PROTON
THE LEADER IN ON SITE GAS GENERATION.

Low-Noble-Metal-Content Catalysts/Electrodes for Hydrogen Production by Water Electrolysis

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Organization: Proton OnSite
Date: June 11th, 2015

Project ID: PD098

Overview

Timeline

- Project Start: 28 June 2012
- Project End: 13 Aug 2015
- Percent complete: 92%

Budget

- Total Funding Spent*
  - $996,357
- Total Project Value
  - $1,150,000
- Cost Share Percentage
  - 0% (SBIR)

*As of March 31, 2015

Barriers

- G. Capital Cost

Table 3.1.4 Technical Targets: Distributed Forecourt Water Electrolysis Hydrogen Protoduction [a, b, c]				
Characteristics	**Units**	**2011 Status**	**2015 Target**	**2020 Target**
Hydrogen Levelized Cost [d] (Production Only)	$/kg	4.2 [d]	3.9 [d]	2.3 [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

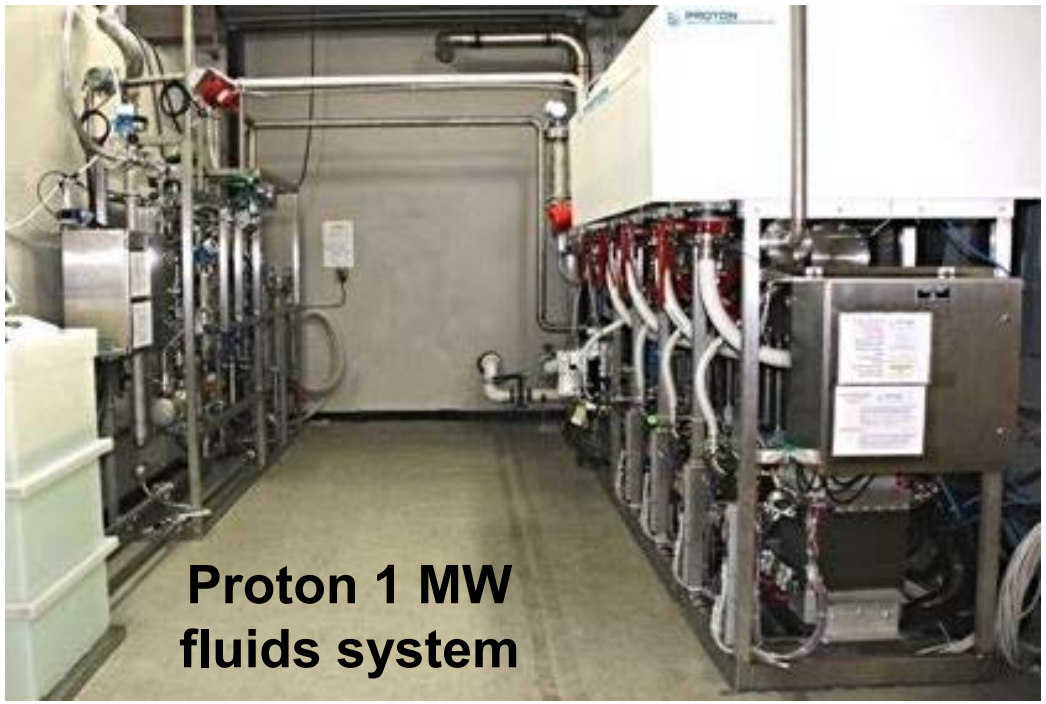
2012 MYRDD Plan

Partners

- Brookhaven National Lab

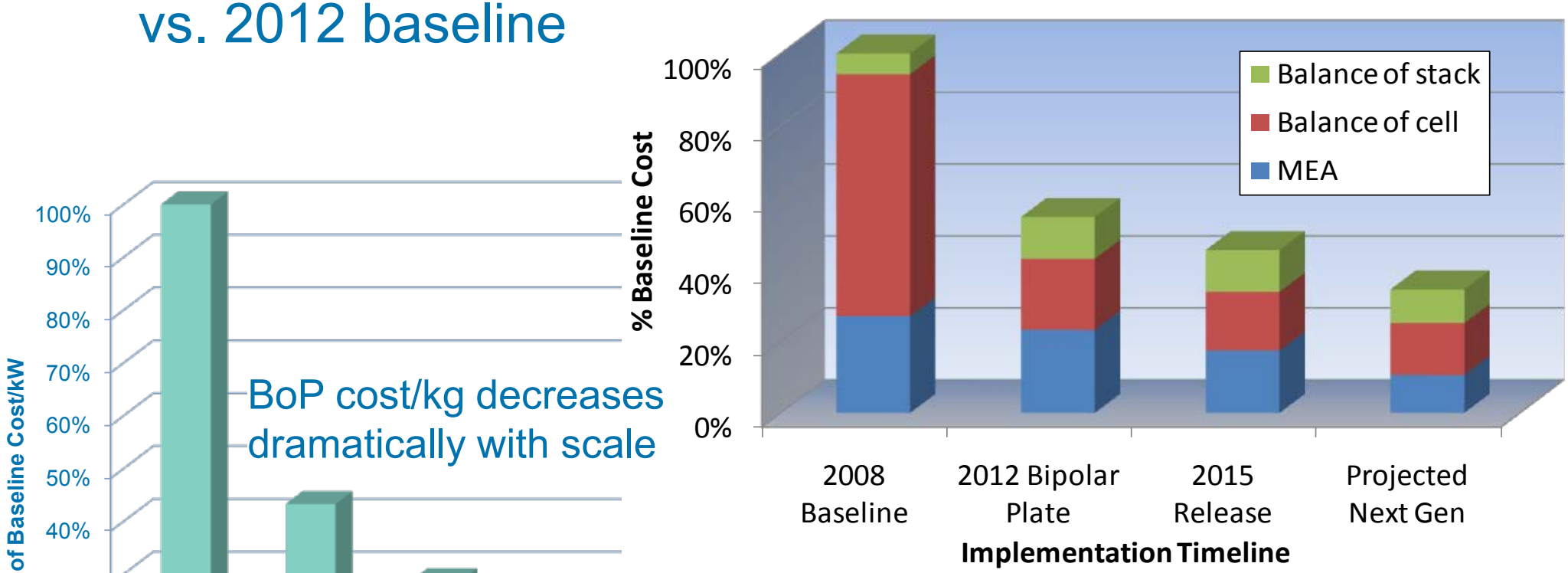
Relevance: PEM Electrolysis

- Reduction of greenhouse gas emissions through renewable hydrogen production
  - Currently produced from fossil fuels
  - Also provides transportation benefit
- Only current technology at relevant scale

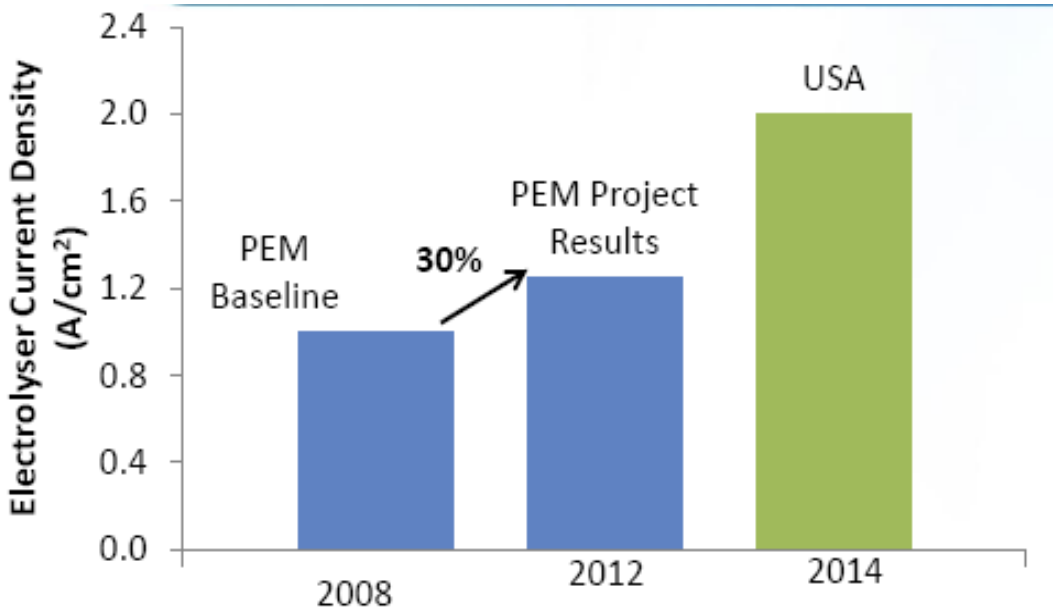


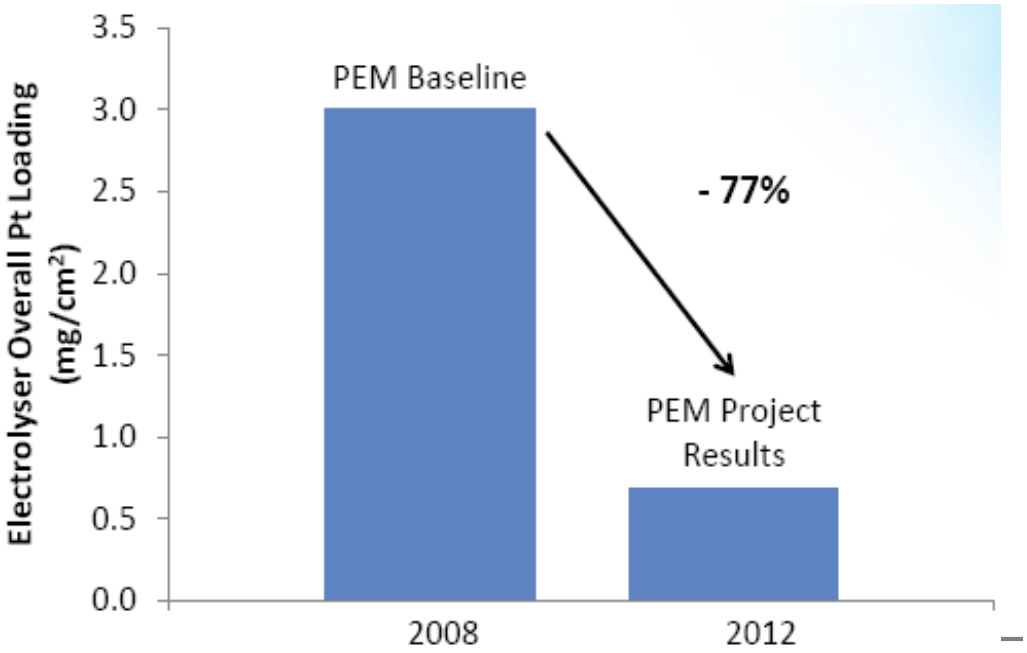
Relevance: Catalyst Loading

- Catalyst becomes a key cost driver at MW scale
  - 30% stack cost reduction possible vs. 2012 baseline

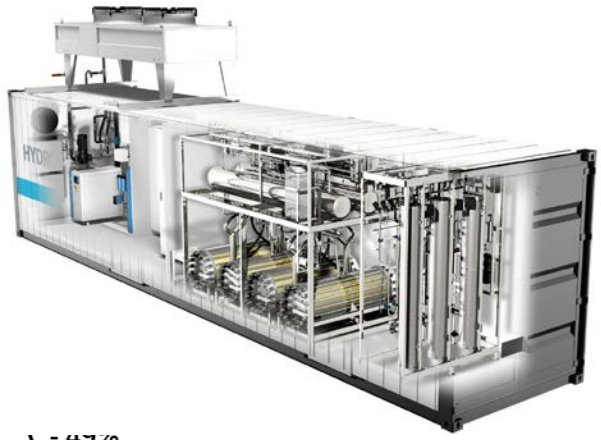


Relevance: EU Competition Growing





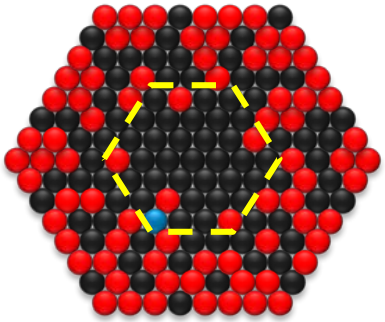
- Need to maintain competitive position in U.S. for energy storage and other applications



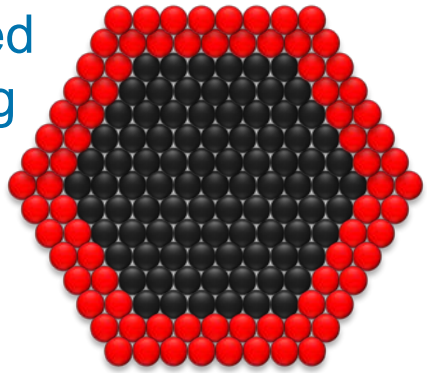
Approach:

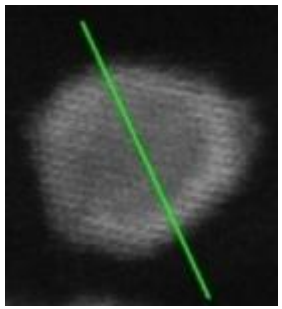
- Reduce electrode cost through highly active core shell catalysts and advanced deposition methods
  - Lowest catalyst loading in combination
  - Addresses both PGM usage and labor costs

Previous methods produced imperfect structure and mixing



Defect-induced partial alloying eliminated.



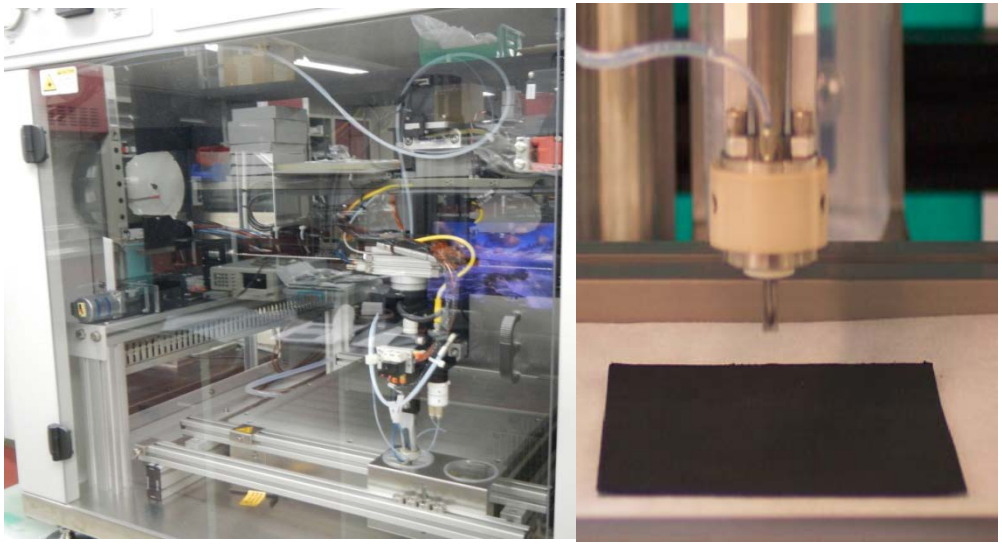


Phase II Project Objectives

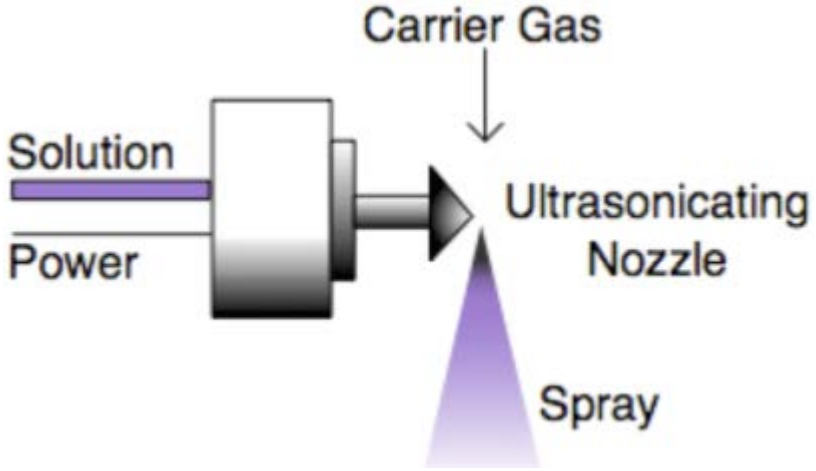
- Automate cathode process and scale up
- Downselect promising anode electrode configurations
- Operate 500 hours with cost-reduced electrodes.
- Demonstrate feasibility for 80% electrode cost reduction

Approach: Manufacturing and GDL Selection

- Ultrasonic spray deposition identified as approach for high-throughput and low labor
- Phase 1: MPLs result in better distribution of catalyst near membrane; need repeatable hydrophilic layer
- Phase 2: Equipment procurement, transfer process



Ultrasonic printer at Proton OnSite (left) and nozzle with GDL material (right).

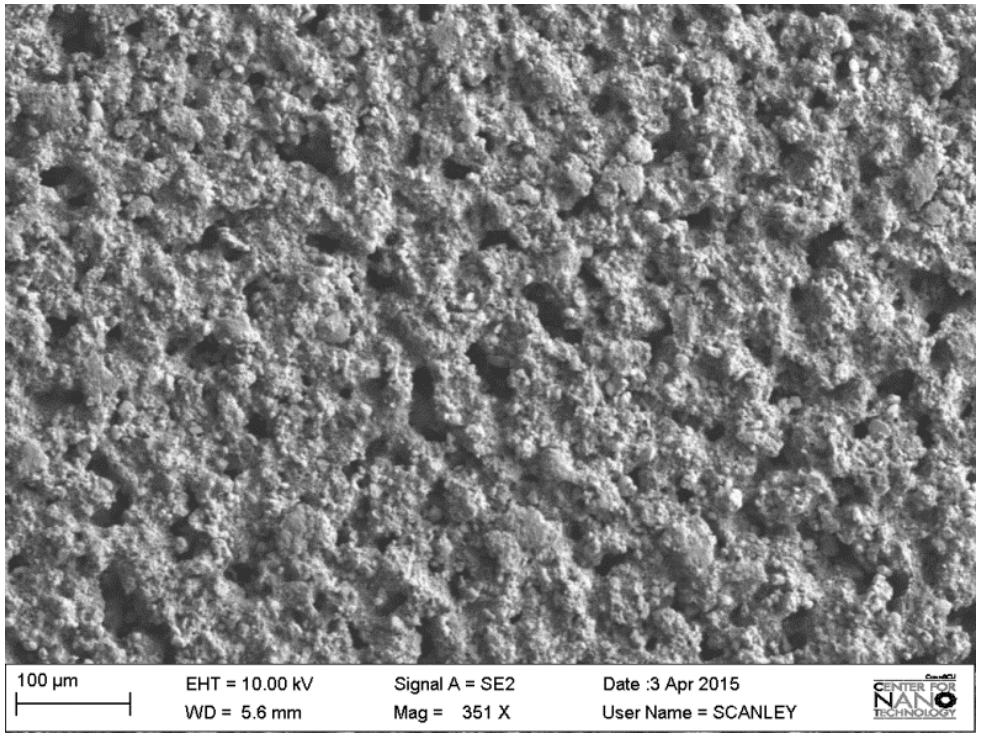


Ultrasonic spray deposition schematic[1]

[1]SPIE Newsroom. DOI: 10.1117/2.1200903.1555

Approach: Anode

- No commercial MPL options for anode GDLs
  - Custom MPL from 3rd party supplier
  - In house fabrication of TiOx MPLs
  - Non-MPL options: binder changes
  - Alternate catalysts
  - Print parameters



Approach: Task Summary

- Task 1.0 Cathode Catalyst
  - Technology transfer
  - Scale-up
- Task 2.0 Cathode Manufacturing
  - Deposition verification
  - Manufacturing development
- Task 3.0 Anode Catalysts
  - Evaluation of synthesized catalysts
  - Evaluation of novel manufacturing methods
- Task 4.0 Anode Electrode
  - Ink formulation for anode catalysts
  - Anode GDE fabrications
  - Structural and component characterization
- Task 5.0 Cell Development and Testing
  - Anode GDL development
  - Cathode GDE incorporation
  - Durability and post-operation assessment
- Task 6.0 Cost Analysis

Accomplishments: Year 1 Milestones

Task #	Milestone Description	Status
6	Project Kick-off: Proton, BNL	100%
1	Demonstrate successful cathode catalyst synthesis and electrode manufacture at Proton	100%
3	Complete study of TiO_x-supported Ru@Ir catalysts in solution electrochemical cells.	100%
4	Demonstrate uniform and robust catalyst layer on Ti GDLs	100%
1	Complete scale up synthesis of cathode catalysts to 10 – 100 g batch level	**100%**
5	Complete cell design analysis for cathode configuration	**100%**

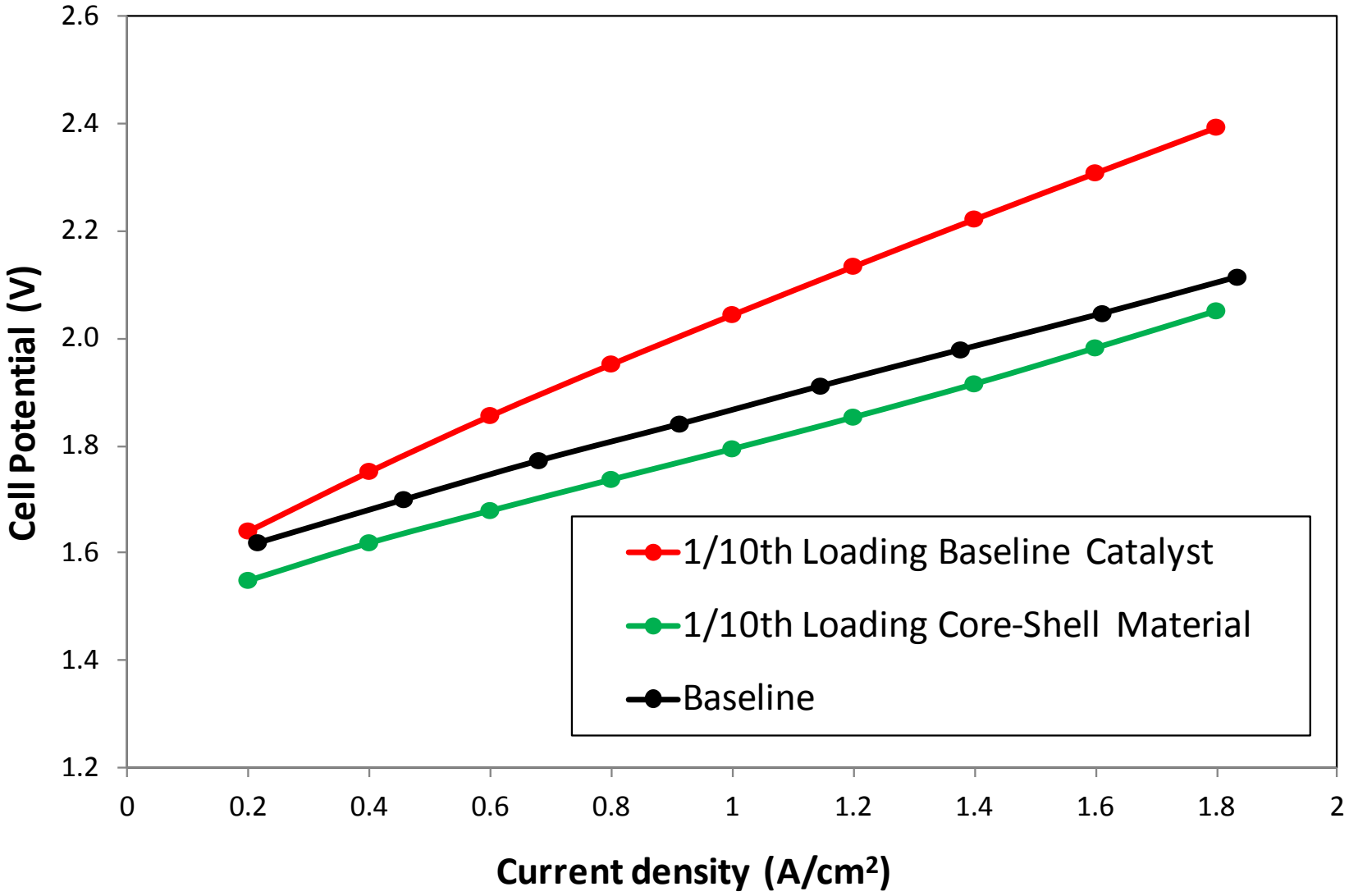
Milestones in green accomplished since last AMR

Accomplishments: Year 2 Milestones

Task #	Milestone Description	Due Date / Completion
2	Downselect optimal cathode material and process for reliable production	**100%**
4,5	Demonstrate improved activity and durability of selected anode GDE samples in cell	**100%**
6	Provide initial cost assessment via H2A model	**100%**
2,4,5	Identify key issues for enhancing durability	**100%**
4,5	Achieve >100 hours durability of developed anode catalyst/GDE	10%
2,4,5	Demonstrate process capability for large active area electrodes	**100%**
2,4,5	Achieve 500 hours of operation at 89 cm^2 cell level	50%
6	Evaluate the benefits of selected anode catalysts/electrodes over the baseline in cost reduction or efficiency boost.	8/30/2015
6	Complete Final Reporting	8/30/2015

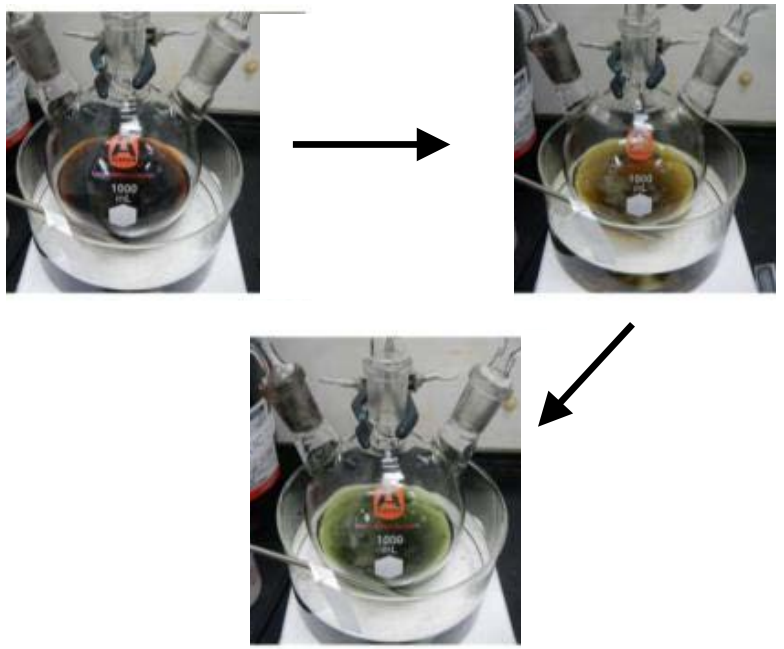
Technical Accomplishments: Catalyst

- Core shell cathode catalyst demonstrates activity advantage
- Enables lower loadings at equivalent performance



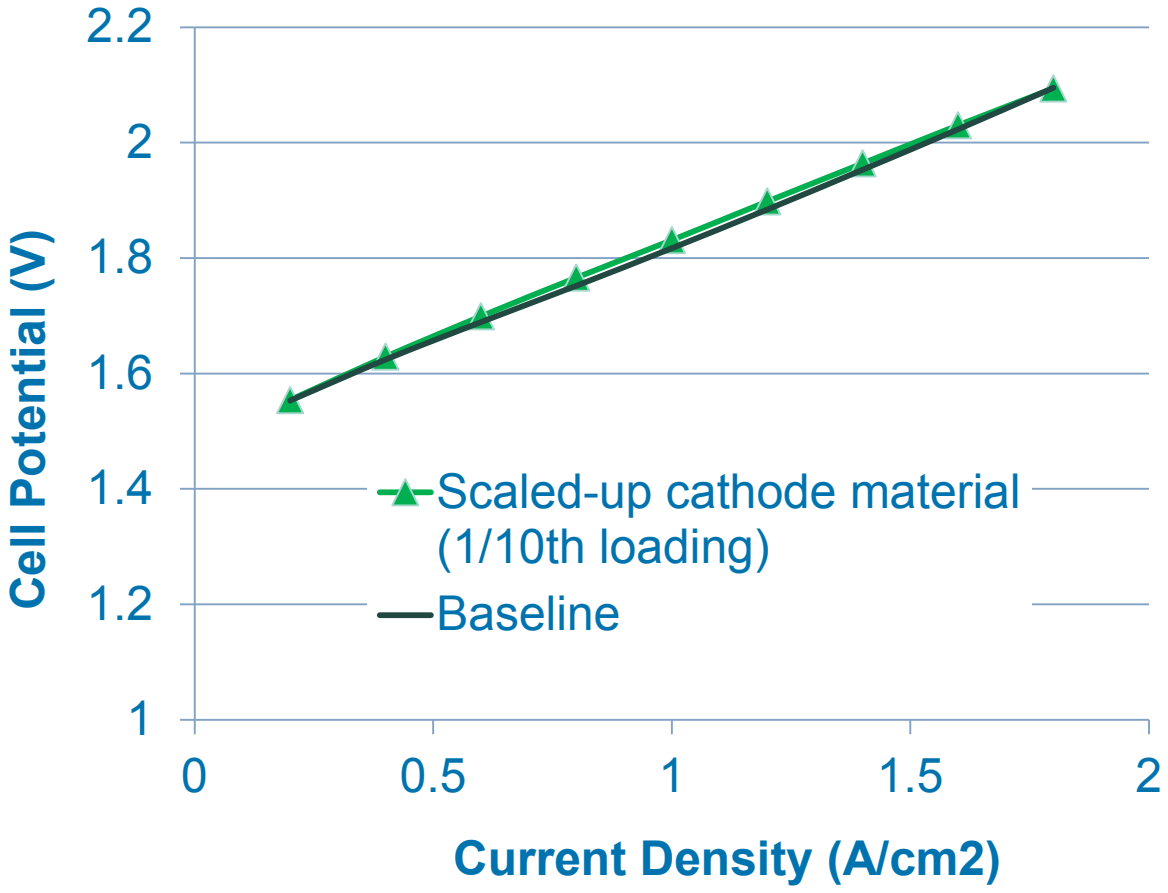
Technical Accomplishments: Scale Up/Tech Transfer

- Scaled process from 1 to 10 g
- Performance met baseline



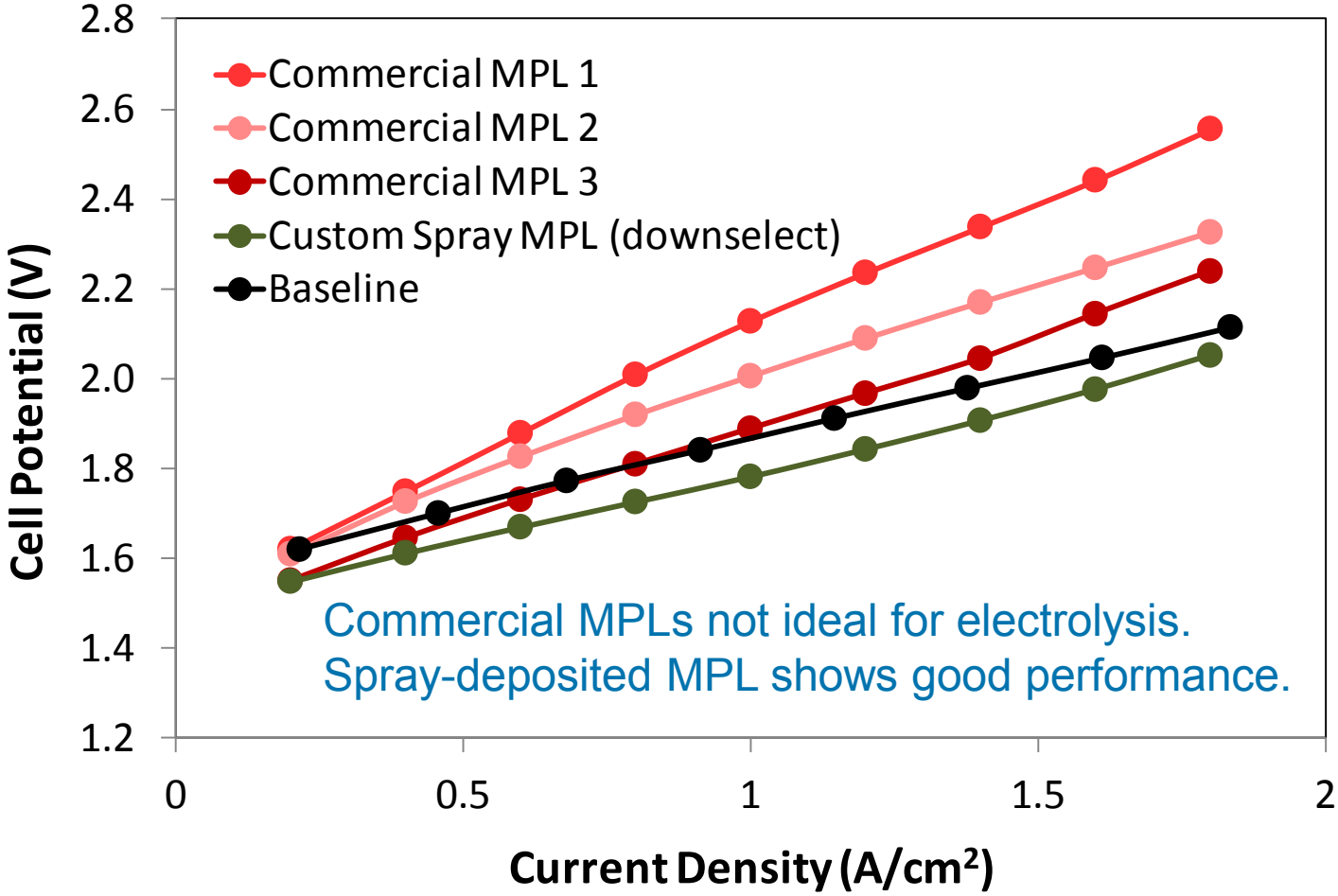
Color transformation: dark brown to green

Safety-qualified hydrogen reducing furnace



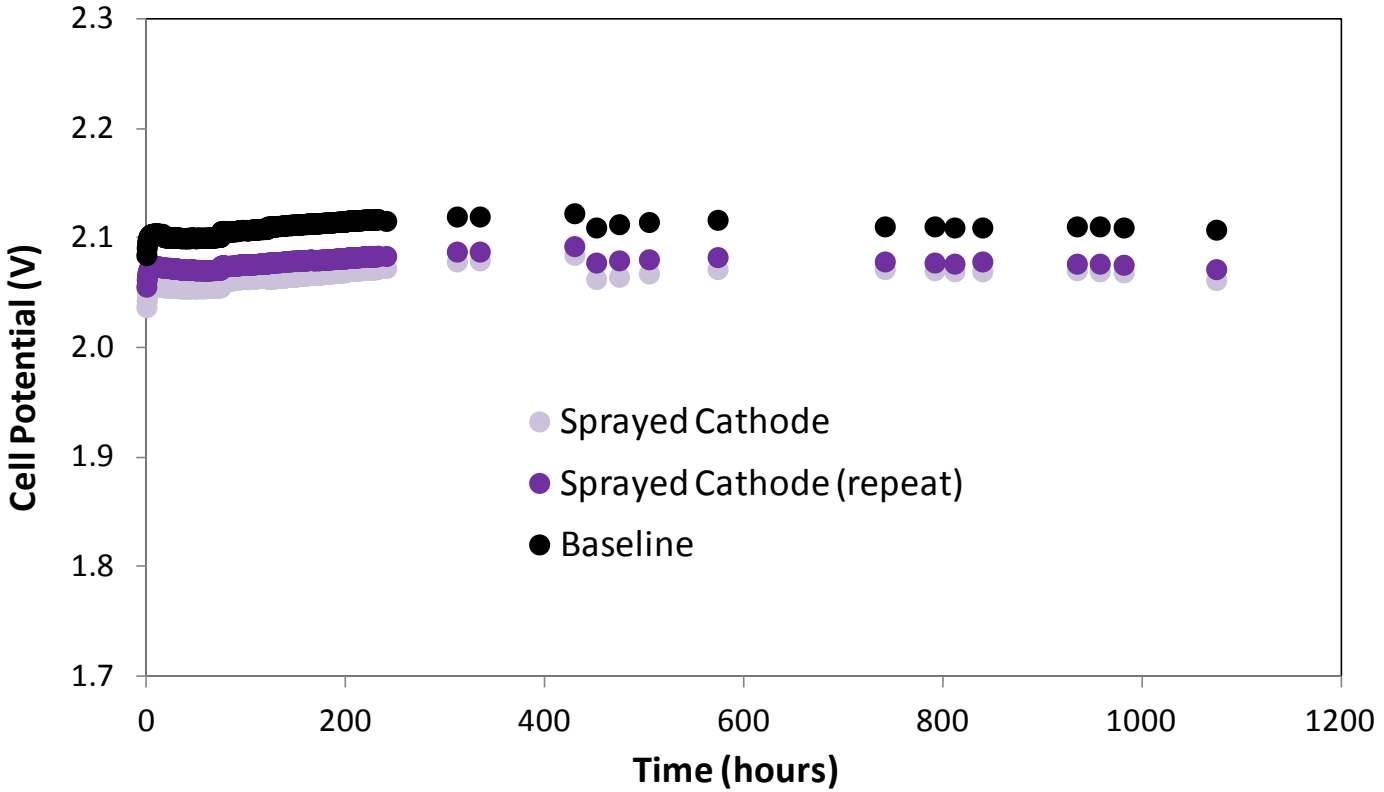
Technical Accomplishments: Manufacturing

- Downselected printing manufacturing method, catalyst, and MPL for cathode
- Durability demonstrated to >500 hours



Technical Accomplishments: Scale Up

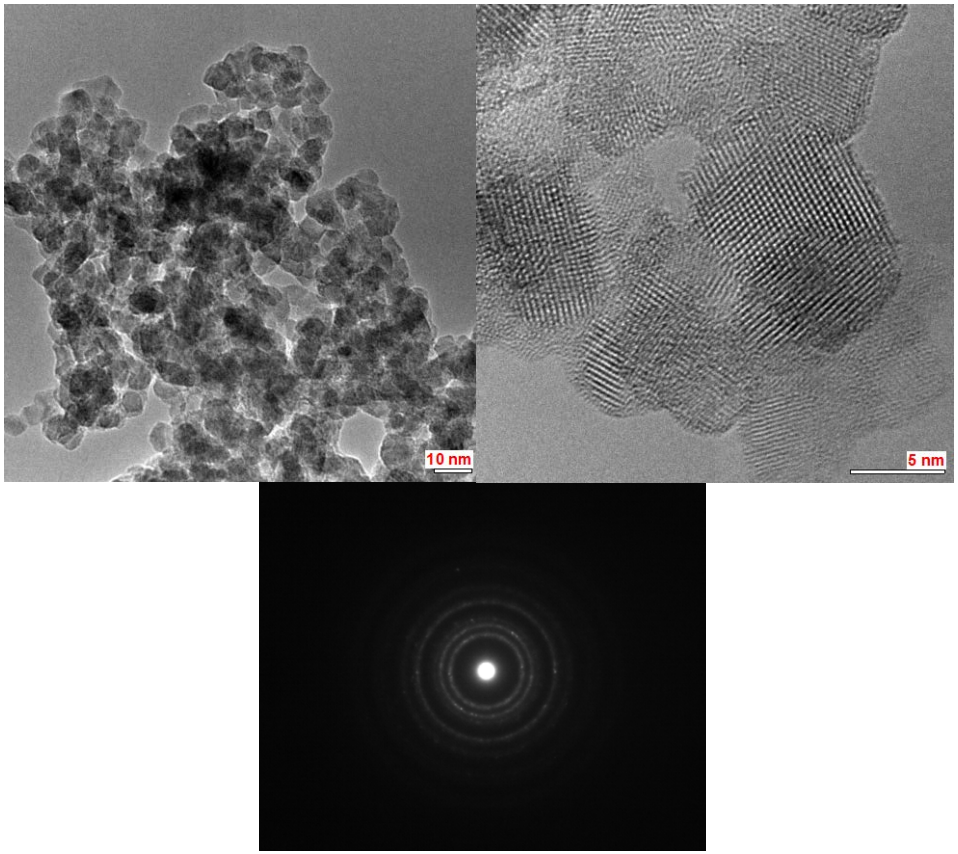
- Large active area electrode qualified using full loaded cathodes (~700 cm^2 area sprayed).



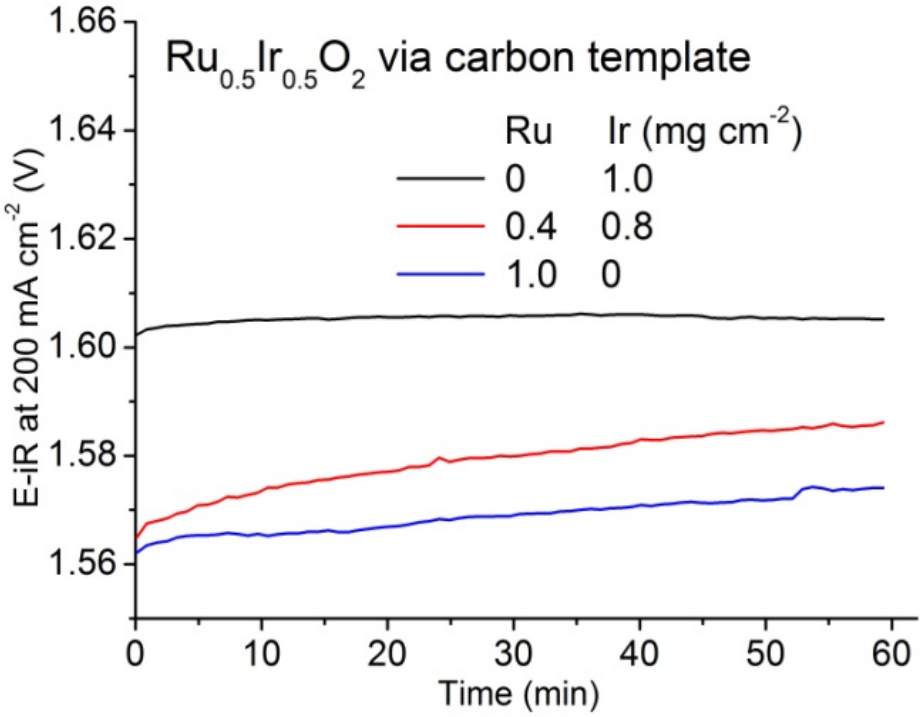
Repeatable baseline performance demonstrated on electrodes cut from large active area print using advanced manufacturing techniques.

Technical Accomplishments: OER Catalyst

- RuO_2 and $Ru@IrO_2$ catalysts synthesized, characterized, and electrochemically tested



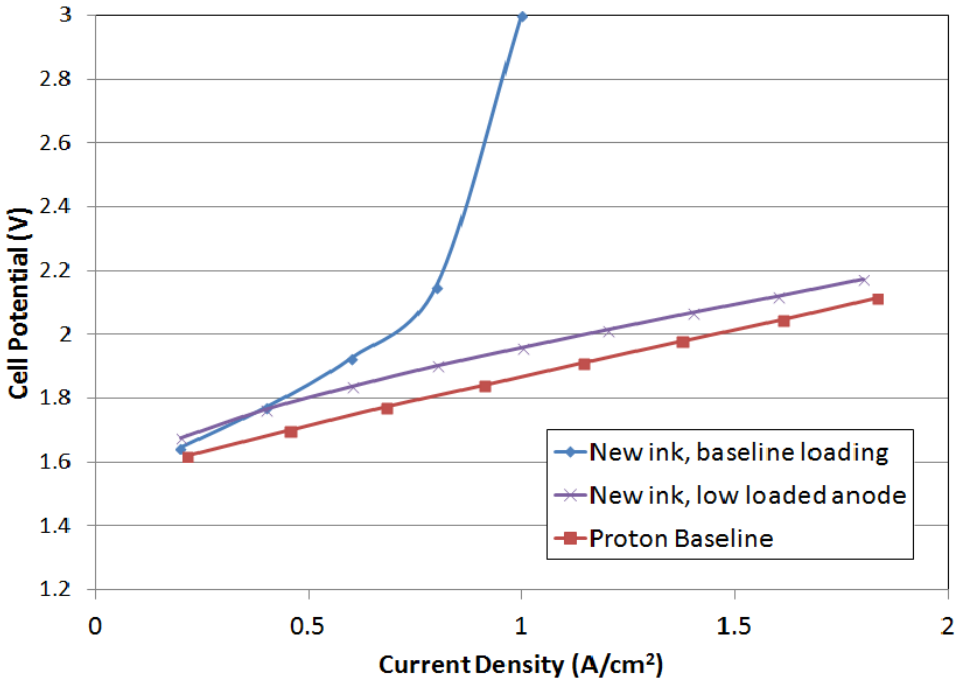
TEM images of uniform ordered RuO_2 particles

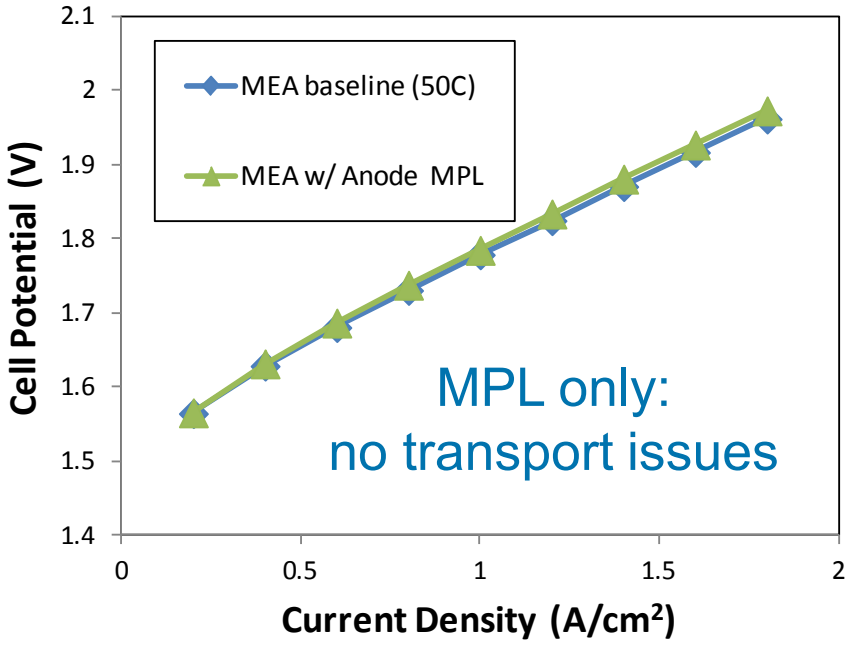


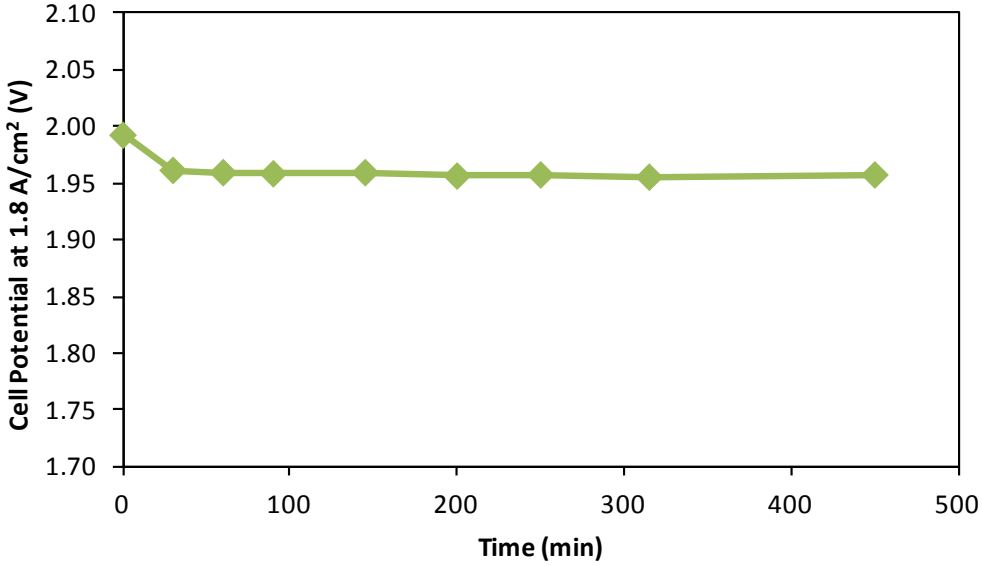
Ru enhances OER activity, but IrO_2 catalysts downselected because of stability

Technical Accomplishments: Anode

- Resolved early mass transport issues
- Anode MPL shown to not impact cell resistance

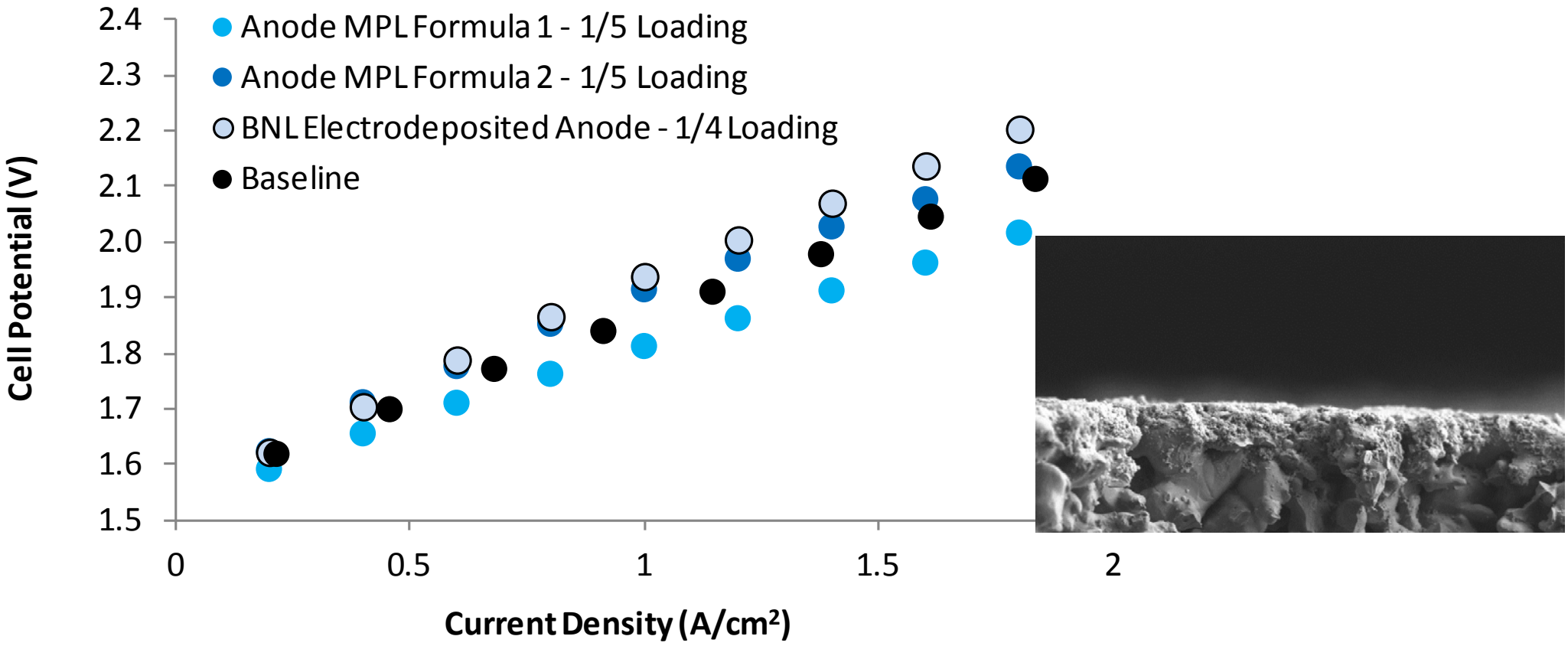






Technical Accomplishments: Anode

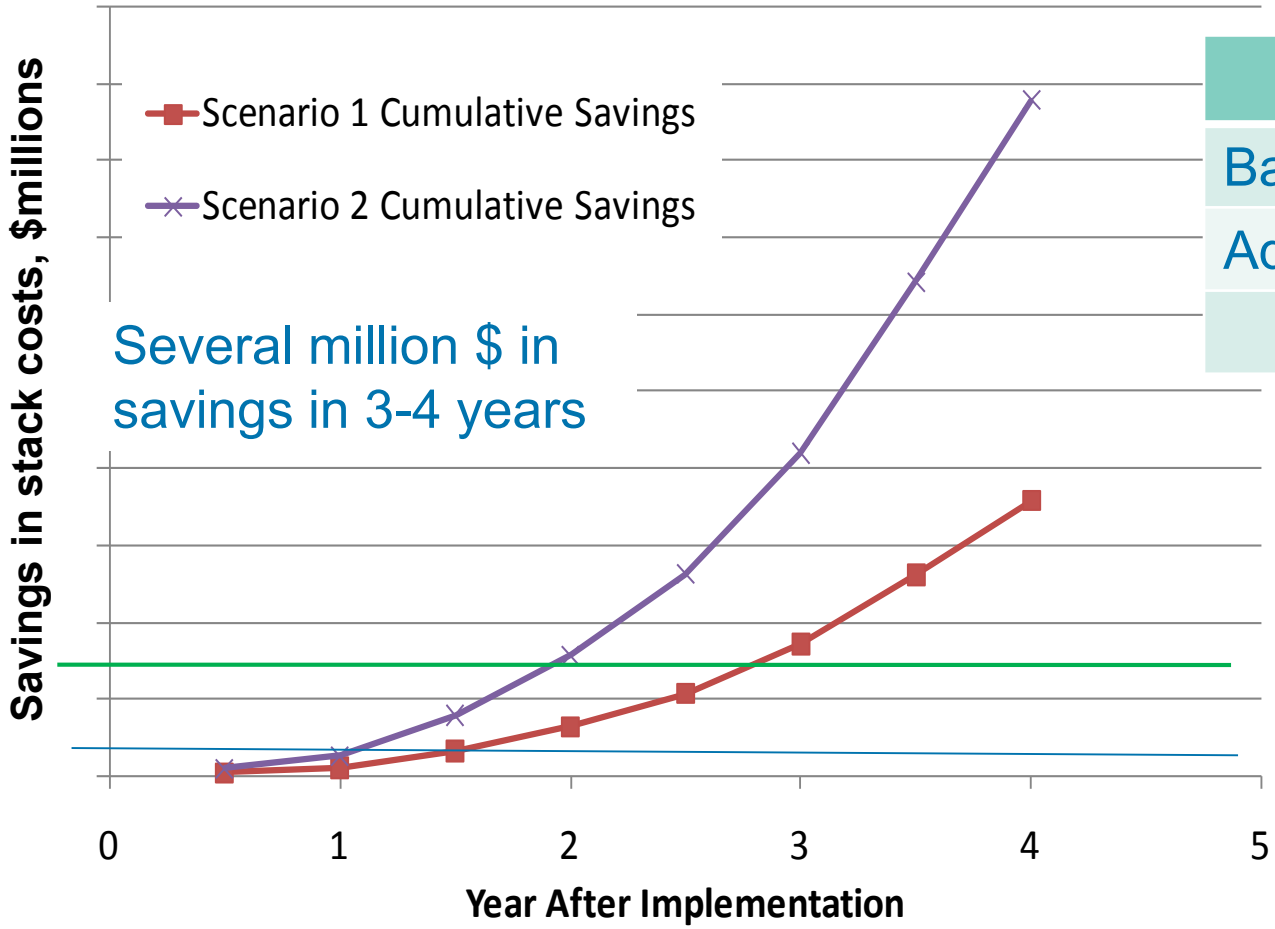
- Proton-made anode MPLs and BNL electrodepositing process enable lower catalyst loadings on the anode



Repeatable baseline performance is achieved using low-loaded anodes.

Technical Accomplishments: Cost

- Advanced approach provides large competitive advantage at MW scale
- Capital cost impact larger than implied by H2A model



	Electricity	$/kg H2
Baseline	$0.06/kWh	$5.10
Advanced	$0.06/kWh	$4.98
$/kW Delta: ~$150		

Future Work

- **Task 2: Cathode Manufacturing**
  - Scale-up down selected cathode configuration to multi-cell commercial stack platform
- **Task 3: Develop Anode Catalysts**
  - Optimize durability and performance of electrodeposited anodes for long-term testing
- **Task 4: Anode Electrode Fabrication**
  - Downselect anode MPL configuration
- **Task 5: Cell Development and Testing**
  - Final demonstration with cost-reduced electrodes
- **Task 6: Cost Analysis**
  - Refine the impact of design changes on the $/kg of H_2

Collaborators

- Brookhaven National Lab
  - Synthesis and characterization of core shell catalyst materials
  - Development of electrode formulations and application methods on GDLs for low catalyst loading
- University of Connecticut (not funded by this project)
  - Paseoguilari group: MPL development
  - Maric group: synergistic alternate anode project
- Printer and accessory suppliers
- Proton cell stack supply chain

Technology Transfer Activities

- Successfully transferred Brookhaven catalyst synthesis to Proton and scaled up batch size
- Exploring manufacturing options for the core-shell cathode catalyst
- Optimizing custom MPL configurations for anode and cathode

Summary

- **Relevance:** Demonstrates pathway to reducing stack capital cost
- **Approach:**
  - Optimize anode catalyst formulation and utilization for 80% cost reduction
  - Identify optimum configuration for manufacturable, ultra-low loaded cathode
- **Technical Accomplishments:**
  - Completed scale up synthesis of cathode catalysts
  - Identified multiple pathways for 80% cost-reduced anode
  - Downselected a manufacturable ultra-low loaded cathode. Showed > 500 hrs durability in production quality hardware
  - Demonstrated process capability for large active area electrodes
- **Collaborations:**
  - Brookhaven National Labs – catalyst and formulation development
  - University of Connecticut – MPL development
- **Proposed Future Work:**
  - Downselect anode MPL configuration for long-term testing
  - Manufacture large active area cost reduced electrodes for final demonstration
  - Perform cost analysis

Acknowledgments

The Proton Team

- Everett Anderson
- Blake Carter
- Chris Capuano
- Luke Dalton
- Nem Danilovic
- Morgan George
- Judith Manco
- Mike Niedzwiecki
- Mike Parker
- Julie Renner
- Andy Roemer

Our Collaborators

- Jia Wang
- Yu Zhang