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Subject: Ionomr Innovations Inc. submission to public consultation

2023 September 23

Dear Members of the ECHA Review Committee,

Thank you for taking PFAS seriously. The importance of eliminating 'forever chemicals' cannot be over-stated. It is well-established that the only solution to control toxic, highly bioaccumulative materials is to eliminate the source, and your rapid action today will prevent incalculable suffering for millennia.

Ionomr Innovations Inc. (Ionomr) is a Canadian advanced materials company spun out of the Holdcroft Lab at Simon Fraser University in Greater Vancouver, Canada. While these classes of materials are unique, experience in hydrocarbon materials was grounded in numerous international collaborations including with leading researchers at Montpelier and a former joint research program with the National Research Council of Canada – Institute for Fuel Cell Innovation (Vancouver). We are experts in polymer chemistry, providing PFAS-free alternatives for electrochemistry, including many hydrogen and battery technologies, the only established 'pure play' startup providing ion-exchange polymer and membrane solutions for both proton-exchange membranes (PEMs) and alkaline-stable anion-exchange membrane materials (AEMs) and their respective ionomers (ion-conducting active polymers as electrode binders).

The main intention of this submission is twofold: first, to provide evidence that 'hydrocarbon' (non-PFAS) direct alternatives in the hydrogen industry to perfluorosulfonic acid (PFSA) proton-exchange membranes & ionomers are viable alternatives according to all commonly accepted metrics and on a short time scale are expected to exceed the performances, durabilities, and operational windows achieved by fluoropolymers. Second, to demonstrate that AEM-based electrolysis technology is viable in the same form-factor and applications as PFSA-based PEM water electrolyzers (PEMWEs). This, despite extremely little investment in their commercialization and integration compared to incumbent materials, on the order of tens of millions compared to several billion Euros or the equivalent.

Ionomr is a willing and capable partner into any concerted effort to scale and integrate these two new materials families, which have from a technology basis addressed longstanding, extremely fundamental issues, primarily with chemical stability, and now offer superior alternatives to PFSA-based systems. We sub-contract for two major European efforts, the UNICORN (Horizon Europe) and ENABLER (EIC Transition) programs, as well as numerous other development efforts within the EU including a partnership with IPCEI awardee Sunfire (https://hydrogentechworld.com/ionomr-innovations-joins-forces-with-sunfire-on-industrial-scale-aem-electrolysis) and worldwide.

I. Fluoropolymer classification

We desire to counter the irrational grouping of fluoropolymers together as non-threatening, that the fluoropolymer industry is proposing. A more sensible approach is a life-cycle analysis[1] and our interpretation with respect to derogations follows the recommendations of an entire consortium of world leaders in PFAS environmental & biological properties[2]:

1) Fluoropolymers that are produced and processed without small-molecule PFAS, that are not expected to break down in service, whose breakdown products do not include fluorinated acids,

for instance granular/ram-extruded PTFE, that emit no acidic PFAS during during use or likely end-of-life (EOL) scenarios. This is Solvay/Sysenqo's "OneWorld" approach, and it is the only sensible approach. High-density PTFE and potentially fluorinated rubbers such as FKM are the only candidates for long-term exemption from PFAS restriction in our view, and these should be controlled at EOL to prevent thermolysis and the emission of 'forever GHGs'.[3]

2) Critical fluoropolymers to electronics and electrochemistry presently produced at large volumes that do not degrade into small molecules of the highest concern (i.e. acidic PFAS), but are processed with and will leach small-molecule PFAS – the only inclusions to this category in our opinion are 'low density' PTFEs (e.g. dielectrics) and PVDF, and potentially fluorinated rubbers. On the basis of both consensus and scale-up being needed the long (ten year) derogation is sensible.
3) Critical fluoropolymers that demonstrably break down into acidic or otherwise strongly bioaccumulative materials during operation, including Nafion®, Aquivion® and similar perfluorosulfonic acids (PFSAs) used in hydrogen systems as membranes, ionomer (active catalyst binder), and some humidifcation systems. The short (five year) derogation makes sense for these applications to allow time for the nascent hydrogen industry to pivot to the viable alternatives presented herein.
4) Non-critical fluoropolymers of 2 or 3, for which no derogation is sensible.

To briefly address the second category, the two major ePTFE, for which PFOS is optimal and recent 'C6' fluorosurfactants are even considered sub-optimal, with no foreseen hope of alternatives despite decades of research by multinational incumbents. Dielectric properties of low-density PTFE in electronics require entrained air, a property that can readily be engineered into specialty polymers but requires development, PVDF for Li-ion cathodes have alternatives and similar[4] but derogations make sense on the basis of the current scale needing to be met. Hydrocarbon chemistries can scale far faster than fluorinated chemistries, and can use existing capabilities in the chemical industry. Alternatives will be very much of benefit to scaling applications such as li-ion batteries, for there is no need to build out factories that can handle extremely reactive substances such as tetrafluoroethylene (TFE), which requires dedicated facilities that are comparably slow and extremely expensive to build (built of Inconel). This is knowledge from multiple members of our team but a difficult fact to cite; however since PFAS of this nature are produced in Europe, detailed process flows and inspection are certainly available to ECHA as they are to the US EPA.[5]

II. Fluoropolymer use in hydrogen-related systems

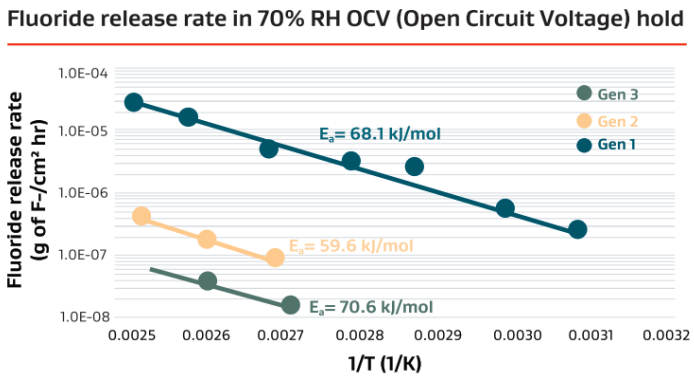
Fluoropolymer criticality to hydrogen applications exists entirely within the third category. Perfluorosulfonic acid polymers critically are employed as the active component of the membrane in conjunction with ePTFE reinforcement, and are a ionomer (active catalyst binder). Other fluorinated materials, typically PTFE powder, are also used as hydrophobic materials in the gas-diffusion layers and occasionally PTFE is used in sealing but this is not a critical application. As membrane-based humidifiers and electrochemical hydrogen compressors, hydrocarbons already offer a superior alternative with markedly lower parasitic losses (hydrogen crossover) and greater temperature range (*vide infra*).

While several hydrogen fuel cell chemistries exist, low-temperature proton-exchange fuel cells (PEMFCs) are based on PFSAs, are critical to the cost-effective energy transition of Europe,[6] and are the only

technology worthy of consideration for derogation. Other emergent chemistries (high-temperature [HT-PEMFCs] and alkaline anion-exchange membrane fuel cells [AEMFCs]) have the capability of being non-PFAS and should not be considered. Similarly, proton-exchange membrane electrolysis is one of four viable electrolysis pathways this decade, and the second most scaled after alkaline electrolyzers (AWE). It is, however, markedly smaller in form-factor and far safer in balancing intermittent renewables, and thus worthy of a short derogation period as well due to the nascent industry and discovery period of Power-to-X/Green hydrogen applications such as the 10 GW recently dedicated to such applications in Denmark.

III. Emissions during PFSA use and end-of-life

While the effectiveness of reaction controls and emission controls such as the absurdly energy-consuming thermal oxidation of process water can be debated by analytical chemists, it is a moot point if molecules of the highest concern, i.e. those that can be expected to be toxic and strongly bioaccumulative,[7] are emitted during operation. These are objectively measurable – please see the attached analytical report, taken from a beginning-of-life fuel cell vehicle's tailpipe emissions, revealing NVHOS (C4 sulfonic acid ether) at 0.68 µg/L after city driving (Sample IMR001) and 0.33 µg/L after highway driving (Sample IMR002). This is corroborated by claims of 'single digit ppb' measurements of PFAS by a representative of W.L. Gore and Associates, the market leader for fuel cell membranes at a recent US Department of Energy and EU Mission Innovation hosted by Lawrence Berkeley National Labs (https://sites.google.com/lbl.gov/pfas-webinar). Nafion® and all PFAS objectively and demonstrably degrade in-situ, with fluoride release rates being plotted.



Public data by W.L. Gore and Associates[8]

While the orders-of-magnitude improvement looks promising, this is only true at beginning-of-life and in real operation once Ceria or other radical-scrubbing materials dissipate from the inlet, typical failure cascades re-activate slowly and the fluoride emission rate (FER, also known as fluoride release rate, FRR) progressively increases.[9,10]

Degradation by ·OH, ·OOH and H3O· radicals is demonstrable by FER, and failure modes include substantial PFAS, including leading analyses of degradation cascades performed by technology leaders in the EU and North America.[10–12]

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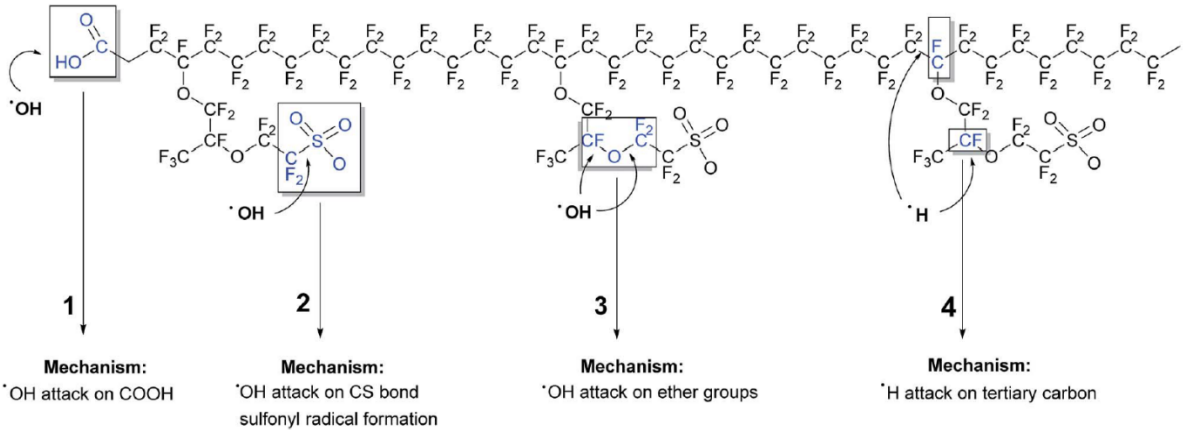
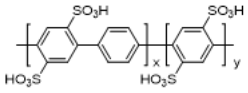


Fig. 8 Summary of the mechanisms of radical attack on the Nafion® polymer structure.

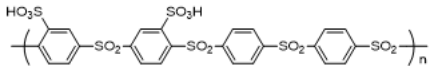
From reference [8] – pathways 1,3,&4 all lead to acidic PFAS emissions

Thermolysis suggests ≥5% of the FER being PFAS[13] and also adds PFOA and analogues to end-of-life considerations where thermolysis is completely necessary to recover precious metals for system economics, but according to the reference degradation pathways this includes a majority of PFOS-like products such as NVHOS with some PFOA-like materials when main chain scission activates as a prevailing degradation route in the low-temperature environments of fuel cells and electrolyzers.

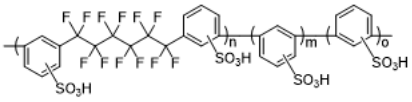
IV. History & critical issues of hydrocarbon alternatives to PFSAs



Poly(*para*-phenylene)s
Litt *et. al. Macromol. Res.* 2004, 12, 545;
Wycisk, Litt *et. al. J. Mater. Chem.* **2012**, *22*, 20907.



Poly(phenylene sulfone)s
J. Maier, Kreuer *et. al. Macromolecules.* **2007**, *40*, 598–607.



Fluorous Block-Copolymers (SPAF)
Uchida, Miyatake, *et. al. ACS Energy Lett.* **2016**, 1, 348.

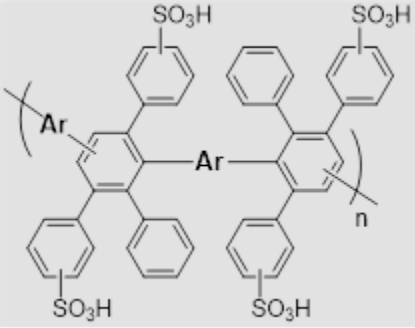
Initial alternatives to PFSAs included sulfonated PEEK (sPEEK) and styrenic sulfonic acids, but in addition to negatives on performance, both chemistries rapidly fail in fuel cell environments due to ether cleavage. Linear chemistries do not afford favourable morphologies either for water-channel formation or for clean electrode materials. A second generation favouring aromatic or 'arylene' (sp2 carbon) heavy structures together with reduction or elimination of ether groups was undertaken to substantial advances in performance and stability, however connecting units were still subject to radical degradation due to the fast addition step compared to perfluorinated chemistries, which even affected fluorinated block type chemistries. The most successful 'second-generation hydrocarbon' employs connecting sulfones (per a public Toray disclosure at 2016 ECS PRiME), the only commercial alternative to Pemion® chemistry, today being commercially employed in electrochemical hydrogen compression and investigated in fuel cells and electrolyzers (e.g. https://www.toray.com/global/news/details/20210906112831.html), with other positive reports of poly(arylene sulfone) sulfonic acids and non-PFAS but fluorinated poly(arylene) sulfonic acids independent of the non-fluorinated/fully hydrocarbon poly(paraphenylene) sulfonic acids described following.[14,15]

It is notable that nearly all second-generation chemistries require high-boiling solvents and employ crosslinking, and have volumetric sulfonic acid densities lower than PFSAs (e.g. ion-exchange capacities, IECs, <2.8 accounting for the differences in densities), resulting in ionomer in the catalyst layer to substantially under-perform and require PFSA chemistries for the electrode ionomer (less than 20% of catalyst coated membrane polymer mass). This is an under-appreciated challenge that is also addressed.

A radical kinetic argument in the early 2010s declared substantial challenges for new hydrocarbon materials discovery efforts and an inability to operate with the new class of inorganic catalytic antioxidants Ce^{3+} and Mn^{2+}.[16] This research effectively ended commercial research into hydrocarbon chemistry and lead to widespread belief within industry that no alternatives were possible. This challenge was later affirmed by a collaboration with the world-leading GM team led,[17] specifically requiring 1) markedly improved chemical stability necessitating HO· radical stabilization for catalytic antioxidants such as Ce^{3+} or Mn^{2+} to be able to act and 2) improved mechanical strength, ***but specifically called out arylene-type structures as being able to reversibly tolerate attack by HO· radicals***. There is a clear implication of 'equal or better' performance also being a necessary, e.g. IECs >2.5 need to be achieved and inflexibility to minimize catalyst poisoning by sulfonic acids was also necessary.

V. Pemion solves the critical issues, demonstrably for PEMFCs and PEMWE

A new class of chemistry has emerged and is being commercialized by Ionomr after these two key challenges were solved: fully polyphenylene sulfonic acids, specifically pre-functionalized



poly(paraphenylene) sulfonic acids with all of the necessary properties for successful fuel cell integration.[18] Investigated by Stille in the 1970s and Sandia National Labs in the 2000s, these rigid rod structures required rigorous controls pre-functionalized that resulted in emergent properties including very high IECs (up to 3.7 theoretical, 3.5 titrated demonstrated),[19] or equivalent weight, EW, of 270) nearly double the solubility limit of most other hydrocarbon chemistries. This class of chemistry rigorously addresses chemical stability issues by enabling reversible HO· radical addition, numerous pathways that do not result mechanical property reducing chain scission or polyaromatic hydrocarbon (PAH) formation (the only potential regulatory concern, extremely minor if true, but in addition to sterics reducing the likelihood of this formation, local ring are more susceptible to subsequent degradation, rigorously preventing both the appearance of carcinogenic high-energy double bonds found in dangerous PAHs and the whole-molecule planarity necessary to cross cell membranes.[20] Multiple variants of these systems display equal to or greater conductivity across the normal temperature and humidity range and exceptional radical stability in the US Department of Energy chemical accelerated stress test ("OCV"), in part by reducing radical concentration and increasing efficiency by reducing gas crossover vs. an equivalent thickness of PFSAs by an average of ~2/3rds across all conditions, further boosting chemical stability *in operando*.[21–23] Synergistic effects with catalytic antioxidants such as Ceria have also been incontrovertibly demonstrated as well as organic antioxidants, including work by the original researchers that had originally most directly addressed the question of hydrocarbon stability (Gubler & coworkers).[24–27]

It is important to note that these materials are not just a 'me too' to performance and durability – they have the potential for greater durability both chemically and mechanically, as well as the fundamental

capability to meet decades-long targets for higher temperature operation, including demonstrable strength at ≥110 °C, solving a key challenge of heat exchanger size due to the limitations of incumbent materials sets, namely rapid degradation above Nafion®'s T-alpha around 85 °C (onset of polymer backbone mobility, sometimes called Tg), after which the material loses effectively all its resilience and essentially any stress results in plastic deformation, leading to thinning, hot-spots, and failure, while Pemion® continues to demonstrate resilience comparable to that of an advanced composite Nafion®-based film at room temperature (see also TGA data following) in analysis by a world-leading group focused on failure analysis.[28,29]

Finally, ionomer in the catalyst layer has shown promise in oxygen-rich environments but also succeeds to achieve >1 W/cm² in typical operating conditions including an air-based oxidant feed[30] and effective parity of performance including greater high-temperature performance and parity at humidities ≥50% employing Pemion® as both membrane and ionomer, including lower area resistance, reasonably suggesting further optimization could achieve greater performances in all conditions.[31]

Internal performance data in industrially relevant conditions is presented following. Comparison of ex-situ properties at room temperature indicate the , making systems easier to control and more tolerant of temperature cycling, corroborating mechanical data.

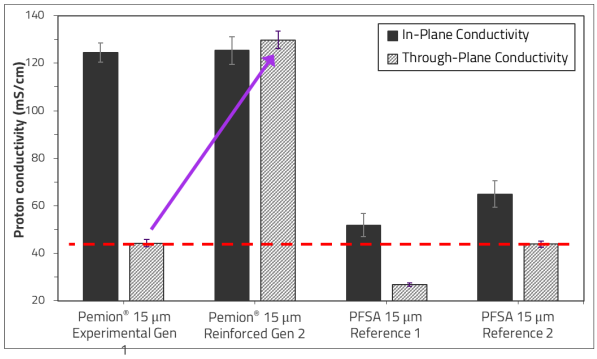


Figure 1. In-plane and through-plane conductivity measured by electrochemical impedance spectroscopy showing anisotropy and preferential properties of Pemion®-based chemistry in ePTFE

Following is data of a fully hydrocarbon membrane, Pemion® with hydrocarbon reinforcement sample EC99-97. Gas crossover 2.0 mA/cm² at 150 kPag symmetrical, c.f. ~8 mA/cm² in the same conditions for state-of-the-art composite PFSA-based materials, "PFSA 1" and "PFSA 2".

Pemion® both ePTFE reinforced and hydrocarbon reinforced equaled or outperformed both market leaders on key metrics (power density) and area resistance in conditions fully optimized to PFSA-based chemistries across the entire breadth of the current operational range:

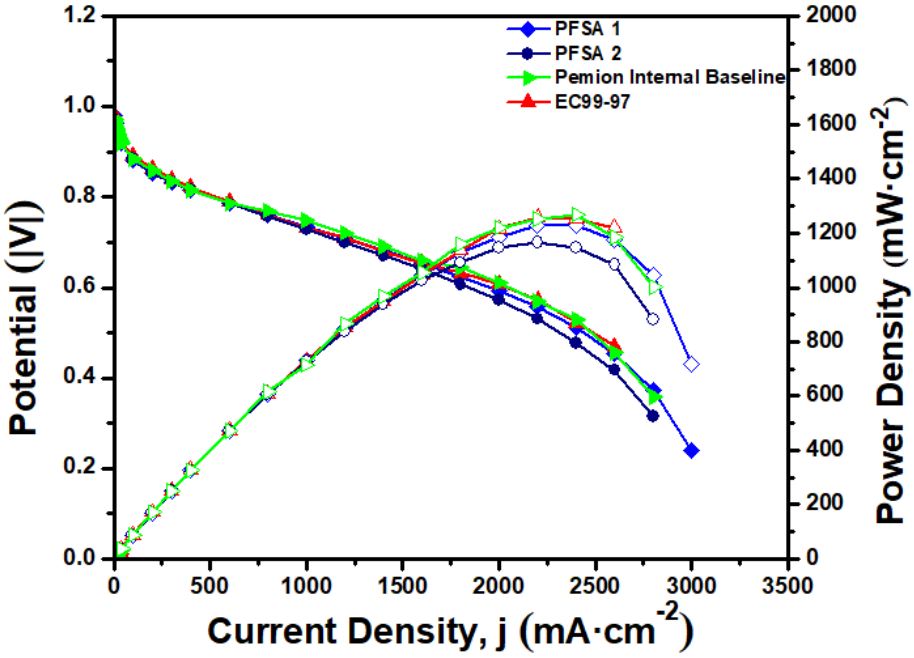


*Figure 2. Polarization data **EC99-97** at 100%/100% RH, H_2/Air, 80 °C, 150 kPa_g*

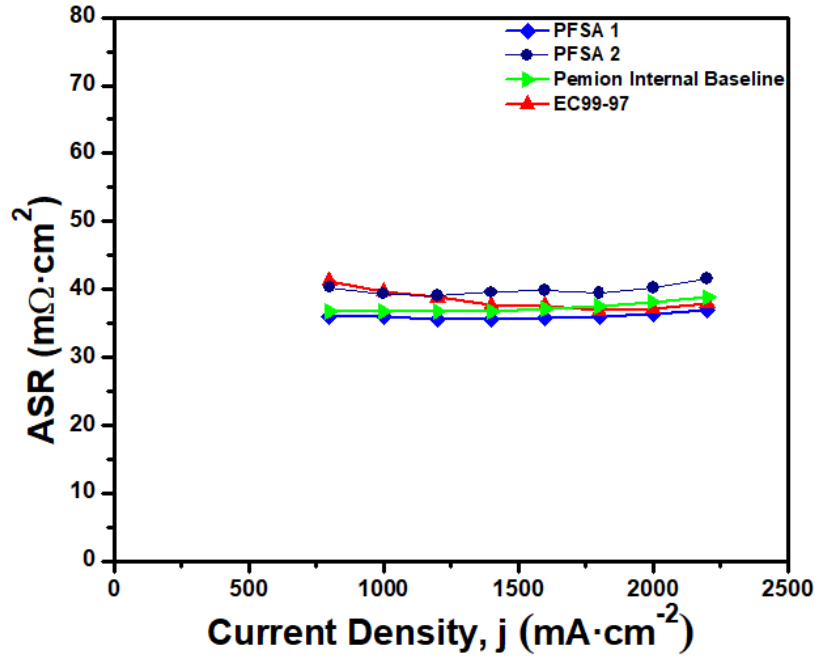


*Figure 3. Area resistance **EC99-97** at 100%/100% RH, H_2/Air, 80 °C, 150 kPa_g*

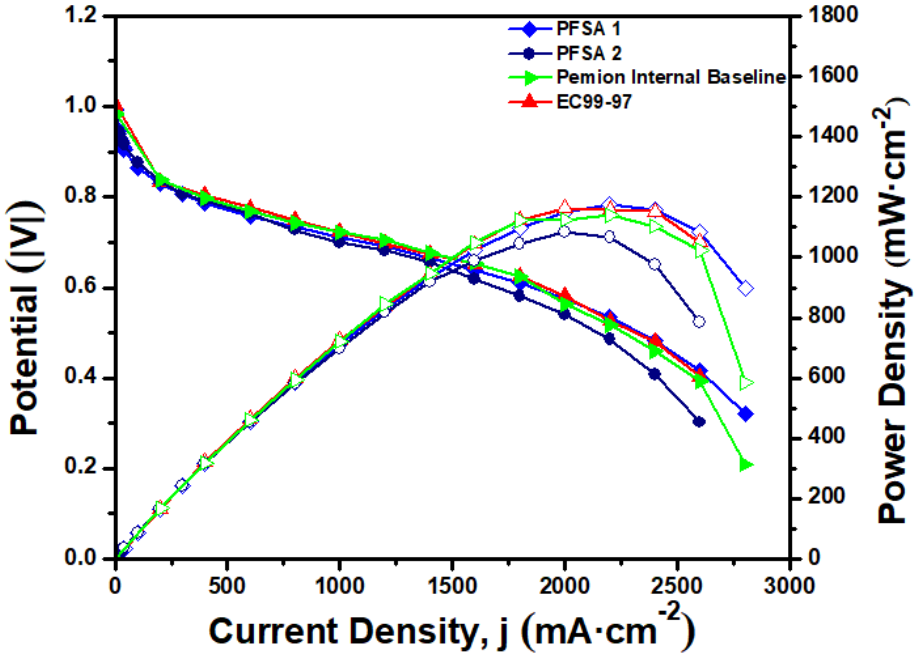


*Figure 4. Polarization data **EC99-97** at 100%/30% RH, H_2/Air, 80 °C, 150kPa$_g$*

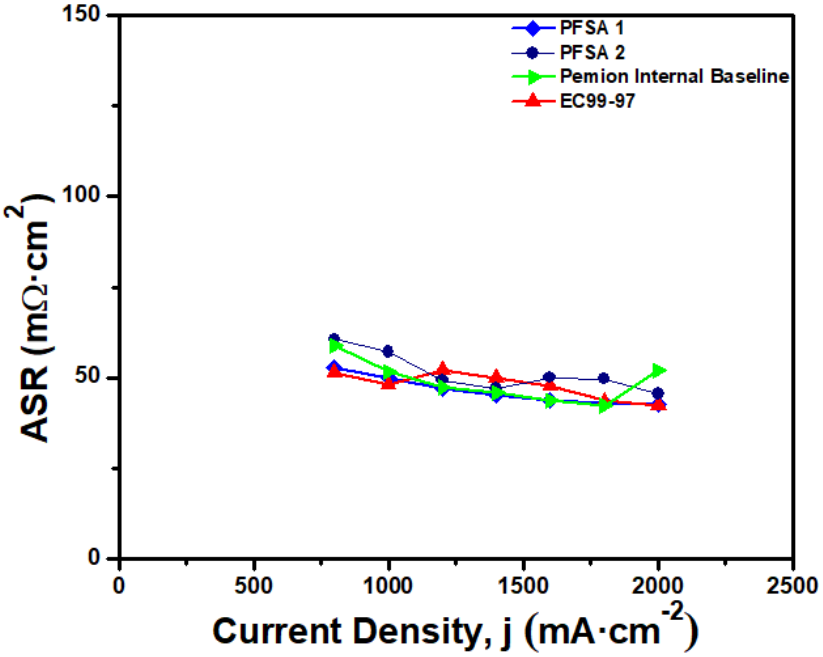


*Figure 5. Area resistance **EC99-97** at 100%/30% RH, H_2/Air, 80 °C, 150kPa$_g$*

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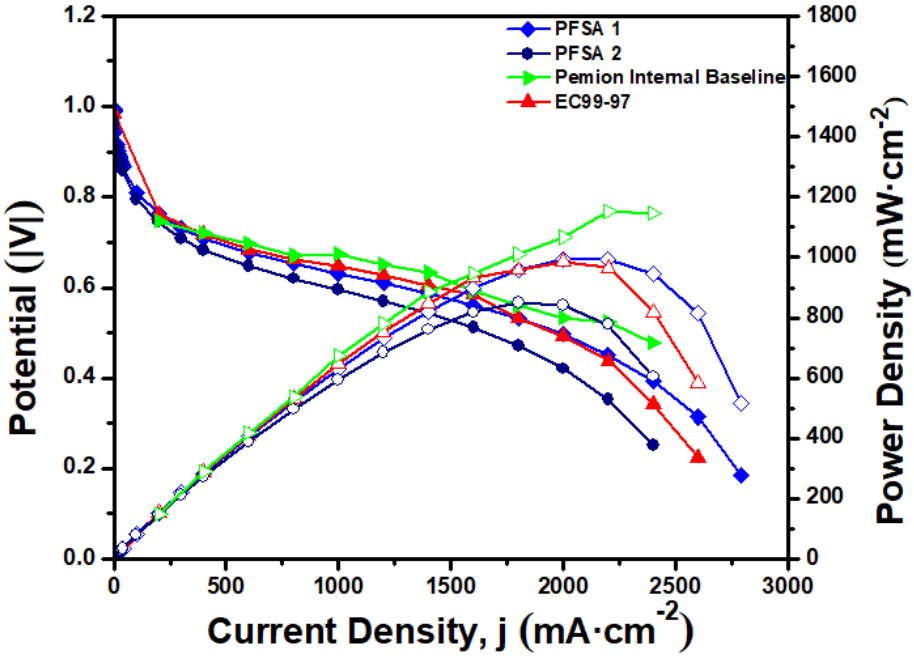


*Figure 6. Polarization data **EC99-97** at 30%/30% RH, H_2/Air, 80 °C, 150kPa$_g$*

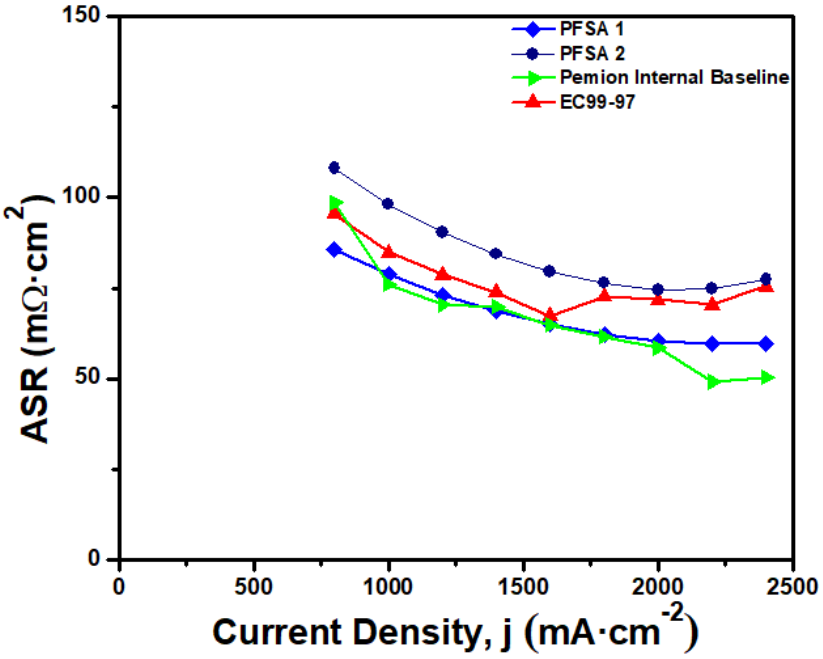


*Figure 7. Area resistance **EC99-97** at 30%/30% RH, H_2/Air, 80 °C, 150kPa$_g$*

The differential cathode humidities mimic real cell conditions with anode recirculation, highlighting an extraordinary power to self-hydrate more effectively as a result of the extremely high IECs achieved, with diffusion on the order of 2x. With minor process improvements to the hydrocarbon reinforcement or the addition of additives, this system would be reasonably expected not to see the dehydration effects exhibited at the highest current densities and extremely dry conditions.

This statement is further corroborated by the extreme performance and stability exhibited in a 3-day test at aerospace-relevant conditions of 110 °C, 50% RH, 3 bar_g in **a 2.5 A/cm² current hold (~1.4 W/cm²)**, with non-optimized (higher than commercial resistance) hardware and Pemion® not differentially adapted in any way for high-temperature operation, showing complete stability compared to a -2.7 mV/h fade exhibited by a state-of-the-art composite PFSA reference. This was performed without antioxidant additives ***to strongly refute assertions that hydrocarbons of this class cannot withstand high current density conditions***. The radical tolerance is there, and there is nothing to hydrolyze or otherwise no catastrophic degradation cascade to activate with this class of materials, unlike many other chemistries prior.

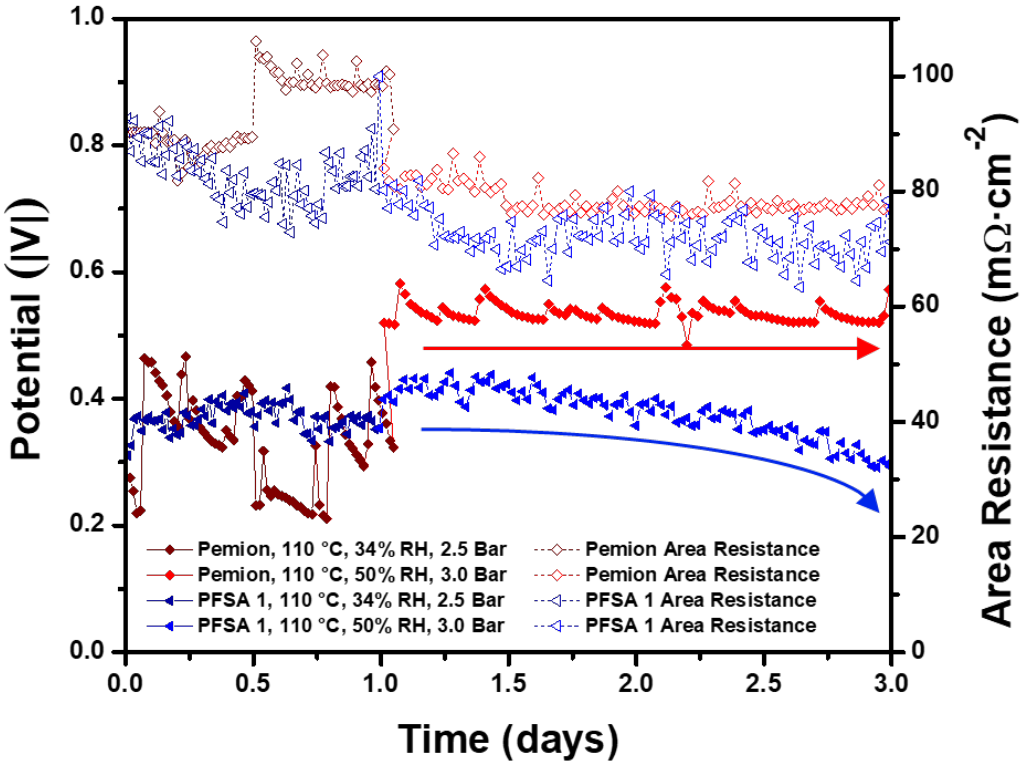


Figure 8: Potential hold data at 110 °C, 50% RH, 3 bar_g in a 2.5 A/cm² current hold (~1.4 W/cm²).

Finally, in a fully hydrocarbon system the self-hydration effect is even more evident in the 'fully hydrocarbon' membrane and ionomer data following. This polarization data achieves in normal conditions (150 kPa_g, >1 W/cm² completely without optimization), refuting the assertion that low gas

solubility matters to achieve acceptable reaction kinetics and the first validation that hydrocarbon ionomers can be successful.

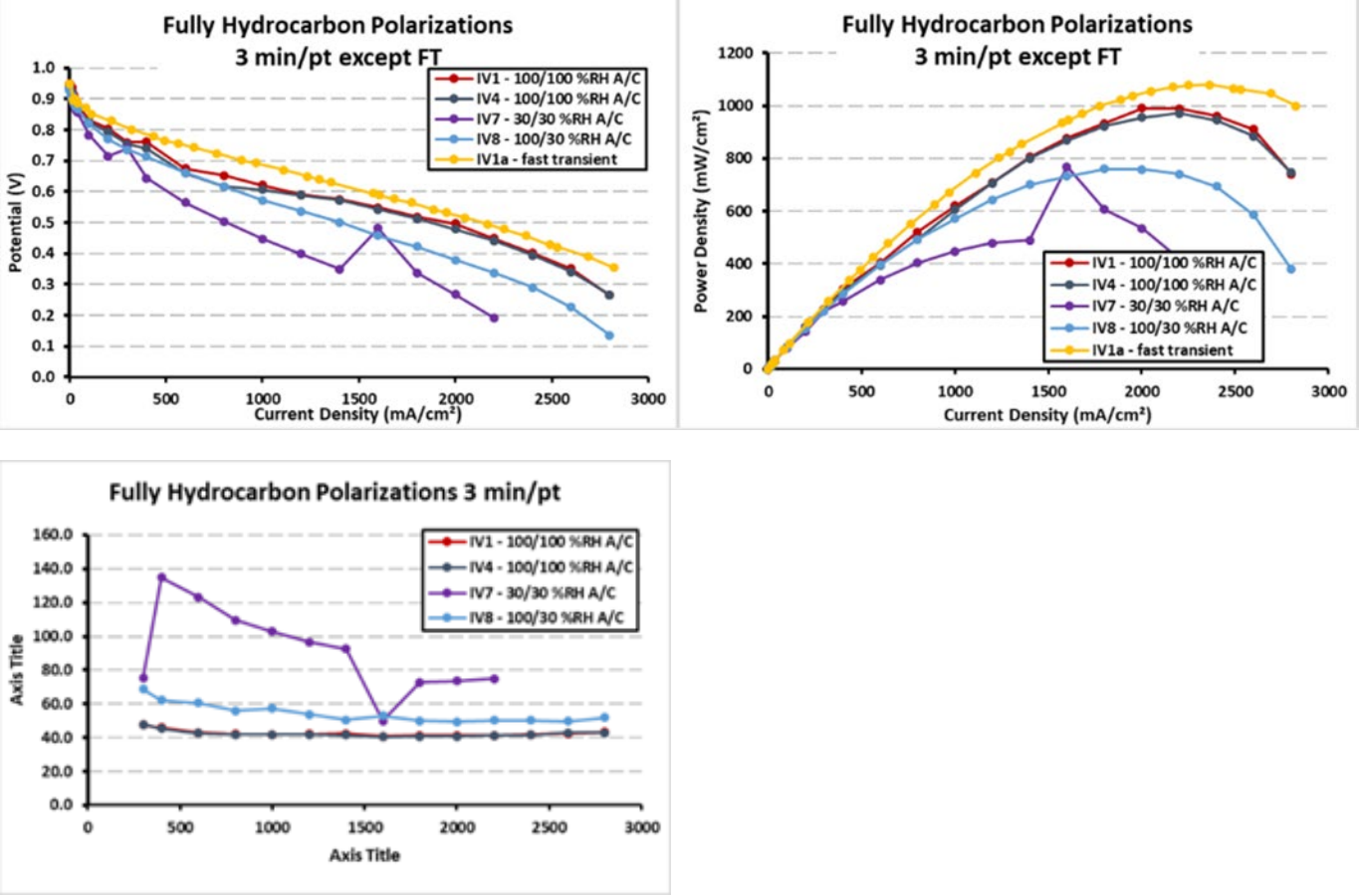


Figure 9: Fully hydrocarbon (Pemion® membrane + ionomer) data, RH as specified, 150 kPa$_g$, 80 °C; a) polarization; b) power density; c) area resistance (lower is better), humidities as specified.

This experimental data directly refutes the assertion that hydrocarbon chemistries can never be an effective ionomer in the catalyst layer, meaning there are literally zero intractable uses of PFAS in hydrogen systems. Partners have corroborated minimal losses in optimized conditions, and this is only the very first days of a new era of electrode design, where success can be rapidly effected with any form of concerted effort even an order of magnitude less than initial efforts with PEMFC development (i.e. more than just a handful of dedicated test systems globally). ***Successful replacement of PFSAs on a performance basis with no losses is expectant and imminent using otherwise at-scale materials and methods.***

Apart from the highly promising objective data, there is ample theoretical basis in the 'agglomerate model' stands in opposition to the dominant 'thin film' theory of ionomer effect, stating that where ionomer agglomerates occur oxygen transport is of no practical consequence to fuel cell operational limitations;[32] but while thin film model dominates PFSA-based ionomer electrodes due to a near-universal annealing step, this is not necessarily the case with hydrocarbon-based chemistries. In fact, 3D structuring is possible due to the inability of these polymers to anneal once the carrier solvent is lost – a

challenge of adaptation to current mass-production processes, yet one that will actually be a benefit to performance and reproducibility of results when adapted to successfully.[33,34]

There is also hope if the thin-film model still dominates meaningfully after advanced electrode design. Our hydrocarbon chemistry can be readily adapted to enhance gas permeability (not desirable as a membrane property) and this is an active undertaking, but even without this there is comparable data. We present some preliminary data of the chronoamperometric determination of oxygen transport comparing PFSAs, sPEEK, advanced second-generation sP4c (CF_3-protected ether, high volume hindered rigid rod polymer), and a high-IEC sulfonated poly(phenylene) sulfonic acid of the Pemion® class showed the last two exhibited same order-of-magnitude oxygem permeabilities across RH conditions, unlike sPEEK. It is also notable that unlike PFSAs where oxygen solubility is in the hydrophobic domains and transport is low, solubility is in the hydrophilic domains and transport is high, potentially delivering oxygen to active sites more effectively alongside protons and bridging the gap between these parameters more effectively than a surface reading would suggest (Figure).

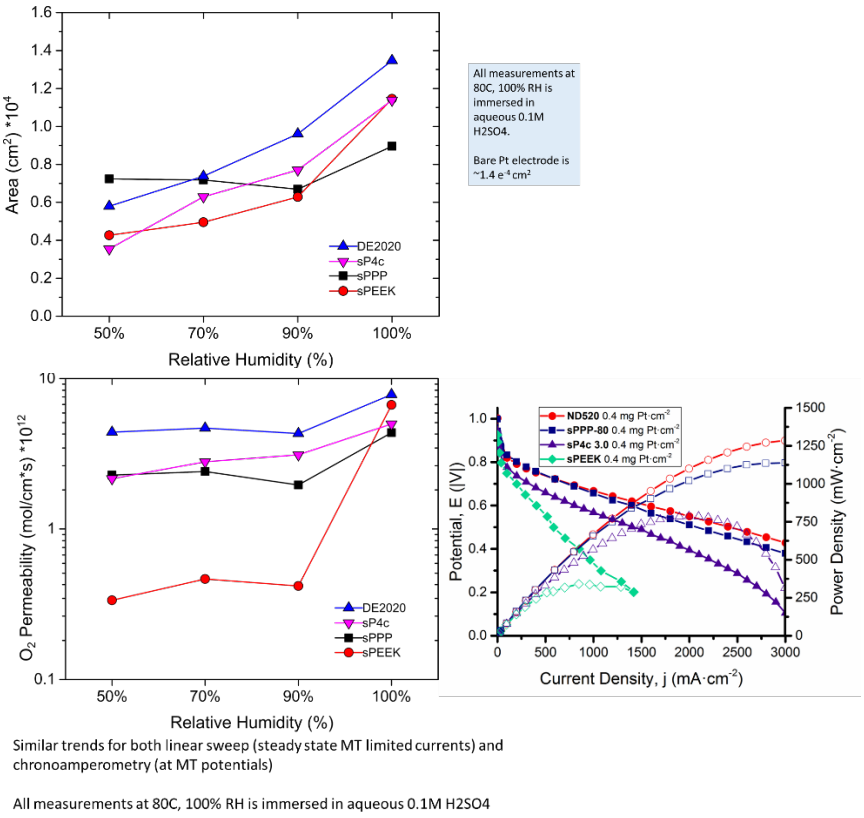


Figure 10: Chronoamperometric fit data for oxygen transport of thin films at varying RH and corresponding polarization data, representing fully systems of that material (membrane + ionomer, 20 wt% ionomer with Pt/C for hydrocarbons, 30 wt% Nafion® D520 with Pt/C accounting for density differences) with oxygen as oxidant, 80°C, 0 bar_g, and a fixed, high stoichiometry 0.5/1.0 slpm H_2/O_2 on a single-cell 5 cm^2 serpentine flow channels).

It must be reinforced that this performance data shows greater versatility of operation and near-parity to beyond-parity across the total range of conditions all despite a strong lack of optimization of the electrode composition and cell components in these experiments specific to Pemion® materials. In the

case of industry-relevant fully hydrocarbon performance data this represents fewer than five research-system days even if this first attempt was backed by years of dedicated research prior to funding.

Secondly, using the **we assert that Pemion is more chemically durable than other chemistries including PFAS** PFSA-based (no Ceria / antioxidants) and advanced hydrocarbon (sP4c, a -CF_3 protected ether, as above) on the basis of the US DOE Chemical Accelerated Stress tests, and further corroborated by long-duration cycling in COCV (Fig. 13), with the 44k cycles also representing over 1000 hours in the highly radical generating conditions at open circuit (OCV).

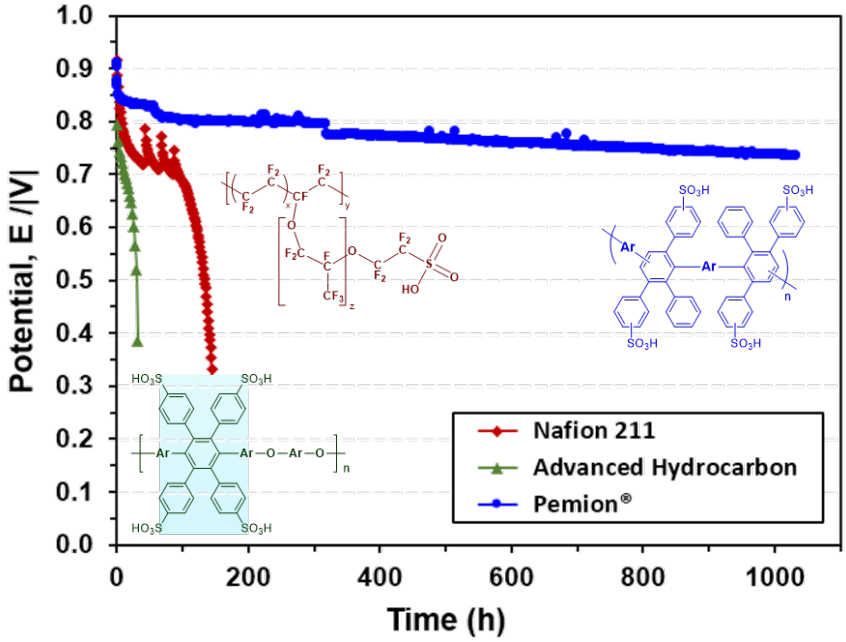


Figure 11: US Department of Energy Chemical Accelerated stress test (OCV), 90 °C.

Mechanical strength is stated as a challenge but humidity cycling has been successful with hydrocarbons[35], hydrocarbon reinforcements of PFSAs (e.g. the EU GAIA project – Fig. 12), and finally in combined systems where hydrocarbon reinforcement appears synergistic with hydrocarbon ion-exchange materials for fully hydrocarbon composite membranes.[36] (. fine and at 8x cross-pressure failure should have been immediate (<10 cycles expected, not several thousand, suggesting orders-of-magnitude better creep resistance, a structure-property relationship corroborated a rigid-rod polymer exhibiting by the high yield-strength, high elastic modulus and most of all high T-alpha of Pemion®).

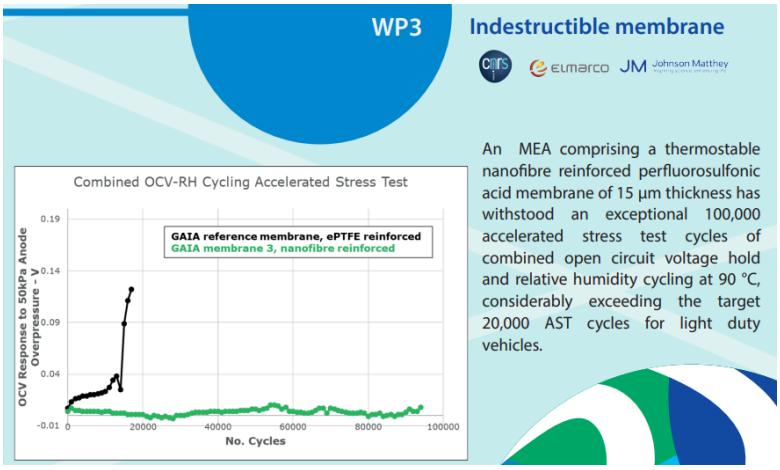
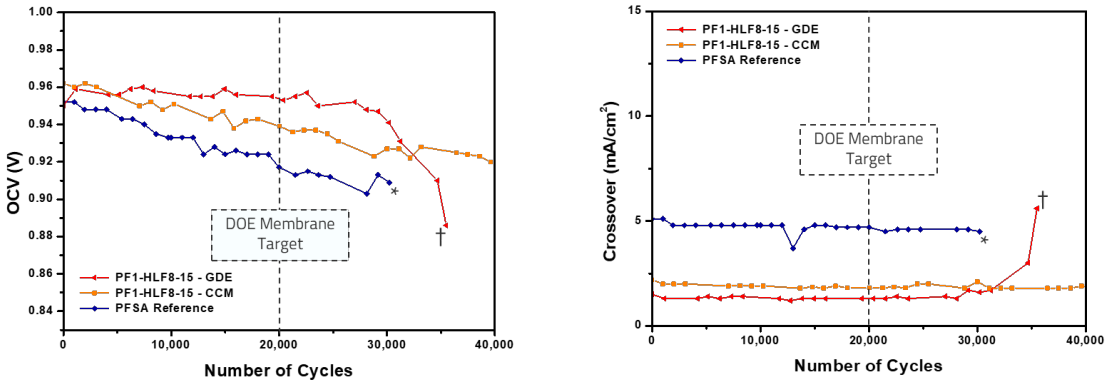


Figure 12: Data from the EU GAIA project demonstrating >5x COCV tolerance to 100,000 cycles of a 15 µm membrane with a hydrocarbon nanofiber reinforcement known to be PBI (stated in newsletter 3) vs. ePTFE https://www.gaia-fuelcell.eu/images/GAIA%20ISSUE2_Final.pdf

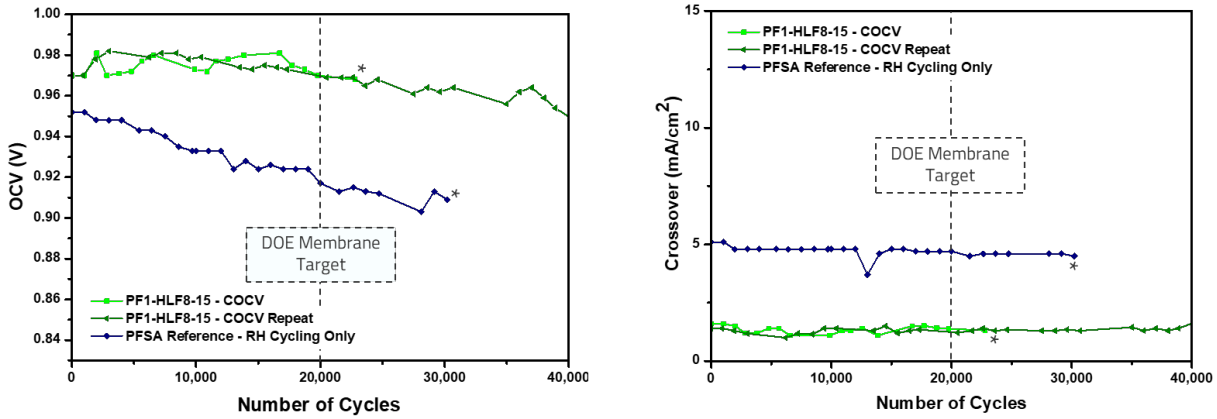
With ePTFE reinforcement, Pemion® more than doubles the target 20,000 cycles in CCM configuration and was deliberately killed by high cross-pressure after 30,000 cycles in GDE configuration (Fig. 13); this is well in excess of durability targets and these materials would doubtless benefit from hydrocarbon composites.



OCV (left) and gas crossover current (right) curves of membranes measured under cycling RH (0 to 100%) at 90 °C.
† Sample cross-pressure increased 8x to induce failure after 30k cycles – did not fail
*** Tests stopped – did not fail.**

Figure 13: US Department of Energy RH cycling test 30/45 wet/dry cycling from 0 to 100 % RH at 90 °C.

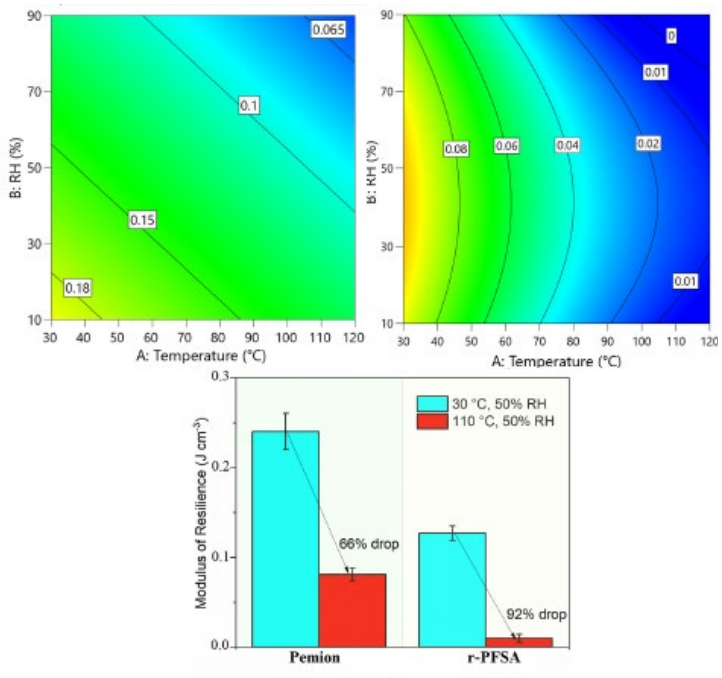
Combined chemical+mechanical data is considered to be the highest bar to pass although it is often stated that many contemporary commercial stacks would fail as major degradation mechanisms and radical types are not formed in real systems due to voltage clipping and other stack management choices such as never reaching full humidification at temperature. Pemion® reproducibly passes this test in GDE configuration and the current challenge is extending this to all methodologies of CCM manufacturing.



OCV (left) and gas crossover current (right) curves of membranes measured under COCV conditions, OCV with cycling RH (0 to 100%) at 90 °C.
*** Tests stopped – did not fail.**

Figure 14: US Department of Energy Conditions for Combined Accelerated Stress Test (OCV hold + RH cycling), demonstrating repeated success of a cell configuration.

The humidity cycling of figures 13 & 14 is notably into a weaker region of Pemion® namely at full humidification at temperatures above 70 °C. This is a completely unrealistic operating condition for real fuel cells, where full humidification is only seen (and necessary for voltage recovery at) low temperatures. In fact, not only is the absolute resilience far higher at all points, the 'hot and dry' cycling is markedly better tolerated (diagonal vs. vertical trend), i.e. cycling within 0-70 % RH at 90 °C or 0-50 % RH at 110 °C is a completely realistic, state of the art operating regime where Pemion® would by these metrics cycle near-indefinitely while PFSA-based chemistries would fail rapidly



Modulus of resilience between the composite Pemion® membrane (top left & bottom left) and advanced composite PFSA (top right & bottom right).[28]

None of these materials contained Ce^{3+} or other inorganic or organic antioxidants. Yet a post-mortem analysis performed by the external-facing characterization group at Ballard revealed a corner edge mechanical failure but ***no statistical thinning of the hydrocarbon membrane despite over 1000 hours at OCV, the PFSA-based catalyst layer exhibited while >50% thinning.***

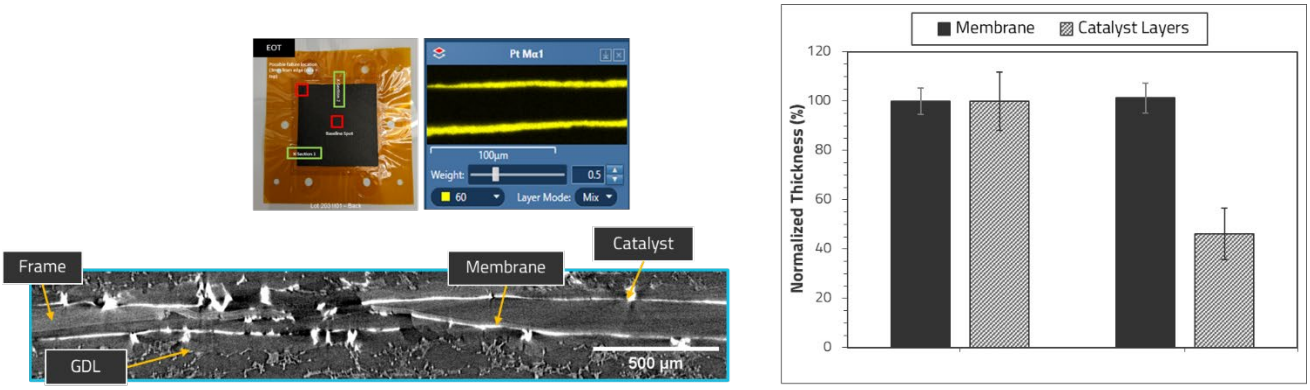
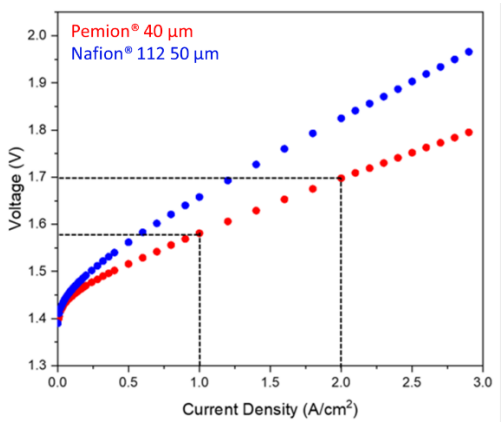


Figure 15: EOL study of the 44,000 cycle GDE.

The degradation products as above are materials such as sulfuric acid and benzenesulfonic acid, orders of magnitude less Lewis Acidic or otherwise catalyst degrading than triflic acid analogues or HF, and readily oxidized off in a voltage recovery cycle if needed, which we have tested to 1.5 V vs. hydrogen (RHE). This combined with lower gas crossover would suggest both longer-lived catalysts, enable green solvent extraction of precious metals as a higher-yield and far greener end-of-life and the lack of HF emission unlocks the ability to use silicone components, such as to replace PTFE-based seals or hydrophobic additives. ***Again, all aspects of hydrocarbons with respect to durability and the interaction with non-CCM components are equal to superior to current systems and the main challenge is engineering, not development, with success considered reasonable, imminent, and expected in*** a timeframe allowing adoption under the shorter derogation.

Finally, although we are a startup that must focus to succeed, we have performed a proof-of-concept direct comparison in PEMWE conditions, with identical catalyst layers (3.5 mg Ir/cm² anode, 1.0 mg Pt/cm² Nafion® D520 as binder), at 70 °C, exhibiting lower area resistance and lower crossover (initial 0.55 Hydrocarbon vs. 0.95% PFSA H_2 in O_2), entirely non-optimized, resulting in a system that would reasonable meet European Hydrogen Partnership's (FCH-JU-II's) targets upon stack conversion due to lower parasitic losses from cell area resistance:



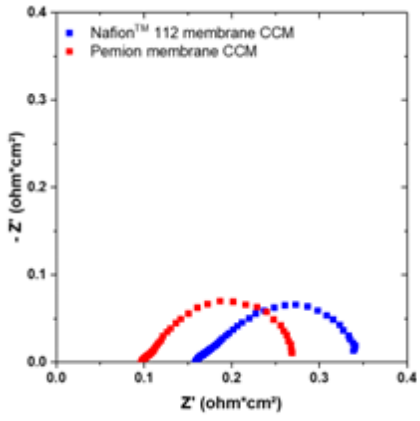


Figure 16: Comparative PEMWE polarization (L) and impedance (R), 70 °C in DI water (18 MΩ).

Scale-up to market requirements is far less of a barrier to total adoption of than simply meeting requirements with incumbent PFSA-based chemistry. The three key control parameters of the incumbent that are extremely difficult to control are innately controlled far better than any PFSA-based chemistry in Pemion® materials (molecular weight range, dispersity, and ion-exchange capacity AKA equivalent weight – see synthesis papers referenced above). Combined with a green chemistry synthesis, the only limitations are in qualifying demand and effective technology transfer to partners in monomer, polymer, and film production to create an all-EU supply chain, more secure and far lower impact than the current supply chain.

The main challenges remaining are adapting current MEA assembly methodologies to a chemistry that doesn't soften or creep under typical hot-pressing conditions <200 °C in a manner that doesn't damage the membrane, which may include direct coating, adaptation of decal-transfer methodologies, direct membrane deposition,[37] or some amalgamation of these. Establishing a proper supply chain of non-fluorinated composite reinforcements of the highest quality, and adapting this chemistry to meet the mildly differential needs of PEMWE (higher hydrated strength, lower gas crossover). ***The critical, fundamental issues of durability and questions about equivalencies of performance have been more than addressed, and now there is a need for development and integration, not for future research.*** These needs are in line with the criteria for short-term derogation.

VI. Aemion AEMWE as a second mainstream alternative to PEMWE

Because of the existence and scale of AWE, PEMWE has a completely viable alternative technology. However, for many critical applications such as grid balancing intermittent renewables to guarantee truly 'green' hydrogen and ease of deployment / central production that is necessary as the footprint of hydrogen expands (no ready way to ship 40-80 ton AWE units into the deserts of Morrocco, Namibia, Patagonia, or Western Australia, much less stack them up on far-offshore platforms), the form factor of PEMWE could be considered critical, and from a cost-perspective of hydrogen they are arguably essential for a large proportion of their deployment, but AEMWE compares extremely favourably as a disruptive technology if remotely similar performance and durability could be achieved (Figure 17).

75% CF	Electricity $/MWh															
Capex ($/kW)	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70
0	$0.21	$0.48	$0.75	$1.01	$1.28	$1.55	$1.81	$2.08	$2.35	$2.61	$2.88	$3.15	$3.41	$3.68	$3.95
50	$0.25	$0.52	$0.79	$1.05	$1.32	$1.59	$1.85	$2.12	$2.39	$2.65	$2.92	$3.19	$3.45	$3.72	$3.99
100	$0.29	$0.56	$0.83	$1.09	$1.36	$1.63	$1.89	$2.16	$2.43	$2.69	$2.96	$3.23	$3.49	$3.76	$4.03
150	$0.34	$0.60	$0.87	$1.14	$1.40	$1.67	$1.94	$2.20	$2.47	$2.73	$3.00	$3.27	$3.53	$3.80	$4.07
AEM 200	$0.38	$0.64	$0.91	$1.18	$1.44	$1.71	$1.98	$2.24	$2.51	$2.78	$3.04	$3.31	$3.58	$3.84	$4.11
250	$0.42	$0.68	$0.95	$1.22	$1.48	$1.75	$2.02	$2.28	$2.55	$2.82	$3.08	$3.35	$3.62	$3.88	$4.15
300	$0.46	$0.72	$0.99	$1.26	$1.52	$1.79	$2.06	$2.32	$2.59	$2.86	$3.12	$3.39	$3.66	$3.92	$4.19
350	$0.50	$0.76	$1.03	$1.30	$1.56	$1.83	$2.10	$2.36	$2.63	$2.90	$3.16	$3.43	$3.70	$3.96	$4.23
400	$0.54	$0.80	$1.07	$1.34	$1.60	$1.87	$2.14	$2.40	$2.67	$2.94	$3.20	$3.47	$3.74	$4.00	$4.27
450	$0.58	$0.85	$1.11	$1.38	$1.65	$1.91	$2.18	$2.45	$2.71	$2.98	$3.24	$3.51	$3.78	$4.04	$4.31
500	$0.62	$0.89	$1.15	$1.42	$1.69	$1.95	$2.22	$2.49	$2.75	$3.02	$3.29	$3.55	$3.82	$4.09	$4.35
550	$0.66	$0.93	$1.19	$1.46	$1.73	$1.99	$2.26	$2.53	$2.79	$3.06	$3.33	$3.59	$3.86	$4.13	$4.39
600	$0.70	$0.97	$1.23	$1.50	$1.77	$2.03	$2.30	$2.57	$2.83	$3.10	$3.37	$3.63	$3.90	$4.17	$4.43
650	$0.74	$1.01	$1.27	$1.54	$1.81	$2.07	$2.34	$2.61	$2.87	$3.14	$3.41	$3.67	$3.94	$4.21	$4.47
700	$0.78	$1.05	$1.31	$1.58	$1.85	$2.11	$2.38	$2.65	$2.91	$3.18	$3.45	$3.71	$3.98	$4.25	$4.51
750	$0.82	$1.09	$1.36	$1.62	$1.89	$2.16	$2.42	$2.69	$2.95	$3.22	$3.49	$3.75	$4.02	$4.29	$4.55
800	$0.86	$1.13	$1.40	$1.66	$1.93	$2.20	$2.46	$2.73	$3.00	$3.26	$3.53	$3.80	$4.06	$4.33	$4.60
850	$0.90	$1.17	$1.44	$1.70	$1.97	$2.24	$2.50	$2.77	$3.04	$3.30	$3.57	$3.84	$4.10	$4.37	$4.64
900	$0.94	$1.21	$1.48	$1.74	$2.01	$2.28	$2.54	$2.81	$3.08	$3.34	$3.61	$3.88	$4.14	$4.41	$4.68
950	$0.98	$1.25	$1.52	$1.78	$2.05	$2.32	$2.58	$2.85	$3.12	$3.38	$3.65	$3.92	$4.18	$4.45	$4.72
1,000.00	$1.02	$1.29	$1.56	$1.82	$2.09	$2.36	$2.62	$2.89	$3.16	$3.42	$3.69	$3.96	$4.22	$4.49	$4.76

PEM AEL

Figure 17: CAPEX vs. electricity cost (~OPEX) cost determining levelized cost of hydrogen, with ranges set by EU targets for CAPEX, and electricity cost range mainly determined by grid-balancing ability, at 75% capacity factor (e.g. optimal paired with and solar, minimal grid contribution).

Durability has been the Achilles heel of AEMWE technology for 2+ decades However, anion-exchange membrane water electrolysis (AEMWE) as uniquely enabled by Ionomr's technology to operate long-term in a continuous 1 M KOH feed at temperature[38,39] makes this a superior replacement to PEMWE entirely independent of the PFAS question, being more cost-effective and stabler, and far less prone to system assembly issues, and completely independent of both PFSA supply chain issues and iridium availability, which together strongly limits deployments of PEMWE both now and in the future, even if thrifting is partially successful despite expectations (e.g. on the order of 50-150 GW of targets ranging from 2500 GW [Tesla master plan pt 3] to 3500 GW [IEA] to 6000 GW [Hydrogen Council 2023]).

Flexbility is necessary for cost-effectiveness of hydrogen production, either through direct, dedicated Power-to-X or as energy arbitrage on a grid. Exhibiting a low CAPEX is necessary to hit point-of-use targets and AEM enjoys considerable advantage beyond the obvious scalability benefits of eliminating iridium, titanium, most or all platinum, and high-grade stainless. The ability to use nickel iron oxide is unique to operation in caustic, as these are otherwise on the order of 8 orders of magnitude less electronically conductive than iridium oxide, with our recommended conditions being 1 M KOH both sides. This enables PEM-like performances for many partners and these experimental results and comparably facile assembly and high reproducibility compared to PEM explained well by recent papers by a consortia of the lead US National Labs.[40,41]

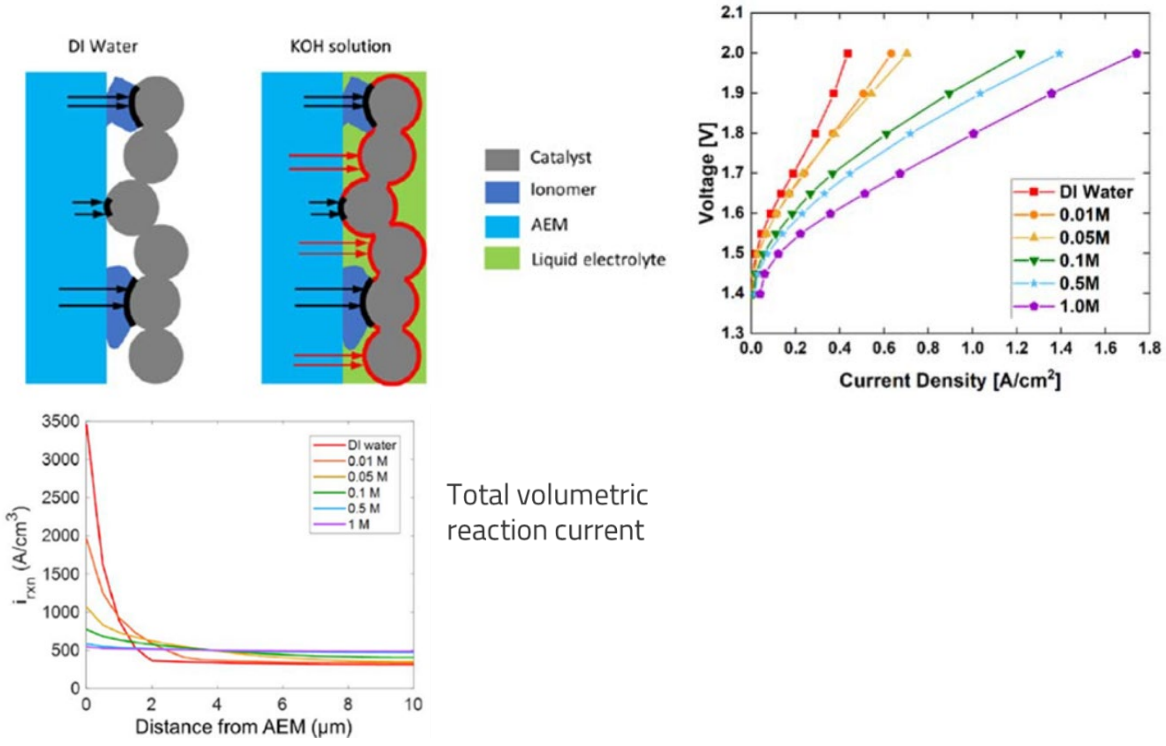


Fig. 18: illustration of the super-powers of AEMWEs – ionic and electronic availability through the liquid electrolyte (top right) enabling markedly higher performances and apparent kinetics (top right) due to the evening of reaction current throughout the catalyst layer to a range >>5x that of DI water (bottom left), further suggesting the reduction of local potential induced degradation events including hot spots and pinholing.[41]

This is further corroborated by our Shell-GCxN program with NREL, where the EU 2024 PEMWE target was immediately overlapped iridium-free (Fig 19).

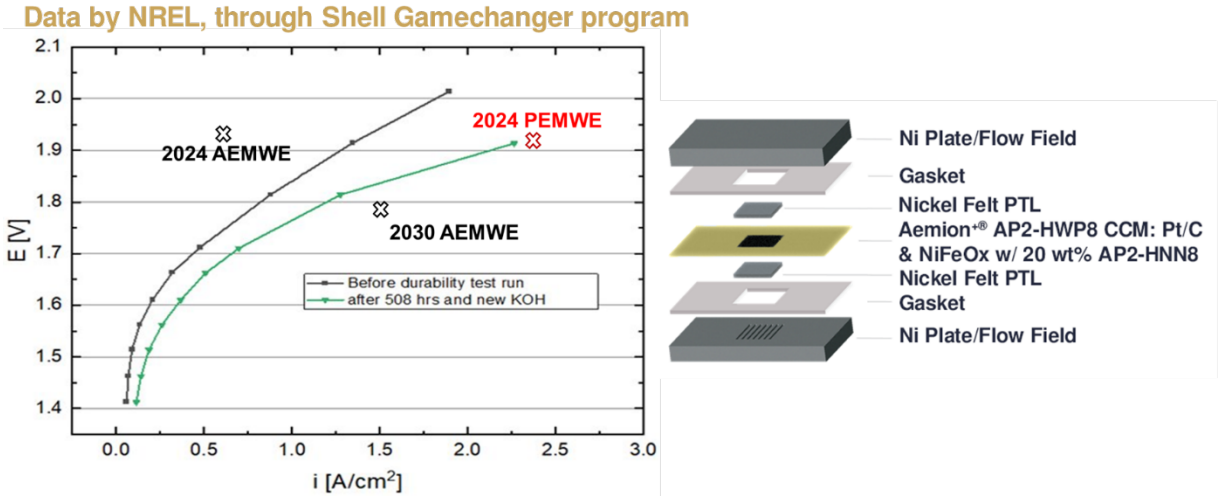
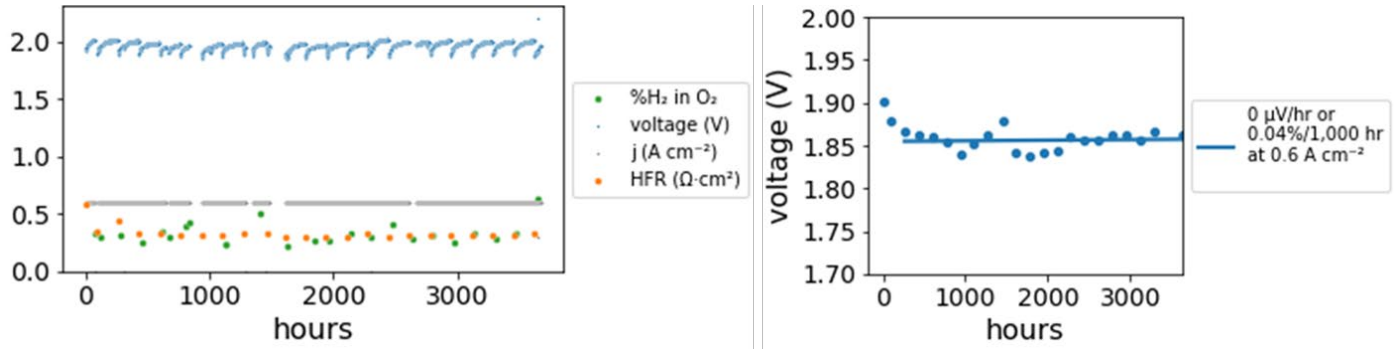


Figure 19: AEMWE data by S. Alia & coworkers at NREL, layers and conditions as specified, 70 °C operation.

It is also notable for other important electrochemical applications, Pemion® can reasonably be adapted for high permselectivity via known pathways, Aemion®-based systems have also demonstrated the lifetime and all key properties for flow battery chemistries including for the market-leading vanadium-based systems (VRFBs), directly replacing PFSA-based chemistries.[42 1]

AEMWE based on Aemion® has been demonstrated for over a year of continuous operation as well as weekly hard stops while maintaining single-digit µV voltage drift, entirely comparable stability to the best AWE and PEMWE systems today, and shown to be independent of current density, unlike other AEM chemistries, attributed to its caustic stability.[43]

While no membrane degradation was determinable (<0.1% area resistance drift in one year, the limit of detection), third generation chemistry has even more reduced degradation at the whole-system level (Fig. 20).



It is reasonable and foreseeable that AEMWE technology in the form-factor and operational ranges of PEMWE systems today will scale to the GW scale and as a disruptive technology will meet and eclipse PEMWE technology within the next decade. This endeavor is also worth of support, again to ensure a

fully European supply chain and independence from the strategically critical reliance on a particularly limited, volatile, and potentially unstable iridium supply.

VII. Conclusion & Partnership

Both hydrocarbon PEMWE and AEMWE technologies have a realistic and qualifiable pathway to reach the multi-GW per year scale before 2030 on the basis of Ionomr's technologies and we are happy to partner with any credible manufacturers to bring this faster and more effectively.

We are happy to provide any form of discovery to ECHA with respect to our chemical processing. As has been qualified by major European chemicals manufacturers, under EU-REACH, it is possible to fully scale and qualify these materials before 2030, eliminating the present PFSA supply bottleneck in the process.

Altogether, your proposed regulation of fluoropolymers is an opportunity to achieve a step-change in hydrogen and other critical electrochemical systems more rapidly than otherwise possible, for a future that is cleaner, more circular, more efficient, and faster to total decarbozination, with a more stable and scalable supply chain, entirely producible within Europe. Advanced electrochemistry with PFAS-free solutions may be little known or appreciated today, but they are a lynchpin technologies for the global energy transformation and we look forward to cooperating with you towards their rapid deployment.

With thanks for your consideration,

Ben Britton, PhD

Founder & CTO, Ionomr Innovations Inc.

[redacted]@ionomr.com | (c) [redacted]

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