H_2@Scale: Experimental Characterization of Durability of Advanced Electrolyzer Concepts in Dynamic Loading

Shaun Alia
National Renewable Energy Laboratory
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Project ID # tv146

Overview

Timeline and Budget

- Project start date: 10/1/2017
- FY17 DOE funding: $400k ($300k NREL, $100k LANL)
- Total DOE funds received to date: $400k
- Percent complete: 20%

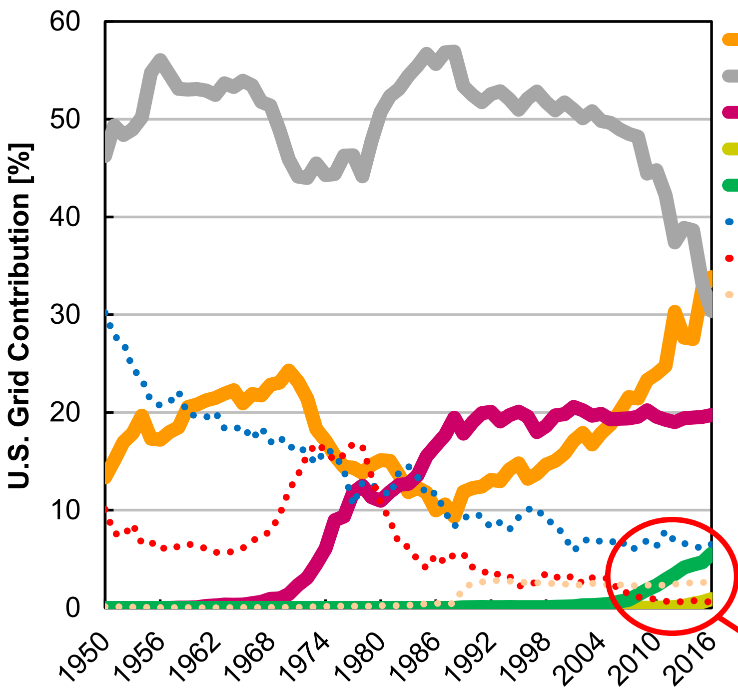
Partners

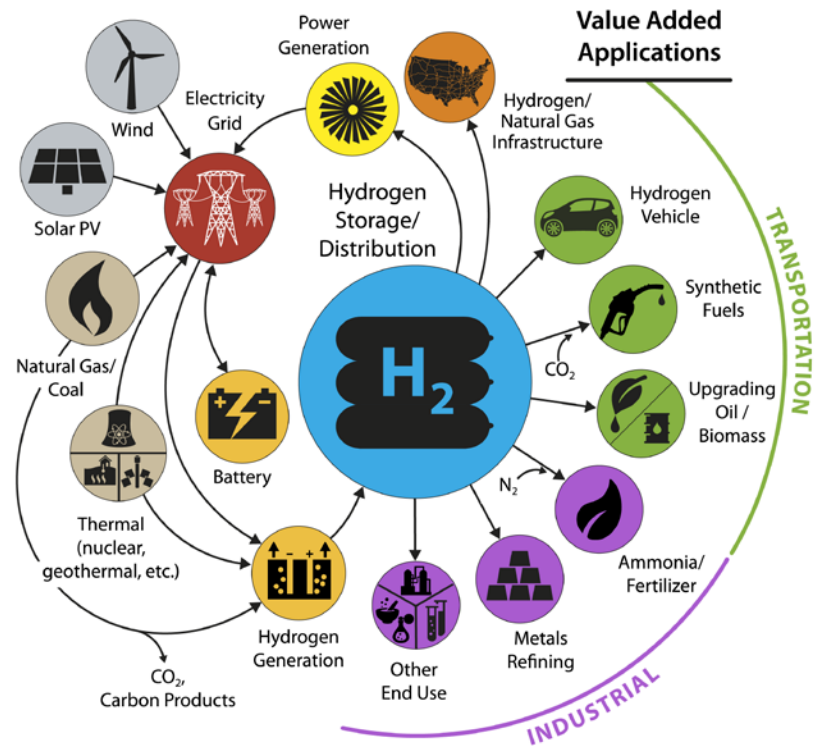
- Los Alamos National Laboratory – Rod Borup

Barriers

- Cost – Feedstock/capital cost reductions are needed to reduce the price of hydrogen by electrolysis.
- Durability – Durability losses have been observed with dynamic loading and intermittent input, and can have a significant impact on the price of hydrogen.

Relevance

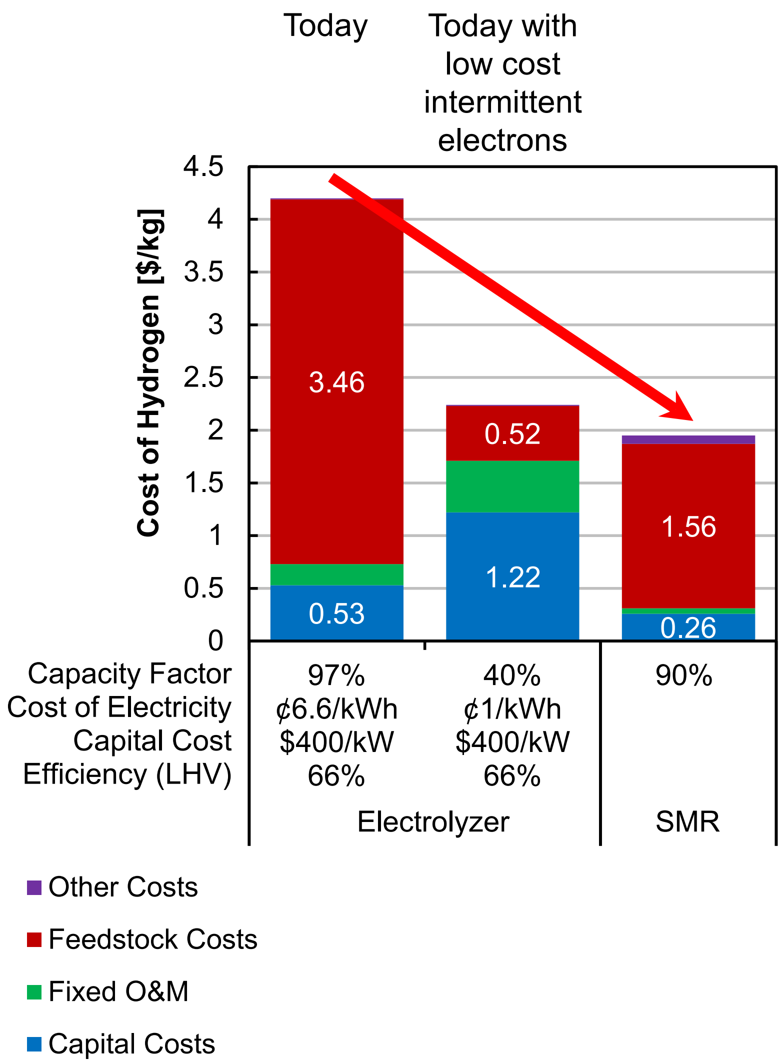




- Increasing use of low-cost, intermittent, renewable energy into the electric grid.
- There is a need for electrolysis to:
  - Store renewable power for reintroduction into the grid
  - Use hydrogen in value added applications

U.S. Grid Contribution adapted from – Electric Power Annual, U.S. Energy Information Administration, https://www.eia.gov/electricity/annual/
H_2@Scale Schematic – B. Pivovar, N. Rustagi, S. Satyapal, *Electrochem. Soc. Interface Spring* **2018**, 27(1), 47-52. DOI:10.1149/2.F04181if

Relevance



- Electrolysis-based hydrogen production needs to become cost-competitive.
- Objectives:
  - Establish baseline performance and durability as a guide to catalyst/electrode development.
  - Evaluate the influence of low loading, intermittency, and system controls on durability

Hydrogen Production Cost adapted from – B. Pivovar, H_2 at Scale, NREL Workshop. U.S. Department of Energy, https://www.energy.gov/sites/prod/files/2016/12/f34/fcto_h2atscale_workshop_pivovar_2.pdf, 2016.

Relevance

Table 3.1.4 Technical Targets: Distributed Forecourt Water Electrolysis Hydrogen Production [a, b, c]				
Characteristics	**Units**	**2011 Status**	**2015 Target**	**2020 Target**
Hydrogen Levelized Cost [d] (Production Only)	$/kg	4.20 [d]	3.90 [d]	2.30 [d]
Electrolyzer System Capital Cost	$/kg $/kW	0.70 430 [e, f]	0.50 300 [f]	0.50 300 [f]
System Energy Efficiency [g]	% (LHV)	67	72	75
	kWh/kg	50	46	44
Stack Energy Efficiency [h]	% (LHV)	74	76	77
	kWh/kg	45	44	43
Electricity Price	$/kWh	From AEO 2009 [i]	From AEO 2009 [i]	0.037 [j]

[a] The H2A Distributed Production Model 3.0 (www.hydrogen.energy.gov/h2a_production.html) used alkaline electrolysis parameters to generate the values in the table with the exceptions described in the notes below. Results are documented in the Current and Future H2A v3 case studies for Forecourt Hydrogen Production from Grid Electrolysis which can be found at http://www.hydrogen.energy.gov/h2a_prod_studies.html.

[b] The H2A Distributed Production Model 3.0 was used with the standard economic assumptions: All values are in 2007 dollars, 1.9% inflation rate, 10% After Tax Real Internal Rate of Return, 100% Equity Financing, 20-year analysis period, 38.9% overall tax rate, and 1% working capital (based on independent review input). A MACRS 7-year depreciation schedule was used. The plant design capacity is 1,500 kg/day of hydrogen. It is assumed that Design for Manufacture and Assembly (DFMA) would be employed and that production would have realized economies of scale.

[c] The plant production equipment availability is 98% including both planned and unplanned outages; four unplanned outages of 14h duration per year; 1 planned outage of 5 days duration per year. The plant usage factor (defined as the actual yearly production/equipment design production capacity) is 90% based on over sizing of the production equipment to accommodate a summer surge in demand of 10% above the yearly average demand.

[d] The levelized cost is equivalent to the minimum required selling price to achieve a 10% annual rate of return over the life of the plant.

[e] Electrolyzer uninstalled capital costs based on independent review panel results [DOE 2009, Current (2009)] State-of-the-Art Hydrogen Production Cost Estimate using Water Electrolysis. Independent Review. NREL/BK-6A1-46676. September 2009 (http://www.hydrogen.energy.gov/pdfs/46676.pdf). "Electrolyzer capital costs are expected to fall to $380/kW for forecourt production." Escalated to 2007 dollars = $430/kW (purchased equipment cost).

[f] Electrolyzer cells capital replacement = 25% of total purchased capital every 7 years (DOE, 2009).

[g] System energy efficiency is defined as the energy in the hydrogen produced by the system (on a LHV basis) divided by the sum of the feedstock energy (LHV) plus all other energy used in the process.

[h] Stack energy efficiency is defined as the energy in the hydrogen produced by the stack (on a LHV basis) divided by the electricity entering the stack. Additional electricity use for the balance of plant is not included in this calculation. Stack energy efficiency is a guideline and the targets do not need to be met as long as the system energy efficiency meets the targets.

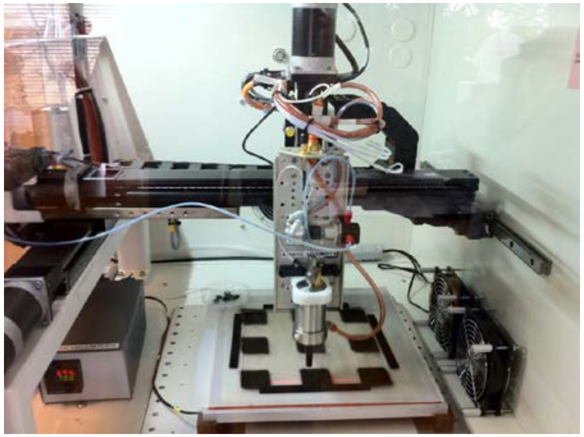
[i] Hydrogen cost is calculated assuming purchase of industrial grid electricity. Electricity prices are taken from the 2009 AEO Reference Case price projections to 2030. Prices beyond 2030 are not available in the 2009 AEO case so they are projected based on the PNNL MiniCAM model output http://www.globalchange.umd.edu/models/gcam/). The average electricity price is $0.063/kWh ($0.061/kWh effective) over the modeled life of the plant for the current (2011) case and $0.070/kWh ($0.069/kWh effective) for the 2015 case.

[j] Electricity cost is assumed to be 3.7¢/kWh throughout the analysis period to meet the $4.00/gge target for dispensed hydrogen.

[k] Costs for the forecourt station compression and storage are consistent with the status and targets in the Delivery MYRD&D section. Storage capacity for 1579 kg of hydrogen at the forecourt is included. It is assumed that the hydrogen refueling fill pressure is 5000 psi for 2010 and it assumed that in 2015 and 2020, the hydrogen refueling fill pressure is 10,000 psi.

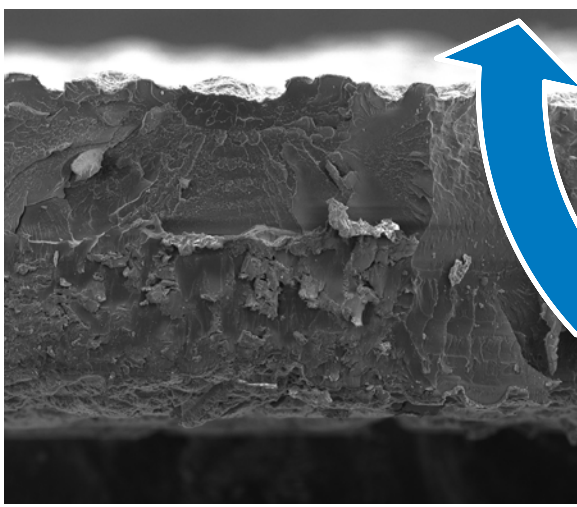
Multi-Year Research, Development, and Demonstration Plan – Fuel Cell Technologies Office, https://www.energy.gov/sites/prod/files/2015/06/f23/fcto_myrdd_production.pdf

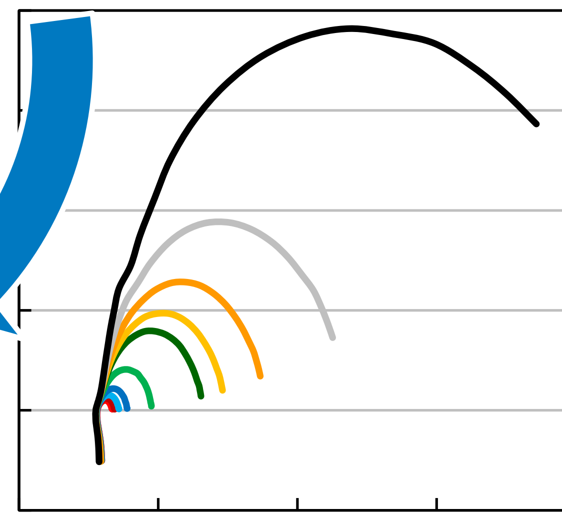
Approach



Electrode Fabrication

Electrolyzer Testing





Characterization

NREL: Cell Diagnostics

LANL: Microscopy

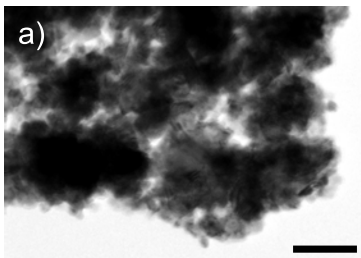
Electrolyzer Test Stand – Greenlight Innovation, http://www.greenlightinnovation.com/electrolyser/

Accomplishments and Progress

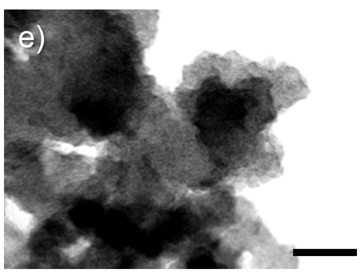
Differences in Half- and Single-Cell Performance, Iridium and Iridium Oxide

- In half-cells – Ir twice as active as Ir oxide, less durable
- In single-cells – Ir comparable in activity, less durable

Iridium

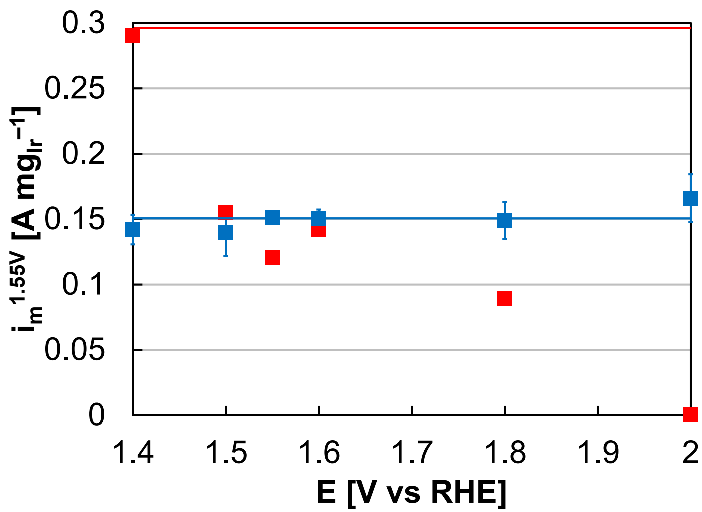


Iridium Oxide

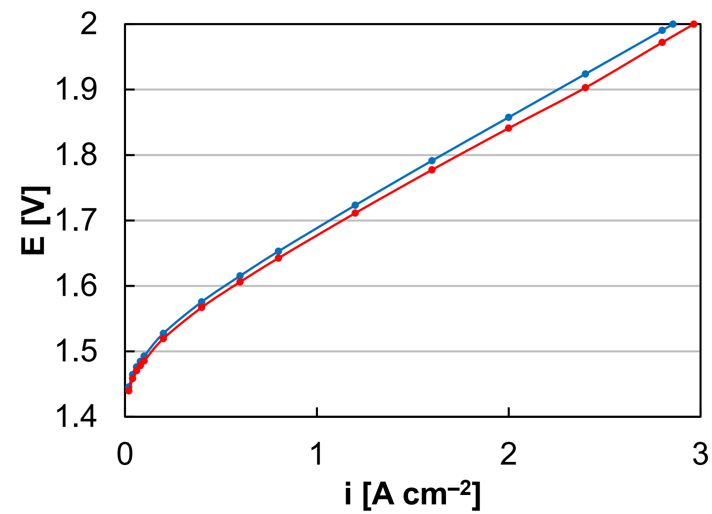


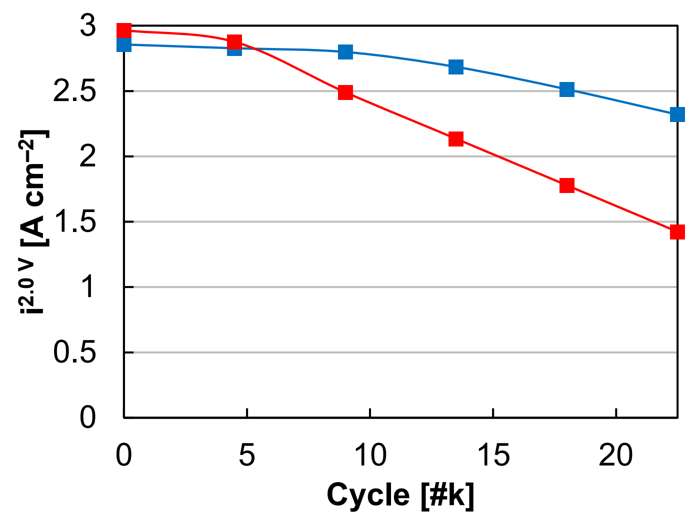
Courtesy of Chilan Ngo, Svitlana Pylypenko, Colorado School of Mines

RDE Half-Cells



MEA Single-Cells

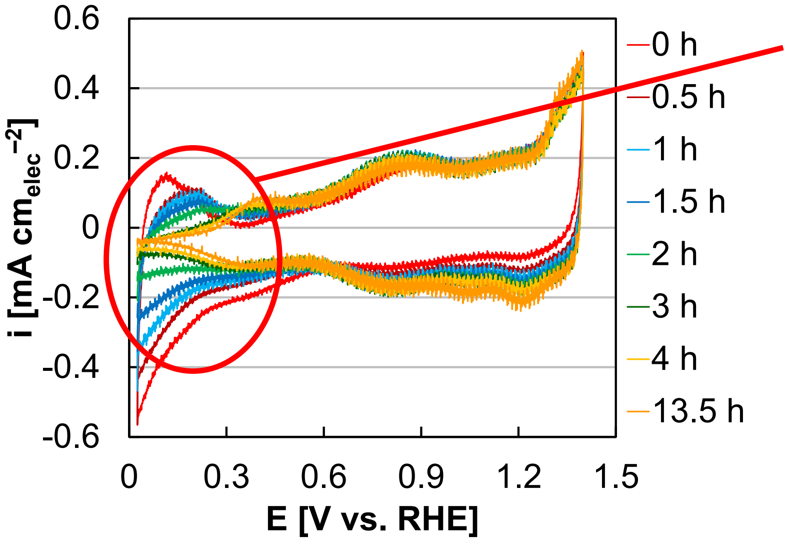




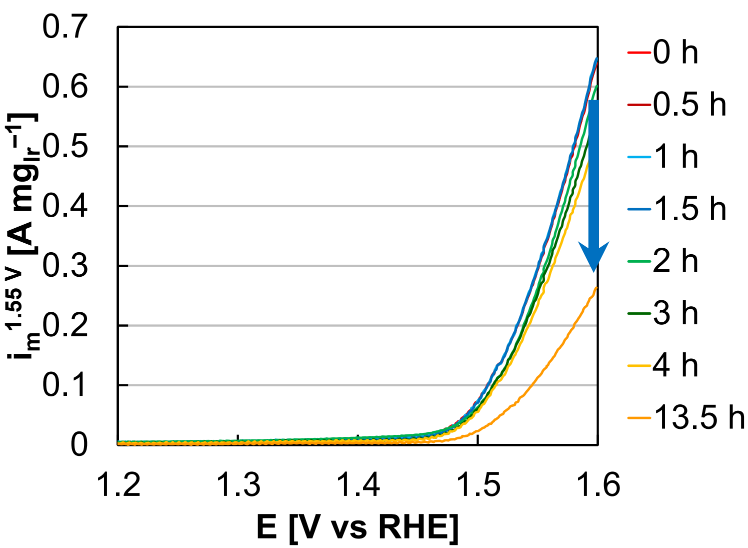
Microscopy and Ir half-cell data – S.M. Alia, B. Rasimick, C. Ngo, K.C. Neyerlin, S.S. Kocha, S. Pylypenko, B.S. Pivovar, *J. Electrochem. Soc.*, **2016**, *163*(11), F3105-F3112. DOI:10.1149/2.0151611jes

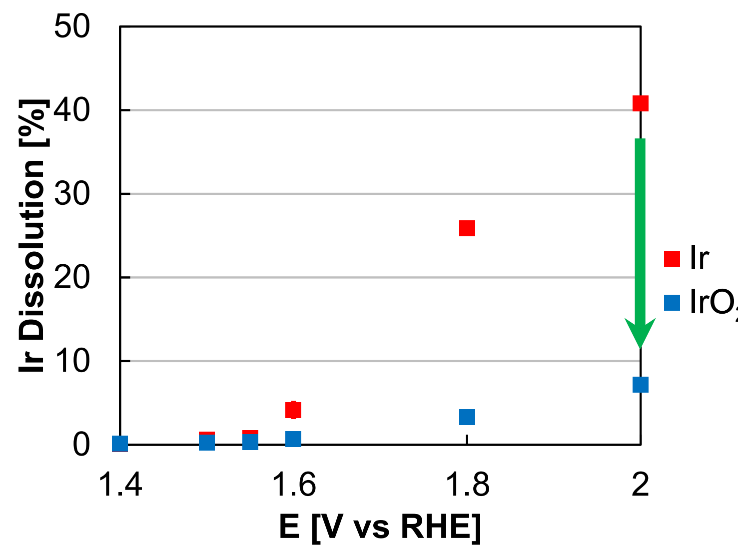
Accomplishments and Progress

Differences in Half- and Single-Cell Performance, Iridium and Iridium Oxide



- Started with Ir (metallic) and applied elevated potential (1.6 V). Ir oxidized near-surface and the half-cell voltammograms/performance approached oxides.
- Single-cell tests incorporate near-surface oxidation in conditioning protocols
- Oxides slowed dissolution kinetics, benefitted single-cell durability





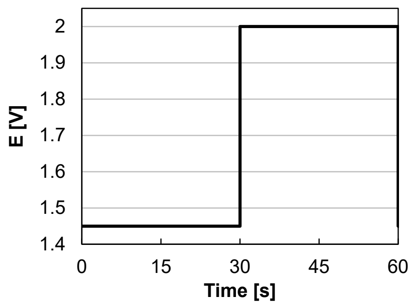
Accomplishments and Progress

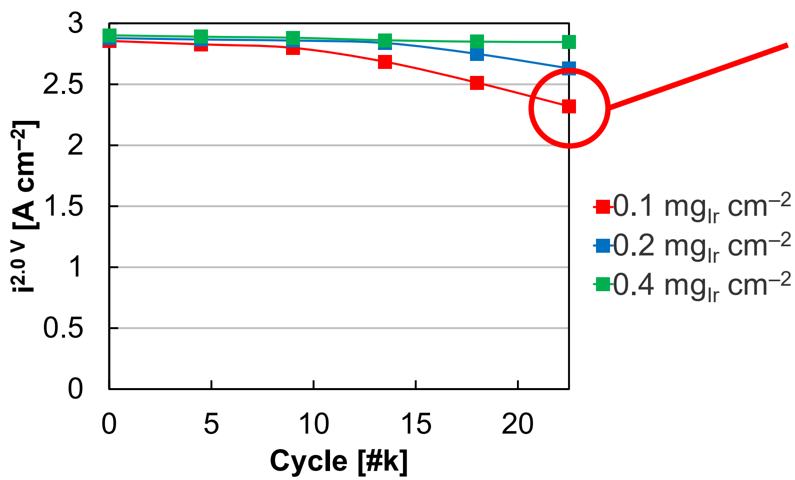
Impact of Loading and Upper Potential

Test Profiles

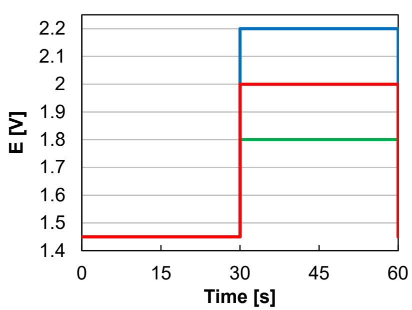
MEA Durability

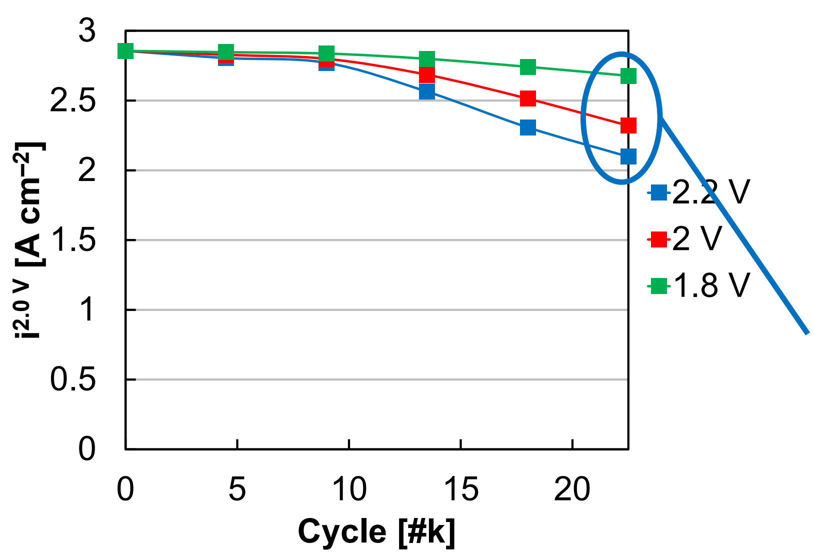
Loading





Upper Potential

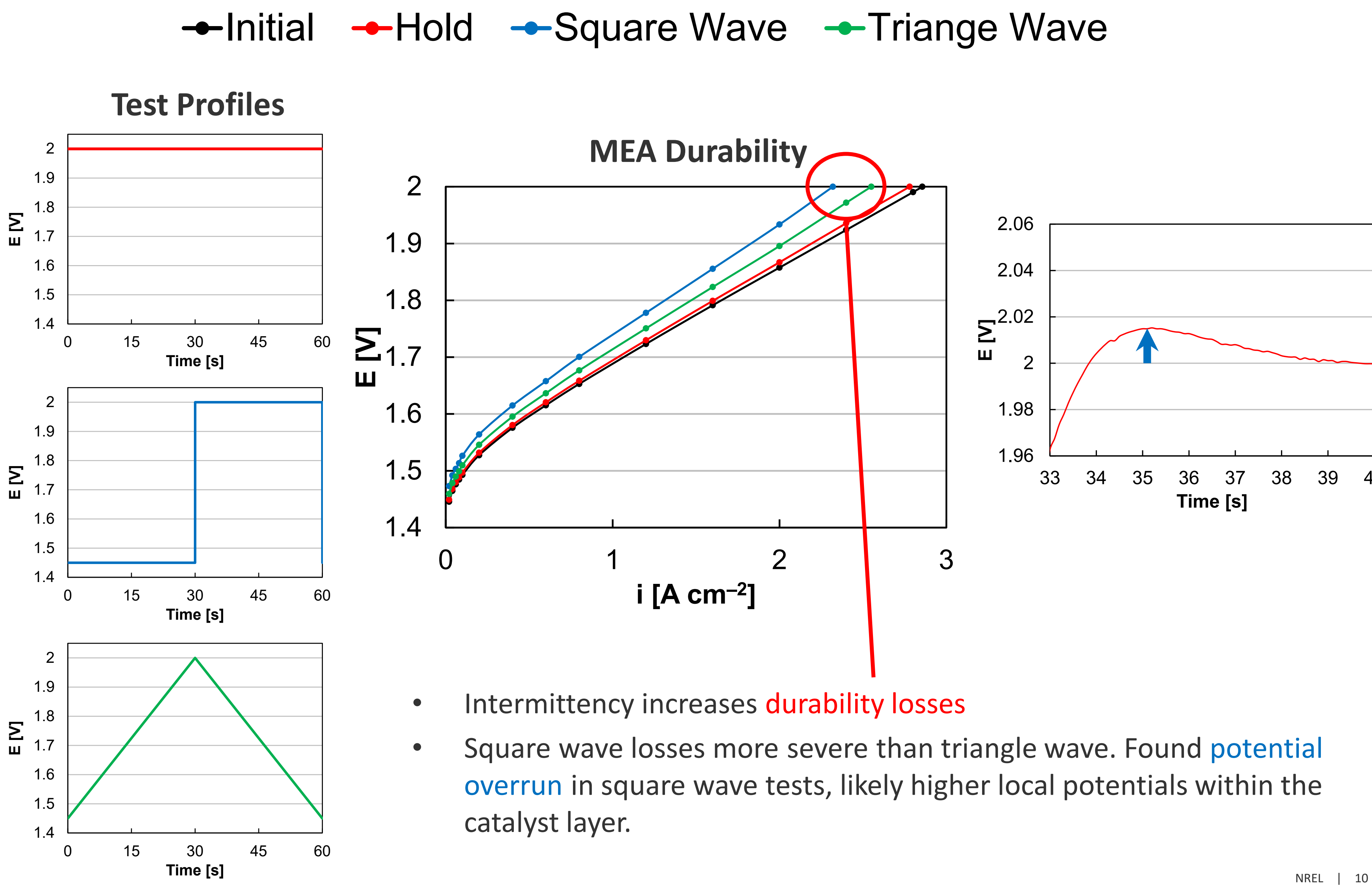




- Low loading required to see durability losses during short time frame
- Iridium loss (dissolution) still occurs at higher loading, but the loading delayed the onset of performance loss and slowed the loss rate.
- Higher potential increases dissolution rates, durability losses

Accomplishments and Progress

Impact of Intermittency

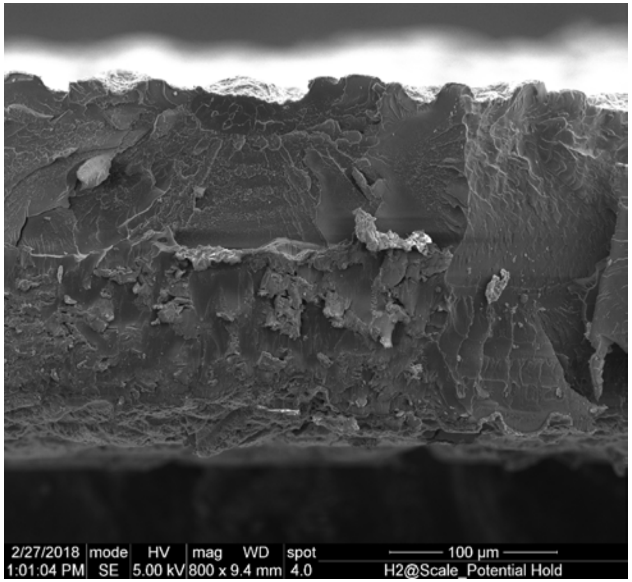


- Intermittency increases durability losses
- Square wave losses more severe than triangle wave. Found potential overrun in square wave tests, likely higher local potentials within the catalyst layer.

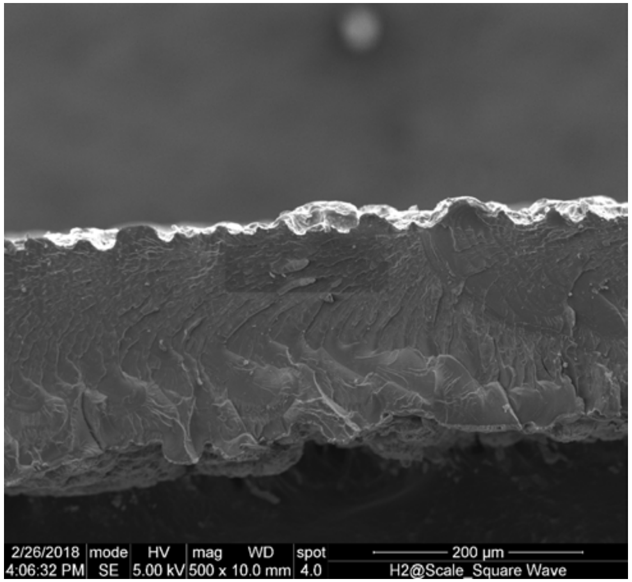
Accomplishments and Progress

Catalyst Layer Thickness, Single-Cell Tests

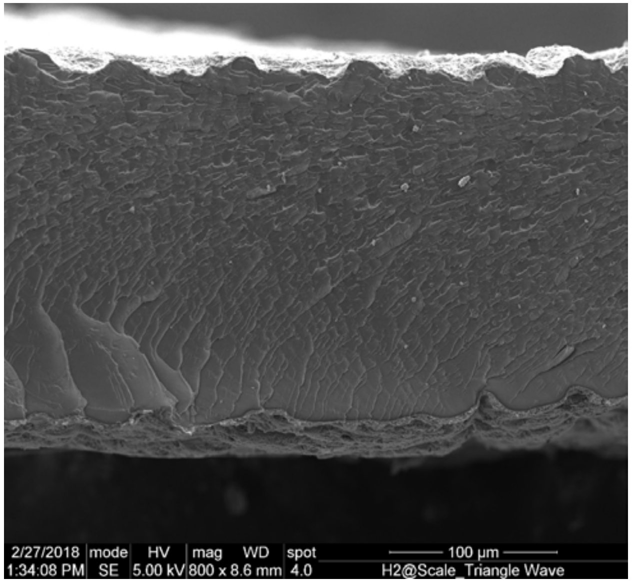
Hold



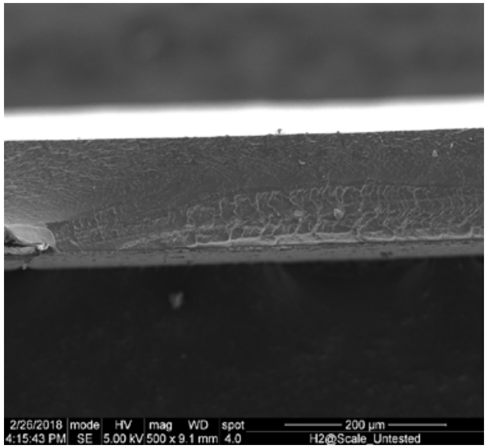
Square Wave



Triangle Wave



Initial



	Initial	Hold	Square Wave	Triangle Wave
[µm]	1.07	1	0.77	0.75

- Losses dissolution-driven
- In microscopy of Ir oxide catalyst layer (anode), found thinning that was more prominent in the square and triangle wave tests.

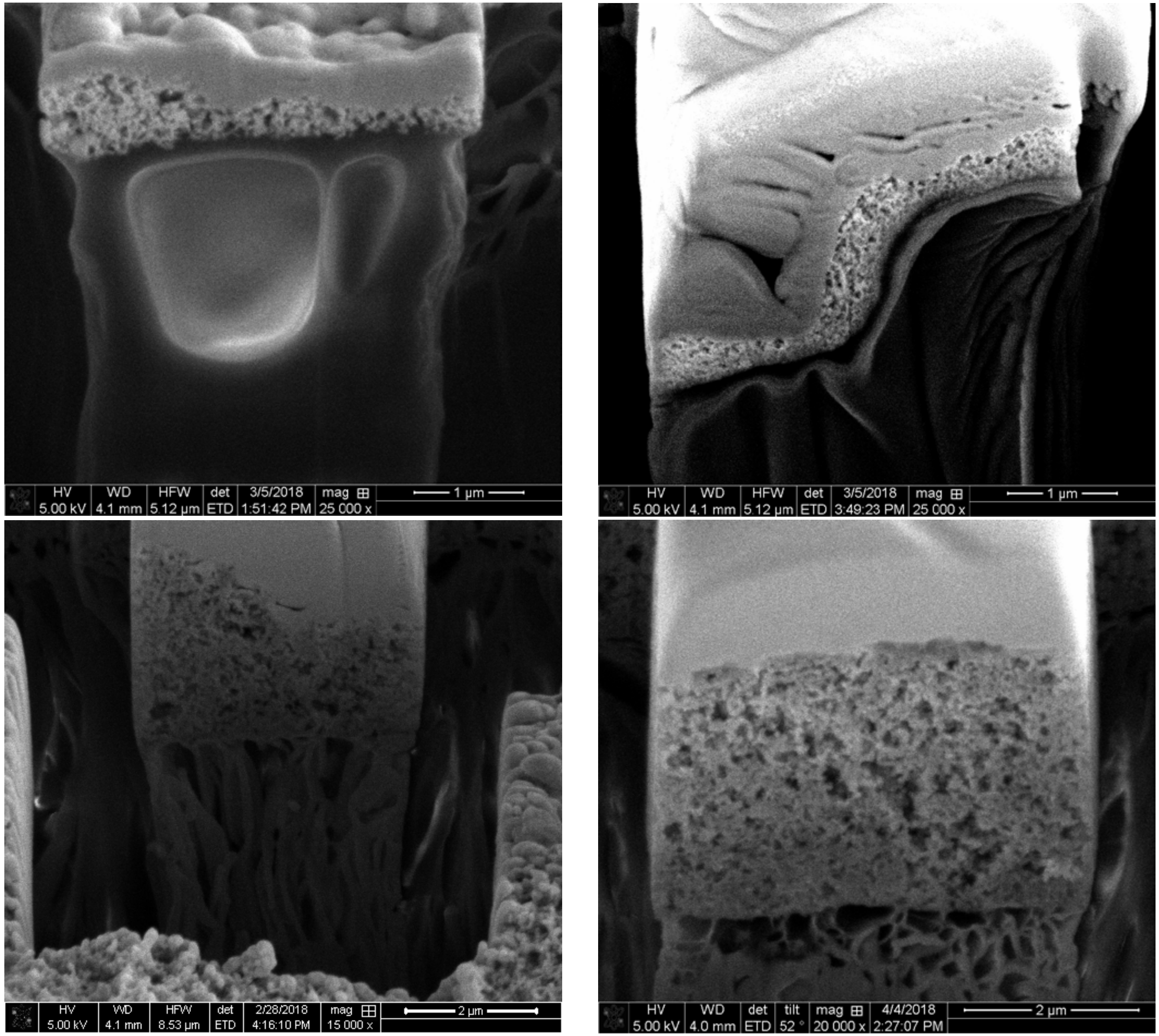
Accomplishments and Progress

Catalyst Layer Porosity, Single-Cell Tests

Initial | Square Wave

Iridium

Platinum



Accomplishments and Progress

Catalyst Layer Porosity, Single-Cell Tests

	Initial	Square Wave
IrO_2 Thickness [µm]	1	0.77
IrO_2 Porosity [%]	38.8	33
IrO_2 Ave Pore Area [µm^2]	0.004	0.002
IrO_2 Equ. Dia. [nm]	52.9	35.9
Pt/HSC Thickness [µm]	4.1	2.51
Pt/HSC Porosity [%]	44.1	45.9
Pt/HSC Ave Pore Area [µm^2]	0.019	0.01
Pt/HSC Equ. Dia. [nm]	126.8	77

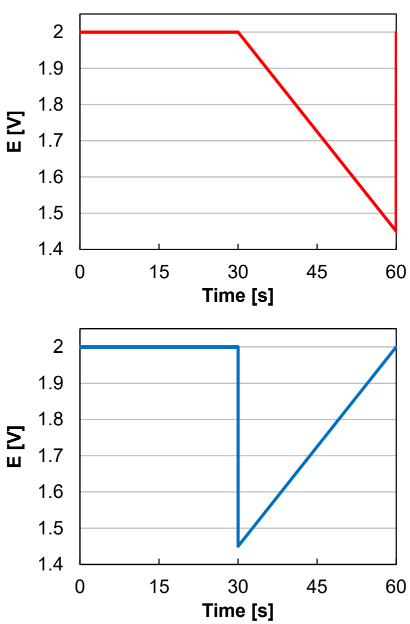
- Although the porosity doesn't change significantly, the equivalent diameter (Equ. Dia.) of the pores decrease.
- The pore area is measured from the images and from that the equivalent diameter is calculated, assuming the pores are a circle.

Accomplishments and Progress

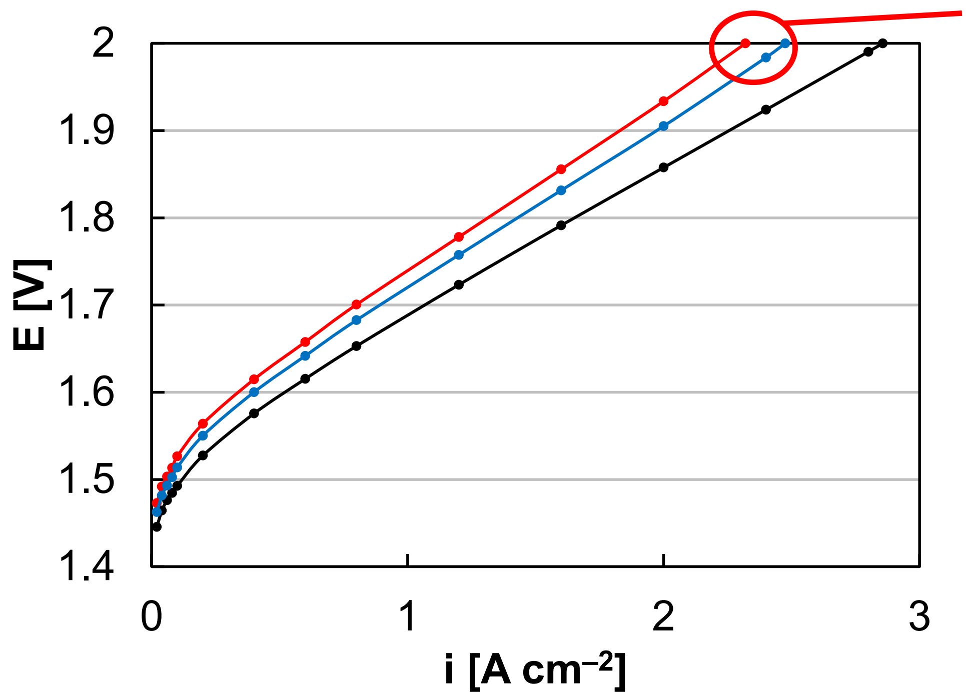
Impact of Ramp Rate

- Initial
- Sawtooth - Square Up
- Sawtooth - Triange Up

Test Profiles



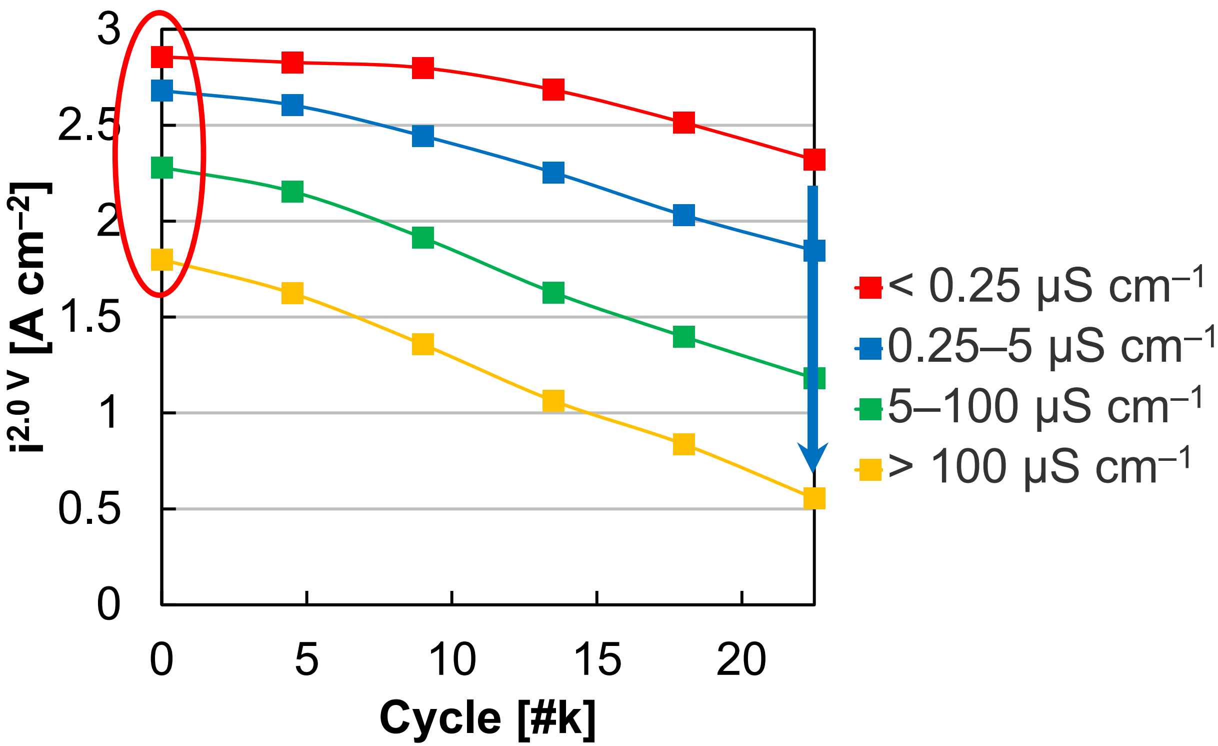
MEA Durability



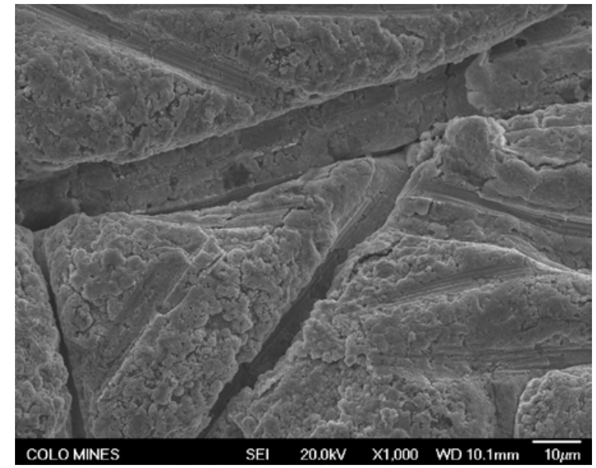
- Immediate (square wave) potential increase 1.45–2 V resulted in larger durability losses.
- Sawtooth – Square Up loss was comparable to Square Wave, suggesting that sudden potential decreases are not as detrimental to durability.

Accomplishments and Progress

Impact of Water Quality



Courtesy of Sarah Zaccarine, Svitlana Pylypenko, Colorado School of Mines



Element	Wt %	At %
O K	2.75	9.46
NiK	96.24	90.26
IrL	0.34	0.10
PtL	0.67	0.19
Total	100.00	100.00

- Water quality effect on MEAs
  - Reduced initial performance
  - Accelerated observed durability losses
- Found large amounts of Ni contamination. Loss rates may change significantly depending on the contaminant.

Accomplishments and Progress

Responses to Previous Year Reviewers' Comments

- This project was not reviewed last year

Collaboration and Coordination

Institutions	Role
National Renewable Energy Laboratory (NREL): Shaun Alia (PI), Grace Anderson, Guido Bender, Bryan Pivovar	**Prime, oversees the project; lead electrode fabrication, ex-situ testing, and electrolyzer testing**
Los Alamos National Laboratory (LANL): Rod Borup, Sarah Stariha	**Sub; materials characterization using x-ray diffraction and microscopy**

Remaining Challenges and Future Work

- Evaluate the influence of low loading, intermittency, and system controls on durability
  - Continue to evaluate potential profiles to quantify the impact of rapidly increasing or decreasing potential.
  - Improve the connection to anticipated electrolysis use
    - Extend the operation time of moderately loaded electrodes (0.1–1 mg_{Ir} cm^{-2}) to project the long term durability of electrolyzers operating intermittently.
    - Use wind/solar profiles to evaluate the use Square and Triangle Wave tests on accelerating electrolyzer durability.
  - Extend the developed performance and durability testing protocols to other iridium-based catalysts (high surface area, novel nanomaterials).

- Evaluate mitigation strategies for durability losses from intermittent operation.

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

Technology Transfer Activities

- Catalyst development (iridium-based nanowires) have been protected by IP.

Summary

- <u>Relevance</u>: The project evaluates electrolyzer durability with dynamic loading, and assesses the ability of water splitting-based hydrogen production to reduce cost (intermittent input, loading) while maintaining performance with extended operation.

- <u>Approach</u>: Establishing baseline performance and durability as a guide to catalyst/electrode development. Evaluating the influence of low loading, intermittency, and system controls on durability.

- <u>Accomplishments and Progress</u>: This project has evaluated the influence of catalyst type, loading, and intermittency on electrolyzer performance and durability. Iridium (metal, hydroxide) surfaces produced high half-cell performance, but oxidize during single-cell conditioning and are more prone to dissolution-based loss than oxides. Although higher loading delays the onset of durability losses, iridium dissolution occurs regardless of loading. Performance loss was accelerated by intermittency and local sites within the catalyst layer may see potentials significantly higher than those applied, accelerating dissolution and loss.

- <u>Collaborations</u>: This project is a collaboration between NREL and LANL.

- <u>Proposed Future Research</u>: See previous slide.

Thank You

www.nrel.gov

Publication Number

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