Energy Materials Network
U.S. Department of Energy

HydroGEN
Advanced Water Splitting Materials

HydroGEN: Low Temperature Electrolysis

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National Renewable Energy Laboratory

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Project ID # P148A

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NREL Transforming ENERGY
BERKELEY LAB Bringing Science Solutions to the World
Sandia National Laboratories
INL Idaho National Laboratory
Lawrence Livermore National Laboratory

Approach: HydroGEN 2.0 and Project Support

Timeline and Budget

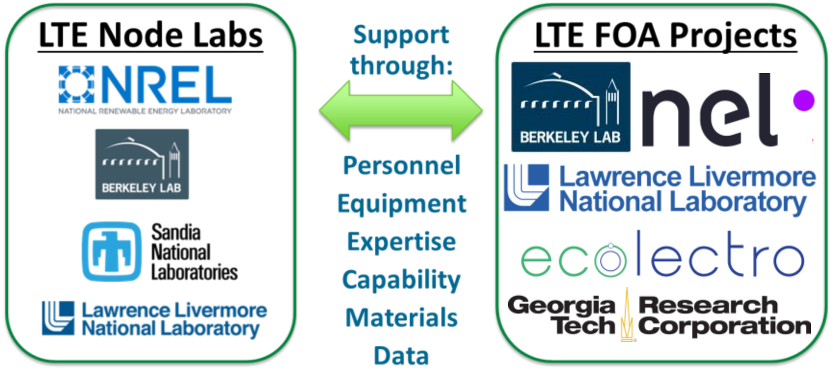
Total DOE funding since June 2016 launch: $61.8M

FY16	DOE Funding: $2M
FY17	DOE Funding: $3.5M
FY18	DOE Funding: $9.9M
FY19	DOE Funding: $8.4M
FY20	DOE Funding: $13.175M
FY21	DOE Funding: $5.7M
FY22	DOE Funding: $9.6M
FY23	DOE Funding: $10.2M
FY24	**DOE Funding: $9.6M** Core Lab R&D ($5.1M) FOA & Lab-Awarded Prjt. Support ($4.5M)

HydroGEN LTE Projects

- Historically supported 8 FOA projects with 41 nodes
- LTE 2.0 with 6 nodes
- Planning to support HydroGEN FOA-awarded and Lab call projects

Support of Lab Call/FOA Projects



New Lab Call Projects:

1. ELY-BIL004: Hierarchical Electrode Design for Highly Efficient and Stable Anion Exchange Membrane Water Electrolyzers: LBNL
2. ELY-BIL005: Studying-Polymers-On a-Chip (SPOC): Increased Alkaline Stability in Anion Exchange Membranes: LLNL

New FOA-Awarded Projects:

1. Alkaline Stable Organic Cations Incorporated into Rigid Polymer Backbones for Enhanced Mechanical Properties of Thin Films: Ecolectro Inc.
2. Low-Cost, Clean AEM Electrolysis through Transport Property Understanding, Manufacturing Scale-up, and Optimization of Electrodes and Their Interfaces: Nel Hydrogen
3. Durable, Low-Cost, Manufacturable AEM Electrolyzer Components: Georgia Tech Research Corporation

Approach: Safety Planning and Culture

- Every National Lab has a rigorous DOE-approved Safety Procedure which is regularly reviewed and monitored by cognizant DOE Field Offices
  - **NREL:** Work Planning and Control (WPC) which uses Integrated Safety Management (ISM)
  - **LBNL:** WPC with ISM
  - **SNL:** Integrated Safety Management System (ISMS)

Integrated Safety Management (ISM) Process can be described:

- Define the scope of work
- Analyze hazards associated with the work
- Develop and implement hazard controls
- Perform work within controls
- Provide feedback and continuous improvement

Engineered Control Strategies Utilized *For Hydrogen*

- ***Prevent a release*** — Use high quality stainless steel tubing, fittings, and components to resist hydrogen embrittlement
- ***Detection*** — Use robust point and area detection to detect leaks
- ***Process control*** — Interlock detection system with process controls to shut off system; low-V heat tape controllers
- ***Ventilation*** — Robust ventilation to quickly evacuate areas
- ***Control of ignition sources*** — Use protected electrical systems that prevent gas ignitions; over-temperature protection for heat tapes
- ***Defense in depth*** – Uses layers of controls in the design. For instance, the ventilation system design for hydrogen generation laboratory is redundant so if one exhaust system fails a redundant system will take the load.

Engineered Controls for Anion Exchange Membrane Electrolysis

- ***Layered control*** – Prevents operation during unsafe conditions, including leaking or loss of electrolyte flow, inconsistent or unexpected heating, insufficient inert flow, or unexpected cell voltage
- ***Release*** – Level and flow sensors prevent operation when water builds in the exhaust line
- ***Backpressure*** – Physical barrier limits hazards due to backpressure operation
- ***Exposure*** – Water flushes allow for hydroxide removal from system prior to disassembly, limiting exposure
- ***Dilution*** – Nitrogen dilutes and removes hydrogen, limiting mixing

Safety Culture Principles

- Everyone is personally responsible for ensuring safe operations
- Leaders value the safety legacy they create
- Staff raise safety concerns because trust permeates the organization
- A questioning attitude is cultivated
- Learning does not stop
- Hazards are identified and evaluated for every task, every time
- A healthy respect is maintained for what can go wrong

LTE 2.0 Approach:

Enabling High Efficiency, Durable AEM Electrolysis Performance

6 Nodes

Goals: Determine the role of the supporting electrolyte and the limiting factors behind water operation in AEM electrolysis

- Evaluate AEM’s ability to approach PEM performance/durability
- Elucidate interactions at the ionomer/catalyst interface to assess ionomer stability and catalyst poisoning
- Understand the impact of catalyst layer composition on performance in a supporting electrolyte
- Delineate the impact of electrolyte conductivity and alkalinity on performance and durability
- Address delamination and longer-term durability due to catalyst layer processing and reordering

Materials Selection

Electronic Structure Modeling (**NREL**)

Ionomer Thin Films (**LBNL**)

Microelectrodes (**LBNL**)

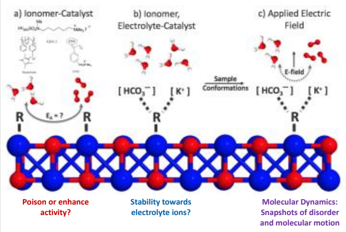
In-situ Cell Testing (**NREL**)

Microscopy (**SNL**)

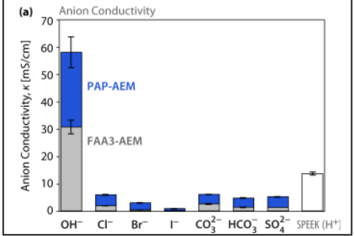
Multiscale Model (**LBNL**)

Materials → **Devices**

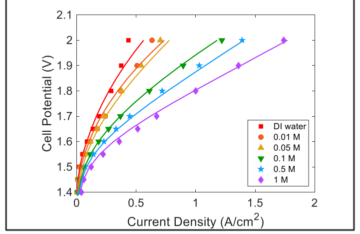
Materials Properties: Catalyst



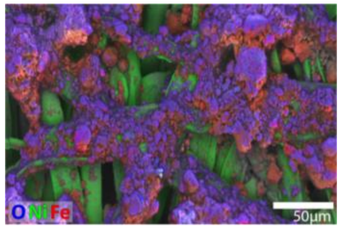
Materials Properties: Membrane



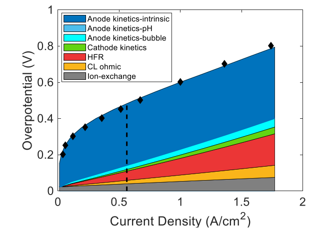
Device: Performance



Device: Microscopy



Device: Analysis

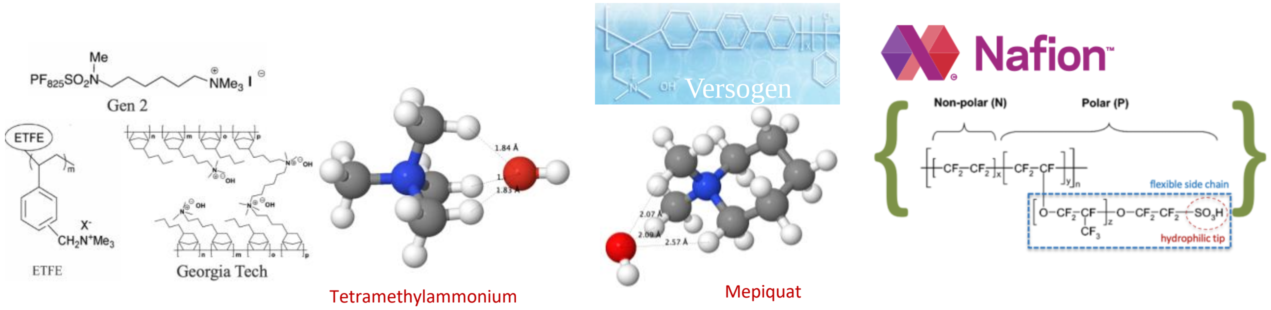


LTE 2.0 Accomplishments:

Understanding Ionomer Effects on Oxygen Evolution

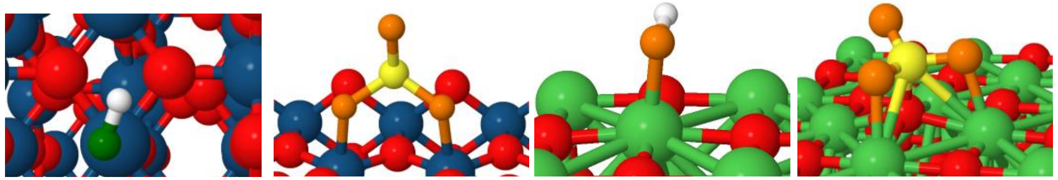
NREL Transforming ENERGY | BERKELEY LAB | Sandia National Laboratories | **6 Nodes**

Approximate Ionomer with Smaller Organic Fragments: Theoretical calculations can give critical insights into ionomer-catalyst chemistry



Ionomer-Catalyst Interactions: N^+R group can poison activity by blocking sites, degrade, or introduce competing reactions to OER

- Does ionomer ***poison the catalyst*** by introducing competing reactions or covering sites?
- Does the ionomer ***remain stable or does it degrade*** into other species?
- Experiment-Theory Assessed Stability on **Versogen, Nafion, and Georgia Tech** Ionomers
- On model IrO_2 and NiO: Nafion's SO_3 *may be competitive or even block metal sites*



Ir-OH*
E_{OH} (eV) = -3.72

Ir-SO_3-Ir*
E_{SO3} (eV) = -3.72

Ni-OH*
E_{OH} (eV) = -1.49

Ni-SO_3-Ni
E_{SO3} (eV) = -1.97

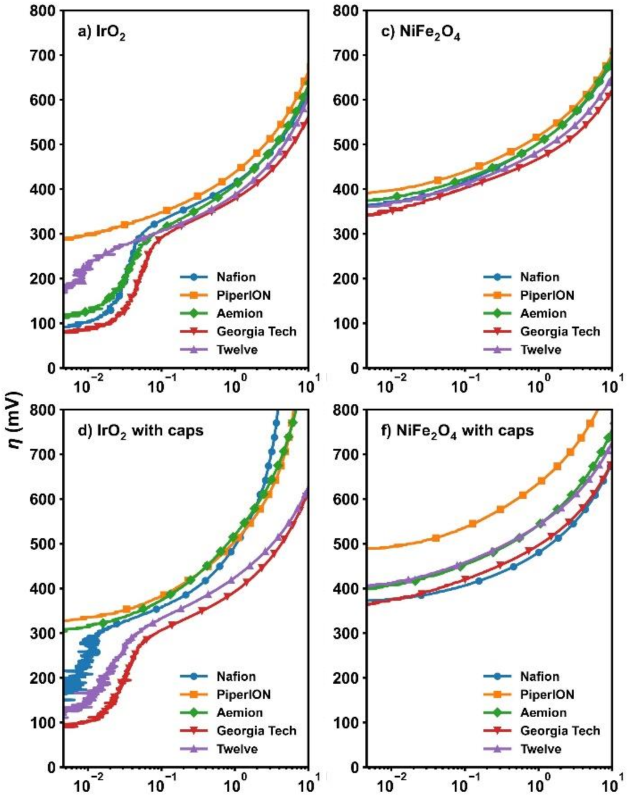
Nafion's SO_3 → *Competitive* to OH on IrO_2

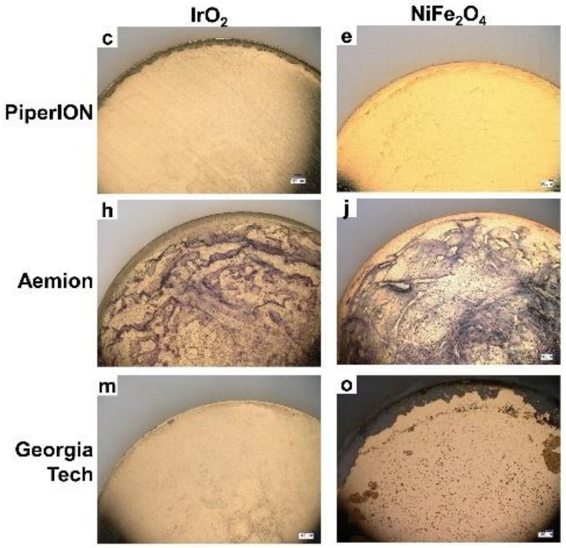
Nafion's SO_3 → *Poison* Ni Sites on NiO

Theory can identify *key limitations or advantages* to specific ionomers, **critical to our understanding of the ionomer/catalyst interface**

Q3 QPM: Develop a measure of ionomer fragment stability on Ni-based catalyst surfaces through ab-initio simulations for 3 ionomer types. Correlate and demonstrate consistency to their relative stability in ex situ testing through the decrease in electrode current over ≥ 10 h.

- Differences in performance observed, particularly with high ionomer content, not fully explained by changes to surface area (estimated by the double layer capacitance)
- Cyclic voltammetry reveals possible catalyst-ionomer interactions, notably changes to and the emergence of new reduction/oxidation pairs

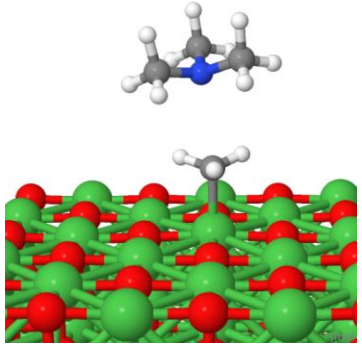




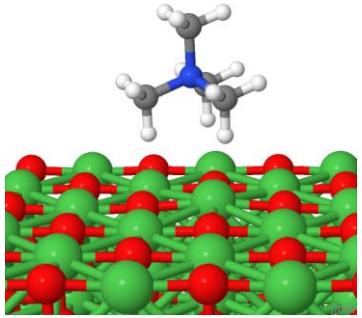
LTE 2.0 Accomplishments:

Understanding Ionomer Effects on Oxygen Evolution's OH

Georgia Tech's $N(CH_3)_4$ → *Unstable* on NiO

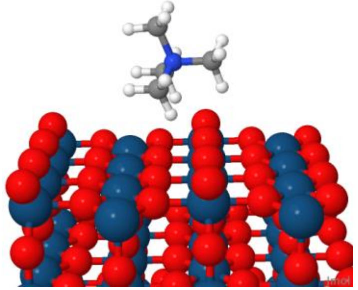


I, E_{ads} (eV) = -1.12
De-Methylation

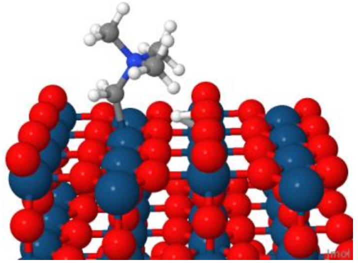


II, E_{ads} (eV) = -1.11
Stable

Georgia Tech's $N(CH_3)_4$ → *Unstable* at OER potentials, will degrade starting at 0.8 V on IrO_2

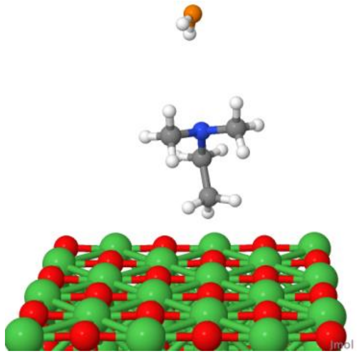


I, E_{ads} (eV) = -4.78
Stable

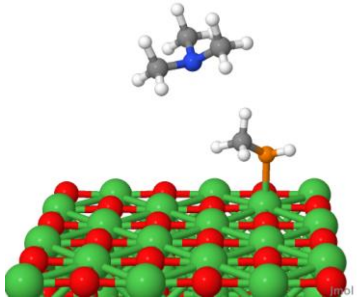


X, E_{ads} (eV) = -4.00
De-protonation

Georgia Tech's $N(CH_3)_4$ + OH* → Multiple Competing Reactions to OER on NiO

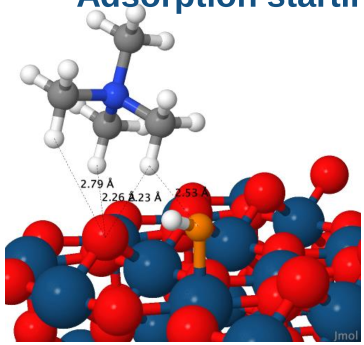


I, E_{ads} (eV) = -1.36
Water Formation

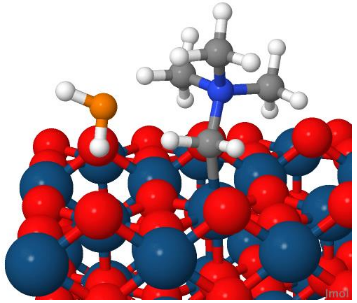


II, E_{ads} (eV) = -1.01
Methanol Formation

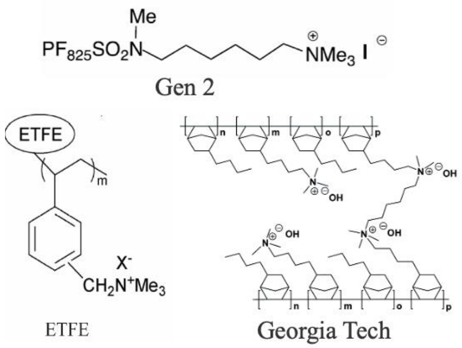
Georgia Tech's $N(CH_3)_4$ + OH* → Water Formation will Compete with OH* Adsorption starting at 0.12 V on IrO_2

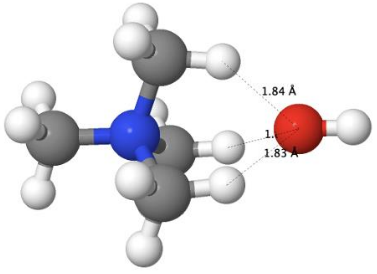


I, E_{ads} (eV) = -4.37
Unreactive, co-adsorption



E_{ads} (eV) = -4.25
Water Formation





Tetramethylammonium

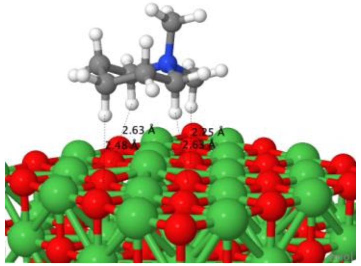
- **ETFE, GEN 2, and Georgia Tech's i**onomers all have the tetramethylammonion cation, **$N(CH_3)_4$** , to transport OH to the surface
- On both **NiO** and **IrO_2**, these ionomers will most likely be unstable and degrade at OER potentials of >1.6 V
  - Degradation can occur through either de-methylation or de-protonation
- On both **NiO** and **IrO_2**, these ionomers will introduce competing reactions to OER
  - Instead of OER: methanol and water formation

LTE 2.0 Accomplishments:

Understanding Ionomer Effects on Oxygen Evolution's OH

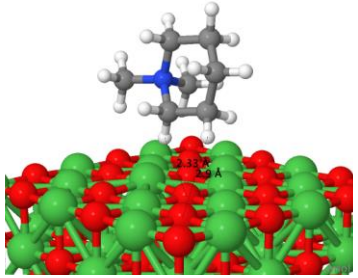
6 Nodes

Versogen on NiO → *Stable,* Ni active sites available



I, E_{ads} (eV) = -0.73

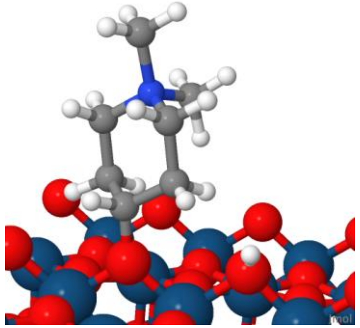
Stable



II, E_{ads} (eV) = -0.67

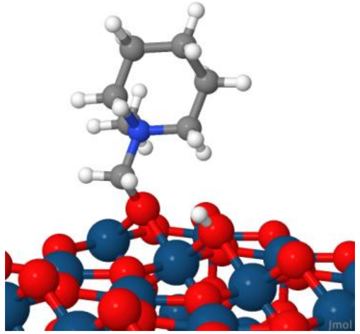
Stable

Versogen → *Unstable* on IrO_2



I, E_{ads} (eV) = -6.41

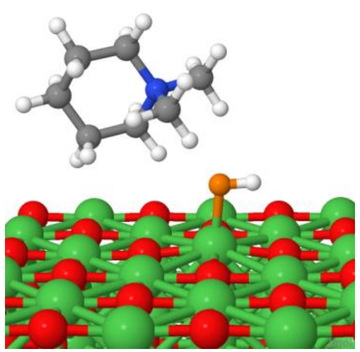
De-protonation



II, E_{ads} (eV) = -6.38

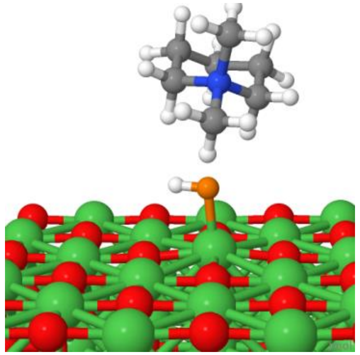
De-protonation

Versogen + OH* on NiO → Ni active sites available



I, E_{ads} (eV) = -0.72

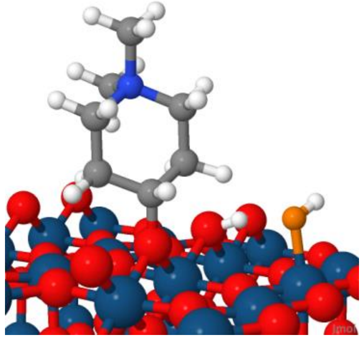
Water Formation



II, E_{ads} (eV) = -0.70

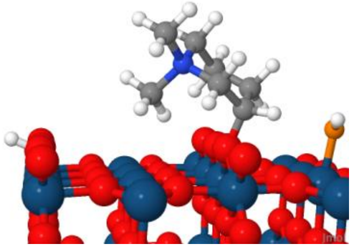
Methanol Formation

Versogen on IrO_2 → Ionomer Degrades, but OH* Adsorption Still Occurs



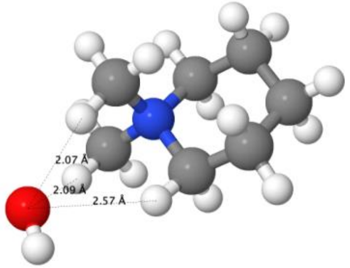
I, E_{ads} (eV) = -6.86

Co-adsorption



E_{ads} (eV) = -6.76

Co-adsorption



- **Versogen's i**onomer utilizes the mepiquat cation, **$C_7H_{16}N$,** to transport OH to the surface
- On **NiO**, Versogen remains stable and metal active sites are available for OH adsorption for OER to occur
- On **IrO_2**, Versogen degrades, but still allows for OH* adsorption to occur

Experiment and theory assessed the stability of three ionomers (Nafion, Georgia Tech, and Versogen):

- **On NiO, IrO_2: *Versogen*** is the most advantageous, allowing for OH* adsorption for OER
- **Nafion** may adsorb too strongly, *poisoning active sites*
- **Georgia Tech** may reduce activity by *introducing competing reactions to OER*

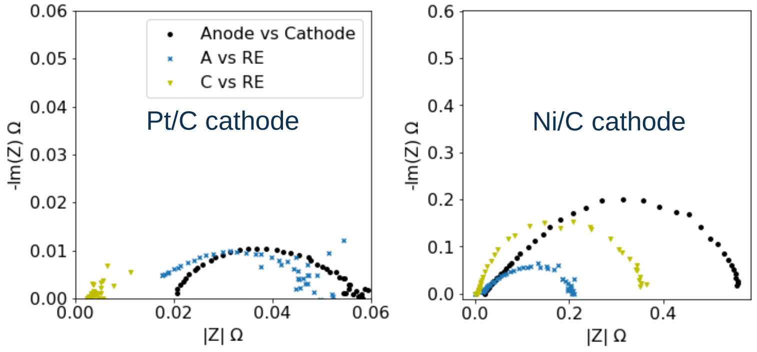
LTE 2.0 Accomplishments:

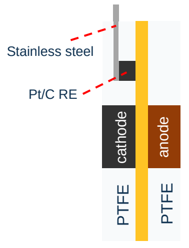
Insight Leveraging Diagnostics, Characterization, Modeling

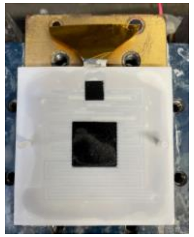
6 Nodes

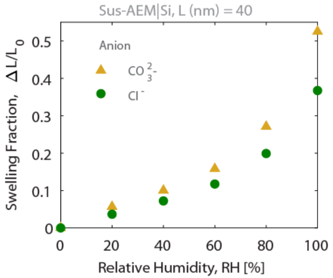
Diagnostics and Characterization

- Internal Pt reference
- Half-cell performance and impedance data reasonable, consistent

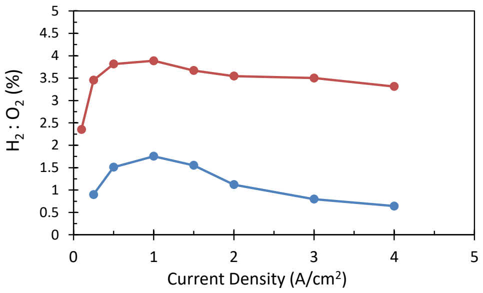








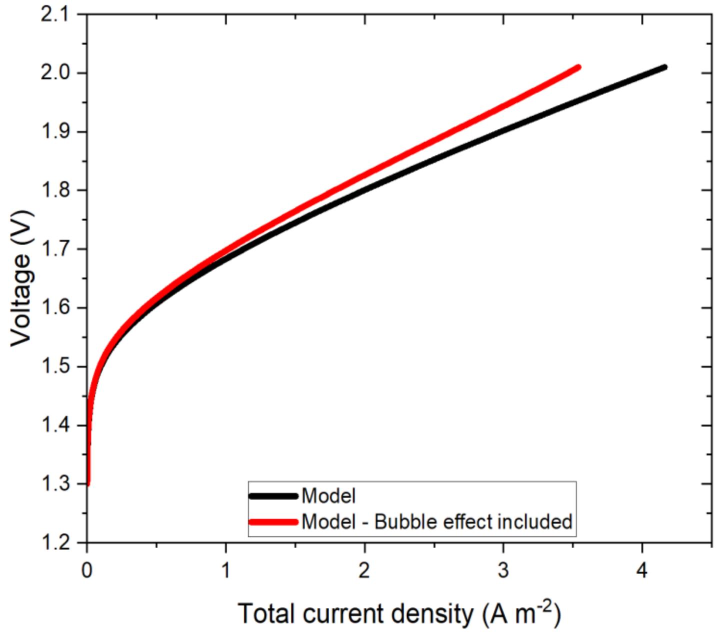
- Ionomer shows reduced thickness swelling compared to its bulk membrane analogue, but overall water content is comparable
- Incorporating LTE 2.0 materials

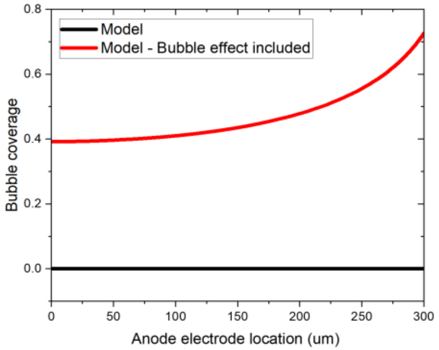


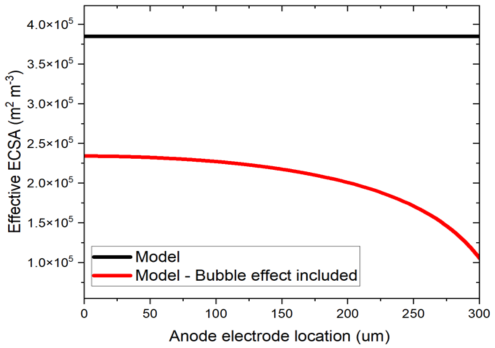
- In-line monitoring of hydrogen crossover rates
- Assess impacts of polymer type and thickness on crossover, degradation considerations

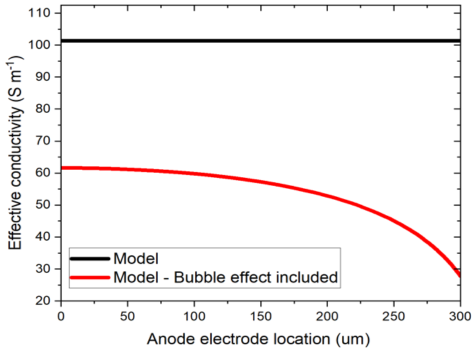
Highlight: Modeling demonstrates the impact of bubble formation on site-access and conductivity, confirming experimental findings in cell kinetics and catalyst layer resistances

- Increased bubble generation turns off more ECSA and distorts more conductive ionic path towards the AEM
- Anode kinetic overpotential increases due to the losing active ECSA
- Ohmic resistance increases due the presence of more bubble in the electrode





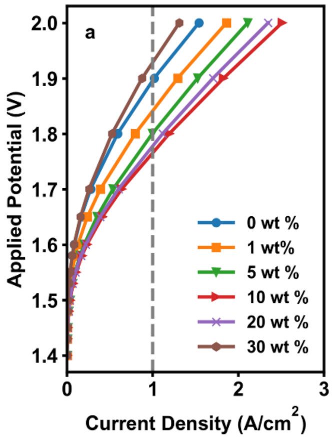


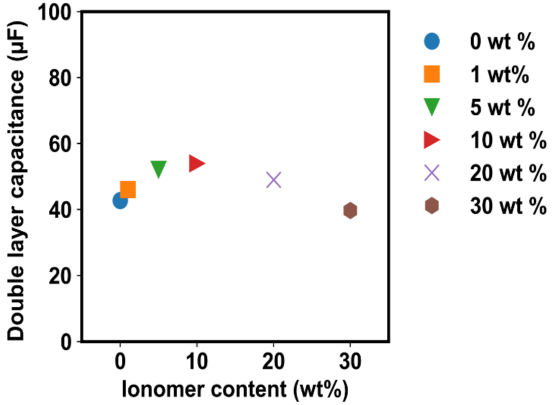


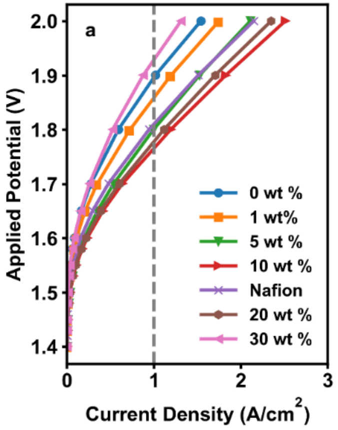
LTE 2.0 Accomplishments:

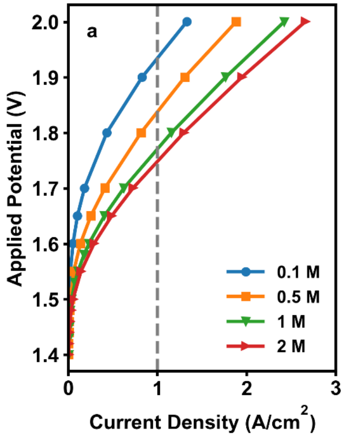
Understanding the Role of the Ionomer

6 Nodes



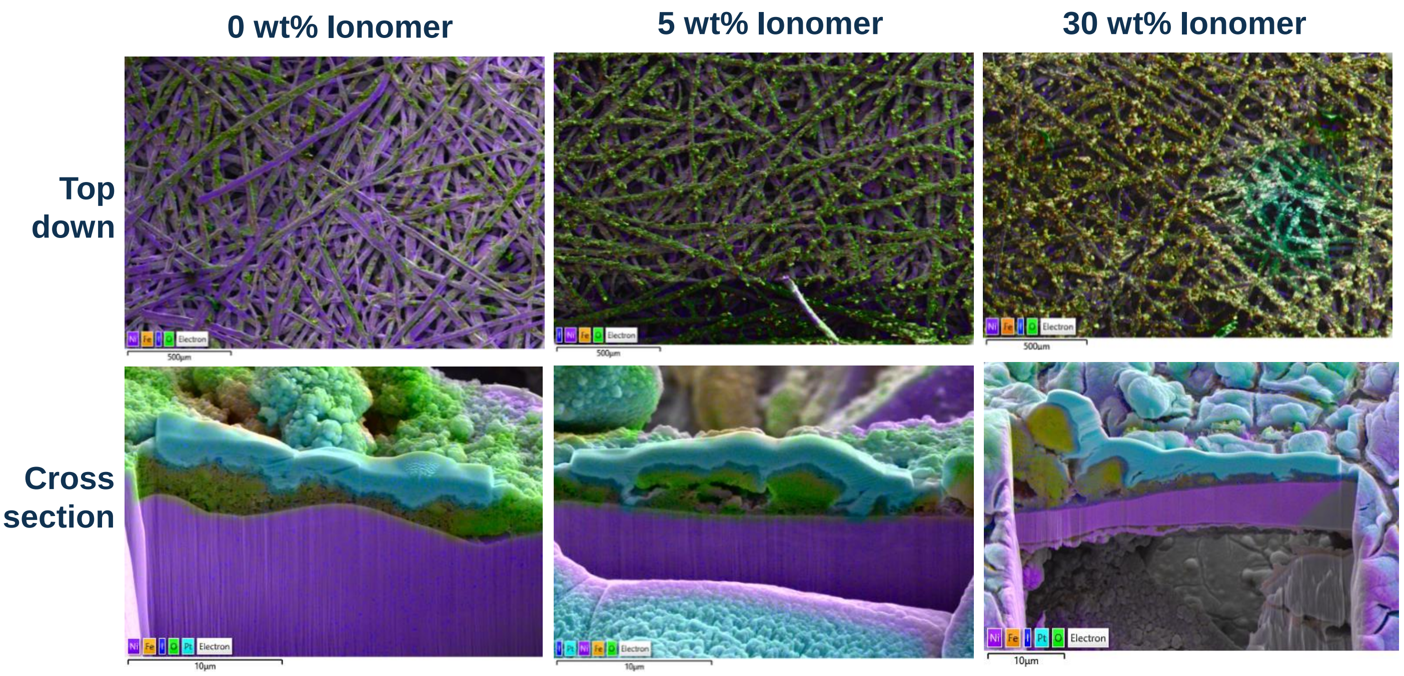






Highlight: Best performance for samples with intermediate ionomer content, associated with improved surface area and site-access. Ionomer needed for catalyst layer integrity (binder), not ion conduction.

- Performance of 10 wt% Nafion similar to 5-20 wt% Versogen, suggests that ionomer is not required for ion conduction
- Kinetic, catalyst resistance improves with electrolyte concentration, suggests that 1 M is sufficient to provide ion conduction

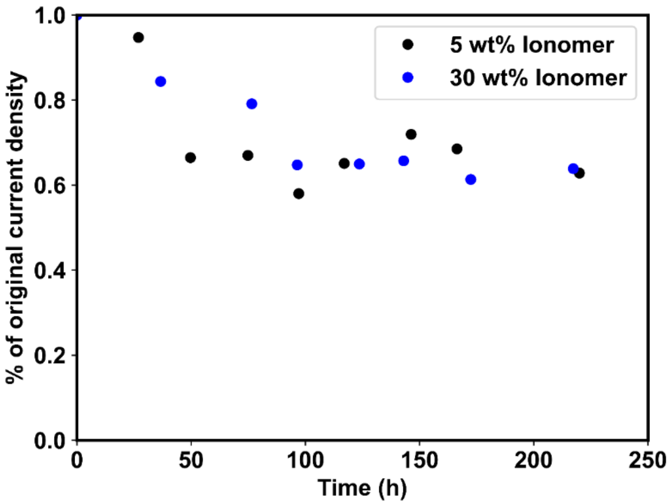


Q1 QPM: Correlate physical catalyst layer properties in microscopy (ionomer distribution, pore structure) to relative kinetic (Tafel and catalyst layer resistance) performance in an aqueous electrolyte for > 3 membrane electrode assemblies.

- Catalyst layer porosity increases with decreasing ionomer content. Conversely, denser and thinner catalyst layers observed for high ionomer content (30 wt%).
- Ionomer hotspots observed for 30 wt% sample – zoomed in image indicates this hotspot has dense, cracked coverage. Suggests inhomogeneity of catalyst/ionomer in the catalyst layer at high content.

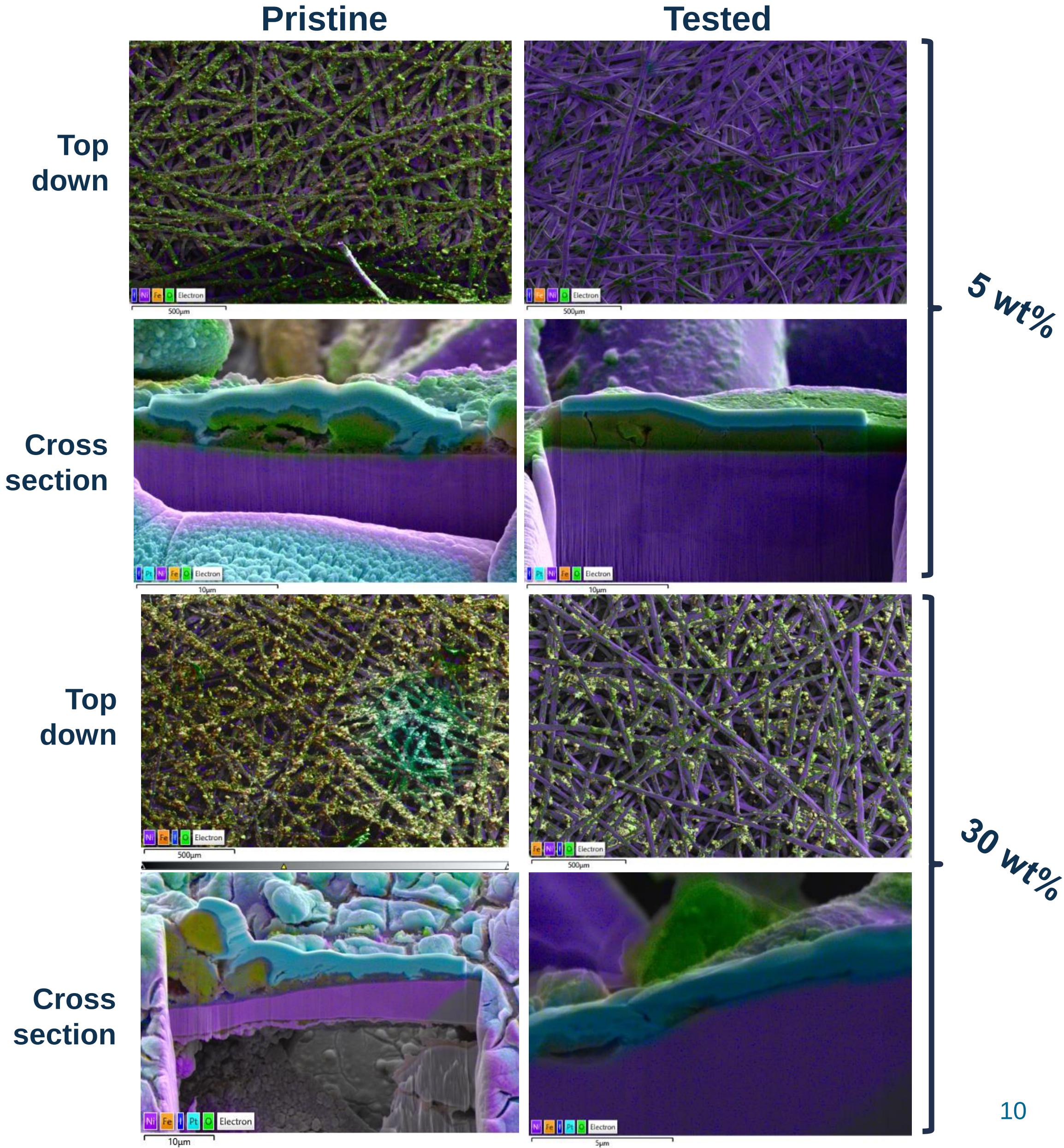
LTE 2.0 Accomplishments:

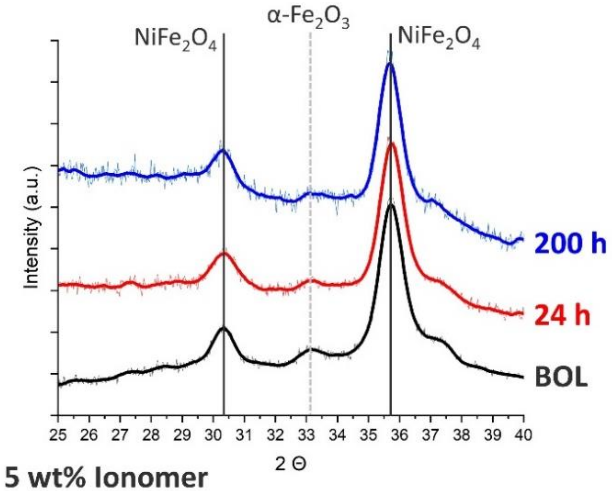
Understanding the Role of the Ionomer



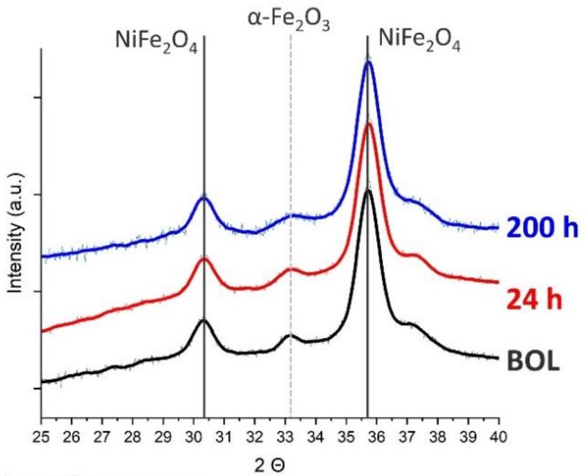
Q1 QPM: Microscopy demonstrates catalyst delamination and loss, confirms that ionomer is needed in electrode stability.

- Catalyst loss is evident for both samples in microcopy results; better adhesion for 30 wt% sample
- Catalyst layer thinning and densification evident in cross sectional images
- Ex situ XRD: α-Fe_2O_3 phase loss observed after testing for both samples





5 wt% Ionomer

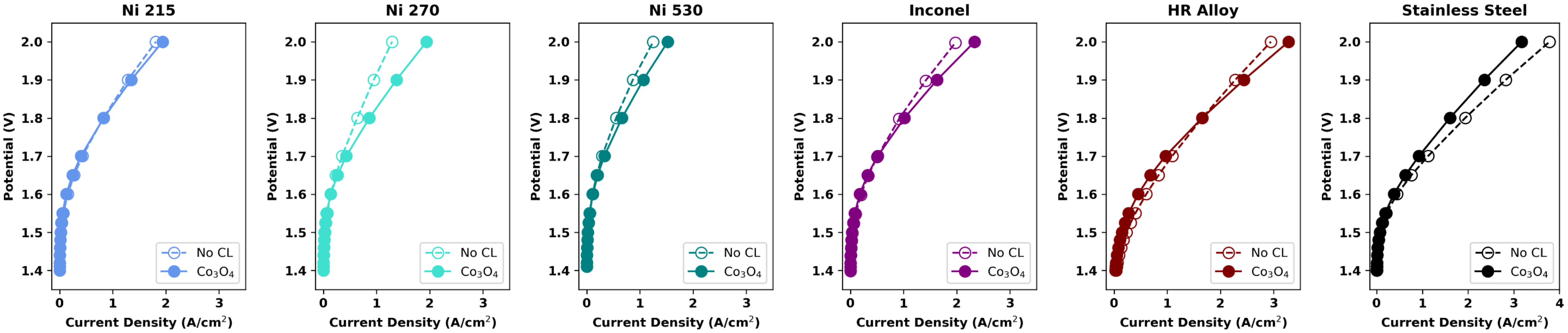


30 wt% Ionomer

LTE 2.0 Accomplishments:

Impact of Porous Transport Layer on Performance

6 Nodes



<table>
<tr><th rowspan="2">PTL</th><th rowspan="2">Composition</th><th rowspan="2">Thicknes s (µm)</th><th rowspan="2">Top Layer Fiber Dimension (µm)</th><th rowspan="2">Porosity (%)</th><th rowspan="2">Average Pore Size (µm)</th><th colspan="2">HFR-free V @ 1 A/cm^2</th></tr>
<tr><th>No CL</th><th>Co_3O_4</th></tr>
<tr><td>Ni 215</td><td>100% Ni</td><td>215</td><td>20</td><td>84</td><td>44</td><td>1.770</td><td>1.751</td></tr>
<tr><td>Ni 270</td><td>100% Ni</td><td>270</td><td>20</td><td>61</td><td>18</td><td>1.845</td><td>1.746</td></tr>
<tr><td>Ni 530</td><td>100% Ni</td><td>530</td><td>20</td><td>60</td><td>16</td><td>1.877</td><td>1.808</td></tr>
<tr><td>Inconel</td><td>60% Ni, 25% Cr, 15% Fe</td><td>600</td><td>12</td><td>65</td><td>22</td><td>1.737</td><td>1.719</td></tr>
<tr><td>HR Alloy</td><td>60% Ni, 22% Cr, 16% Mo, 2% Fe</td><td>290</td><td>4</td><td>45</td><td>7</td><td>1.591</td><td>1.632</td></tr>
<tr><td>Stainless Steel</td><td>65% Fe, 18% Cr, 14% Ni, 3% Mo</td><td>430</td><td>2</td><td>44</td><td>9</td><td>1.663</td><td>1.628</td></tr>
</table>

Highlight: Transport layer clearly utilized in anode reactivity, approaches 4 A cm^{-2} at 2 V without catalyst layer

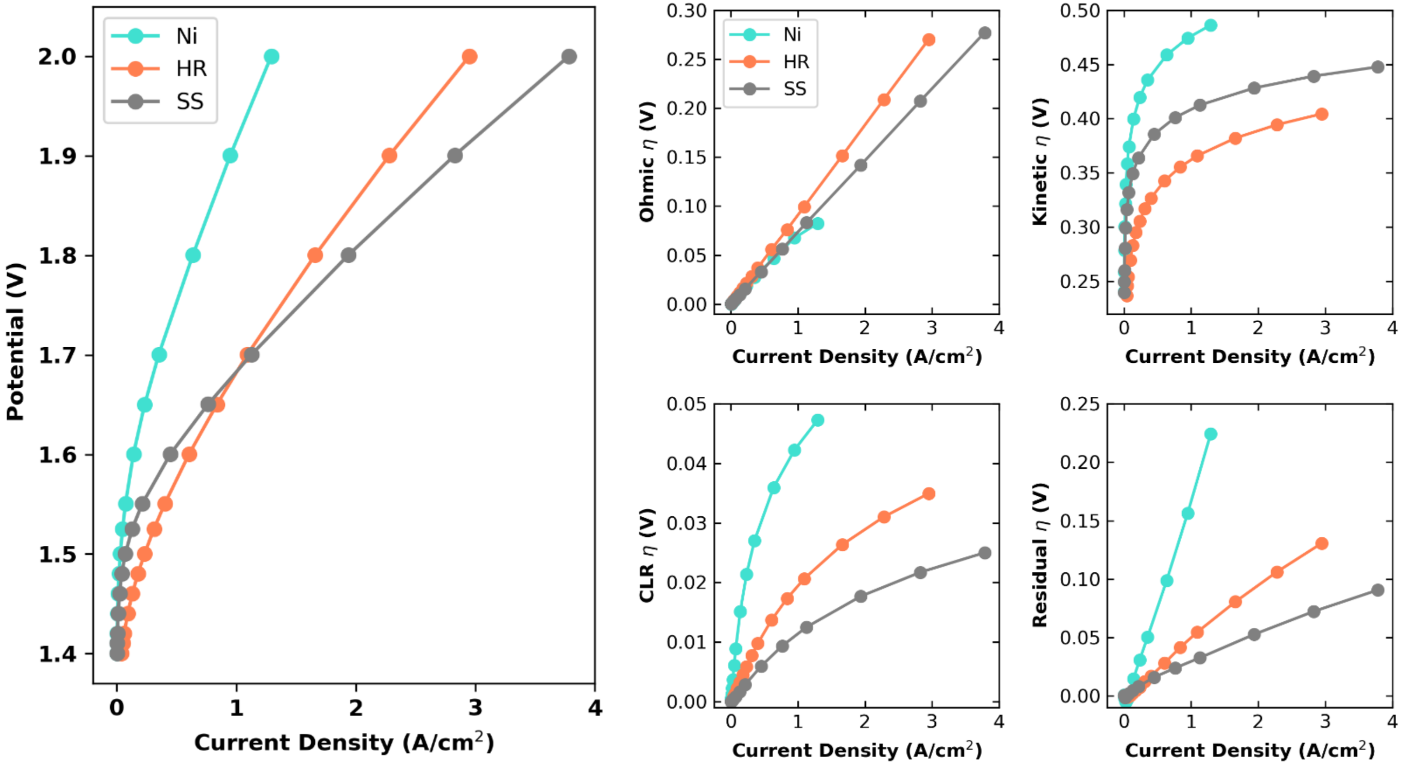
- Improved activity through the addition of other elements (Fe, Cr, Mo) and/or the improved morphology
- Nickel transport layers less active, likely required for long-term durability

Anode: none or 0.5 mg$_{TM}$ cm^{-2} Co_3O_4 (USRM); **Cathode:** 0.3 mg$_{Pt}$/cm^2 Pt/C (TKK); **Electrolyte:** 1 M KOH; **Temperature:** 80 °C; **Membrane:** PiperION TP-85 (80 µm); **Ionomer:** PiperION TP-85 (30 wt%); **Cathode GDL:** MGL280 C paper; **Anode PTL:** Ni 18-025 (Ni) or ST10AL3 Alloy HR (HR) or XL601S AISI 316L (SS) (Bekaert)

LTE 2.0 Accomplishments:

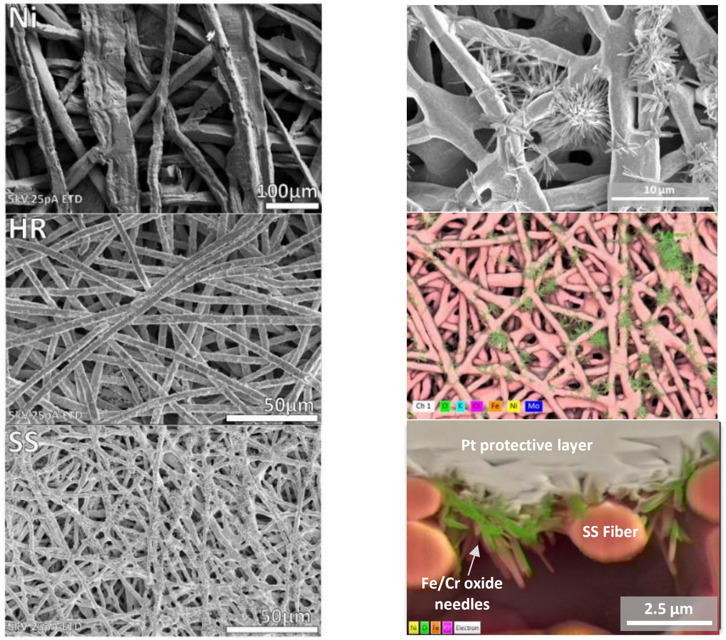
Porous Transport Layer without a Catalyst Layer

6 Nodes



Polarization curves and voltage loss breakdown for Ni, HR alloy (HR), and stainless steel (SS) PTLs as anode catalysts. HR has the best kinetic performance, while SS shows low catalyst layer resistance and mass transport losses.

Metrics/PTL	Ni	HR	SS
HFR-free Potential at 1 A/cm^2 (V)	1.845	1.591	1.609
Current Density at 2 V (A/cm^2)	1.293	2.950	3.783



(Left) Top-down SEM images for bare Ni, HR, and SS PTLs after AEMWE testing. **(Right)** Top-down and cross-section SEM images of the SS PTL showing leaching of Fe and Cr out of the fibers after AEMWE testing.

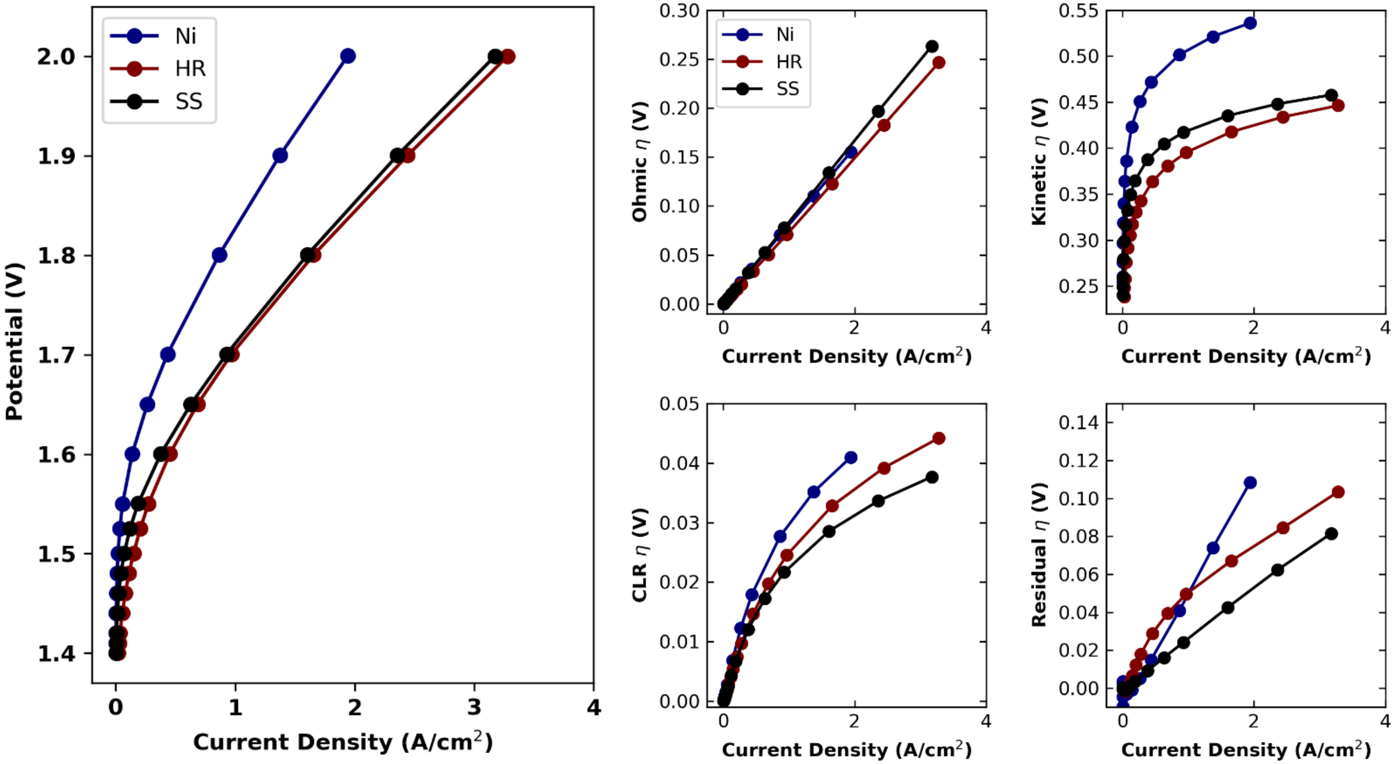
Highlight: Transport layer affects ohmic, kinetic, catalyst layer resistance, and mass transport losses

- HR (NiCrMoFe alloy) has best kinetic performance, SS has smallest pore size and lowest CLR and transport losses
- SS is least stable, with Fe/Cr leaching out of the fibers

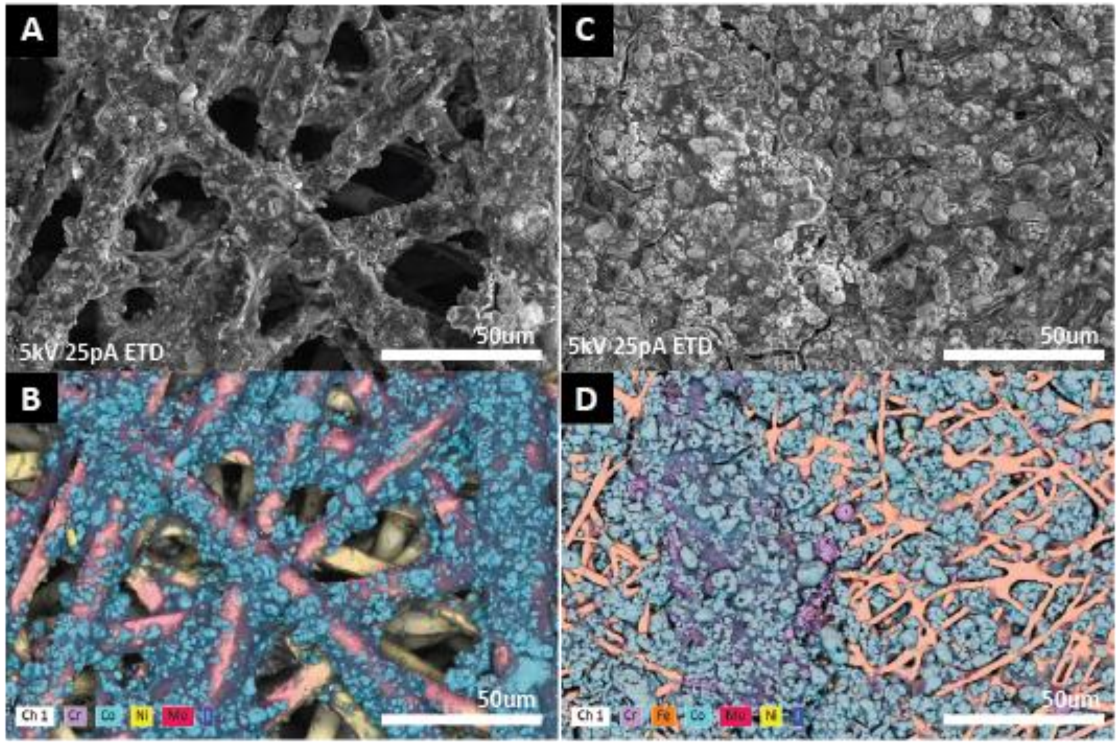
Anode: none; **Cathode:** 0.3 mg$_{Pt}$/cm^2 Pt/C (TKK) **Electrolyte:** 1 M KOH; **Temperature:** 80 °C; **Membrane:** PiperION TP-85 (80 µm); **Ionomer:** PiperION TP-85 (30 wt%); **Cathode GDL:** MGL280 C paper; **Anode PTL:** Ni 18-025 (Ni) or ST10AL3 Alloy HR (HR) or XL601S AISI 316L (SS) (Bekaert)

LTE 2.0 Accomplishments:

Porous Transport Layer with a Catalyst Layer



Polarization curves and voltage loss breakdown for Ni, HR, and SS PTLs with Co_3O_4 catalyst layer. HR and SS show much better kinetics and lower catalyst layer resistance than Ni.



Top-down SEM images and EDS maps for (**A-B**) Co_3O_4 on HR alloy PTL and (**C-D**) Co_3O_4 on SS PTL after AEMWE testing.

Metrics/PTL	Ni	HR	SS
HFR-free Potential at 1 A/cm^2 (V)	1.746	1.632	1.628
Current Density at 2 V (A/cm^2)	1.942	3.280	3.174

Q1 QPM: SEM shows that catalyst layer morphology depends on the PTL, and in particular catalyst layer uniformity and coverage is higher for the SS PTL, with no visible fibers. Leaching of Fe and Cr still occurs with a catalyst layer but is minimized.

Anode: 0.5 mg_{TM} cm^{-2} Co_3O_4 (USRM); **Cathode:** 0.3 mg_{Pt}/cm^2 Pt/C (TKK); **Electrolyte:** 1 M KOH; **Temperature:** 80 °C; **Membrane:** PiperION TP-85 (80 µm);
Ionomer: PiperION TP-85 (30 wt%); **Cathode GDL:** MGL280 C paper; **Anode PTL:** Ni 18-025 (Ni) or ST10AL3 Alloy HR (HR) or XL601S AISI 316L (SS) (Bekaert)

LTE 2.0 Accomplishments:

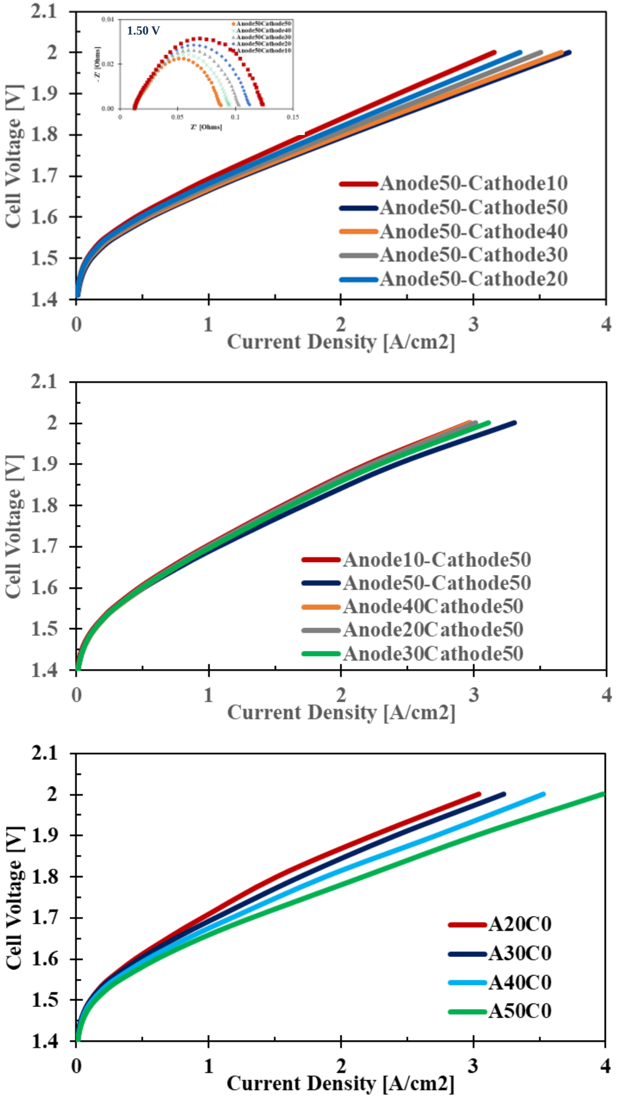
Effect of Operational Parameters

NREL Transforming ENERGY · BERKELEY LAB · Sandia National Laboratories · 6 Nodes

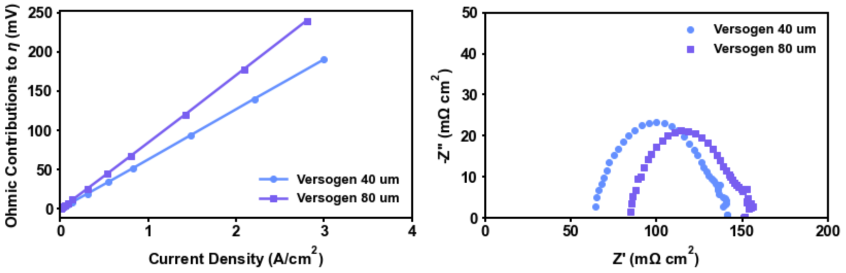
Q2 QPM: Leverage ex and in situ resistance/impedance measurements to separate sources for electronic and ionic resistance for ≥ 2 membrane electrode assemblies varying catalyst layer deposition approach. Correlate to modeling to demonstrate consistency in overpotential sources and compare kinetic performance (cell at 1 A cm^{-2}) and catalyst layer utilization (cell-level model) data to down select catalyst layer fabrication approach.

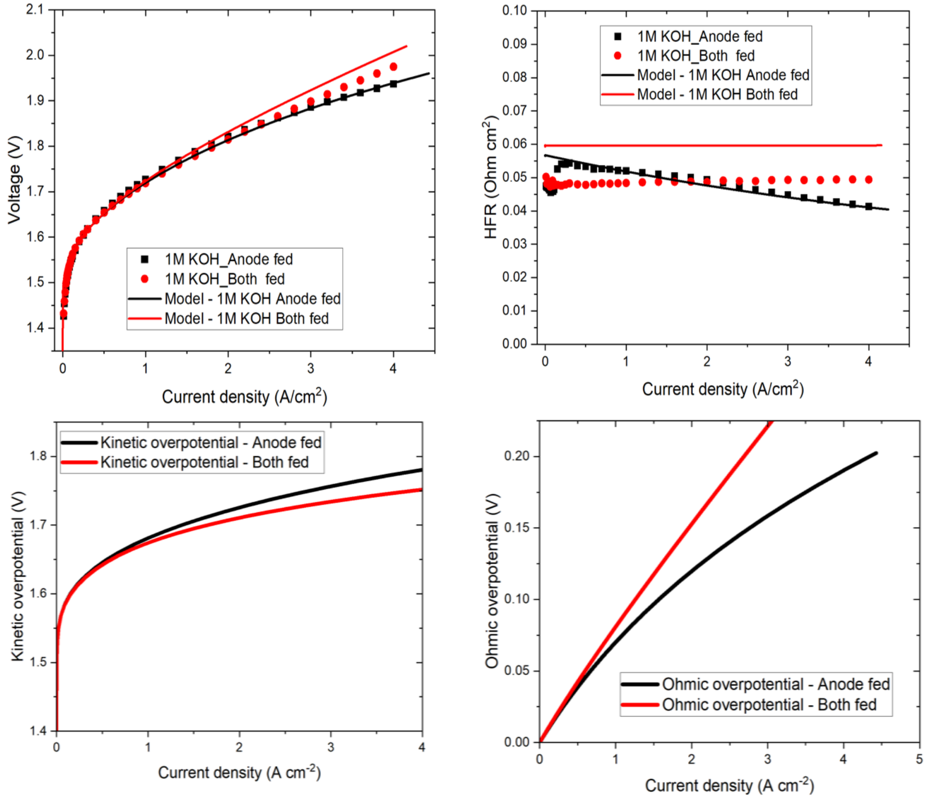
Agreement between modeling and cell testing when incorporating different flow parameters, particularly with decreasing HFR at higher current density during dry cathode operation.

Electrolyte Flow



Membrane Thickness



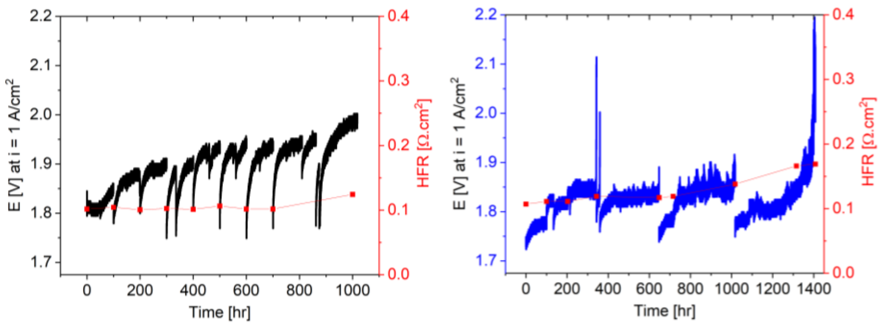


Highlight: Although feeding both anode and cathode is decreases the kinetic overpotential, it has a higher ohmic overpotential

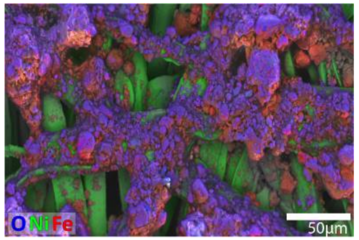
- For anode feed, the concentration gradient between anode/cathode is higher, improved mass transport
- Feeding liquid electrolyte increases bubbles entrapment

LTE 2.0 Accomplishments:

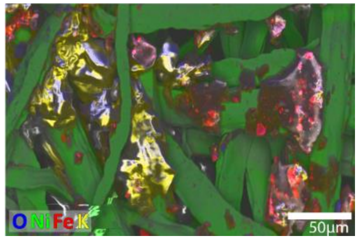
Degradation Mechanisms and Accelerated Test Development



Durability at 1 A/cm^2 for MEAs with NiFe anode catalyst layer and (a) Ni and (b) SS PTLs

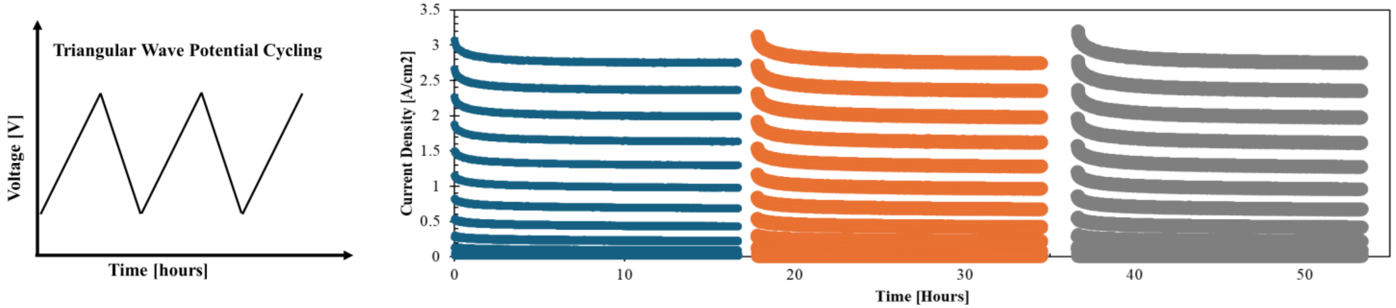


NiFe Catalyst, Initial

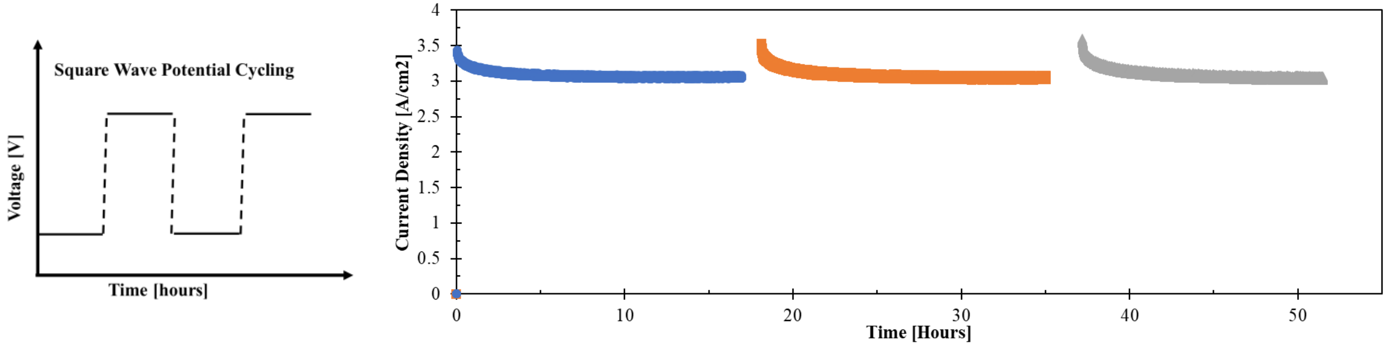


NiFe Catalyst, After Test

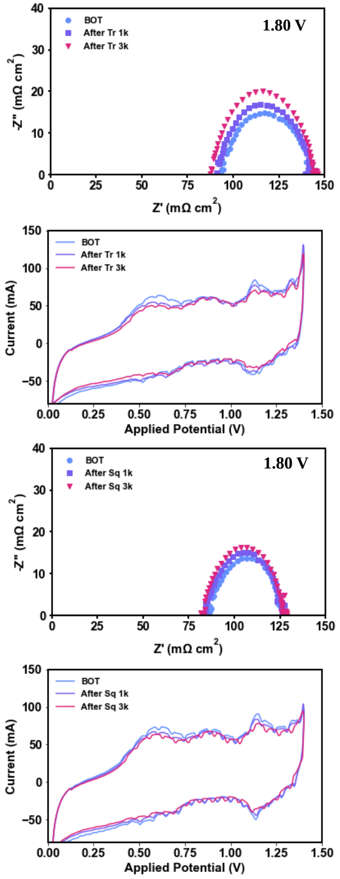
Q4 Milestone: Testing of at least 3 membrane electrode assemblies with commercial materials for at least 500 h to set a benchmark performance decay rate and understand relevant degradation processes.



Triangle wave stability (1.45–2 V) with Co anode catalyst layer and Ni PTL



Square wave stability (1.45–2 V) with Co anode catalyst layer and Ni PTL

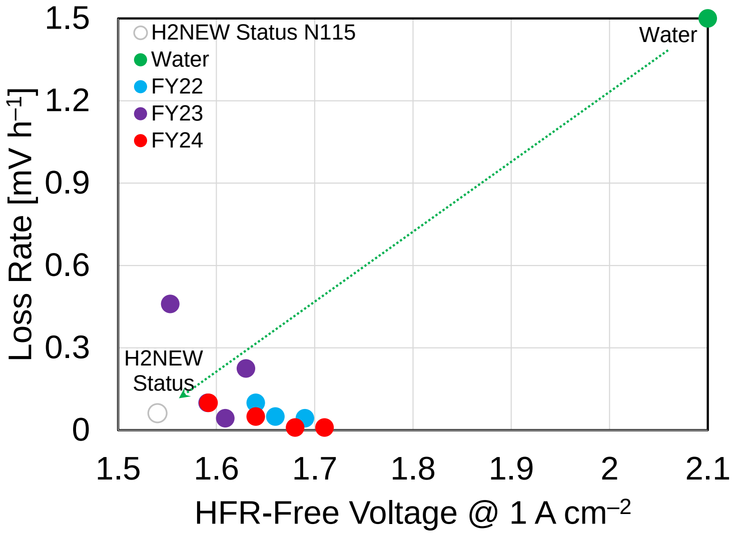


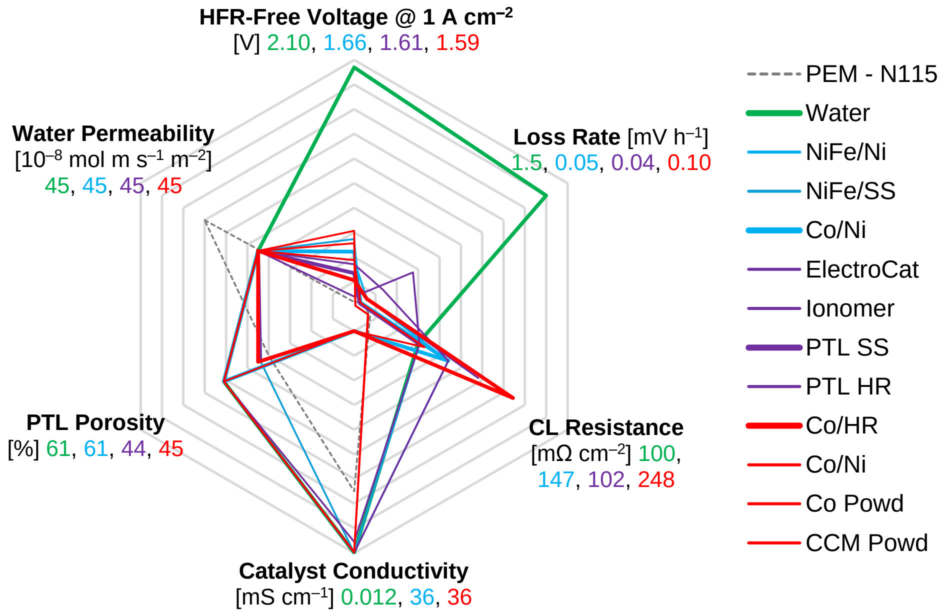
Highlight: Probing durability testing through extended operation for loss mechanisms and to evaluate operational strengths/vulnerabilities. Developing accelerated stress tests at the component- and cell-level.

- Increased mobility of Fe a consideration. Dissolution of Fe in the catalyst layer can lead to delamination. Dissolution of Fe in the transport layer can lead to lower site-access and interfacial resistances.
- Short-term load fluctuation leads to a recoverable performance loss, likely due to passivation and gas formation impacting site-access. Minimal changes in kinetics found, from voltammetry and impedance.

LTE 2.0, Summary of Accomplishments

- Ionomer stability can range considerably depending on the catalyst material, even on the typically non-reactive model NiO and on the benchmark PGM IrO_2 with degradation introducing competing reactions to OER such as alcohol or water formation
- Established the role of the ionomer in catalyst layers and probed the impact of various ionomers on catalyst reactivity and stability, leveraging modeling to understand catalyst-ionomer interactions
- Demonstrated performance improvements through the screening of transport layers and optimization of ionomer content and ionomer integration strategies, leveraging microscopy to understand performance differences between catalyst/transport layers
- Began durability testing to establish loss mechanisms and to development component- and cell-level accelerated stress tests





Future Work

- LTE 2.0
  - Evaluate OH* coverage effects on ionomer stability; determine transition state barriers to oxygen evolution in the presence of the ionomer to assess changes to OER activity
  - Establish an understanding of how various ionomer chemistries and catalyst compositions modify catalyst layer reactivity-stability relationships
  - Optimize catalyst layer composition and processing technique to improve site-access, catalyst layer resistances, and device performance and durability
  - Understand the impact of catalyst layer electronic and ionic conduction on catalyst layer resistance and cell performance
  - Establish benchmark performance decay rates and understand relevant degradation processes; create durability testing framework for component- and cell-level stress tests.

- Leverage HydroGEN nodes to enable successful HydroGEN FOA and Lab call projects

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

Validation of AEMWE Testing Protocols

Accomplishments & Progress

P170

Validation Goals: Ensure each protocol can be universally applied across the AWST community to produce repeatable results that can be reported and compared;

Current LTE validation sites: LANL, NREL, University of Oregon, coordinated by NEL

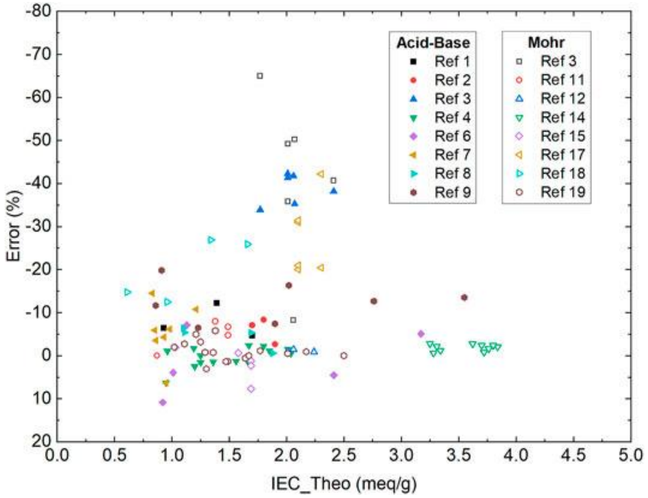
Test Protocols Validation in Process:

1. Ion Exchange Capacity (IEC)
   - LTE-P-7 SOP on the HydroGEN Data Hub
   - Standard Operating Protocols for Ion-Exchange Capacity of Anion Exchange Membranes, Frontiers in Energy Research Journal, Vol 10 – 2022. (7,539 views, 1,050 downloads) https://doi.org/10.3389/fenrg.2022.887893
2. Alkaline Stability of AEMs
   - LTE-P-22 SOP on the HydroGEN Data Hub
   - Assessing the Oxidative Stability of Anion Exchange Membranes in Oxygen Saturated Aqueous Alkaline Solutions, Frontiers in Energy Research Journal, Vol 10 – 2022.(3,215 views, 675 downloads) https://doi.org/10.3389/fenrg.2022.871851

Validation site example: Leverage HydroGEN Consortium Capabilities

HydroGEN Advanced Water Splitting Materials

NREL, LBNL, SNL, INL, and LLNL



Summary of Errors versus Theoretical IEC values from typical aggregated from the AEMs reported. (https://doi.org/10.3389/fenrg.2022.887893)

Responses to Reviewers

Degradation mechanisms studies should be planned. Most durability data was short, which limits the significance of project progress.

- Durability testing has been limited due to equipment and test stand bandwidth. Increased efforts in durability studies have been planned and are reflected in LTE 2.0 Accomplishments slides and the Q4 Milestone.
- Q4 Milestone: Testing of at least 3 membrane electrode assemblies with commercial materials for at least 500 h to set a benchmark performance decay rate and understand relevant degradation processes. These tests will vary the materials evaluated and/or operation parameters, and leverage HydroGEN nodes to determine how losses are observed and the component/process involved. Durability understanding will be achieved through: advanced diagnostics to separate individual component degradation (NREL); microscopy to determine changes in ionomer and pore content/distribution (SNL); multiscale modeling to determine the impact of ionomer/pore content of performance (LBNL); and relative ionomer stability with different material sets (NREL).

In the future, the consortium can provide a year-to-year progress (since 2016) that would provide an overall outlook of the accomplishments.

- A figure of merit has been included tracking cell-level performance and durability data to provide year-to-year progress since the start of the LTE 2.0 project in FY21. A spider chart has also been included tracking component and cell-level properties for the broader anion exchange membrane low temperature electrolysis technology.

Collaboration, Effectiveness

- Interfacing between HydroGEN and IEA Annex 30 in benchmarking
- Interfacing between HydroGEN and ElectroCat in catalyst benchmarks
- Contributions to the Meta Data development for the HydroGEN Data Center
- Advanced Water Splitting Technology Benchmarking and Protocols Workshop – September 20-22, 2023; next meeting planned for June 11-12, 2024.

LTE 2.0 Team		
NREL Transforming ENERGY	BERKELEY LAB Bringing Science Solutions to the World	Sandia National Laboratories
Shaun Alia Ai-Lin Chan Huyen Dinh Mai-Anh Ha Melissa Kreider Ross Larsen Douglas Marsh Meital Shviro Noor Ul Hassan Emily Volk	Sarah Berlinger Tugrul Ertugrul Jingjing Liu Xiong Peng Adam Weber Rito Yanagi	Josh Sugar Jamie Trindell Arielle Clauser

Presentations and Publications

Presentations:

- M. E. Kreider, H. Yu, L. Osmieri, E. K. Volk, P. Zelenay, D. A. Cullen, S. M. Alia, Investigating the Effects of Anode Catalyst Conductivity and Loading on Performance for Anion Exchange Membrane Water Electrolysis, [Oral Presentation], 245th Electrochemical Society (ECS) Meeting, San Francisco CA
- S. M. Alia, M. E. Kreider, A. L. Chan, N. Ul Hassan, A. L. Clauser, J. D. Sugar, Materials Integration and Catalyst Interfaces in Anion Exchange Membrane, Low Temperature Electrolysis, [Oral Presentation], 245th Electrochemical Society (ECS) Meeting, San Francisco CA
- N. Ul Hassan, S. M. Alia, B. S. Pivovar, W. E. Mustain, In-Situ Diagnostic Tools and Analysis to Identify Root Causes for Voltage Loss in Anion Exchange Membrane Water Electrolyzers, [Oral Presentation], 245th Electrochemical Society (ECS) Meeting, San Francisco CA
- E. K. Volk, S. Kwon, S.M. Alia, Voltage-Breakdown Analyses in Anion Exchange Membrane Electrolyzers –the Contributions of Catalyst Layer Resistance on Overall Overpotentials, [Oral Presentation], 2023 American Institute of Chemical Engineers (AIChE) Annual Meeting, Orlando FL
- S. M. Alia, Materials, Integration, and Durability Challenges in Low Temperature Electrolysis, [Oral Presentation], 2023 American Institute of Chemical Engineers (AIChE) Annual Meeting, Orlando FL.
- S. M. Alia, M. Kreider, E. K. Volk, A. L. Chan, A. L. Clauser, J. D. Sugar, Materials Integration and Catalyst Interfaces in Anion Exchange Membrane, Low Temperature Electrolysis, [Oral Presentation], 244th Electrochemical Society (ECS) Meeting, Gothenburg, Sweden.
- E. K. Volk, R.R. Beswick, S. Kwon, S.M. Alia, Electrochemical activation of $NiFe_2O_4$ for the oxygen evolution reaction in alkaline media, [Oral Presentation], 243rd Electrochemical Society (ECS) Meeting, Boston MA
- S. Intikhab, E.K. Volk, R.R. Beswick, H. Yu, D.A. Cullen, S. Kwon, S.M. Alia, “Materials Integration, Catalyst-Ionomer Interfaces, and Durability Implications in Anion Exchange Membrane-Based Low Temperature Electrolysis” 243rd Electrochemical Society (ECS) Meeting, Boston MA
- A. W. Tricker, J. K. Lee, J. R. Shin, A. Z. Weber, X. Peng, Design Principles for Hydroxide Exchange Membrane Water Electrolyzers, 243rd Electrochemical Society (ECS) Meeting, Boston MA

Publications:

- Ha, M.-A.; Larsen, R., Multiple Reaction Pathways for the Oxygen Evolution Reaction May Contribute to IrO2 (110)’s High Activity, *J. Electrochem. Soc.*, **2021**, 168, pp. 024506.
- Emily K. Volk, Melissa E. Kreider, Stephanie Kwon, and Shaun M. Alia, Recent progress in understanding the catalyst layer in anion exchange membrane electrolyzers – durability, utilization, and integration, *EES Catalysis*, **2024**, 2, 109, DOI: 10.1039/d3ey00193h
- Emily K. Volk, Stephanie Kwon, and Shaun M. Alia, Catalytic Activity and Stability of Non-Platinum Group Metal Oxides for the Oxygen Evolution Reaction in Anion Exchange Membrane Electrolyzers, *Journal of the Electrochemical Society*, **2023**, 170, 064506, DOI: 10.1149/1945-7111/acd605