Ref. Ares(2024)4602744 - 26/06/2024

IONOMR
INNOVATIONS

PFAS Replacement in the Hydrogen Economy/Electrochemistry

ECHA Technical Submission: https://tinyurl.com/IonomrECHA
Canada Gazette submission: https://tinyurl.com/CanadaPFAS

Outline

1) **Intro to H2 and CCU foci**

2) **Research Challenges** - the high bar set for PFSA replacement

3) **Drivers to innovate** – *both* direct replacement and indirect substitutions enable a better, safer, cost-effective, and world-scalable clean energy economy

4) **Support for acceleration** – a mere four projects for an all-EU supply chain hydrogen economy

50+ Employees

Rochester, NY, USA & Vancouver, Canada

$50M+ USD Funding incl. Bekaert, ArcelorMittal, Shell, Chevron, Samsung, Asahi Kasei, & SAIC

Two Breakthrough Materials Families

Company Overview

Ionomr – the leader in next-gen ion-exchange materials

Diverse Marketplace

Hydrogen Production, Fuel Cells & CCUS

Industry Experts

Supported by more than 10 years / 100K hours of R&D

Innovative

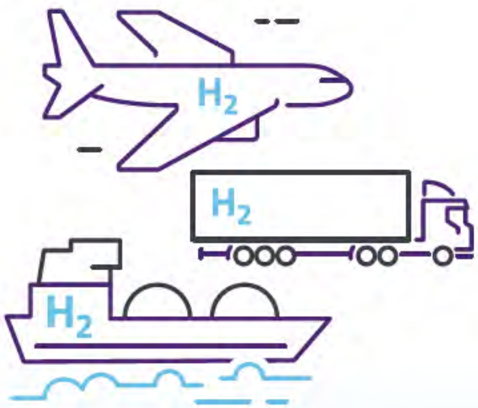
50-year breakthroughs in both AEM and PEM solutions

Protected IP

Broad patent portfolio incl. composition-of-matter

Target Verticals

Heavy Duty Fuel Cells



Green Hydrogen

CO_2 Capture & Conversion (CCU)

Cost & Efficiency Breakthrough

The first durable, high performance non-PFAS, and the first high-temperature operation, a 30+ year goal, enabling large reductions to system cost & complexity

Enabling CAPEX-effective H_2

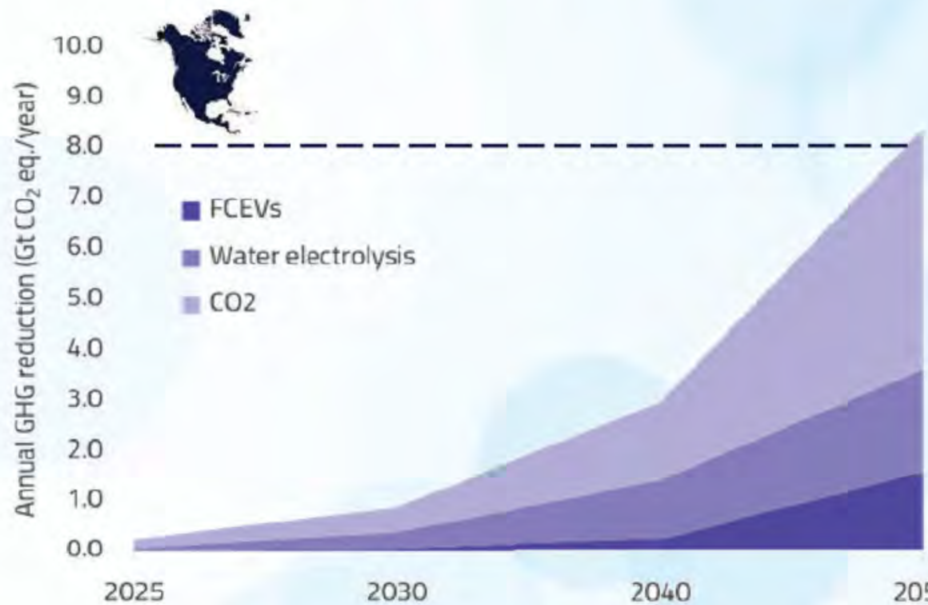
10,000+ hour durability demonstration of the first AEMWEs operating in industry-relevant conditions & form factors, exceeding EU 2024 goals

Unlocking Carbon-to-Value

Integrated in numerous electrochemical systems for carbon capture and conversion, incl. the first long-lived direct conversion to high-value ethylene/'C2+'

Decarbonizing the Most Difficult GHGs

Ionomr's target markets H_2 & CCU capable of >8 Gt CO_{2eq} per year by 2050



"Limiting warming to 1.5 °C would reduce economic damages relative to 2 °C… the accumulated global benefits will exceed US $20 trillion" – Burke et al (Nature, 2019)

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Additional Applications

Next-Gen Batteries

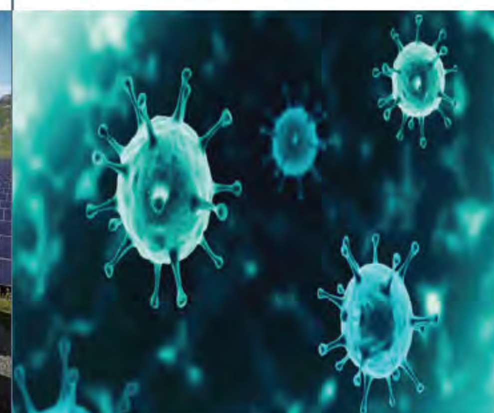
- Li-ion Electrode Additives
- Advanced Solid-State + Na/K Separators & Coatings
- LiS, Li-Air, solid-state NiMH

Long-Duration Energy Storage

- Hydrogen Compression
- Redox Flow Batteries
- Metal-Air Batteries

Anti-Microbial Coatings

- Surface coatings
- Fabrics
- Plastics integration

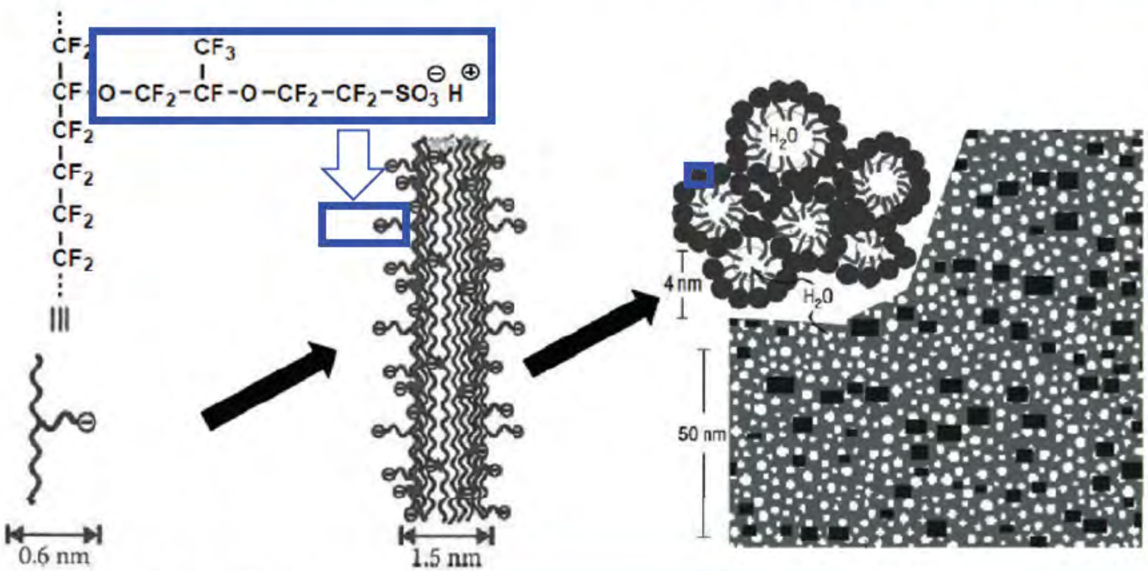


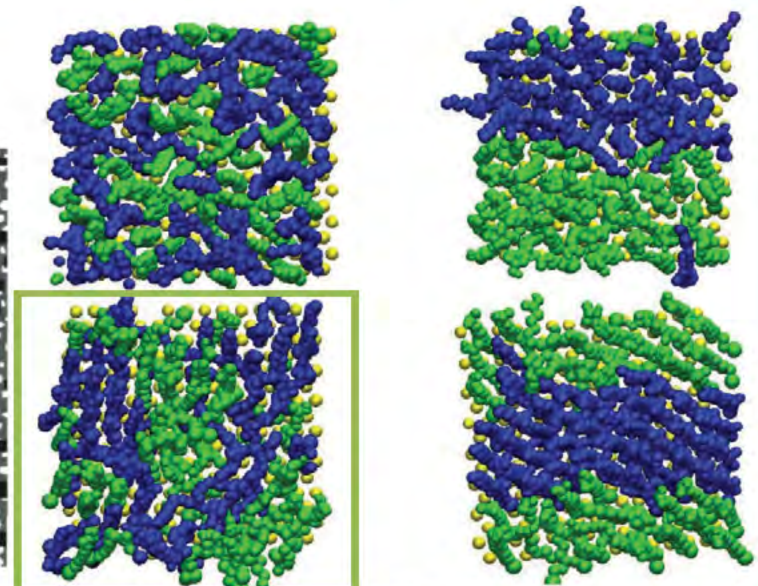
Chemicals & Circular Economy

- Lithium Hydroxide
- Battery Recycling
- Process Water Re-use

Ion-Exchange Materials in Target Applications

- Perfluorosulfonic acids (PFSAs) – Nafion (Chemours), with Aquivion (Solvay/Syensqo), & formerly 3Mion – underlie all the most efficient & safe electrochemistry
- Main negative application properties are low softening point (Tg) & high gas permeability
- Functional units degrade into molecules of the very highest concern





[1] C&EN 100(24), 2022
[2] M Eikerling *et al* J. Chem. Phys. 2008 & KD Kreuer *et al* Chem. Rev. 2005

Only functional strategy is non-predictive to develop

Acidic Fluoropolymers Measurably Degrade

- Even if acidic fluoropolymers can be made without surfactants & process aids, they degrade into materials of the highest concern & impact (PFOS & PFOA-like materials C2-C12)
- Additional issue is PFOS/GenX or similar is needed for ePTFE processing, used for reinforcement

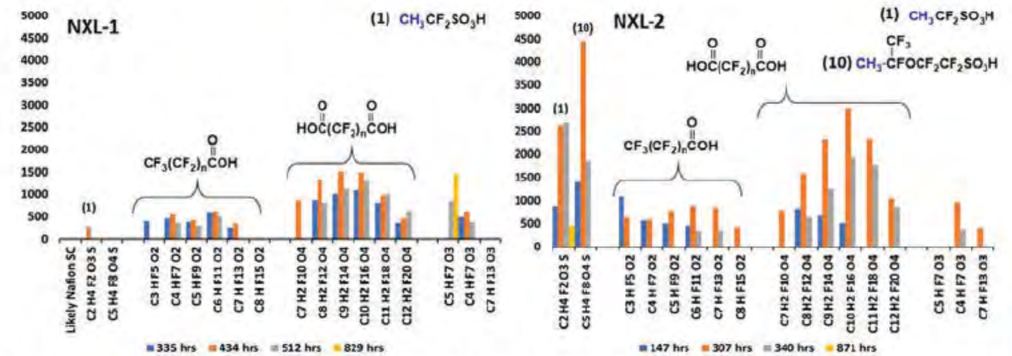
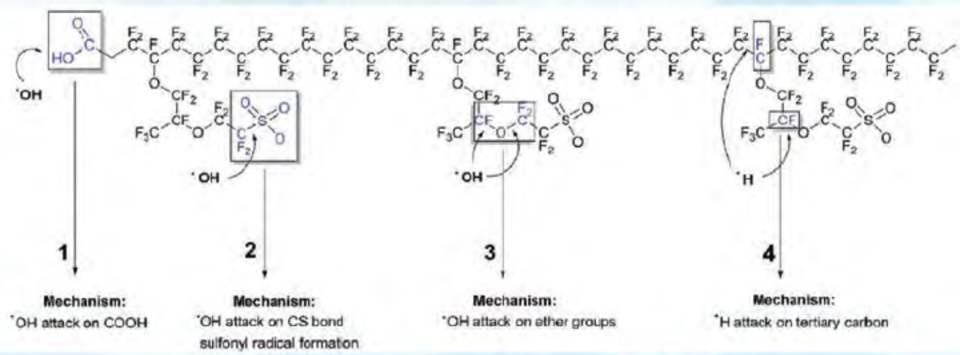
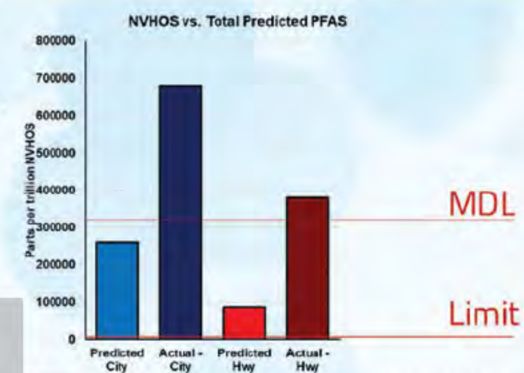


Figure 8. Fragments detected from Nafion XL Membrane-1 (left) and Membrane-2 (right) cathode effluent water at four time points. (Note: no fragments detected in the NXL-1 51 h and NXL-2 24 h samples).





- Fluoride release is typically only measured but direct PFAS acid emissions
- range from ~5% (WL Gore) to ~33% (3M) of measured F^- release
- In particular the H· pathways are unprotected (R)

[1] M. Yandrasits & coworkers *J. Electrochem. Soc. Rep.* 168(2), 2021. DOI: 10.1149/1945-7111/abe56a
[2] M. Bodner *et al.* ECS Trans 2017 80(8), 2017. DOI: 10.1149/08008.0559ecst
[3] L. Ghassemzadeh, K.D. Kreuer, & cowoerkrs *J Power Sources* 2009.
[4] M Zaton, J Roziere, & DJ Jones, *RSC Sustain. Energy Fuels* 1(3) 2017.

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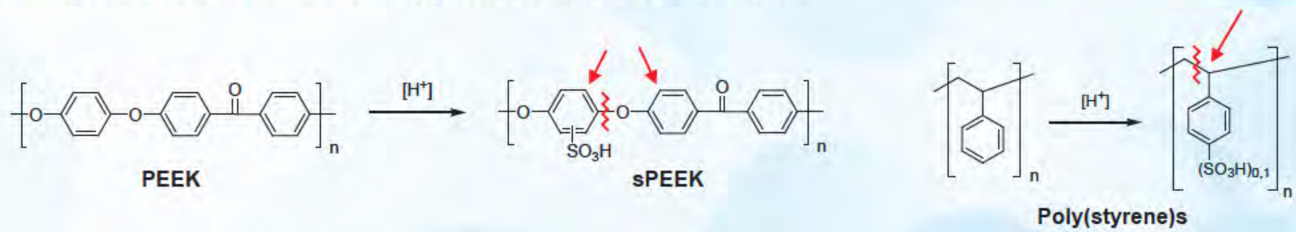
Initial Hydrocarbons Performed, Failed on Durability

Sulfonated derivatives of poly(ether ether ketone) and poly(styrene)

- Higher degrees of acid functionalization (IECs ~2.5) performed well Nafion (IEC ≈ 1.0) but borderline water soluble
- Lower gas crossover – better efficiency
- Honda (working vehicles) and NASA (Gemini earth-orbiting mission 1962 - 1965)



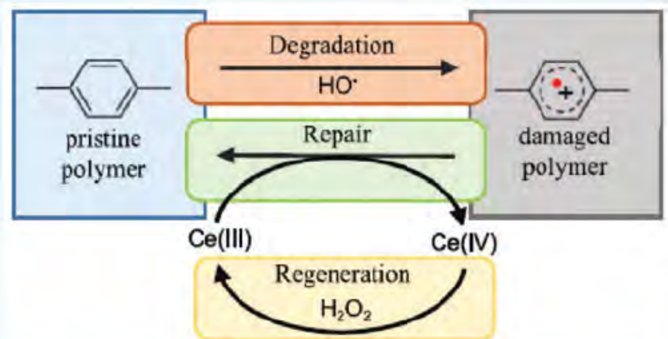
Challenges

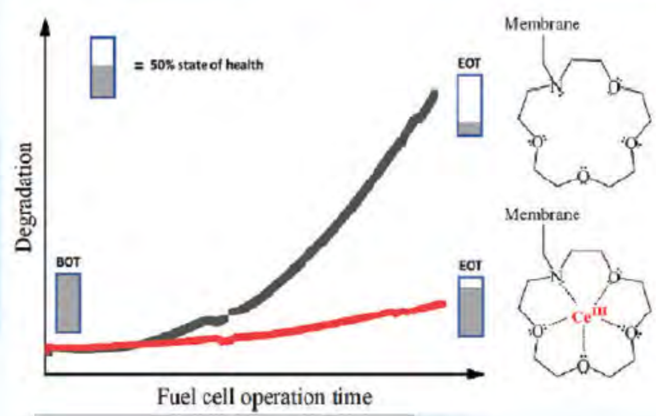
- Chemical stability – far greater sensitivity to oxidative degradation than PFSAs
- Performance across design window, especially in electrodes – conductivity highly sensitive to hydration state
- **No viable fixes to these issues**
  - 'Protection' routes turned these into PFAS
  - Acid functionalization control (post-functionalized)
  - Dimensional and mechanical instabilities
  - Solubility in hot water at IECs > 2.5 meq. g^{-1}

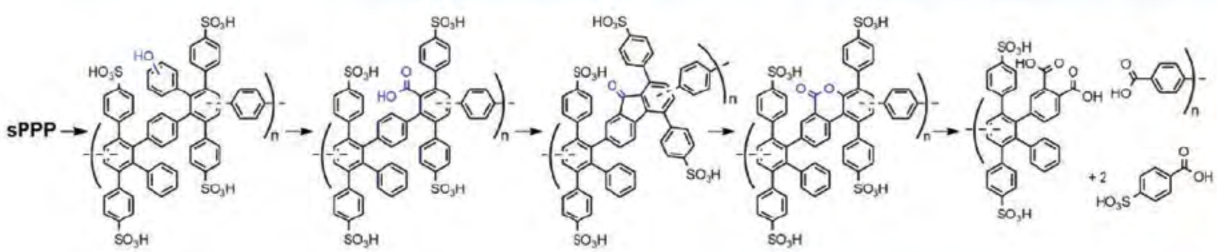
The First Stable Hydrocarbon PEMs

Polyphenylenes have been developed as innately stable, but also the only known non-F systems capable of self-repair

- Reversible fast radical addition step
- Many paths not resulting in chain scission
- Addresses key concern, the long-duration chemical stability







[1] de Wild, Gubler *et al.J Power Sources*. **2023**, 560, 232525;
[2] Adamski, Peressin, Holdcroft *Materials Advances* **2021**, 2, 4966.
[3] Holmes, Holdcroft *et al. Chem Mater* **2019**, 31, 1441-1449.

Two Breakthrough Chemistries, Four Products

Polymer

Ionomer (electrode binder) powders

Pemion®

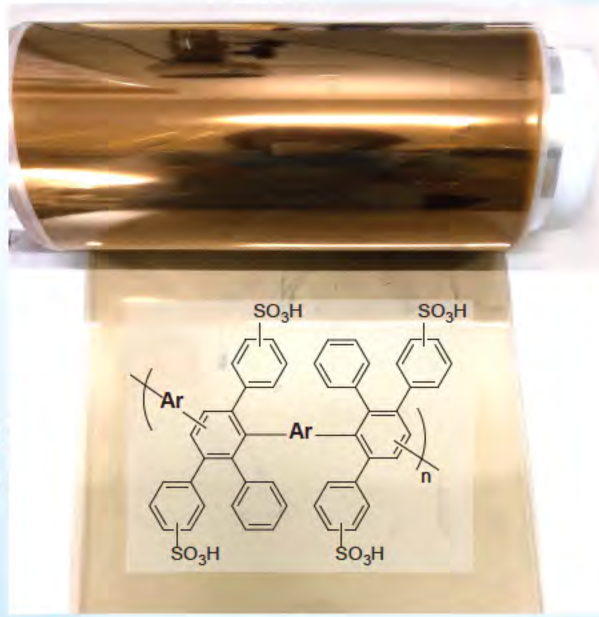
Aemion®

Developmental breakthroughs in AEM (2008) & PEM (2012) from a world-leading materials lab @ SFU. Patents and know-how from fundamental ideas and processes to specific formulations, coating, device and integration

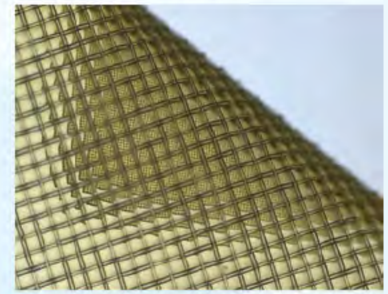
Films/Membranes

Composites (nonwoven & woven)

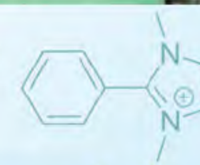
Pemion®



Aemion®



Unprotected
= Unstable



Protected
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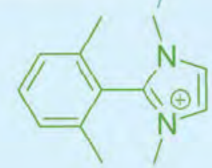


Pemion® Provides Transformative Properties

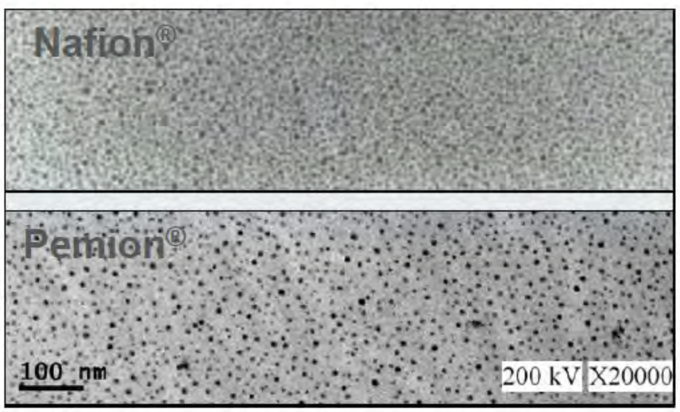
An ideal PEM should have:	PFSA	Pemion®
High performance Proton-conductivity, water transport	✓	✓
Selectivity Minimal permeability to gases (H_2, N_2, O_2)	!	✓
Durability Long lifetimes to meet system requirements	✓	✓
Cost-effective and scalable chemistries To meet rapidly growing PEM demands	!	✓
Be made from env't-friendly materials To match the goals of the hydrogen ecosystem	✗	✓
High temperature stability For *in-situ* operation up to 120 °C*	✗	✓

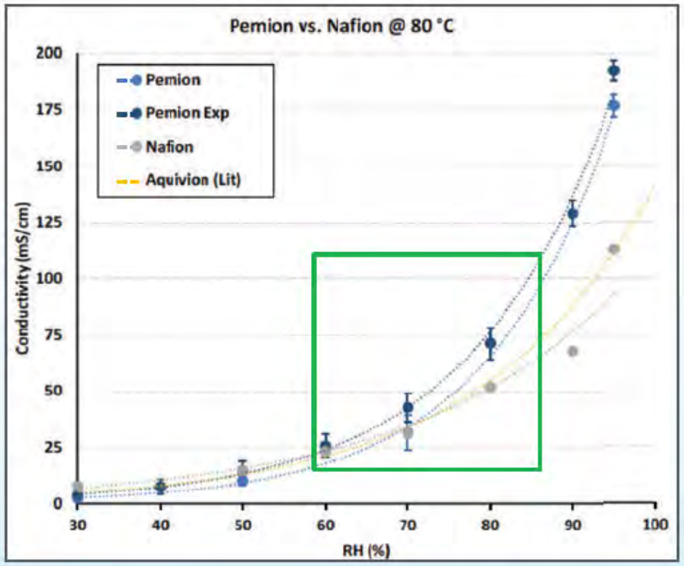
*DOE, Clean Hydrogen-JU, NEDO, Toyota Motor Corp.

Out-Performing PFSAs

- Mid humidity (RH) range (60-85%) *ex-situ* approximates low RH fuel cell operation → water transport from fully humidified H_2 recirculation
- Conductivity > 1.5x advantage vs. PFSAs at 80 °C
- >2 to >>3x advantage at room temperature & below

Pemion exhibits well-defined phase segregated morphology linked to high protonic conduction





Ex-situ **in-plane conductivity of monolithic films at 80 °C as a function of RH: Pemion as-produced, mid-range RH controlled Pemion variant c.f., Nafion 211, and Aquivion (yellow line, literature).**

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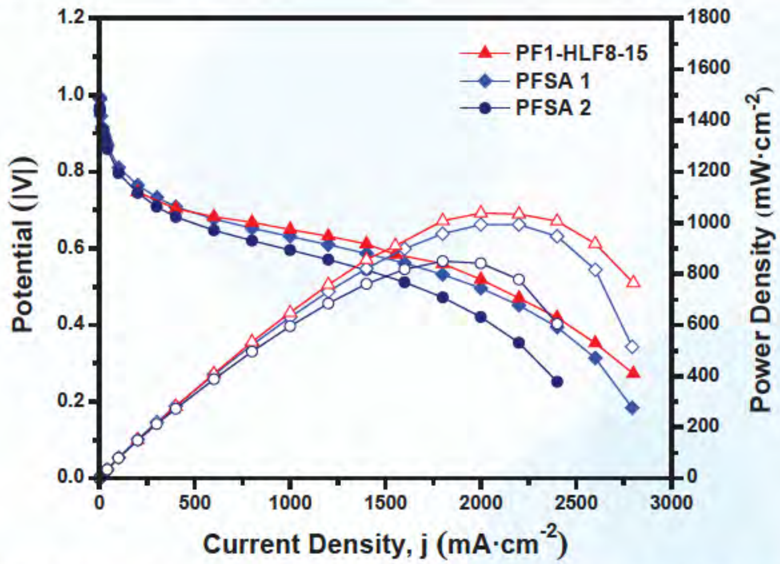
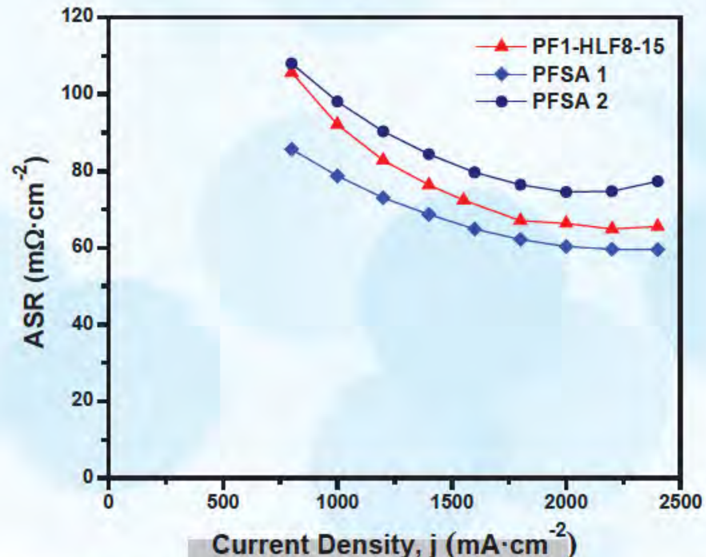
Pemion® – Ultra-Low-Humidity Performance

Exceptional performance in extremely low-RH conditions meets or exceeds SOTA PFSAs

- **Completely unprecedented for hydrocarbon-based materials**
- Enabling PFSA replacement in all use-cases. Lower area resistance combined with greater temperature capabilities again indicates electrode engineering will exceed performance significantly.





Graph 3: Polarization (left) and resistance (right) curves of membranes measured under 30/30 % RH, H_2/Air 150 kPa_g symmetrical, 80 °C (3 min/pt)

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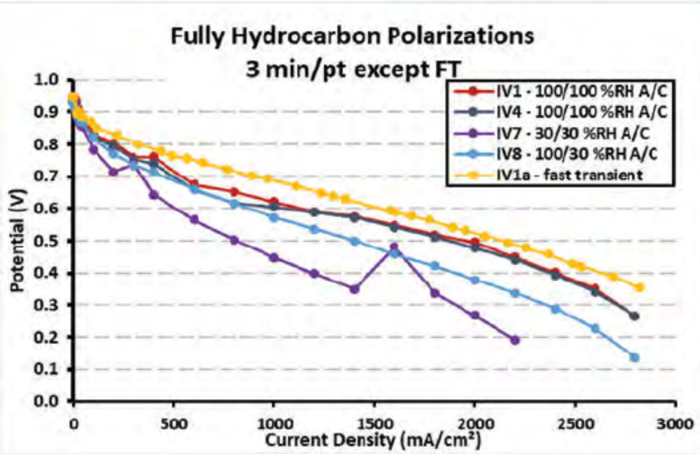
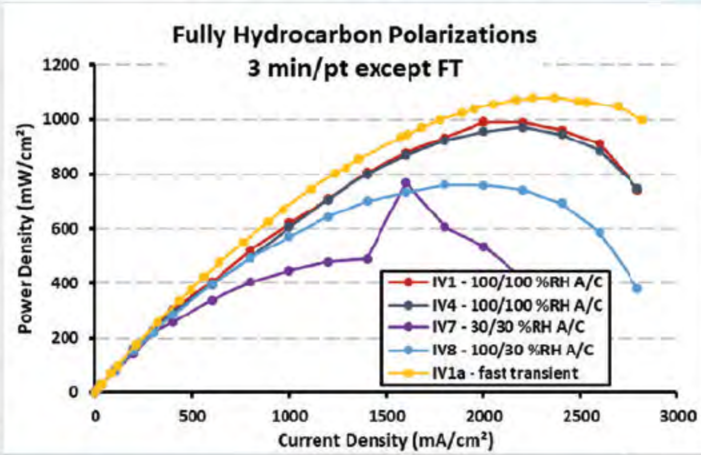
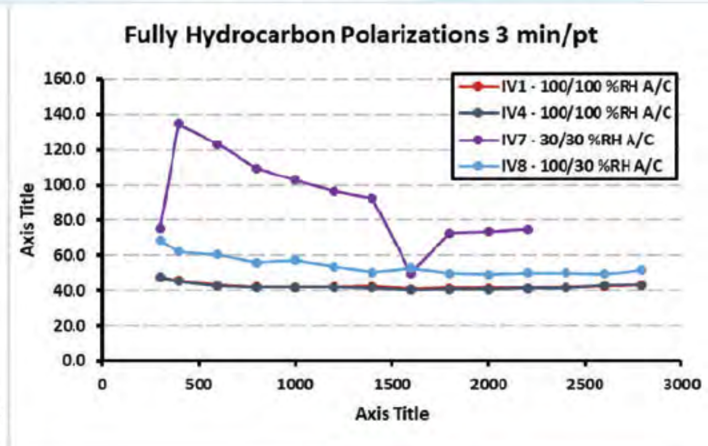
Pemion® – Fully Hydrocarbon Performance

Highly preliminary data in non-optimized conditions, but performances near-parity

- **Comparable area resistance in all conditions, comparable kinetics both high and low RH**
- Strong indicator unit cell design & optimization fully effective to approximate performance parity







High Temperature Operability ≥110 °C

Pemion: No observable losses over 72 hour test – High performance and voltage stability

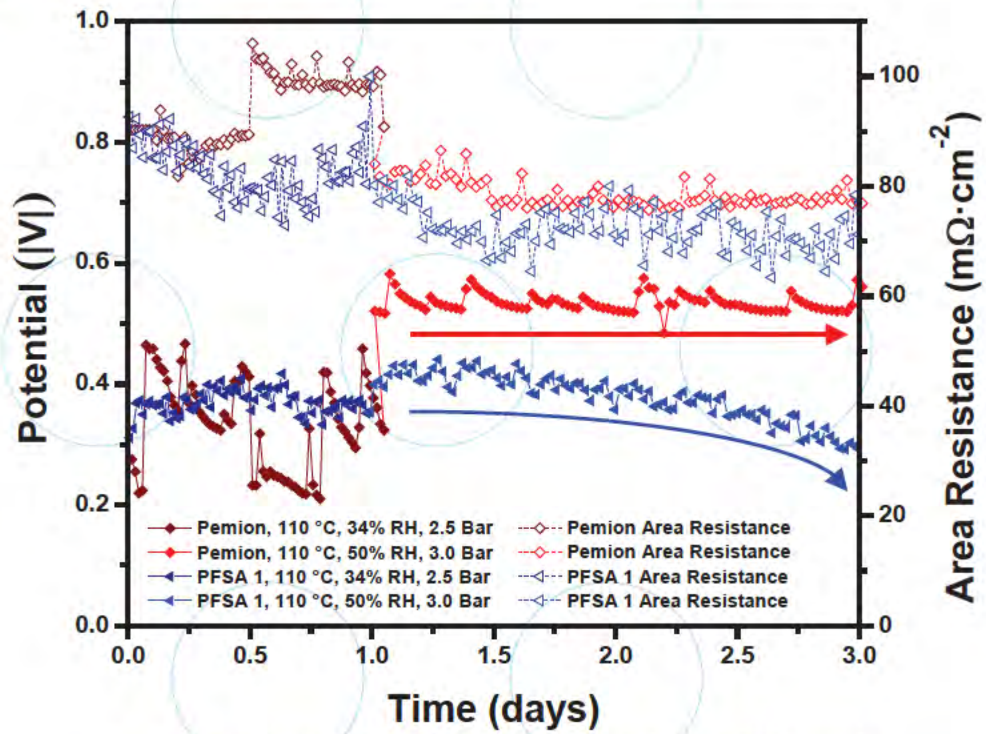
PFSA: 30% performance loss over 48 h (-2.7 mV/h)

Potential to unlock:
- HD stack 'right-sizing'
- Small heat exchangers
- Aviation applications

Conditions:
- 2.5 A/cm² current hold (~1.4 W/cm²)

1. 24 h at 34% RH, 2.5 bar_g, 1.5/1.8 H_2/air stoich., then
2. 48 h at 50% RH, 3 bar_g, 1.5/1.8 H_2/air stoich.

Strong indicators of benefits at full scale w/ anode recirculation & enhanced water flux



Graph 5: Potential (left axis) and area resistance (right axes) membranes measured under HT operation at 110 °C.

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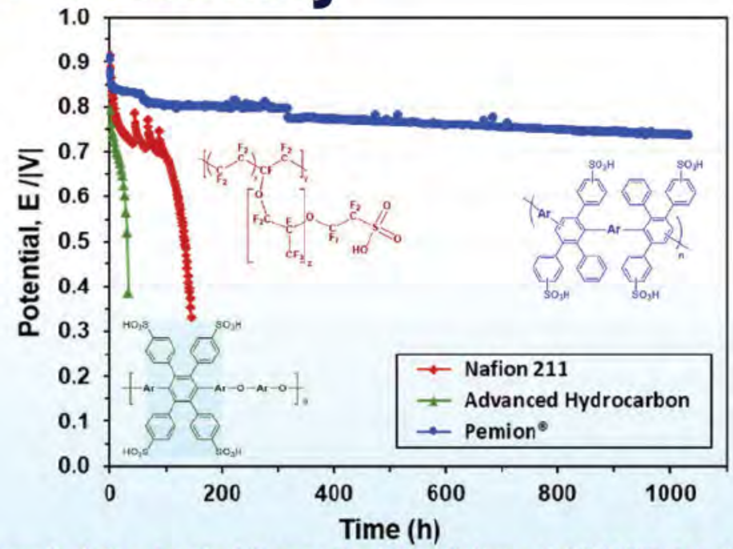
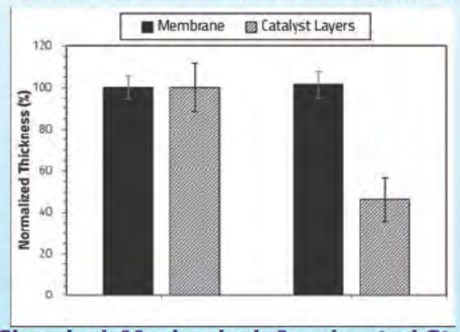
Pemion® – Extreme Chemical Stability

The Pemion® polymer is **inherently chemically resilient** against radical-induced degradation

- 1000 h without failure (2x DOE membrane target) **without radical scavengers**
- DOE-specified chemical stability accelerated stress test – extended hold at open circuit voltage under 30% RH, 90 °C
- Successful PEMFC operation after accelerated stress test @ ~70% of initial performance
- **Harsher stress test exhibited no membrane thinning** with no radical scavengers while >50% reduction in PFSA-based catalyst layers, an entirely unexpected result



DOE Chemical Accelerated Stress Test Conditions at 30/30 % RH, 90 °C, OCV

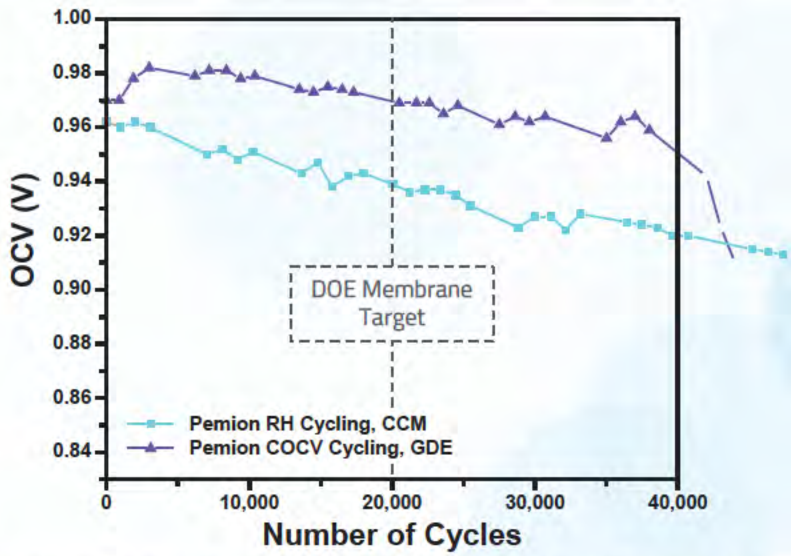


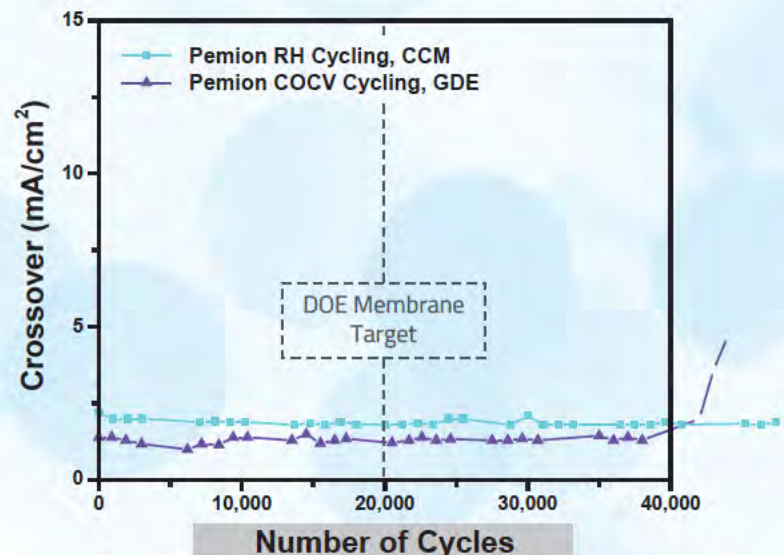
DOE Combined Chemical-Mechanical Accelerated Stress Test Conditions

Pemion® >2x US DOE Durability Targets

First and only hydrocarbon-based material to ever achieve main industry durability targets

- Multiple tests showcase limited degradation across entire target timeline
- **20k cycle target achieved, and doubled**, under combined chemical/mechanical (COCV cycling) via DOE protocol
- Membrane gas crossover < ⅓ PFSA membranes for life of test



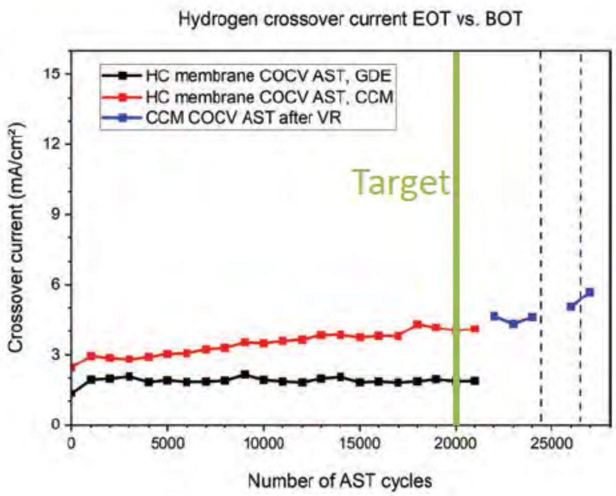


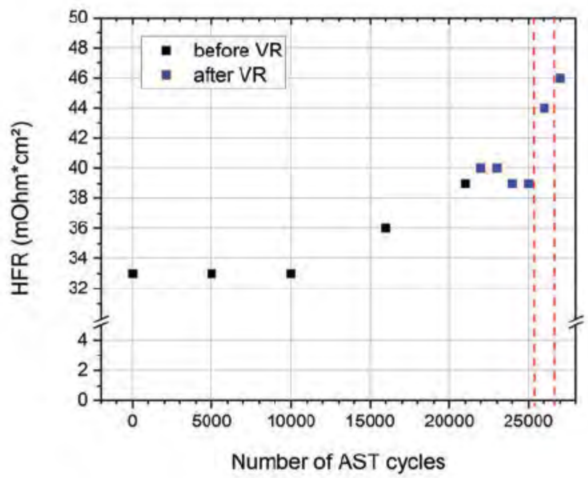
Graph 7: OCV (left) and gas crossover current (right) curves of membranes measured under COCV (OCV and cycling RH 0 to 100%) at 90 °C.

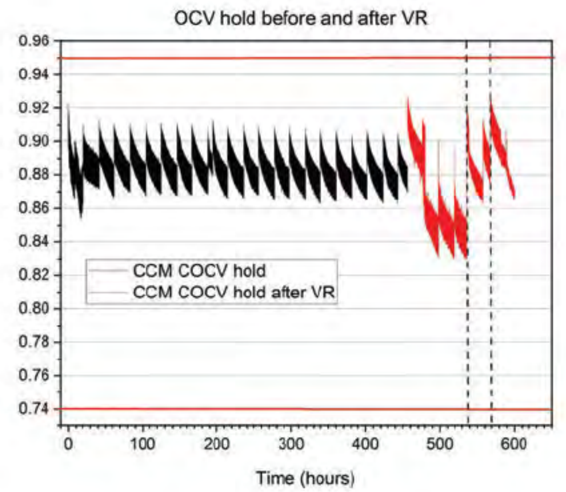
*** Tests stopped – did not fail.**

AST OCV chemical-mechanical
OCV hold, current x-over and HFR: before and after VR

ionysis



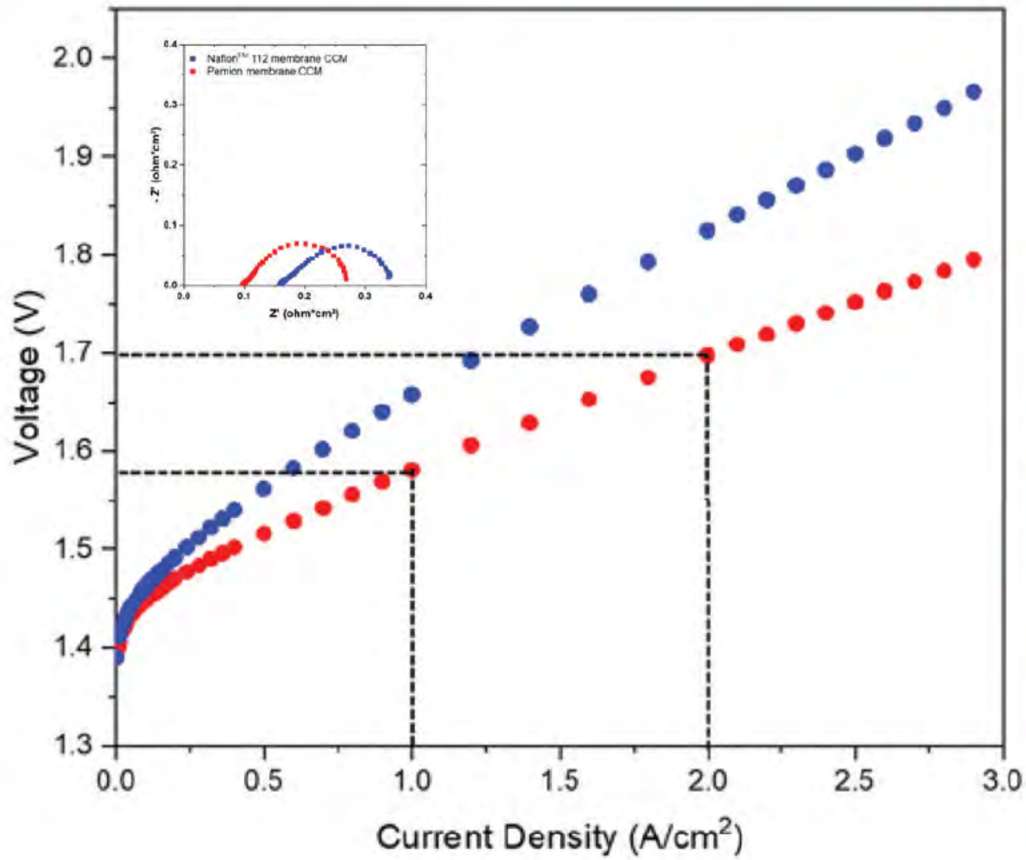




- GDE setup: HLF8 + PFSA- based electrodes
- CCM setup: HLF8 + HNN8-based electrodes

- 20k target was passed in GDE and CCM setup
- Voltage recovery (0.08-0.12 V steps for 1h at 140 % RH) to increase stress to the membrane
- Accelerated degradation after application of VR procedure, but no instant failure
- Hypothesis: oversaturation in VR accelerates degradation
  - **critical for real application (e.g. cold/wet, start-up/shut-down conditions)**

PEMWE Proof of Concept



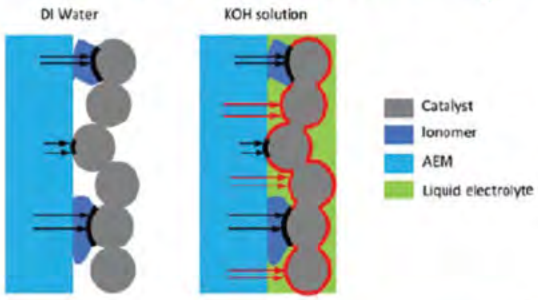
In-situ Results

- Significantly performance gain, >ultimate targets
- 5x lower hydrogen crossover (parasitic loss) markedly improves safety & efficiency
- Stable methods found for integration

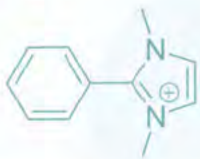
Further Requirements:

- Dedicated membrane engineering (known additives, known processes, no technology risks)
- Test system capacity – no capable stands today, relying on partners is 5-10x slower than in-house

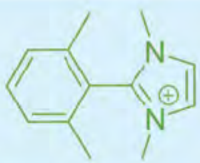
Aemion+®, the only Alkaline-Stable AEM

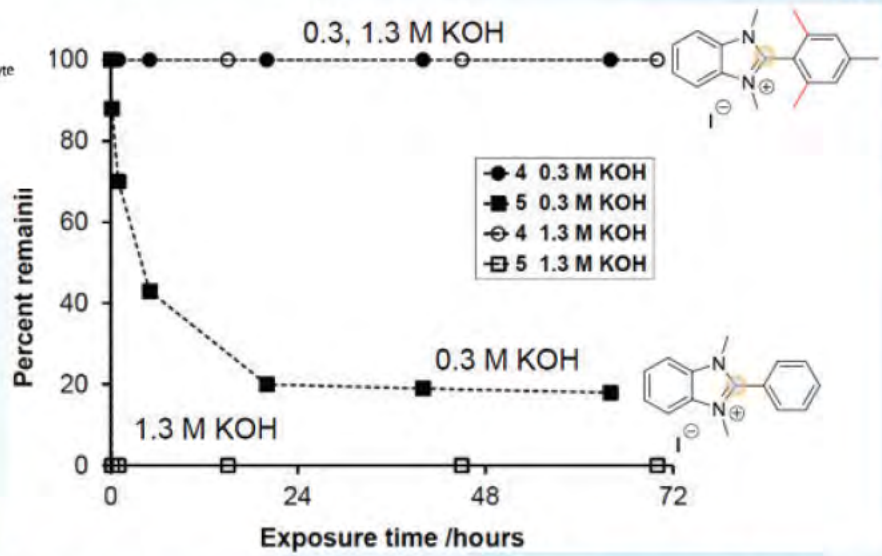


Unprotected
= Unstable

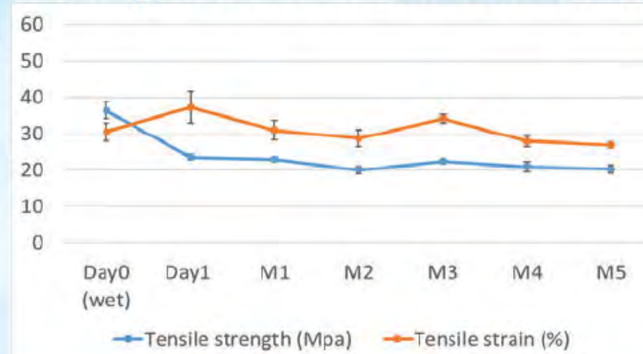


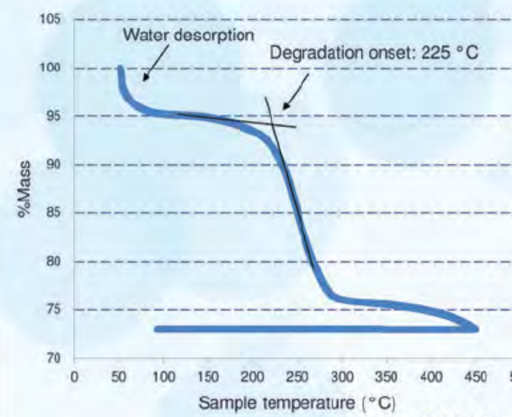
Protected
= Stable
Aemion+®





Stable for >4x NREL round-robin that failed every known material at the time



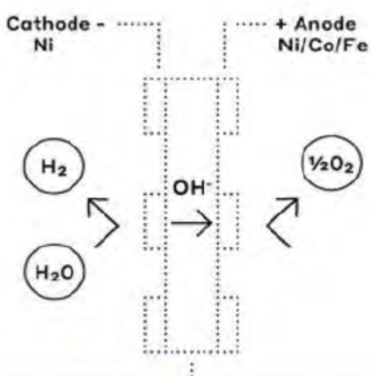


Physical protection (sterics) leads to the only <u>indefinite stability achieved</u> in industry-relevant, hot alkaline conditions (≥70 °C)

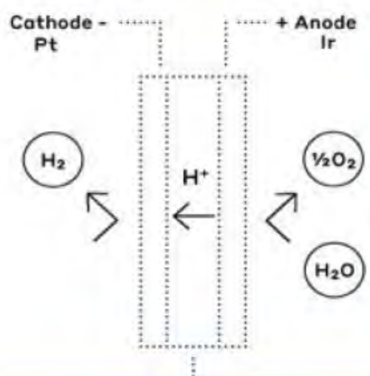
See Weber & coworkers, ECS, 2021 - https://doi.org/10.1039/C6EE00656F
Also see Danilovic & coworkers, ECS 2022 – https://doi.org/10.1149/1945-7111/ac4fed

Aemion+® Unlocks Disruptive Hydrogen Economics

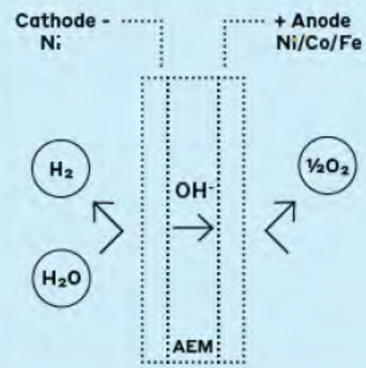
Alkaline electrolysis



PEM electrolysis



AEM electrolysis



AEMWE is a hybrid of the two systems – AEL components and PEMWE design, de-risking scalability

	AEL $500/kW	PEM $650/kW	AEM <$350/kW	EU Clean H_2 JU 2030 #s
BENEFITS ✓	Scalable	Highly Compact	Compact + Scalable	
✓	High Stability	Pairs with Renewables	Pairs with Renewables	
ISSUES ✗	Very Large Systems	Scale Issues: Ir & PFAS	Moderate Performance	**Ionomr's Breakthroughs Solve These**
✗	Poor Renewables Pairing	Very High Cost	Poor Durability	
✗	Low Safety at Pressure	Toxic Material Use	Poor Consistency	

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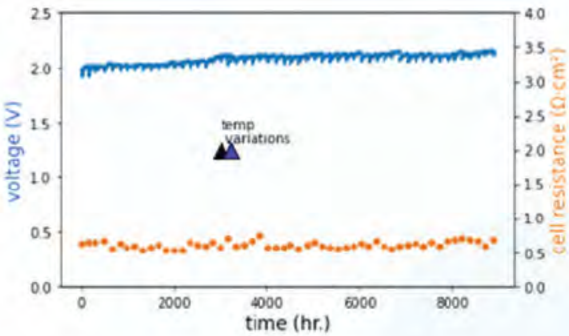
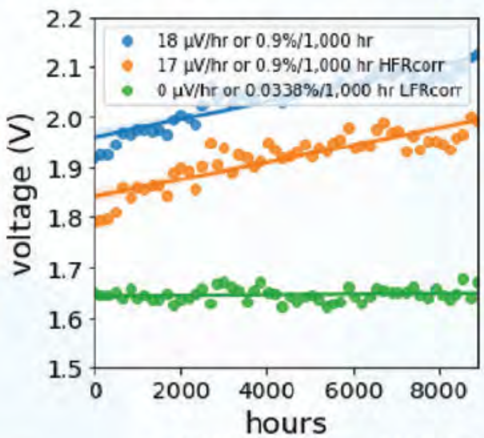
Breakthrough Durability & Performance

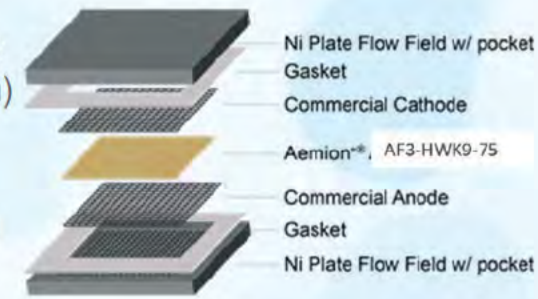


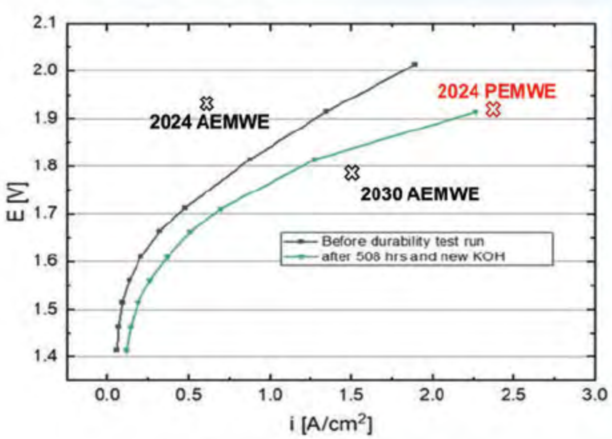


Measured cell voltage

'Low frequency' resistances (metal component oxidation)

No membrane-associated losses

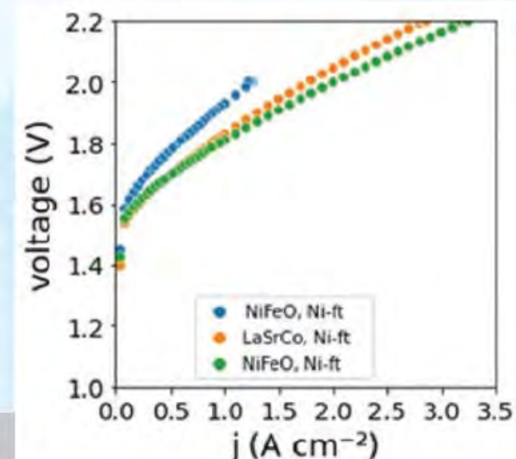




Exceed'ng every ˉ 24 EU target, now achieving all 2030 targets

Numerous demonstrations of breakthrough durability, >1000x achieved in AEMWE:

- No measurable membrane degradation in tests over 1 year **(10,000+ h to date)**
- Multiple whole-system degradation points >5000 h showing 'ultimate' target >100,000 h to failure



← S. Alia & coworkers @ NREL, through Shell Gamechanger program

NiMR INNOVATIONS

Resources Needed for Speed & OEM-Motivation

1) **Regulatory pressure is the only true way to motivate the marketplace**
   - Major pressure at present to 'sell what you have' and minimize development isn't honest about supply chain risk for PFAS products due to liability alone (see: 3M) and we also need to eliminate iridium

2) **Significant direct support – development & system test labs, coating equipment, large pilots** – Ionomr, Bekaert, Siemens Energy, Ionysis+[Fuel Cell OEM like PowerCell] funding (IPCEIs or similar) would soundly impact all targets in only four projects

3) **Retrofit support for existing automated systems (e.g. R2R coaters)** – for the few companies who have already built manufacturing lines that need to be adapted to new materials

4) **Keep the faith** – this is only a win for technology, scalability, the economy, and European energy security / supply chain because with climate-critical technology and multiple markets >30% CAGR, everyone *can* be winners

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Thank You!

ECHA Technical Submission: https://tinyurl.com/IonomrECHA
Canada Gazette submission: https://tinyurl.com/CanadaPFAS

[redacted]
[redacted]@ionomr.com [redacted]