Overall Research on Electrode Coating Processes (OREO)

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DOE AOP #10.2.0.502
June 6-8, 2022

DOE Hydrogen Program
2022 Annual Merit Review and Peer Evaluation Meeting

Project ID: TA050

Project Goal

- The cost of MEAs is a significant portion of stack and system manufacturing cost estimates. MEA costs are dominated by material costs – processing costs are generally small.
- *However, extrapolations of cost at high volumes to ascertain the decrease of cell or stack cost associated with economies of scale* ***assume roll-to-roll (R2R) processing technologies that have not been proven at scale***. In particular, they have not been proven in their ability to
  - Process FC and EC materials at high quality
  - Form electrode morphologies that will provide acceptable electrochemical performance.
- Project Goal: Address these unknowns by bringing together a unique network of experts in FC and EC ink/electrode fabrication, novel materials, advanced characterization, and in situ device testing, who have capabilities to
  - **Evaluate and compare material and process parameters across a wide range of different processes of interest to industry**
  - Access a common and unique platform of characterization tools to **enable understanding of the impact of materials, inks and processes on the nano- and micro-scale structure of the electrode, and how this impacts MEA performance**.
- The intended outcomes of this project will be cost savings and acceleration of commercialization of MEAs for electrolyzers and fuel cells.

Overview

Timeline and Budget

- Project start date: 10/01/2019
  - Proposed for 3 years
- Total DOE funds received to date: $900,000 (fully funded)
  - All partners funded separately (not by HFTO)

Barriers

Barrier	Target
A. Lack of high-volume MEA processes	$20/kW (2025) at 100,000 stacks/yr
H. Low levels of quality control	

Partners

- Fraunhofer ISE (Ulf Groos)
  - Funded via Germany
- University of Connecticut (Jasna Jankovic)
- Colorado School of Mines (Svitlana Pylypenko)
  - UConn and Mines funded via NSF and the states of Connecticut and Colorado

Relevance

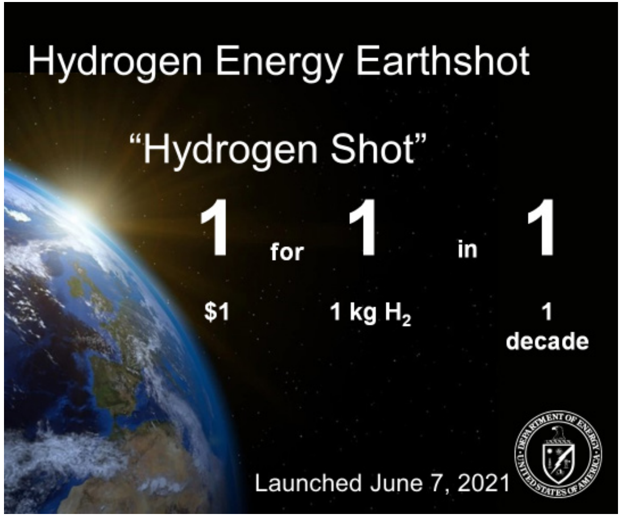
Hydrogen Energy Earthshot: Key Enablers for Lower Cost Electrolytic H2

Stetson, Hydrogen Program Annual Merit Review plenary, 2021

- Low-cost electricity
- High electrical efficiency
- **Low-cost capital expense**
- **Increased durability-lifetime**
- **Low-cost manufacturing processes**
- **Manufacturing at MW-scale**

Addressed by OREO Collaboration

ENERGY earthshots U.S. DEPARTMENT OF ENERGY | Hydrogen



Bipartisan Infrastructure Law (BIL)

- Total of $9.5B authorized and appropriated for Clean Hydrogen in Nov. 2021 over 5-year period (FY22-FY26)
- <u>Section 815</u>: $0.5B Clean Hydrogen Manufacturing and Recycling
  - "**RD&D projects to advance new clean H2** production, processing, delivery, storage and use equipment **manufacturing technologies and techniques**"
- <u>Section 816</u>: $1.0B Clean Hydrogen Electrolysis Program
  - Goal: To **reduce the cost of hydrogen produced using electrolyzers** to less than $2 per kilogram of hydrogen by 2026

Approach

- Leverage broad range of coating/processing technologies and expertise at NREL and ISE
- Utilize a common and unique set of advanced characterization tools at the two university partners to understand the impacts of ink and coating parameters on electrode morphology
- Perform in situ testing at NREL and ISE to understand these impacts on MEA performance
- Leverage broad industry relationships and participation in HFTO and AMO consortia

Date	Milestone/Deliverable (status as of 4/12/21)	Complete
6/21	Complete plans for meeting or workshop in year 3	100%
9/21	Perform EC ink and coating studies exploring the limits of catalyst solids	100%
9/21	Coordinate on quarterly meetings and two joint publications	90%
12/21	Correlate between catalyst properties and ink behaviors	100%
3/22	Compare three Pt/HSC catalysts for processing differences	100%
6/22	Hold a workshop to present OREO results to the community	25%
9/22	Coordinate with ISE to compare IrOx coating processes	25%
9/22	Coordinate on quarterly meetings and two joint publications	50%

Approach

Goals:

1. Identify relevant process-related questions regarding fuel cell and electrolyzer electrode processing
2. Address those questions by performing a broad range of electrode studies to understand the impact of ink, coating, and drying conditions on electrode morphology and performance
   - Durability studies are out of scope for OREO; however, samples fabricated within OREO have been and will be used within H2NEW Task 3 (see P196c)activities to understand durability aspects

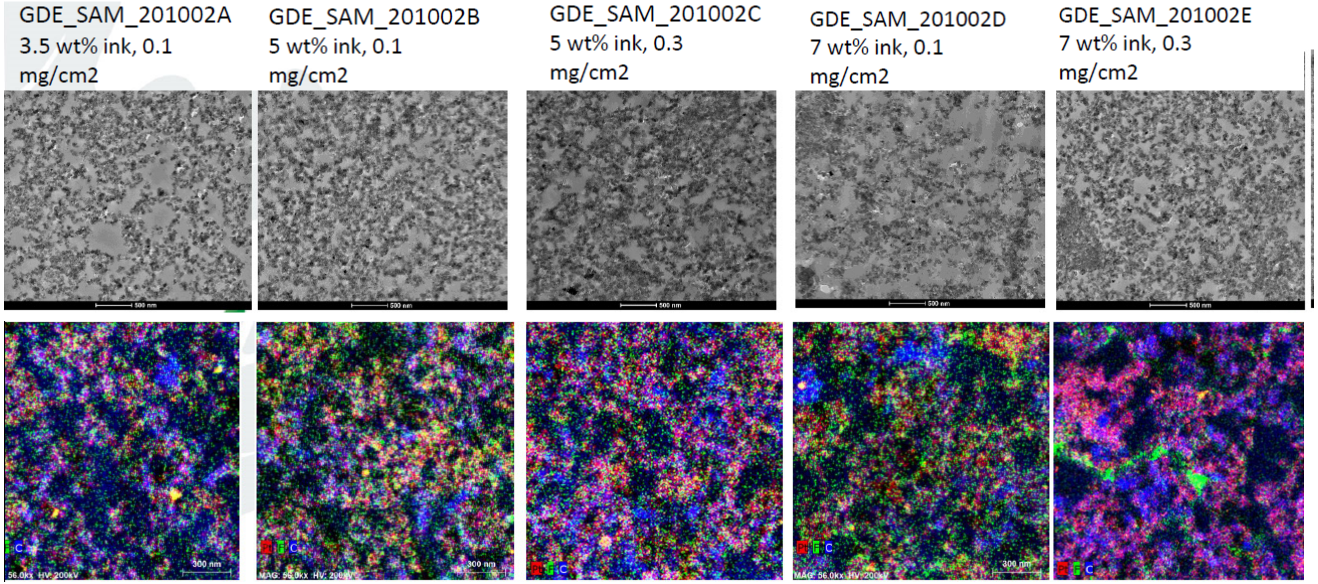
Studies during FY2022:

- Study 1: Understand the impact of Pt/HSC catalyst solids loading on electrode morphology
- Study 2: Understand the impact of support type and Pt wt.% on ink properties and coating
- Study 3: Understand the impact of differences in supplier for 50% Pt on HSC catalysts on inks and coating
- Study 4: Understand the impact of drying conditions on Pt/C electrode morphology
- Study 5: Understand the impact of coating shear on Pt/C electrode morphology
- Study 6: Understand the impact of ball milling time on Pt/C ink properties
- Study 7: Understand the impact of coating process type on IrOx anode coating window and morphology

Accomplishments

Impact of Pt/HSC solids loading on electrode morphology

- R2R slot-die-coated electrodes fabricated from 3.5, 5, and 7 catalyst wt.% inks (all at 0.9 I:C), and coated at two target loadings
- Results: STEM/EDS shows a range of porosity and dispersedness of catalyst and ionomer
  - In situ testing pending

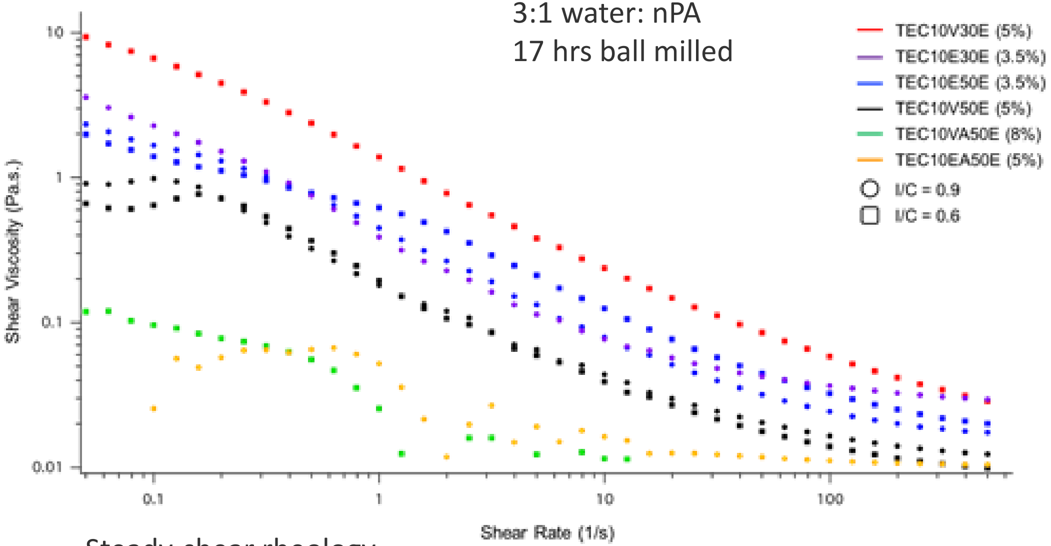


Accomplishments

Impact of support type and Pt wt.% on ink properties and coating

- Used Ketjen, Vulcan, and graphitized supports with 30 and 50 wt.% Pt (see backup slides for full listing of catalysts and formulations)
- Result: Support type, Pt wt.% on support, and catalyst wt.% in ink all impact rheology

Ink:
3:1 water: nPA
17 hrs ball milled



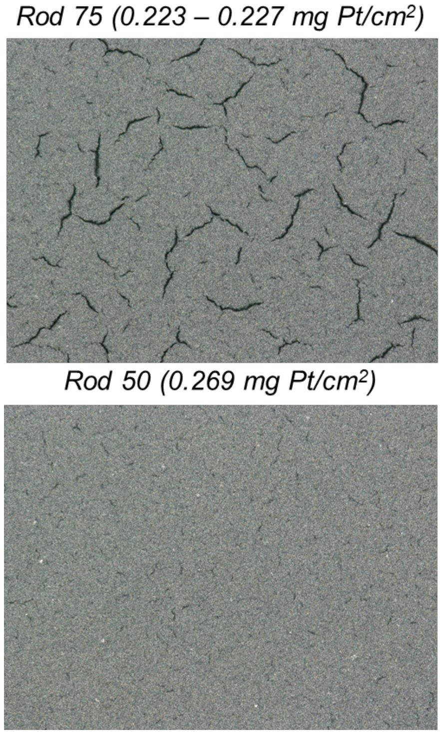
Steady-shear rheology

Accomplishments

Impact of support type and Pt wt.% on ink properties and coating

- Result: Electrode surface morphology was a strong function of Pt wt.% and support type

Comparison of Vulcan (top) and graphitized Vulcan (bottom) catalyst inks at 50 Pt wt.% and I/C of 0.9



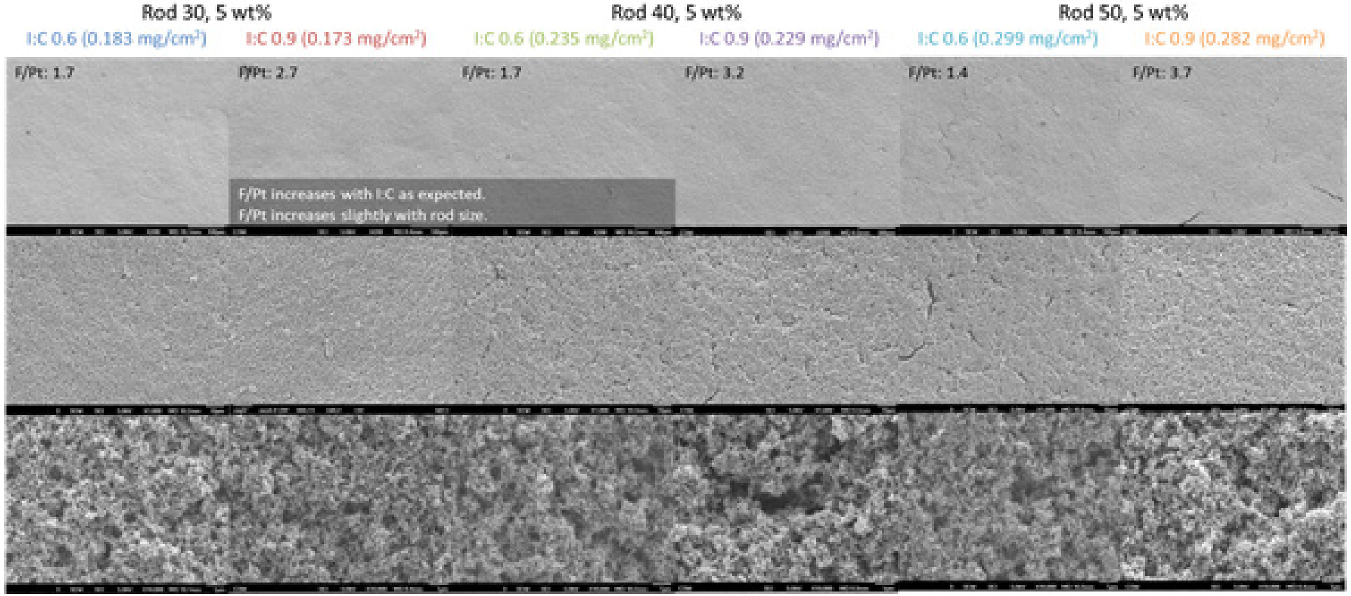
Comparison of Vulcan catalyst inks at 30 (top) and 50 (bottom) Pt wt.% at I/C of 0.6

Accomplishments

Impact of support type and Pt wt.% on ink properties and coating

- Cracking increases as thickness increases (as expected)
- Nano-scale morphology similar, possibly with slightly larger pores at higher I:C

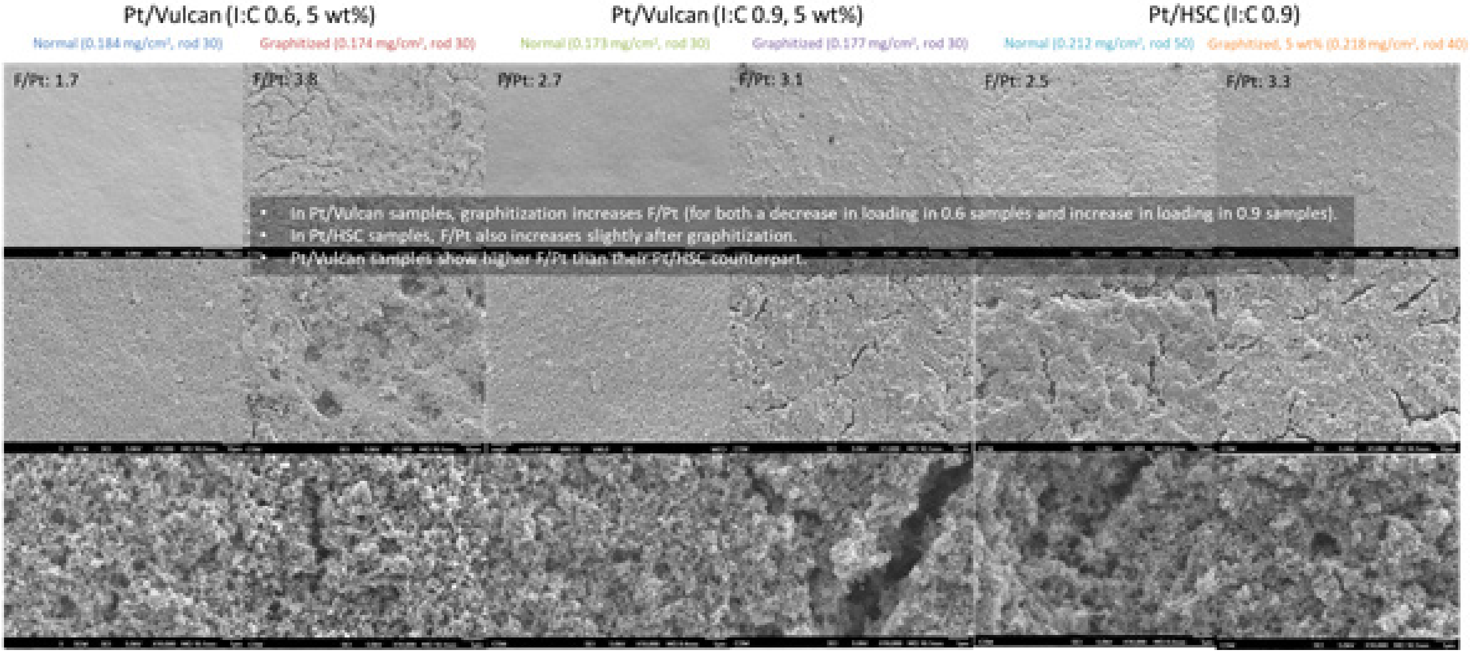
SEM at three magnifications and F/Pt by ESD (top of each column) of 5 catalyst wt.% Pt/Vu ink at three wet thickness and two I:C



Accomplishments

Impact of support type and Pt wt.% on ink properties and coating

- Graphitized Vulcan has more surface structure (roughness, cracking) than standard
- Not much difference resulting from the HSC inks

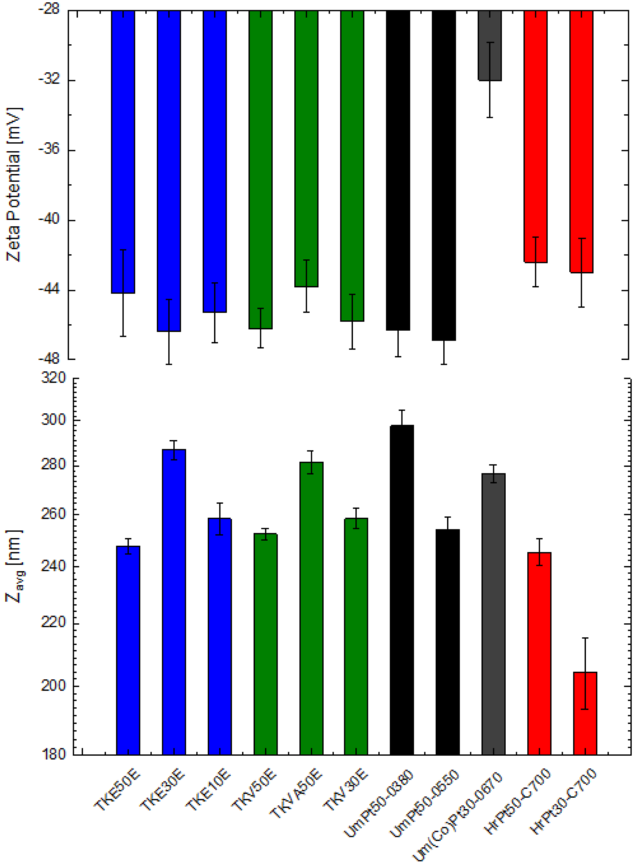


SEM of 5 catalyst wt.% Pt/Vu and Pt/HSC inks, comparing resulting surface structure for standard and graphitized supports

Accomplishments

Impact of support type and Pt wt.% on ink properties and coating

- Dilute inks measured with DLS
- Result: Heraeus Pt/HSC inks had lower particle size and zeta potential
  - Mainly comparable results from rest of the catalysts

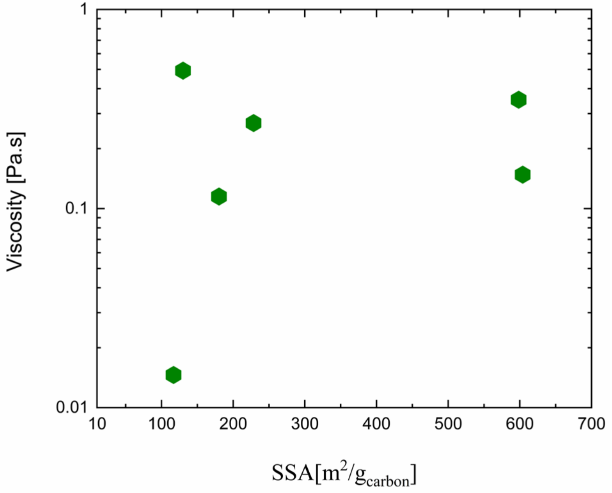


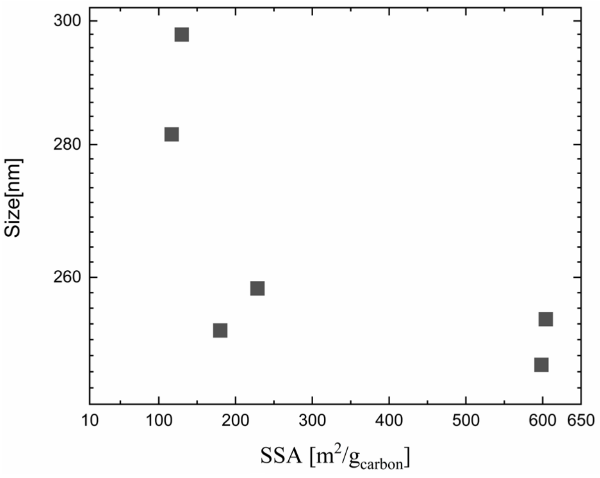
Zeta potential (top) and Zavg particle size (bottom) analysis of dilute Pt/C inks by DLS

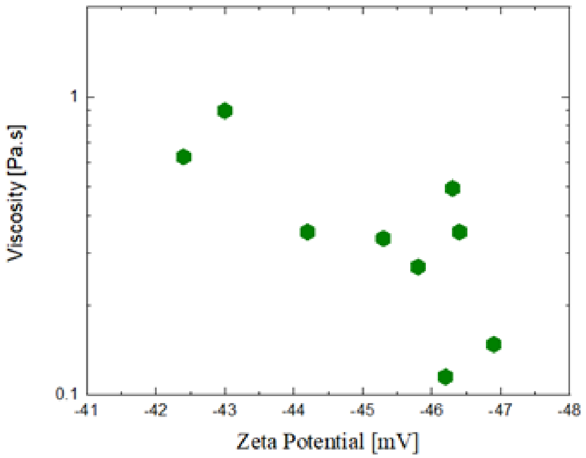
Accomplishments

Impact of support type and Pt wt.% on ink properties and coating

- Property/ink correlations
  - Viscosity (at 1/s) and Zavg size from DLS correlate weakly with support surface area
  - Viscosity (at 1/s) correlates relatively strongly with zeta potential





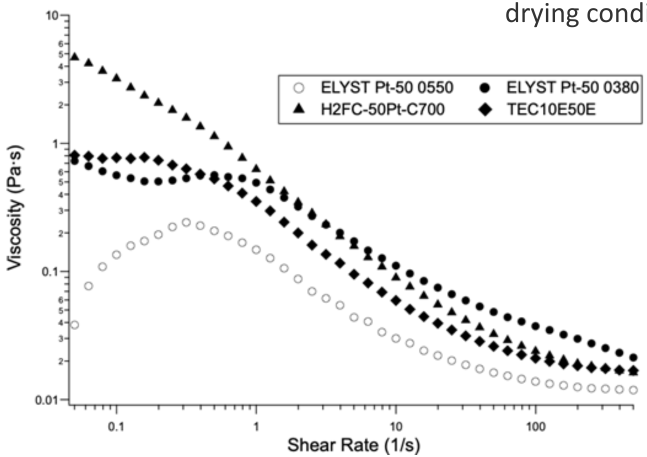


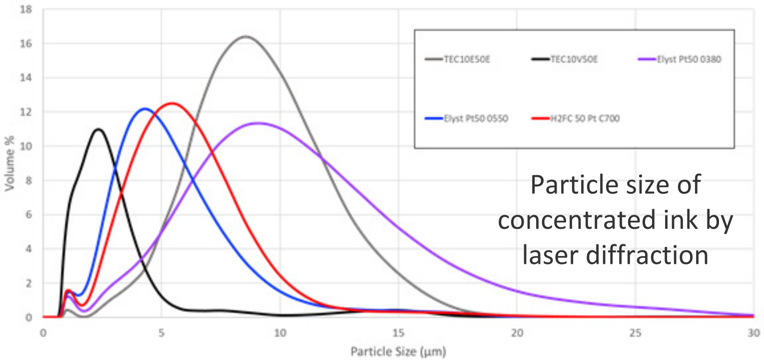
Accomplishments

Electrodes with same I:C, dispersion media, catalyst solids, and coating and drying conditions

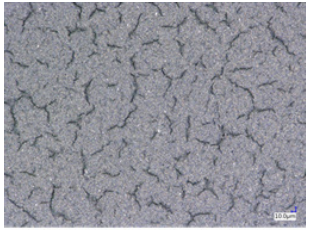
Impact of supplier processing on ink properties and coating

- Performed ink and coating comparison of 50 wt.% Pt on HSC catalysts from 3 suppliers
- Result: Generally, higher high-shear viscosity and larger particle size in the ink minimized cracking in the electrode

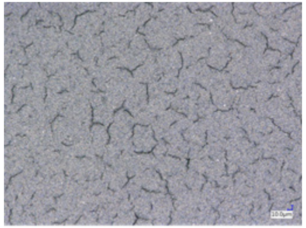




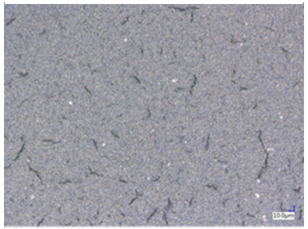
Particle size of concentrated ink by laser diffraction



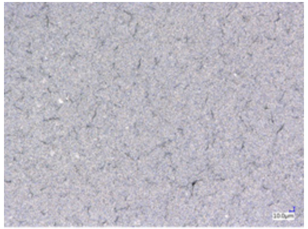
Pt/HSC (TEC10E50E)



Umicore (ELYST Pt50-05500)



Heraeus (H2FC-50 Pt-C700)

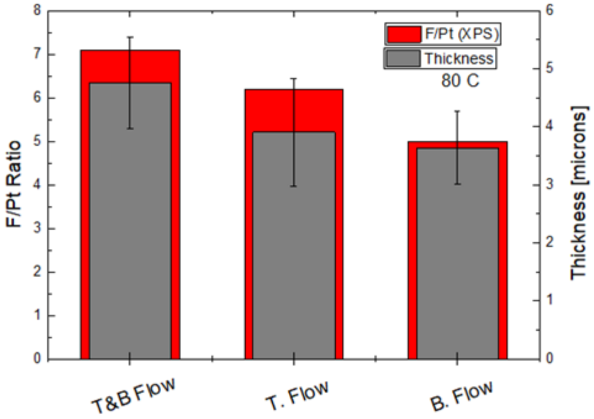


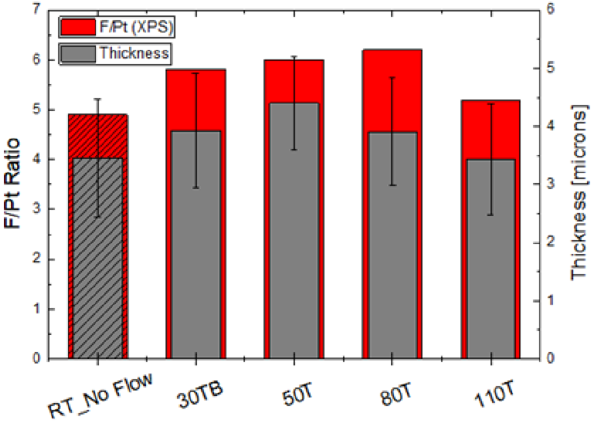
Umicore (ELYST Pt50-0380)

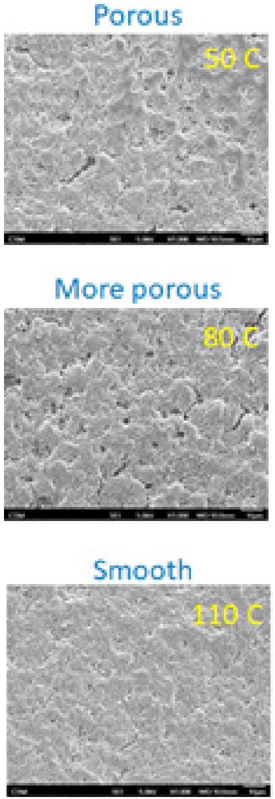
Accomplishments

Impact of drying conditions on electrode morphology

- For convective drying flows at 80C, electrode thickness (from SEM) and surface F/Pt ratio (XPS) trend as top+bottom flow > top flow > bottom flow
- Surface F/Pt and electrode thickness have non-monotonic responses to increasing drying temperature, indicating opposing behaviors
  - Surface porosity follows the same general trend, where lower and higher temperature cases are relatively smoother





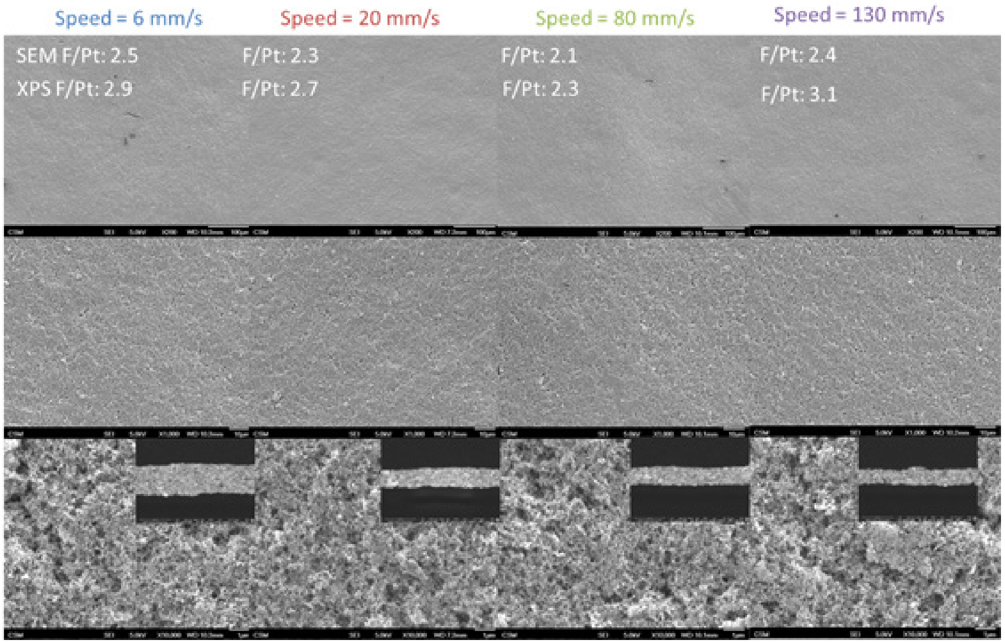


See backup slide for samples and conditions

Accomplishments

Impact of coating shear on electrode morphology

- Coated with #50 rod
- Surface SEM shows little impact of speed-induced shear
- However, coating thickness is significantly reduced with increased shear
- Surface F appears to have a minima at intermediate shear

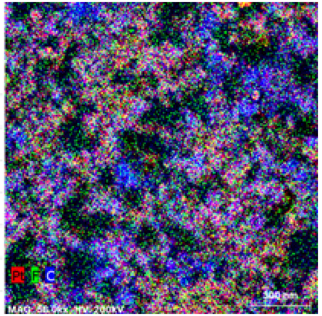


SEM at 3 magnifications, cross-section TEM in the bottom row, EDS F/Pt (first value) and XPS F/Pt (second value) for electrodes coated with #50 Mayer rod at 4 application speeds

See backup slide for samples and conditions

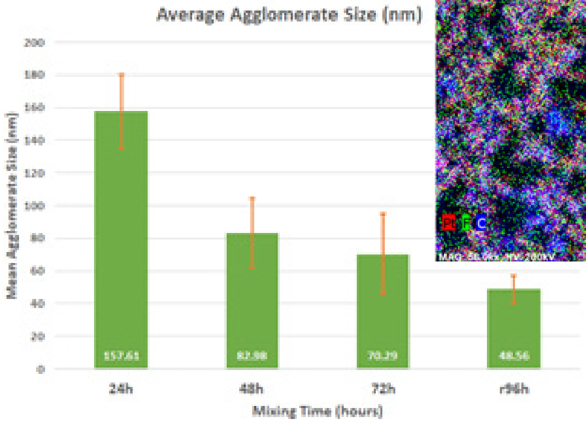
Accomplishments

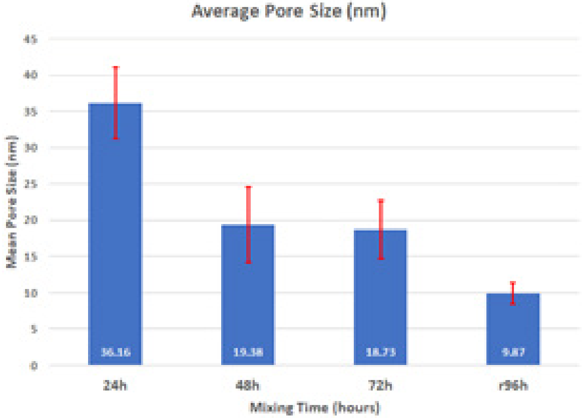
Example cross-section TEM with EDS



Fuel Cell electrode ball milling time study

- Experiment: understand impact of ball milling time on electrode morphology (I:C = 1.0, nPA-rich ink)
  - *Prior results showed that electrode cracking increased with increasing milling time, from 24 to 96 hours*
- Result:
  - Advanced data processing methods applied to cross-section TEM imaging
  - Agglomerate and pore size decrease with milling time
  - This matches other results where increased ink particle size correlated with decreased crack formation



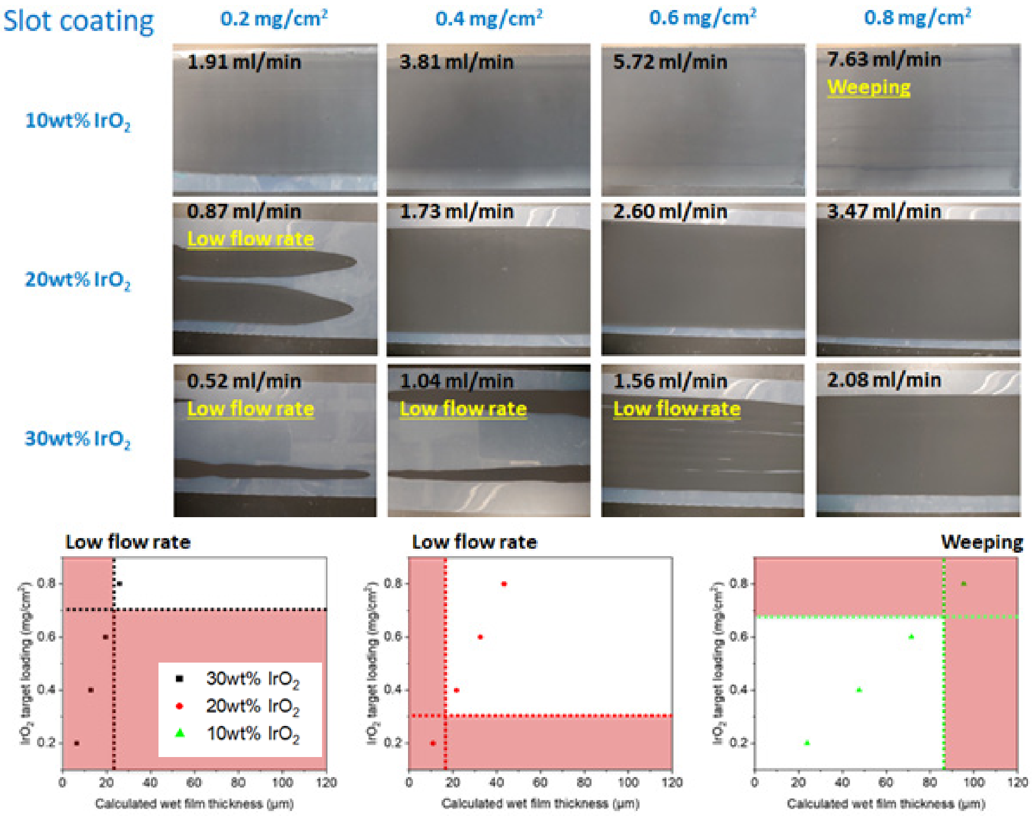


Accomplishments

See backup slide for samples and conditions

LTE coating process comparison study

- Experiment: understand the impact of scalable coating method on coatability and anode morphology
  - Compare slot die and gravure process windows using inks with 3 catalyst solids loadings over a range of wet thickness/catalyst loading
- Slot die Result: Due to the low typical viscosity of IrOx inks, even at high solids loading, uniform slot die coatings were observed in a limited range of conditions
  - 0.4 loading electrode with 20 wt.% ink performed comparably to sprayed comparator (see P196c)

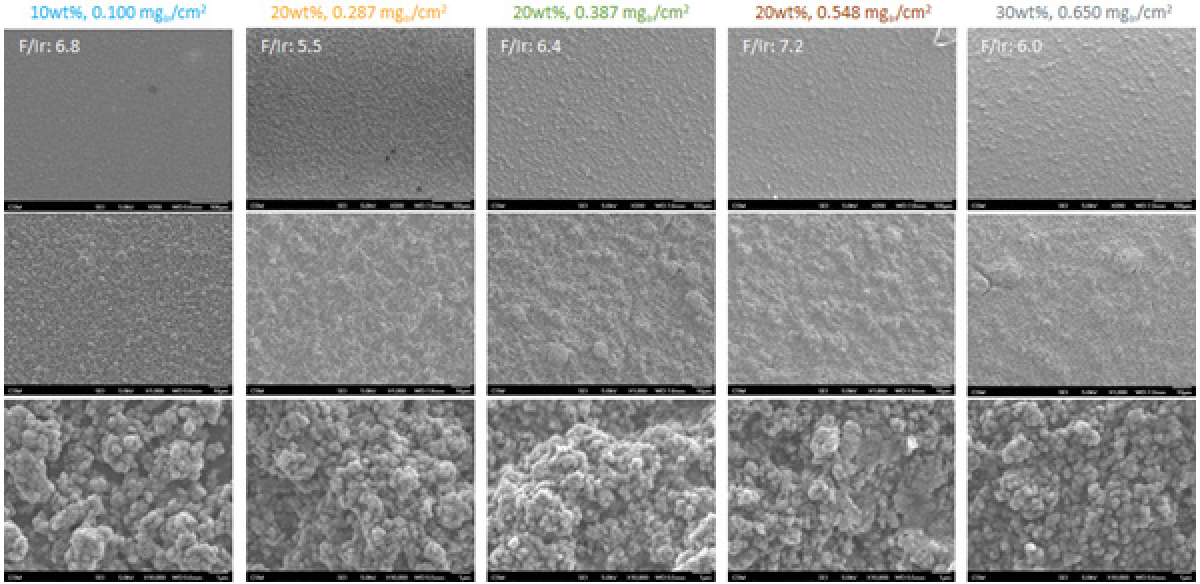


Slot die process window depiction

Accomplishments

LTE coating process comparison study

- SEM/EDS performed of slot die coated anodes
- Results:
  - Lower loaded samples appear to have smoother surface
  - Structure at high mag appears similar
  - F/Ir from EDS increases with thickness for the 20 wt.% inks



SEM at three magnifications for five slot die coated cases with F/Ir from EDS for each case inset in the top image of each column

Responses to Reviewer Comments

Comment: “Activity would benefit from having a parameter matrix to convey the multitude of parameters to characterize…”

Response: We agree with and thank the reviewer for this comment. We have added a parameter matrix in the backup slides.

Comment: “It is unclear whether the study of Mayer rod coating method is appropriate for at-scale manufacturing processes.”

Response: We appreciate the reviewer’s comment and heartily agree that the goal of the project should be information that is relevant to scalable processes. Fortunately, we have found that small-scale Mayer-rod coating studies correlate very well with R2R gravure coating studies. Thus, we find that Mayer rod studies are a useful scoping tool for later R2R experiments, where much less ink, substrate, and time are required to obtain results that can inform more focused (and expensive) R2R studies.

Comment: “…emphasis is needed on understanding how coating parameters control resulting structure and properties.”

Response: We absolutely agree, and in FY22 have been able to obtain significantly more nano- and micro-structural analysis from the university partners to understand these process-structure relationships.

Comments regarding lack of understanding of the interaction and fear of duplication of effort with H2NEW and M2FCT

Response: We appreciate the comment and agree that this is something that we must work at to ensure we’re leveraging but not overlapping efforts. Generally, the efforts within OREO are more process-science focused, whereas scaling studies within H2NEW and M2FCT are more related to specific materials or structures for a specific set of application targets. Also, note several interactions in our Accomplishments, for example where OREO samples were used within H2NEW and leveraged the greater emphasis on and infrastructure for performance and durability testing.

Collaboration and Coordination

- University of Connecticut and Colorado School of Mines
  - Provide **common and unique** advanced characterization tools for inks and electrodes
  - Coordinated U.S. funding via NSF and states of CT and CO
- Fraunhofer ISE
  - Access a **different set of electrode processing capabilities** for broad comparison
- NREL hosted visiting researchers from ISE, UConn, and CSM
- Industry partners in NSF project: Pajarito Powders, Forge Nano, GM, Giner
- Industry partners via NREL relationships: GM, Plug Power, Nel, 3M, Gore
- Leveraging NREL's leadership and participation in M2FCT, H2NEW, AMO R2R Multi-lab Collaboration

Remaining Challenges and Barriers

- Need better understanding of how manufacturing processing conditions impact performance of FC and EC materials
- There is also a need to understand any limitations of specific coating methodologies or other process conditions to enable manufactures to properly select processes that will be suitable for their materials or product specifications
- Understanding integration of novel materials will speed up transition from lab-scale processes to manufacturing
- Manufacturing of electrolyzer MEAs is much less mature than fuel cells, therefore less is known about the impacts of ink formulations and processing conditions on electrochemical performance

Proposed Future Work

In the final partial year of the project (as currently funded) we will focus on:

- Collaboration and coordination with ISE
  - The ISE activity did not receive their funding until half-way through the NREL effort
- Addressing electrolysis anode-related processing challenges
- In situ electrochemical testing
  - We have had resourcing issues for in situ testing that have recently been addressed
- Publishing of the copious results from the collaboration jointly with the university partners

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

Summary

- The goals of the OREO International Collaboration directly support the Hydrogen EarthShot and the BIL Clean Hydrogen sections
- The project leverages a unique set of industrially-relevant coating processes and analytical tools to determine relationships between materials, processes, and performance
- The wide-ranging results presented herein aim to assist industry in scaling up fuel cell and electrolyzer electrodes, in coordination with H2NEW and M2FCT

Acknowledgements:

NREL Team: Scott Mauger, Sunil Khandavalli, Carlos Baez-Cotto, Sanghun Lee

CSM Team: Svitlana Pylypenko, Michael J. Dzara, Sarah Zaccarine, Samantha Medina, Jayson Foster, Sara Kim, Olivia Bird

UConn Team: Jasna Jankovic, Andres Godoy, Mariah Batool

Thank You

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NREL/PR-5900-82792

This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Hydrogen and Fuel Cell Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

NREL Transforming ENERGY

Technical Backup and Additional Information

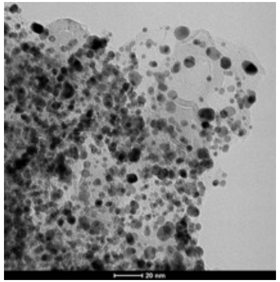
Technology Transfer Activities

- The OREO collaboration will pursue technology transfer via
  - Direct engagement with industry through partner and consortium relationships
  - Joint publications and presentations at relevant conferences
  - Unique project-supported meetings
    - International Conference on Electrolysis and co-located fuel cell processing session, June 2022, Golden, CO

Relevance

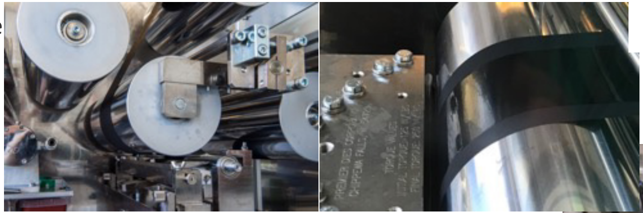
- HFTO Multi-year RD&D Plan – Manufacturing R&D barriers and milestones
  - Task 1: 1.2 Develop processes for direct coating of electrodes on membranes or gas diffusion media, 1.3 Develop continuous MEA manufacturing processes that increase throughput and efficiency and decrease complexity and waste
  - Task 5: 5.5 Develop correlations between manufacturing parameters and manufacturing variability and performance and durability of MEAs
- Leverage and support FY2020 HFTO consortia scale-up-focused activities (M2FCT & H2NEW)
- 2020 DOE Hydrogen Program Plan: "…R&D efforts can help achieve economies of scale in manufacturing… **key opportunities include: High-speed manufacturing techniques for processes such as… coating, roll-to-roll processing**"
- 2020 "Roadmap to a US Hydrogen Economy": "…**cost targets achieved driven by investments in manufacturing and process development and increasing production scale**… improvements in manufacturing processes and supply chains should be prioritized."

Approach: Leveraging Unique Processing Platforms and Advanced Characterization Methods



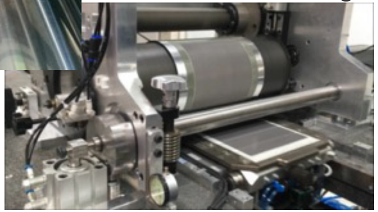
Materials
(Industry Partners)
Benchmark and novel catalyst

Gravure



Slot Die

Screen Printing



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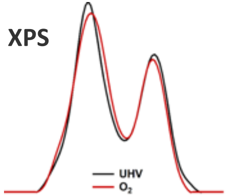
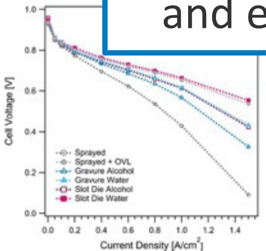
Processing
(NREL/ISE)
Multiple R2R processing platforms

XPS



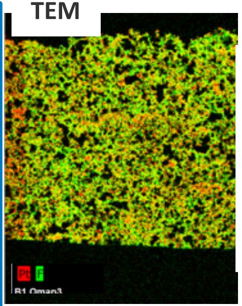
Binding Energy (eV)

Electrochemical Testing
(NREL/ISE)
In situ testing of fuel cell and electrolysis MEAs

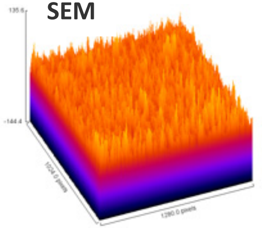


Advanced Characterization
(Mines/UConn)
Common and unique tools for CL and MEA characterization

TEM



SEM



Parameter Matrix

	Hot Press	Drying	Speed	Process	Substrate	Mixing	Solids	Disp Media	Ionomer
Cat/Sup		✓		✓		✓	✓	★	✓
Ionomer		✓		✓			✓	★	
Disp Media		★		★	★	★	★		
Solids				✓		★			
Mixing				✓ ★					
Substrate	★			★					
Process									
Speed									
Drying									

✓ **Addressed by OREO study**

★ **Addressed via other efforts**

Preliminary assessment of priority

Green: High priority – data/know-how suggests there will be effects worth exploring

Yellow: Medium priority – need more data to confirm if there is an expected trend worth exploring

Accomplishments and Progress: GDEs Prepared to study impacts of catalyst type

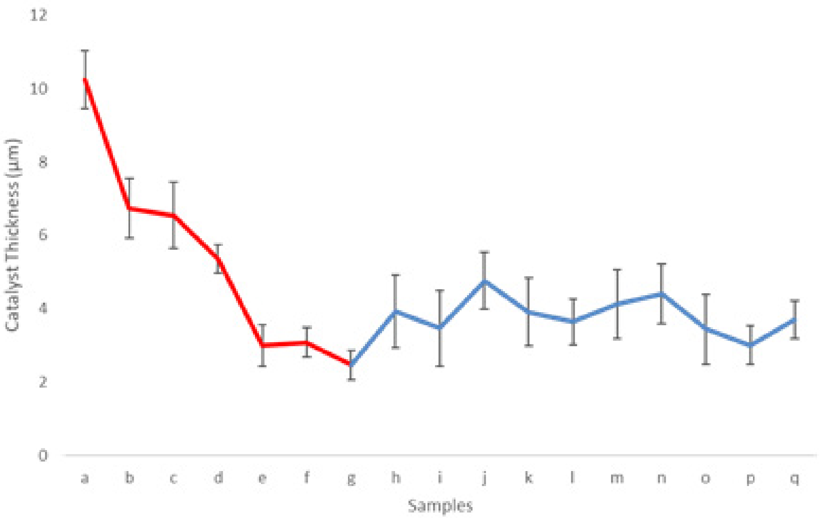
Catalyst Type	Catalyst wt %	I/C	Pt loading (mg/cm²)	C loading (mg/cm²)	Rod size
TEC10V50E (Pt/Vulcan)	5	0.6 / 0.9	0.184 / 0.173	0.216 / 0.203	30
			0.235 / 0.229	0.276 / 0.269	40
			0.299 / 0.282	0.351 / 0.331	50
TEC10V30E (Pt/Vulcan)	5	0.6	0.202	0.471	60
			0.248	0.579	75
TEC10E50E (Pt/HSC)	3.5	0.6 / 0.9	0.218 / 0.212	0.256 / 0.249	50
TEC10E30E (Pt/HSC)	3.5	0.9	0.164	0.383	75
	5		0.106	0.247	30
TEC10VA50E (Pt/Graph. Vulcan)	5	0.6 / 0.9	0.174 / 0.177	0.204 / 0.208	30
	8	0.6	0.270	0.317	30
		0.9	0.238	0.279	
TEC10EA50E (Pt/Graph. HSC)	5	0.9	0.218	0.256	40

Accomplishments

Sample table and electrode thickness (from cross-section TEM) for fuel cell electrode shear (a-g) and drying (h-q) studies

- Ink:
- Electrodes: rod coated onto Freudenberg H23C8 GDL
  - Coated with rods having different volume factors and at different draw-down speeds
  - Dried at room temp or in lab oven at 80C or in our R2R air floatation ovens at 30, 50, 80 and 110C, and different top and/or bottom flow conditions

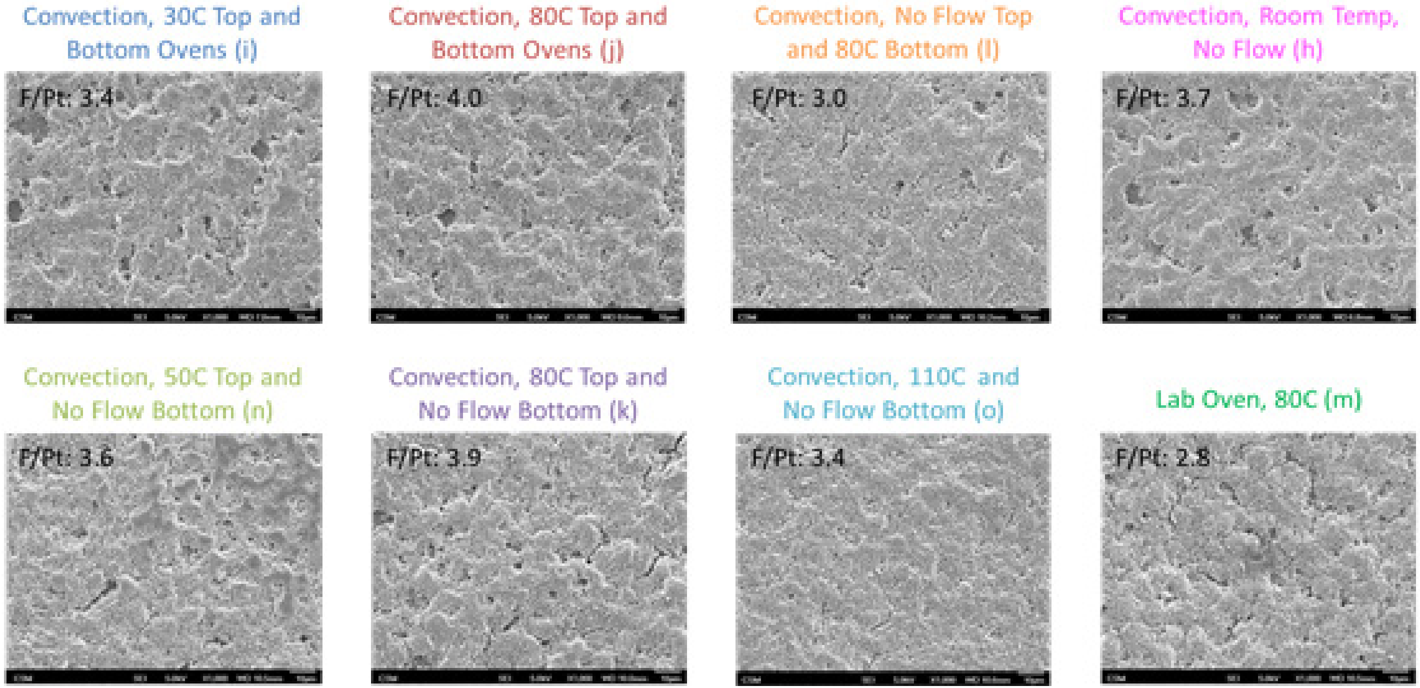
GDE_SK_210319a	OREO, Rod #50, speed = 6 mm/s
GDE_SK_210319b	OREO, Rod #50, speed = 20 mm/s
GDE_SK_210319c	OREO, Rod #50, speed = 80 mm/s
GDE_SK_210319d	OREO, Rod #50, speed = 130 mm/s
GDE_SK_210319e	OREO, Rod #20, speed = 6 mm/s
GDE_SK_210319f	OREO, Rod #20, speed = 80 mm/s
GDE_SK_210319g	OREO, Rod #20, speed = 130 mm/s
GDE_SK_210320h	OREO, Drying Effect, Convection Oven, Room Temp, No flow
GDE_SK_210320i	OREO, Drying Effect, Convection Oven, 30C Top and Bottom Ovens
GDE_SK_210320j	OREO, Drying Effect, Convection Oven, 80C Top and Bottom
GDE_SK_210320k	OREO, Drying Effect, Convection Oven, 80C Top and No flow bottom
GDE_SK_210320l	OREO, Drying Effect, Convection Oven, No flow top and 80C bottom
GDE_SK_210320m	OREO, Drying Effect, Lab Oven, 80C
GDE_SK_210320n	OREO, Drying Effect, Convection Oven, 50C Top and No flow bottom
GDE_SK_210320o	OREO, Drying Effect, Convection Oven, 110C Top and No flow bottom
GDE_SK_210320p	OREO, Solvent Effect, 25%H2O-75%nPA, Convection Oven, 30C Top and Bot
GDE_SK_210320q	OREO, Solvent Effect, 15%H2O-85%nPA, Convection Oven, 30C Top and Bott



Accomplishments

Impact of drying conditions on electrode morphology

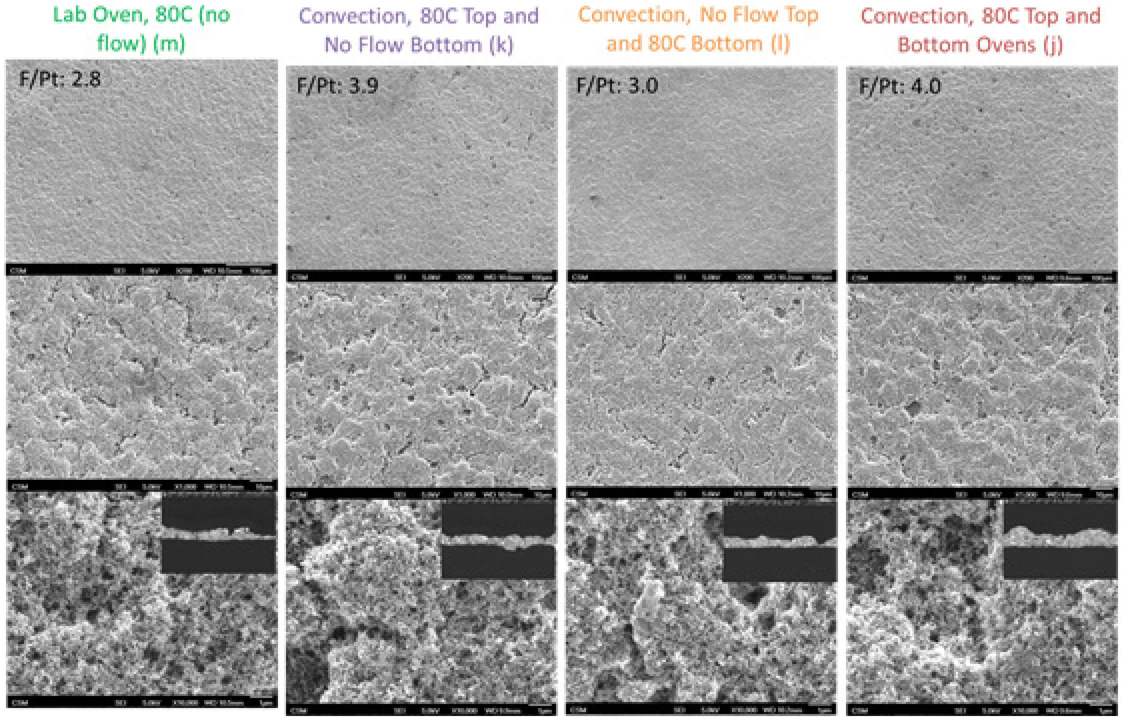
- Top-down SEM and EDS F/Pt at all 8 drying conditions



Accomplishments

Impact of drying conditions on electrode morphology

- SEM at 3 magnifications and EDS F/Pt for four drying cases
  - SEM EDS results indicate segregation of F to the surface during drying is maximized by convective flow from the top (i.e., onto the wet layer)
    - Same result as from XPS

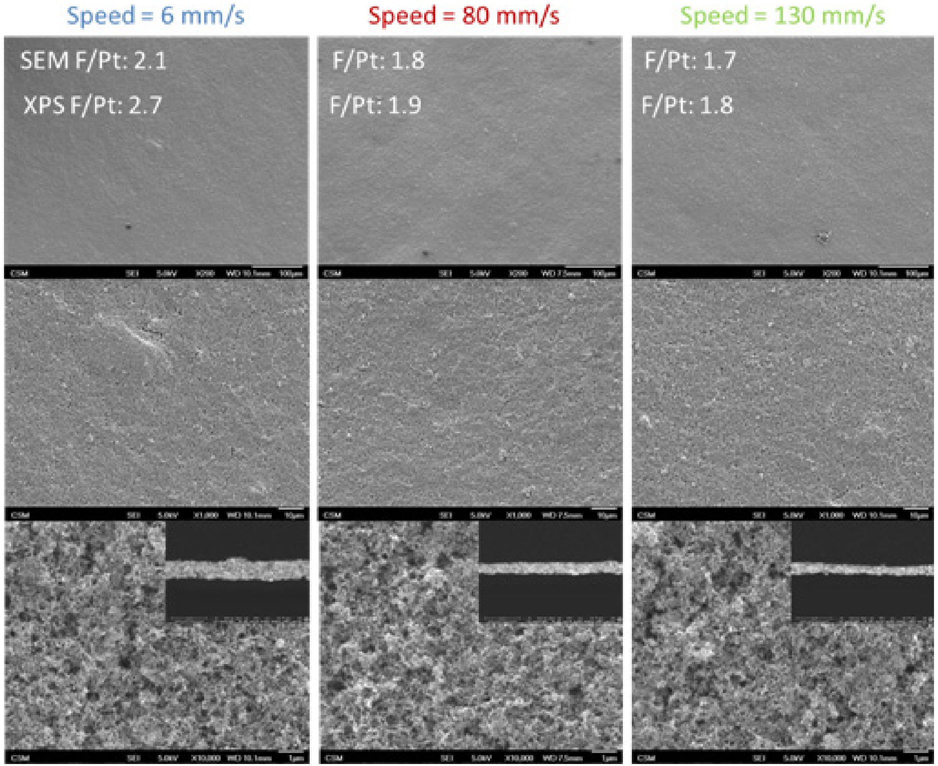


Cross-section TEM inset in bottom row

Accomplishments

Impact of coating shear on electrode morphology

- Coated with #20 rod
- Surface SEM shows little impact of speed-induced shear
- Coating thickness is significantly reduced as shear increases
- Surface F decreases as shear increases

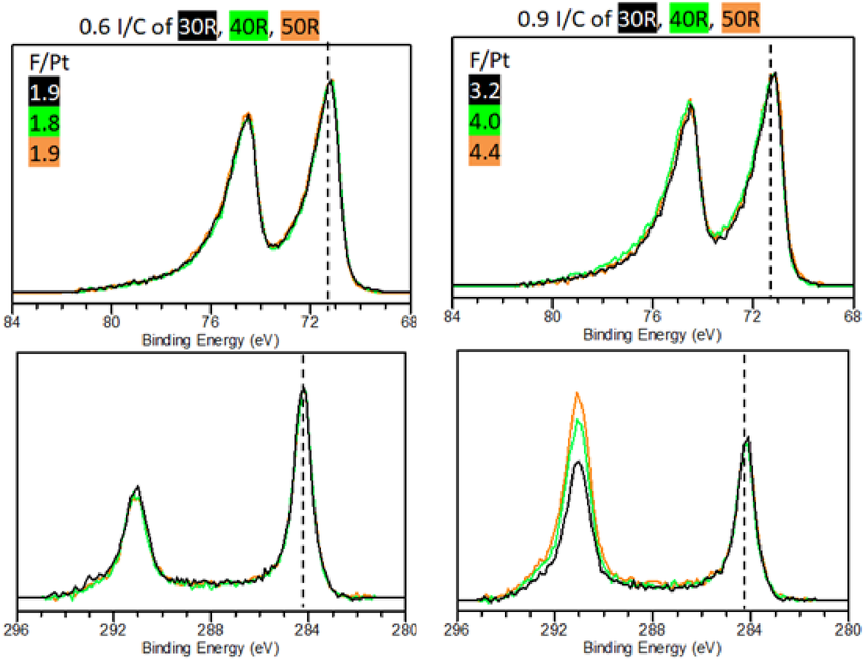


SEM at 3 magnifications, cross-section TEM in the bottom row, EDS F/Pt (first value) and XPS F/Pt (second value) for electrodes coated with #20 Mayer rod at 3 application speeds

Accomplishments

Impact of ink and coating parameters on surface F content

- *GDE surface F content has been shown to be an indicator of performance*
- Experiment: Pt/Vu and Pt/HSC inks at 0.6 and 0.9 I:C, rod-coated at 3 wet thicknesses (30R, 40R and 50R rods)
- Result: For low ionomer case using Pt/Vu catalyst, surface F shows little change with wet thickness
  – However, for high (excess) ionomer case, thicker wet films have higher surface F

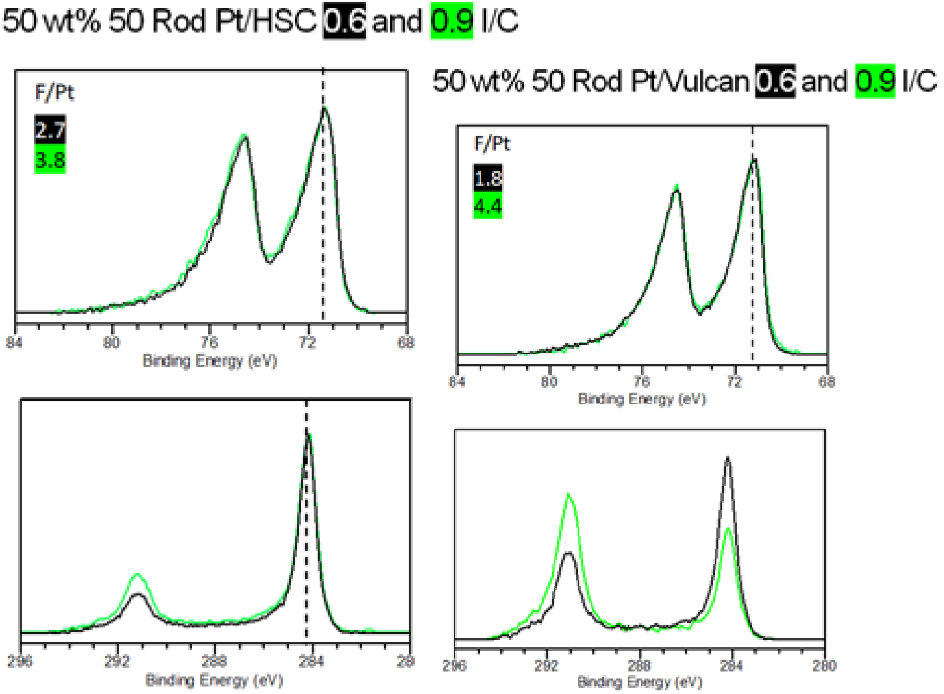


XPS F/Pt data for Pt/Vu inks at 0.6 and 0.9 I:C rod-coated at 3 wet thicknesses

Accomplishments

Impact of ink and coating parameters on surface F content

- Result: For low ionomer case we observe higher surface F for the Pt/HSC ink
- However, for the high ionomer case, we observe higher surface F for the Pt/Vu case

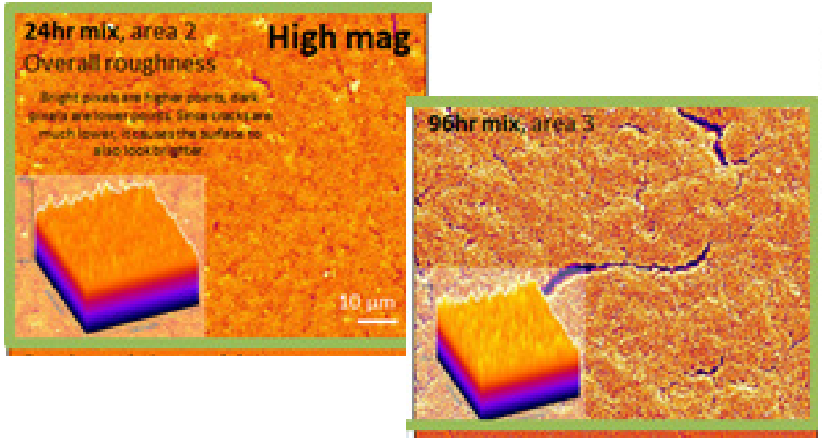


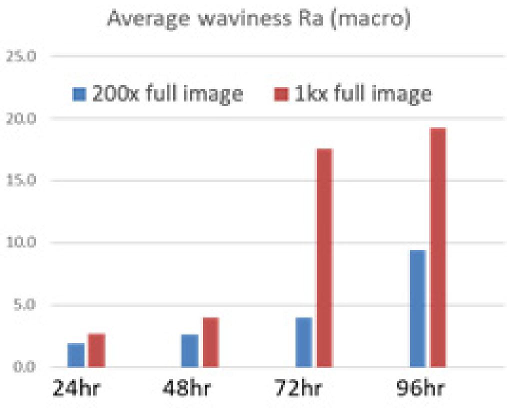
XPS F/Pt data for Pt/HSC (left) and Pt/Vu (right) inks at 0.6 and 0.9 I:C using #50 rod

Accomplishments

Fuel Cell cathode ball milling time study

- Result:
  - Advanced data processing applied to surface SEM imaging
  - Both micro- (between cracks) and macro-scale (including cracks) surface roughness observed to increase with ball milling time





Accomplishments

LTE coating process comparison study

- Experimental design:
  - Ink: 0.2 I:Cat; 10, 20, and 30 wt.% catalyst solids
    - nPA:water was 50:50 for 20 and 30 wt.% inks
    - nPA:water was 75:25 for 10 wt.% ink, to increase viscosity
  - Slot die flowrates varied to achieve target loadings
  - Gravure roller volume factors changed to achieve target loadings

Slot coating

		Catalyst Layer Loading (mg/cm2)			
		0.2	0.4	0.6	0.8
10 wt%	Estimated Flow Rate (mL/min)	1.91	3.81	5.72	7.63
20 wt%		0.87	1.73	2.60	3.47
30 wt%		0.52	1.04	1.56	2.08

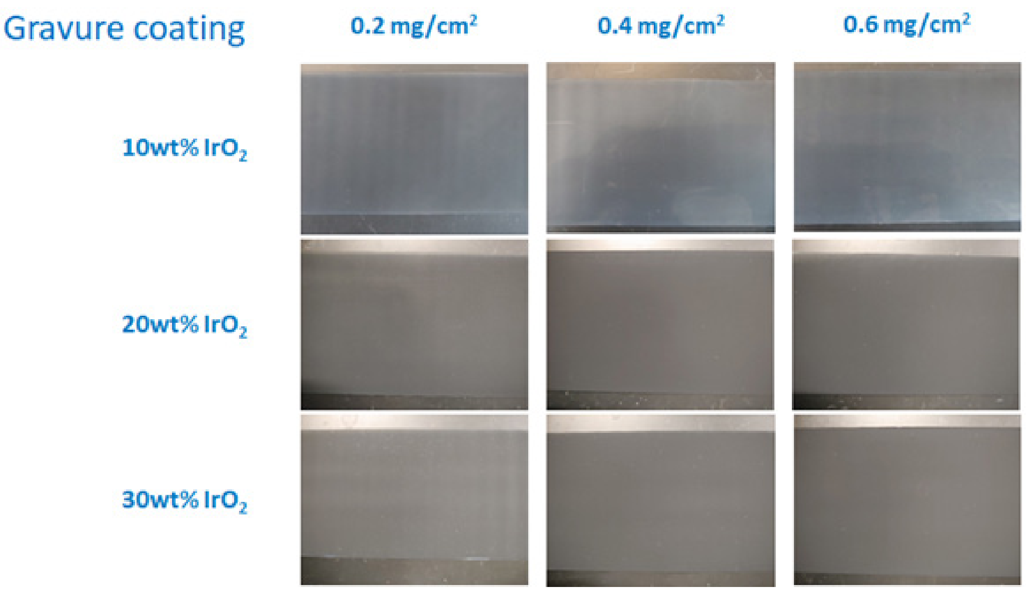
Gravure coating

		Catalyst Layer Loading (mg/cm2)		
		0.2	0.4	0.6
10 wt%	Cylinder sizes	R60	R30	R25
20 wt%		R120	R80	R38
30 wt%		R150	R120	R80

Accomplishments

LTE coating process comparison study

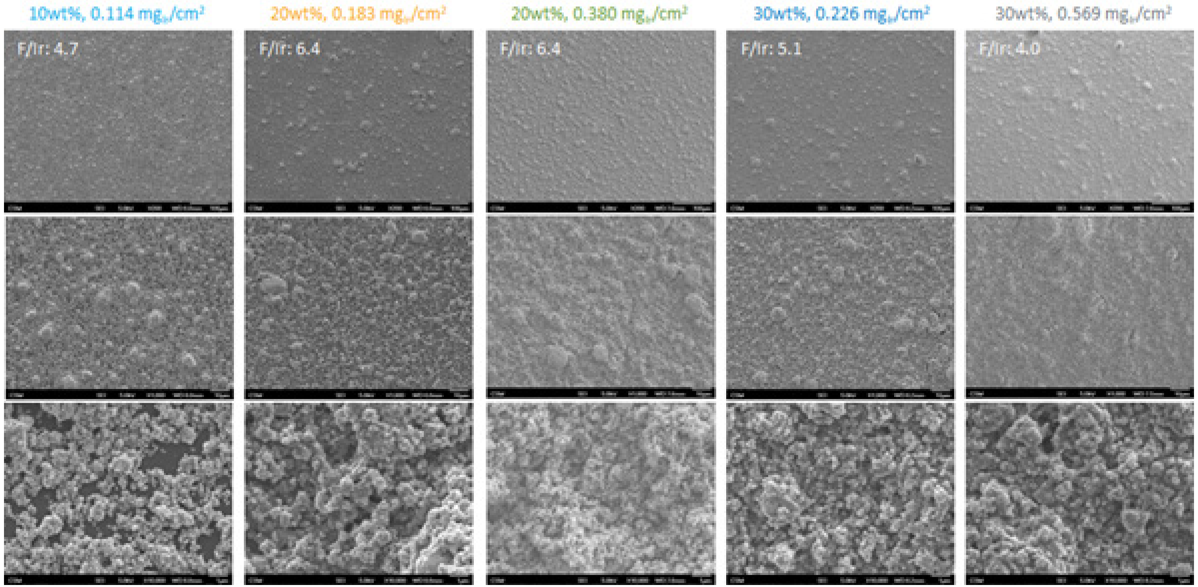
- Gravure Result: Selecting cylinder volume factor enabled visually uniform coatings at all conditions
  - Gravure is generally more suitable for Newtonian inks
  - Similar to the slot die case, in situ testing of the 0.4 loaded electrode at 20 wt.% showed comparable performance to sprayed baseline
  - However, later high-resolution optical microscopy showed micro-voids in some of the ~0.2 mg Ir/cm2 electrodes (see P196c)



Accomplishments

LTE coating process comparison study

- SEM/EDS performed of gravure coated anodes
- Results:
  - Low and medium mag imaging indicates larger agglomerates than slot die coated
  - Structure at high mag appears to be of finer scale than for slot die
  - Coating in 10 wt.% solids case appears discontinuous (verified later via optical microscopy)
  - F/Ir has a maxima at the 20 wt.% cases

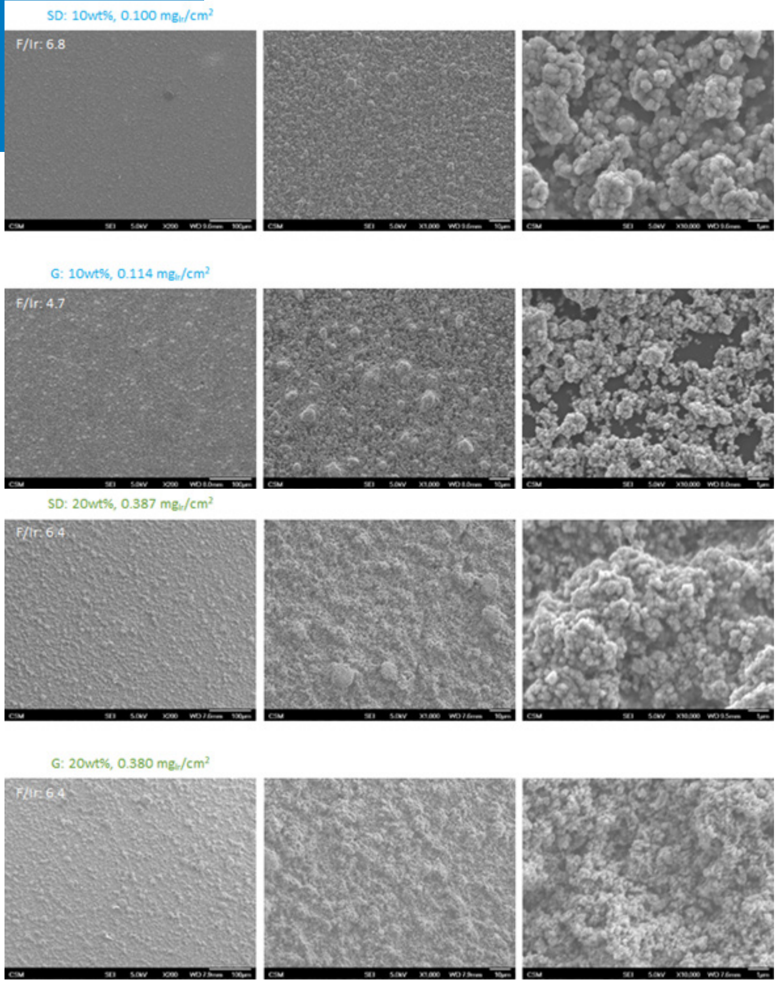


SEM at three magnifications for five gravure coated cases with F/Ir from EDS for each case inset in the top image of each column

Accomplishments

LTE coating process comparison study

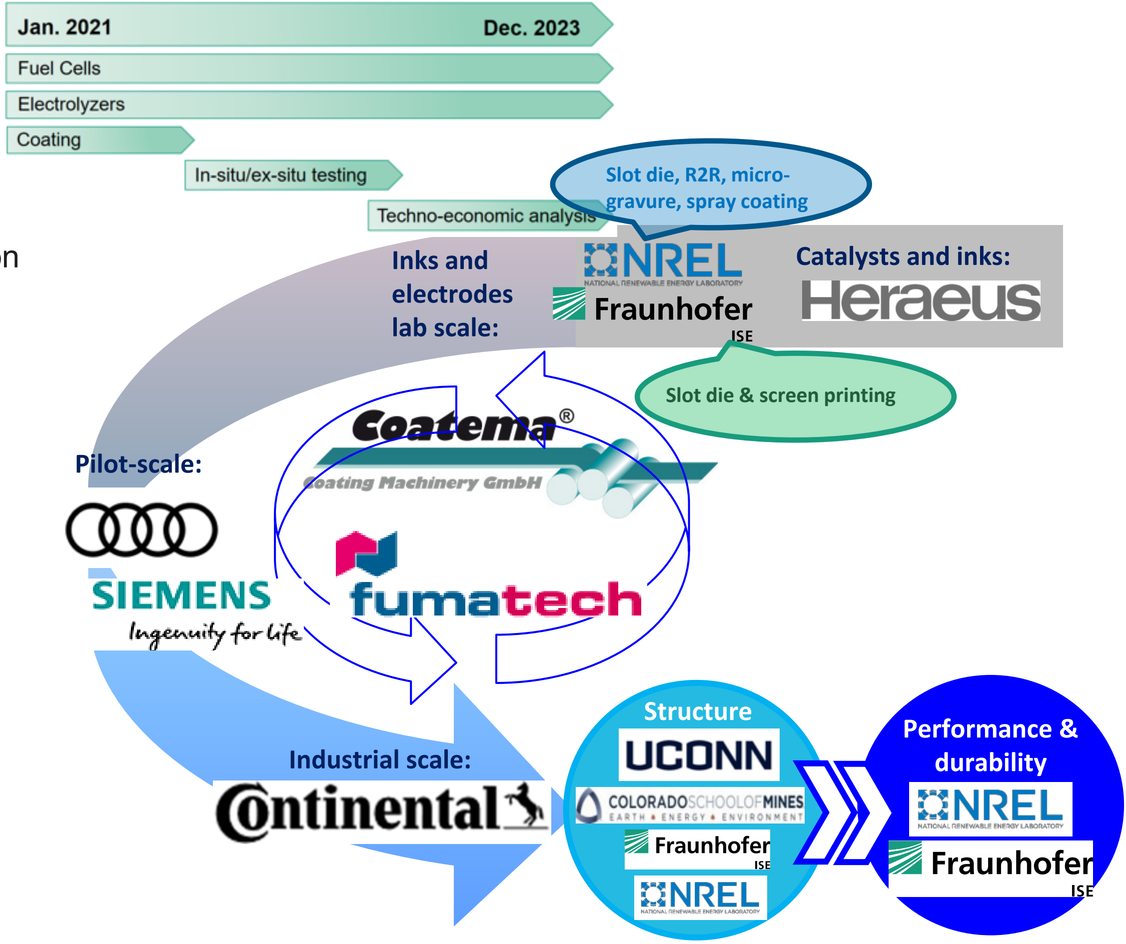
- SEM/EDS comparison of slot die and gravure coated anodes with 10 and 20 wt.% inks
- Results
  - At the lower solids loading, the surface structures look quite different and have very different F/Ir
    - Also, the gravure-coated anode appears to be discontinuous
  - At the higher solids loading, the surface structure and the F/Ir appear similar
    - Both slot die and gravure coated anodes showed good performance at 0.4 loading (P196c)



SEM at three magnifications (left to right) for the four labeled cases

Collaboration and Coordination: Partners in Germany (slide provided by Fraunhofer ISE)

- **German side:** lab scale to industrial scale catalyst and electrode development for fuel cells and electrolyzers
- Delay in funding → Funding started in January 2021 (project budget 4,3 Mio € and funding 2.7 Mio. €)
- ***Fraunhofer ISE:*** leads the project, performs ink and electrode lab scale fabrication, in-situ characterization
- **NREL and ISE:** coordinating selection of materials and components and discussing common protocols
- ***Heraeus:*** development of catalysts and inks
- ***Coatema***: expert on the slot die coating → advisory
- ***Fumatech:*** membrane requirements
- ***Audi***: MEA manufacturing/automotive fuel cell requirements
- ***Siemens:*** will specify requirements for electrolyzer catalyst layers
- ***Continental***: up-scaling the lab scale production at Fraunhofer ISE
- **UConn and Mines:** Structural characterization and structure-property-performance correlations



Progress toward DOE Targets or Milestones

- This project has the goal of assisting industry in accelerating the scale-up of MEA and stack materials, toward program cost and timeline targets
- The project is focused on addressing these needs for high priority applications such as water electrolyzers and fuel cells for heavy-duty applications