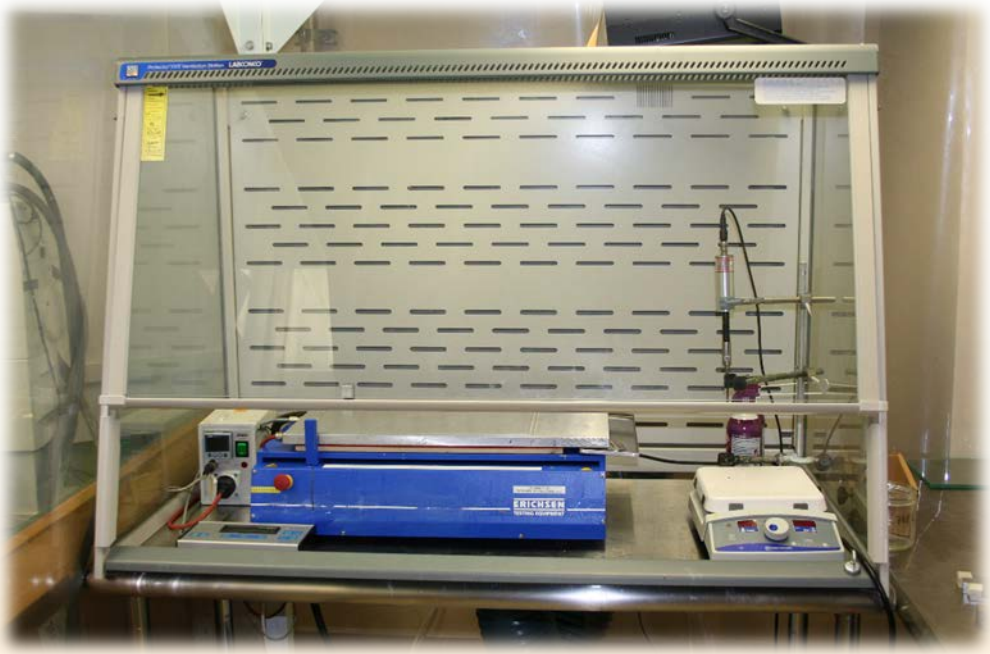
- Demonstrated reproducible control of molecular weight
- Polymerization parameters defined
- Further optimized processes to reduce solvent waste
- SOP's in place ready for scale-up

Ionomers

- Improved reactor design
- Reaction conditions optimized for reproducibility
- Purification procedures defined
- SOP's in place ready for scale-up
- Quality control parameters defined

SOP's and QC parameters will be updated to incorporate scale-up developments

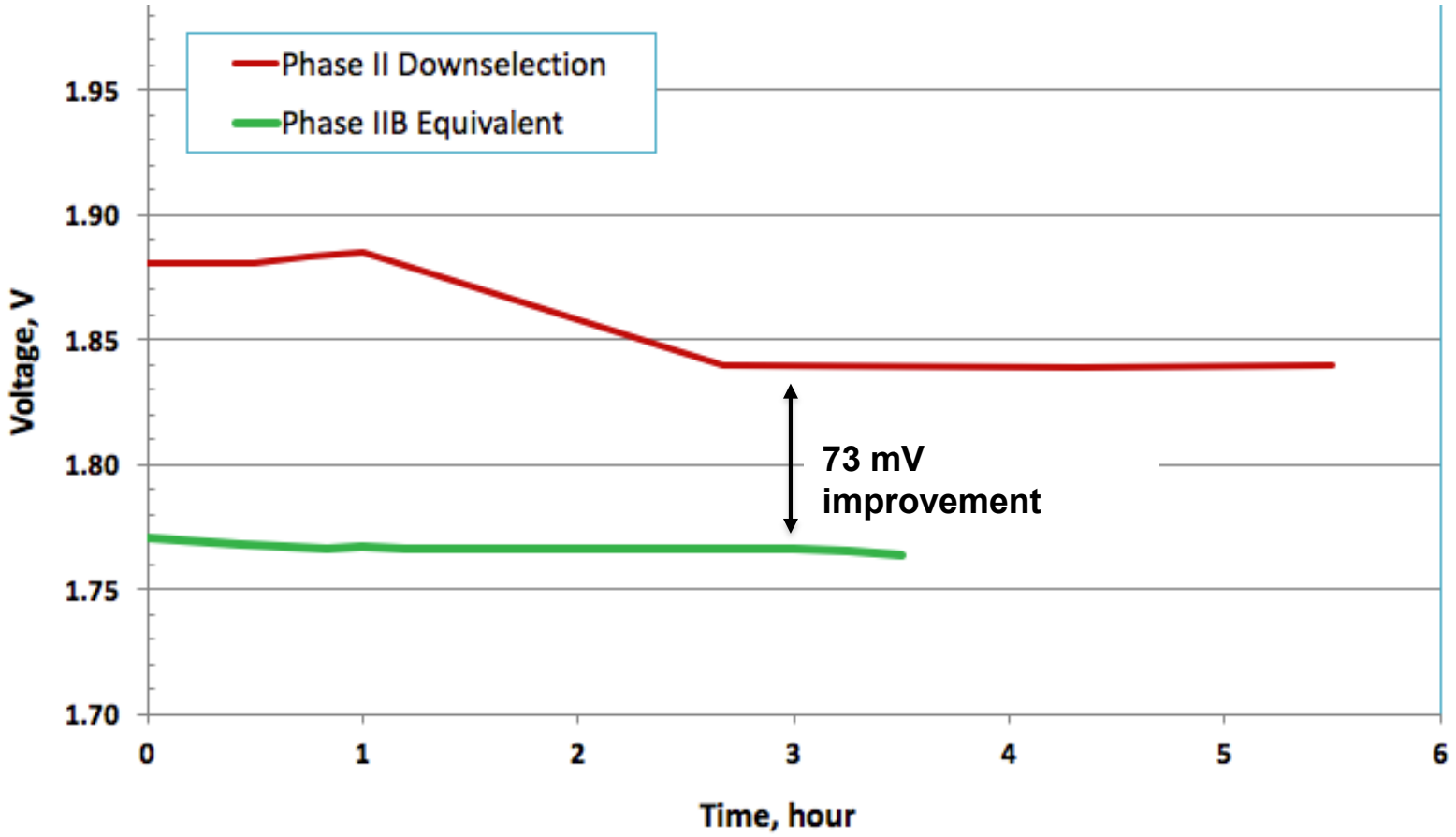
Membrane Configuration Down-Selection



Erichsen Automated (Heated) Casting Table in Clean Room

- Current Membrane Down-Selection based on:
  - 45 different membranes (from 19 different ionomers) – Phase II
  - 15 different membranes (from 10 different ionomers) – Phase IIB
- SOPs refined
- Appropriate for commercial continuous casting
  - Discussed trials with engineers at a commercial coater facility

Net Performance Improvements



Stable short term durability with enhanced performance
Longer term durability tests in progress

Cross-over Mitigation Development

- Proton is currently working on a strategy to mitigate cross-over of hydrogen into the oxygen stream.
  - Final configuration will be capable of maintain safe levels at hydrogen differential pressure of 30 bar (435 psi).
- The process is being developed to have flexibility across multiple membrane chemistries.
- Initial work conducted on a commercial membrane of thickness comparable to the Tetramer solution.
  - Process feasibility is currently being demonstrated and will be transferred to the Tetramer membrane in later Q2 ’18.
- Hydrogen levels are measured at various current densities to evaluate effectiveness during system turn-down states.

Summary of Achievements

- Proprietary polymer architectures have shown performance exceeding current commercial electrolyzer membranes through the use of thinner membranes, while maintaining low hydrogen crossover and excellent durability.
- Hydrophilic / hydrophobic tuning has been used to optimize performance while maintaining backbone integrity.
- Over 30 polymer structures have been explored to understand the trade-offs between performance and durability.
- Over 60 membranes have been assessed to determine optimum configuration.
- All procedures have been validated and SOPs have been optimized to accommodate scale up.
- Roll coating approaches to the current membrane configuration have been assessed by a commercial coater who is keen to initiate trials.

Collaborator

Proton OnSite:

A leader in on-site hydrogen generation and the largest manufacturer of hydrogen generators across the globe.

Critical Role:

Testing and qualification of membranes materials according to commercial specifications.

Cell design and manufacturing.

Future Work for Phase IIB

- Scale-up down-selected materials and demonstrate reproducibility.
- Perform casting trials with commercial coater and assess membranes for performance and consistency.
- Optimize cell design and membrane conditioning steps.
- Build prototype to determine longevity under customer operating conditions.
- Perform final cost analysis.

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

Electrolyzer Development Summary

Relevance – The need still exists for improved electrolyzer membranes that will enable the cost effective production of hydrogen. Further development is needed to enhance grid stabilization and facilitate renewable remote energy storage.

Approach – Tetramer's synthetic approach to new polymer molecular architectures has generated versatile ionomers that have outperformed commercial membranes.

Technical Accomplishments – Detailed on previous slides. New monomers and polymers were successfully synthesized which have shown improved electrolyzer performance.

Collaborations – Partners in place to evaluate polymers and build both prototype and fully commercial modules with down selected materials.

Future Work – Reproducibility will be evaluated, a prototype will be built and tested and a detailed final cost analysis will be performed.

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