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

June 5–8, 2023

Project ID # P148A

DOE Hydrogen Program 2023 Annual Merit Review and Peer Evaluation Meeting

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

Approach: HydroGEN 2.0 Project Added to LTE Activities

HydroGEN LTE Projects

- 8 FOA projects with 41 nodes
  - 3 currently supported (in Accomplishments)
  - 5 with closeout contributions (in Technical Backup)
- 2 Supernodes with 14 nodes
- LTE 2.0 with 4 nodes

LTE Node Labs

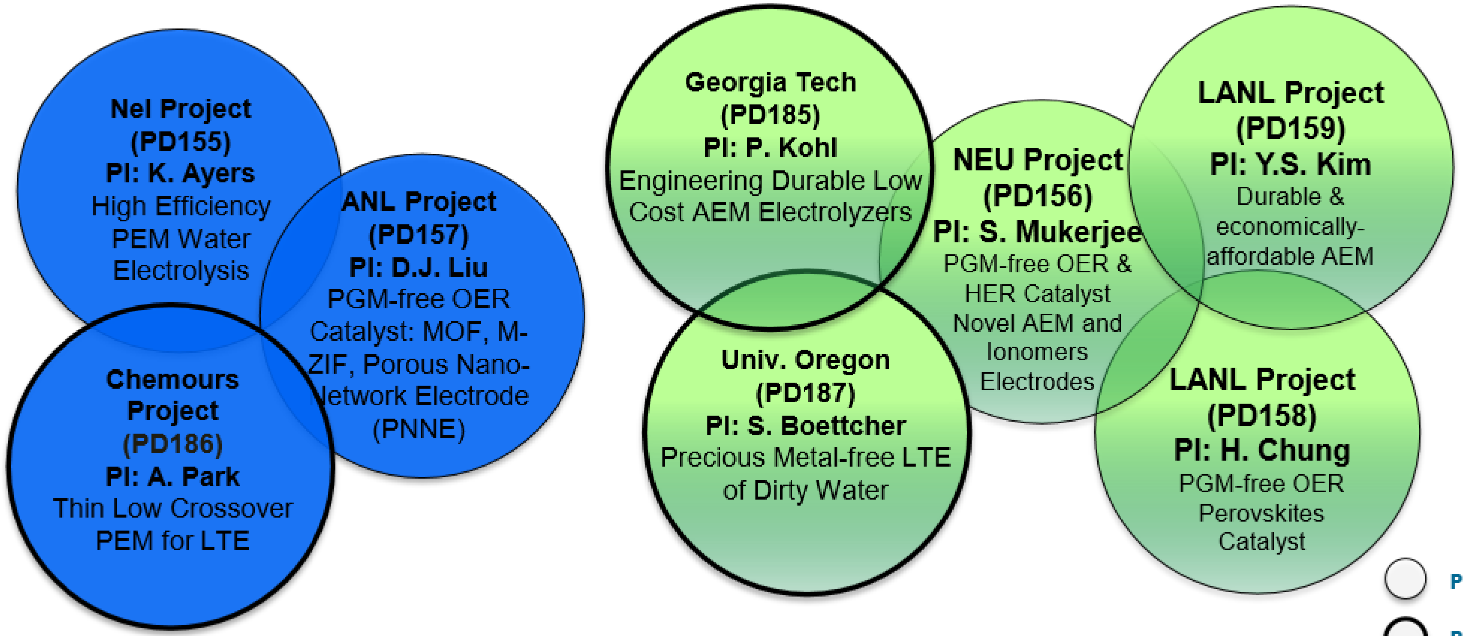
NREL
Berkeley Lab
Sandia National Laboratories
Lawrence Livermore National Laboratory

Support through:

Personnel
Equipment
Expertise
Capability
Materials
Data

LTE FOA Projects

nel
Argonne National Laboratory
Northeastern University
Los Alamos National Laboratory (2)
Georgia Institute of Technology
Chemours
University of Oregon



Nel Project (PD155)
PI: K. Ayers
High Efficiency PEM Water Electrolysis

ANL Project (PD157)
PI: D.J. Liu
PGM-free OER Catalyst: MOF, M-ZIF, Porous Nano-Network Electrode (PNNE)

Chemours Project (PD186)
PI: A. Park
Thin Low Crossover PEM for LTE

Georgia Tech (PD185)
PI: P. Kohl
Engineering Durable Low Cost AEM Electrolyzers

NEU Project (PD156)
PI: S. Mukerjee
PGM-free OER & HER Catalyst Novel AEM and Ionomers Electrodes

LANL Project (PD159)
PI: Y.S. Kim
Durable & economically-affordable AEM

Univ. Oregon (PD187)
PI: S. Boettcher
Precious Metal-free LTE of Dirty Water

LANL Project (PD158)
PI: H. Chung
PGM-free OER Perovskites Catalyst

○ Projects added FY'18
○ Projects added FY'20

Supernodes	A. Weber T. Ogitsu	Understanding OER Across pH Ranges Through Multiscale, Multi-Theory Modeling	Discussed in PEC, P148A
	H. Dinh B. Pivovar	Linking LTE/Hybrid Materials to Electrode Properties to Performance	Discussed here in LTE, P148
LTE 2.0	S. Alia B. Pivovar	Enabling High Efficiency, Durable AEMWE Performance	

PEM: Understanding and improving materials

AEM: Developing and understanding materials

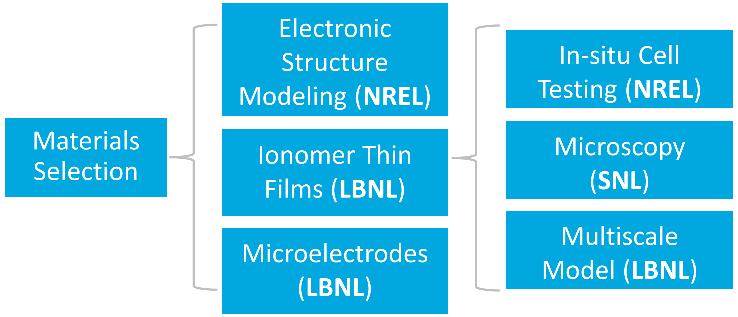
LTE 2.0 Approach:

Enabling High Efficiency, Durable AEM Electrolysis Performance

NREL Transforming ENERGY | BERKELEY LAB | Sandia National Laboratories | **5 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**)

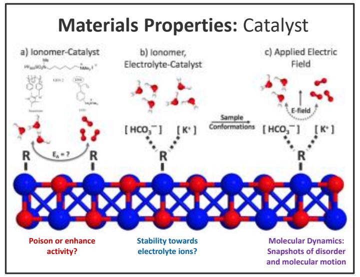
Ionomer Thin Films (**LBNL**)

Microelectrodes (**LBNL**)

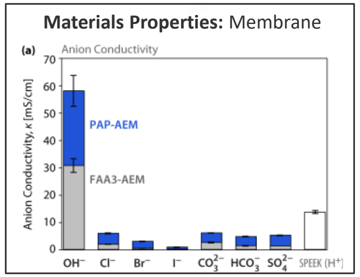
In-situ Cell Testing (**NREL**)

Microscopy (**SNL**)

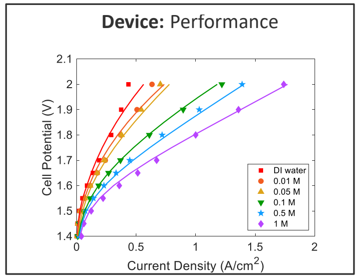
Multiscale Model (**LBNL**)



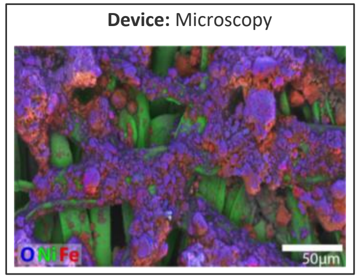
Materials Properties: Catalyst



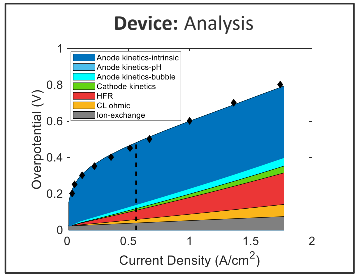
Materials Properties: Membrane



Device: Performance



Device: Microscopy



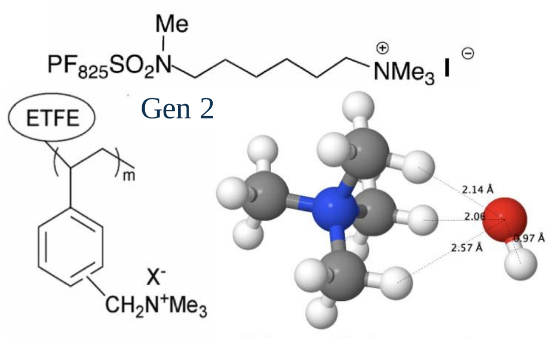
Device: Analysis

LTE 2.0 Accomplishments:

Understanding Ionomer-Catalyst Effects on OER

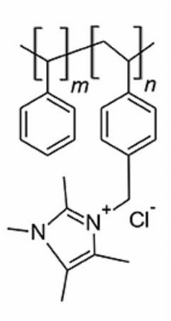
5 Nodes

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

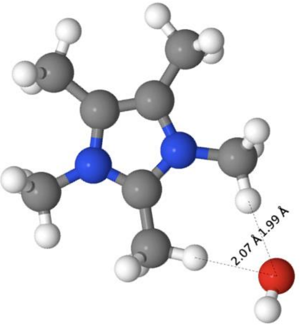


ETFE

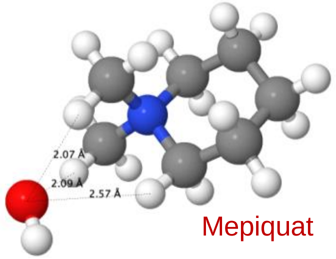
Tetramethylammonium



Sustainion



Methyl-imidazolium



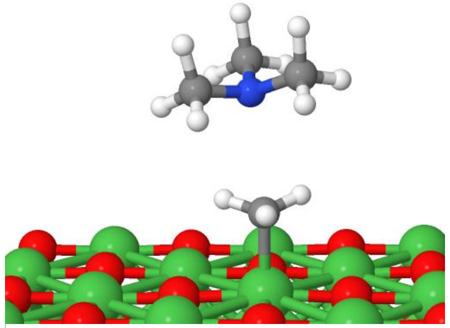
Mepiquat

Ionomer/Catalyst Chemistry Can Impact Material Performance and Stability:

- Does the ionomer ***poison the catalyst*** by introducing competing reactions or covering up active sites?
- Does the ionomer ***remain stable or does it degrade*** into other species?
- Ideal: Ionomer stable, metal active sites available for OH adsorption

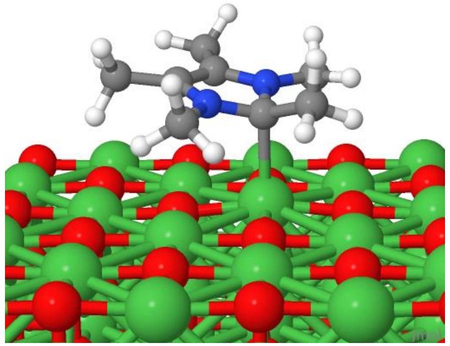
Ionomer-Catalyst Interactions: N^+R group can poison activity by blocking sites, degrade, or introduce competing reactions to OER

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



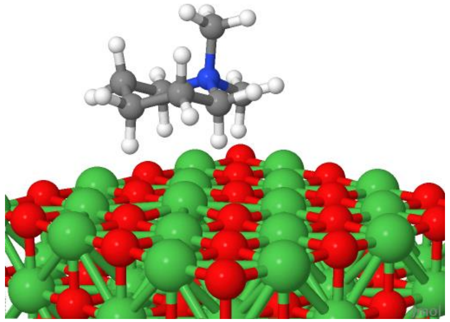
ETFE/Gen 2 → Ionomer Unstable, Degradation

I, E_{ads} (eV) = -0.69



Sustainion → Stable, Active Sites Available for OH

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



Versogen → Stable, Active Sites Available for OH

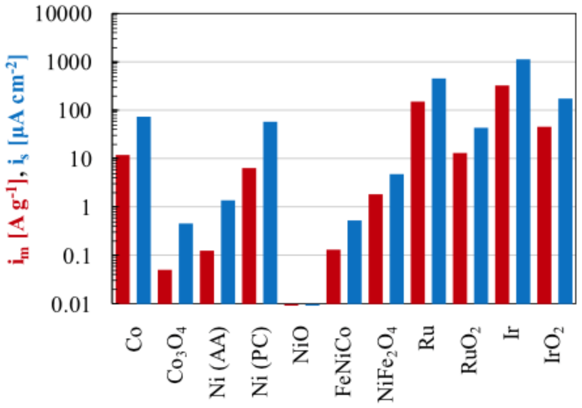
- ***E_{ads} (eV) of OH* = -1.49, all ionomers bind weaker than OH****
- ***Sustainion and Versogen Ionomers*** *are stable* and *do not block Ni sites*
- ***ETFE, GEN 2 Ionomers*** are *unstable* and *poison active sites*:
  - Degradation via de-methylation

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

LTE 2.0 Accomplishments:

Understanding Ionomer-Catalyst Effects on OER

Interest in mixed materials, due to significantly greater activity than pure NiO



Anderson *et al* 2020 *J. Electrochem. Soc.* **167** 044503

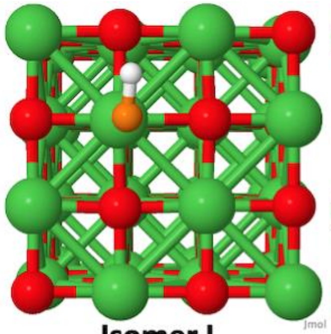
NiO nearly inactive for OER compared to other commercial baselines of oxide materials:

- $NiFe_2O_4$ > FeNiCo >>NiO

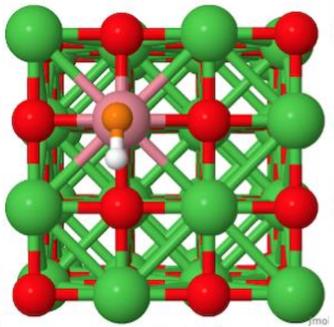
Theoretical Model:

- Limit our mixed material model to a single dopant in order to fully examine the geometric and electronic effects of a nearby transition metal e.g. Fe and Co dopants
- Systematically assess adsorption of ionomer vs OH*

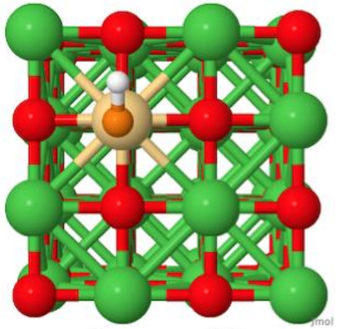
OH* Adsorption Strength Increases with Inclusion of Transition Metals, Fe and Co



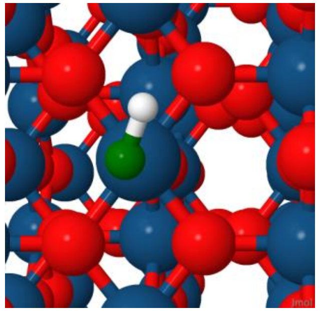
Isomer I
E_{OH} (ev) = -1.49
Ni-OH* (atomic)



Isomer I
E_{OH} (ev) = -2.40
Co-OH*



Isomers I-II
E_{OH} (ev) = -3.25 to -3.24
Fe-OH*



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

- Co, Fe considerably **increases OH* Binding**
- OH* adsorption strength **closer to OH* adsorption on IrO_2** with inclusion of Fe
- ***Stronger OH* Adsorption Means Ionomer Less Likely to Block Metal Sites***
- ***OH* adsorption similar to that of IrO_2 may increase activity***

Theory can showcase that the presence of different transition metals can change the *binding trends* of key reaction intermediates

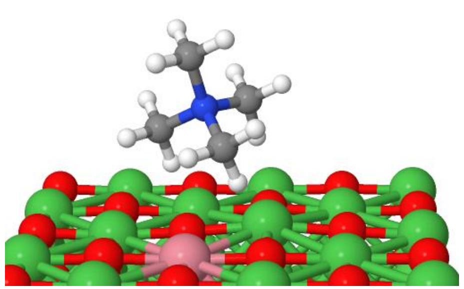
LTE 2.0 Accomplishments:

Understanding Ionomer-Catalyst Effects on OER

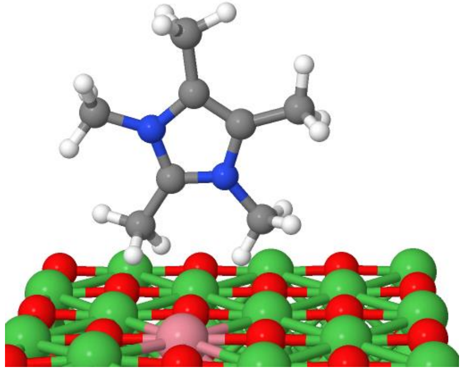
5 Nodes

The Inclusion of Transition Metals, Fe and Co *stabilizes* all ionomer fragments, including ETFE/GEN 2’s tetramethylammonium

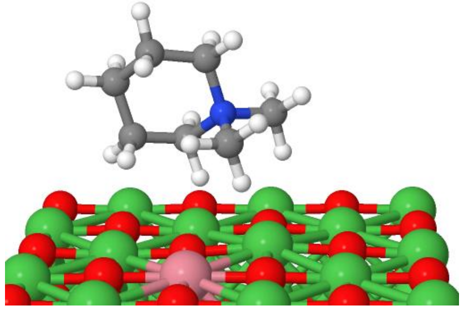
I, E_{ads} (eV) = -1.79



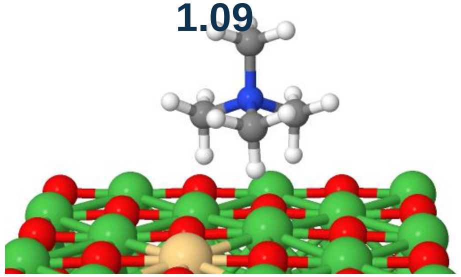
I, E_{ads} (eV) = -1.45



I, E_{ads} (eV) = -1.45

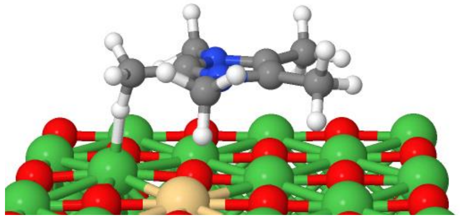


I, E_{ads} (eV) = -1.09



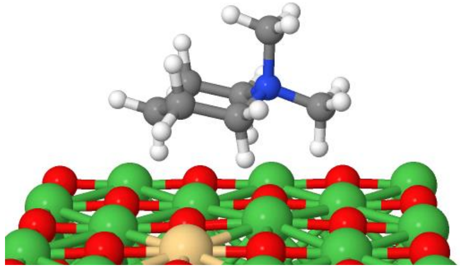
ETFE/Gen 2 → Stable, Active Sites Available for OH

I, E_{ads} (eV) = -0.74



Sustainion → Stable, Active Sites Available for OH

I, E_{ads} (eV) = -0.77



Versogen → Stable, Active Sites Available for OH

- On NiO, ***ETFE, GEN 2 Ionomers*** are *unstable* and *poison active sites*:
  - Degradation via de-methylation
- The addition of Fe and Co ***stabilizes the tetramethylammonium fragment***: the de-methylation present in NiO does not occur
- Although OH* is *bound more strongly* on Fe- and Co-NiO surfaces, the ionomers ***remain weakly bound compared to OH****

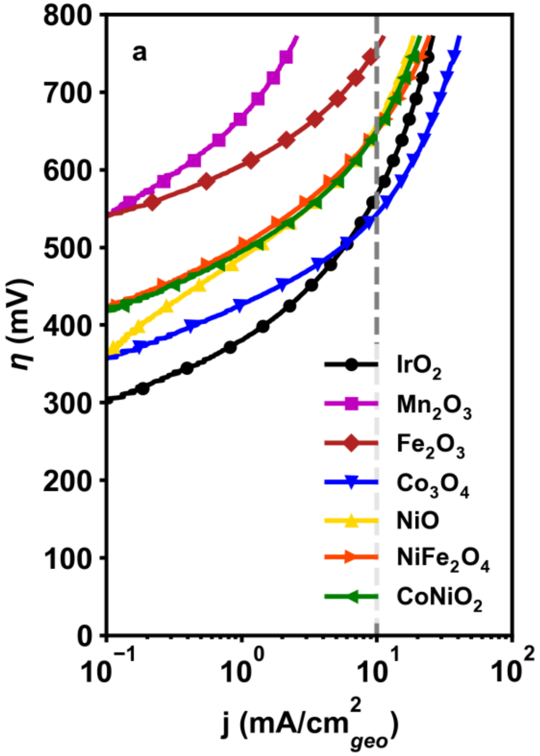
Theory can potentially predict the relative stability of ionomer fragments on mixed-metal surfaces, **critical to our understanding of the ionomer/catalyst interface**

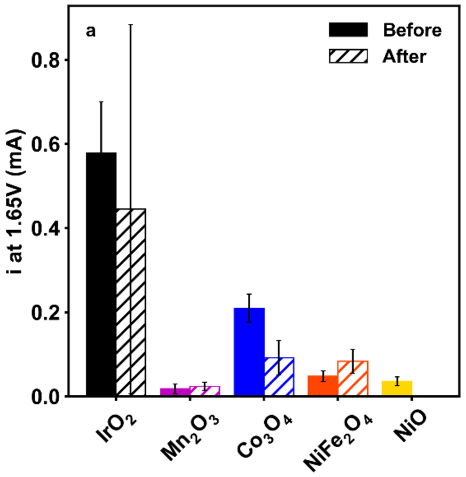
LTE 2.0 Accomplishments:

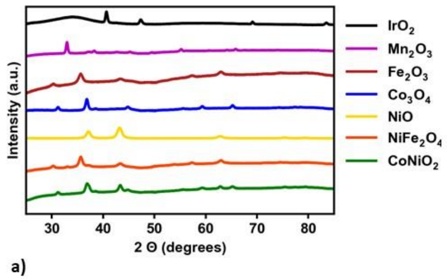
Catalyst Screening for Oxygen Electrode

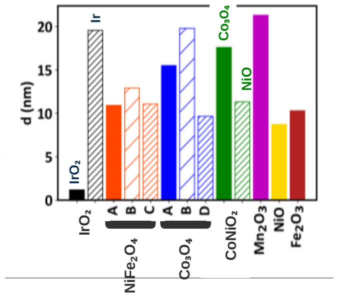
5 Nodes

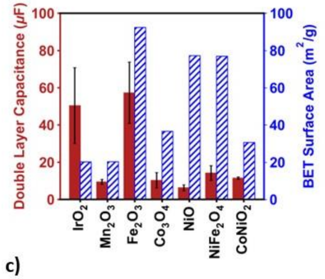
Ex-situ Materials Characterization



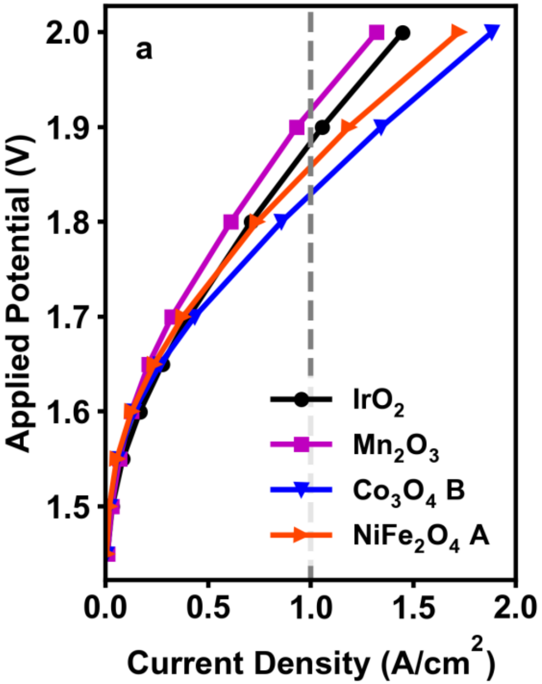


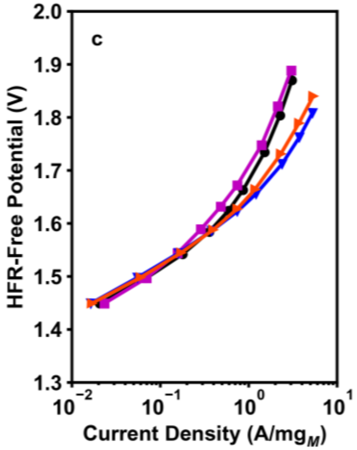


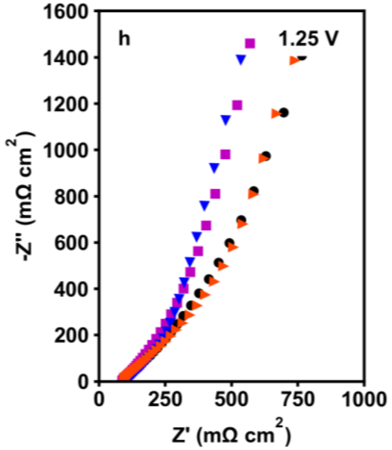




Membrane Electrode Assembly Testing







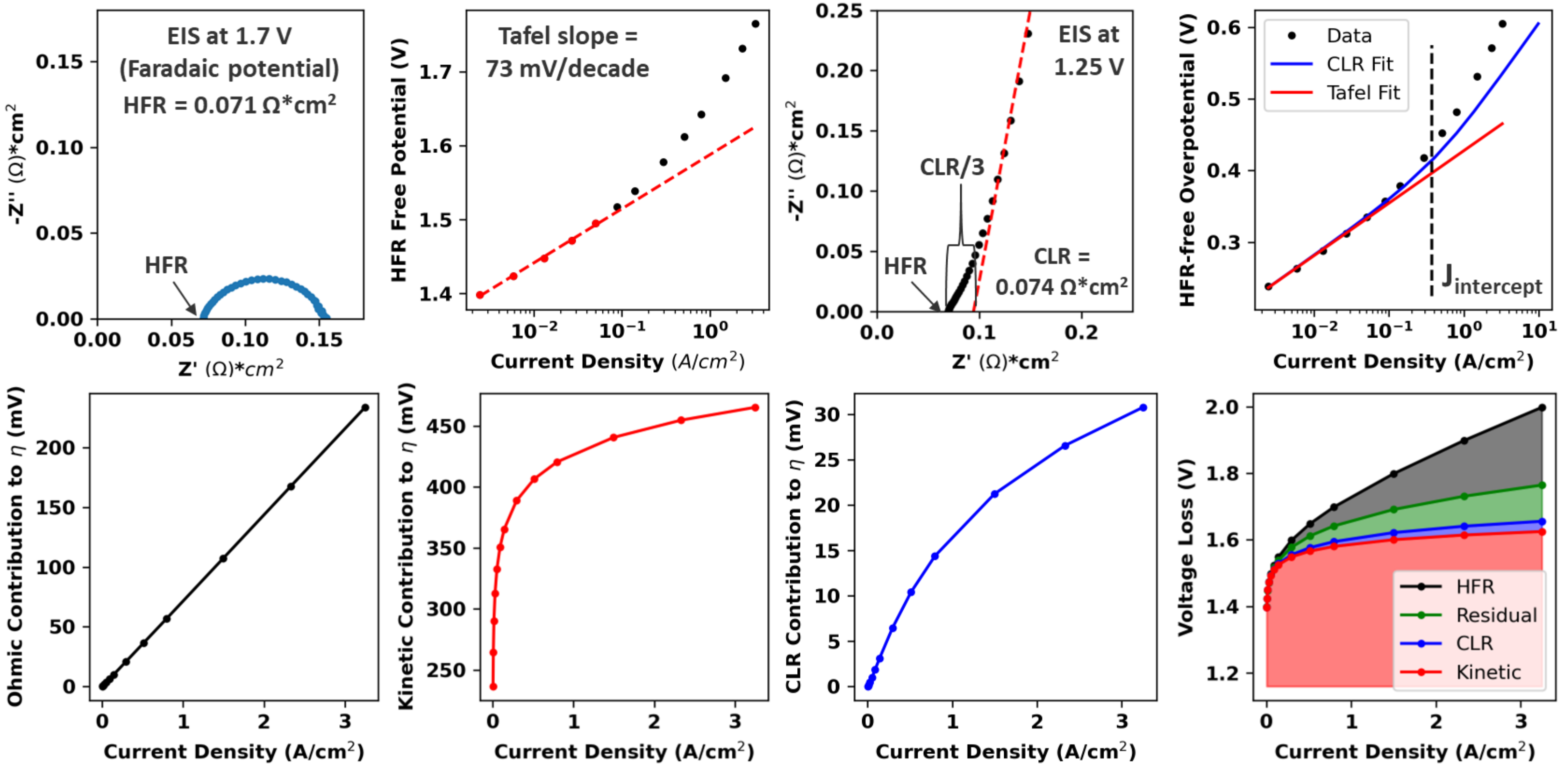
- Baselining activities for commercial materials, goal of improving catalyst kinetics to reach technology target
- Nickel-iron ($NiFe_2O_4$) and cobalt (Co_3O_4) leveraged as platinum group metal (PGM) -free baselines due to promising performance
- Ni-Fe oxide activity improvement in stability testing due to high initial Fe content

Volk et al., Journal of the Electrochemical Society (2023) [Under Review]

LTE 2.0 Accomplishments:

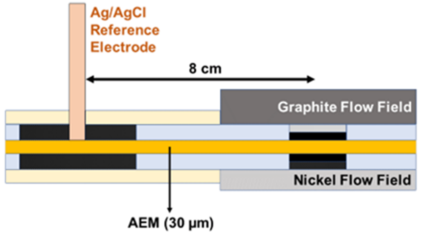
Diagnostics and Resistance Analysis in Continuum Model

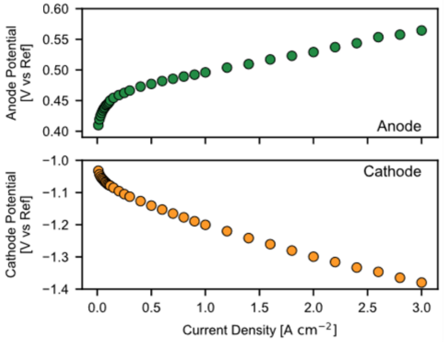
High Frequency Resistance Determination → Tafel Slope Calculation → Catalyst Layer Resistance Determination → Voltage Loss Fitting



- Improved diagnostics to resolve catalyst layer resistance and anode/cathode contributions
- Suggests pathways for performance and durability improvements
- Agreement between diagnostics and continuum model

Reference Cell

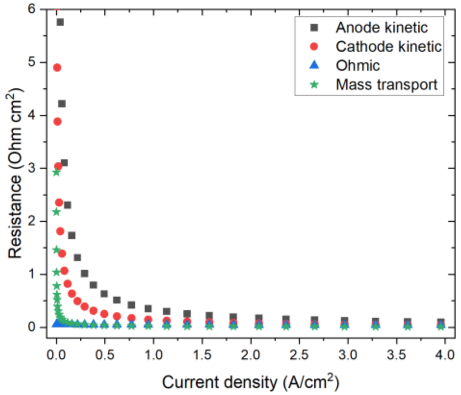




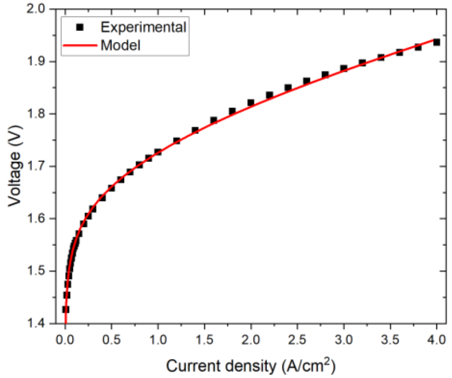
A. W. Tricker, et. al, " *Journal of Power Source* 567 (2023) 232967

Resistance analysis utilizes power-loss method

$$P = IV = I^2R \qquad \Delta V_k = \frac{\int_{V_k} \nabla\cdot\boldsymbol{p_k}\, dv_k}{I_{cell}} \qquad \Delta R_k = \frac{\int_{V_k} \nabla\cdot\boldsymbol{p_k}\, dv_k}{I_{cell}^2}$$



The 1D continuum model successfully predicts experimental polarization curve

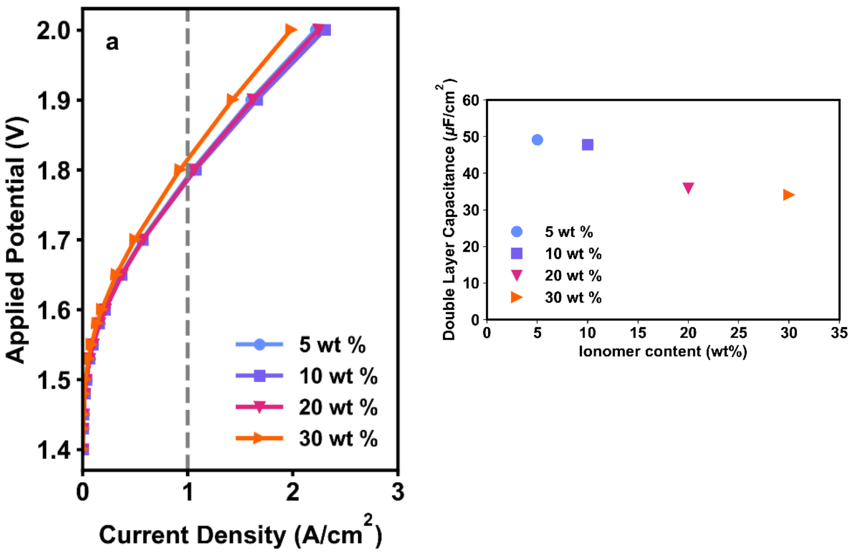


LTE 2.0 Accomplishments:

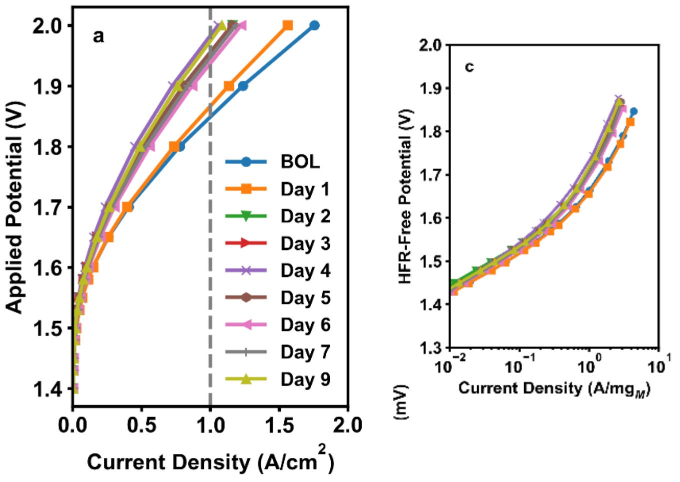
Nickel-Iron Anodes, Ionomer Content

5 Nodes

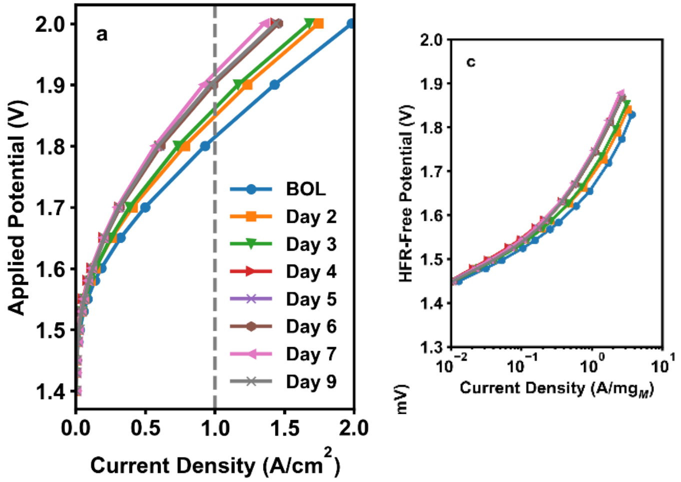
Decrease Ionomer Content



Extended Operation, 5 wt. % (200h)



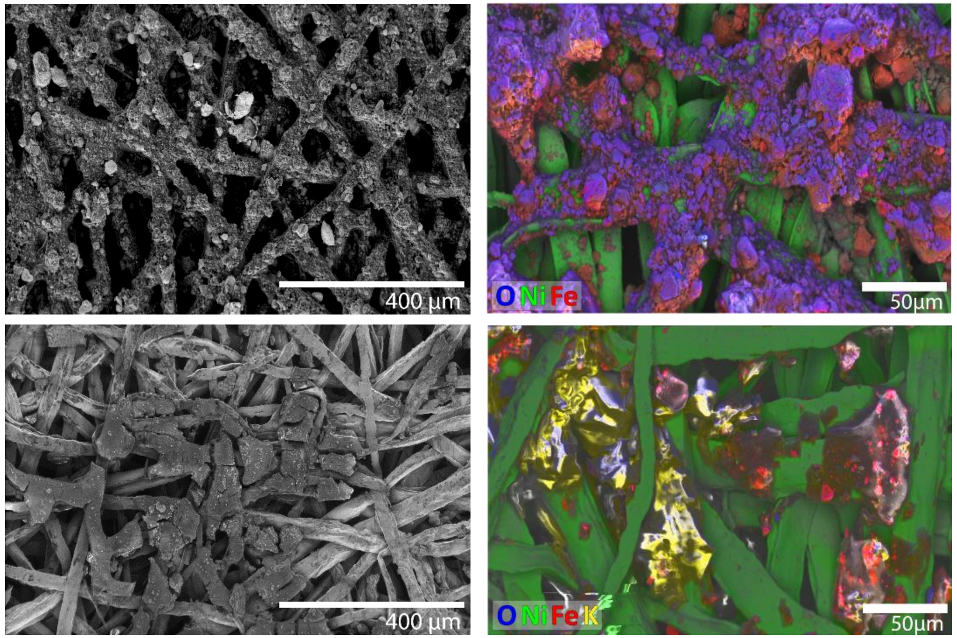
Extended Operation, 30 wt. % (200h)



- Higher ionomer content partially blocked active sites, as show in the decrease in double layer capacitance with increased ionomer
- To what degree is ionomer needed in a supporting electrolyte?
  - Role in electrode integrity
  - Hydroxide conduction versus contaminant impact
- Lower ionomer content improved kinetics, similar (to slightly higher) loss in extended operation
- Catalyst layer mobility during extended operation, iron loss

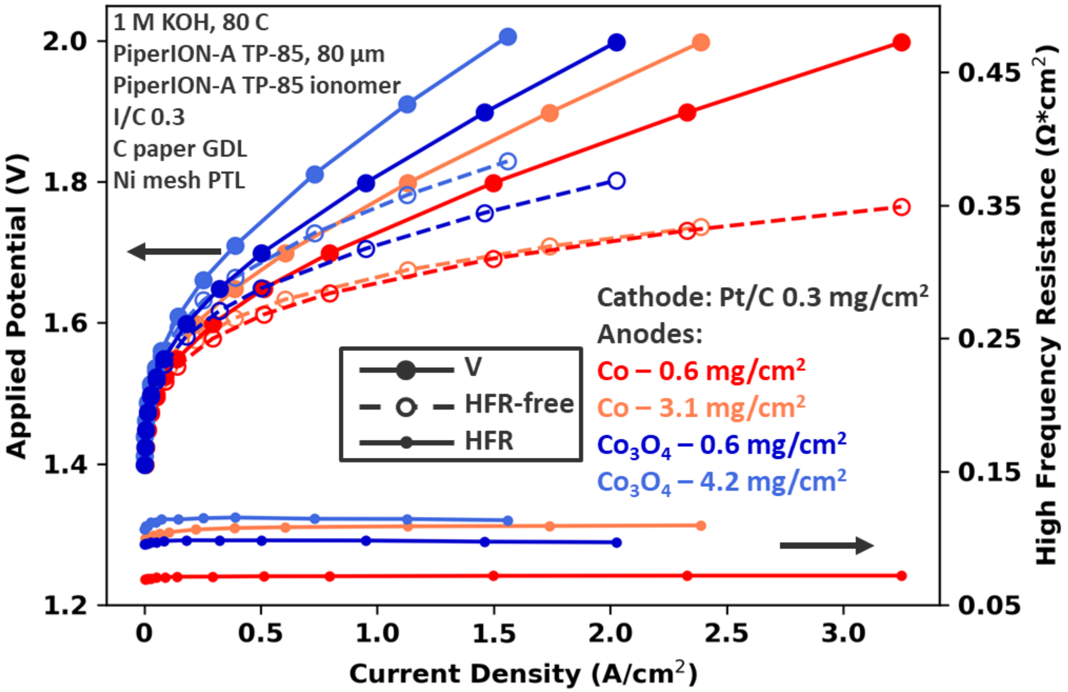
Initial Catalyst Layer

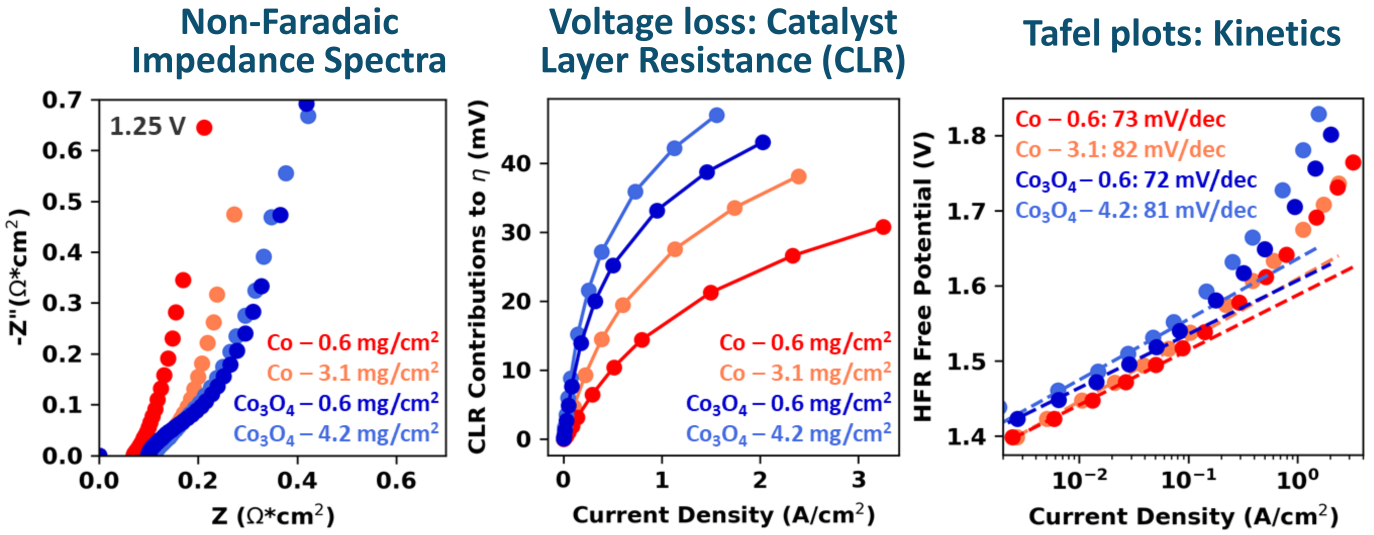
After Durability Testing



LTE 2.0 Accomplishments:

Cobalt Anodes, Effect of Conductivity and Loading




Non-Faradaic Impedance Spectra

Voltage loss: Catalyst Layer Resistance (CLR)

Tafel plots: Kinetics

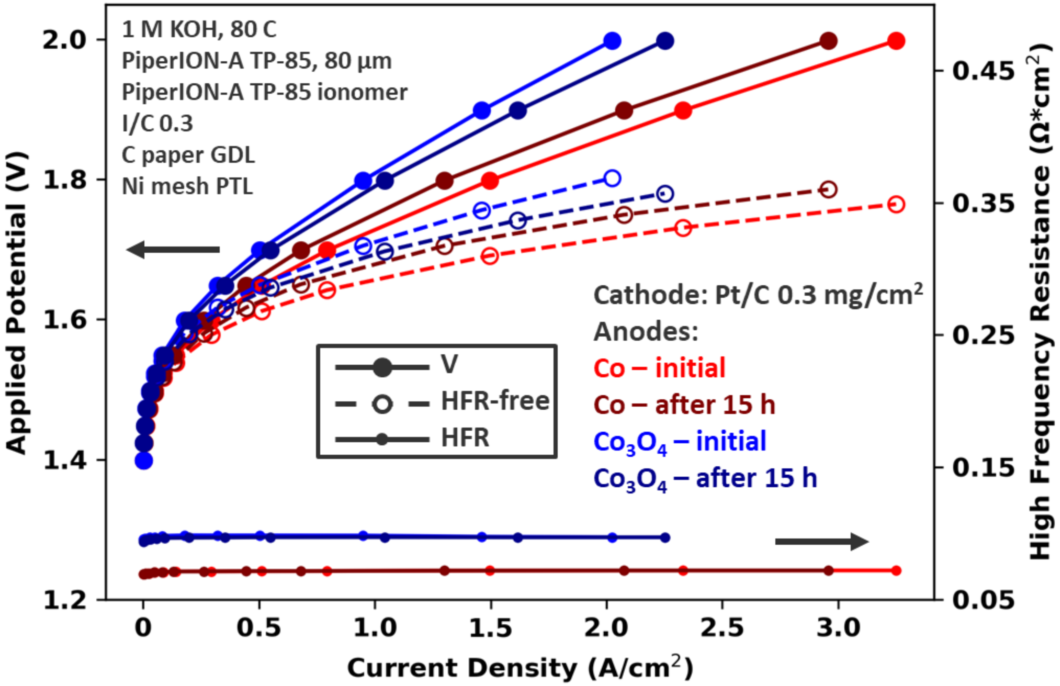
	HFR (Ω*cm²)	CLR (Ω*cm²)	Tafel (mV/dec)
Co (0.6 mg/cm²)	0.071	0.074	73
Co (3.1 mg/cm²)	0.105	0.147	82
Co_3O_4 (0.6 mg/cm²)	0.097	0.320	72
Co_3O_4 (4.2 mg/cm²)	0.112	0.420	81

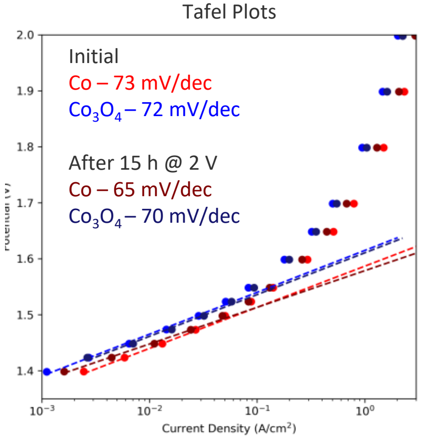
- Metallic cobalt (Co) has higher performance than Co_3O_4 due to higher kinetics, lower catalyst layer resistance (CLR), compared to Co_3O_4
- Increased anode loading leads to lower performance due to higher HFR, CLR, and Tafel slopes
- Short-term stability tests
  - Co performance decreases slightly due to decrease in number of active sites and exchange current density
  - Co_3O_4 performance improves due to decrease in CLR
- **Low-loaded, metallic Co anode has higher initial performance, retains performance advantage after stability test**

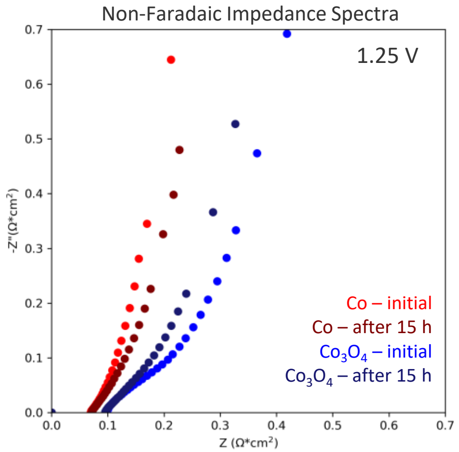
LTE 2.0 Accomplishments:

Cobalt Anodes, Extended Operation

NREL Transforming ENERGY · BERKELEY LAB · Sandia National Laboratories · **5 Nodes**

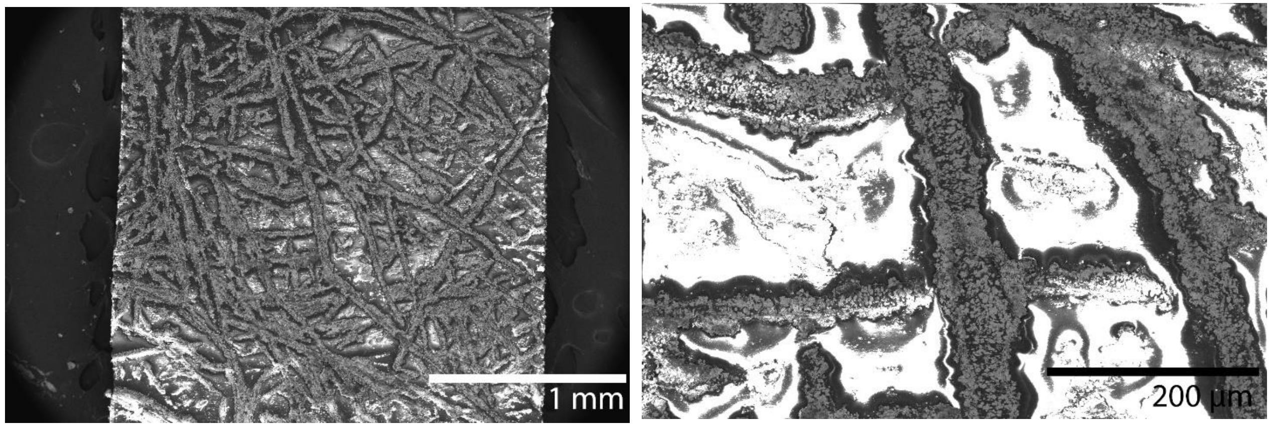






	HFR (Ohm*cm²)	CLR (Ohm*cm²)	Tafel (mV/dec)
Co pre	0.071	0.074	73
Co after 15 h	0.072	0.072	65
Co_3O_4 pre	0.097	0.320	72
Co_3O_4 after 15 h	0.096	0.239	70

Cobalt oxide (Co_3O_4) Catalyst Layer, After Durability Testing



- Cobalt metal performance decreases slightly → decrease in number of active sites and site-specific activity
- Cobalt oxide (Co_3O_4) performance improves → decrease in catalyst layer resistance
- Minimal catalyst layer compositional change after 400 h testing, catalyst layer transferred and embedded in the membrane

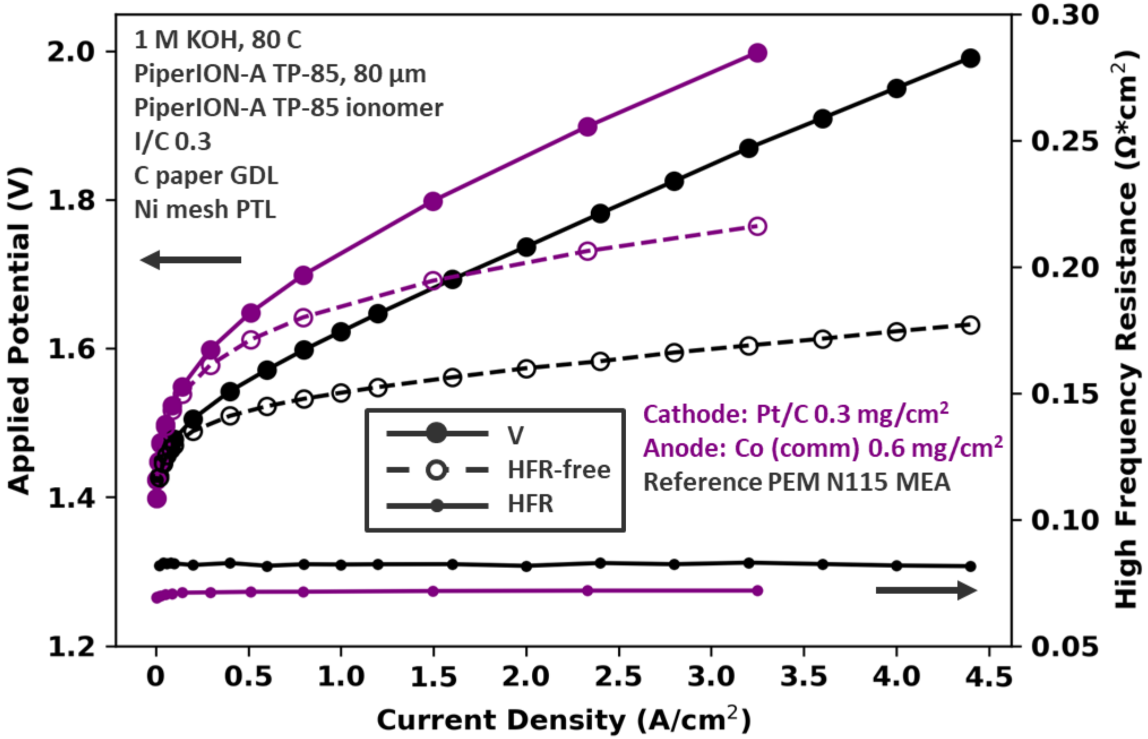
LTE 2.0 Accomplishments:

Technology Milestone, Supporting Electrolyte

5 Nodes

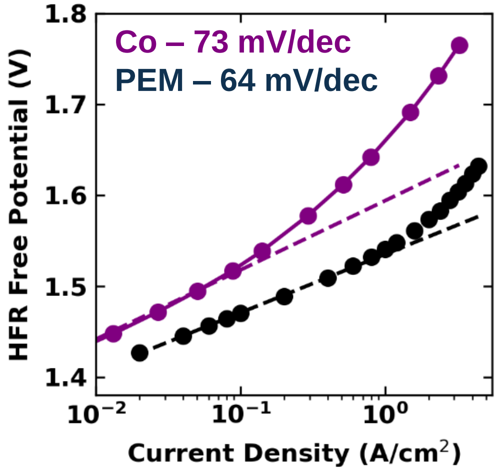
Name/ Description	Incorporating experiment and modeling, down-select AEM supporting electrolytes (type, concentration) and operating conditions (materials choices, flow configurations, temperature) that demonstrating cell overvoltage within 50 mV (HFR-free) of commercial Nafion at 1 A/cm^2.
Criteria	Demonstrate AEMWE in a supporting with a cell overvoltage within 50 mV (HFR-free) of commercial Nafion at 1 A/cm^2.

- Milestone related to performance, comparison to Nafion/PEM
- AEM performance challenges, HFR-free:
  - Poor anode catalyst kinetics
  - Large catalyst layer resistance penalty, particularly for low conductivity, commercial non-PGM oxides
  - Catalyst layer challenges of balancing site-access and mechanical integrity, conductivity and passivation, interfacial engineering and materials availability



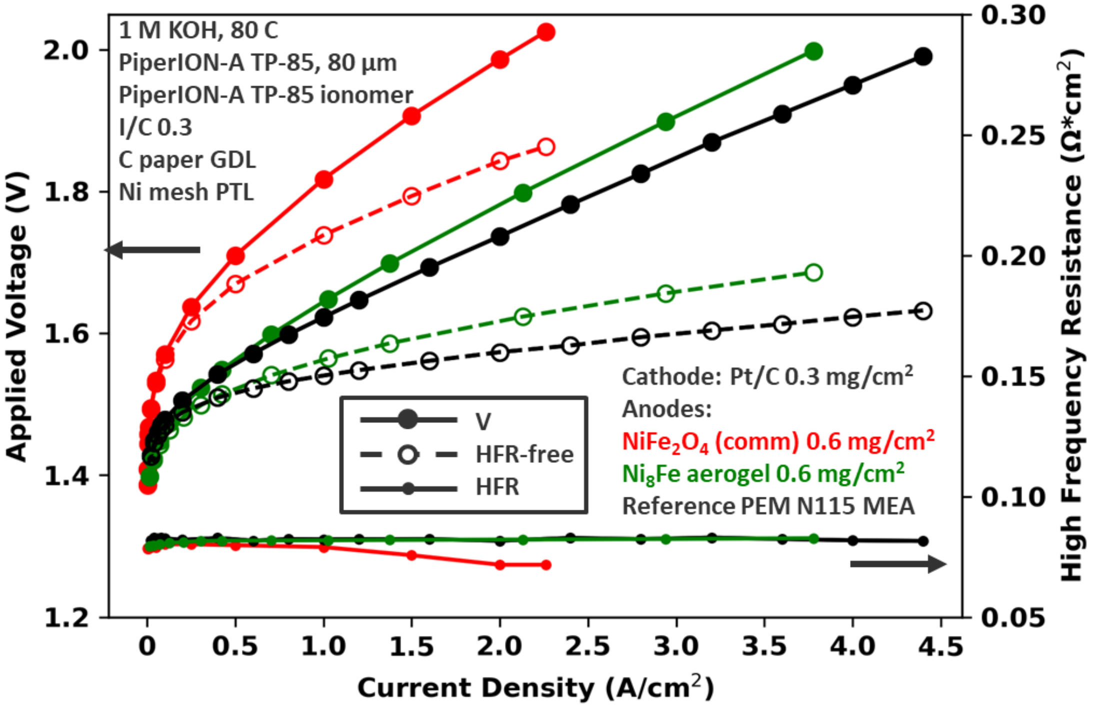
1.655 (HFR-free) at 1 A/cm^2
Q4 milestone: 1.591 V (HFR-free) at 1 A/cm^2

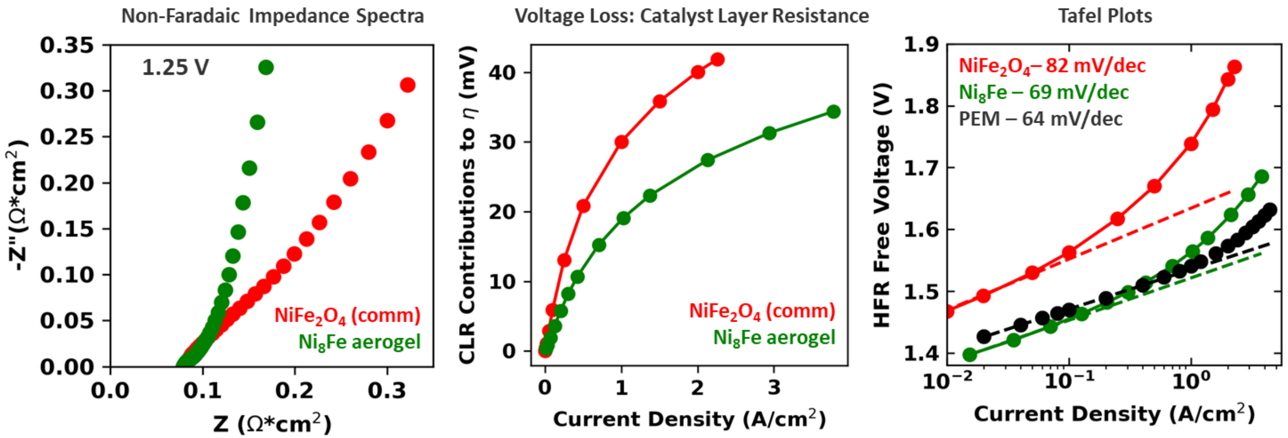
	HFR (Ω*cm^2)	CLR (Ω*cm^2)	Tafel (mV/dec)	V @ 1 A/cm^2 (HFR-free)
Co	0.071	0.074	73	1.728 (1.655)
PEM	0.083	0.008	64	1.623 (1.541)



Progress Towards LTE Performance Milestone of PGM-free OER Catalyst

***Milestone (9/30/2023)**: LTE Catalyst Testing in AEM MEA. **Criteria:** Incorporating ElectroCat-developed catalysts, demonstrate cell overvoltage reduction of more than 50 mV (HFR-free) compared to commercial baseline catalysts (NiFeOx, established in HydroGEN EMN) at 1 A/cm^2. Comparisons between novel and commercial catalysts would maintain consistent supporting electrolytes (1 M KOH) and operating conditions, including materials choices, flow configurations (wet/wet), and temperature (80 °C).*





System	HFR (Ω cm^2)	CLR (Ω cm^2)	Tafel (mV/dec)	$V_{HFR\text{-}free}$ (V) at 1.0 A cm^{-2}
NiFe$_2$O$_4$	0.078	0.197	82	**1.739**
NiFe 8:1	0.082	0.078	69	**1.559**
PEM 115 MEA	0.083	0.008	64	**1.541**

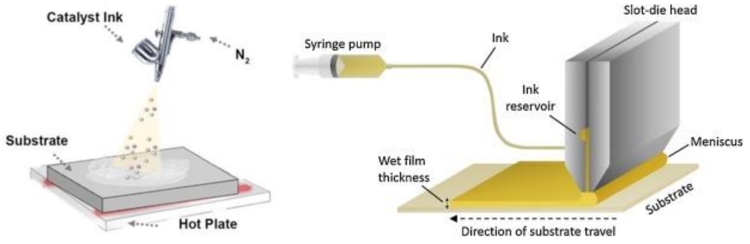
- **Highlight: ElectroCat FY23 annual milestone exceeded by 130 mV with NiFe 8:1 catalyst** – 1.559 V *vs.* 1.739 V baseline established with NiFe$_2$O$_4$ catalyst
- **Highlight**: By reaching *iR*-free voltage of 1.559 V NiFe 8:1 catalyst also meeting the **HydroGEN FY23 Q4 milestone**: *"Demonstrate AEMWE in a supporting electrolyte with a cell overvoltage within 50 mV (HFR-free) of commercial Nafion at 1 A/cm^2"*. (Voltage reached with NiFe catalyst within 18 mV of the PEM 115 MEA performance.)

LTE 2.0 Accomplishments:

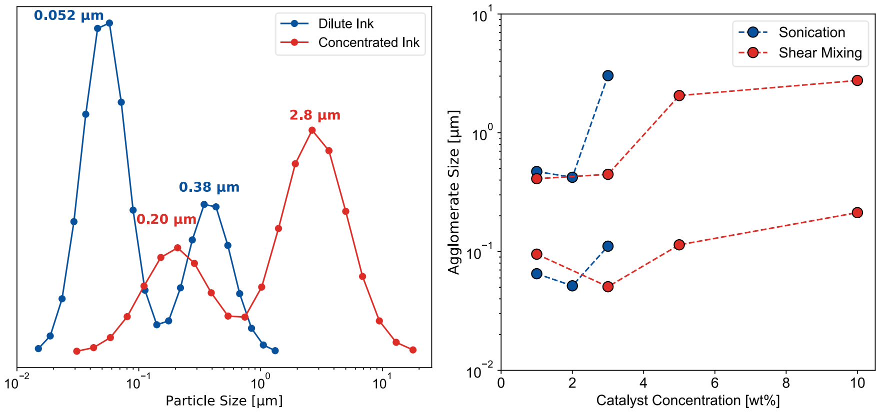
Ink Characterization and Catalyst Layer Fabrication

NREL Transforming ENERGY | BERKELEY LAB | Sandia National Laboratories | 5 Nodes

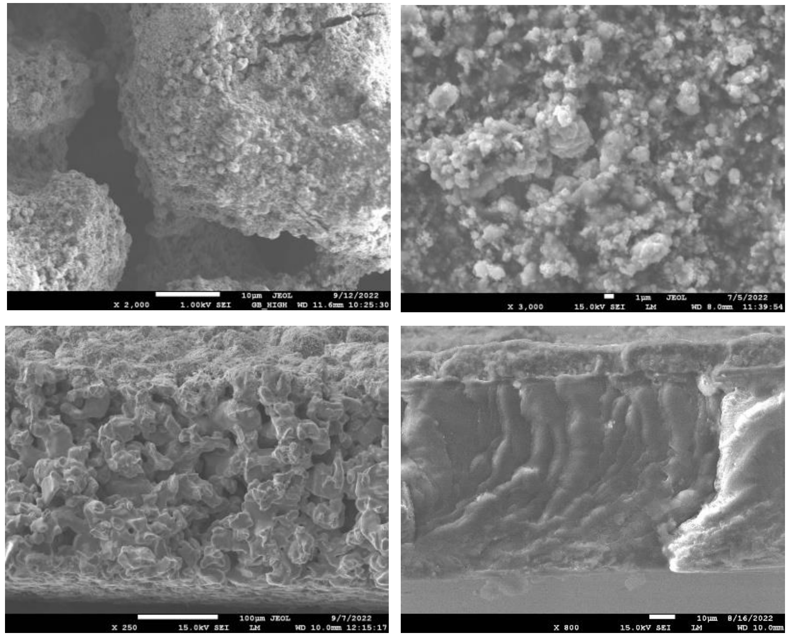
Compared airbrush (dilute ink, ~1wt% catalyst) to slot die (concentrated ink, ~10 wt% catalyst) electrode fabrication



Increasing ink concentration results in larger catalyst/ionomer agglomerates



Larger agglomerates result in larger catalyst particles in the electrode catalyst layer



Airbrush Catalyst Layer

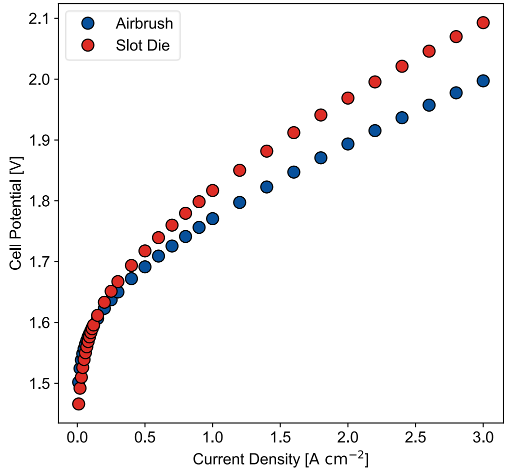
Slot Die Catalyst Layer

Airbrush PTE Cross Section

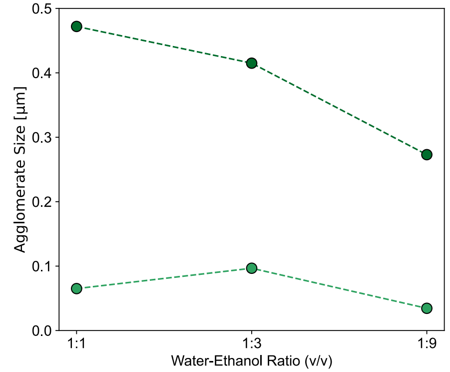
Slot Die CCM Cross Section

- Catalyst ink concentration influences agglomerate size, catalyst layer properties, and ultimately cell performance
- Controlling ink properties will require tuning of concentrated ink formulations

Significant difference in cell performance based on fabrication method



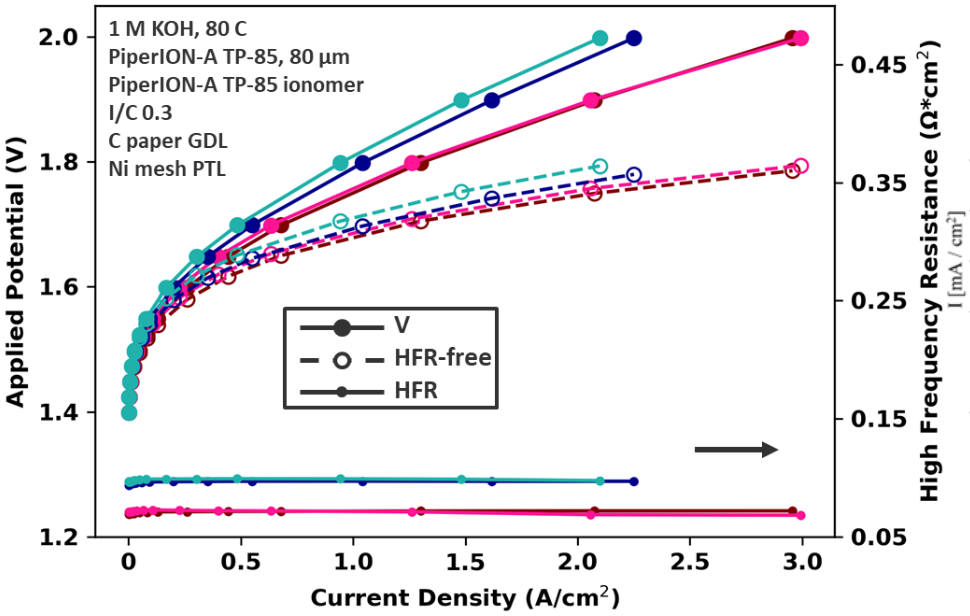
Ink formulation can be used to control agglomerate size

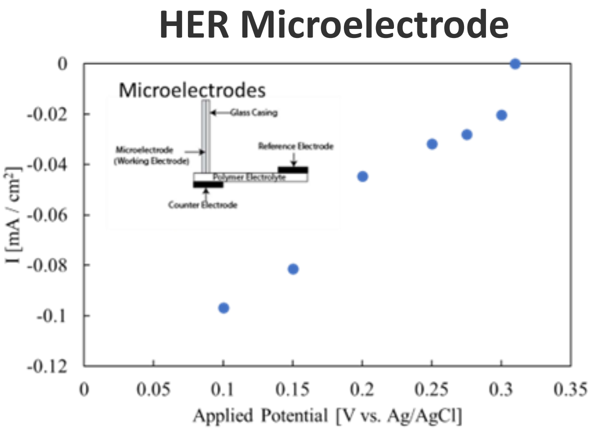


LTE 2.0 Accomplishments:

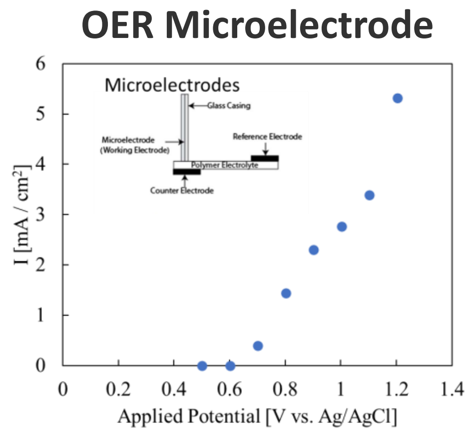
Cathode Water Consumption and Effects of Dry Operation

5 Nodes

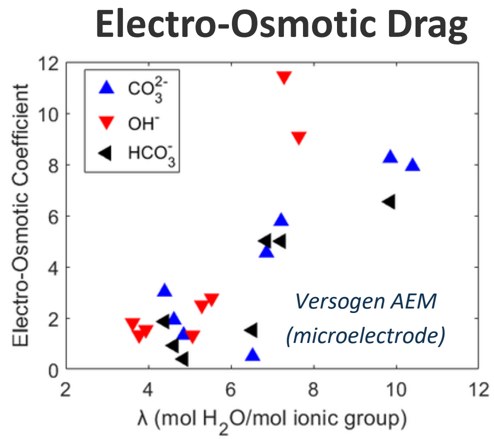




HER Microelectrode

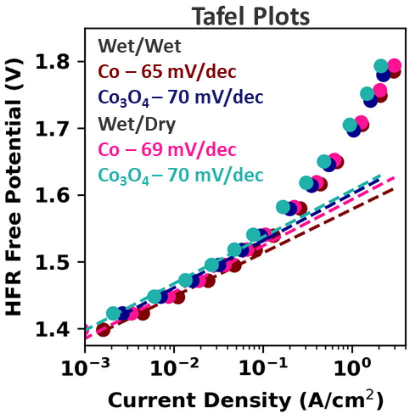


OER Microelectrode



Electro-Osmotic Drag

	HFR (Ohm*cm^2)	CLR (Ohm*cm^2)	Tafel (mV/dec)
Co wet/wet	0.072	0.072	65
Co wet/dry	0.071	0.073	69
Co_3O_4 wet/wet	0.096	0.239	70
Co_3O_4 wet/dry	0.096	0.345	70

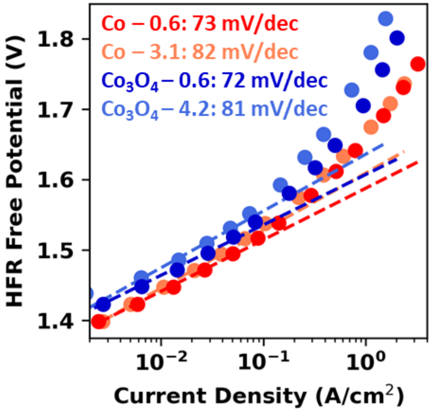


Tafel Plots

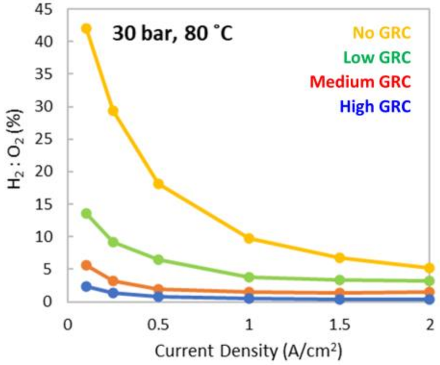
- Cathode a larger concern in anion exchange membrane (AEM) electrolysis
  - Kinetics and transport are factors
  - Poor catalyst-ionomer interaction at the hydrogen electrode (microelectrode)
- Feeding electrolyte to the anode simulates backpressure and requires transport across the membrane to the cathode (electro-osmotic drag)
- **Anode only feed has minimal effect on initial performance for Co and Co_3O_4 catalysts**

Summary of Accomplishments

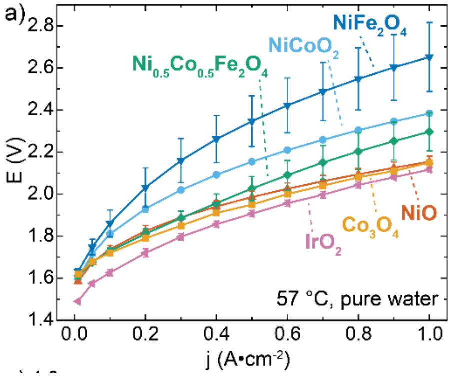
- LTE 2.0
  - Doping nickel oxide (NiO) with cobalt, iron can both stabilize ionomers and enhance OH* adsorption, comparable to iridium oxide (IrO_2), potentially increasing catalyst durability and oxygen evolution activity
  - Screening of commercial materials improved membrane electrode assembly kinetics to approach technology target
  - Incorporated diagnostics that improved resolution of loss type and cause. Materials challenges including balancing site-access and mechanical integrity, catalyst/transport layer conductivity and passivation, and nonideal interfacial contact, all affect performance of the technology.
- (P185) P. Kohl. Minimized durability losses (30 µV/1000 hr at 1.77 V for 270 hr at 1 A/cm^2) and distinguish between degraded materials (catalyst, ionomer, PTL, AEM) and harmless conditioning of nickel, stainless steel, or other components.
- (P186) A. Park. Quantified effect of GRC loading and identified membrane protrusion into the PTL as potential risk factor for hydrogen crossover stability. Making GRC membranes more resistant to topographical changes has been a priority.
- (P187) S. Boettcher. Identified and characterized key degradation modes of AEM electrolysis in pure and contaminated water associated with ionomer oxidation at the anode and develop new catalyst and mitigation strategies for high performance and durability.



P186 A. Park



P187 S. Boettcher



Future Work

- LTE 2.0
  - Optimize catalyst layer composition and processing technique to improve site-access, catalyst layer resistances, and device performance
  - 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

- Leverage HydroGEN nodes to enable successful completion and continuation of the seedling projects, depending on which budget period they are in

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

Responses to Reviewers

The demarcation of HydroGEN 2.0 and Hydrogen from Next-generation Electrolyzers of Water (H2NEW) based on current technology readiness levels (TRLs) is smart and practical to move the two consortiums forward. It is a good idea to focus HydroGEN 2.0 on low-TRL areas of AWS R&D, since low-temperature polymer electrolyte membrane (PEM) electrolyzers are far more advanced compared to other AWS routes. Although the HydroGEN 2.0 scope seems to specifically exclude PEM-based LTE technologies, it is not clear why PEM electrolysis projects are still in the portfolio.

- The Chemours seedling (P146, A. Park) is the only HydroGEN EMN effort in PEM-based LTE technologies. This seedling began in 2019, prior to the demarcation of HydroGEN/H2NEW and has met milestone and GNG decisions.

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

Seedling Leads	Seedling Teams	LTE 2.0 Team	
Shannon Boettcher Paul Kohl Andrew Park	Chemours PAJARITO POWDER FUEL CELL CATALYSTS ADVENT nel Argonne NATIONAL LABORATORY OAK RIDGE National Laboratory Los Alamos NATIONAL LABORATORY EST. 1943 UNIVERSITY OF OREGON UCIRVINE Georgia Institute of Technology Rensselaer Northeastern University UofSC South Carolina University at Buffalo The State University of New York UNIVERSITY OF DELAWARE	NREL Transforming ENERGY Shaun Alia Ai-Lin Chang Huyen Dinh Mai-Anh Ha Melissa Kreider Ross Larsen Doug Marsh Bryan Pivovar Meital Shviro Emily Volk	BERKELEY LAB Bringing Science Solutions to the World Grace Anderson Tugrul Ertugrul Xiong Peng Johnny Petrovick Andrew Tricker Adam Weber Sandia National Laboratories Josh Sugar Jamie Trindell Arielle Clauser

Presentations and Publications

Publications

- E.K. Volk, S. Kwon, S.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) [Under Review]
- A. W. Tricker, J. L. Lee, J. R. Shin, N. Danilovic, A. Z. Weber, X. Peng, “Design and operating principles for high-performing anion exchange membrane water electrolyzers,” Journal of Power Source 567 (2023) 232967, https://doi.org/10.1016/j.jpowsour.2023.232967

Presentations

- 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 ECS Meeting (May 28 – June 2, 2023)
- E.K. Volk, R.R. Beswick, S. Kwon, S.M. Alia, “Electrochemical Activation of NiFe2O4 for the Oxygen Evolution Reaction in Alkaline Media” 243rd ECS Meeting (May 28 – June 2, 2023)
- S.M. Alia, S. Intikhab, M.-A. Ha, S. Ghosal, “(*Invited*) Materials Integration, Durability, and Perspectives in Anion Exchange Membrane-Based Low Temperature Electrolysis” 241st ECS meeting (May 29 – June 2, 2022)
- E.K. Volk, “Establishing half- and single- cell baselines for the oxygen evolution reaction (OER) on non- platinum group metal (PGM) oxide electrocatalysts in alkaline media”, Poster Presentation, International Conference on Electrolysis, (July 2022)
- E.K. Volk, “Establishing half- and single- cell baselines for the oxygen evolution reaction (OER) on non- platinum group metal (PGM) oxide electrocatalysts in alkaline media”, Oral Presentation, ACS Colloids and Surface Science Symposium, (July 2022)
- X. Peng, “The Cutting-edge in Clean Electrolysis for Green Hydrogen Production”, Invited talk, U.S. Frontiers of Engineering Symposium (September 22, 2022)
- X. Peng, “Pathways to Terawatt Scale Electrolysis—— Importance of Interfaces and Underexplored Opportunities”, Fuel Cell Gordon Research Conference (July 27, 2022)
- A. W. Tricker, “Tuning Catalyst-Ink Formulations for Blade Coating of Hydroxide-Exchange-Membrane Water Electrolyzers”, 242nd ECS meeting (October 9-13,2022)