H2NEW
Hydrogen from
Next-generation
Electrolyzers of Water
U.S. DEPARTMENT OF ENERGY

H2NEW: Hydrogen (H2) from Next-generation Electrolyzers of Water Overview

Director: Bryan Pivovar, National Renewable Energy Laboratory (NREL)

Deputy Director: Richard Boardman, Idaho National Laboratory (INL)

WBS 12.1.0.519

Date: 5/7/2024

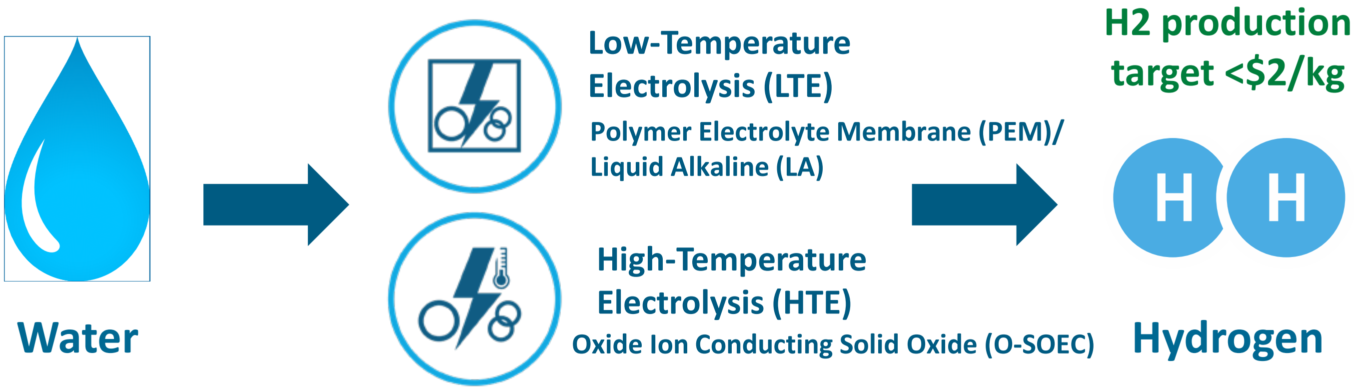
DOE Hydrogen Program 2024 Annual Merit Review and Peer Evaluation Meeting

NREL/PR-5F00-89648

Project ID # P196

Project Goals

Goal: H2NEW will address components, materials integration, and manufacturing R&D to enable manufacturable electrolyzers that meet required cost, durability, and performance targets, simultaneously, in order to enable **$2/kg hydrogen** (by 2026 on way to H2 Shot target, $1/kg by 2031).



Water

Low-Temperature Electrolysis (LTE)

Polymer Electrolyte Membrane (PEM)/
Liquid Alkaline (LA)

High-Temperature Electrolysis (HTE)

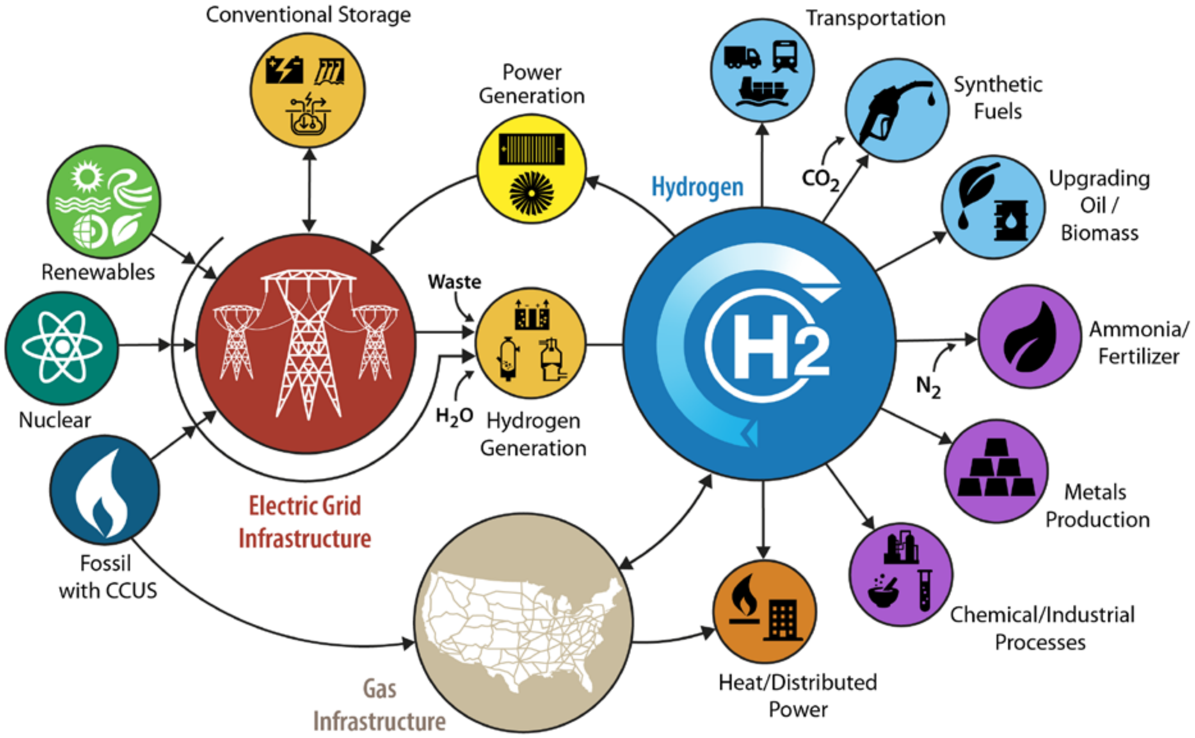
Oxide Ion Conducting Solid Oxide (O-SOEC)

H2 production target <$2/kg

Hydrogen

H2NEW has a clear target of establishing and utilizing experimental, analytical, and modeling tools needed to provide the **scientific fundamental understanding** of electrolysis cell **performance**, **cost**, and **durability tradeoffs** of electrolysis systems under predicted future operating modes

Potential Impact – H2NEW connection to H2@Scale



Illustrative example, not comprehensive

https://www.energy.gov/eere/fuelcells/h2-scale

- Making, storing, moving and using H2 more efficiently are the main H2@Scale pillars and all are needed.
- Making H2 is the inherently obvious, first step to spur the wide-ranging benefits of the H2@Scale vision.
- Electrolysis has most competitive economics and balances increasing renewable generation challenges.

Overview

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Timeline and Budget

- Start date: **October 1, 2020**
- FY21 DOE funding: **$10M (75% PEM, 25% O-SOEC)**
- FY22 DOE funding: **$10M (75% PEM, 25% O-SOEC)**
- FY23 DOE funding: **$28M (45% PEM, 20% LA, 35% O-SOEC)**
- FY24 DOE funding: **$28M (45% PEM, 20% LA, 35% O-SOEC)**

Detailed AMR posters on each task:

- See slide 9

Consortium Team*

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

INL
Idaho National Laboratory

Argonne
NATIONAL LABORATORY

Pacific Northwest
NATIONAL LABORATORY

Los Alamos
NATIONAL LABORATORY

BERKELEY LAB
Bringing Science Solutions to the World

OAK RIDGE
National Laboratory

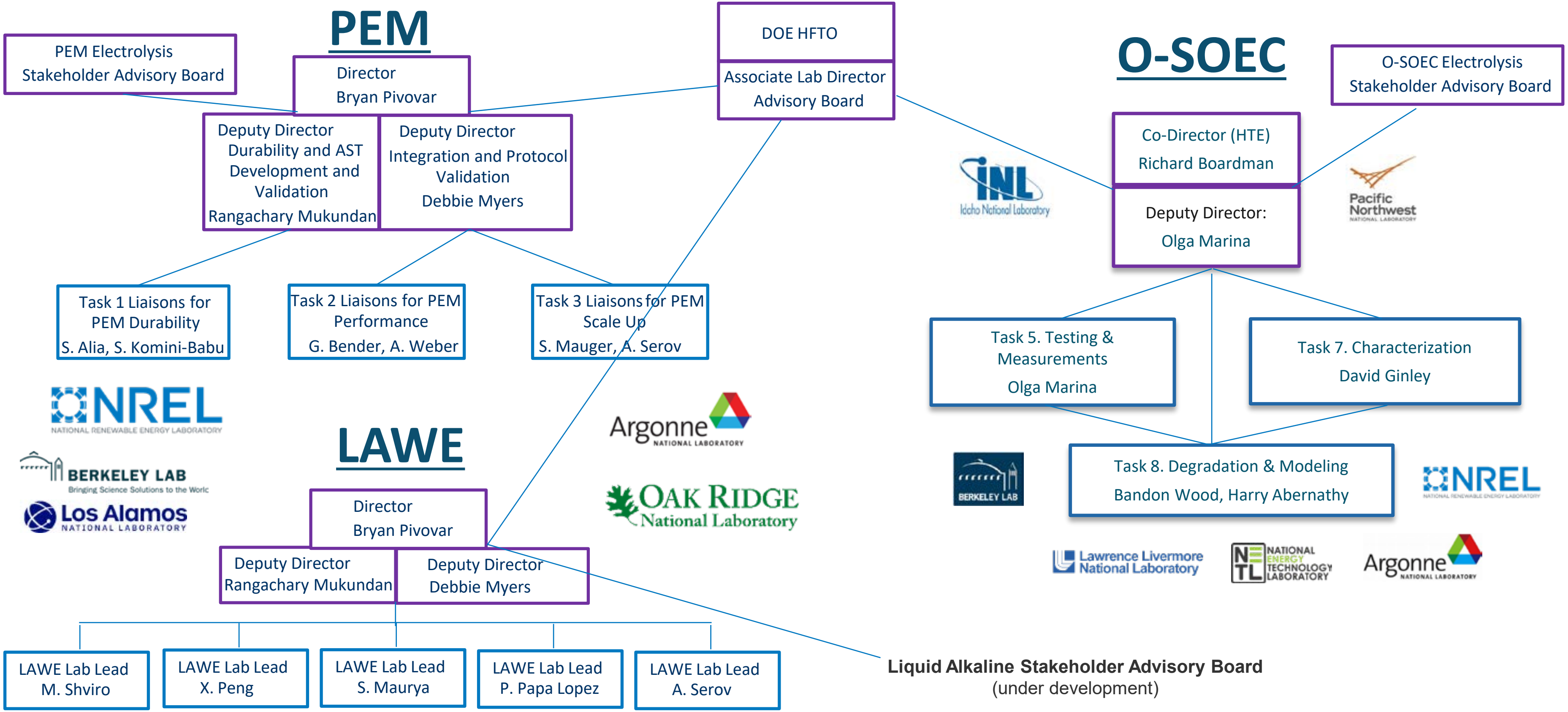
NETL
NATIONAL ENERGY TECHNOLOGY LABORATORY

Lawrence Livermore National Laboratory

- NIST, SLAC
- UC-Irvine
- Carnegie Mellon Univ
- Colorado School of Mines

* Expansion adds additional national lab, academic, and industrial partners through FOA (2922, Topic 2 and 3) projects and Lab Call

Consortium (Leadership) Structure



PEM

PEM Electrolysis Stakeholder Advisory Board

Director
Bryan Pivovar

Deputy Director
Durability and AST Development and Validation
Rangachary Mukundan

Deputy Director
Integration and Protocol Validation
Debbie Myers

Task 1 Liaisons for PEM Durability
S. Alia, S. Komini-Babu

Task 2 Liaisons for PEM Performance
G. Bender, A. Weber

Task 3 Liaisons for PEM Scale Up
S. Mauger, A. Serov

DOE HFTO

Associate Lab Director Advisory Board

O-SOEC

O-SOEC Electrolysis Stakeholder Advisory Board

Co-Director (HTE)
Richard Boardman

Deputy Director:
Olga Marina

Task 5. Testing & Measurements
Olga Marina

Task 7. Characterization
David Ginley

Task 8. Degradation & Modeling
Bandon Wood, Harry Abernathy

LAWE

Director
Bryan Pivovar

Deputy Director
Rangachary Mukundan

Deputy Director
Debbie Myers

LAWE Lab Lead
M. Shviro

LAWE Lab Lead
X. Peng

LAWE Lab Lead
S. Maurya

LAWE Lab Lead
P. Papa Lopez

LAWE Lab Lead
A. Serov

Liquid Alkaline Stakeholder Advisory Board
(under development)

Collaborations and Coordination

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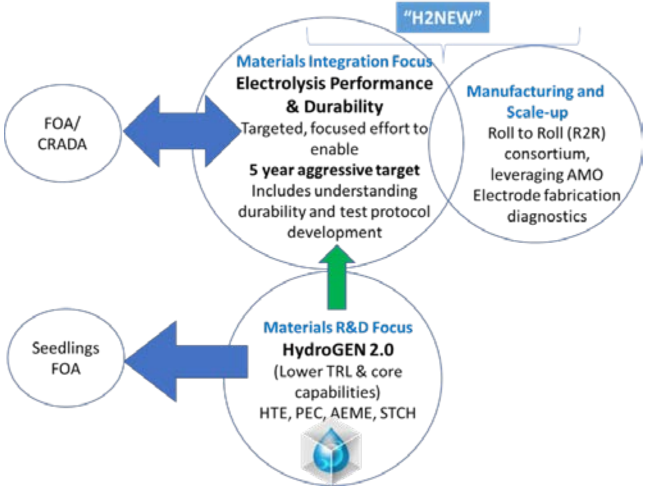


"H2NEW"

FOA/ CRADA

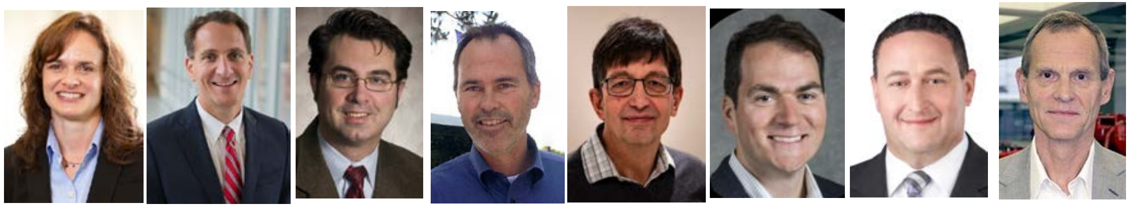
Materials Integration Focus
Electrolysis Performance & Durability
Targeted, focused effort to enable
5 year aggressive target
Includes understanding durability and test protocol development

Manufacturing and Scale-up
Roll to Roll (R2R) consortium, leveraging AMO
Electrode fabrication diagnostics

Seedlings FOA

Materials R&D Focus
HydroGEN 2.0
(Lower TRL & core capabilities)
HTE, PEC, AEME, STCH

PEM Stakeholder Advisory Board Members



- **Kathy Ayers**, VP R&D, Nel Hydrogen
- **Cortney Mittelsteadt**, VP Electrolyzer Technology, Plug Power
- **Andy Steinbach**, Specialist Materials Science, 3M
- **Jack Brouwer**, Professor, U.C. Irvine
- **Mark Mathias**, Consultant, retired (GM)
- **Nemanja Danilovic**, Director, Electric H2
- **Marc Gurau**, Senior Manager, Chemours
- **Wayne Eckerle**, VP PEM Electrolyzer Stack Product Development, Cummins

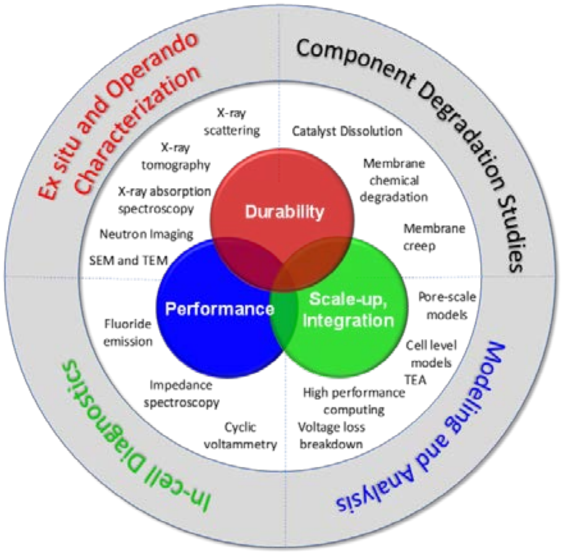
HTE Stakeholder Advisory Board Members

- **Tony Leo**, Chief Tech. Officer & Exec. VP, FuelCell Energy
- **John Pietras**, Sr. Principal Scientist, Group Leader, Saint-Gobain
- **Scott Swartz**, Founder & CTO, Nexceris
- **Jittisa Ketkaew**, Bloom Energy, Principal Technologist
- **Greg Tao**, Vice President, Chemtronergy
- **Joe Hartvigsen**, Co-Founder & CEO, OxEon Energy
- **Elango Elangovan**, Chief Scientific Officer, OxEon Energy

- Leveraging across other HFTO consortia:
- HydroGEN 2.0
- ElectroCat 2.0
- Million Mile Fuel Cell Truck
- Roll to Roll
- Numerous industrial, academia, and international interactions: (IEA, ASTWG, materials suppliers, informal collaborations)
- Select group of advisors representing OEMs, Tier 1 suppliers, analysis and manufacturing interests.

NREL NATIONAL RENEWABLE ENERGY LABORATORY · Argonne NATIONAL LABORATORY · Los Alamos NATIONAL LABORATORY · BERKELEY LAB Bringing Science Solutions to the World · OAK RIDGE National Laboratory · Lawrence Livermore National Laboratory · Pacific Northwest NATIONAL LABORATORY · INL Idaho National Laboratory · NETL NATIONAL ENERGY TECHNOLOGY LABORATORY · NIST Center for Neutron Research

Approach: H2NEW Cross-technology Methodology



Ex situ and Operando Characterization

X-ray scattering

X-ray tomography

X-ray absorption spectroscopy

Neutron Imaging

SEM and TEM

Component Degradation Studies

Catalyst Dissolution

Membrane chemical degradation

Membrane creep

Durability

Performance

Scale-up, Integration

Pore-scale models

Cell level models

TEA

Modeling and Analysis

High performance computing

Voltage loss breakdown

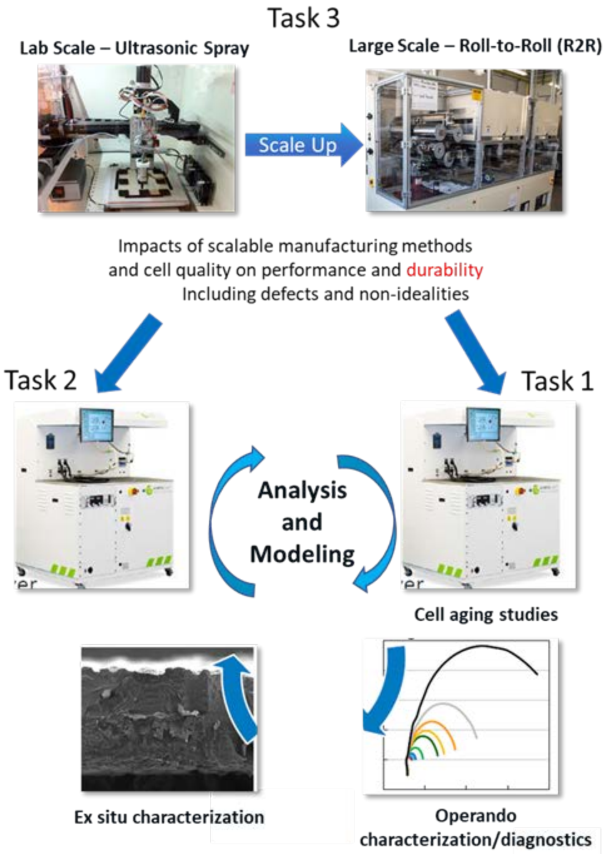
In-cell Diagnostics

Fluoride emission

Impedance spectroscopy

Cyclic voltammetry

- Durability
  - Establish fundamental degradation mechanisms
  - Develop accelerated stress tests
  - Determine cost, performance, durability tradeoffs
  - Develop mitigation
- Performance
  - Benchmark performance
  - Novel diagnostic development and application
  - Cell level models and loss characterization
- Scale-up
  - Transition to mass manufacturing
  - Correlate processing with performance and durability
  - Guide efforts with systems and technoeconomic analysis



Task 3

Lab Scale – Ultrasonic Spray

Scale Up

Large Scale – Roll-to-Roll (R2R)

Impacts of scalable manufacturing methods and cell quality on performance and durability Including defects and non-idealities

Task 2

Task 1

Analysis and Modeling

Cell aging studies

Ex situ characterization

Operando characterization/diagnostics

Safety

- H2NEW is NOT required to submit a safety plan for review by the Hydrogen Safety Panel
- 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, ANL:** WPC with ISM
  - **LANL, PNNL:** ISM by an Integrated Work Management (IWM) process
  - **NETL**: ISM systems based upon ISM Guiding Principles and Core Functions
  - **INL:** ISM by an Integrated Work Management (IWM) process
  - **LLNL, ORNL:** Research Hazard Analysis and Control (RHAC) System

- **Integrated Safety Management Process:**
  - **Define the scope of work**
    - What are you going to do?
    - Do I know how to perform this work and if not, what training do I need
  - **Analyze hazards associated with the work**
    - What are the hazards to people, environment, and equipment?
    - What can go wrong?
  - **Develop and implement hazard controls**
    - How can the hazards be eliminated/mitigated?
    - Are the necessary controls in place?
  - **Perform work within controls**
    - Follow the plan that incorporates the controls and be aware of any new hazards
  - **Provide feedback and continuous improvement**
    - Make sure people who need to know are aware of successes and issues

H2NEW AMR Presentations

- **H2NEW Overview (Oral)**
  - H2NEW: Hydrogen (H2) from Next-generation Electrolyzers of Water Overview: https://www.hydrogen.energy.gov/pdfs/review24/p196_pivovar_boardman_2024_o.pdf

- **Polymer Electrolyte Membrane (PEM)**
  - Task 1: Durability and AST Development: https://www.hydrogen.energy.gov/pdfs/review24/p196a_mukundan_2024_p.pdf
  - Task 2: Benchmarking and Performance: https://www.hydrogen.energy.gov/pdfs/review24/p196b_myers_2024_p.pdf
  - Task 3: Manufacturing, Scale-Up, and Integration: https://www.hydrogen.energy.gov/pdfs/review24/p196c_mauger_2024_p.pdf

- **Joint Low T Electrolysis (LTE: PEM/LAWE)**
  - Task 3c/9ciii: System and Technoeconomic Analysis: https://www.hydrogen.energy.gov/pdfs/review24/p196d_badgett_2024_p.pdf

- **Liquid Alkaline (LAWE)**
  - Task 9: Liquid Alkaline: https://www.hydrogen.energy.gov/pdfs/review24/p196h_shviro_2024_p.pdf

- **Oxide-conducting – Solid Oxide Electrolysis (O-SOEC)**
  - Task 5: Durability and AST Development: https://www.hydrogen.energy.gov/pdfs/review24/p196e_marina_2024_p.pdf
  - Task 7: Cell Characterization: https://www.hydrogen.energy.gov/pdfs/review24/p196f_ginley_2024_p.pdf
  - Task 8: Multi-Scale Degradation Modeling: https://www.hydrogen.energy.gov/pdfs/review24/p196g_wood_2024_p.pdf

H2NEW Activities: Low Temperature Electrolysis (LTE)

Approach: Select FY 24 LTE Milestones*

Milestone Name/Description	Due Date	Type	Status
Quantify properties (volume fraction, pore size distribution, tortuosity, and catalyst spatial distribution) of porous transport layers and electrodes, with and without microporous layers toward quantifying the impact on performance and durability.	12/31/2022	QPM	Complete
Develop and validate a reference electrode system to be used as a probe for LAWE cell degradation.	3/31/2022	QPM	Complete (slide 41)
Decide on a "figure of merit" that will guide data analysis and acquisition for benchmarking PEM cell performance and degradation rate and for tracking consortium progress toward the overall consortium goals. The status of the figure of merit will be reported in the annual milestone and in AMR presentations to show H2NEW current (2023) status and progress.	3/31/2023	QPM	Complete (slide 13)
Quantify PEM sources of voltage decay during long term (> 1000 hours) steady state durability test. Perform advanced diagnostics to quantify contributions from anode degradation, cation contamination, interface resistance changes, and electrode structure changes.	6/30/2023	QPM	On Track (slide 19)
Demonstrate agreement in liquid alkaline electrolysis single-cell performance between H2NEW labs within +/- 50 mV at 1 A/cm$_2$ at V < 2.0V and operating temperature > 60°C.	9/30/2024	Mile-stone	On Track (slide 39)
Show the status, in the form of the figure of merit established in Q2, for the future generation membrane-electrode assembly (FuGeMEA) toward meeting the $2/kg H2 shot target.	9/30/2024	Mile-stone	Complete (slide 13)
Engage in at least 9 activities that support recruitment of students and alumni of Minority Serving Institutions, including national lab personnel going to MSIs/HBCUs/TCUs, hosting visits from professors and/or students from those institutions, attending conferences such as NOBCChE and SACNAS, and/or other related activities. Recruit at least one postdoc or research scientist from an MSI, HBCU, or TCU or part of a STEM underrepresented population to work on H2NEW activities.	9/30/2024	Mile-stone	On Track (slide 68)

*Partial list, see associated 2024 AMR posters for additional details (links on slide 9)

Accomplishment: Recent Bottom-up Cost Analysis for PEM Electrolyzers Stack Focus

https://www.nrel.gov/docs/fy24osti/87625.pdf

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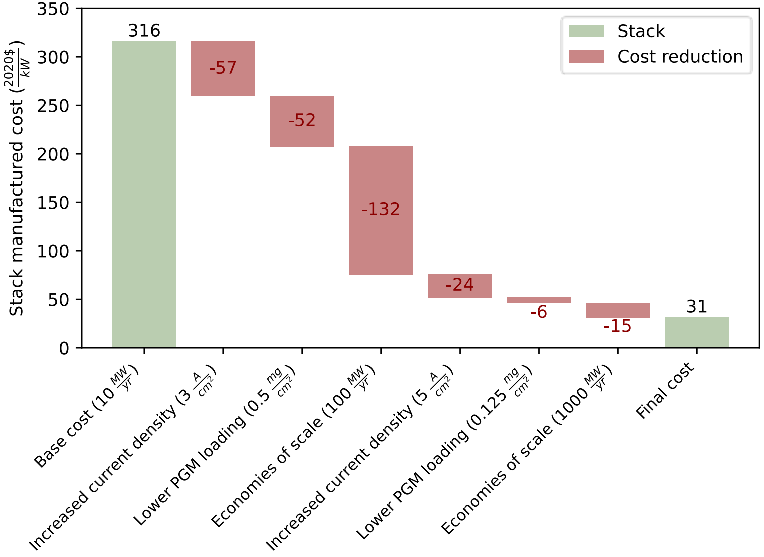
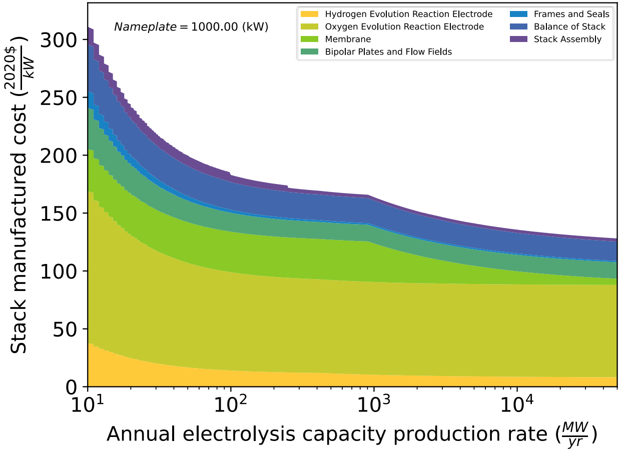
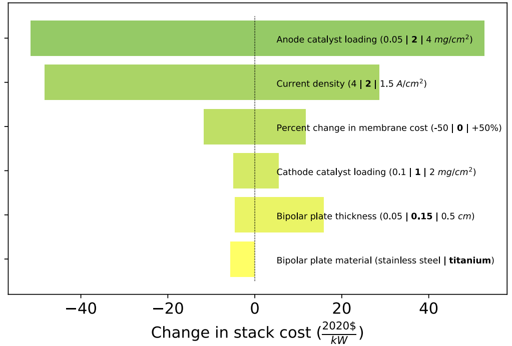
Technoeconomic analysis (TEA) allows for better informed decisions on research focus

Waterfall chart analysis outlines strategies to reducing stack manufactured costs





Manufacturing volume analysis highlights anode (Iridium) catalysts as biggest cost driver (have high loading 2 mg/cm^2 and no salvage value)



Tornado charts can be used to identify strongest cost drivers

Relevance and Impact – Figure of Merit (PEM)

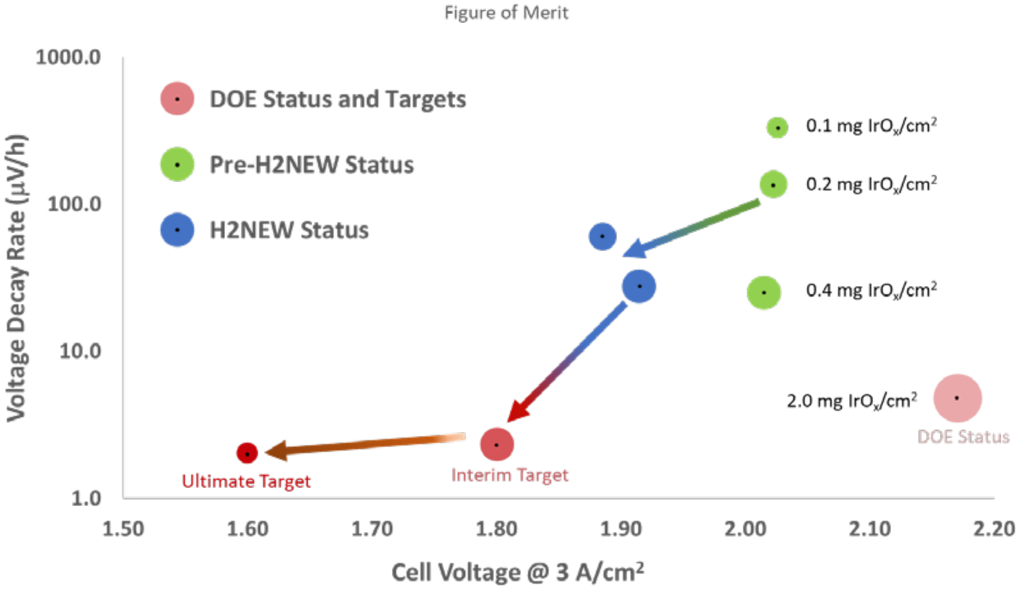
PEM Figure of Merit

- Enables tracking consortium progress toward the overall consortium goals
- Needs to include cost, performance and durability considerations

*Electrolyzer Stack Goals **by 2026***	
	LTE PEM
Total PGM content	**< 0.5 mg/cm²**
Performance	**1.8 V/cell @ 3 A/cm²**
Degradation Rate	**< 2.3 μV/hr**

Levers to improve cell voltage:

- Reduced ohmic losses
  - Advanced polymer electrolytes
  - Engineered membranes (thinner, GRCs/GRLs, reinforced, additives)*
- Reduced kinetic (anode) losses
  - Advanced (OER) catalysts
  - Electrode architectures, advanced PTLs/PTEs, and integration*

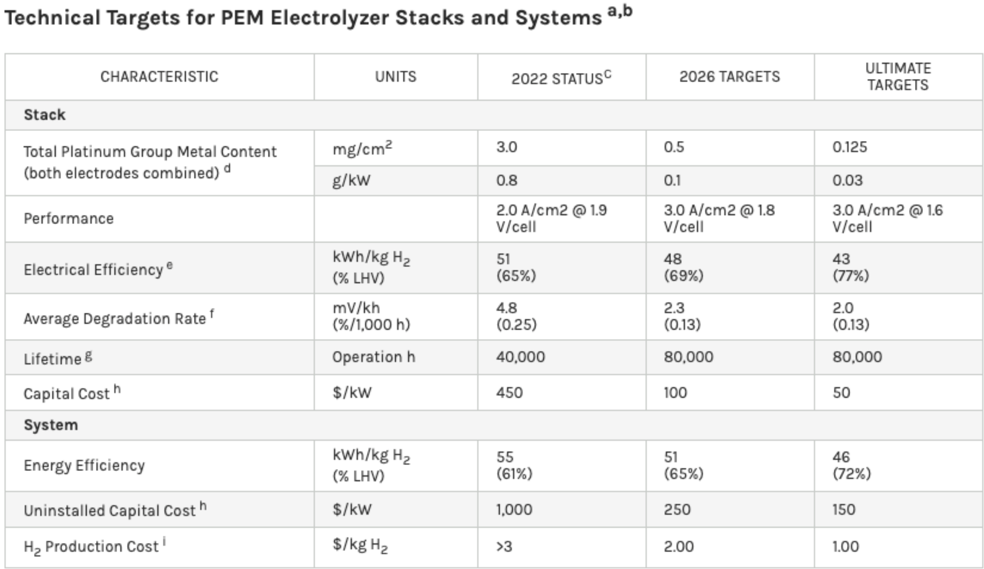


Levers to improve voltage decay:

- More durable catalysts/membranes
- Electrode architectures, processing and integration*
- Operating strategies*
- Contaminant mitigation*

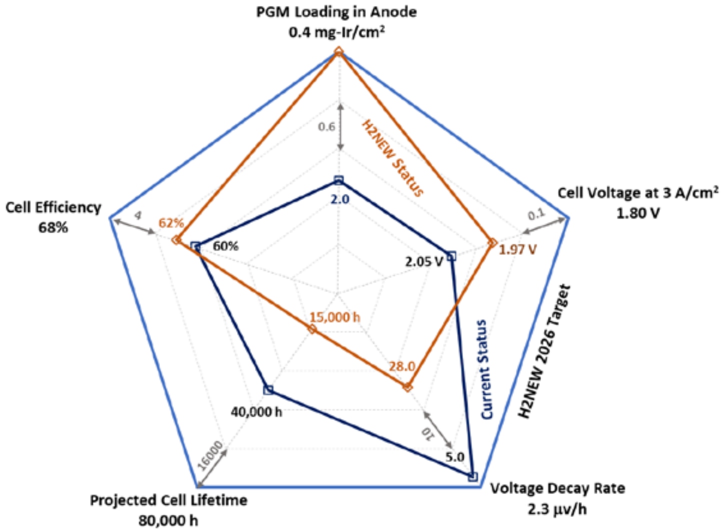
* Included in core H2NEW lab activities (FOA awards service all areas)
Additional information on Figure of Merit development in backup slides (75-77)

Relevance and Impact – PEM Spider Chart



Technical Targets for PEM Electrolyzer Stacks and Systems [a,b]

CHARACTERISTIC	UNITS	2022 STATUS[C]	2026 TARGETS	ULTIMATE TARGETS
Stack				
Total Platinum Group Metal Content (both electrodes combined) [d]	mg/cm^2	3.0	0.5	0.125
	g/kW	0.8	0.1	0.03
Performance		2.0 A/cm2 @ 1.9 V/cell	3.0 A/cm2 @ 1.8 V/cell	3.0 A/cm2 @ 1.6 V/cell
Electrical Efficiency [e]	kWh/kg H_2 (% LHV)	51 (65%)	48 (69%)	43 (77%)
Average Degradation Rate [f]	mV/kh (%/1,000 h)	4.8 (0.25)	2.3 (0.13)	2.0 (0.13)
Lifetime [g]	Operation h	40,000	80,000	80,000
Capital Cost [h]	$/kW	450	100	50
System				
Energy Efficiency	kWh/kg H_2 (% LHV)	55 (61%)	51 (65%)	46 (72%)
Uninstalled Capital Cost [h]	$/kW	1,000	250	150
H_2 Production Cost [i]	$/kg H_2	>3	2.00	1.00



- Spider chart also captures cost, performance, durability tradeoff considerations
  - Low cost (H2NEW Status) system has durability challenges
  - Durable system (Current Status) has cost challenges
- H2NEW has benchmarked current and FuGeMEA status and will track advances compared to these baselines

Accomplishments

- 2024 AMR Select LTE Highlights*
  - Task 1 – PEM Durability
    - Dissolution studies – Supported catalysts and PTLs
    - Quantifying degradation losses by mechanism
    - AST Development - 1000hr durability experiments
    - AST Development – Effect of Temperature
    - Effect of GRC on start/stop degradation
    - Membrane Mechanical/Chemical degradation
  - Task 2 – PEM Performance
    - Baselining fabrication and performance
    - High-pressure hardware design
    - Advanced diagnostics and characterization
  - Task 3 – PEM Scale-up
    - Low loading MEA uniformity
    - MEA impact on PTL screening
    - Thrifting Ir with Pt
  - Porous Transport Layer (PTL) (cross task effort)
    - Surface roughness
    - Micro-porous layer (MPL) characterization
  - Gas Recombination Catalyst (GRC) (cross task effort)
    - Impacts of GRC location
    - Closing the hydrogen molar flow balance
    - Modeling GRC hydrogen crossover
  - Task 9 – Liquid Alkaline
    - Baselining (Round Robin) cell testing
    - Benchmarking – Cell activation
    - Reference electrode development
    - Cell modeling – Loss quantification
    - Electrode and catalyst evaluation
    - Dissolution studies
  - Task 3c/9cii – Systems/Technoeconomic Analysis
    - PEM TEA Update (slide 11)
    - LAWE Waterfall Pathways
    - LAWE Systems Analysis

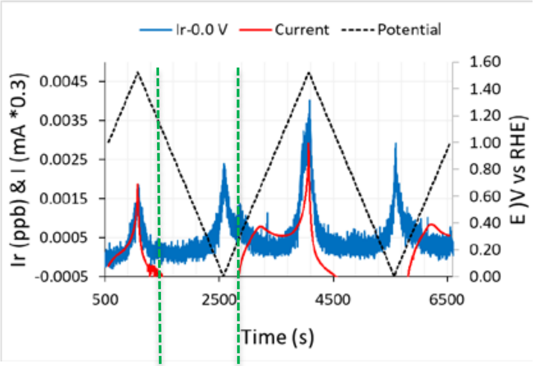
*Select highlights of efforts since previous AMR (https://www.hydrogen.energy.gov/pdfs/review23/p196_pivovar_boardman_2023_o.pdf)
*Expanded content available in poster presentations (see slide 9 for links)

Low Temperature Electrolysis (LTE)

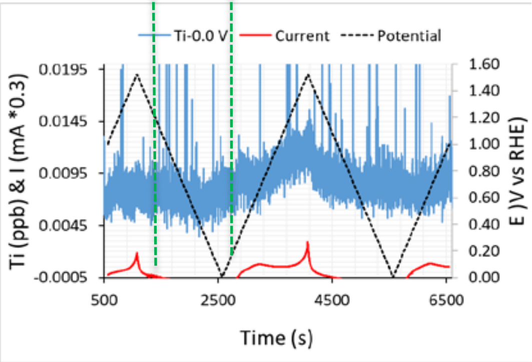
Task 1: Durability (more content in AMR Poster P196a)

Accomplishments and Progress: Quantifying metal dissolution rates from IrO2/TiO2 catalyst and PTLs – online ICP-MS

Ir dissolution (Catalyst)



Ti dissolution (Catalyst)



Fundamental understanding of electrochemical stability of cell materials is critical. H2NEW ICP-MS efforts have proven particularly valuable.

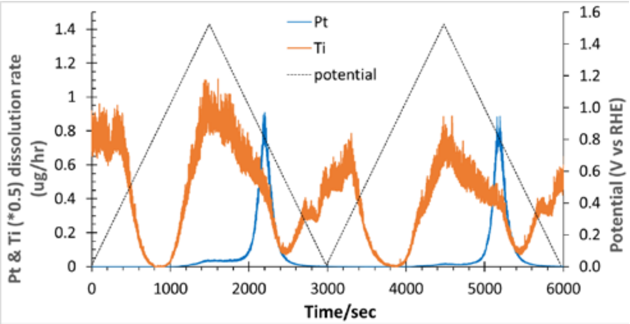
Catalyst

- Rutile IrO_2/TiO_2 has lower Ir dissolution rates than AA IrOx H2NEW baseline catalyst
- Ti dissolution potential range corresponds with that of Ir
- Tie to cell findings described in p196a poster

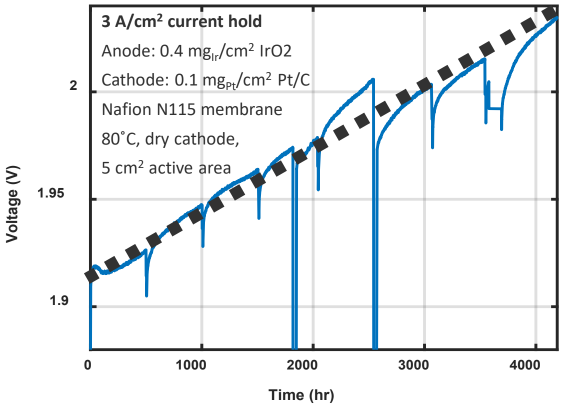
Pt-coated Ti PTL

- Ti dissolution rate is > 40x higher than Pt dissolution
- Dissolution in two potential regimes: > 0.9 V and < 0.6 V
- Next: impact of PTL coating methods, FOA support, tie to cell findings

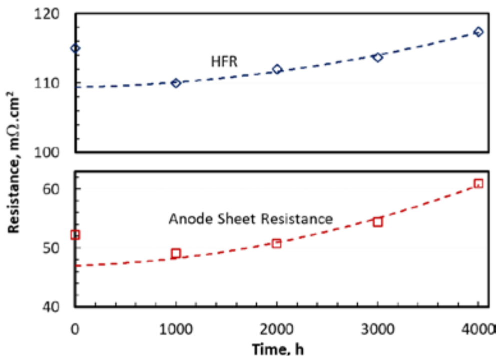
Ti Dissolution (PTL)



Accomplishments and Progress: Baseline Degradation Rate - Breakdown for 4000 hr test



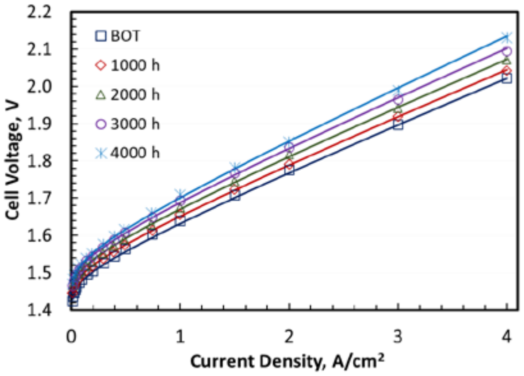
4000 hour test - V(t)



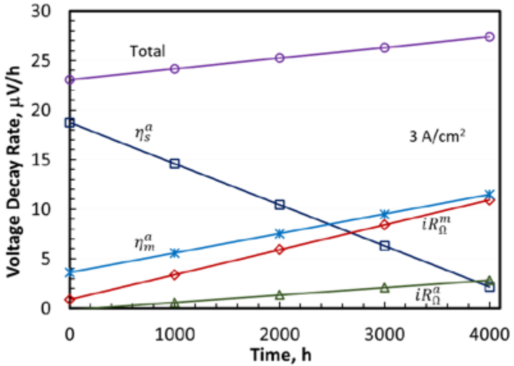
Breakdown of decay rates

Need to better understand cell degradation

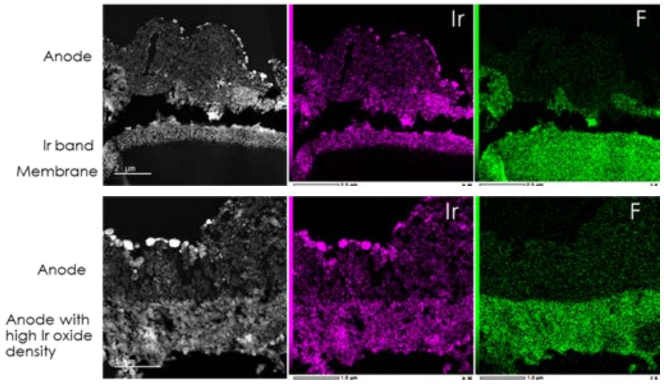
- Total decay rate is a composite of ohmic, iR_{Ω}, anode kinetic, η_s, and residual decay, η_m, rates
- Quantified rates with model
- Ir deposition in membrane and cathode
- Structural changes in the anode



Polarization curves



Analysis of Decay Rate Trends



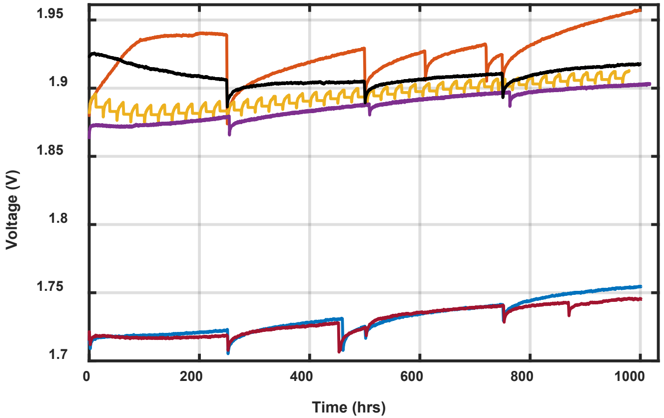
Post-Mortem Characterization

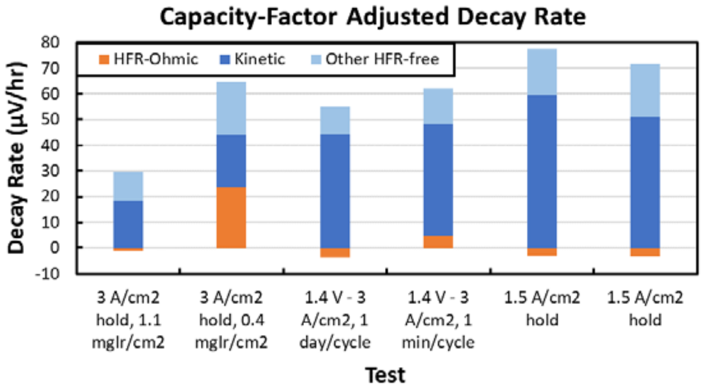
Accomplishments and Progress: Comparison of Decay Rates Under Varying Power Profiles

Need to screen multiple operating conditions:

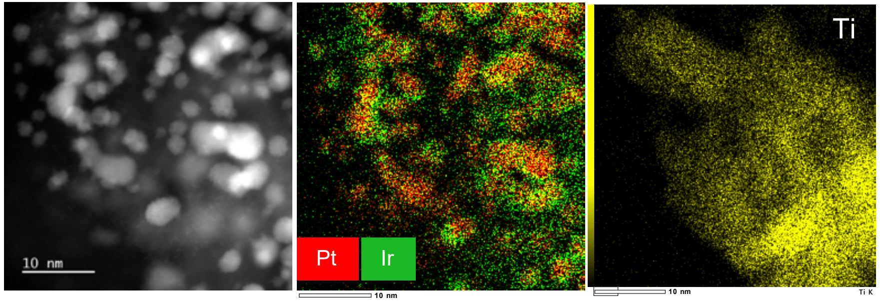
- Strong impact of anode loading on decay rate (1000 h tests)
- Similar decay rates for different profiles on a per-hydrogen produced basis. Higher ohmic decay for 3 A/cm^2 indicates difference in mechanism.
- Ir and Ti in cathode observed only for 3 A/cm^2

Test Profile	Anode Loading
3 A/cm^2 hold	1.1 mg$_{Ir}$/cm^2
3 A/cm^2 hold	0.4 mg$_{Ir}$/cm^2
1.4 V - 3 A/cm^2, 1 day/cycle	0.4 mg$_{Ir}$/cm^2
1.4 V - 3 A/cm^2, 1 min/cycle	0.4 mg$_{Ir}$/cm^2
1.5 A/cm^2 hold	0.4 mg$_{Ir}$/cm^2
1.5 A/cm^2 hold	0.4 mg$_{Ir}$/cm^2





Current hold: Ir and Ti migration to cathode



Accomplishments and Progress: Effect of Temperature on Degradation Rate

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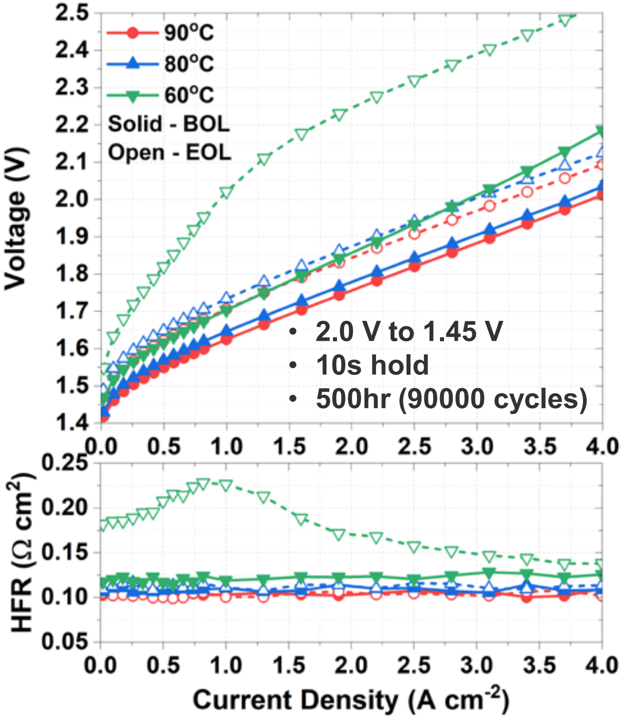
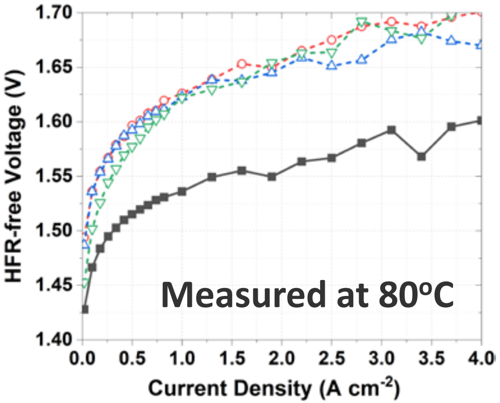
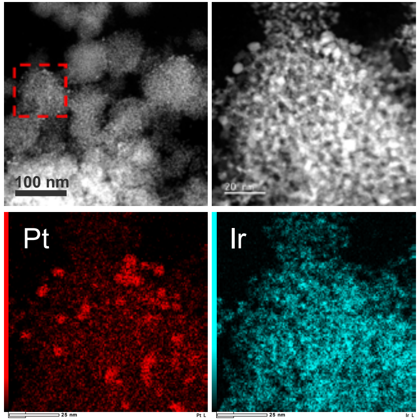


- 2.0 V to 1.45 V
- 10s hold
- 500hr (90000 cycles)

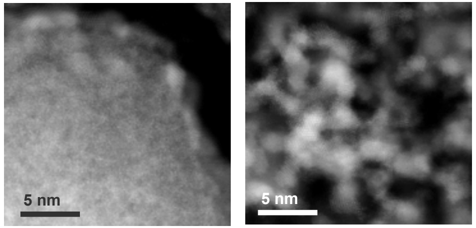


Measured at 80°C

- **Anode**: catalyst loading, 0.12 mg_{Ir}/cm^2 Alfa Aesar IrO_2; Pt-coated 2GDL10-0.25. **Cathode**: catalyst loading, 0.1 mg_{Pt}/cm^2 TEC10V50E; MGL370; **Active area**: 5 cm^2



	80 °C	90 °C
	At.%	At.%
Ti	2.5	6.0
Ir	97.5	88.0
Pt	N.A	6.0

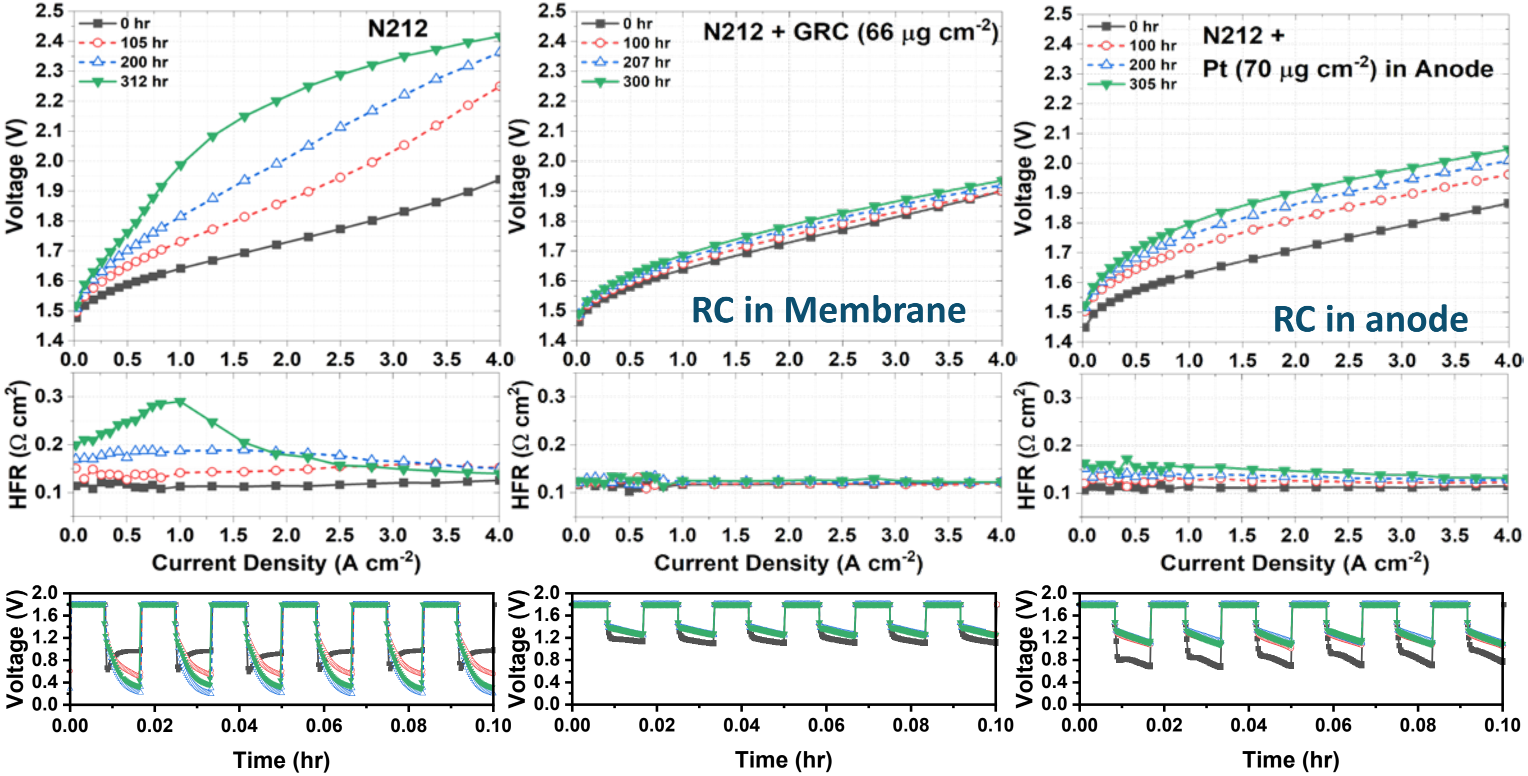


- Higher degradation observed at 60°C but mostly recovered when cell temperature increased to 80°C
- Anode gas bubble coverage and transport differs at 60°C compared to 80°C and 90°C
- Greater kinetic loss observed at higher temperature (80°C, 90°C > 60°C)
- More Ti and Pt observed in the Ir band after AST at 90°C
- Amorphous IrOx transformed to small crystallites after AST test (similar to 4000 hour tests)

Cell Temperature: 80 °C; Anode H_2O: 10 ml min^{-1}; Active area: 5 cm^2; Pressure: 1 atm

Accomplishments and Progress: Mitigation - Recombination Catalyst (RC)

Startup/Shutdown Cycle: ON (1.8 V) – OFF (OCV); 30s step;



Lower ohmic losses/higher operating currents (thin membranes) targeted for low hydrogen cost

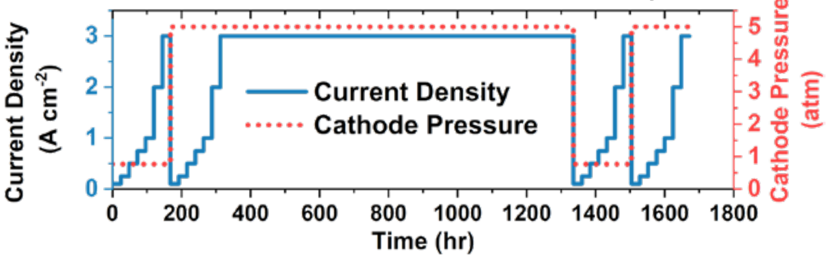
- Recombination catalysts (RCs) needed for safety, possibly durability concerns
- Major changes in cell durability witnessed with recombination catalysts during start-stop AST
- OCV is highly impacted by presence of recombination catalyst and likely impacting cell durability

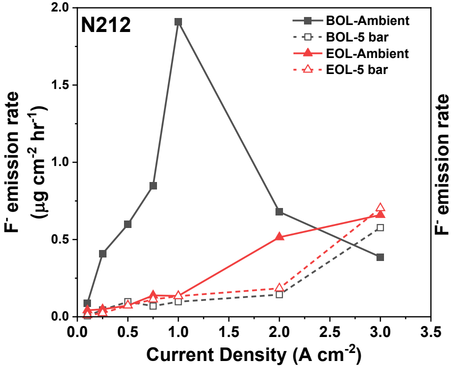
- **Anode**: catalyst loading, 0.12 mg_{Ir}/cm^2 Alfa Aesar IrO_2; Pt-coated 2GDL10-0.25. **Cathode**: catalyst loading, 0.1 mg_{Pt}/cm^2 TEC10V50E; MGL370.

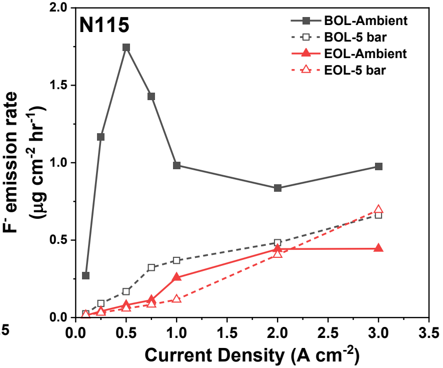
Cell Temperature: 80 °C; Anode H_2O: 50 ml min^{-1}; Active area: 25 cm^2; Pressure: Ambient (0.77 atm)

Accomplishments and Progress: Membrane Degradation Mechanical/Chemical

Membrane chemical durability

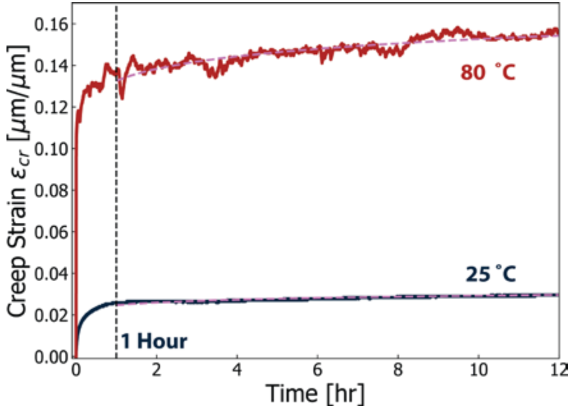






Much of PEM H2NEW focus has been on anodes, but membrane durability considerations are growing due to target on thinner membranes and higher operating currents

Development and application of in-situ and ex-situ testing, less mature, but expanding



- F$^-$ emission high at BOT: Potentially due to break-in/conditioning factors
- Degradation increases with current density
- Degradation decreases with back pressure

No PFAS compounds found (yet) in water from electrolysis tests

- N115 exhibits a nonlinear creep strain
- Strain increases at higher temperature
- Ex-situ characterization confirms and helps quantifies creep-induced thickness change

Anode: catalyst loading, 0.4 mg$_{Ir}$/cm^2 Alfa Aesar IrO_2; Pt-coated 2GDL10-0.25. **Cathode**: catalyst loading, 0.1 mg$_{Pt}$/cm^2 TEC10V50E; MGL370;

Cell Temperature: 80 °C; Anode H_2O: 75 ml min^{-1}; Active area: 50 cm^2;

Low Temperature Electrolysis (LTE)

Task 2: Performance and Benchmarking (more content in AMR Poster P196b)

Accomplishments and Progress: Benchmarking PEM MEA Fabrication and Performance

PEMWE Cell Benchmarking

- Critical to ensure lab to lab results are meaningful
- H2NEW is engaged in international efforts through the IEA to achieve harmonization in cell hardware, conditioning, and testing
- IEA efforts have been completed and an article published this FY in *Applied Energy* (https://doi.org/10.1016/j.apenergy.2023.121898)
- H2NEW internal efforts focus on achieving harmonization in cell performance testing **AND** MEA fabrication

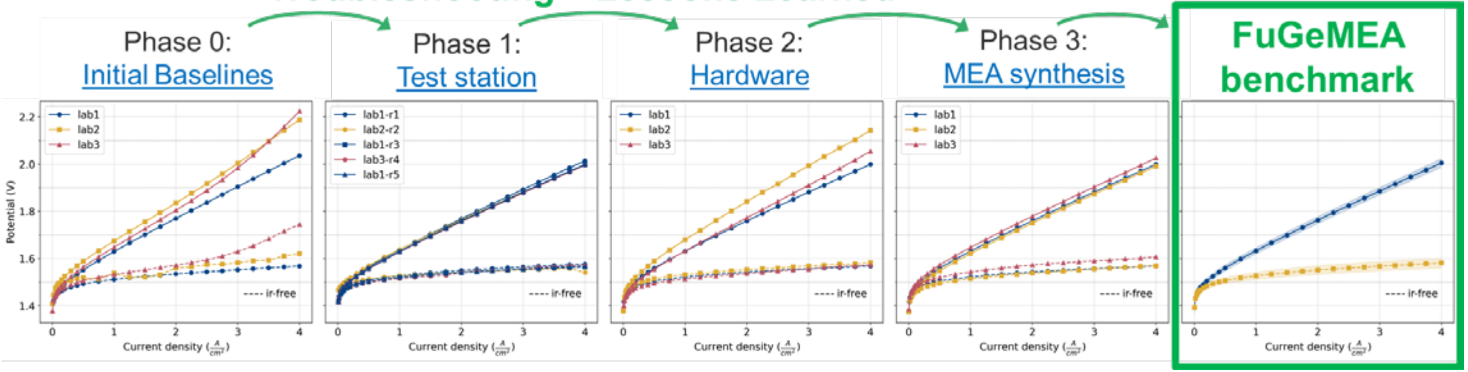
H2NEW Internal Benchmarking Progress

- Three H2NEW labs iterated first on traveling cell testing to achieve standardized performance (Phases 0 - 2)
- Iterated on fabrication of "Future Generation Membrane-Electrode Assembly" (FuGeMEA) with down-selected components (0.4 $mg_{Ir}cm^{-2}$)
- 95% confidence at 4 A cm^{-2}: ±18 mV
- Manuscript to be submitted in FY24 Q3

H2NEW Internal Benchmarking Future Work

- Expand to catalyst that can enable work on lower loadings
- Harmonization of high-pressure and H_2 crossover characterization
- Determine H2NEW baseline degradation rate data (with Task 1) for FY24 "Figure of Merit" Milestone

Troubleshooting = Lessons Learned



Phase 0: Initial Baselines

Phase 1: Test station

Phase 2: Hardware

Phase 3: MEA synthesis

FuGeMEA benchmark

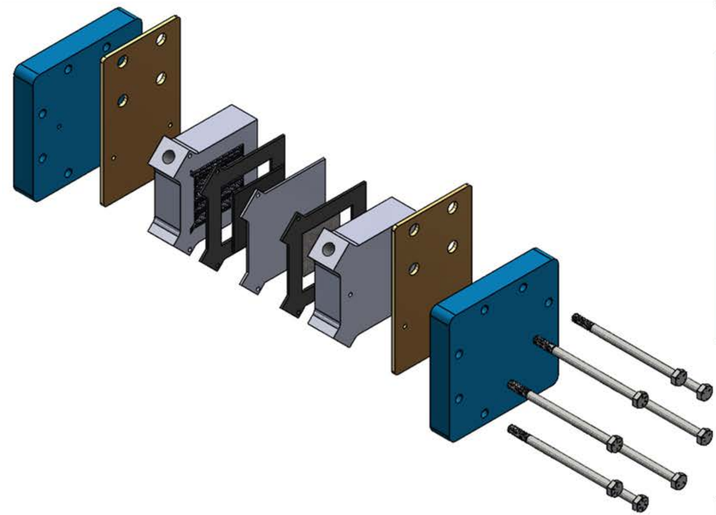
Accomplishments and Progress: High Pressure Hardware Design Completed and Disseminated

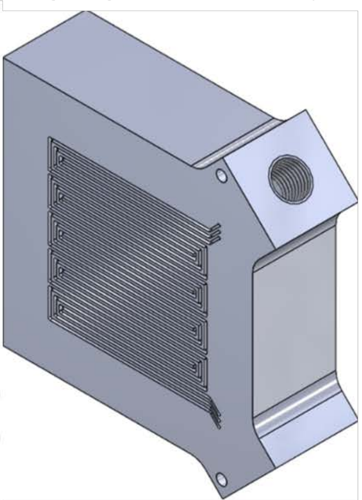
High Pressure Hardware Design Motivation

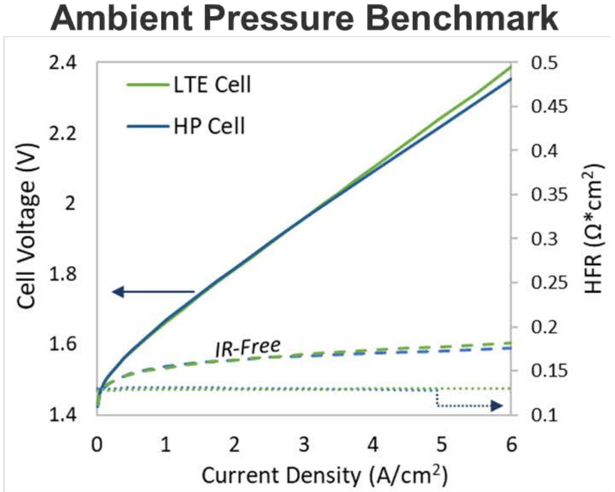
- High pressure hardware for testing single cells is not commercially available
- H2NEW needed to develop the hardware for use at the consortium test labs and as a service to the broader PEMWE community

High Pressure Hardware Design Results and Next Step

- $25 cm^2$, 30 bar hardware design completed and made standard H2NEW design
- Performance validated against that of standard ambient pressure hardware
- Design Published: DOI 10.7799/2205626: https://data.nrel.gov/submissions/223
- Positive feedback from industry and research institutes received with regards to the value for their work, their business and/or the LTE community as a whole
- On-going work: 50 cm^2 prototype in production







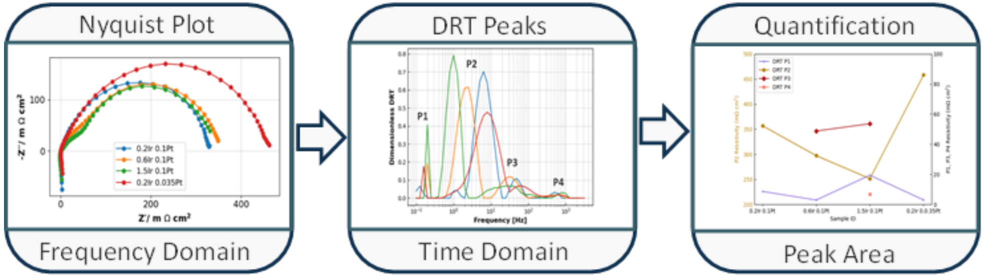
High Pressure Hardware Dec/Jan website statistics: Views 319, Downloads: 113

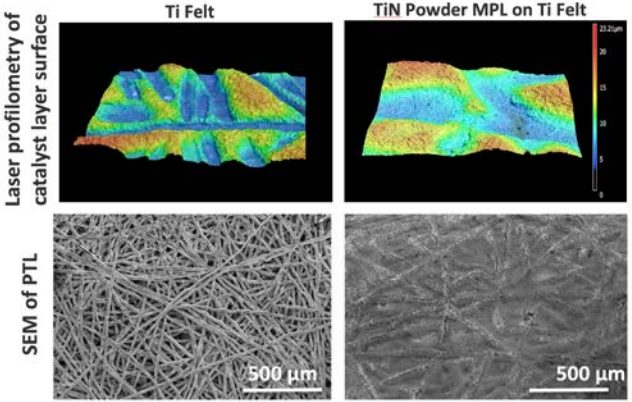
Accomplishments and Progress: Advanced PEMWE Diagnostics

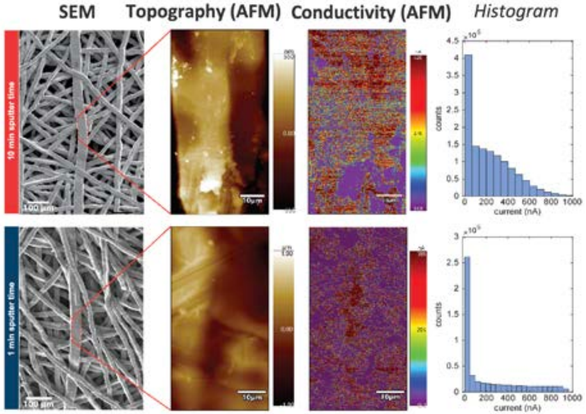
Development of diagnostic and characterization tools to answer research questions

Examples:

- Distributed relaxation time (DRT) analysis of electrochemical impedance spectroscopy data improves quantification of losses
- Laser Profilometry method to quantify porous transport layer embossment into anode catalyst layer/membrane
- Conductive Atomic Force Microscopy (AFM) characterization to determine the impact of oxide formation on Ti PTL and Pt PTL coating thickness on local conductivity variations







Low Temperature Electrolysis (LTE)

Task 3: Manufacturing, Scale-up and Integration (more content in AMR Poster P196c)

Accomplishments and Progress: Improve Uniformity of Roll-to-Roll Coated, Low Loaded Iridium Oxide Anode

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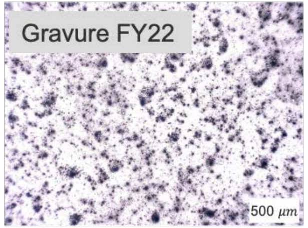
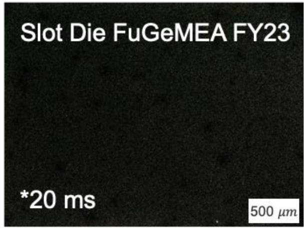
- In FY22, attempts to fabricate low loaded IrO_2 PEMWE electrodes ($\leq 0.2mg_{Ir}/cm^2$) at scale resulted in catalyst layer homogeneity issues
- FY23 work (since last AMR) focused on improving this homogeneity and determining impact on MEA performance/durability

DEC-SL-20210928_GravureR120 (Cell 1)



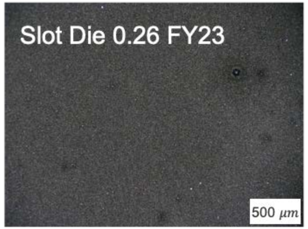
$0.206\ mg_{Ir}/cm^2$

DEC-RC-20230530B (Cell 2)



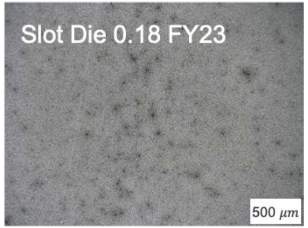
$0.400\ mg_{Ir}/cm^2$

DEC-RC-20230602B (Cell 3)

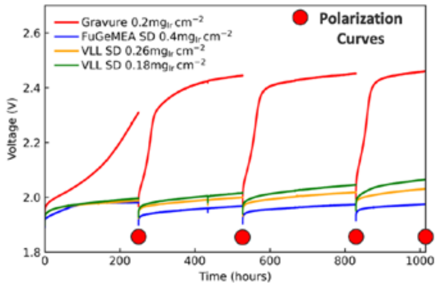


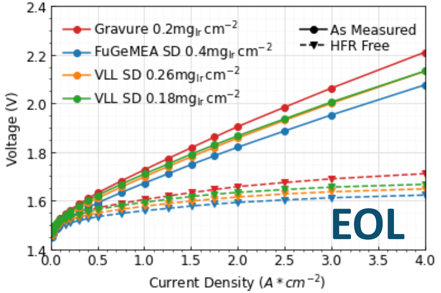
$0.260\ mg_{Ir}/cm^2$

DEC-RC-20230601A (Cell 4)



$0.179\ mg_{Ir}/cm^2$





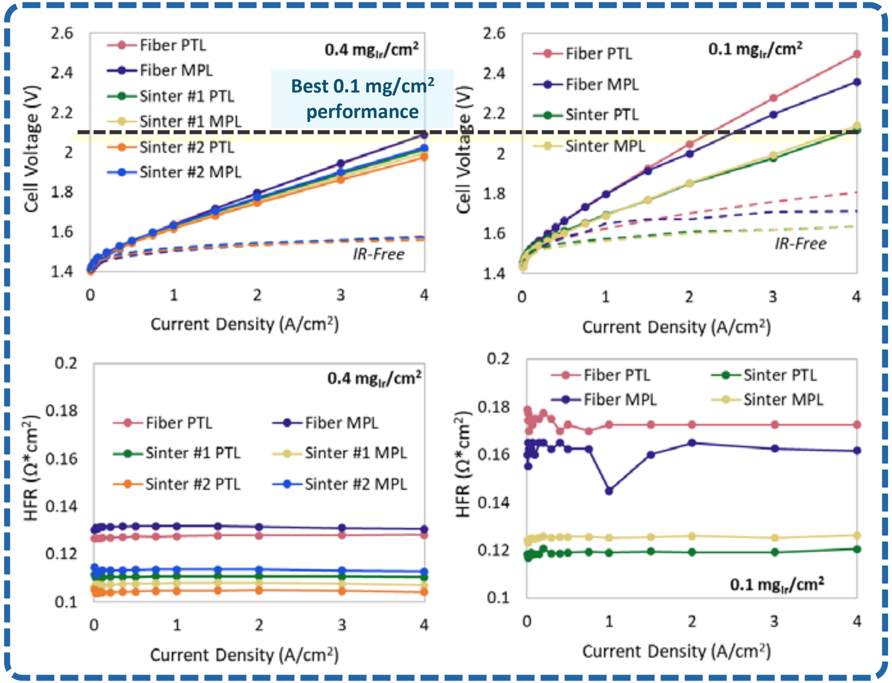
- **Homogeneity was improved through new mixing and coating processes**
- **Steady-state MEA behavior at $3A/cm^2$ showed significant differences between FY22 anode (red) and FY23 anodes of similar loading**
- **Cell performance at end of life reflected similar trends to steady state voltage measurements**
- **Collaborating with durability task to better understand results**

Accomplishments and Progress: MEA impact on PTL screening

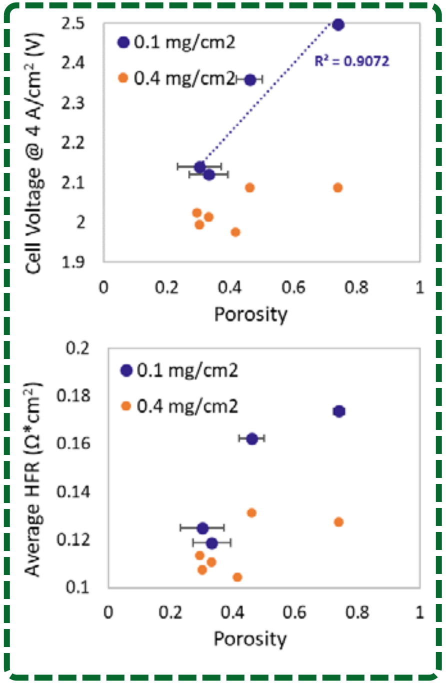
Improved PTLs-PTL/Electrode interfaces are critical for optimized cost, performance, and durability

- BOL performance screened for commercial PTLs with 0.1 and 0.4 mg_{Ir}/cm^2 anodes
- **FuGeMEA anode loadings (0.4 mg_{Ir}/cm^2) do not allow us to easily differentiate between different PTL morphologies**
- **Lower anode loadings (0.1 mg_{Ir}/cm^2) lead to much larger performance differences**

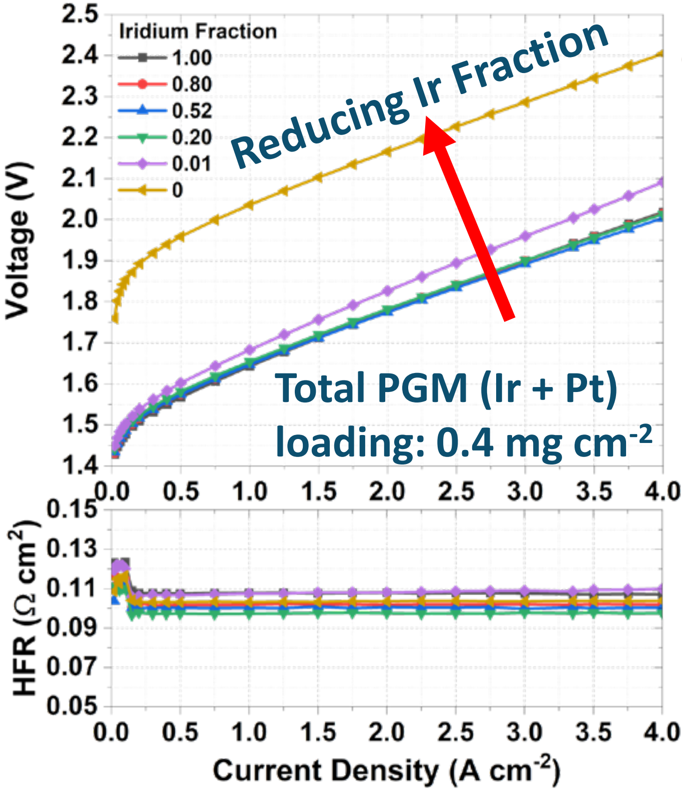
Performance

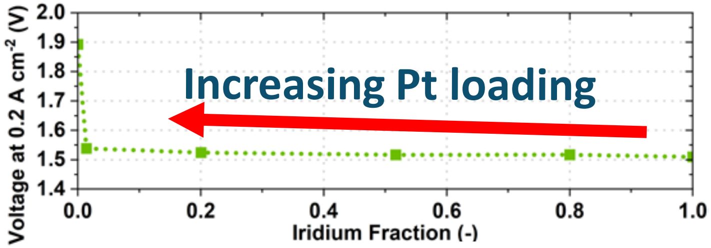


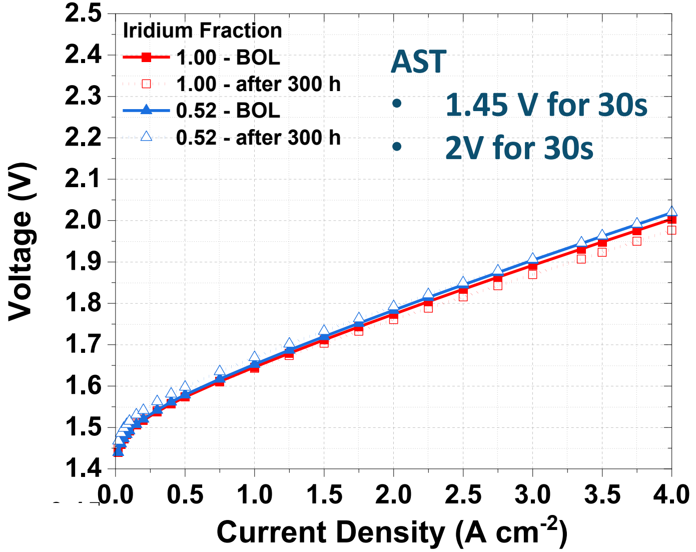
Structure <-> Performance



Accomplishments and Progress: Platinum Black as Electron Conductive Additive in Anode







AST
- 1.45 V for 30s
- 2V for 30s

Major cost driver to reduce Ir loading

- Pt offers advantages over Ir (lower cost, higher abundance, more noble/conductive)
- Pt effective at thrifting Ir from a performance standpoint up to very low Ir%
- Durability impacts need further study

Iridium fraction	In-plane e^- conductivity (S/cm)
1.00	2.69
0.80	16.64
0.52	24.15
0.20	30.43
0.01	82.72

Substituting Ir with Pt could significantly **reduce the cost without loss in performance**

Anode: 0.4 mg/cm^2, PTL: 2GDL10-0.25; **Cathode**: 0.1 mg$_{Pt}$/cm^2 TEC10V50E, GDL: MGL370; **Membrane:** N115

Low Temperature Electrolysis (LTE)

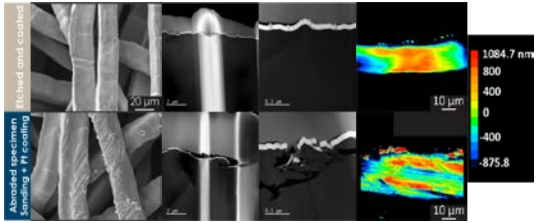
PTLs (Porous Transport Layers)

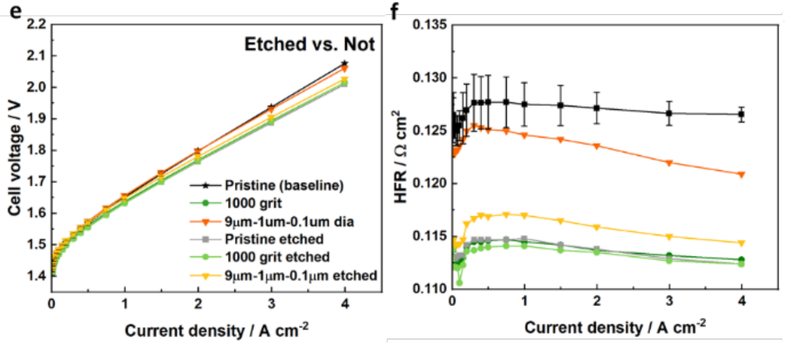
Cross-task effort (additional information found in Posters 196a, b and c)

Progress and Accomplishments: Impact of Porous Transport Layer Surface Roughness on Performance

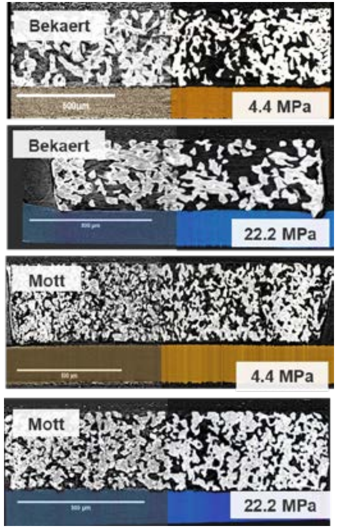
PTL/Anode interface is critical for performance and durability

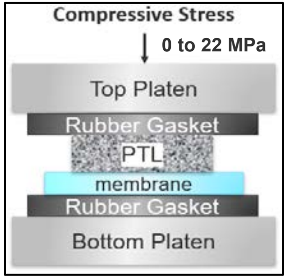
- PTL surface roughness from abrasions or etching can improve cell performance by increasing interfacial contact area to the catalyst layer
  - PTL surfaces were modified before Pt-coating by abrasion with sandpaper or with a chemical etch, introducing micrometer-scale surface roughness
- Introduction of micrometer-scale roughness appears to improve contact area and conduction at the PTL/CL interface. Smooth-polished surfaces show less benefit than rough surfaces, indicating that there is an optimal PTL surface roughness for cell performance.
- Quantification of local strain and roughness at PTL-membrane interface shows that membrane-PTL interface is rougher for fiber PTLs than for sintered PTLS; protrusions in PTLs puncture wet membranes; dry membranes undergo greater strain than wet membranes.

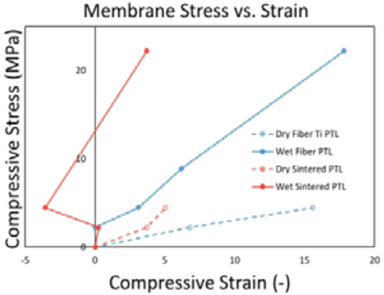




Synchrotron X-ray micro-CT



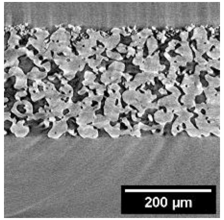


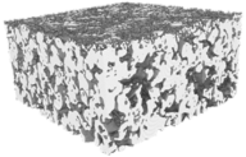


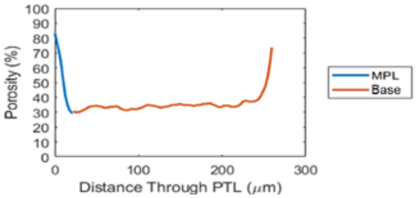
Progress and Accomplishments: Micro-porous Layer Characterization

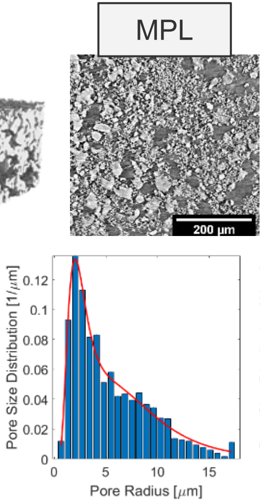
Microporous Layers (MPLs) can improve PTL/electrode interface but are not well characterized/understood

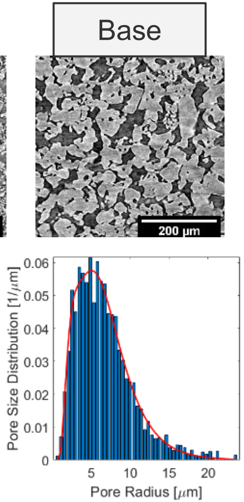
- Understanding Property – Performance relationships through advanced material characterization
- MPL is integrated into the PTL, significantly increasing contact area with catalyst layer (by 25-30%)
- By increasing MPL surface density, contact with the catalyst layer can be further increased
- Future work will address the importance of MPLs for enabling:
  - Thin membrane materials
  - High pressure operation
  - Low catalyst loadings











Synchrotron Micro X-ray Computed Tomography of H2NEW-fabricated Ti MPL on PTL

Thickness (µm)	Porosity % (through plane, avg)	Average Pore Radius (µm)	Tortuosity Factor	
			In-plane	Through-plane
Overall: 269 ± 8.2 **MPL:** 17.6 ± 5.7 **Base:** 249 ± 4.3	**MPL:** 51.8 ± 19 **Base:** 35.2 ± 5.2	**MPL:** 5.79 ± 3.7 **Base:** 6.95 ± 3.7	**MPL:** 1.73 **Base:** 2.78	**MPL:** 1.94 **Base:** 2.57

Low Temperature Electrolysis (LTE)

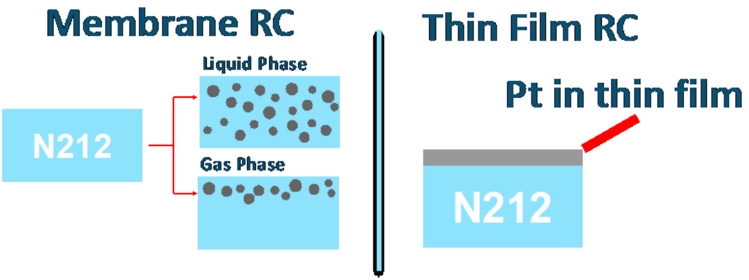
RCs/CLs (Recombination Catalysts/Layers)

Cross-task effort (additional information found in Posters 196a, b and c)

Accomplishments and Progress: Investigating Impact of Recombination Catalyst Loading and Location

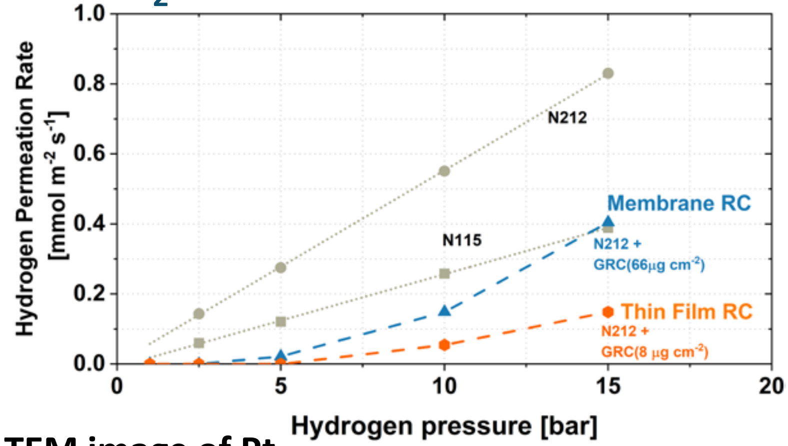
We need RC membranes for maximum cost efficiency with minimal RC loading. Fundamentals of RC membranes poorly explored.

- Multiple RC fabrication routes explored - two select approaches involve Pt particle deposition inside N212.

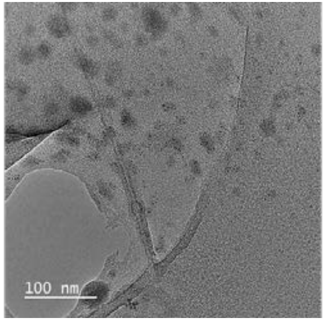


- Extremely low loadings achieved, localization of Pt near the anode allows for effective thrifting while limiting crossover. Additional approaches being pursued with data being supplied to modeling efforts.

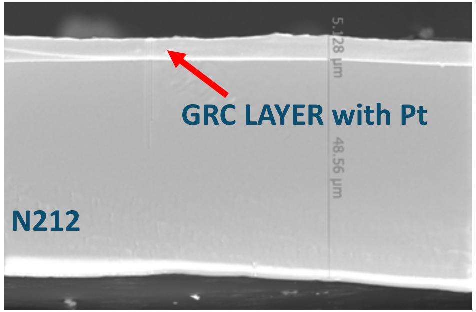
Ex-Situ H_2 Permeation Rate Measurement



TEM image of Pt in Membrane RC



SEM image of Thin Film RC



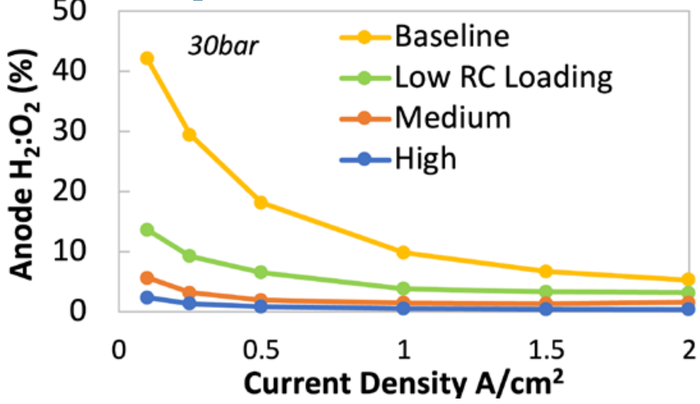
Cell Temperature: 80 °C; Anode H_2O: 75 ml min^{-1}; Gas flow rate: 300 sccm; Active area: 50 cm^2

Accomplishments and Progress: Understanding Hydrogen-Oxygen Recombination

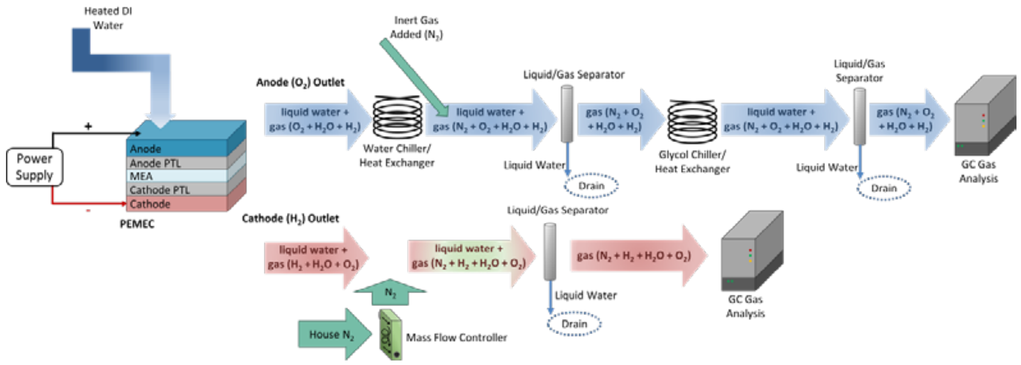
Hydrogen crossing through membrane represents a safety hazard and is a source of efficiency loss

- Hydrogen-oxygen recombination catalysts (RCs) mitigate the hazard of crossover hydrogen
- An accounting of all the hydrogen (i.e., closing the molar flow balance) is needed safety, performance and even durability considerations
  - For complete molar flow balance, hydrogen evolved from cathode needs to be quantified: capability being developed and validated
- Key findings:
  - Pt coating on PTL acts as a RC; necessary to use Ir coating on PTL for molar flow balance
  - Pressure-dependent studies illustrate that oxygen is the limiting reactant in gas recombination mechanism at GRC
  - Data needs to be provided to modelers for full picture understanding of H2 within PEMECs

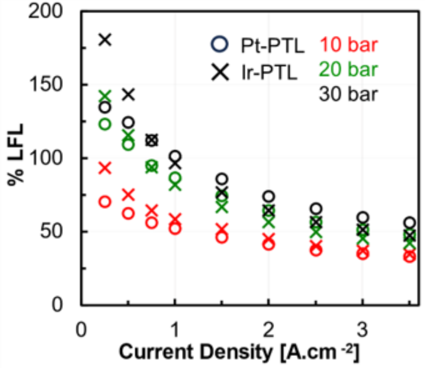
H_2 Safety at Pressure Operation



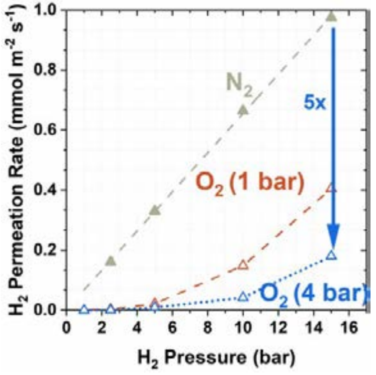
Closing Molar Flow Balance



H_2/O_2 recombination on PTL



H_2/O_2 recombination at RC

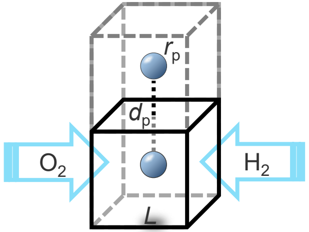


Accomplishments and Progress: Modeling Hydrogen Crossover Effects and Recombination-Catalyst Efficacy

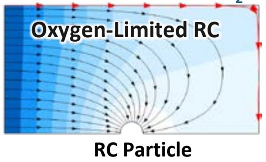
PEMWE cell models are critical to understand crossover mechanisms and develop mitigation strategies – especially for turning down ratio at low PEMWE current density.

- ➢ Complementary macroscopic and microscopic PEMWE models have been developed to provide insight into transport and kinetics that influence RC efficacy for mitigating H_2 content in the anode effluent.
- ➢ The models account for cell operational conditions (differential pressure, current density) and RC morphological parameters (particle size, layer thickness, and location) yielding a description of local conditions of RC particles, which are validated by experimental measurements.

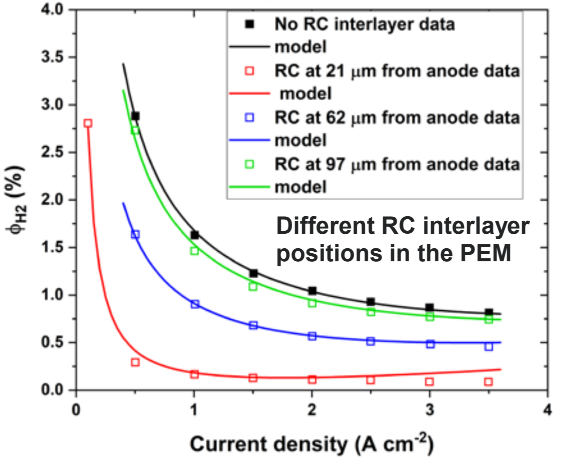
Modeling an Isolated RC Particle



Dimensionless Conc. of O_2

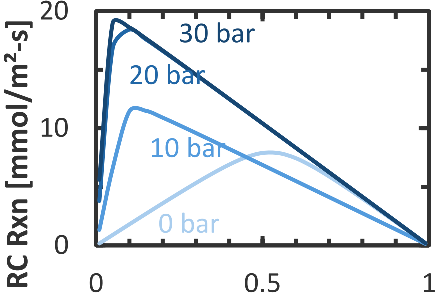


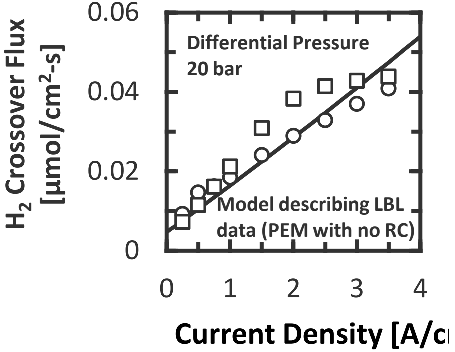
P_{ca} = 10 bar; P_{an} = 1 bar; T = 80 °C



Different RC interlayer positions in the PEM

Optimization of RC Placement Under Differential Pressure





Differential Pressure 20 bar

Model describing LBL data (PEM with no RC)

Data for top right plot is from A. Martin et al., *J. Electrochem. Soc.* **2021**, *168*, 094509

H2NEW Activities: Low Temperature Electrolysis (LTE)

Liquid Alkaline (more content in AMR Poster P196h)

Accomplishments and Progress: Baselining (Round Robin)
Standardization of LA cell testing

LAWE Cell Test Baselining

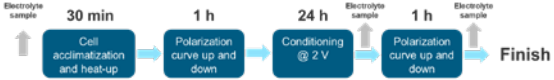
- Critical to ensure lab to lab results are meaningful
- H2NEW is engaged in international efforts and internal efforts to achieve standardization
- IEA efforts show a wide spread moving to second phase
- H2NEW internal efforts have achieved higher level of harmonization

Next:

- Harmonization of iron content in the electrolyte
- Harmonization of temperature measurement and heating

International (IEA Round Robin)

- Cell designed by FZ Jülich and fabricated by one contractor for all participants (9)
- Large deviations, identified factors
  - Iron availability in electrolyte differs
  - Different heating methods
  - Deviations in flow and electrolyte concentration


Electrolyte sample

30 min
Cell acclimatization and heat-up

1 h
Polarization curve up and down

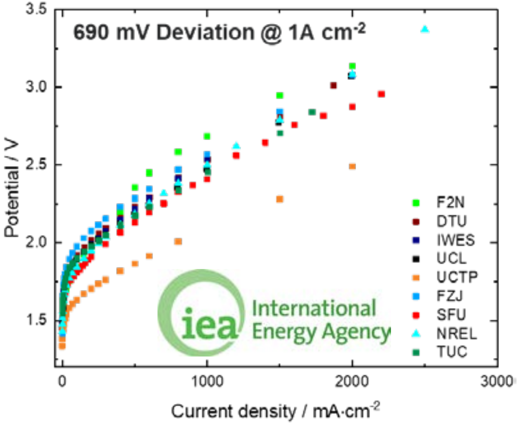
24 h
Conditioning @ 2 V

Electrolyte sample

1 h
Polarization curve up and down

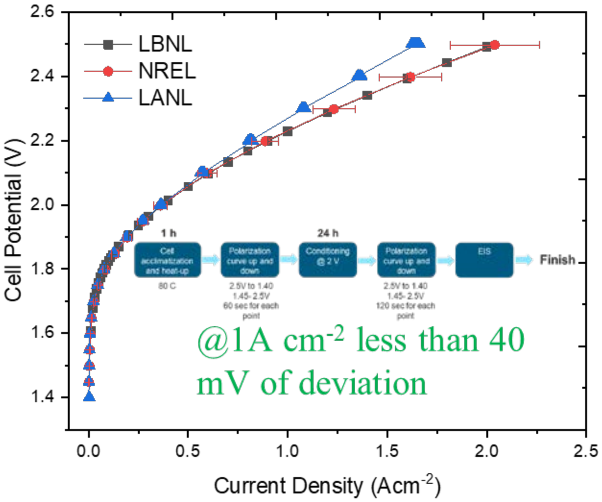
Electrolyte sample

Finish



H2NEW (Internal Round Robin)

- Three H2NEW labs have iterated on cell testing to achieve standardized performance
- Additional efforts to further align performance look at
  - electrolyte concentration
  - Other Ohmic effects

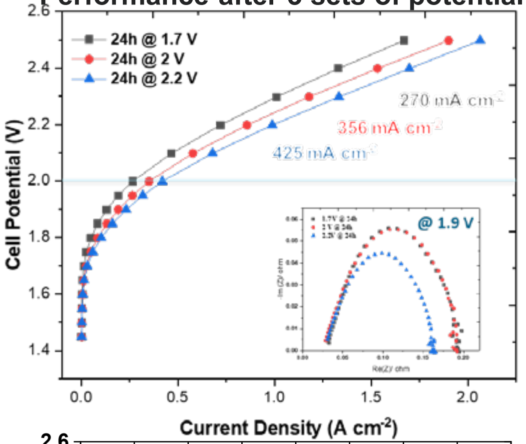


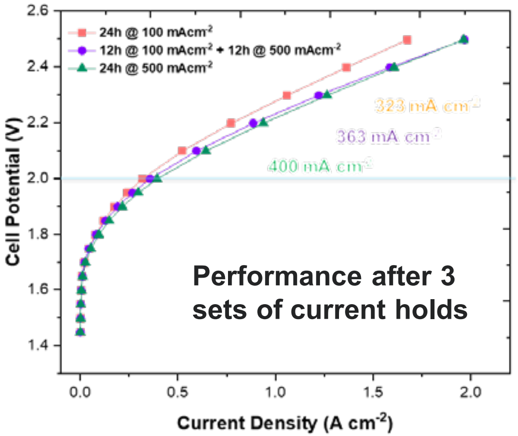
@1A cm^{-2} less than 40 mV of deviation

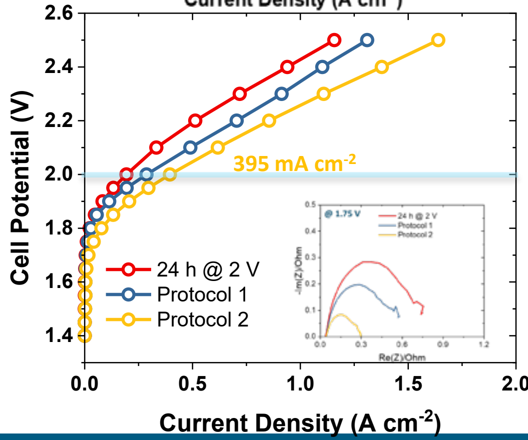
Accomplishments and Progress: Benchmarking the development of activation protocols

- The mechanism and impact of cell activation for liquid alkaline water electrolysis (LAWE) is not well understood and critical for performance and durability testing
- **Activation protocols such as current hold or potential cycling led to varying cell performances**. A correlation between surface composition and morphology will be studied further to fully understand the effect of the activation step
- An improved activation protocol enables the development of more efficient and durable systems, leading to increased hydrogen production rates and reduced energy consumption. As well as quantification of degradation rates

Performance after 3 sets of potential holds







Protocol 1:

20 cycles between 2 V – 0.8 V

2 V: 60 s – 0.8 V 60 s

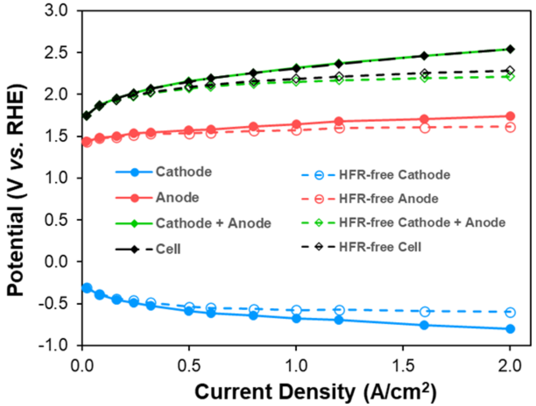
Protocol 2:

20 cycles between 2 V – 0.2 V

2 V: 60 s – 0.2 V 60 s

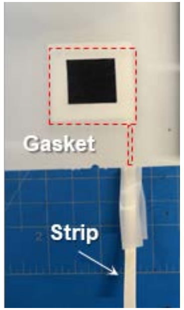
Accomplishments and Progress: Reference Electrode Integrated liquid alkaline cell

- Reference electrodes are critical for decoupling loss mechanisms effecting performance and quantifying degradation losses over time.
- We have developed and applied reference cell approaches and have provided them for model validation. These results have shown high consistency and allow for separation of ohmic, cathode and anode overpotential losses.
- Applying reference electrodes to degradation studies is a coming step.



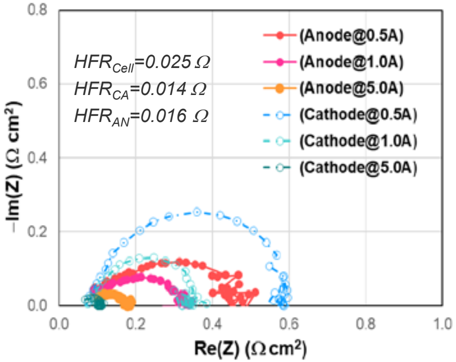
Feasibility test of reference integrated LA cell:

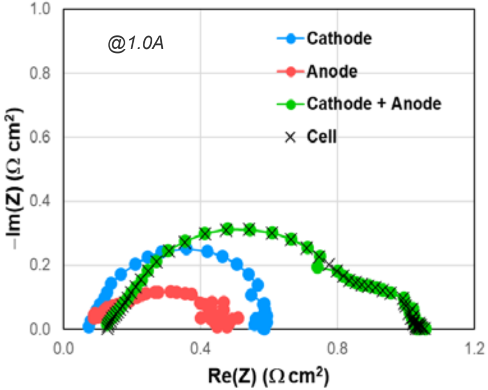
- Independent potential reading of cathode and anode
- Well-matched Pol-curve w/ and w/o iR-compensation
- Constant HFR_{CA} and HFR_{AN} regardless of the applied current
- Well-matched Nyquist plot b/w the sum and the entire cell profile



Experimental parameters

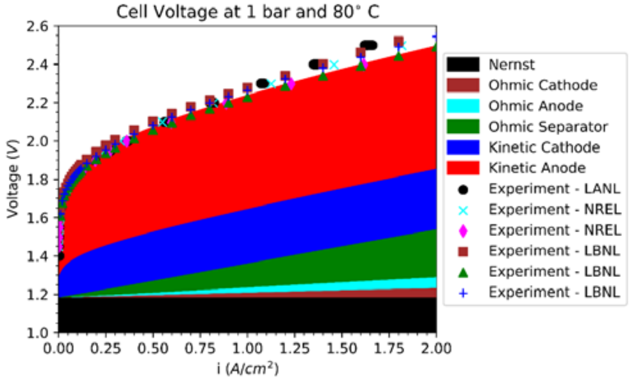
- Ni foam (5cm², ~300µm) for the cathode and anode
- 30% wt.% KOH, T = 80 ⁰C, 50 ml min⁻¹
- Calibration: +0.86V (Thermodynamic)
- No activation before the test
- Amp: 5% of the DC current, 0.2 Hz – 10,000 Hz

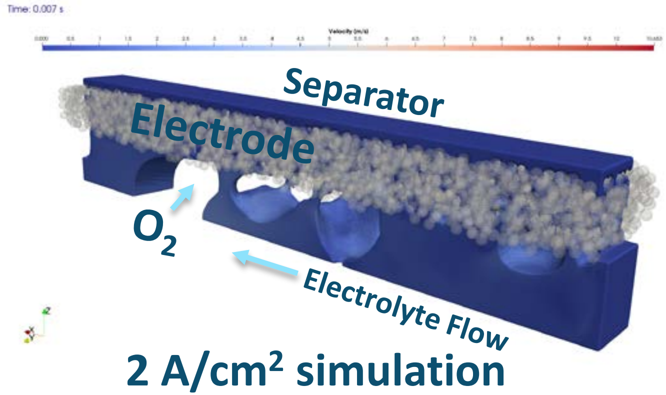


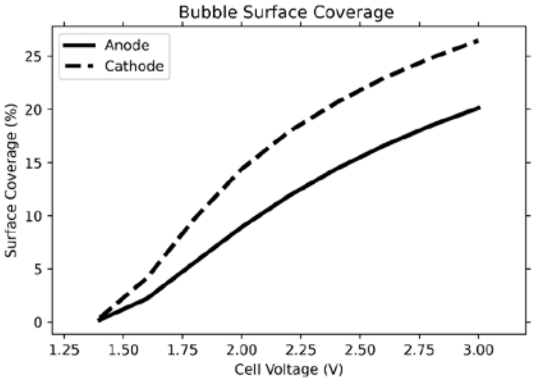


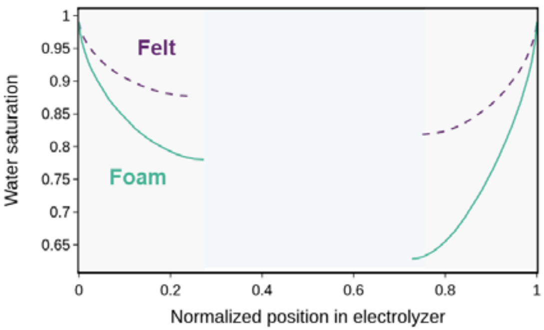
Accomplishments and Progress: LAWE cell modeling

- LAWE cell models are critical to understand performance losses and degradation.
- LAWE cell model has been developed and validated within 10% of H2NEW experimental data.
- Gas dynamics/Multiphase flow (bubble formation) studies play a critical role on LAWE performance. We have modeled dynamics and average bubble content of LAWE cells including impact of anode vs. cathode and felt vs foam electrodes.
- We will further validate these tools with experimental data, expand into degradation studies, and supply findings to TEA/Systems analysis efforts





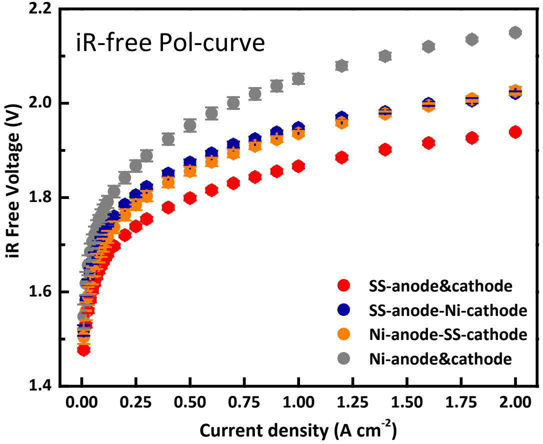


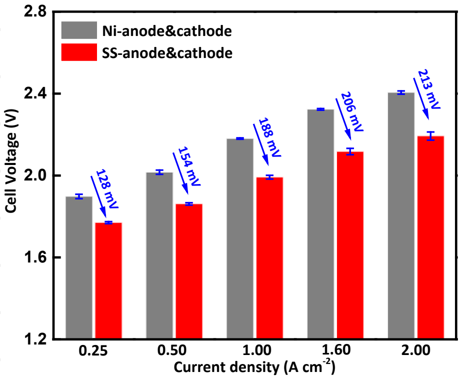


Accomplishments and Progress: Electrode and catalyst evaluation

Electrode evaluation

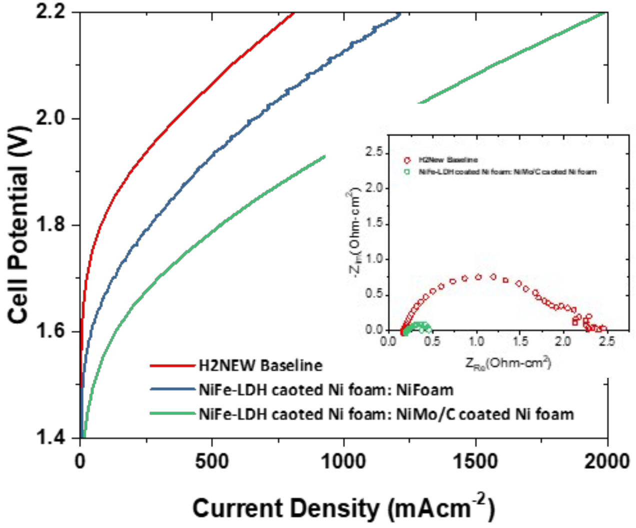
- Improving cell performance is critical for LAWE commercial competitiveness. The choice of Ni (stability) and Fe (activity) or other transition metal is common research area of interest.
- SS electrode is more active for both OER and HER than Ni electrode and enhances the LAWE performance as both anode and cathode, due to presence of NiFe, and NiMo active species for OER and HER.
- **Voltage reduction of 213 mV @2.0 A cm^{-2} using SS as electrodes for LAWE**
- Stability and degradation remain concerns for evaluation.





Catalyst evaluation

- NiFe layered double hydroxides (LDH) are widely known as highly active alkaline OER catalysts.
- NiFe LDH anode electrodes combined with a NiMo/C cathode, result in a 3-fold increase in current density at 2.0 V.
- Stability and degradation are remaining concerns that need further investigation



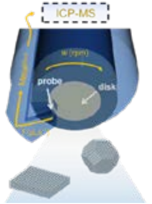
Accomplishments and Progress: Dissolution studies of Ni and stainless steel (SS)

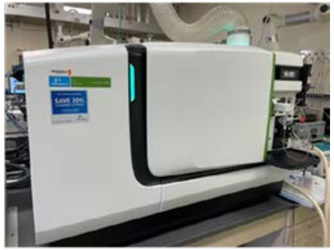
- Electrode and electrode catalyst stability for highly performing LAWE anodes and cathodes is a major challenge. Quantifying degradation is challenging for trace metal ions (Fe, Ni) under 7M KOH conditions.
- In situ and ex situ ICP-MS methods developed to allow for practical measurements of metal ion dissolution to be obtained under device relevant conditions.
- Ni dissolution from SS316 higher than pure Ni.
- Dissolution of SS alloy components (Fe, Cr, Mo) is far greater on foam electrode, 3-5 times more for Mo and about 10 times more Fe dissolution
- Ni dissolution from foam or disk equivalent.
- Purification of KOH to remove background trace of Ni and Fe are required for precise quantification of dissolution at onset potentials.

Advanced degradation studies required for understanding durability constraints during dynamic operation

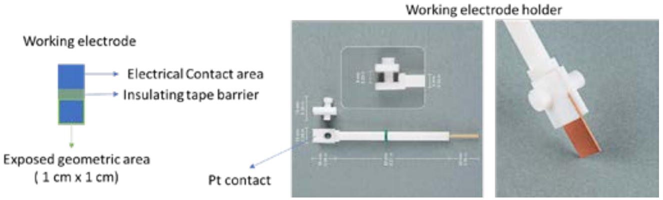
In situ

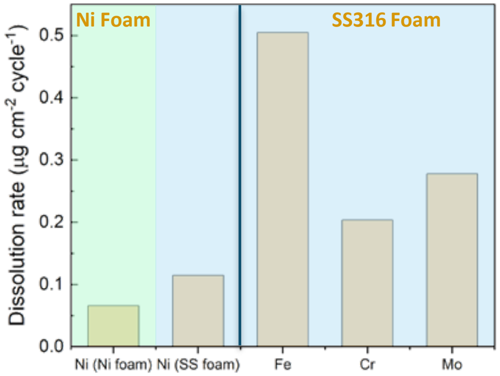
SPRDE ICP-MS

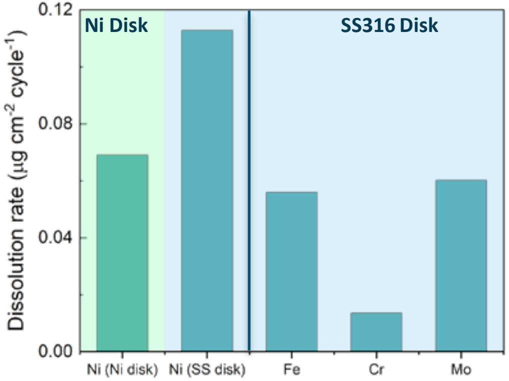




Ex situ







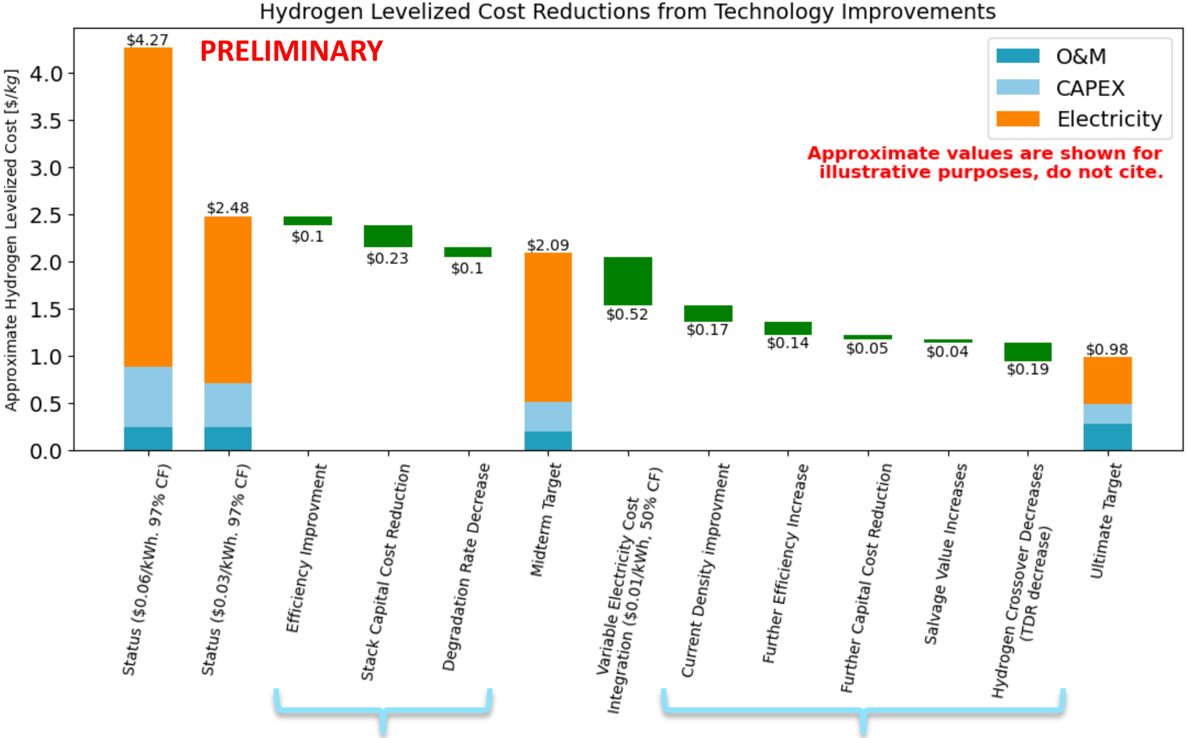
Low Temperature Electrolysis (LTE)

Task 3c/9ciii: Analysis (more content in AMR Poster P196d)

Accomplishment: Initial Economic Parameterization Study of Liquid Alkaline Water Electrolyzers

H2NEW analysis activities help to identify the most critical R&D targets for experimental efforts.

Waterfall chart analysis outlines strategies to reducing hydrogen levelized costs. These are our first efforts into this area and are being expanded upon (PEMWE parallel, slide 12).

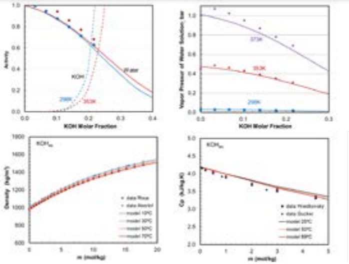


Accomplishment: System Modeling of Liquid Alkaline (LA) Electrolyzer - Major Sub-Models and Components

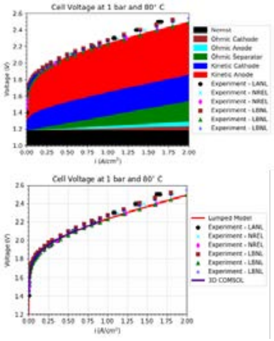
Objective: Develop system models to quantify and assess the economic impact of LAWE cost, performance, operation, and durability tradeoffs and connect with techno-economic analysis.

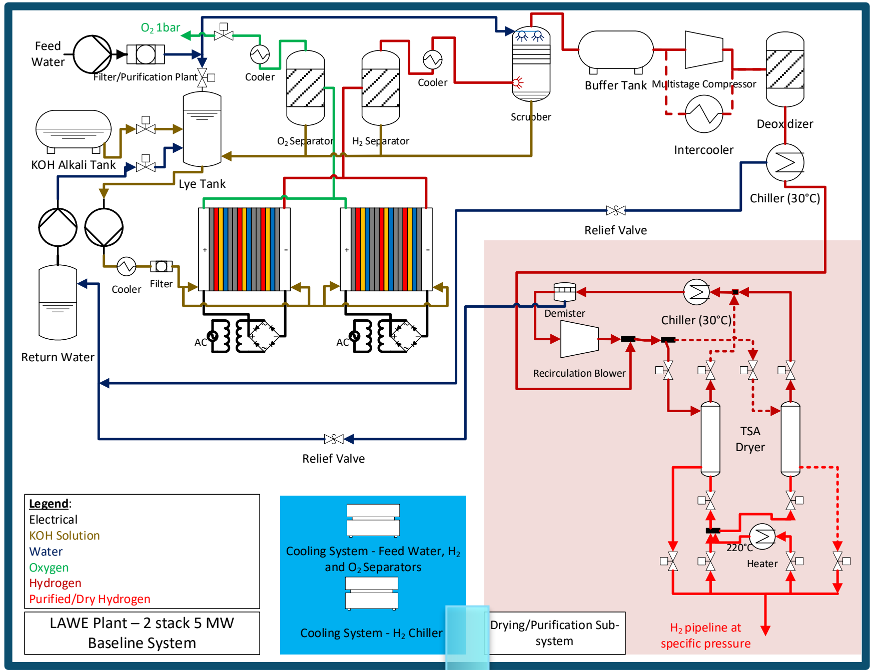
FY24 Summary: Integration of (1) cell model (with crossover) based on H2NEW Ni-Foam baseline cell configuration and (2) KOH thermodynamic model into system model. Preliminary simulations confirm stack as largest electrical energy cost.

Input: $KOH_{(aq)}$ Thermodynamic Model



Input: LA Cell Model (Pol Curves)

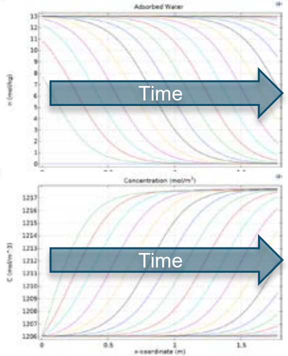




Input: Stack and BoP Parameters

- Stack parameters and dimensions
  - Lifetime
  - Thermal balance
  - Pressure drop
- Balance of Plant
  - Pumping costs
  - Dynamic operation and turn down ratios

Input: TSA/PSA Dryer Model



Output: System Model (GCTool)

- Electrical energy consumption
- Dynamic operation regimes
- BoP sizing and tradeoffs

H2NEW Activities: High Temperature Electrolysis (HTE)

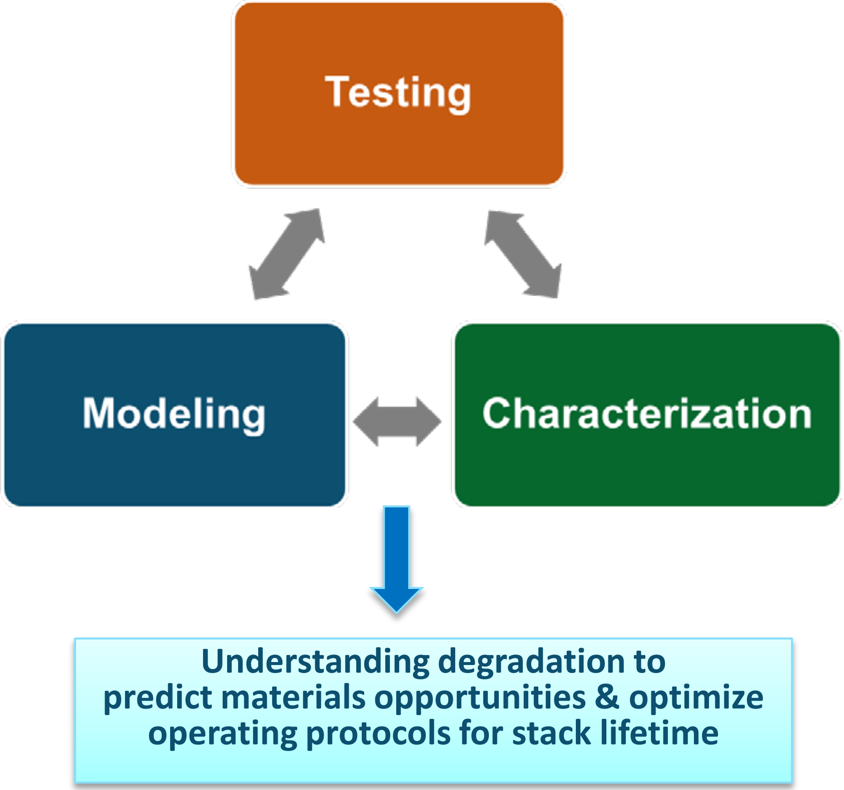
Richard Boardman, H2NEW Deputy Director, and HTE Lead

Approach: Select FY 24 HTE Milestones* (From 55 total)

Milestone Name/Description	Due Date	Type	Status
Determine: (1) Impact cation migration from the oxygen electrode to the barrier layer-electrolyte interface and the electrolyte and secondary phase formation, (2) Effect of operating conditions on the GDC barrier layer, (3) Impact of pulsing/cycling, (4) Diffusion length of Sr and/or other relevant cations as a function of temperature, (5) SOEC/SOFC mode switching, (6) Ni redistribution in the steam electrode; (7) plus additional related QPMs	12/31/2022	QPM	Complete (Slides 55-59)
Build 8 new standardized test stands for testing of 5cm x 5cm planar cells at PNNL, INL, and LBNL (including pressurized button cell stand at PNNL); Restart in-operando button cell with intermittent XRD analysis of air electrode (at PNNL). Recalibrate NETL SOEC multi-physics model using new experimental and microstructural characterization data	3/31/2023	QPM	Complete (Slides 58, 59, 61)
Determine effect of Ni-YSZ microstructure on cell performance and durability; Complete partial redox cycle testing; Recommission pressurized test stand for electrolysis testing of planar cells up to 20 bar; Incorporate characterization techniques to spatially track cation exsolution and secondary phase formation in large format cells; Quantify the difference in transient states within the air and steam electrodes when an SOEC is operated under dynamic loading conditions. Evaluate PWM Cell operation for identifying degradation mechanism time scales and decoupling voltage and current relationships; Assemble database of at least 100 synthetic microstructures for LSCF electrodes	6/30/2023	QPM	On Track (Slides 62, 65, 66)
Establish effect of steam utilization on the degradation rates; Determine if elevated pressure accelerates degradation by > 20%; Identify factors limiting cell performance and durability when tested with metal interconnects, Etc.	9/30/2024	QPM	On Track (Slide 58)
Complete total cell testing of >20,000 hours; Complete design, build, and validate in-operando synchrotron XRD capability; Identify factors limiting cell performance and durability when tested with full interconnect train; Etc.	9/30/2024	Milestone	On Track

*Partial list, see associated 2024 AMR posters for additional details (links on slide 9)

Approach: Integrated testing, characterization & modeling



Testing

Modeling

Characterization

Understanding degradation to predict materials opportunities & optimize operating protocols for stack lifetime

Performance testing: Evaluate cell performance as a function of time under different operation conditions (including AST)

- Representative materials prototypes, with testing protocols
- High throughput button cell testing for 1000's of hours – establish consistency among three testing Laboratories
- Larger planar cells for realistic conditions (flows, concentration and heat gradients, metal interconnects, sealants, etc.
- Optimization of operating conditions and systems design

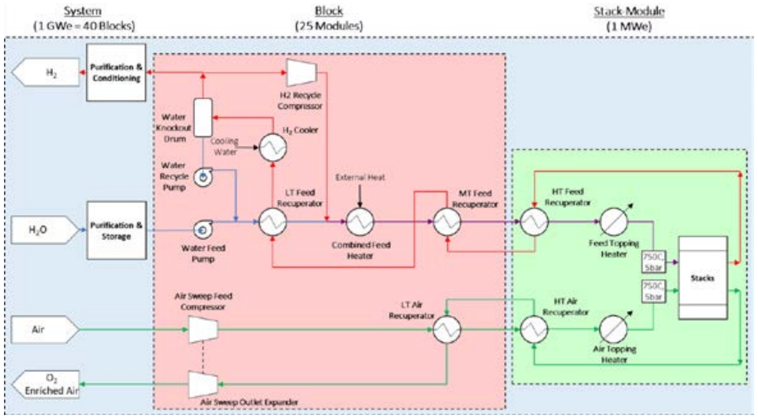
Characterization: Identify materials physical and chemical properties and transitions and determine degradation phenomena and pathways

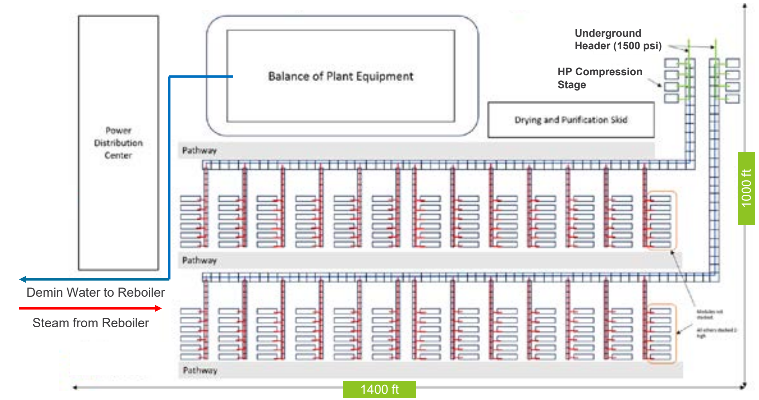
- Correlate changes to operating condition
- Integrate with modeling to develop predictive models

Modeling: Determine mechanisms of degradation, end of life, and help direct testing conditions

- Elucidate impact of degradation mechanisms on performance
- Use characterization data to develop & validate predictive models
- Project operating performance for 10,000's of hours

Relevance: Levelized Cost of Hydrogen (LCOH) for HTE: Stack Modules → Module Blocks → System

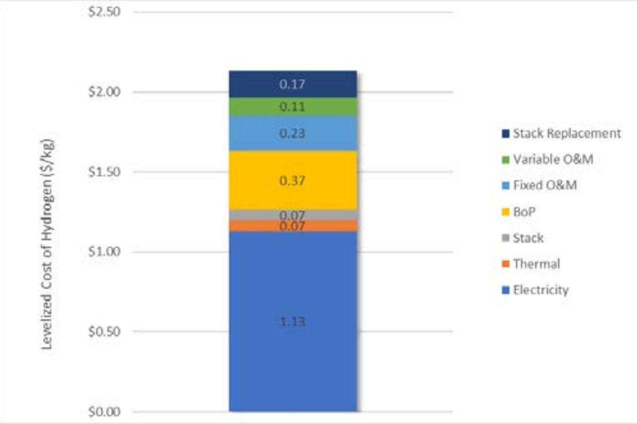


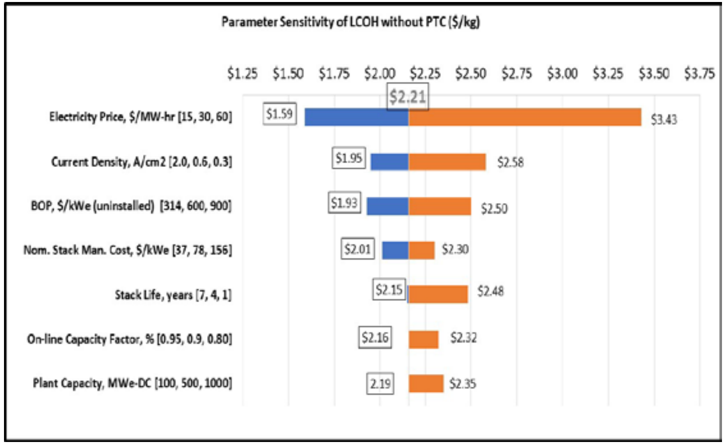


Typical 500 MW_{nom} HTEF Layout.

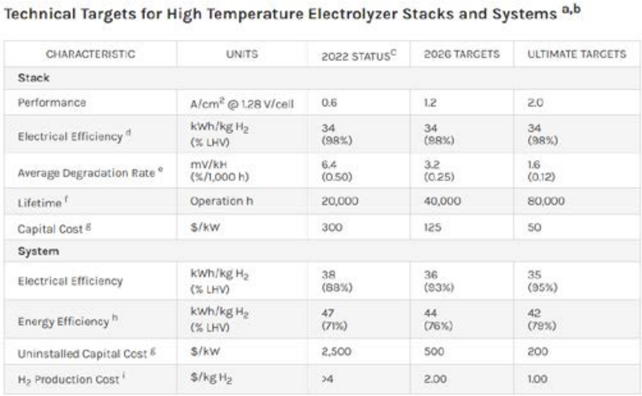
— Low Pressure (<5 PSIG) — Intermediate Pressure (200-300 PSIG) — High Pressure (~1500 PSIG)

- **HTE cost analyses**
  - INL prototype systems with heat integration; Aspen Process evaluator for capital costs; Pilot plant test modules for power use efficiencies
  - Strategic Analysis bottom-up costs for stacks, component costing, engineering design, permitting, construction, contingencies, etc.
  - DOE-NE Program economic assessments & Architectural Engineering for scalable, full-size plants
  - Hybrid markets (grid and hydrogen production)
- **H2NEW Impacts**
  - Set targets to increase the life and performance of stacks and systems
  - Understanding and controlling degradation and damage during rapid cycling of stacks used for ancillary grid services will allow HTE systems to operate in dynamic markets to exploit low-cost electrons
  - Understanding operating parameters will allow extended use of stacks and systems components



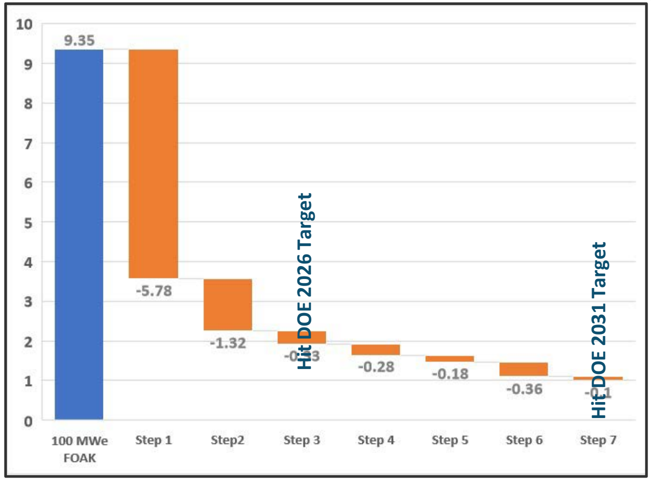


Relevance: Reducing LCOH through Optimized Stack & System Efficiency Optimization set by performance targets



Technical Targets for High Temperature Electrolyzer Stacks and Systems [a,b]

CHARACTERISTIC	UNITS	2022 STATUS[c]	2026 TARGETS	ULTIMATE TARGETS
Stack				
Performance	A/cm^2 @ 1.28 V/cell	0.6	1.2	2.0
Electrical Efficiency [d]	kWh/kg H_2 (% LHV)	34 (98%)	34 (98%)	34 (98%)
Average Degradation Rate [e]	mV/kH (%/1,000 h)	6.4 (0.50)	3.2 (0.25)	1.6 (0.12)
Lifetime [f]	Operation h	20,000	40,000	80,000
Capital Cost [g]	$/kW	300	125	50
System				
Electrical Efficiency	kWh/kg H_2 (% LHV)	38 (88%)	36 (93%)	35 (95%)
Energy Efficiency [h]	kWh/kg H_2 (% LHV)	47 (71%)	44 (76%)	42 (79%)
Uninstalled Capital Cost [g]	$/kW	2,500	500	200
H_2 Production Cost [i]	$/kg H_2	>4	2.00	1.00



Reference Plant: First-of-a-Kind (FOAK) ($9.35/kg-H2)

- < 100 MWe-DC HTE facility, 80% on-line capacity
- $60/MWe-hr power from grid; with electrically-heated steam boiler for HTE facility
- $300/kWe stack manufacturing costs (operated at 0.6 A/cm^2); 2.5-year stack life
- $2,200/kWe uninstalled balance of plant (BOP) costs (custom equipment supply)
- **Step 1. H2NEW initial impact ($3.57/kg-H2)**
  - 500 MWe-DC HTE facility; 90% on-line capacity
  - $125/kWe stack manufacturing costs (operated at 1.2 A/cm2); 4-year stack life
  - $375/kWe uninstalled BOP costs (high volume commercial equipment supply)

Step 2. Electrically connect HTE plant to existing nuclear power plant ($2.25/kg-H2)

- 500 MWe-DC Nth-of-a-Kind HTE Plant
- $30/MWe-hr direct power purchase from nuclear power plant

Step 3. Thermal integration with nuclear power plant or other source by 2026 ($1.92/kg-H2)

Step 4. Continue H2NEW stack and BOP progress by 2028 ($1.64/kg-H2)

- $65/kWe stack manufacturing costs (operated at 1.5 A/cm2); 7-year stack life
- $314/kWe uninstalled BOP costs (optimized thermodynamics and materials)
- 95% on-line operating capacity

Step 5. H2NEW Ultimate Targets by 2031 ($1.46/kg-H2)

- $50/kWe stack manufacturing costs (operated at 2.0 A/cm2); 7-year stack life
- $150/kWe uninstalled BOP costs

Step 7 Achieve dynamic operating conditions to support grid markets ($1.1/kg-H2)

- $22.00/MWe Direct power purchase when nuclear plant reduces production costs and receives capacity payments for spinning reserves in flexible grid/hydrogen market

Step 6. Reaching H2 Earthshot Target by 2031 ($1.00/kg-H2)

- Sweep oxygen for industrial market sales (e.g., oxy-fired with CO_2 sweep)
- Obtain heat from industry heat provider

Accomplishments

- 2024 AMR Select HTE Highlights*
  - Task 5 – Testing & Measurements
    - 12,000 hrs Baseline Durability Tests in 50 and 90% Steam
    - Factors to Mitigate Sr and Ce/Gd Migration
    - AST Durability Tests in 95-99% Steam
    - SOEC Operation Under Elevated Pressure
    - Cell Scaleup and Large Size Cell Testing
  - Task 7 – Advanced Characterization
    - Operando HT XRD, High throughput
    - Nano CT studies of Ni:YSZ H2 electrode
  - Task 8 – Degradation Modeling
    - Modeling Performance and Stability for LSCF
    - Sr permeation and growth of $SrZrO_3$
    - Ni-YSZ Electrode Coarsening
  - System Cost Modeling
    - LCOH for HTE (Slides 51-52)

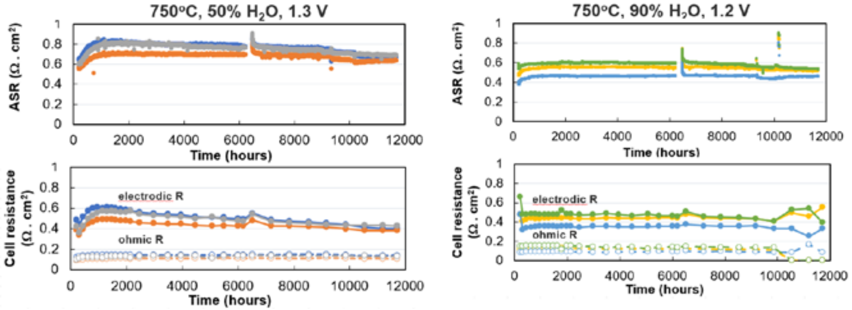
*Select highlights of efforts since previous AMR (https://www.hydrogen.energy.gov/pdfs/review23/p196_pivovar_boardman_2023_o.pdf)
*Expanded content available in poster presentations (see slide 9 for links)

High Temperature Electrolysis (HTE)

Task 5: Durability Testing and AST Development
(more content in AMR Poster P196E)

Accomplishments and Progress:
Completed 12,000 hrs Baseline Durability Tests in 50 and 90% Steam

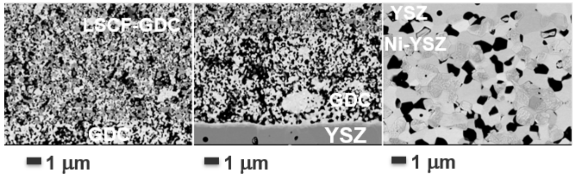
Post-test analyses revealed no new degradation mechanisms compared to 1000, 3000, 6000 hours cells



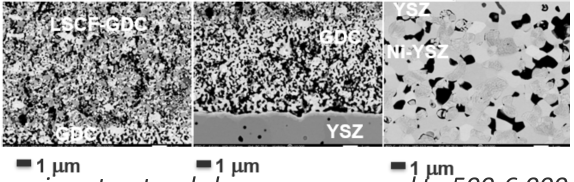
*Degradation rate **after** initial break-in period **-0.27±1.00 %/kh** in 50% steam and **0.17±0.45 %/kh** in 90% steam*

- Multiple SOEC button cells (3 repeats) were tested near or below thermoneutral voltage, 1.2-1.3 Volt, at 750°C in both 50% and 90% steam vs air
- Based on EIS data, initial degradation is due to an electrodic resistance increase
- Stable performance over the following 11,000 hours
- Ohmic losses and OCV did not change during testing

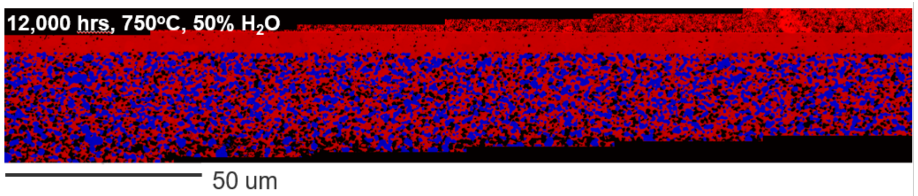
750°C, 50% H_2O, 1.3 V

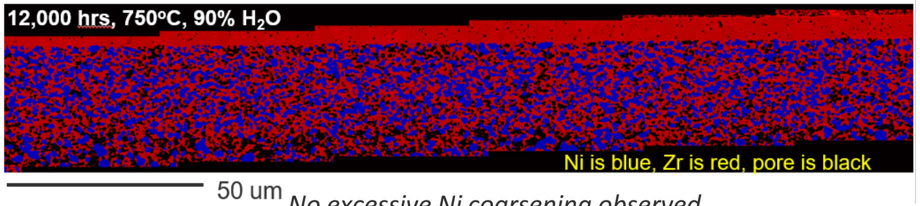


750°C, 90% H_2O, 1.2 V (i=0.7 A/cm²)



No microstructural changes compared to 500-6,000 hrs cells

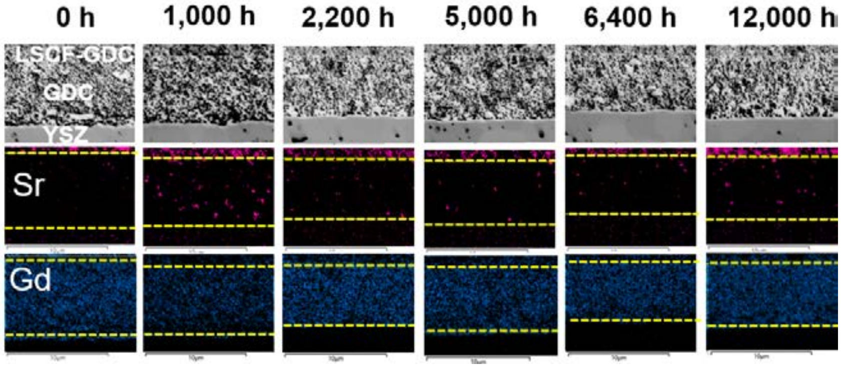




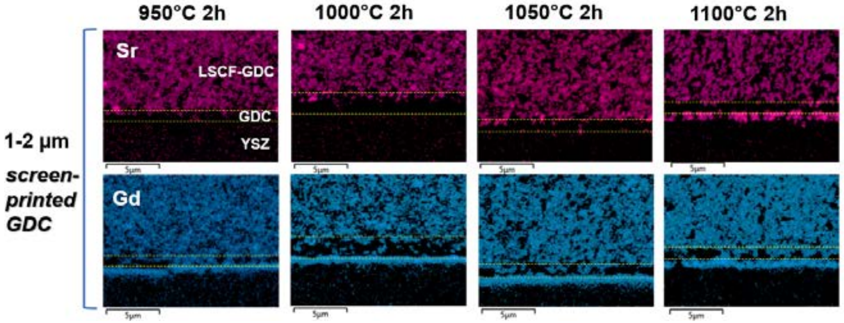
No excessive Ni coarsening observed

Accomplishments and Progress:
Identified Factors to Mitigate Sr and Ce/Gd Migration and Improve SOEC Durability

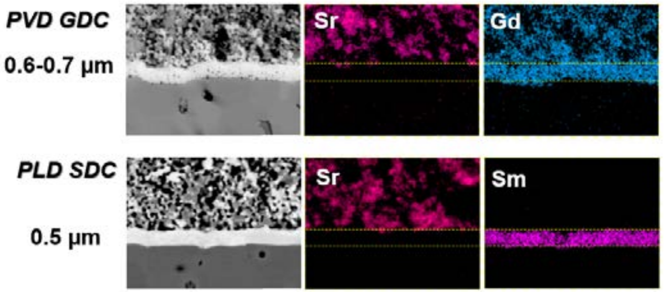
No change in Sr migration and Ce/Gd reactivity with YSZ during SOEC testing at 750°C for up to 12,000 hours



- To increase SOEC performance and operation life, a comprehensive study of Sr and Ce/Gd migration into YSZ by varying the barrier layer fabrication approaches and thicknesses was completed
- Sr migration and $SrZrO_3$ formation was evaluated vs varied thickness and density of GDC and LSCF sintering temperature
- Dense thin GDC films were effective in blocking Sr migration



With a porous barrier layer, Sr migration during electrode fabrication increases with increasing LSCF sintering temperature and decreasing barrier thickness

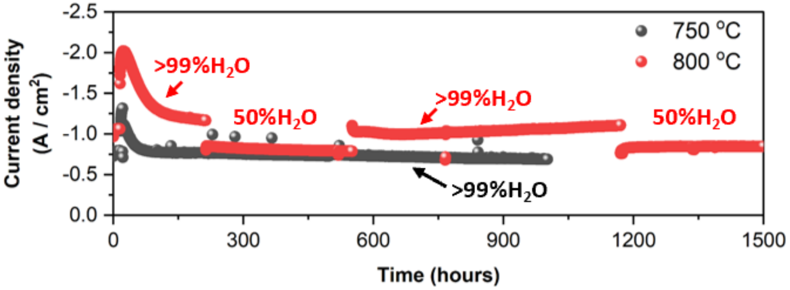


With a dense barrier layer, no Sr migration observed.

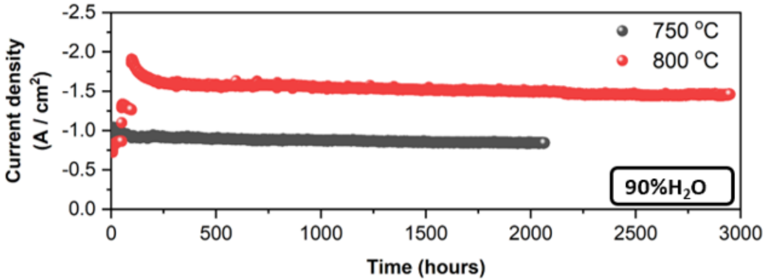
No Gd/Ce interdiffusion occurs after co-firing with LSCF at 1000°C

Accomplishments and Progress: Completed AST Durability Tests in 95-99% Steam, 1.3-1.7 V, 750 and 800°C for up to 3000 hrs, and Dynamic Cycling

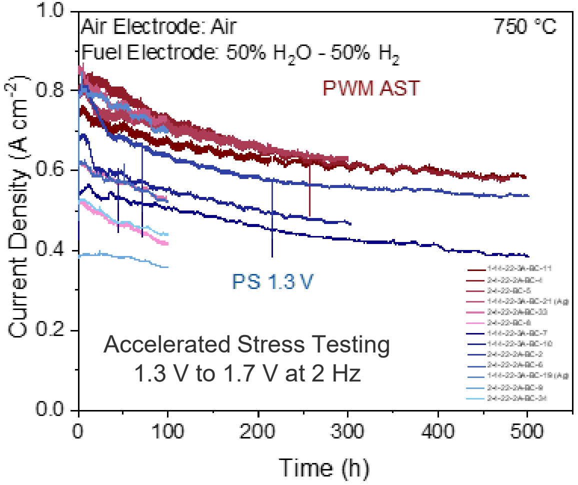
Unexpected H_2 loss will not cause irreversible cell failure during SOEC operation at 750-800°C



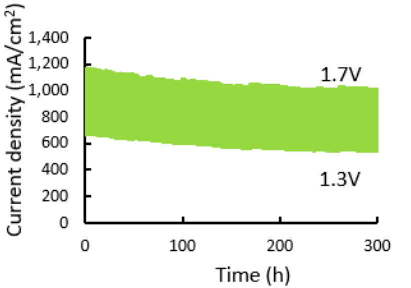
- AST development utilizing
  - higher steam content
  - applied voltages
  - rapid voltage cycling (pulse width modulation)
  - thermal cycling and steam content cycling

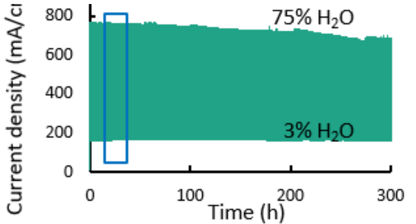


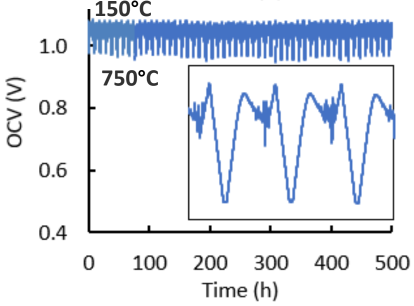
Developing AST using pulse width modulation and dynamic operation



SOEC operation is compatible with intermittent electricity sources, steam content fluctuations

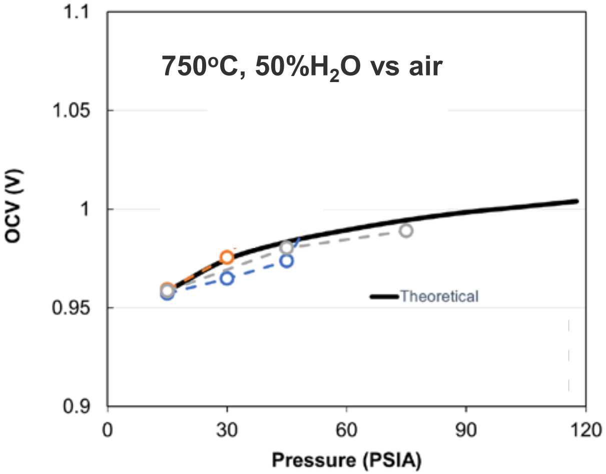


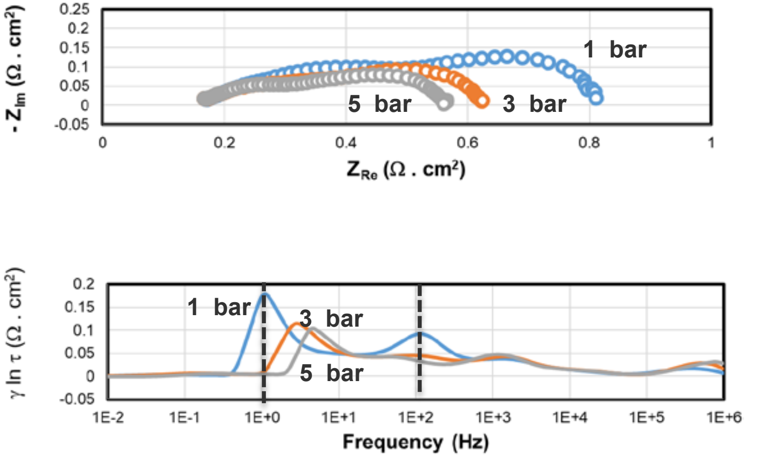




Accomplishments and Progress: Demonstrated SOEC Operation Under Elevated Pressure

High pressure operation offers opportunities for H_2 cost reduction



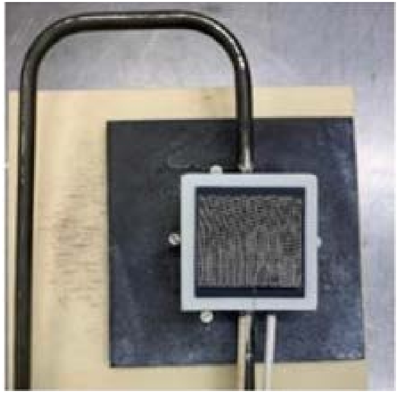


Pressurized button cell

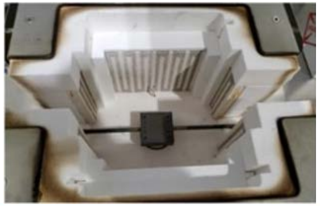
- SOEC performance increases with pressure (tested at 750°C, 1-5 bar)
- Low frequency (mass transport) and mid-frequency (diffusion) processes are suppressed
- Long-term tests to be performed

Accomplishments and Progress:
Cell Scaleup and Large Size Cell Testing Capability Development

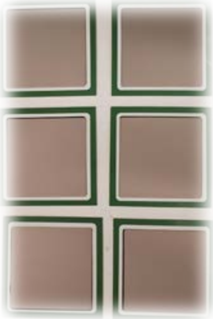
Larger format cell testing needed

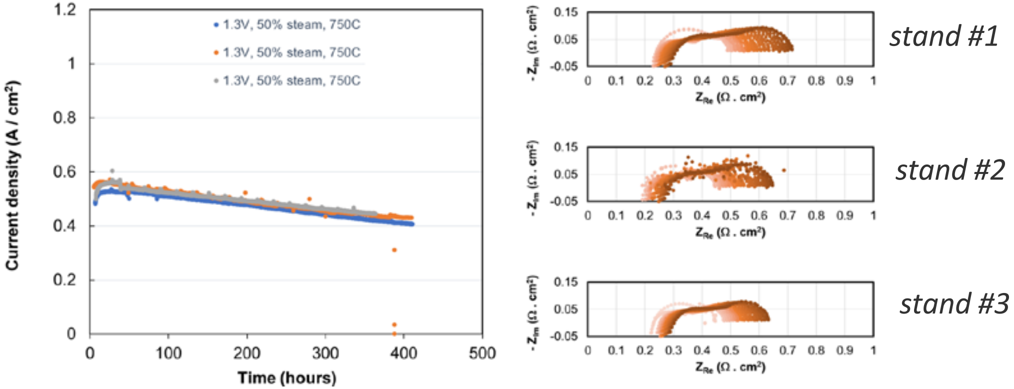


Cell sealing



- 5 cm x 5 cm cell test stands are being commissioned at multiple labs
- Baselining using commercial manifolds
- Benchmarking cell testing without and with metal interconnects





Comparing cell performances in 3 different test stands at 1.3 V in 50% steam at 750^{o}C

High Temperature Electrolysis (HTE)

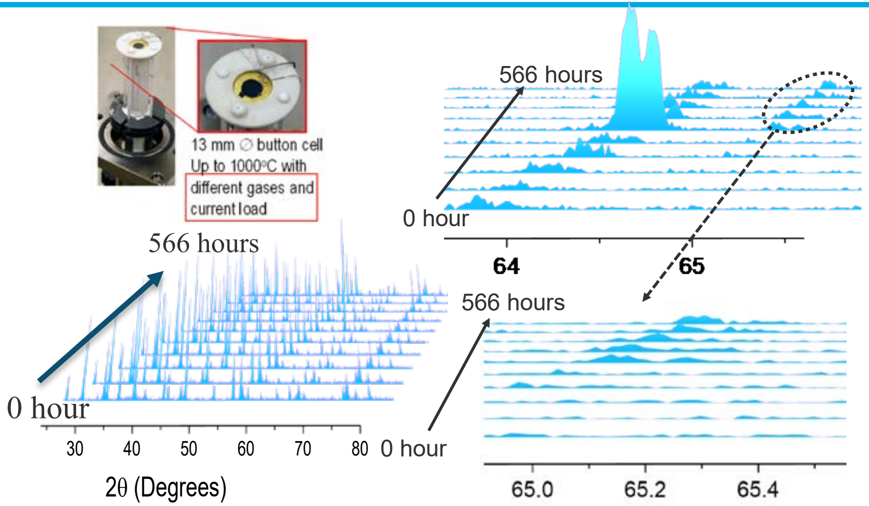
Task 7: Advanced Characterization
(more content in AMR Poster P196e and p196f)

Accomplishments and Progress: Advanced Diagnostic Development

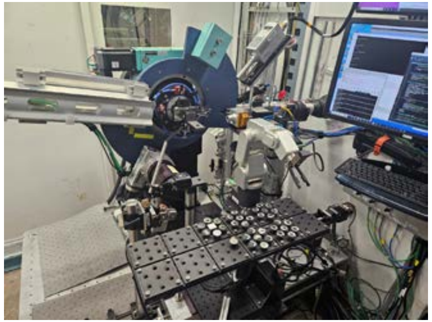
Operando HT XRD, High throughput XRD

Novel in-situ diagnostics allow for real time evaluation of structural changes

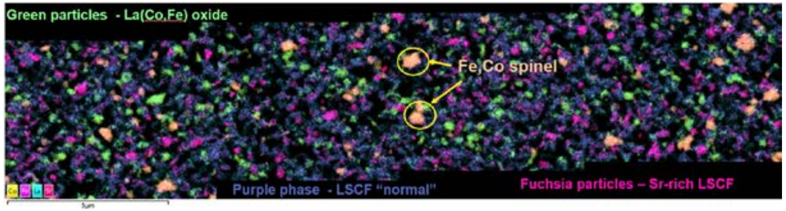
- LSCF-GDC oxygen electrode stability was evaluated using *operando* High Temperature XRD
- Co/FeOx phase developed in LSCF during SOEC operation was detected in real time
- Consistent with post-test ex situ SEM/EDS analysis and Fe, Co spinel formation



XRD collected at 750°C at 1.3 V in 40% steam in hydrogen



Developing a high-throughput XRD robot capable of testing 80 button cells per day



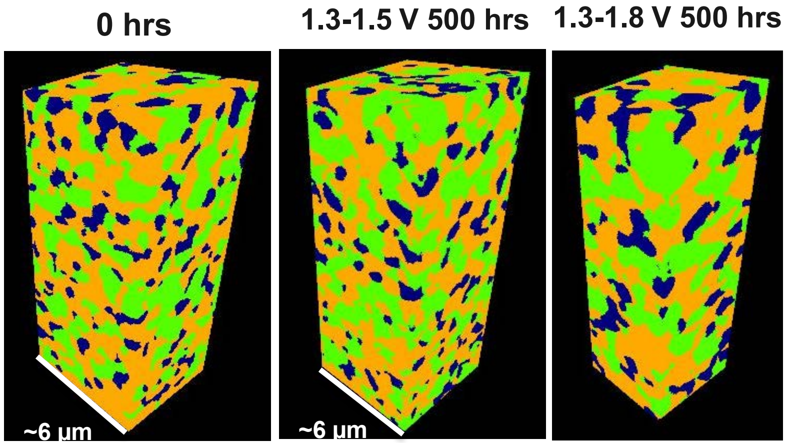
Post-test SEM/EDS shows Fe,Co spinel presence in LSCF

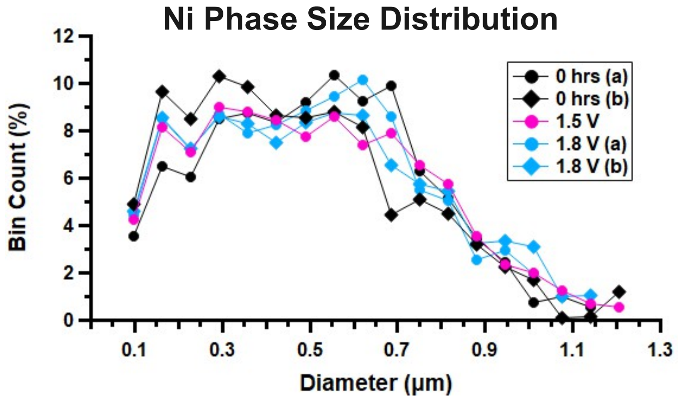
Accomplishments and Progress: Nano CT studies of Ni:YSZ H_2 electrode

Ni in YSZ electrode potentially susceptible to coarsening/migration, negatively impacting performance

- Cells stepped from 1.3 to 1.5 and 1.8V (1 min hold at each voltage) for 500 h (50% steam, 750C)
- Nano CT allows comparison between aged and pre-test samples
- TPB, Ni, Pore, and YSZ characteristics can be determined
- No indication of Ni migration/coarsening following voltage cycling for 500 hours

ID	**TPB Density (µm/µm³)**	**Ni %, Size, & Connectivity**	Pore %, Size, & Connectivity	YSZ %, Size, & Connectivity
0 hrs (2)	**3.3**	**32.3%; 493 nm; 99.3%**	15.1%; 380 nm; 85.7%	52.6%; 559 nm; 99.9%
1.5 V	**3.3**	**36.3%; 514 nm; 99.6%**	13.4%; 361 nm; 82.6%	50.3%; 524 nm; 99.9%
1.8 V (2)	**3.7**	**34.3%; 503 nm; 99.1%**	15.6%; 397 nm; 91.5%	50.1%; 523 nm; 99.9%





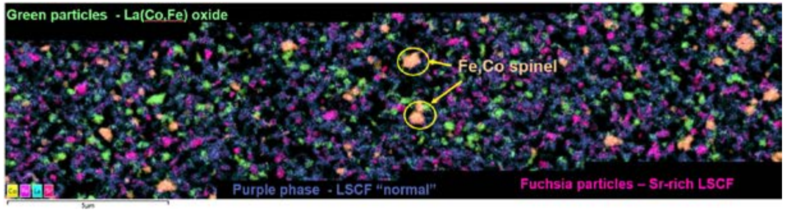
High Temperature Electrolysis (HTE)

Task 8: Multiscale Modeling
(more content in AMR Poster P196g)

Accomplishments and Progress: Modeling Performance and Stability for LSCF

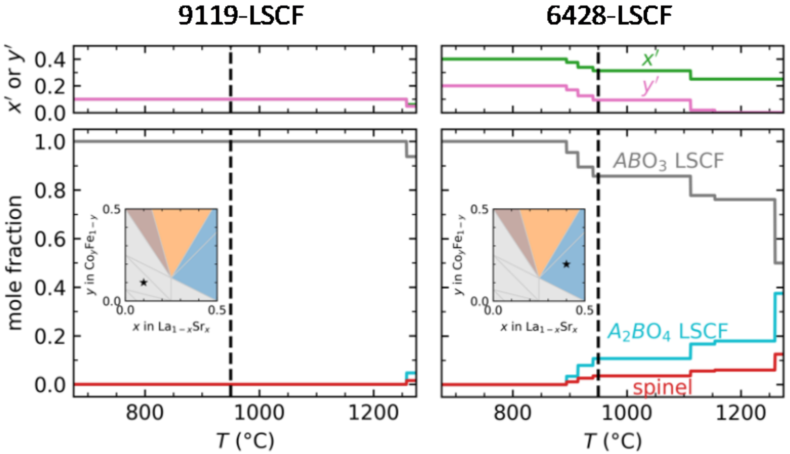
Experiments show formation of secondary phases in LSCF electrode

- DFT predicts that decreased Sr in nominal LSCF can substantially improve durability at high T and low pO_2 but at the expense of oxygen transport, suggesting an optimal composition
- Higher T, lower pO2 promote LSCF decomposition to spinel, Ruddlesden-Popper phases in 6248-LSCF but not in 9119-LSCF
- Correlation between experiment and modeling has been shown, but needs further effort



Post-test SEM/EDS shows Fe,Co spinel presence in LSCF

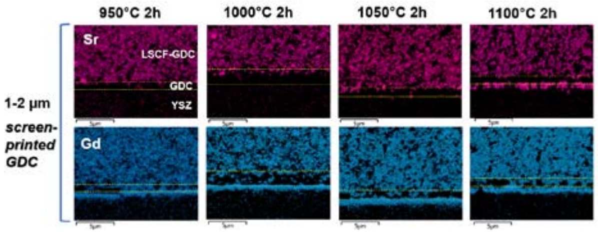
$$La_{1-x}Sr_xCo_yFe_{1-y}O_3 \rightarrow La_{1-x'}Sr_{x'}Co_{y'}Fe_{1-y'}O_3$$
$$+ Co_3O_4 + La_{0.5}Sr_{1.5}Co_{0.25}Fe_{0.75}O_4 \ (+ O_2)$$

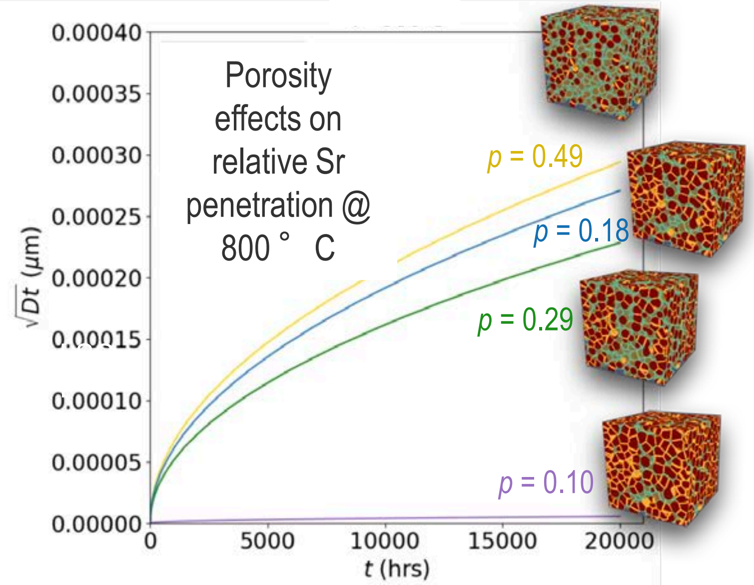


Accomplishments and Progress: Predicting critical thresholds for Sr permeation and growth of $SrZrO_3$

Formation of $SrZrO_3$ is detrimental to cell performance and durability

- Mesoscale simulations predict
  1) critical porosity that can suppress fast Sr diffusion channels
  2) growth rates of Sr-containing phases
- Open pore channels for fast Sr diffusion form at higher porosities ($p \gtrsim 0.18$) but close off below a percolation threshold of $p \lesssim 0.1$. Barrier layer film densification should help mitigate degradation.
- Results consistent with experimental findings



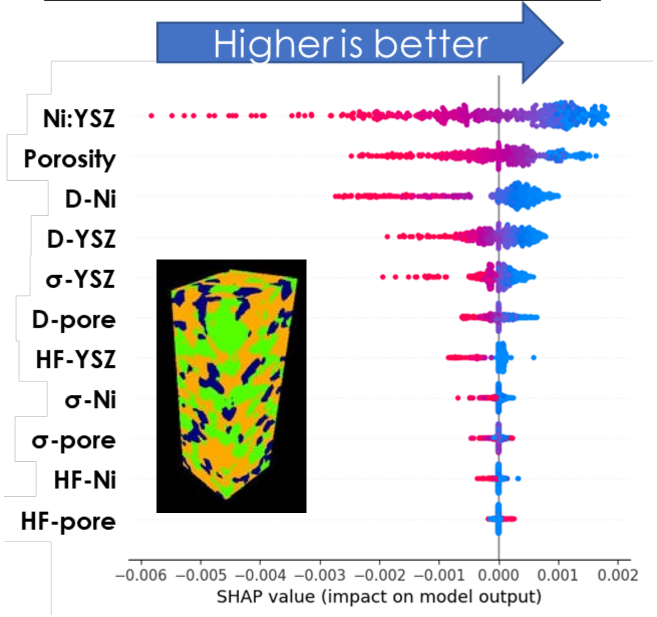


Accomplishments and Progress: Ni-YSZ Electrode Coarsening Simulations

Ni susceptible to coarsening, negatively impacting performance

- Performance degradation due to electrode coarsening was simulated for over 500 cells with different steam electrode microstructures varying over 11 dimensions (e.g., porosity, Ni/YSZ particle size, particle size distribution, phase fraction distribution, etc.)
- Machine learning analysis reveals impact of Ni-YSZ electrode microstructural features on lifetime performance for electrode coarsening simulations over 1000 h at 800 C at 1.3 V
- Simulation data used to suggest changes in baseline microstructures to increase lifetime performance
- Efforts underway to correlate modeling results with experiments

Impact on Lifetime H_2 Produced [kg/cm²/khr]



D = particle/pore size, σ = Particle size distribution

HF = Heterogeneity (Phase fraction distribution)

Ni:YSZ = Ni to YSZ phase ratio

Responses to Previous Year Reviewers' Comments (FY23)

- Several comments regarding novel materials development, collaborations, and H2NEW core lab focus were made including: "new catalyst (TiO2 supported catalyst) and thinner membrane (e.g., Gore 80 micro membrane) are not included", "Incorporation of new and emerging materials is valuable and expected to happen soon", "collaboration with the industry is weak at this time", "The project is still performed solely by national laboratories, so industry participation is largely missing"
  - **We agree with these statements and are happy with the recent announcements for BIL FOA 2922 Topic 2 and Topic 3 Awardees as well as Lab Call (DE-LC-0000022) that we expect this situation to improve significantly over the next year (plus). Where we increase H2NEW engagement with industry and academics and leverage the novel materials development work funded through these awards that have been outside the core H2NEW scope. We expect added challenges with interactions and coordination, but have spent much of the past few years, preparing to support these efforts and integrate/ synergize them with core H2NEW efforts.**
- There were a couple of comments regarding the synergies and leverage between low temperature and high temperature electrolysis approaches: "LTWE and high-temperature water electrolysis (HTWE) are quite different in terms of materials, approaches, and technology readiness levels (TRLs). Therefore, it is not logically reasonable to combine them into one presentation. They can be split into two different projects or presentations.", "the project can be divided into two projects, LTWE and HTWE, which can be presented separately."
  - **We agree the materials challenges and technical focus of the different topic areas are distinct and could be presented separately, but we find high synergy between topical areas: PEM, LAWE and O-SOEC and have leveraged learnings in each area to another. Having distinct and separate activities could potentially impact this type of beneficial communication.**
- A few comments related to progress, objectives, and prioritization: "Significant progress has been made. However, because of the large amount of information and many details given in the presentation, it is difficult to assess the effect of the accomplishments/progress toward the project and DOE goals.", "The priority for the different project activities is not well defined. It appears that activities/focus areas have been selected based on expertise at national laboratories."
  - **Presenting on the vast effort of H2NEW is challenging and conveying succinctly the rationale for focus in an AMR presentation is challenging. We have tried to expand upon this with the development of a Figure of Merit to help clarify progress towards DOE goals and with increased content along these lines in the supporting posters for H2NEW. H2NEW leadership and HFTO continuously review focus and priorities within (LAWE, PEM and O-SOEC) research thrusts. Going forward the core H2NEW lab efforts will be balanced with those of FOA awardees in this regard. While activities/focus areas leverage expertise at National Labs, the focus of H2NEW is progress towards DOE goals and targets.**

DEIA/Community Benefits Plans and Activities

- H2NEW core labs do not currently have DEIA/Community Benefits Plans, but FOA awarded projects are expected to and H2NEW core labs have significant DEIA efforts
  - UPR PIRES RENEW Project – NREL hosted 4 students and 2 faculty members from Puerto Rican Universities in the summer of 2023 (continuing in 2024 and 2025)
  - Mentoring/Support of efforts of MSI faculty including – Chris Rhodes (Texas St), Lisandro Cunci (UPR – Rio Piedras), Abel Chuang (UC-Merced)
  - Recruited Graduate Education Minority (GEM), Student Trained in Applied Research (STAR), and Science Undergraduate Laboratory Internship (SULI) summer interns to work at NREL
  - Mentored graduate students, postdocs, and early career researchers to chair conference sessions
  - Seminar at Florida International University and talked to students about durability of polymer electrolyte water electrolyzers. Plans to visit more MSIs to give talks about hydrogen and recruit students.
  - LANL hosted 2 summer students from UT- Rio Grande Valley working on Liquid Alkaline Water Electrolysis.
  - Argonne recruited minority SULI Summer students. Argonne has initiated a joint appointment with a University of Illinois – Chicago professor – UIC is an MSI
  - Posted open positions to society job boards to attract diverse applicant pool (NSBE, AWS, AABE, NAAAP)

RENEW PIRES Project Poster Session (NREL, July 2023)

UT-RGV summer students (LANL, summer 2023)

HTE In-Person Meeting PNNL, March 4-6, 2024

LTE In-Person Meeting Napa, CA, February 21-23, 2024

Remaining Challenges/Proposed Future Work (LTE) (Refer to P149a,b,c,d & h for more detail at Task Level)

Task 1 (Durability): Aging Studies; Mitigation Strategies; Ex-situ Characterization of MEAs/components/interfaces; Ex-situ Catalyst Durability; Ex-situ Membrane Durability; Accelerated Stress Test Development

Task 2 (Performance): Performance benchmarking, baselining, validation; Cell performance testing in support of electrode development; Ex-situ studies focused on performance factors; Cell level model development

Task 3 (Scale-up): MEA fabrication, Interface engineering (inks, electrodes, cell integration and interfaces); Components (porous transport layers, recombination layers)

Task 3c (Analysis): Performance, manufacturing, and system models; Durability factors; Energy system integration

Task 9 (Alkaline): Fundamental degradation mechanisms, AST development, Benchmarking, Baselines, Modeling, Scale-up

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

Remaining Challenges and Barriers (HTE)

(Refer to P196e,f & g for more detail at Task Level)

Task 5: Durability Testing and AST Development

1. SOEC materials and component degradation mechanisms are the result of multiple, coupled phenomena derived from operating conditions and a comprehensive and accurate understanding of the interplay of these phenomena remains to be established
2. Larger planar cell test stand capacity is needed to fully understand cell degradation phenomena

Task 6: Task Integration and Protocol Validation

1. H2NEW is generating large volumes of data that require review, validation, and interpretation

Task 7: Advanced Characterization

1. In-operando testing is needed to reduce the number of test samples and to expedite AST outcomes

Task 8: Multiscale Modeling

1. Defining and modeling the mechanisms requires the combined talents, experience and capabilities of each of the Lab Consortium
2. Degradation processes at the YSZ|GDC|LSCF-SDC interface are probably coupled in a non-linear fashion

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

Collaboration and Coordination

NREL Team Members: Shaun Alia, Alex Badgett, Carlos Baez-Cotto, Guido Bender, Isabell Berry, Sarah Blair, Eric Boerner, Joe Brauch, Ai-Lin Chan, Huyen Dinh, Dave Ginley, Radhika Iyer, Sunil Khandavalli, Scott Mauger, Samantha Medina, Woo Yeong Noh, Elliot Padgett, Makenzie Parimuha, Chance Parrish, Bryan Pivovar, Elias Pomeroy, Cheryl Reuben, Robin Rice, Daniela Ruiz, Meital Shviro, Sarah Shulda, Lauren Sittler, Chris Skangos, Colby Smith, Jennifer Sosh, Sam Ware, Jacob Wrubel, James Young, Jason Zack, Diana Zhang

INL Team Members: Richard Boardman, Micah Casteel, Dong Ding, Josh Gomez, Jeremy Hartwigsen, Nick Kane, Fred Steward, Lucun Wang, Daniel Wendt, Wie Wu

LBNL Team Members: Grace Anderson, Claire Arthurs, Anyka Bergeson-Kreller, Ashley Bird, Hanna Breunig, Ethan Crumlin, Arthur Dizon, , Ramachandra Gawas, Elizabeth Greenberg, Rebecca Hamlyn, Jason Keonhag Lee, Doug Kushner, Ahmet Kusoglu, Grace Lau, Eric Lees, Tamim Mohammed, Rangachary Mukundan, Xiong Peng, Paul Rudnicki, Michael Tucker, Guanzhi Wang, Adam Weber

PNNL Team Members: Jie Bao, Seraphim Belko, Chris Coyle, Dan Edwards, Julian Escobar, Michael Fuller, Jamie Holladay, Surendra Karki, Long Le, Tian Liu, Olga Marina, Matt Olszta, Sangbong Ryu, Lorraine Seymour, Renaldo Springer, Dewei Wang

ANL Team Members: Frederick Agyapong-Fordjour, Rajesh Ahluwalia, Chris Arges, Ronald Emmons, Luke Johnson, Nancy N. Kariuki, Samuel J. Kazmouz, A. Jeremy Kropf, Zhao Li, Di-Jia Liu, Debbie Myers, Kaline Nascimento da Silva, Pietro Papa Lopes, Dennis Papadias, Jae Hyung Park, Jui-Kun (Michael) Peng, Matt Sweers, Jiaxin Wang, Xiaohua Wang, Xiaoping Wang

ORNL Team Members: David Arregui-Mena, Dave Cullen, Flavio Dal Forno Chuahy, Neus Domingo, Tomas Grejtak, Xiang Lyu, Shawn Reeves, Alexey Serov, Todd Toops, Hanyu Wang, Haoran Yu, Michael Zachman

LANL Team Members: Tanvir Arman, Sergio Diaz-Abad, Kaustubh Khedekar, Yu Seung Kim, Siddharth Komini Babu, Daniel Leonard, Kui Li, Yuanchao Li, Sandipkumar Maurya, Jacob Spendelow

LLNL Team Members: Sourav Chatterjee, Tae Wook Heo, Kaihua Ji, Jonas Kaufman, Namhoon Kim, Kyoung Kweon, Andrew Rowberg, Brandon Wood, Henry Yu

NETL Team Members: Harry Abernathy, William Epting, Yinkai Lei, Tianle Cheng, Tao Yang, Fei Xue, Greg Hackett

NIST Affiliate Team Members: Michael Daugherty, Daniel Hussey, David Jacobson, Jacob LaManna

SLAC: Nick Strange

University Collaborators: Jayson Foster, Svitlana Pylypenko (PI), Lonneke van Eijik, Max Shepherd, Genevieve Stelmacovic, Brian Gorman (CSM); Kara Ferner, Shawn Litster (PI), Fausto Pasmay (CMU); Devashish Kulkarni, Jack Todd Lang, John Stansberry, Cliff Wang, Iryna Zenyuk (PI) (UCI); Scott Barnett, Peter Voorhees (NU), Xiao-Dong Zhou (UL-L), Paul Salvador (CMU), William Kent (CMU)

ASTWG Collaborators: Kathy Ayers (Nel Hydrogen), Nemanja Danilovic (Electric Hydrogen), Corky Mittelsteadt (Plug Power), Andrew Park (Chemours), Udit Shrivastava (Cummins), Andrew Smeltz (De Nora)

Other Partnerships and Collaborations: MIT, B. Khaykovich; FZ Jülich, Germany; Fraunhofer ISE, Freiburg, Germany; Paul Scherrer Institute, Aargau, Switzerland, IEA Annex 30 Working Group; Gen-IV International Forum for Hydrogen Production (Canada, France, Japan, England, United States)

Summary

- Significant science advances within H2NEW since inception
  - Establishment of capabilities (staff/facilities)
  - Execution of R&D scope
- Significant expansion in 2023 tied to Bipartisan Infrastructure Law (BIL) funding
  - Expansion of PEM and O-SOEC scope
  - Addition of LAWE as a R&D area
- HFTO FOA 2922 and Lab Call DE-LC-0000022 to leverage H2NEW assets and expand scope of efforts to date – novel materials development and supply chain considerations in particular.

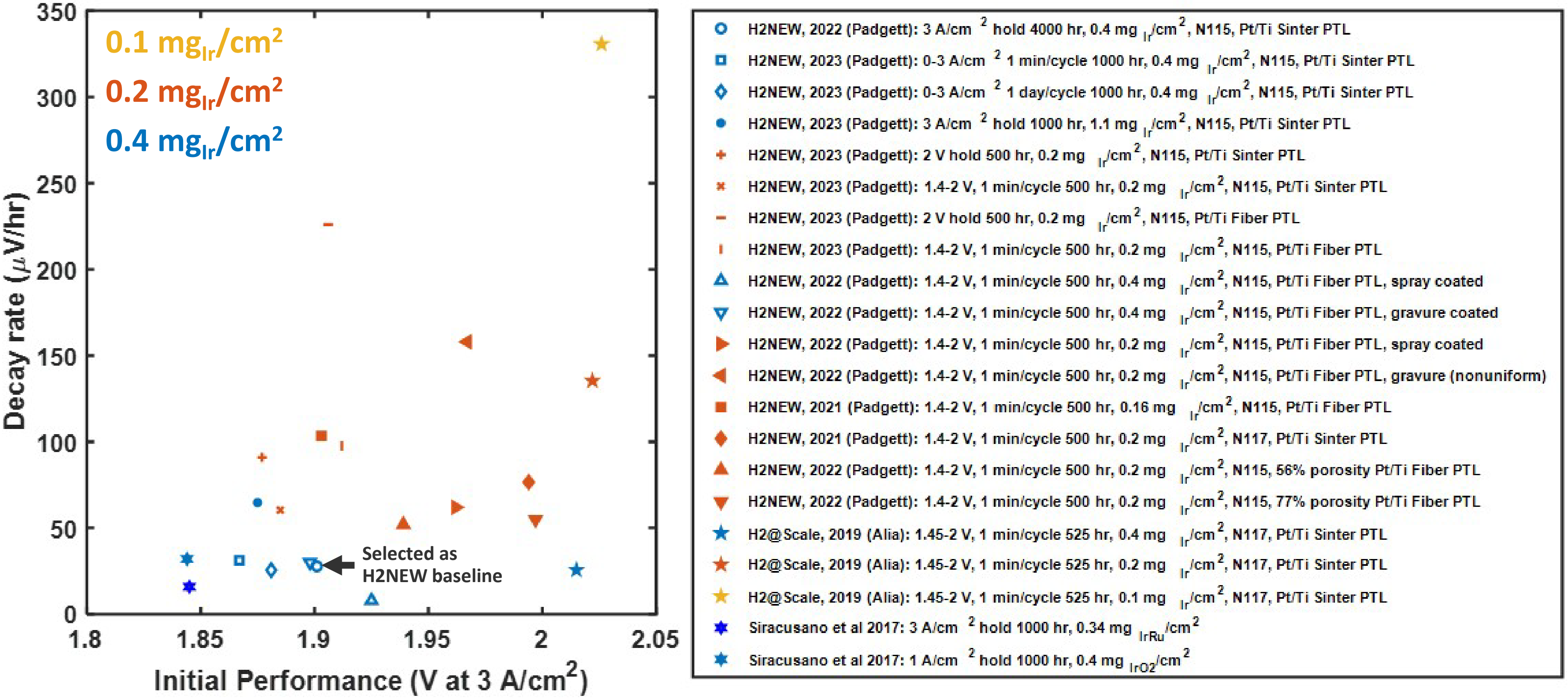
Technical Backup and Additional Information Slides

Technology Transfer Activities

- All H2NEW laboratories are actively engaged with industry both within and outside of the consortium partners and seek to provide H2NEW developed technology and knowledge to help the electrolysis community
  - Including CRADAs, SPPs, TSAs, etc.
- Engagement through Stakeholder Advisory Boards seek to determine areas of most benefit and highest commercial interest
- High pressure PEM hardware design published: DOI 10.7799/2205626: https://data.nrel.gov/submissions/223
- H2NEW website
  - https://h2new.energy.gov/
- Upcoming engagement with HFTO FOA 2922 and Lab Call (DE-LC-0000022) awardees

Figure of Merit: H2NEW And Literature Comparison

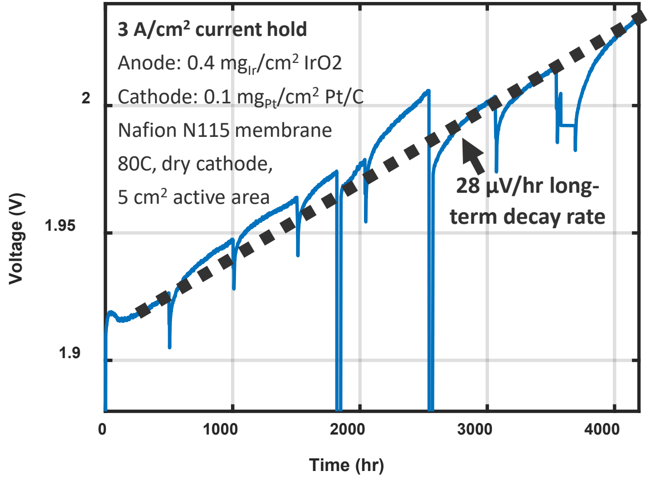
Survey of H2NEW durability testing and literature results with complete enough data reported for figure of merit comparison:



Selection of Baseline Test for H2NEW Figure of Merit

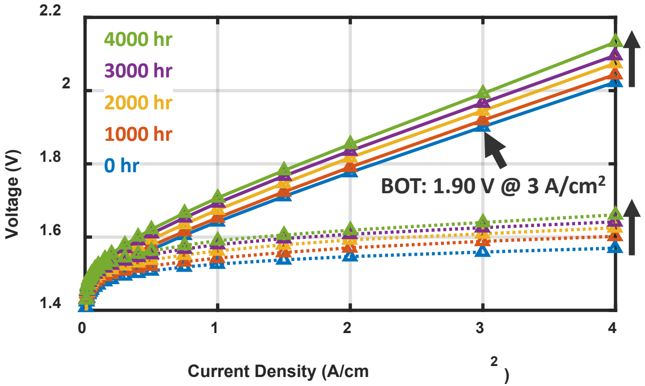
Baseline selected: 4000 hr durability test run with conditions matching DOE interim targets (3 A/cm^2, 0.5 mg$_{PGM}$/cm^2: 0.4 mg$_{Ir}$/cm^2 anode, 0.1 mg$_{Pt}$/cm^2 cathode) and H2NEW FuGeMEA cell configuration. Steady-state test condition is representative of established electrolyzer applications and comparable to more published literature.

Long-term test enables measurement of steady decay rates after initial variability and conditioning effects. Test included thorough impedance diagnostics to support analysis of degradation mechanisms.



3 A/cm^2 current hold
Anode: 0.4 mg$_{Ir}$/cm^2 IrO2
Cathode: 0.1 mg$_{Pt}$/cm^2 Pt/C
Nafion N115 membrane
80C, dry cathode,
5 cm^2 active area

28 µV/hr long-term decay rate

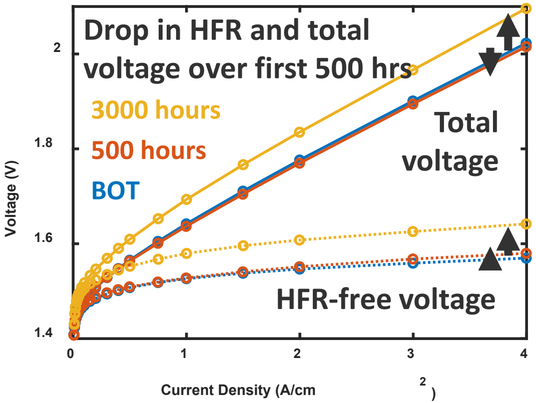


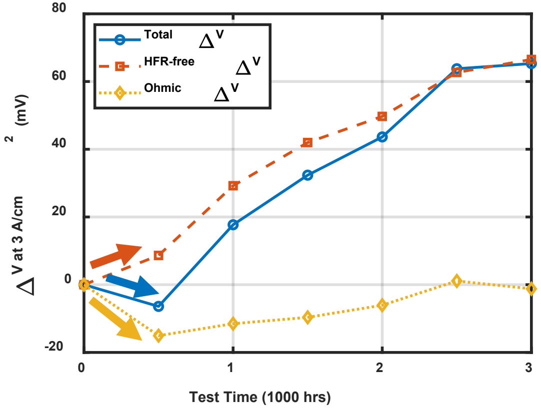
BOT: 1.90 V @ 3 A/cm^2

Figure of Merit Methodology Considerations

Consideration for figure of merit design and baseline result selection:

- Overall cell voltage is a key factor in efficiency, capturing performance of multiple components and cell integration.
- HFR-free voltage decay rate primarily tracks anode catalyst degradation.
- Overall voltage decay rate includes other processes:
  - Membrane creep (can cause voltage decrease)
  - Membrane poisoning or degradation
  - Interface and electrode resistances
- Conditioning effects are significant in the first several hundred hours, making testing beyond 500 hours ideal for measuring long-term decay trends.





Presentations (LTE)

243rd ECS Meeting, Boston, MA May 28th – June 2nd, 2023

- A. Dizon, E. Padgett, A. Adesso, J. A., R. Mukundan, B. S. Pivovar, S. M. Alia, and A. Z. Weber, " Mathematical Modeling of the Performance-Degradation Mechanisms of Cation-Contaminated Proton-Exchange-Membrane Water Electrolysis"
- G. Stelmacovich, L. van Eijk, M. Walker, D. A. Cullen, S. Ware, J. L. Young, G. Bender, and S. Pylypenko, "Optimization of Time-of-Flight Secondary Ion Mass Spectrometry for Analysis of Porous Transport Layers"
- D. Arregui-Mena, D. A. Cullen, N. Domingo Marimon, G. Stelmacovich, S. Pylypenko, S. Ware, and G. Bender, "Electron Microscopy Investigation of Porous Transport Layer Coatings"
- C. Liu, J. A. Wrubel, E. Padgett, and G. Bender, "Effects of Porous Transport Layer Coating Inhomogeneities on PEM Water Electrolyzer"
- (Invited) G. Bender, S. Ware, T. Schuler, Z. Kang, and J. L. Young, "Effects of PTL Coating Thickness on PEM Water Electrolyzer Performance"
- E. Padgett, A. Adesso, J. A. Wrubel, B. S. Pivovar, and S. M. Alia, "Performance Losses and Recovery from Cation Contaminants in PEM Water Electrolysis"
- N. N. Kariuki, D. J. Myers, J. H. Park, X. Wang, and R. Ahluwalia, "Potential Dependence of Ir Dissolution Using Time-Resolved Measurements"
- D. J. Myers, B. S. Pivovar, R. Mukundan, S. M. Alia, G. Bender, S. A. Mauger, S. Komini Babu, A. Serov , A. Badgett, and R. Ahluwalia. "(Invited) Recent Polymer Electrolyte Membrane (PEM) Electrolysis Research Advances in the Hydrogen from Next-Generation Electrolyzers of Water (H2NEW) Consortium"
- J. Foster, X. LIU, E. Creel, J. Li, H. Yu, D. A. Cullen, N. N. Kariuki, J. Park , D. J. Myers , A. Serov, and S. Pylypenko. "Investigation of Surface Chemistry of Pemwes Iridium Oxide Catalyst Layers as a Function of Ink Aging Time"
- A. Serov, X. Lyu, E. Creel, H. Yu, D. A. Cullen, N. N. Kariuki, J. Park, D. J. Myers, R. Rice, E. Padgett, S. A. Mauger, G. Bender, J. Foster, and S. Pylypenko. "(Invited) Catalysts, Inks and Electrodes for PEM Water Electrolysis: Scalable Approach for Highly Performed Catalyst Layer Fabrication"

Fall ECS Meeting, Gothenburg, Sweden, October, 2023

- Kaustubh Khedekar, Kui Li, Ryan Gebhardt, Andrew Park, Rod L. Borup, and Siddharth Komini Babu. "Fundamentals of Gas Permeation in PEM Water Electrolyzers Operated at High Pressures"
- Kui Li, Kaustubh Khedekar, Mahlon Wilson, Jacob S. Spendelow, and Siddharth Komini Babu. "Enhancing Durability of Polymer Electrolyte Membrane Water Electrolyzer through Incorporation of Gas Recombination Catalyst in Membrane"
- S. M. Alia, A. L. Chan, S. Medina, K. S. Reeves, H. Yu, D. A. Cullen, J. Park (Argonne National Laboratory), N. N. Kariuki, A. J. Kropf, and D. J. Myers, "Materials Mitigation Strategies and Anode Catalyst Durability in Low Temperature Electrolysis"
- J. A. Wrubel, S. Ware, J. L. Young, E. Padgett, L. Hu, R. Rice, and G. Bender, "Understanding Porous Transport Layer Structure-Property-Performance Relationships in PEM Water Electrolyzers"
- (invited) D.A. Cullen, H. Yu, J.D. Arregui-Mena, E. Padgett, S. Alia, G. Bender, S.K. Babu, R. Mukundan, "Electron Microscopy Investigation of Electrolyzer Degradation." 244th ECS Meeting, October 8-12, 2023, Gothenburg, Sweden
- Uekert, T., Wikoff, H. M., & Badgett, A. Electrolyzer and Fuel Cell Recycling for a Circular Hydrogen Economy. Advanced Sustainable Systems, n/a(n/a), 2300449. doi:https://doi.org/10.1002/adsu.202300449 - Note that this work was not funded by H2NEW but did collaborate with H2NEW researchers.
- (invited talk) A. Kusoglu. "Electrochemical Characterization of Catalyst/Ionomer Interfaces"
- (invited talk) R. Mukundan. "Importance of Accelerated Stress Tests in Accelerated Discovery of Energy Materials"

Presentations (LTE)

2023 AIChE Annual Meeting, Orlando, FL, December 2023

- Siddharth Komini Babu, Tanvir Arman, Sergio Diaz Abad, Abdurrahman Yilmaz, Jacob LaManna, Daniel S. Hussey, Jacob S. Spendelow. "Novel Porous Transport Layers for Polymer Electrolyte Membrane Water Electrolyzers" Invited
- E. W. Lees, A. T. Bell, A. Z. Weber, "Modeling the Effect of Material Properties on Liquid Alkaline Water Electrolyzer Performance", 2023 AIChE Annual Meeting, Orlando FL, November 6th, 2023.

Telluride Science Research Center (TSRC) Workshop; PGM and PGM-free Electrocatalysts: Oxygen and Hydrogen Evolution Catalysts, Telluride, Colorado, March 19, 2024

- D Myers, N Kariuki, J H Park, X Wang, A Star, R Ahluwalia, D Cullen, and H Yu, "Understanding the Potential Dependence of Ir Dissolution from IrO2 PEM Electrolyzer Anode Catalysts Through Modeling of Time-Resolved Measurements,"

18th Topical Conference on Quantitative Surface Analysis, Portland, OR, November 2023

- Foster, J., Lyu, X., Padgett, E., Mauger, S., Serov, A., Pylypenko, S., X-ray Photoelectron Spectroscopy Analysis of PEMWE Catalyst Layers with Focus on Catalyst-Ionomer Interface, Poster

FY23 NREL Energize Forum

- Alex Badgett, "Decarbonization of the electric power sector and implications for low-cost hydrogen production from water electrolysis".

Microscopy and Microanalysis Meeting, July 23-27, 2023 St. Paul, MN

- M.J Zachman, A.N. Williams, L.F. Kourkoutis, D.A Cullen. "Cryogenic FIB and (S) TEM for Energy Storage and Conversion Materials Research"

EFCF 2023 Low-Temperature Fuel Cells, Electrolysers & H2 Processing, Lucerne, Switzerland, July 7, 2023

- (Invited, Keynote) Debbie J. Myers and David A. Cullen, "Advances in the Characterization of Low-Temperature Fuel Cell and Electrolyzer Catalysts and Electrodes."

Presentation to Johnson Matthey Technical Center, September 28, 2023

- (Invited) Debbie J. Myers and David A. Cullen, "Advances in the Characterization of Low-Temperature Fuel Cell and Electrolyzer Catalysts and Electrodes".

Second Gigaton Hydrogen Workshop in Tokyo, Japan

- Alex Badgett, "Hydrogen at the Gigaton Scale: Framing Materials, Resource, and R&D Opportunities" 2023.

Florida International University, Seminar

- R. Mukundan. Durability of PEM Fuel Cell and Electrolyzer Materials.

4th International Conference on Electrolysis (ICE 2023), Sun City, South Africa, September 1, 2023

- (invited) R. Mukundan. *Durability of Polymer Electrolyte Membrane (PEM) Water Electrolyzers*

Global HyPT Kickoff, Tempe AZ, February 12, 2024

- B. Pivovar. *H2@Scale and H2NEW*

40th Swiss Electrochemsitry Symposium, Aarau, Switzerland, April 17, 2024

- (invited) B. Pivovar. *Challenges in Getting Low Temperature Electrolysis to Scale*

Presentations (HTE)

6th Hydrogen Economy Program organized by University of Houston in collaboration with the American Institute of Chemical Engineers (AIChE), March 2024

- O.A. Marina, High Temperature Electrolyzers for Hydrogen and Chemicals Production, Lecture

ICACC 2023 20th International Symposium on Solid Oxide Cells, Daytona Beach, FL, January 2024

- (invited) H.W. Abernathy, W.K. Epting, Y. Lei, Y. Yang, P. Salvador, “Using simulation to study solid oxide cell degradation,”
- (invited) O.A. Marina, L. Le, C. Coyle, R. Springer, T. Liu, S. Belko, D. J. Edwards, M. Olszta, J. Bao, "Investigating Durability of Solid Oxide Electrolysis Cells"
- W.K. Epting, H.W. Abernathy, Y. Lei, G. Hackett, T. Kalapos, “A Machine Learning Framework for Rapid Assessment and Optimization of SOC Electrodes from Low Resolution Data,”
- Y. Lei, Y. Lee, W.K. Epting, J.H. Mason, T. Cheng, H.W. Abernathy, G. Hackett, Y. Wen, “Simulation Ni redistribution in the hydrogen electrodes of solid oxide cells: The effect of initial microstructural properties

5th Hydrogen Economy Program organized by University of Houston in collaboration with the American Institute of Chemical Engineers (AIChE), September 2023

- O.A. Marina, High Temperature Electrolyzers for Hydrogen and Chemicals Production, Lecture

4th International Conference on Electrolysis (ICE 2023), Sun City, South Africa, August 2023

- (invited) Marina O.A., L.Q. Le, C.A. Coyle, J. Bao, J.D. Escobar, T. Liu, "Investigating Durability of Solid Oxide Electrolysis Cells"

American Ceramic Society, Materials Challenges in Alternative & Renewable Energy 2023 (MCARE 2023), Bellevue, Washington, August 2023

- Karki S.B., L.M. Seymour, L.Q. Le, R.E. Springer, T. Liu, C.A. Coyle, K.D. Meinhardt, O.A. Marina, "Development of Strontium Free Alternative Oxygen Electrodes for Solid Oxide Electrolysis Cells (SOECs)."

IEEE Green Technologies (GreenTech) Conference, April 3-5, 2024, Springdale, Arkansas

- B. Poudel, D. Wendt, T. McJunkin, N. Kang, R. Boardman, "Baseload Hydrogen Production Using Nuclear and Renewable Energy: A Comparative Analysis, 2024

Presentations (HTE)

18th International Symposium on Solid Oxide Fuel Cells (SOFC-XVIII), Boston, MA, May 2023

- L. Le, C. Coyle, L. Seymour, J. Zaengler, J. Escobar, T. Liu, J. Bao, O.A. Marina, "Ni-YSZ Electrode Stability in Solid Oxide Electrolysis Cells Operated in 90-98% Steam"
- T. Liu, D. J. Edwards, L. Le, C. Coyle, L. Seymour, M. Olszta, K. D. Meinhardt, O. A. Marina, "Phase Evolution in (La0.6Sr0.4)0.95Co0.2Fe0.8O3-Δ Oxygen Electrodes after SOEC Operation"
- J. Bao, J. Fitzpatrick, N. Karri, B. Koeppel, K. D. Meinhardt, O. A. Marina, Structural Reliability Analysis of Large Planar Steam Solid Oxide Electrolysis Cells
- D. Wang, J. Bao, B. Koeppel, K. D. Meinhardt, O. A. Marina, "Long-Term Degradation Models for the Solid Oxide Electrolysis Cell"
- M. Olszta, T. Liu, J. Escobar, L. Le, O. A. Marina, "Understanding La_2NiO_4-$La_{0.5}Ce_{0.5}O_2$ Oxygen Electrode Phase Evolution in a Solid Oxide Electrolysis Cell"
- S. Karki, L. Seymour, L. Le, C. Coyle, R. Springer, J. Escobar, K. Meinhardt, O.A. Marina, "Strontium Free Cu-Doped La_2NiO_4 Oxides as Promising Oxygen Electrodes for Solid Oxide Electrolysis Cells"
- Y. Lei, T. Cheng, T. Yang, W.K. Epting, H.W. Abernathy, Y.H. Wen, “Modeling the Distribution of Oxygen Partial Pressure in the Electrolyte of Solid Oxide Cells and Its Implication on Microstructure Evolution in the Hydrogen Electrode.”
- M. C. Tucker, B. Hu, Z. Zhu, M. M. Welander, F. Shen, T. L. Skafte, G. Y. Lau, "Metal-Supported Solid Oxide Cells for Energy Conversion, Electrolysis, and Chemical Synthesis"
- N. Kane, "Accelerated Stress Testing of Standard Solid Oxide Electrolysis Cells"
- J. Hartvigsen, "Development of Long Duration Button Cell Test Stands and Testing Protocols"

American Institute of Chemical Engineers 2023 Annual Meeting, Orlando Florida, November 2023

- J. Gomez, "Advances in High Temperature Electrolysis for Sustainable Hydrogen Production: Insights form Idaho National Laboratory's Renewable Energy Research Portfolio, AICHE (Nov 5-11, 2023)

Materials Research Society Fall Meeting, Boston, MA, November 2023

- J. Kaufman, T. Hsu, K. Kweon, and B.C. Wood, “Accelerated Training of Cluster Expansion Models for Simulating Complex Oxides in High-Temperature Energy Conversion Applications”

Presentations (HTE)

Electrochemical Society Fall Meeting, Göteborg, Sweden, October 2023

- (invited) B. C. Wood, "Multiscale simulations of materials degradation in hydrogen production and storage applications"

American Chemical Society Fall Meeting, San Francisco, CA, August 2023

- (invited) K. E. Kweon, A. Rowberg, N. Kim, H. Yu, and B. C. Wood, "Multiscale integration for cation diffusion in Gd-doped ceria interlayer for solid oxide electrolysis cell"

New Zealand Hydrogen Symposium, Wellington, New Zealand, February 2024

- (invited plenary) B. C. Wood, "Overview of the U.S. DOE hydrogen production and storage consortia: A computational perspective"

Publications (LTE)

1. Khandavalli, S., Park, J., Winter, H. Myers, D.; Ulsh, M.; Mauger, S. (2023) Viscoelasticity enhancement and shear thickening of perfluorinated sulfonic acid ionomer dispersions in water-alcohol solvent mixtures. *Macromolecules* **2023**, 56, 6988−7005.
2. J.K. Lee, G. Y. Lau, A. Bergeson-Keller, A. Kusoglu, X. Peng, and M.C. Tucker, Pioneering Microporous Layers for Proton-Exchange-Member Water Electrolyzers via Tape Casting, Applied Functional Materials, Submitted
3. Jason K. Lee, Grace Anderson, Andrew W. Tricker, Finn Babbe, Arya Madan, David A. Cullen, José' D. Arregui-Mena, Nemanja Danilovic, Rangachary Mukundan, Adam Z. Weber, Xiong Peng, "Ionomer-free and recyclable porous-transport electrode for high-performing proton-exchange-membrane water electrolysis". *Nat Commun. 14, 4592,* ***2023***. https://doi.org/10.1038/s41467-023-40375-x
4. Lyu, X.; Foster, J.; Rice, R.; Padgett, E.; Creel, E. B.; Li, J.; Yu, H.; Cullen, D. A.; Kariuki, N. N.; Park, J. H.; Myers, D. J.; Mauger, S.; Bender, G.; Pylypenko, S.; Serov, A. Aging Gracefully? Investigating Iridium Oxide Ink's Impact on Microstructure, Catalyst/Ionomer Interface, and PEMWE Performance. *Journal of Power Sources* **2023**, *581*, 233503. https://doi.org/10.1016/j.jpowsour.2023.233503.
5. Ferner, K. J.; Park, J.; Kang, Z.; Mauger, S. A.; Ulsh, M.; Bender, G.; Litster, S. Morphological Analysis of Iridium Oxide Anode Catalyst Layers for Proton Exchange Membrane Water Electrolysis Using High-Resolution Imaging. *International Journal of Hydrogen Energy* **2024**, *59*, 176–186. https://doi.org/10.1016/j.ijhydene.2024.02.020.
6. Liu, C.; Wrubel, J. A.; Padgett, E.; Bender, G. Impacts of PTL Coating Gaps on Cell Performance for PEM Water Electrolyzer. *Applied Energy* **2024**, *356*, 122274. https://doi.org/10.1016/j.apenergy.2023.122274.
7. Liu, C.; Wrubel, J.; Padgett, E.; Bender, G. The Impacts of Membrane Pinholes on PEM Water Electrolysis. *Journal of Power Sources* **2023**, *581*, 233507. https://doi.org/10.1016/j.jpowsour.2023.233507.]
8. Badgett, A., Brauch, J., Saha, P., & Pivovar, B. (2023). Decarbonization of the Electric Power Sector and Implications for Low-Cost Hydrogen Production from Water Electrolysis. *Advanced Sustainable Systems, n/a(n/a), 2300091. doi: https://doi.org/10.1002/adsu.202300091*
9. Badgett, A., Brauch, J., Thatte, A., Rubin, R., Skangos, C., Wang, X., . . . Ruth, M. (2024). *Updated Manufactured Cost Analysis for Proton Exchange Membrane Water Electrolyzers. Retrieved from United States: https://www.osti.gov/biblio/2311140*, https://www.osti.gov/servlets/purl/2311140
10. Chen, Y., Stelmacovich, G., Mularczyk, A., Parkinson, D., Babu, S. K., Forner-Cuenca, A., . . . Zenyuk, I. V. (2023). A Viewpoint on X-ray Tomography Imaging in Electrocatalysis. *ACS Catalysis, 13*(15), 10010-10025. doi:10.1021/acscatal.3c01453
11. Wang, X., Star, A. G., & Ahluwalia, R. K. (2023). Performance of Polymer Electrolyte Membrane Water Electrolysis Systems: Configuration, Stack Materials, Turndown and Efficiency. *Energies, 16*(13), 4964. Retrieved from https://www.mdpi.com/1996-1073/16/13/4964

Publications (LTE)

12. Wang, X., Star, A. G., & Ahluwalia, R. K. (2023). Performance of Polymer Electrolyte Membrane Water Electrolysis Systems: Configuration, Stack Materials, Turndown and Efficiency. *Energies, 16*(13), 4964. Retrieved from https://www.mdpi.com/1996-1073/16/13/4964
13. Cliffton Wang, Keonhag Lee, Christopher Pantayatiwong Liu, Devashish Kulkarni, Plamen Atanassov, Xiong Peng, and Iryna V. Zenyuk. Design of PEM water electrolysers with low iridium loading. International Materials Reviews, Volume 69, Issue 1, February 2024, Pages 3-18
14. Khandavalli, S., Park, J. H., Winter, H. H., Myers, D. J., Ulsh, M., & Mauger, S. A. (2023). Viscoelasticity Enhancement and Shear Thickening of Perfluorinated Sulfonic Acid Ionomer Dispersions in Water–Alcohol Solvent Mixtures. Macromolecules, 56(17), 6988-7005. doi:10.1021/acs.macromol.3c00383
15. Liu, C., Wrubel, J., Padgett, E., & Bender, G. (2023). The impacts of membrane pinholes on PEM water electrolysis. *Journal of Power Sources, 581*, 233507. doi:https://doi.org/10.1016/j.jpowsour.2023.233507
16. Liu, C., Wrubel, J. A., Padgett, E., & Bender, G. (2024). Impacts of PTL coating gaps on cell performance for PEM water electrolyzer. *Applied Energy, 356*, 122274. doi:https://doi.org/10.1016/j.apenergy.2023.122274
17. Padgett, E., Bender, G., Haug, A., Lewinski, K., Sun, F., Yu, H., Cullen, D.A., Steinbach, A.J., Alia, S.M., (2023). Catalyst Layer Resistance and Utilization in PEM Electrolysis. J. Electrochem. Soc. 170, 084512. DOI: https://doi.org/10.1149/1945-7111/acee25

Publications (HTE)

1. T. Liu, J.D. Escobar, M.J. Olszta, O.A. Marina, Role of phosphorus impurities in decomposition of La2NiO4–La0.5Ce0.5O2-δ oxygen electrode in a solid oxide electrolysis cell, *Journal of Power Sources,* 2024, 589, 233748, doi.org/10.1016/j.jpowsour.2023.233748
2. J. Hartvigsen, J. Gomez, N. Kane, M. Casteel, C. Priest, L. Wang, C. White, R. Boardman, D. Ding, Development of Long Duration Button Cell Test Stands and Testing Protocols, *ECS Transactions*, 2023, 111 (6), 1761-1770, doi 10.1149/11106.1761ecst
3. N. Kane, J. Hartvigsen, M. Casteel, C. Priest, J. Gomez, L. Wang, C. White, R. Boardman, D. Ding, Accelerated Stress Testing of Standard Solid Oxide Electrolysis Cells, *ECS Transactions*, 2023, 111 (6), 2139-2146, doi 10.1149/11106.2139ecst
4. S. B. Karki, L. Seymour, L. Le, C. Coyle, R. Springer, J. Escobar, K. Meinhardt, O. A. Marina, Strontium Free Cu-Doped La_2NiO_4 Oxides as Promising Oxygen Electrodes for Solid Oxide Electrolysis Cells, *ECS Transactions*, 2023, 111(6), doi 10.1149/11106.0201ecst
5. Y. Lei, T. Cheng, T. Yang, W. K. Epting, H. W. Abernathy, Y. H. Wen. Modeling the Distribution of Oxygen Partial Pressure in the Electrolyte of Solid Oxide Cells and Its Implication on Microstructure Evolution in the Hydrogen Electrode, *ECS Transaction,* 2023, 111(6), 965, doi 10.1149/11106.0965ecst
6. T. L. Cheng, Y. Lei, Y. Chen, Y. Fan, H. Abernathy, X. Song, Y. H. Wen. Oxidation of nickel in solid oxide cells during electrochemical operation: Experimental evidence, theoretical analysis, and an alternative hypothesis on the nickel migration. *Journal of Power Sources, 2023, 569*, 232991 doi.org/10.1016/j.jpowsour.2023.232991
7. J. H. Prosser, B. D. James, B. M. Murphy, D. S. Wendt, M. J. Casteel, T. L. Westover, L. T. Knighton, Cost Analysis of Hydrogen Production by High-Temperature Colid Oxide Electrolysis, Internationa Journal of Hydrogen Energy 49 (2024) 207-227; https://doi.org/10.1016/j.ijhydene.2023.07.084
8. B. Poudel, D. Wendt, T. McJunkin, N. Kang, R. Boardman, "Baseload Hydrogen Production Using Nuclear and Renewable Energy: A Comparative Analysis, 2024 IEEE Green Technologies (GreenTech) Conference, April 3-5, 2024, Srpingdale, Arkansas
9. C.M. Priest, J.Y. Gomez, N.J. Kane, J.L. Hartvigsen, L. Wang, D. Ding, M.J. Casteel, F. F. Stewart and G. Wu, Challenges in Practical Button Cell Testing for hydrogen Production from High Temperature Electrolysis of Water, *Frontiers in Energy Research*, 2023, 11, https;//doi.org/10.3389/fenrg.2023.1278203

Special Recognition and Awards

- Bryan Pivovar elected Fellow of the Electrochemical Society (2023)

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