Power for the Real World

2009 DOE Hydrogen Program Review

Advanced Cathode Catalysts and Supports for PEM Fuel Cells

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3M Company

May 20, 2009

Powered by 3M

Project ID: FC_17_Debe

DOE Hydrogen Program

Overview

Timeline

- Project start : April 1, 2007
- Project end : March 30, 2011
- 50% Complete (3/30/09)

Budget

- Total Project funding **$10.43MM**
  - $8.34 MM DOE and FFRDC
  - $2.09 MM 3M share
- Received in FY08: $1.621 MM
- Est. Funding for FY09: $1.962MM

Partners

- Dalhousie University (J. Dahn, D. Stevens)
- JPL (S. R. Narayanan, C. Hays)
- ANL (N. Markovic, V. Stamenkovic)
- Project Management – 3M

Barriers

A. Electrode and MEA Durability

B. Stack Material & Mfg Cost

C. Electrode and MEA Performance

DOE Technical Targets

Electrocatalyst/ MEA		2010	2015
Lifetime Hrs, > 80°C		2000	5000
Mass Activity(A/mg)		0.44	0.44
PGM, (g/KW rated)		0.3	0.2
Performance (W/cm^2)	@ Rated	1	1
	@ 0.8V	0.25	0.25

Additional Interactions

GM Fuel Cell Activities - Honeoye Falls
LANL(NIST), ORNL(TEM), ANL (modeling)
Proton Energy Sys.; Giner EC Sys. LLC
Various Vendors: for GDM components

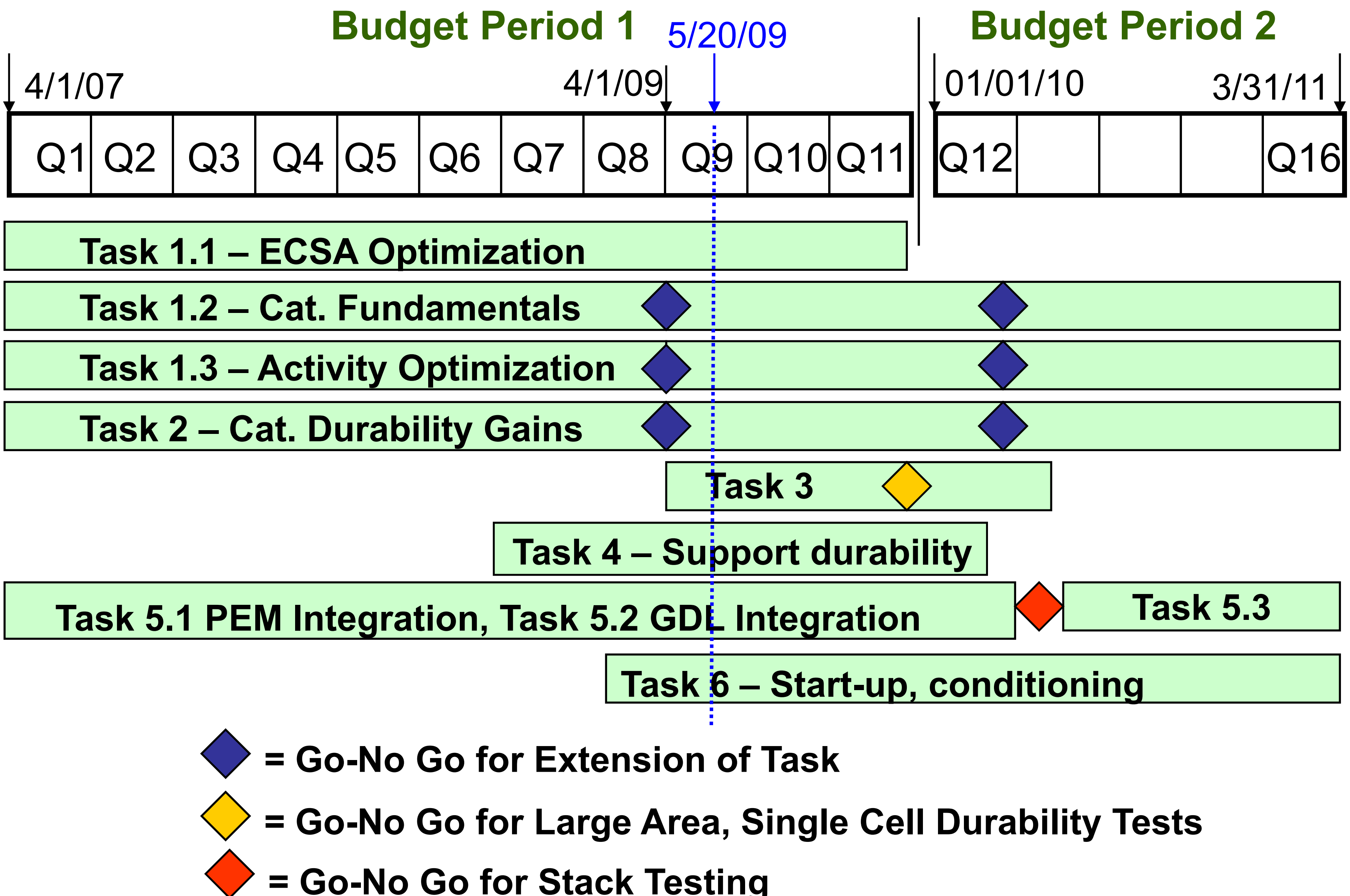
Overall Project Objectives

Development of a durable, low cost, high performance cathode electrode (catalyst and support), that is fully integrated into a fuel cell membrane electrode assembly with gas diffusion media, fabricated by high volume capable processes, and is able to meet or exceed the 2015 DOE targets.

Objectives for Past Year

- Define and implement multiple strategies for increasing NSTF support surface area, catalyst activity and durability, with total loadings of $\leq$ 0.25 mg-Pt/cm^2 /MEA
- Work closely with subcontractors to fabricate and screen new electrocatalysts using high throughput characterization methods, for activity and durability gains
- Conduct fundamental studies of the NSTF catalyst activities for ORR
- Apply more severe accelerated tests to benchmark the NSTF/MEA durability
- Define and implement multiple strategies to optimize the MEA water management
- Advance the high volume roll-good NSTF catalyst / membrane integration
- Work closely with system integrator to validate NSTF functional properties/issues

Project Timeline and Milestones



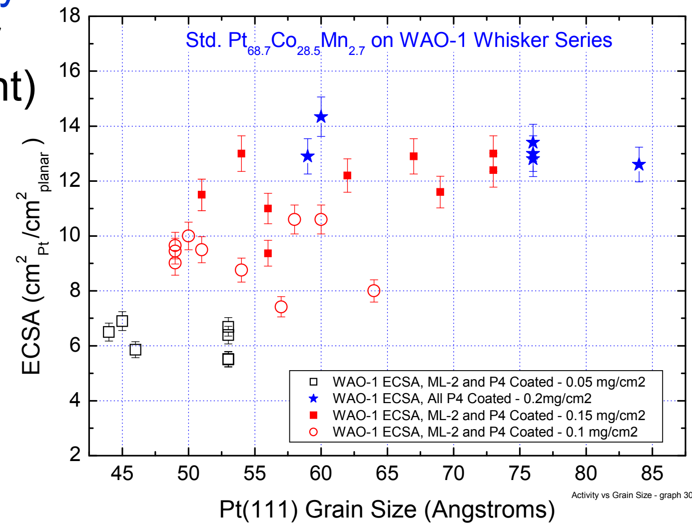
Technical Progress: Task 1 - NSTF catalyst and support fundamentals

NSTF fundamentals – A key focus ~ 500 MEA's in past 9 months

Increased understanding of fundamentals of whisker geometry:

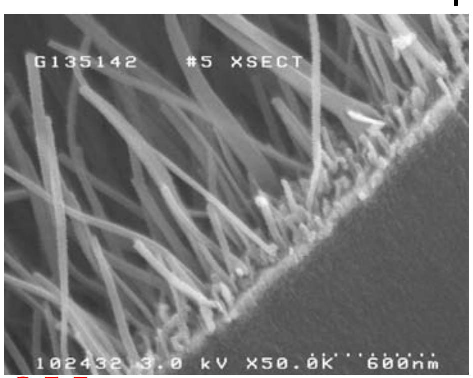
- determining process conditions to generate desired whisker geometric characteristics (on roll-good production equipment)
- two of three designed experiments completed for whisker growth: SEM characterization, fuel cell testing for 14 metrics
- relating whisker characteristics to ultimate catalyst ECSA, particle size, shape, and how those relate to activity
- developed model for calculating catalyst ECSA as a function of whisker geometric factors: N(μm^{-1}),L(μm), ρ_{alloy}, Pt loading, roughness factors, backplane deposition

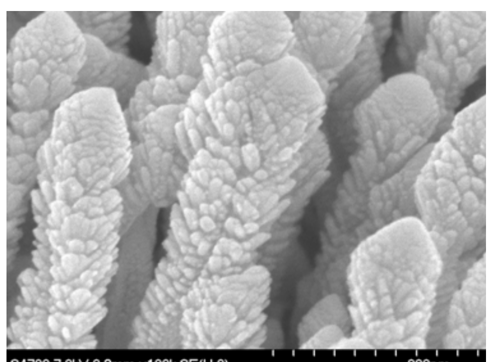
ECSA vs fcc grain size & loading



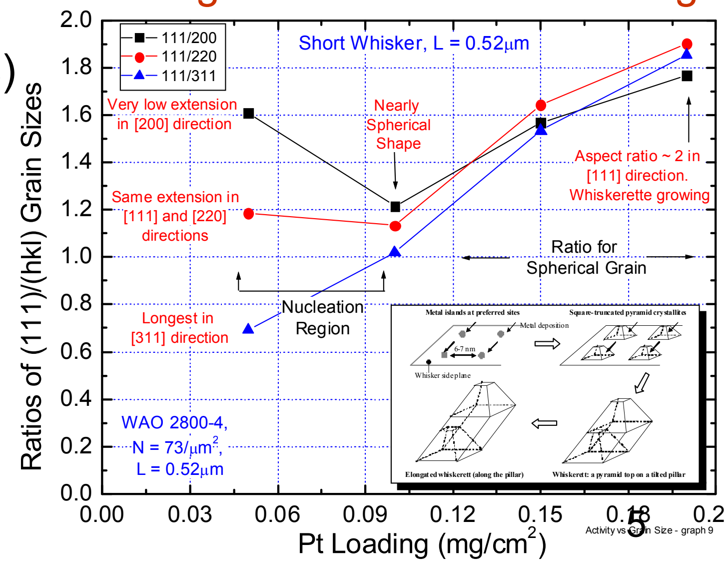
Increase knowledge of how to control the critical factors determining ORR for a given catalyst type and loading:

- catalyst composition (> 30 Pt alloys in hundreds of MEAs)
- grain size, optimum crystal facets, lattice parameters
- surface structure or composition modulation.





Pt fcc grain size ratios vs loading



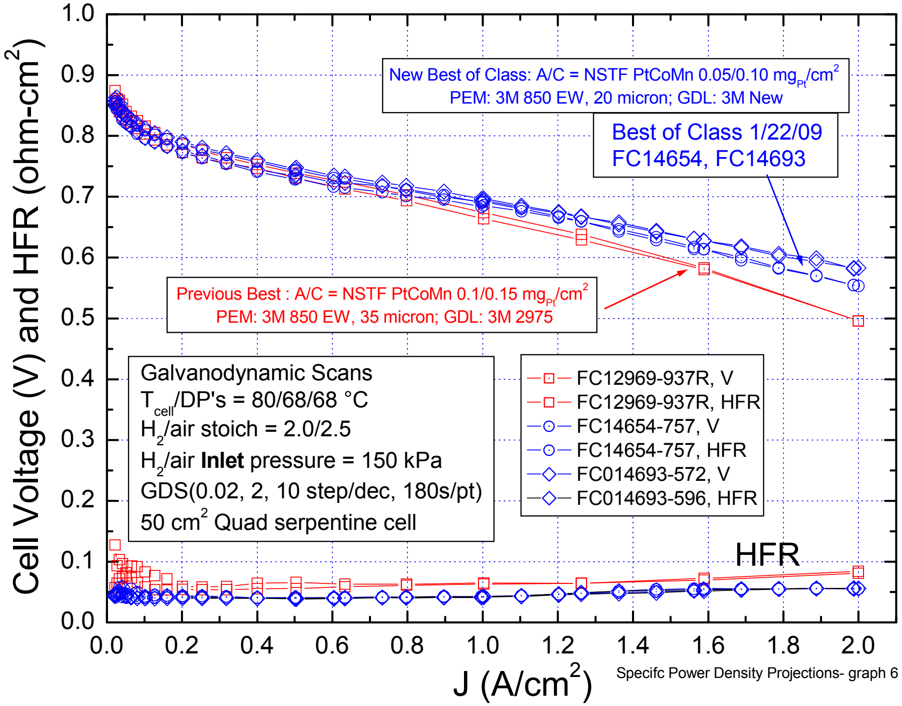
Technical Accomplishments: Higher power density, reduced Pt loading

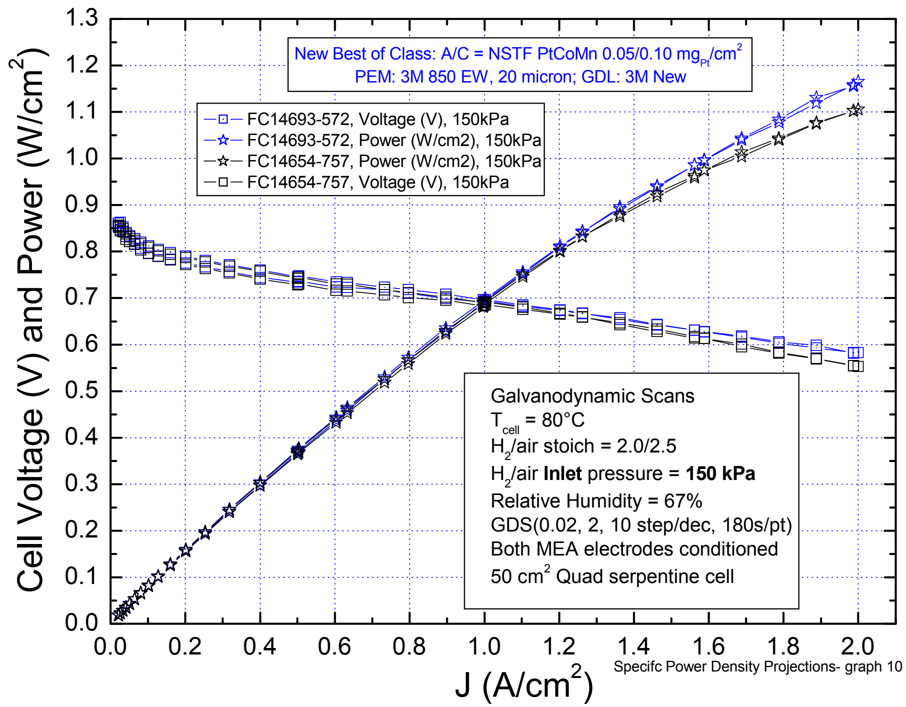
MEA Modifications

- 40% reduction in total Pt loading
- 40% reduction in PEM thickness
- Improved GDL

150 kPa H_2/Air, 80°C, 67%RH

- 34% reduction in HF impedance
- 40% reduction in mass transport loss
- 85 mV gain at 2 A/cm^2





Baseline Best-of-Class MEA - Oct., 2007

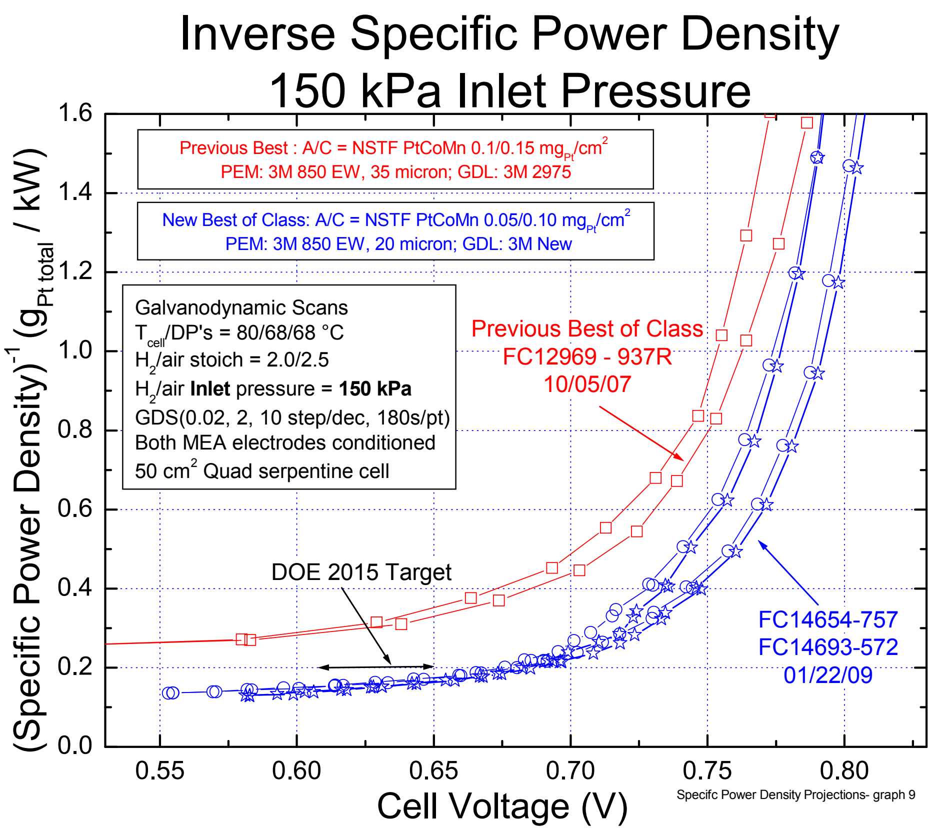
- A/C = 0.1/0.15 mg$_{Pt}$/cm^2 PtCoMn
- 35 micron 3M PEM
- Non-standard 3M GDL

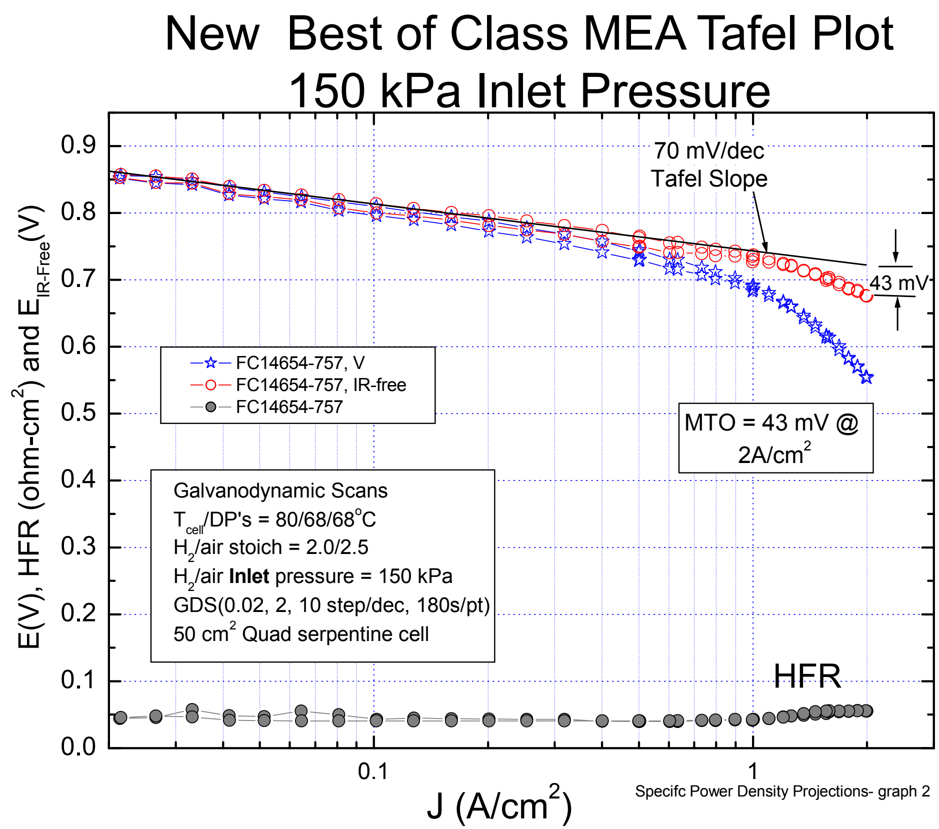
Baseline Best-of-Class MEA - Jan., 2009

- A/C = 0.05/0.10 mg$_{Pt}$/cm^2 PtCoMn
- 20 micron 3M PEM
- Improved 3M GDL

Technical Accomplishments: Higher power density, reduced Pt loading

- 48% reduction in g_{Pt} / kW at peak power over 2007 - 2008 baseline
- 40% reduction in mass transport over-potential at 2 A/cm^2 at 150kPa





New Baseline MEA exceeds DOE 2015 targets for Inverse Specific Power Density at 150kPa (< 0.18 $g_{Pt\ total}$ / kW)and total Pt loading: 0.15 mg_{Pt}/cm^2 of MEA

Open Circuit Voltage Hold Test

Conditions: 90°C, 30% RH, 250 kPa/200 kPa
H_2 Air, CF = 696/1657 sccm

Targets: 200 hours, H_2 crossover $\leq$ 20 mA/cm^2,
F^- ion release monitored only

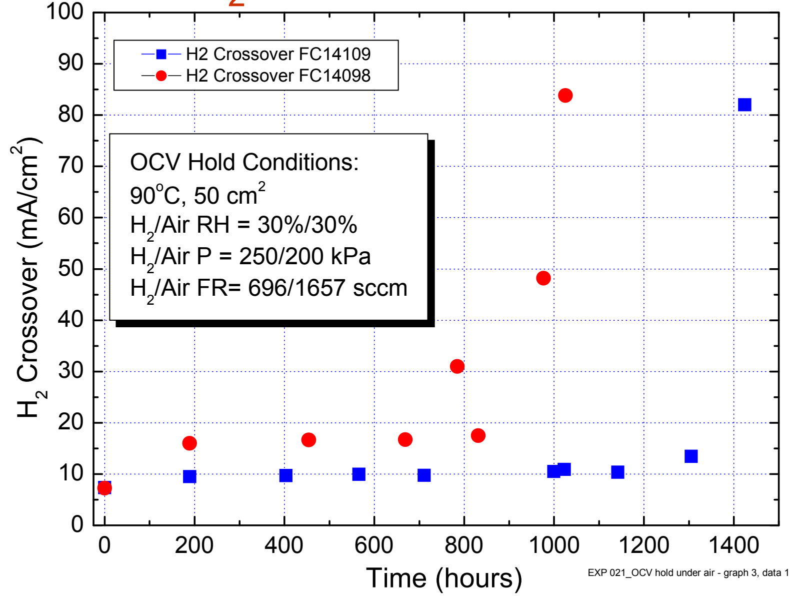
PEM: 3M 20 μm, with stabilizing additive

Catalyst: NSTF 0.1/0.15 PtCoMn,

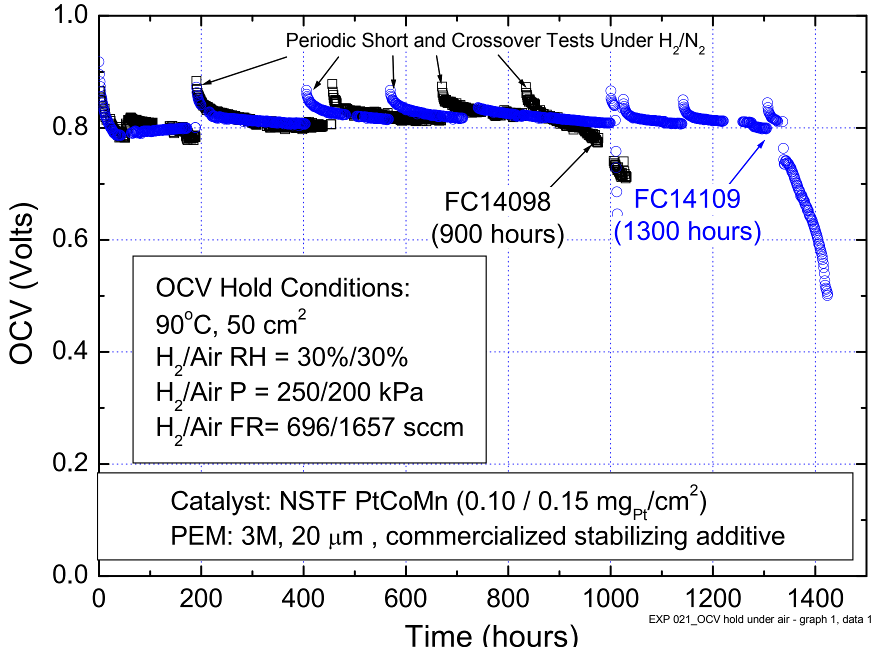
Results:

- > 900 hours with F^- rate < 0.5 μg/cm^2/day
- H_2 X-over < 20mA/cm^2 for 0 < t < 800 hrs.

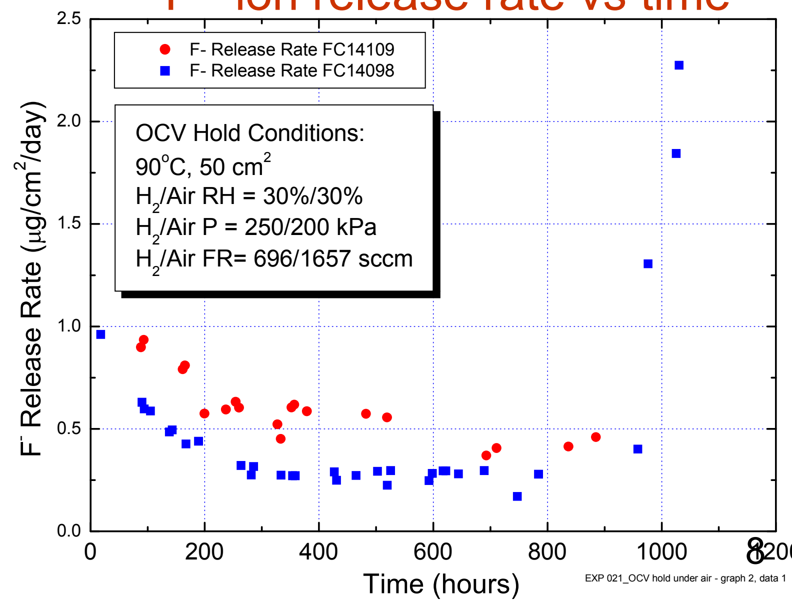
H_2 Crossover vs time



OCV vs time

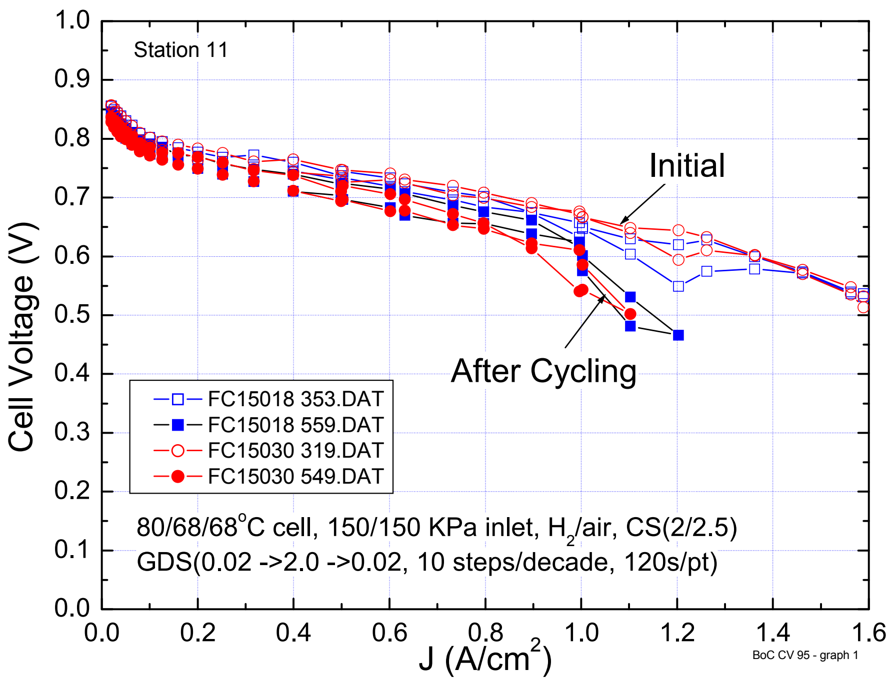


F^- ion release rate vs time



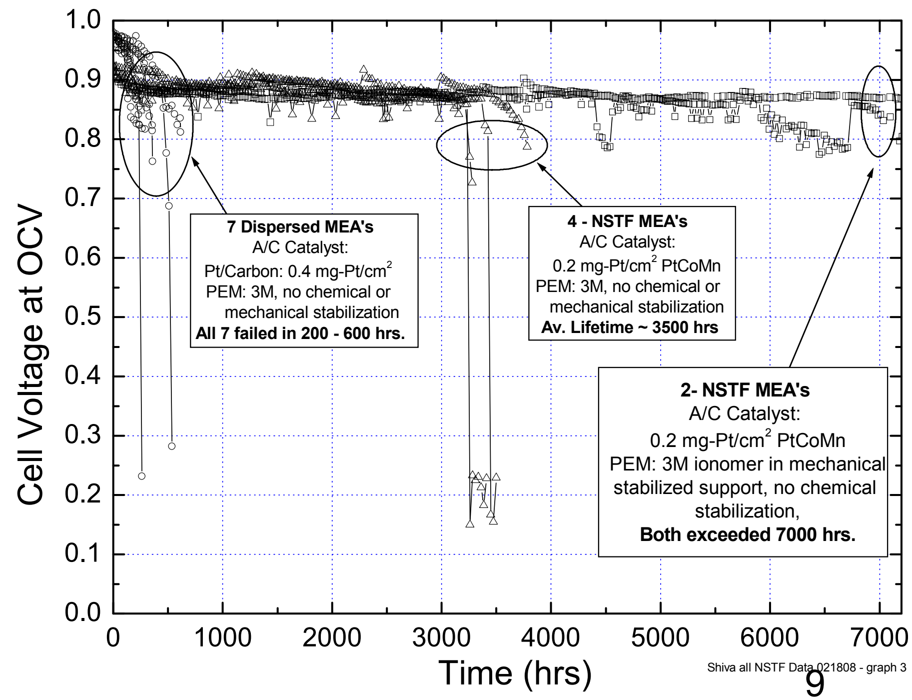
Hi Voltage CV Cycling

- 0.6 – 1.2 V, 20 mV/sec, 200kPa H_2/N_2 at 95/95/95 °C cell/dew points .
- 4000 cycles with periodic metrics. (~ stable between 4000 and 12000 cycles.)
- Results shown for 2 new best of class CCMs: 0.05/0.10 PtCoMn, 20 μm PEM: 2 MEA's
  1) -0.6% loss and +5% gain in Spec. Act.
  2) -20% and -30 % loss of ECSA (cm^2_{Pt}/cm^2_{geo})



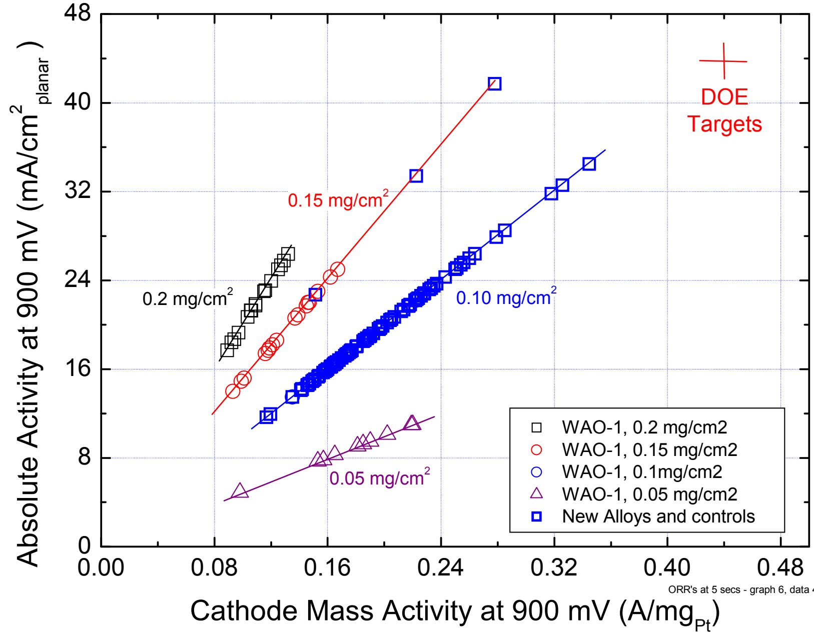
Load Cycling Durability

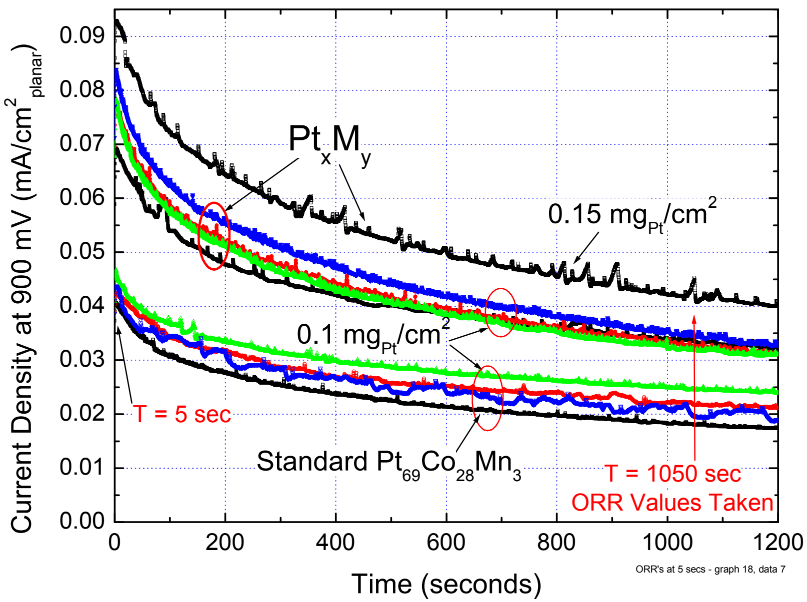
- Test protocol in 2008 Review, FC1
- MEA: 0.2 mg/cm² NSTF PtCoMn, 3M ionomer without stabilizing additives, with mechanical stabilization (W. L. Gore).
- 1st MEA > 7300 hrs reported in 2008
- 2nd MEA now completed over 7000 hrs
- Exceeds DOE-2015 5000 hour target



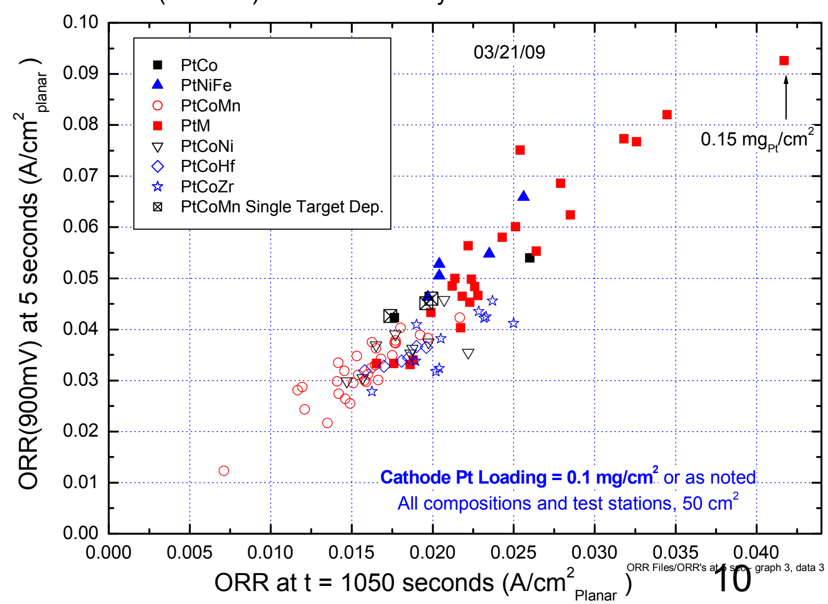
Technical Accomplishments: Higher activity alloy catalysts for ORR

- New NSTF alloy compositions
  - All 50 cm^2 cell tests at 3M
  - many tens of new compositions made and tested
- DOE/GM metric for ORR activity:
  - 150kPa H_2/O_2, 100%RH, 0.9V(15-20 min)
  - Activity targets:0.044 mA/cm^2_{geo} , 0.44 A/mg_{Pt}
  - Correlation to real H_2/air performance?
  - Different Pt oxidation rates for different alloys?
- Results since Dec. '08: 100% increase in activity
  - (33)PtCoMn: 0.164 $\pm$ 0.024 A/mg_{Pt} at 0.1 mg_{Pt}/cm^2
  - (3)Pt_xM_y : 0.33 $\pm$ 0.01 A/mg_{Pt}, at 0.1 mg_{Pt}/cm^2





ORR(900 mV) Absolute Activity at 5 seconds vs 1050 seconds.



Technical Accomplishments – *NSTF ORR Activity and E1/2 from RDE*

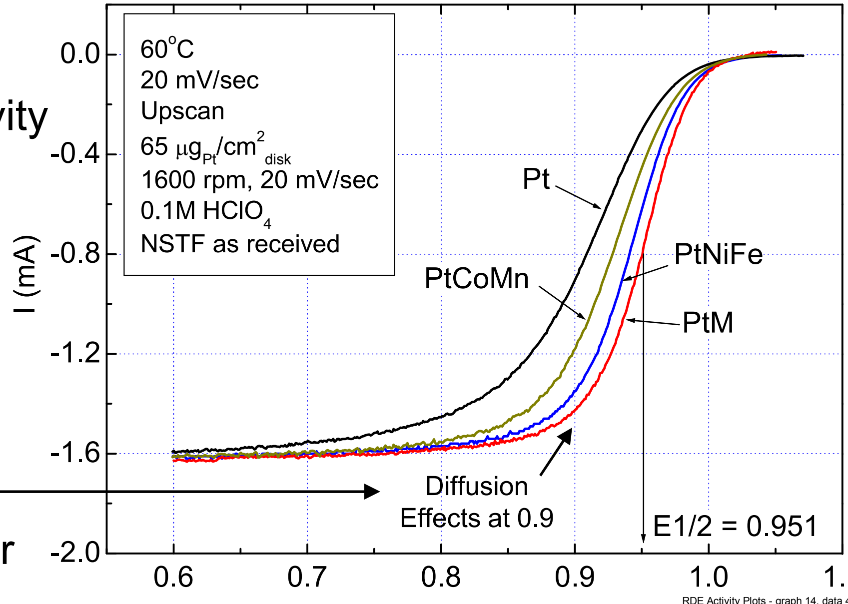
V. Stamenkovic, D. van der Vliet, N. Markovic

Argonne NATIONAL LABORATORY

Fundamental Studies of NSTF Catalysts

- **RDE characterization of 3M fabricated NSTF alloy catalysts**
  - 30-80 mg sample lots of NSTF catalyst coated whiskers
  - 14 alloy sample lots evaluated since December 2008
  - Loading studies determined best loading of 65 μg/cm^2_{disk}
  - 3 to 8 repeat measurements for each catalyst type
  - Activity values obtained at 20°C and 60°C
  - Catalysts are intrinsically "acid washed" in RDE measurement, but not for fuel cell tests.
- **Post-fabrication processing**
  - Applied to as-received NSTF catalysts
  - Screening of process conditions for best activity
  - High Resolution SEM characterization

NSTF RDE Polarization Curves (up-voltage sweep shown)



Results

- Measure highest kinetic and mass activity of any catalyst reported.
- Highest $E_{1/2}$ values reported => strong case for setting new standard of measurement at 950 mV
- Identified optimum post-fabrication parameters for increased activity

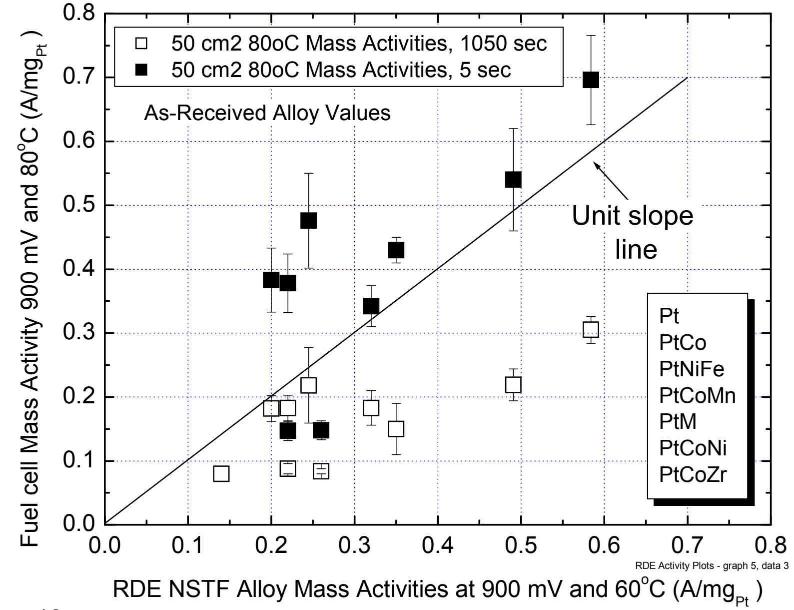
Technical Accomplishments – *NSTF ORR Activity and E1/2 from RDE*

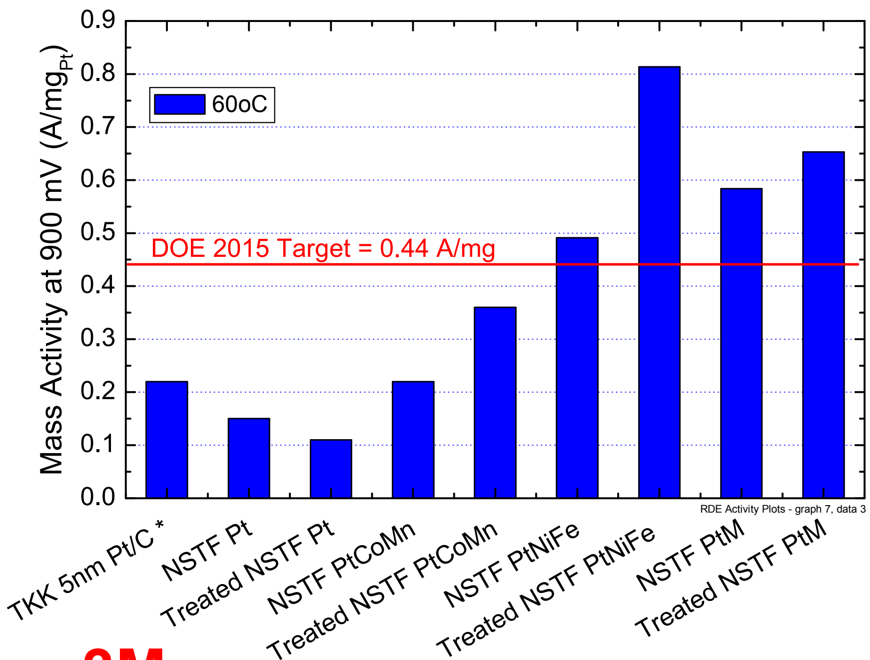
Argonne NATIONAL LABORATORY

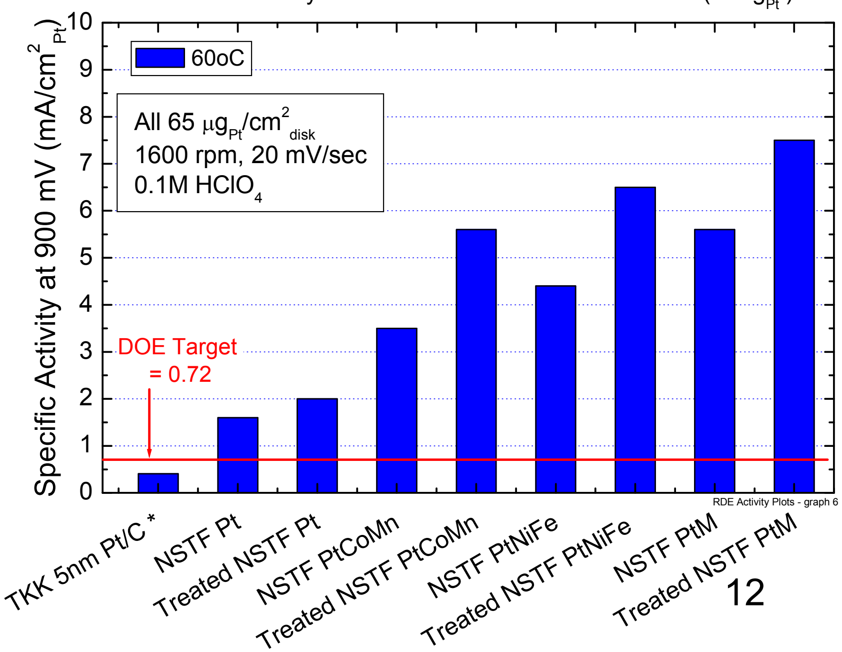
V. Stamenkovic, D. van der Vliet, N. Markovic

Results (continued)

- Mass and specific activities of new NSTF alloy candidates can exceed DOE 2015 targets
- ANL RDE and 3M 50cm^2 fuel cell mass activities at 900 mV quantitatively close: FC 5 sec ORR activity values closer to RDE values.
- Post fabrication treatment can further increase activities of several alloys tested.
- Several exceed the DOE 2015 mass activity target







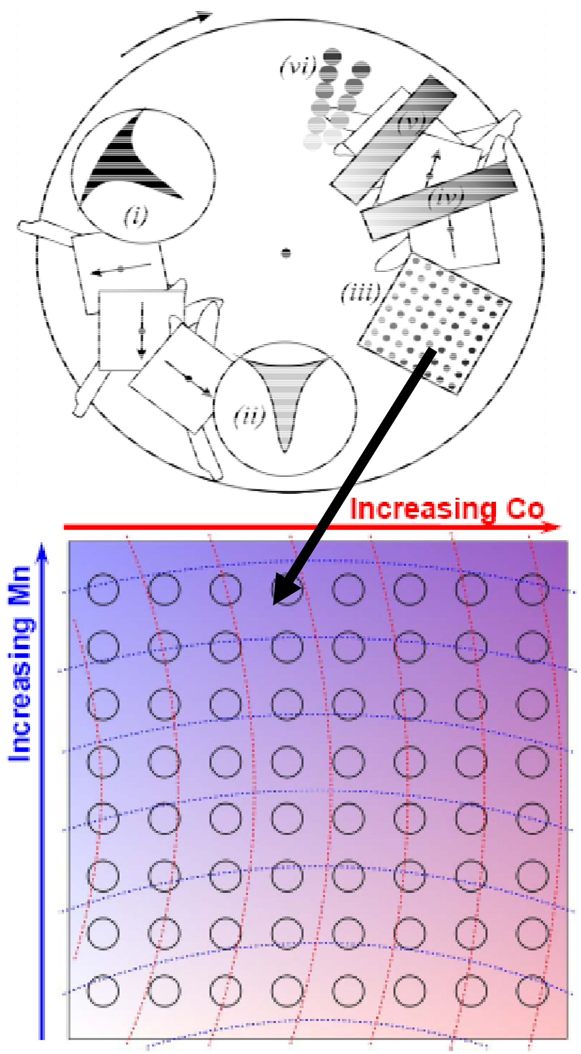
Technical Accomplishments: New NSTF catalysts

Prof. Jeff Dahn, David Stevens, Arnd Garsuch, and students

DALHOUSIE UNIVERSITY *Inspiring Minds*

Advanced catalysts by compositional spread screening at Dalhousie University

- 64-electrode arrays of thin film catalysts deposited onto NSTF whiskers, made into MEAs at 3M, tested at Dal. U.
- 129 libraries fabricated and tested through 3/20/09 (vs. 60 last yr.)
  - 3 basic configurations (over, under, intermixed w/Pt)
    - 16 Pt binary, 10 Pt ternary, 10 Pt compound systems investigated in the intermixed configuration) (vs. 25 last yr.)
- Compositional, structural and functional performance mapping by: electron microprobe, XPS, XRD, ECSA, ORR, high V cycling durability, acid soak resistance.
- Extensive proprietary results limit what can be shown

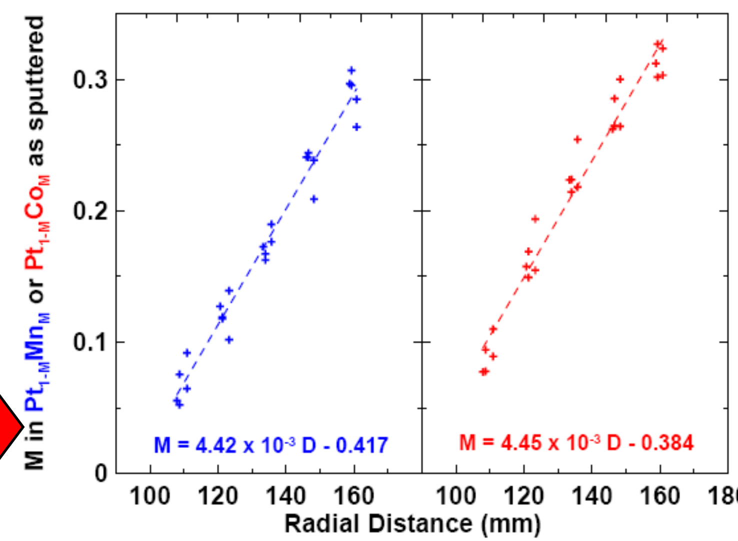


Circles show positions of fuel cell electrodes.

Dotted lines represent contours for constant Mn and Co respectively.

Example of composition control with PtCoMn

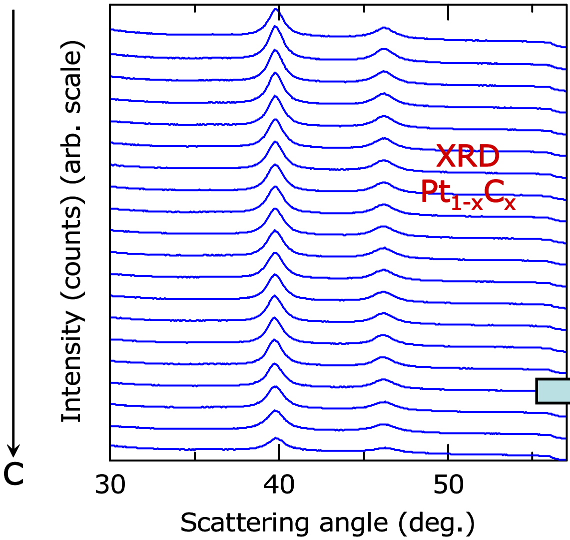
PtCoMn Ternary – Microprobe Data

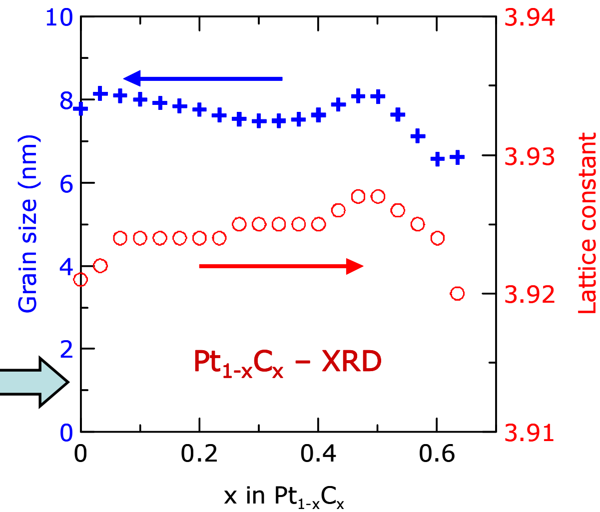


Technical Accomplishments: Example: $Pt_{1-x}C_x$

Prof. Jeff Dahn, David Stevens, Arnd Garsuch, and students

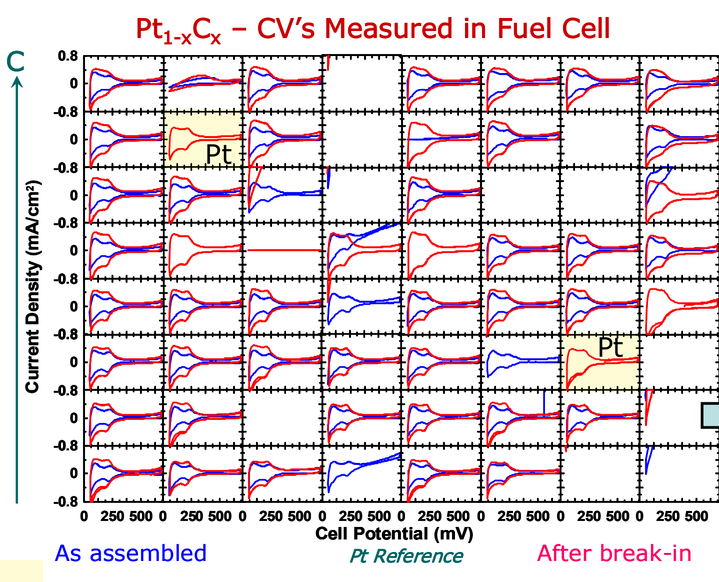
DALHOUSIE UNIVERSITY Inspiring Minds

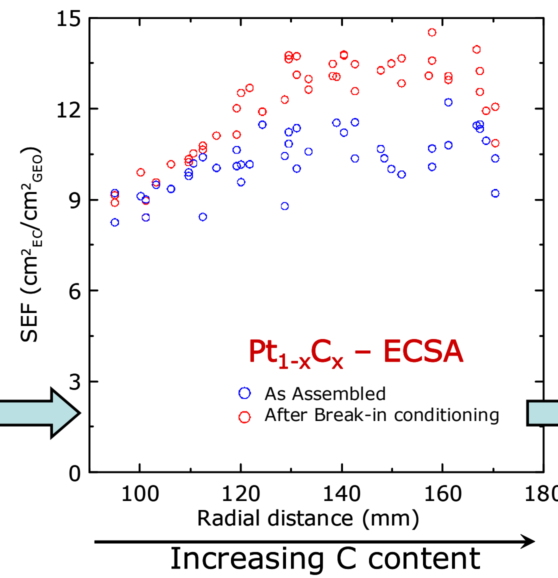


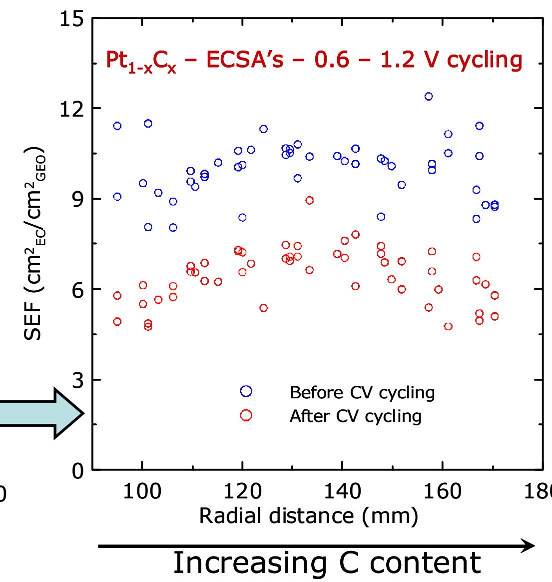


Examples of 64 Array Mappings vs Compositions:

- fcc(hkl) grain sizes
- Pt fcc lattice parameter
- Cyclic voltammograms
- ECSA before and after break-in or high voltage cycling
- ORR before and after high voltage cycling.
- After acid corrosion
- HOR







Technical Accomplishments and Progress: GDL Optimization for NSTF CCM

Electrode backing (EB) carbon paper : Designed Experiment

- 7 commercial roll-good papers
  - Variables: wet proofing and MPL coating area weight (necessary due to variable EB)
- 3 commercial fully coated GDLs also evaluated

Results: Fuel cell results for all were significantly poorer than 3M baseline GDL

Baseline carbon paper improvement : Designed Experiment

- Variables : wet proofing and MPL area weights
- Seven fuel cell performance metrics

Results:

- No single set of GDL parameters were optimum for all seven fuel cell metrics.
- For steady state cool performance, optimal GDL parameters were different for dry conditions (0 % RH) and wet conditions (100 % RH).
- Good second order linear regression fits were obtained for three responses (PDS, cathode stoich. sensitivity, and % RH sensitivity at 90/60/60 ^{o}C).

Asymmetric anode/cathode GDLs with baseline EB paper : Designed Experiment

- 2^{4-1} factorial with center point replication
- Variables : wet proofing and MPL coating area weight
- **Still in progress -** Largest improvement so far was for extreme difference for anode and cathode GDLs: high wet proofing and MPL weight for anode and low wet proofing and MPL weight for anode.

Best GDL Approaches Identified to Date

GDL	PDS, 70 C	GDS, 7.35 psig, 80 C	GDS, 14 psig, 85 C	Cathode Stoich Sensitivity	% RH Sens.,	Steady State Cool Start amps/cm^2 at 0.6 V			
	V at J = 1.2	V at J = 1.5	V at J = 1.5	V at 1.4 CS, 80 C	Volts at 90/50/50 C/%RH/%RH	30 C, 0/0	30 C, 100/100	40 C, 0/0	40 C, 100/100
Baseline GDL	0.607	0.540	0.600	0.522	0.588	0.342	0.209	0.540	0.250
GDL A	0.603	0.584	0.625	0.521	0.612	0.305	0.172	0.490	0.203
GDL B	0.623	0.591	0.628	0.531	0.536	0.295	0.120	0.514	0.169
GDL C	0.602	0.578	0.629	0.498	0.596	0.277	0.130	0.467	0.154
GDL D	0.595	0.567	0.614	0.510	0.612	0.334	0.200	0.549	0.235

- Greatest higher temperature improvements were for GDL Type B (15 mV for PDS and 30 to 50 mV for GDS).
- Generally poorer steady state cool performance results than for baseline GDL.
- Overall best results with minimal impact on steady state cool performance was for GDL D.

Collaborations

Subcontractors

- Dalhousie University : Subcontractor, extensive collaboration
- ANL (Markovic group): Subcontractor, extensive collaboration
- NASA-JPL: Subcontractor, extensive collaboration

System Integrators and stack manufacturers (partial list)

- GM Fuel Cell Activities -Honeoye Falls: Extensive collaboration outside of DOE H_2 program with materials generated at 3M under this contract. Multi-year single cell performance and activity validations, stack testing, cold/freeze start and water management evaluations, PEM and GDL integration, durability testing, fundamental modeling studies.
- Proton Energy Systems – Performance testing of NSTF MEAs in electrolyzers. Moderate interaction, started in past year and ongoing.
- Giner EC Systems, LLC – Performance testing of NSTF MEAs in electrolyzers. Moderate interaction, started in past year and ongoing.

National Laboratories

- LANL (Borup group) – Neutron imaging of NSTF MEA's at NIST. Occasional.
- ORNL (K. More) - TEM imaging of NSTF catalysts. Occasional.
- ANL (Ahluwalia group) - Systems modeling with 3M supplied NSTF MEA property and functional performance data as requested. Ongoing for several years.

Future Work

Water Management Improvement

- Optimize the GDL materials and physical construction for more effective liquid water transport at low temperatures without compromising high temperature performance under dry conditions. Tailor the GDL for both anode and cathode independently to optimize performance over a wider range of operating conditions.

Start-up conditioning (New Task 6)

- Continue to explore break-in conditioning protocols and catalyst/membrane components to reduce MEA break-in conditioning time to < 3 hours.

Cathode Catalyst Mass Activity Gain

- Continue to fabricate and test new catalyst compositions and structures to exceed target mass activity of 0.44 A/mg_{Pt} and which meet all other performance requirements.
- Achieve 50% gain in surface area of NSTF supports over current NSTF baseline without loss of specific activity or durability under most severe accelerated test.

Durability Improvement

- Reduce by 50% any losses in surface area, activity or mass transport over-potential under the more severe fast high voltage cycling protocol (4000 cycles, 0.6 – 1.2 V under H_2/N_2 at 20mV/sec at 95/95/95 ^oC).

Stack testing

- Initiate Task 3, to begin MEA component down-selection for large area, single cell performance and durability testing.

Project Summary : Status Against DOE Targets – March, 2009

Characteristic	Units	Targets 2010 / 2015	3M Status – 3/09 (mfg'd roll-good)
PGM Total Content	g_{Pt}/kW_e rated in stack	0.3 / 0.2	**< 0.18g_{Pt}/kW for cell V < 0.67 V** in 50 cm^2 cell at 150kPa inlet
PGM Total Loading	mg PGM/cm^2 of total MEA area	0.3 / 0.2	**0.15 with current PtCoMn alloy** (A/C = 0.05/0.10)
Durability under Load Cycling	Hours, T ≤ 80°C Hours, T > 80°C	5000 / 5000 2000 / 5000	**> 7000 hours** in 50cm^2 cell at 80/64/64°C
Mass Activity (150kPa H_2/O_2 80°C. 100% RH)	A/mg-Pt @ 900 mV, 150kPa O_2	0.44 / 0.44	**0.16 A/mg in 50 cm^2 w/ PtCoMn** **0.33A/mg in 50 cm^2 with new Pt_xM_y**
Specific Activity (150 kPa H_2/O_2 at 80°C, 100% RH)	μ A/cm^2-Pt @ 900 mV	720 / 720	**2,100 for PtCoMn, 0.1mg_{Pt}/cm^2** **2,500 for new Pt_xM_y , 0.1mg_{Pt}/cm^2**
Accel. Loss: 30,000 cycles, 0.7 – 0.9V step, 30 s hold at 80/80/80°C	- mV at 0.8 A/cm^2 % ECSA loss	< 30mV < 40% / 40 %	**~ 0 mV loss at 0.8 A/cm^2** **~ 0% loss ECSA**
Accel. Loss: 200 hr hold @ 1.2 V at 95°C, H_2/N_2, 150kPa, 80% RH	- mV at 1.5 A/cm^2 % ECSA loss	< 30mV < 40% / 40%	**+ 25mV gain at 1.5 A/cm^2** **~ - 17% loss ECSA**
OCV hold without PEM failure under 250/200 kPa H_2/air, 90°C, 30%RH	Hours mA/cm^2	200 < 20	**900 – 1300** **H_2 Crossover < 20 mA/cm^2,** F^- ion release rate < 0.5 μg/cm^2-day
Accel. Loss: 4,000 cycles 0.6 -1.2V, 20mV/sec, 95/95/95°C, 270kPa,H_2/N_2	ORR Specific Activ % ECSA loss	??	**+ 5% gain in mA/cm^2 $_{Pt}$** **- 30 % loss of cm^2_{Pt} / cm^2_{planar}**

Project Summary: Overview for 2009

Relevance: Critically focused on overcoming the three most critical barriers for fuel cell MEA development (A, B, C on Overview slide)

Approach: Builds on 12 year DOE/3M funded development of NSTF catalyst and MEA technology that fundamentally has higher specific activity, removes all durability issues with carbon supports, much reduced losses due to Pt dissolution and membrane chemical attack, with high volume manufacturing advantages.

Technical Accomplishments and Progress: In 50 cm^2 cell tests, have exceeded the DOE 2015 targets for specific power density (g_{Pt}/kW), total PGM loadings, and multiple accelerated durability tests (including OCV hold and load cycling). Have demonstrated new alloys that approach the 0.44 A/mg_{Pt} mass activity target in 50 cm^2 cells and exceed 0.8 A/mg_{Pt} in RDE measurements.

Technology Transfer/Collaborations: Extensive interactions with key partners has been productive in developing methods to increase catalyst activities and surface areas. Extensive interactions with a major systems integrator has been critical to validate performances and identify real world gaps and issues, while initial work with electrolyzer integrators offer technology assessment for H_2 generation.

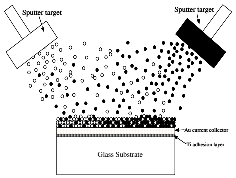
Proposed Future Research: Strongly focused on advancing NSTF MEA materials for improved water management with robust operating windows, and implementing increased mass activity and higher durability in practical catalysts.

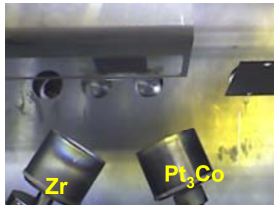
Additional Slides

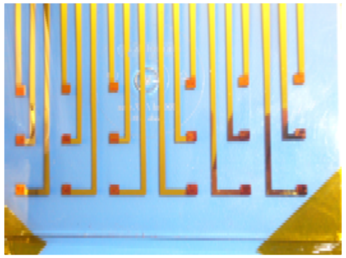
JPL: Preparation and Characterization of NSTF-Coated Electrode Arrays using novel rotating electrolyte approach

C. C. Hays and S. R. Narayanan

Co-sputtering of Alloy NSTF



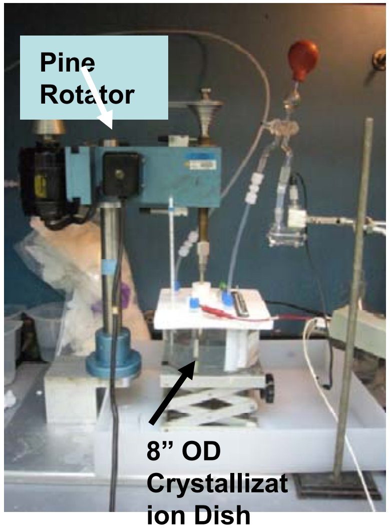




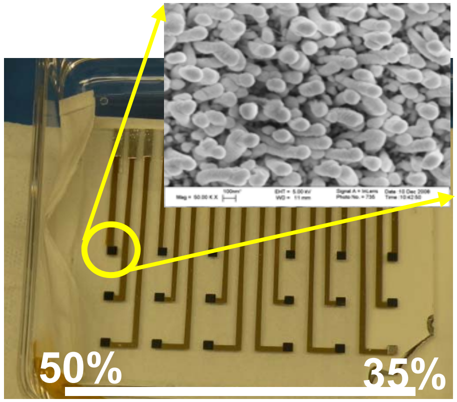
Composition Range on Electrode Array

E-11 $Pt_{49.9}Co_{37.4}Zr$ 12.7	E-12 $Pt_{47.3}Co_{35}Zr_{1}$ 7.7	E-13 $Pt_{40}Co_{35}Zr_{25}$	E-14 $Pt_{33.8}Co_{32.7}Zr$ 33.5	E-15 $Pt_{32.5}Co_{28.6}Zr$ 38.9	E-16 $Pt_{35.8}Co_{30}Zr_{34.2}$
E-21 $Pt_{52.1}Co_{36.5}Zr$ 11.4	E-22 $Pt_{45.1}Co_{36.9}Zr$ 18	E-23 $Pt_{39}Co_{35.3}Zr_{2}$ 5.7	E-24 $Pt_{33.4}Co_{32.6}Zr$ 34	E-25 $Pt_{32}Co_{30.1}Zr_{3}$ 7.9	E-26 $Pt_{37.5}Co_{29.2}Zr_{33.3}$
E-31 $Pt_{50.5}Co_{33.2}Zr$ 16.3	E-32 $Pt_{44.7}Co_{35}Zr_{2}$ 0.3	E-33 $Pt_{39.2}Co_{36.6}Zr$ 24.2	E-34 $Pt_{33.4}Co_{32.8}Zr$ 33.8	E-35 $Pt_{35.1}Co_{28.5}Zr$ 36.4	E-36 no whiskers

Electrochemical Cell

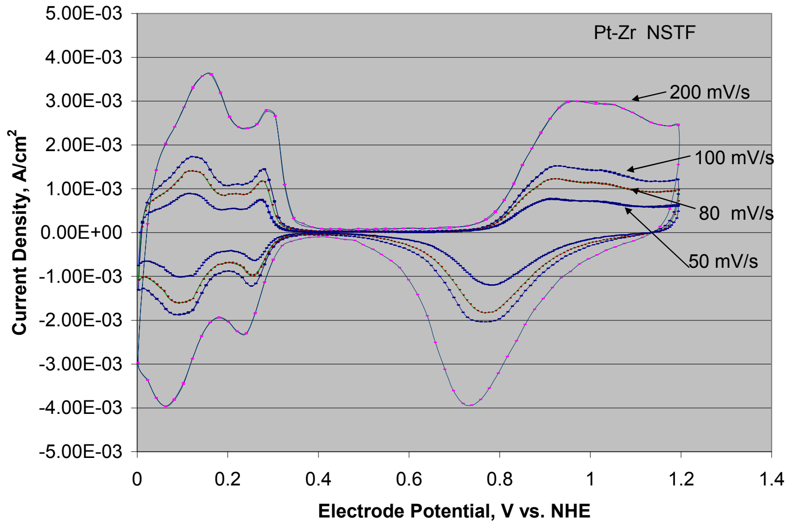


Multi-electrode NSTF Array



Pt-Content in Array (At.%)

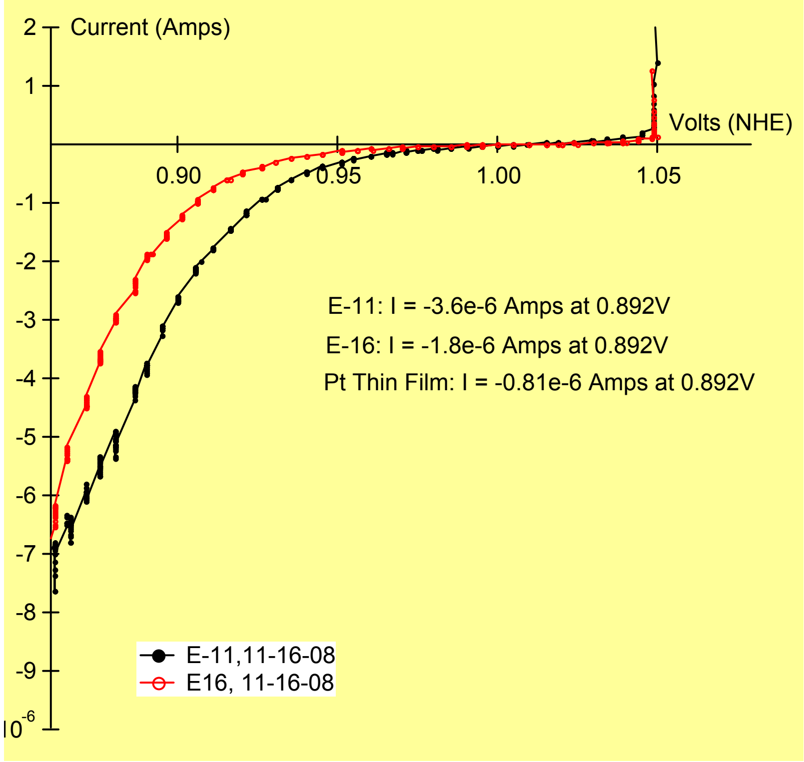
Electrochemical Surface Area



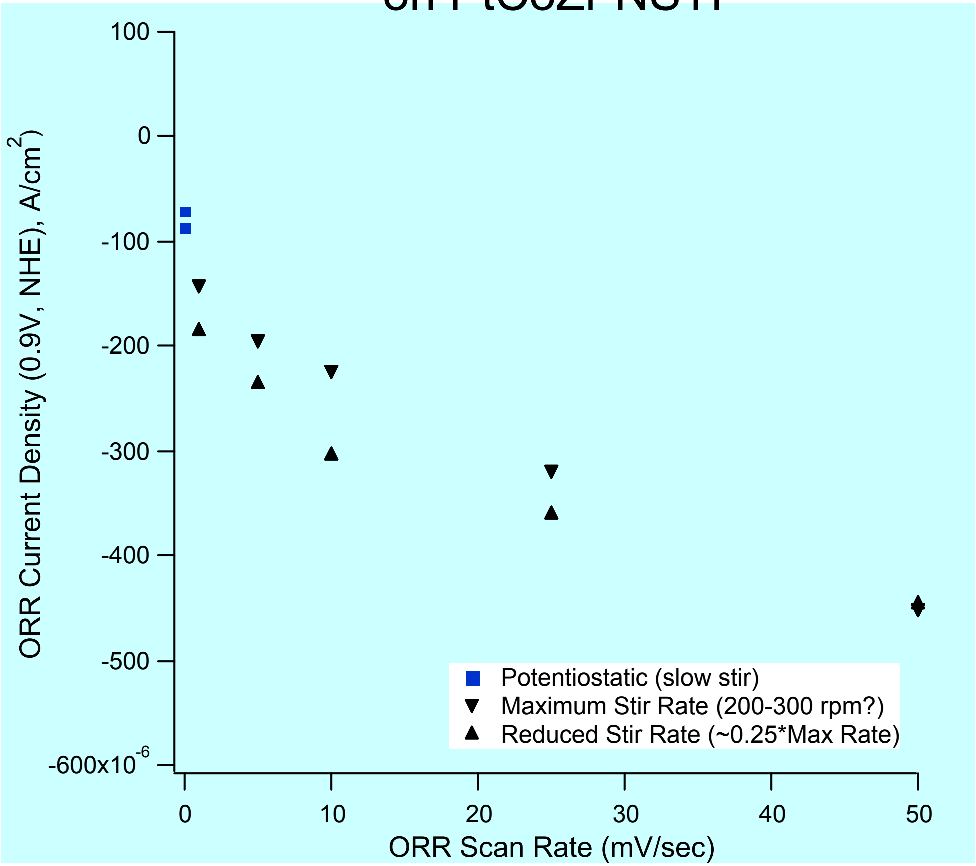
JPL: Preparation and Characterization of NSTF-Coated Electrode Arrays using novel rotating electrolyte approach

C. C. Hays and S. R. Narayanan

Polarization Curves for ORR with rotating electrolyte apparatus



Scan Rate Measurements for ORR on PtCoZr NSTF

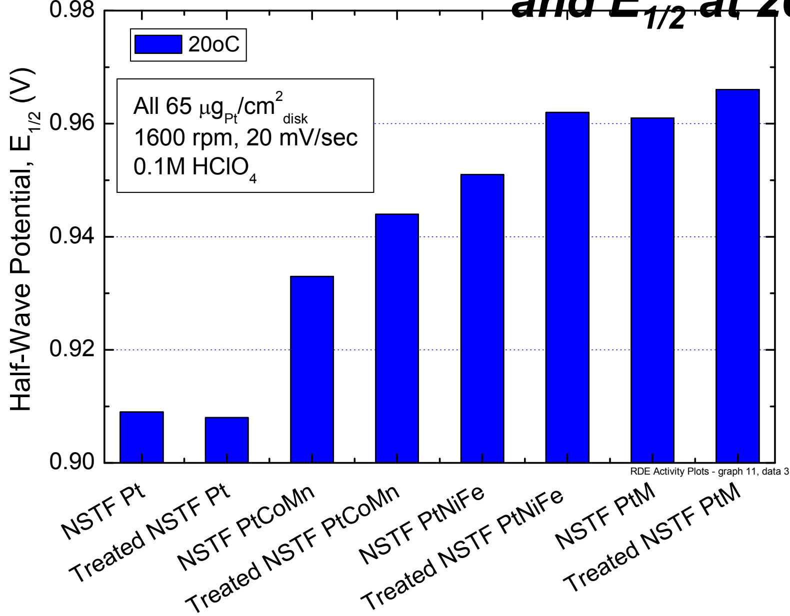


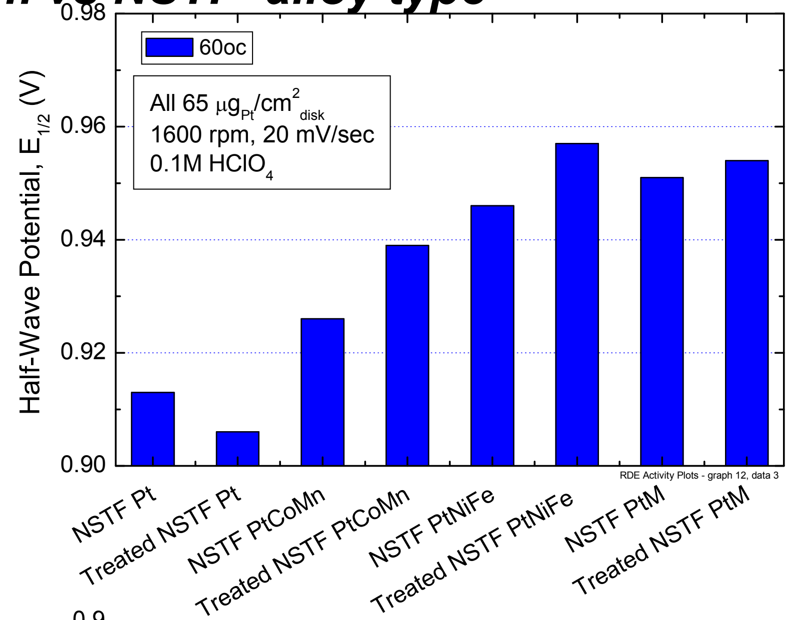
Limiting currents (not presented) are about three times less than RDE measured at Dalhousie on the same NSTF configuration at 400 rpm.

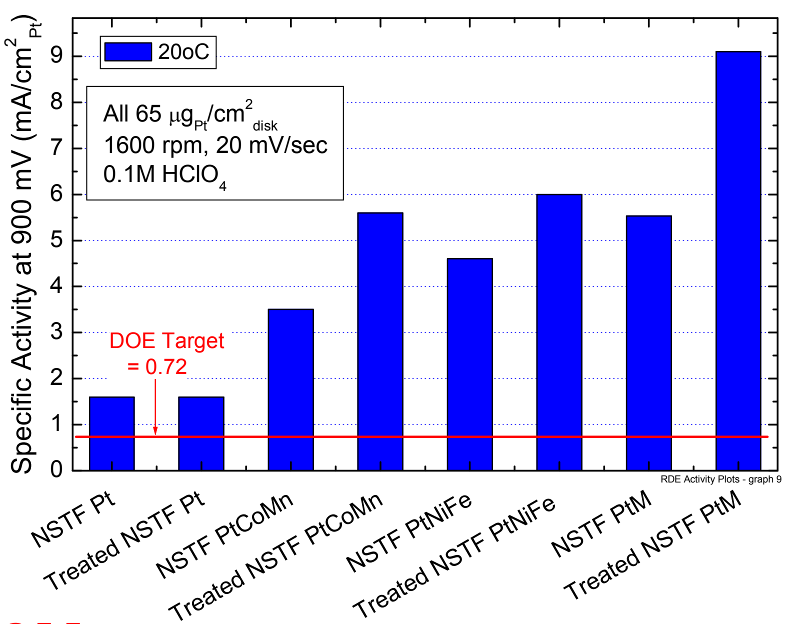
The current at 0.9 V at 50 mV/s is 3 – 4 times that measured at 1 mV/s.

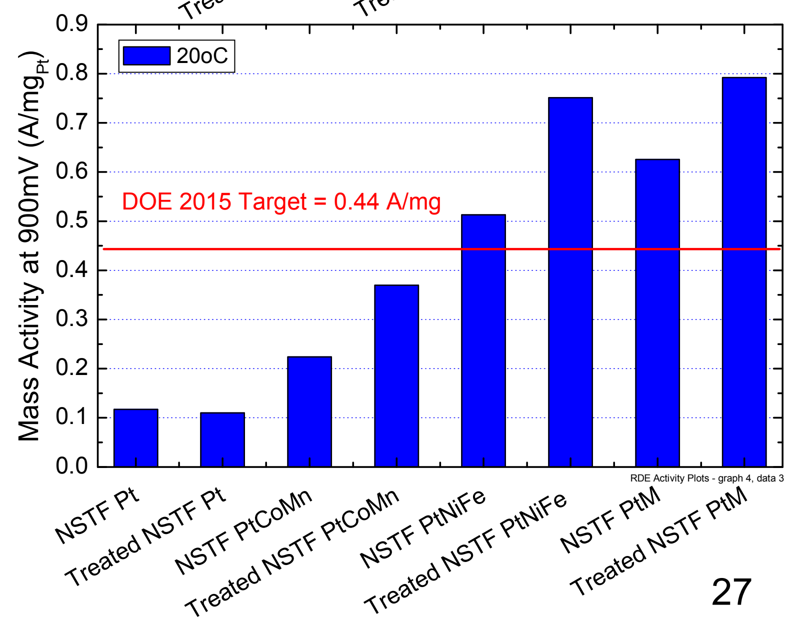
Technical Accomplishments – *RDE ORR (0.9 v) Activity and $E_{1/2}$ at 20°C from vs NSTF alloy type*

Argonne NATIONAL LABORATORY



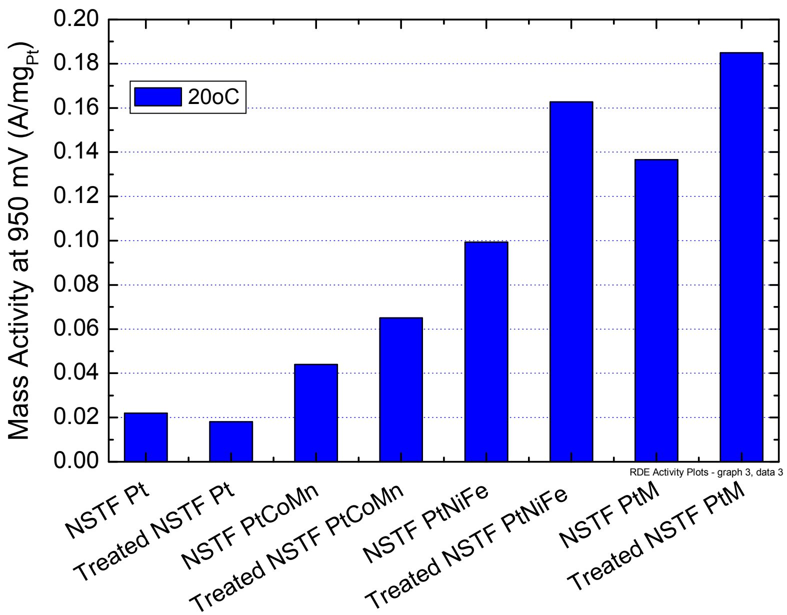


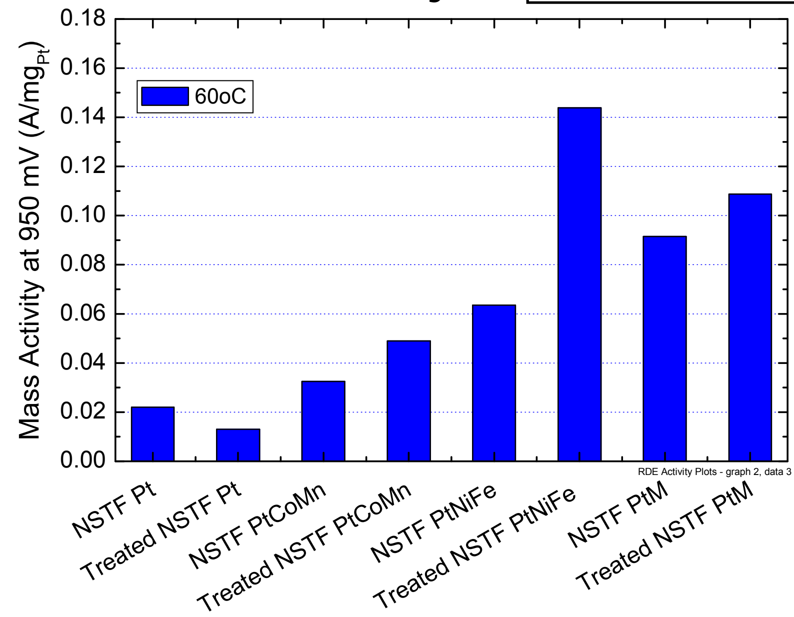


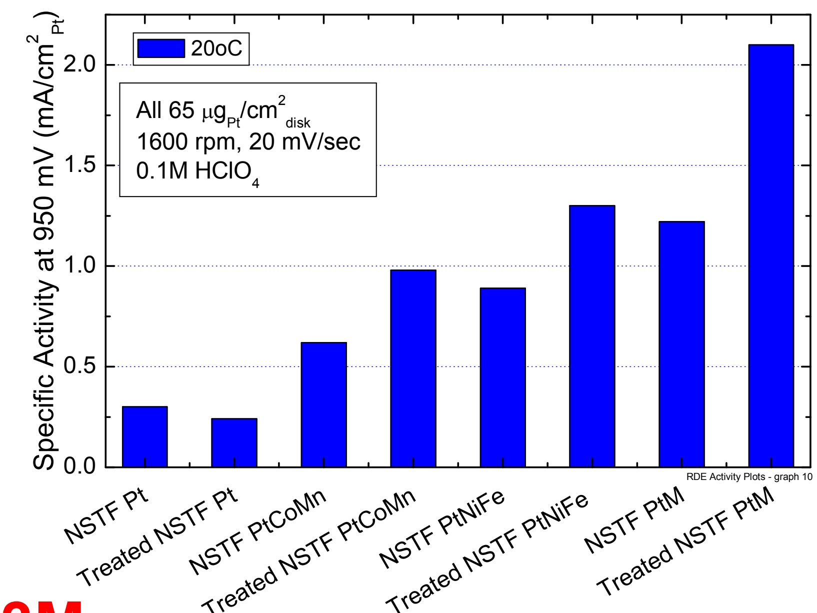


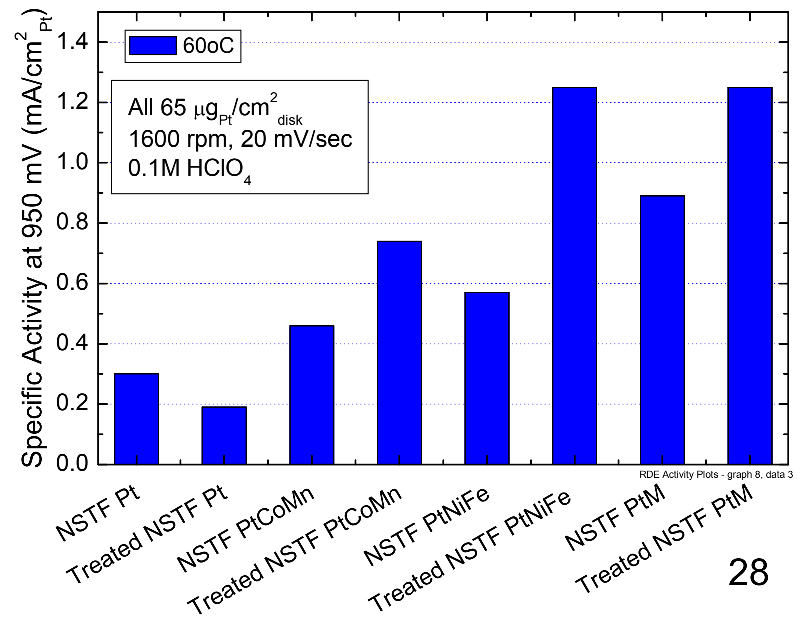
Technical Accomplishments – *RDE ORR Activity at 950 mV and 20 and 60 °C vs NSTF Alloy*

Type





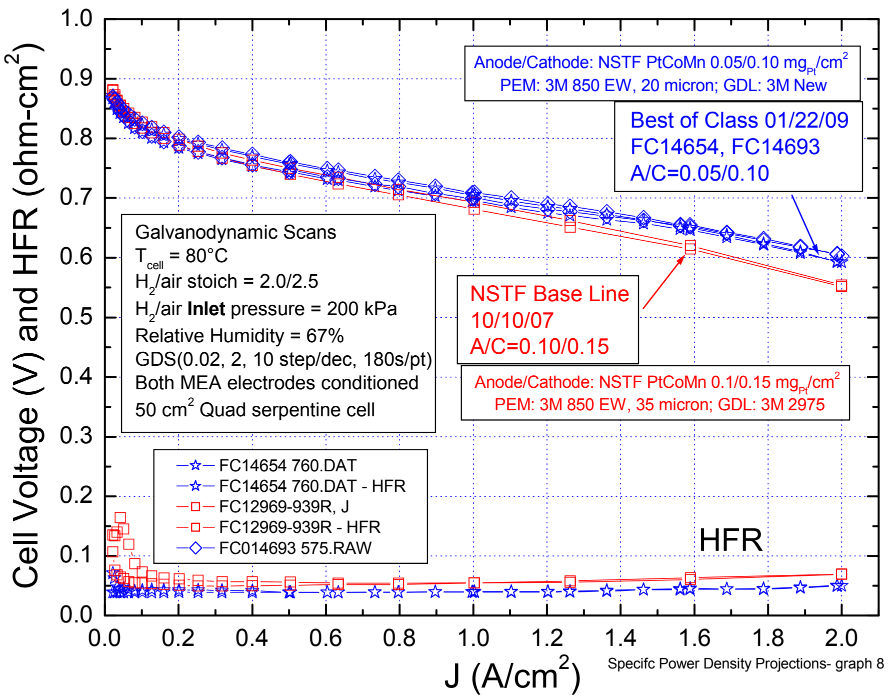




GDS Polarization Curves

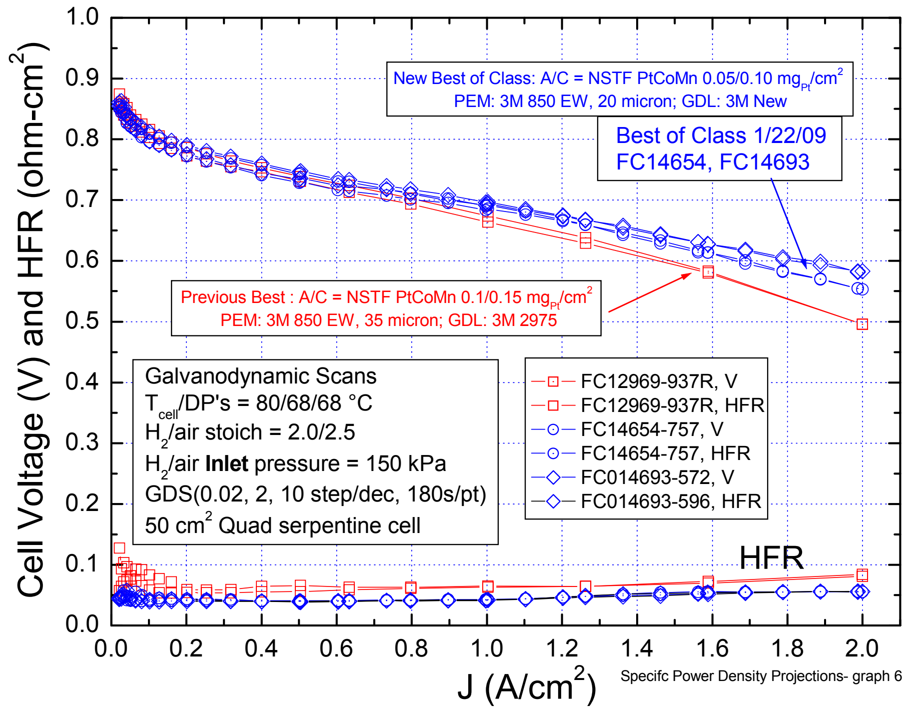
200 kPa

- 50mV gain at 2 A/cm^2
- 28% reduction in impedance



150 kPa

- 85mV gain at 2 A/cm^2
- 34% reduction in impedance



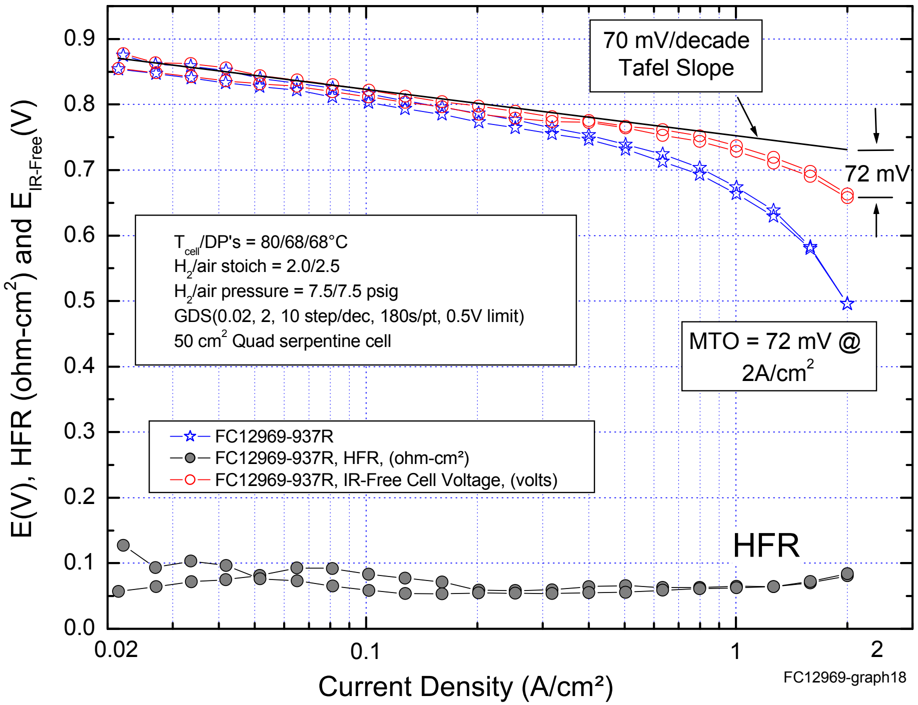
Improvement from:

- 40% reduction in Pt loading
- 20 vs 35 µm thick 3M PEM
- Improved 3M GDL

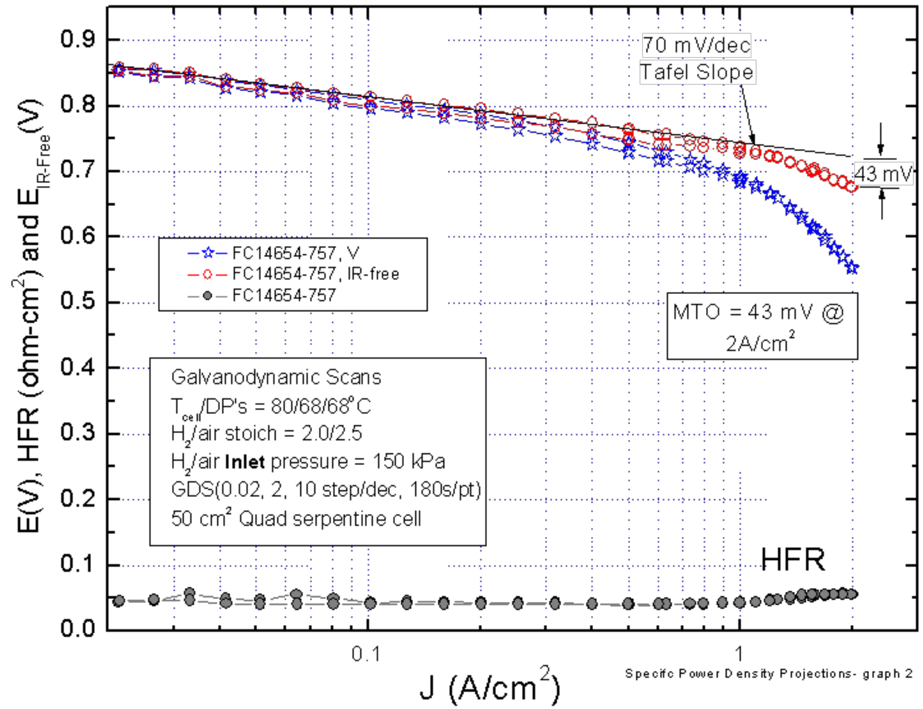
Technical Accomplishments: higher power density, reduced loading

- 40% reduction in Pt loading
- 40% reduction in mass transport over-potential at 2 A/cm², 150kPa

Previous Best of Class



New Best of Class



Baseline Best of Class MEA - Oct., 2007

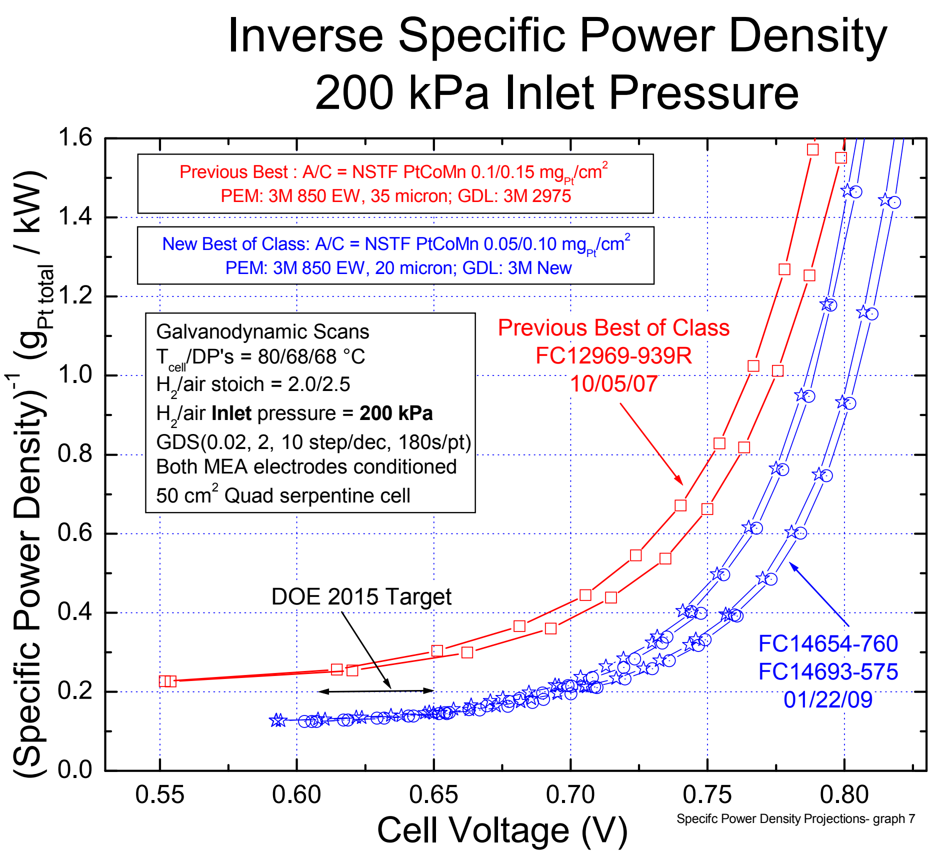
- A/C Loading = 0.1/0.15 mg_{Pt}/cm^2
- 35 micron 3M PEM
- Std. 3M GDL

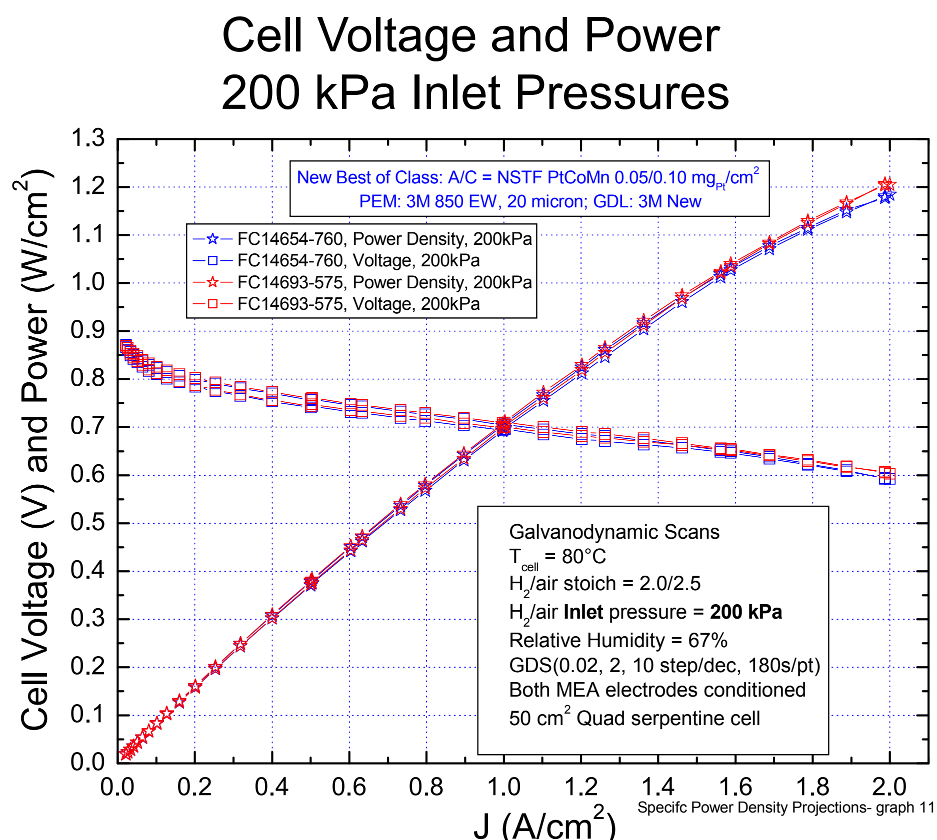
Baseline Best of Class MEA - Jan., 2009

- A/C Loading = 0.05/0.10 mg_{Pt}/cm^2
- 20 micron 3M PEM
- New 3M GDL

Technical Accomplishments: higher power density, reduced loading

- 48% reduction in specific power density at peak power
- 40% reduction in Pt loading
- Exceeds DOE-2015 targets for Specific Power Density and total PGM loading



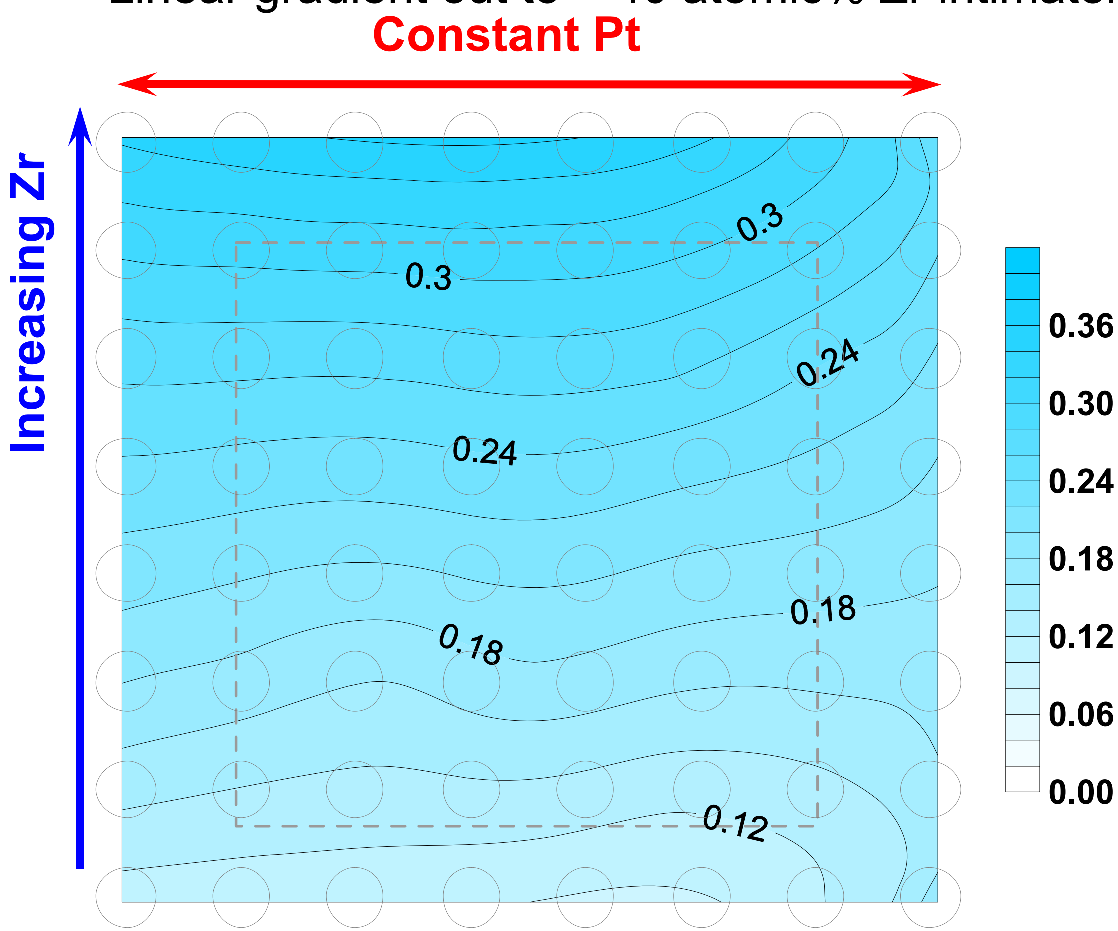


DALHOUSIE UNIVERSITY Inspiring Minds

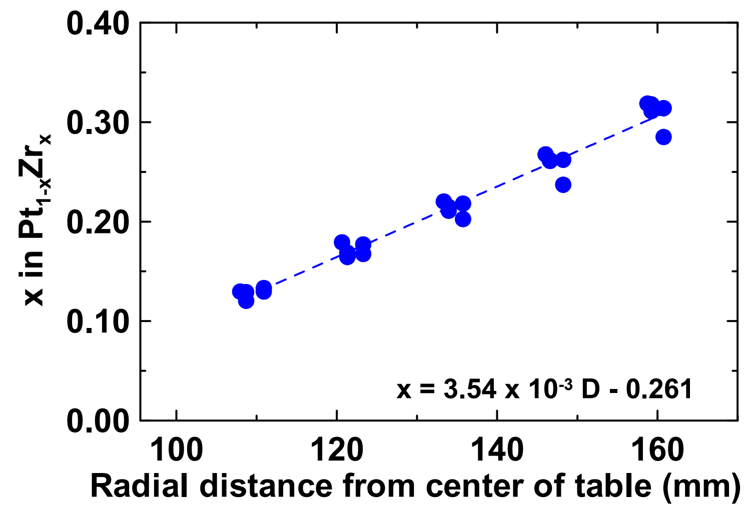
Example Study
to Illustrate the Methodology
- $Pt_{1-x}Zr_x$ -

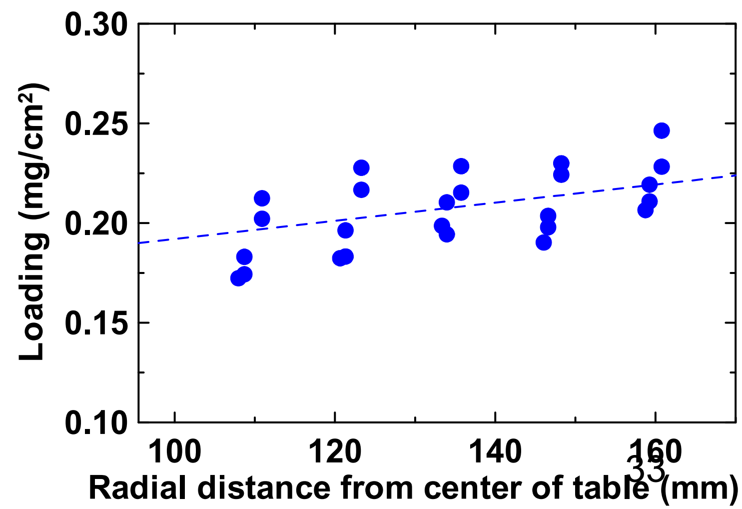
Example of $Pt_{1-x}Zr_x$ Binary Study: Sputtering Details

- Constant Pt, ~75 nm planar equivalent (~0.15 mg/cm^2)
- Linear gradient out to ~ 40 atomic% Zr intimately mixed with the Pt

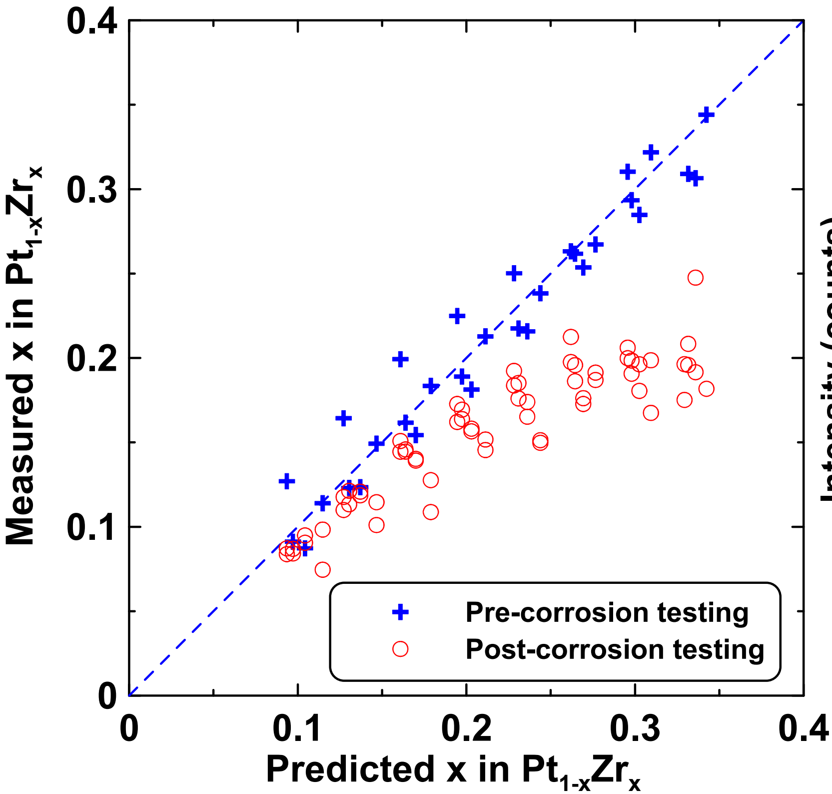


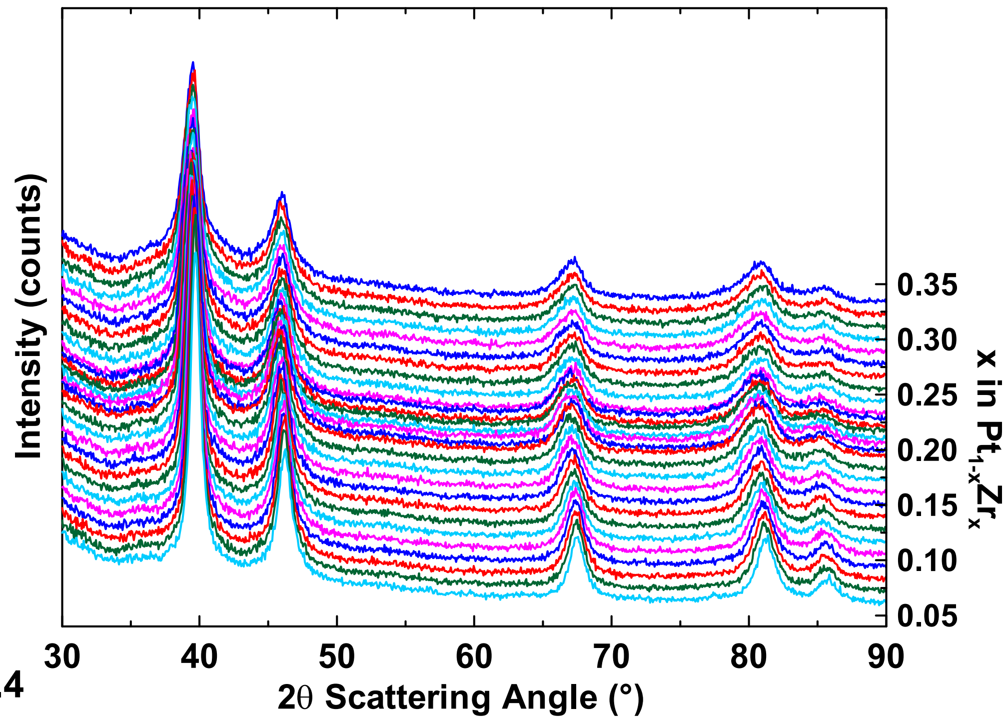
Dashed rectangle shows region measured with microprobe. Circles show positions of FC channels





Example of $Pt_{1-x}Zr_x$ Binary Study: Corrosion Testing, XRD Data

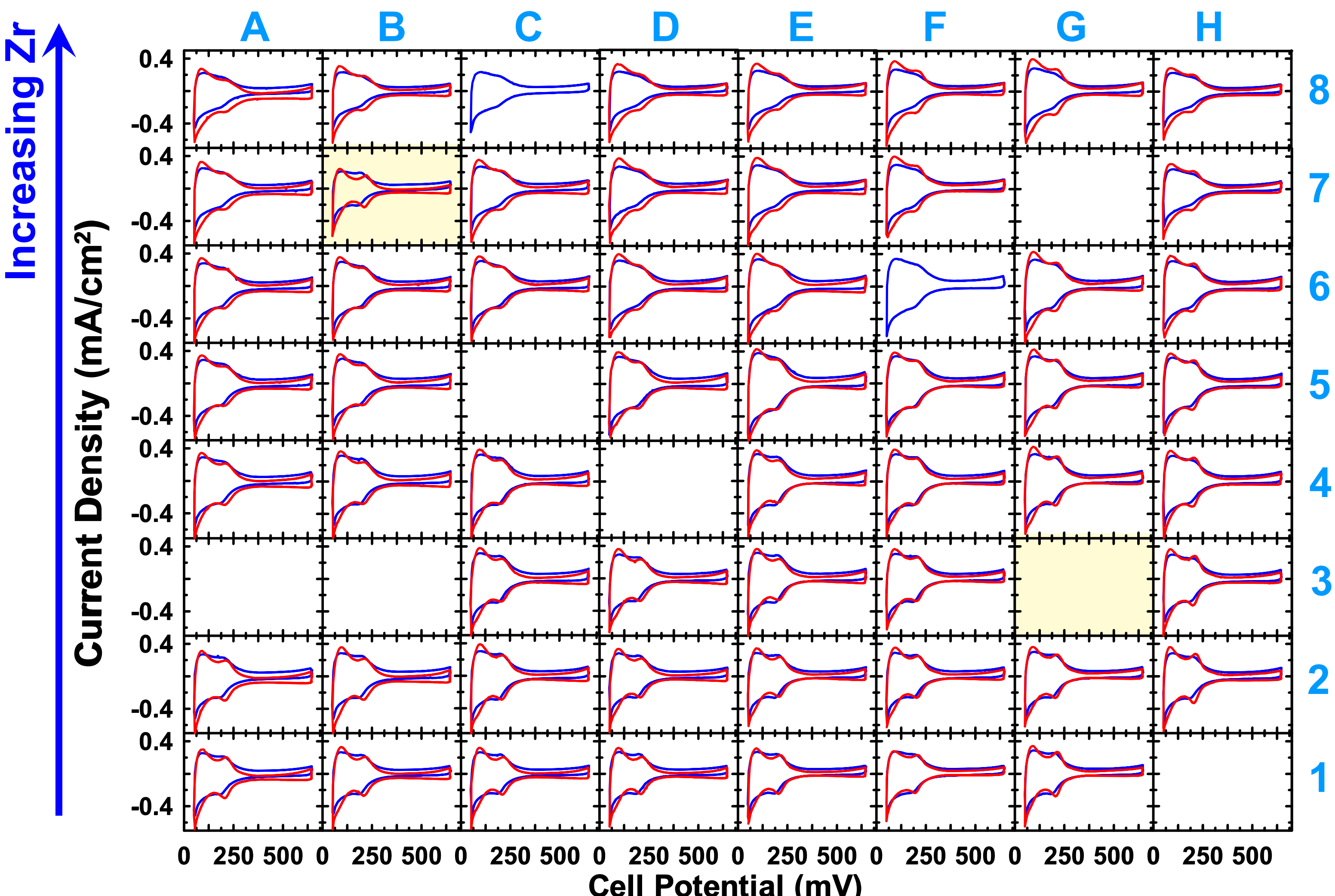




14 days, 80°C, 0.5 M H_2SO_4

Extract grain size and lattice parameters as a function of composition

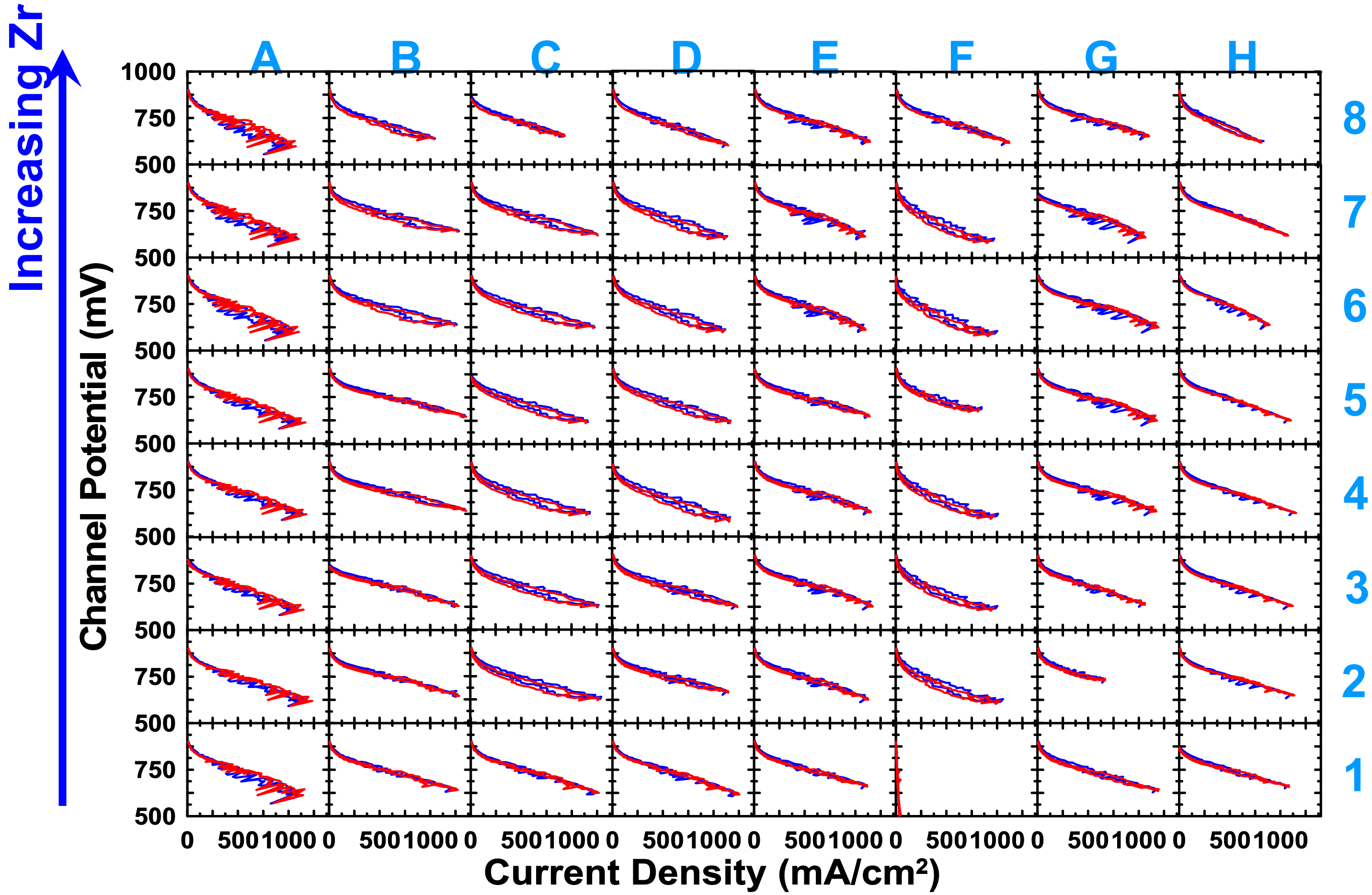
Example of $Pt_{1-x}Zr_x$ Binary Study: Cyclic Voltammetry



Before break-in conditioning

After break-in conditioning

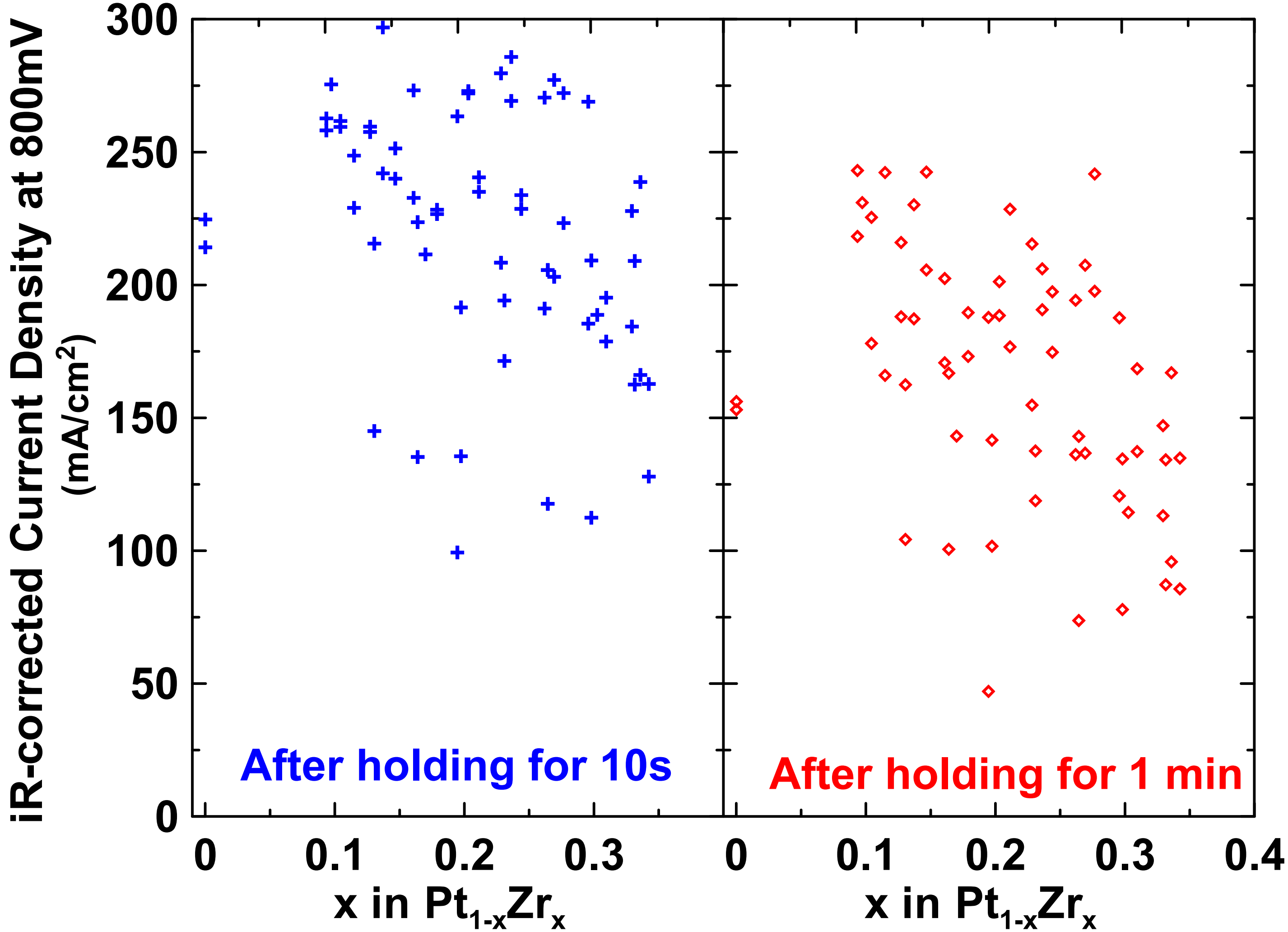
Example of $Pt_{1-x}Zr_x$ Binary Study: ORR performance under O_2



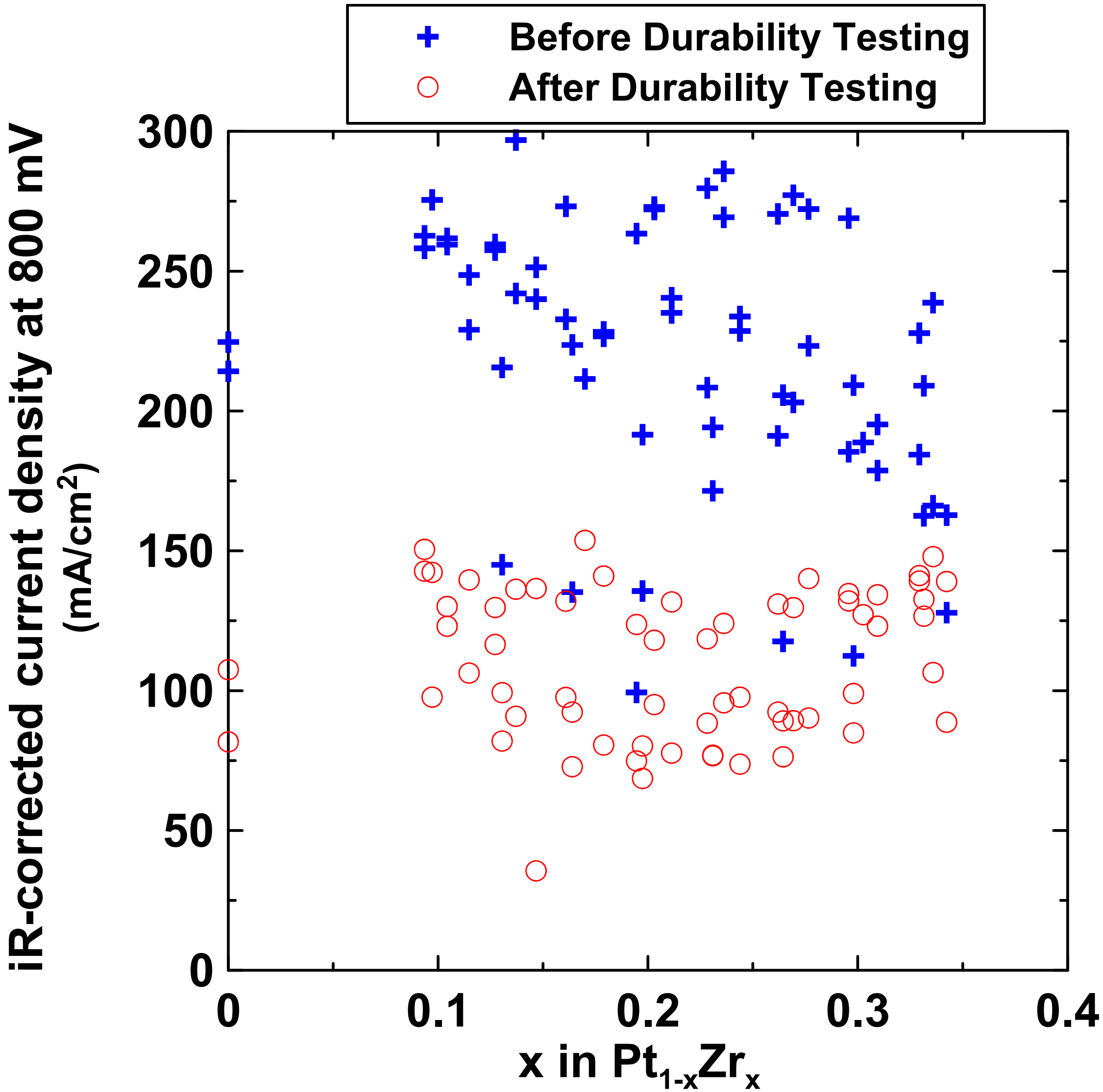
After 10s at potential

After 1 min at potential

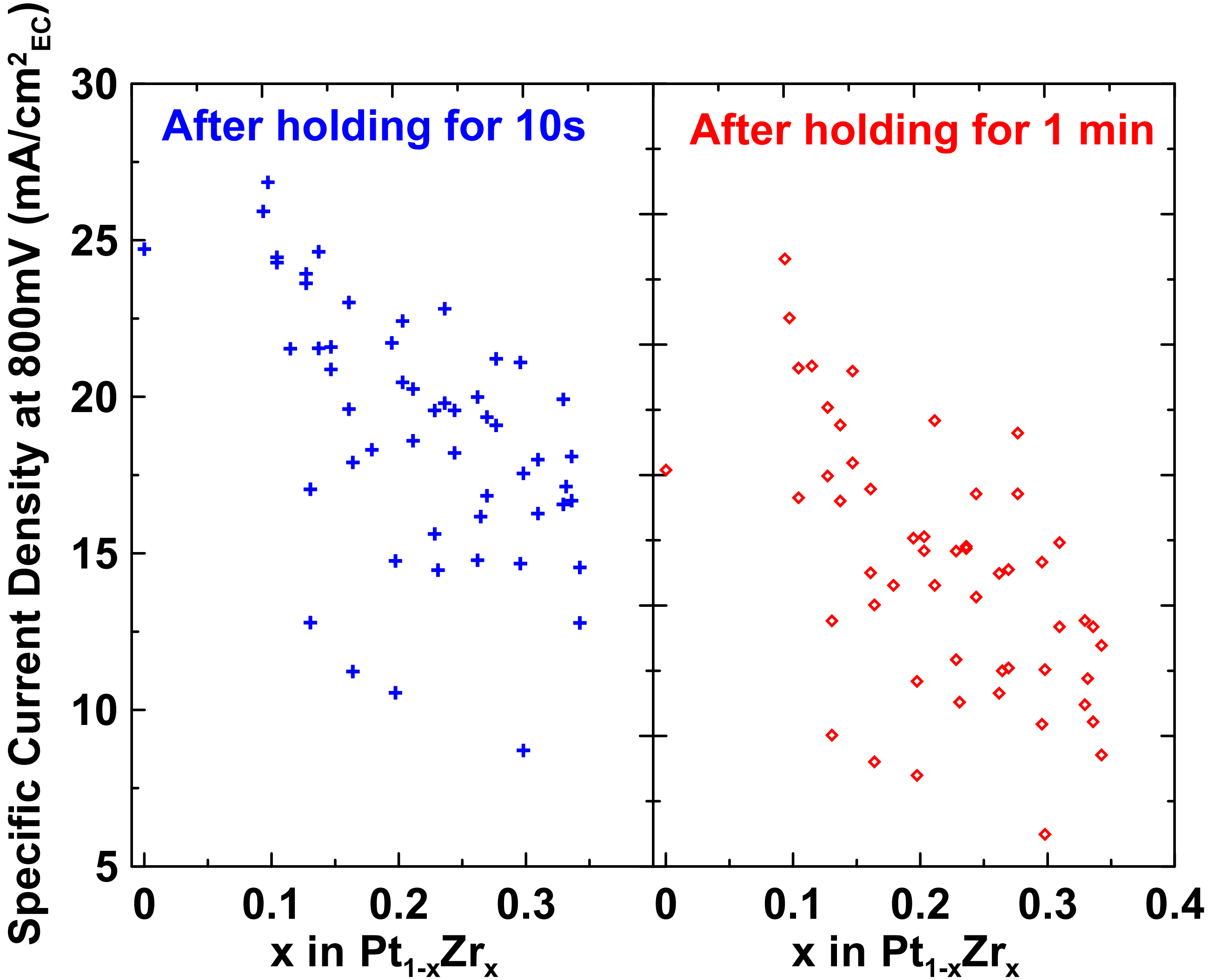
Example of $Pt_{1-x}Zr_x$ Binary Study: ORR performance under O_2



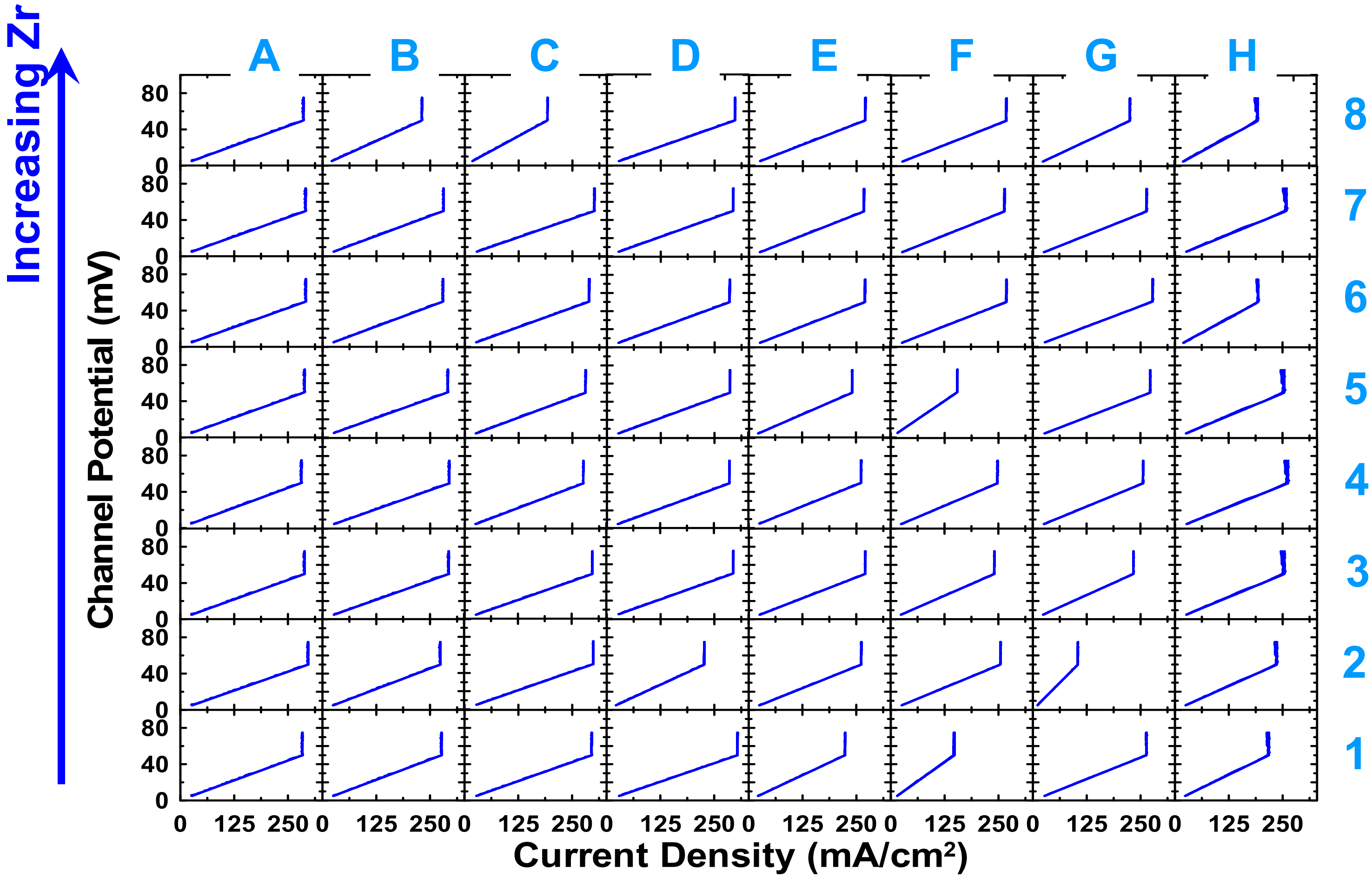
Example of $Pt_{1-x}Zr_x$ Binary Study: ORR specific activity



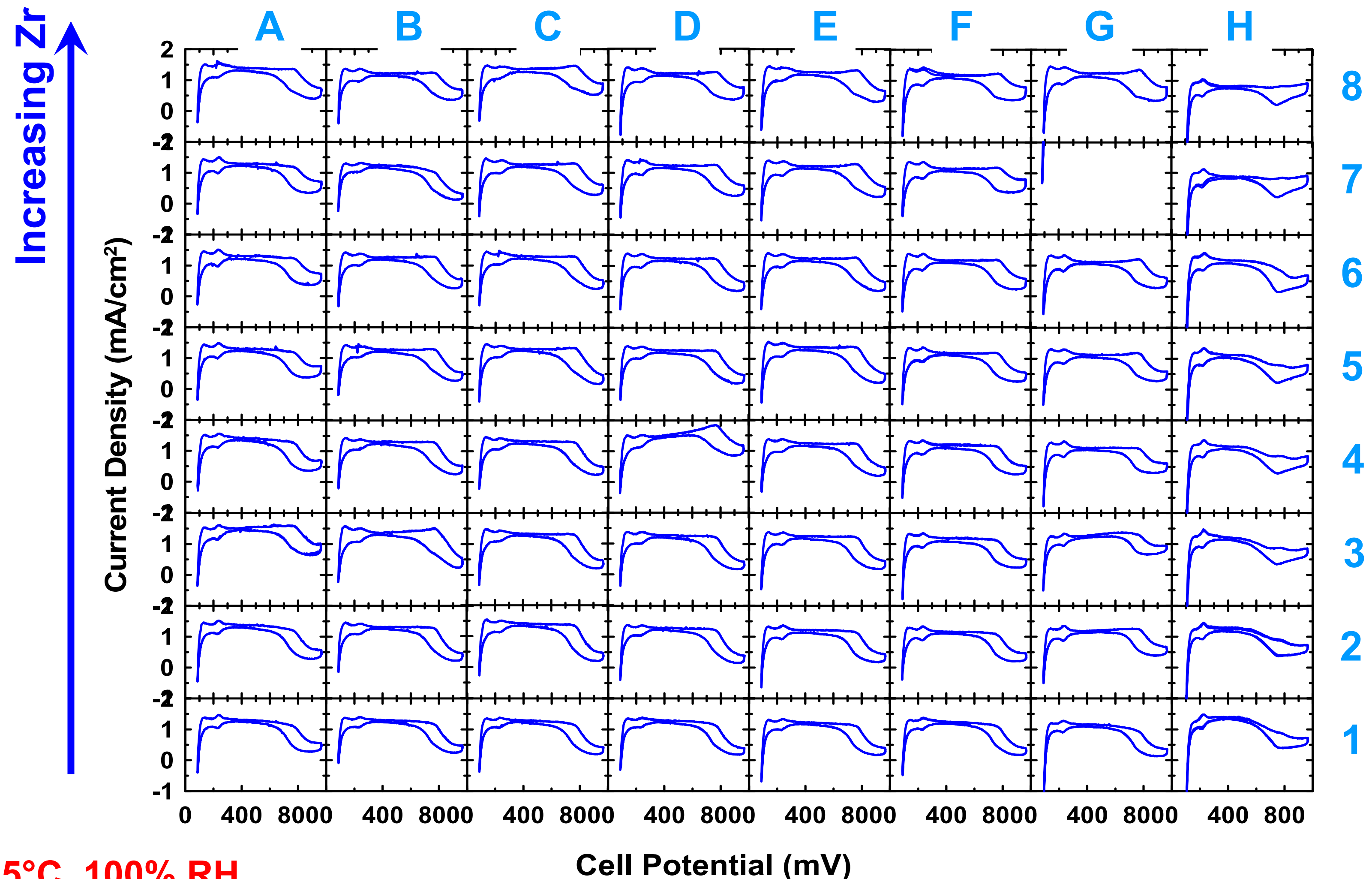
Example of $Pt_{1-x}Zr_x$ Binary Study: ORR specific activity



Example of $Pt_{1-x}Zr_x$ Binary Study: H_2 oxidation performance

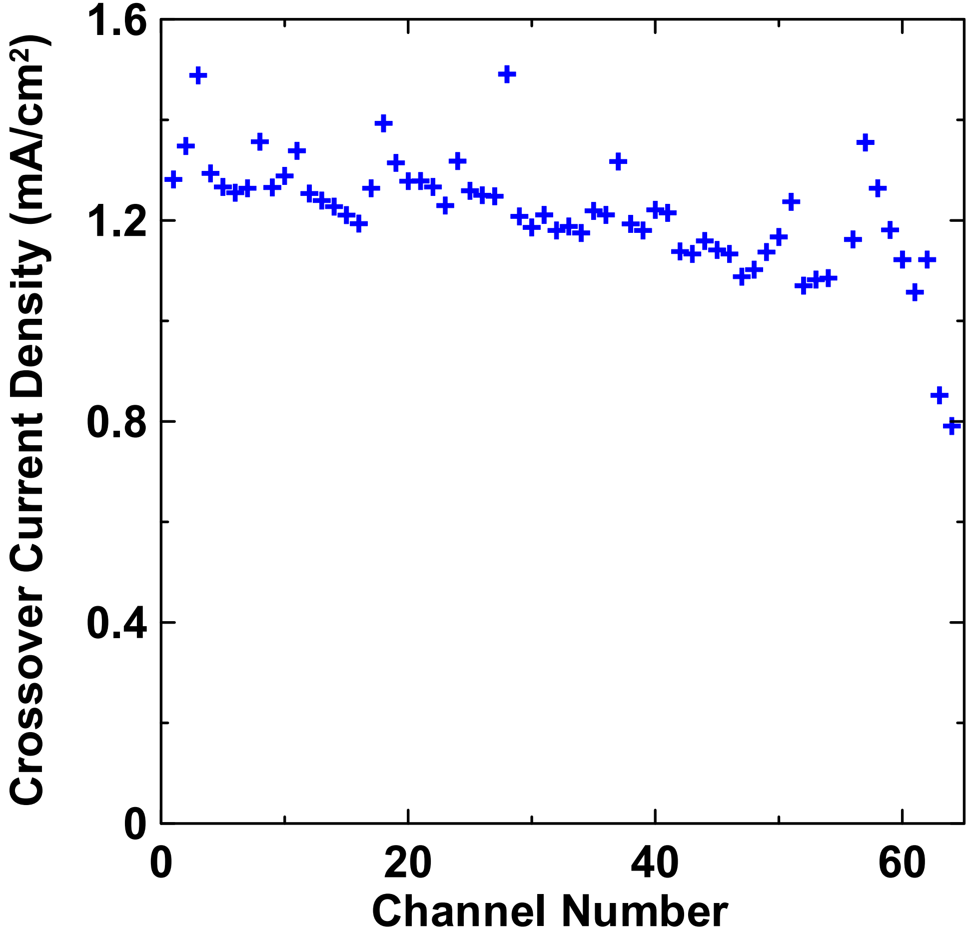


Example of $Pt_{1-x}Zr_x$ Binary Study: Crossover determination

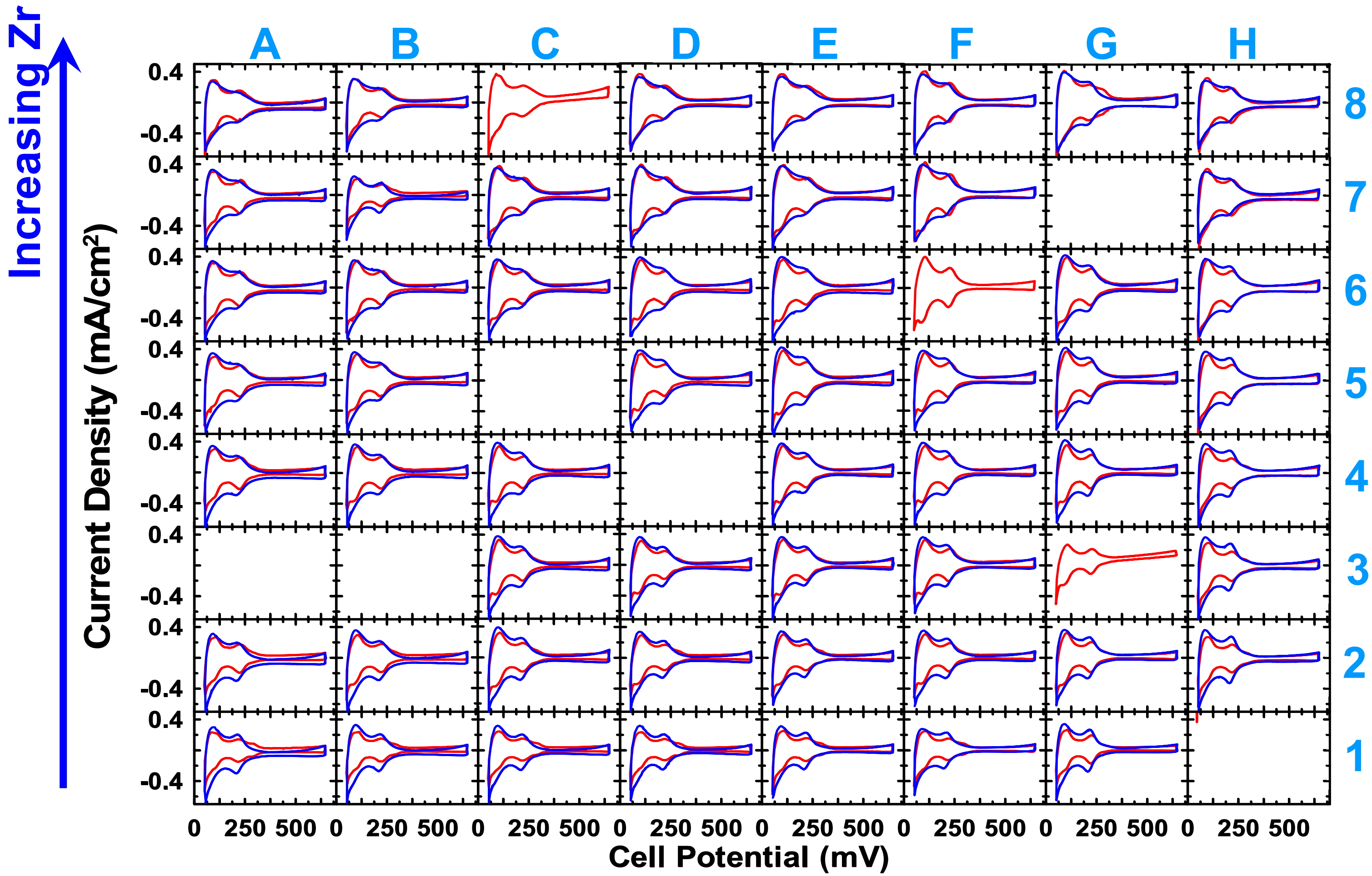


75°C, 100% RH

Example of $Pt_{1-x}Zr_x$ Binary Study: Crossover determination



High Voltage CV Cycling 600 – 1200 mV cycling



Before CV Cycling

After CV Cycling (3000 cycles)