Extended Surface Electrocatalyst Development

Co-PIs Shaun Alia (presenting), Bryan Pivovar
National Renewable Energy Laboratory
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DOE Hydrogen and Fuel Cells Program
2018 Annual Merit Review and Peer Evaluation Meeting

Project ID #FC142

This presentation does not contain any proprietary, confidential, or otherwise restricted information.
Overview

Timeline and Budget

• Project start: December 2015
• Project end: March 2019
• % complete: 95%

• Total project budget: $ 3399k
  – Total recipient share: $ 399k
  – Total DOE share: $ 3000k

• DOE Budget plan
  – FY 2016 $ 1000k
  – FY 2017 $ 1000k
  – FY 2018 $ 1000k

Barriers

• Durability
• Cost
• Performance

Partners

• Colorado School of Mines (CSM) – Svitlana Pylypenko
• University of Delaware (Delaware) – Yushan Yan*
• University of Colorado – Boulder (CU) – Al Weimer
• ALD Nanosolutions (ALDN) – Karen Buechler

*through 3/1/17
Review Period Objectives:

• Pt catalysis remains a primary limitation for fuel cells. We have pursued synthesis of novel extended thin film electrocatalyst structures (ETFECS) for improved cost, performance, and durability.

• Incorporation of ETFECS to meet DOE MEAs targets for fuel cell performance and durability.

### Table 3.4.13 Technical Targets: Electrocatalysts for Transportation Applications

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Units</th>
<th>2011 Status</th>
<th>Targets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pt group metal total content (both electrodes)</td>
<td>g / kW (rated)</td>
<td>0.19b</td>
<td>0.125</td>
</tr>
<tr>
<td>Pt group metal (pgm) total loading</td>
<td>mg PGM / cm² electrode area</td>
<td>0.15b</td>
<td>0.125</td>
</tr>
<tr>
<td>Loss in initial catalytic activity</td>
<td>% mass activity loss</td>
<td>48b</td>
<td>&lt;40</td>
</tr>
<tr>
<td>Electro catalyst support stability</td>
<td>% mass activity loss</td>
<td>&lt;10b</td>
<td>&lt;10</td>
</tr>
<tr>
<td>Mass activity</td>
<td>A / mg Pt @ 900 mV_{Rfree}</td>
<td>0.24b</td>
<td>0.44</td>
</tr>
</tbody>
</table>

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a) PGM content and loading targets may have to be lower to achieve system cost targets.


c) Durability measured in a 25-50 cm² MEA during triangle sweep cycles at 50 mV/s between 0.6 V and 1.0 V at 80°C, atmospheric pressure, 100% relative humidity, H₂ at 200 scm and N₂ at 75 scm for a 50 cm² cell. Based on U.S. DRIVE Fuel Cell Tech Team Component Accelerated Stress Test and Polarization Curve Protocols ([link](http://www.uscar.org/commands/files_download.php?files_id=267)), Electro catalyst Cycle and Metrics (Table 1). Activity loss is based on loss of mass activity, using initial catalyst mass, at end of test.

d) Durability measured in a 25-50 cm² MEA during a hold at 1.2 V in H₂/N₂ at 80°C, 150 kPa absolute, 100% relative humidity. Based on U.S. DRIVE Fuel Cell Tech Team Component Accelerated Stress Test and Polarization Curve Protocols ([link](http://www.uscar.org/commands/files_download.php?files_id=267)), Catalyst Support Cycle and Metrics (Table 2). Activity loss is based on loss of mass activity, using initial catalyst mass, at end of test.

e) Test at 80°C H₂/O₂ in MEA; fully humidified with total outlet pressure of 150 KPa; anode stoichiometry 2; cathode stoichiometry 9.5 (as per Gasteiger et al. Applied Catalysis B: Environmental, 56 (2005) 9-35).
**Approach**

**Catalyst and Membrane Electrode Assembly Development**

- **Ni Nanowires**
  - Commercial

- **Fuel Cell Diagnostics**
  - NREL: performance, durability, transport

- **Characterization**
  - NREL: electrochemical
  - CSM: microscopic

- **Atomic Layer Deposition (ALD)**
  - CU: initial studies/novel chemistry;
  - ALD Nanosolutions: scale up

- **MEA Fabrication/Optimization**
  - NREL: composition, processing

- **Catalyst Post-Processing**
  - NREL: annealing, leaching

- **50 nm**
- **1 μm**

**Graph**

- Current Density [mA/cm²] vs. Cell Potential [V]
  - 500 mV (initial)
  - 577 mA/m² (initial)
  - 500 mV (5k cycle)
  - 413 mA/m² (5k cycle)

**Images**

- Ni Nanowires
- Pt + Ni (annealed and leached)
<table>
<thead>
<tr>
<th>Qtr</th>
<th>Due Date</th>
<th>Type</th>
<th>Milestones, Deliverables, or Go/No Go Decision</th>
<th>Type</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q3</td>
<td>6/30/2018</td>
<td>Regular</td>
<td>Quantify the non-Fickian O₂ transport resistance of at least 3 unique electrodes containing PtNiNW electrocatalysts, a key metric for achieving high performance at low loading.</td>
<td>Quarterly Progress Measure</td>
<td>Met</td>
</tr>
<tr>
<td>Q1</td>
<td>12/31/2018</td>
<td>Regular</td>
<td>Demonstrate synthesis of at least 5 batches of PtNiNW samples by ALD synthesis at quantities of 10g or greater.</td>
<td>Quarterly Progress Measure</td>
<td>Met</td>
</tr>
<tr>
<td>Q2</td>
<td>3/31/2019</td>
<td>Regular</td>
<td>Demonstrate MEA performance that exceed the DOE 2020 mass activity target (440 mA/mgPt) for ALD batch sizes greater than 10g.</td>
<td>Annual Milestone</td>
<td>Met</td>
</tr>
</tbody>
</table>
**Approach**


- **Pt ALD**
- **Anneal**
- **Acid**

Ni NW → Pt ALD → Anneal → Acid → 65-80 wt% Pt

- H$_2$ annealing key to increasing alloying/specific activity.
- Reasonably high surface areas obtained (40+ m$^2$/g)
- Acid leaching removes excess Ni (poisoning concern)
Accomplishments and Progress

Acid leaching studies: ALD compared to SGD

**SGD:** broken wires after 3M acid treatment

**ALD:** wires intact, smooth, uniform even after harsh acid treatment

**Table 1: Pt L\textsubscript{3} edge EXAFS**

<table>
<thead>
<tr>
<th></th>
<th>Bond</th>
<th>N</th>
<th>R(Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SGD</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>As synth</td>
<td>Pt-Pt</td>
<td>12</td>
<td>2.74</td>
</tr>
<tr>
<td>H\textsubscript{2} 250°C</td>
<td>Pt-Pt</td>
<td>5.7</td>
<td>2.69</td>
</tr>
<tr>
<td></td>
<td>Pt-Ni</td>
<td>5.7</td>
<td>2.56</td>
</tr>
<tr>
<td>H\textsubscript{2} 250°C, 1M H\textsubscript{2}SO\textsubscript{4}</td>
<td>Pt-Pt</td>
<td>6.8</td>
<td>2.71</td>
</tr>
<tr>
<td></td>
<td>Pt-Ni</td>
<td>3.24</td>
<td>2.60</td>
</tr>
</tbody>
</table>

| **ALD**  |          |    |      |
| As synth | Pt-Pt    | 11.2 | 2.74 |
| H\textsubscript{2} 250°C | Pt-Ni | 10.5 | 2.57 |
| H\textsubscript{2} 250°C, 3M H\textsubscript{2}SO\textsubscript{4} | Pt-Pt | 12 | 2.76 |
| H\textsubscript{2} 250°C, 3M H\textsubscript{2}SO\textsubscript{4}, H\textsubscript{2} 250°C | Pt-Pt | 5.7 | 2.69 |
|          | Pt-Ni    | 6.3 | 2.60 |

- ALD: lose PtNi alloy, reduced performance.
- But robustness of ALD wires allows us to try re-annealing step to regain activity.
Accomplishments and Progress

Effect of Alloaying on Acid Leached Nanowires

- Key differences noted between SGD, ALD synthesis and performance
- Lost ALD activity from acid leaching can be regained by reannealing

Accomplishments and Progress
ALD Synthesis (CU) with co deposition of Pt and Ni (2018)

- Established Pt ALD route has produced catalysts of reasonable activity, but has been limited because H\textsubscript{2} annealing step required for Ni incorporation into Pt lattice. Lack of control over Ni in Pt shell (ECA and specific activity limitations).

- Co-deposition of Pt and Ni by ALD potentially allows independent control over Ni content and more homogeneous composition.

- Co NWs employed to allow independent compositional analysis of Ni and Pt.
Accomplishments and Progress
ALD Synthesis with co deposition of Pt and Ni (CU)

Schematic of bimetallic ALD process:

Ni ALD

Pt ALD

Δ + H₂

CoNWs

CoNWs

x cycle Ni-O₂

y cycle Pt-O₂

Varying ALD temperature changes growth rate

Varying supercycle ratio used to control Pt and Ni wt%

Annealing for lattice contraction and oxide reduction

In situ H₂ annealing added between supercycles

ALD examined with variety of process conditions
Accomplishments and Progress
Characterization of nanowires made by ALD co-deposition of Pt and Ni

- As synth already shows PtNi alloy (see arrow) due to annealing step during ALD.
- Loss of Ni, Co, PtNi alloy with acid leaching
- Difficulty in retaining Ni
Accomplishments and Progress
ALD (ALDN)  Scale up of catalyst synthesis

- **Fluidized Bed Reactors**
- **Vacuum Rotating Drum Reactors**

- ALD NanoSolutions has multiple reactors and scales from 5g batch to 3 mt/day continuous.
- Research FBR used to synthesize 15g catalyst batches.
- Show reasonable RDE activity and pursuing acid leaching, MEA testing.
- Additional nanowire order has been ordered to continue large scale synthesis and testing.
Accomplishments and Progress
Project mid point go/no go milestone (2018)

**Go/No-go: Demonstrate a mass activity of >440 mA/mg\textsubscript{Pt} at 0.9V (DOE 2020 Target) in fuel cell tests while also meeting at least one of FCTO's MEA durability targets**

- Mass activity improvement from 2017 AMR, now meets DOE mass activity target.
- Activity trend with ALD O\textsubscript{2} concentration consistent between RDE and MEA.

### Durability Testing
Protocol: Triangle sweep cycle, 5000 cycles, 500 mV/s, 1.0-1.5 V

**Target:** <40% loss in initial catalytic activity

<table>
<thead>
<tr>
<th>Cycles</th>
<th>(i_m^{0.9V}) [mA/mg]</th>
<th>% Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>577</td>
<td></td>
</tr>
<tr>
<td>5000</td>
<td>411*</td>
<td>28.8</td>
</tr>
</tbody>
</table>

\(i_m^{0.9V}\) > 440 mA/mg

DOE Durability Target

*following voltage recovery
Accomplishments and Progress
Accomplished FY19 Annual Milestone

Demonstrate MEA performance that exceed the DOE 2020 mass activity target (440 mA/mg_{Pt}) for ALD batch sizes greater than 10 g.

<table>
<thead>
<tr>
<th>(i_m^{0.9V})</th>
<th>463 mA/mg_{Pt}</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECSA</td>
<td>35.5 m²/g_{Pt}</td>
</tr>
<tr>
<td>(i_s^{0.9V})</td>
<td>1226 μA/cm²_{Pt}</td>
</tr>
</tbody>
</table>

PtNi mixed with Vulcan XC72
PtNi:C – 2:1 (w/w)
I/C – 0.5

Ionomer and carbon dispersed separately from PtNi

PtNi mixed with carbon/ionomer prior to coating
Accomplishments and Progress
Incorporation of Carbon Blacks

- Ketjenblack improved high-current-density performance (2018)
- Carbon types incorporated into large-batch ALD MEAs to study effect: Ketjenblack (KB), Vulcan XC72 (Vu), Graphitized Carbon Nanofibers (GCNF)
- In-situ performance suggests carbon shape may be important for electrode structure
- Evaluating alternative fabrication process, coating Pt-Ni, C/ionomer separately

Accomplishments and Progress
Evaluation of Nickel Leaching

- Low magnification STEM images and EDS maps show small amounts of Ni in membrane
- Higher magnification of PtNi nanowires show Pt and Ni in catalyst layer

<table>
<thead>
<tr>
<th>Element</th>
<th>[norm. wt.%]</th>
<th>[norm. at.%]</th>
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</thead>
<tbody>
<tr>
<td>Fluorine</td>
<td>96.20</td>
<td>97.81</td>
</tr>
<tr>
<td>Sulfur</td>
<td>3.03</td>
<td>1.82</td>
</tr>
<tr>
<td>Potassium</td>
<td>0.71</td>
<td>0.35</td>
</tr>
<tr>
<td>Nickel</td>
<td>0.06</td>
<td>0.02</td>
</tr>
</tbody>
</table>

0.02 at% Ni in membrane
Trace K contaminant
Accomplishments and Progress
Large batch catalyst MEAs similar to small batch MEA

- Large-batch ALD synthesis/scalable coating MEAs result in similar performance small-batch ALD synthesis/spray-coating MEAs

<table>
<thead>
<tr>
<th>Batch Size</th>
<th>Carbon Type</th>
<th>$i_{m,0.9V}$ [mA/mgPt]</th>
<th>ECSA $[m^2/gPt]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 g</td>
<td>Ketjen</td>
<td>507</td>
<td>22.6</td>
</tr>
<tr>
<td>10 g</td>
<td>Ketjen</td>
<td>469</td>
<td>30.8</td>
</tr>
<tr>
<td>10 g</td>
<td>Vulcan</td>
<td>463</td>
<td>35.5</td>
</tr>
</tbody>
</table>

PtNi:C – 2:1 (w/w)
Refinements in ALD synthesis and coating procedure likely to improve performance of scalable MEAs
Accomplishments and Progress
Responses to Previous Year (2018 AMR) Reviewer’s Comments

• **Reviewer Comment:** One primary challenge is that it is unclear whether the ETFECS structure with the hollow core (after dealloying) will be stable against electrochemical cycling, which does not appear to have been assessed to any significant extent. Another aspect of concern is that there appears to be relatively little MEA testing with exposure to hydrogen/air with state-of-the-art components (e.g., thin polymer electrolyte membrane [PEMs]); this testing process is critical for assessing impacts of residual transition metals.

• **Response:** Multiple reviewers noted that durability was an issue that hadn’t yet been probed in detail. We have previously demonstrated that we were able to meet the stop-start durability target and meet the project mid-point go/no-go decision. We have focused remaining project resources in obtaining higher performing MEAs prior to probing durability.

• **Reviewer Comment:** The team needs to come up with a verified process, such as the acid-leaching step, to make the MEA fabrication process viable. It is well known in the PEM technical community that any leftover Ni in the electrode will quickly destroy the membrane, significantly decrease cell performance, and affect durability. This project does not define a method for verifying that Ni does not and will not leach out of this catalyst.

• **Response:** We have focused on MEA testing of materials approximately 70 wt. % Pt or higher to improve the viability of MEA fabrication and durability. We have verified low Ni leaching rates with ICP-MS in half-cell testing and found significantly less Ni dissolution compared to unleaded materials.

• **Reviewer Comment:** Performance variations are very high for both types of testing, suggesting that significant additional efforts on optimization of both the catalyst and the catalyst layer will be required.

• **Response:** We have shifted focus to larger scale batches (10 g) for testing to mitigate variability performance variability.
## Collaborations

<table>
<thead>
<tr>
<th>Institutions</th>
<th>Role</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>National Renewable Energy Laboratory (NREL):</strong></td>
<td>Prime, Oversees the project, lead catalyst synthesis and characterization; lead electrode fabrication and fuel cell testing; techno-economic analysis</td>
</tr>
<tr>
<td>Bryan Pivovar (co-PI), Shaun Alia (co-PI), KC Neyerlin, Katie Hurst, Jason Zack, Scott Mauger, Ahmad Mayyas</td>
<td>Prime, Oversees the project, lead catalyst synthesis and characterization; lead electrode fabrication and fuel cell testing; techno-economic analysis</td>
</tr>
<tr>
<td><strong>University of Delaware (Delaware):</strong></td>
<td>Sub; Support work in providing Ni nanostructures</td>
</tr>
<tr>
<td>Yushan Yan, Jarrid Wittkopf</td>
<td>Sub; Support work in providing Ni nanostructures</td>
</tr>
<tr>
<td><strong>Colorado School of Mines (CSM):</strong></td>
<td>Sub; Materials characterization using spectroscopy and microscopy</td>
</tr>
<tr>
<td>Svitlana Pylypenko, Sarah Zaccarine, Chilan Ngo, Samantha Medina</td>
<td>Sub; Materials characterization using spectroscopy and microscopy</td>
</tr>
<tr>
<td><strong>University of Colorado-Boulder (CUB):</strong></td>
<td>Sub; ALD synthesis including both Pt and Ni using both oxidative and reductive chemistry</td>
</tr>
<tr>
<td>Al Weimer, Will Medlin, Wilson McNeary</td>
<td>Sub; ALD synthesis including both Pt and Ni using both oxidative and reductive chemistry</td>
</tr>
<tr>
<td><strong>ALD Nanosolutions (ALDN):</strong></td>
<td>Sub; ALD consultation, scale up and business-case analysis</td>
</tr>
<tr>
<td>Karen Buechler, Joe Spencer</td>
<td>Sub; ALD consultation, scale up and business-case analysis</td>
</tr>
</tbody>
</table>

Beam time at SLAC (Johanna Nelson Weker)
Mai-Anh Ha (UCLA) Office of Science SCSGR awardee
Shawn Litster (Carnegie Mellon)
Electrocatalysts:
- ALD – Optimization of scale-up batches at 10 g batch size and beyond.
- Pt/Ni ALD co-deposition
- Post-processing optimization (annealing and acid leaching)
- Characterization and optimization (electrochemical and structural studies)

MEA Fabrication and Optimization:
- Optimization of electrode structure/performance using ALD materials.
- Isolation and minimization of overpotential losses in MEA electrodes.
- Evaluation and minimization of local oxygen transport and proton transport resistances to improve high current density performance.
- Durability studies to quantify and minimize performance losses.

Any proposed future work is subject to change based on funding levels.
Technology Transfer Activities

Intellectual Property
Nanowires have been IP protected.
Continual development of additional IP.

Industrial Interactions:
ALD NanoSolutions as an appropriate industrial partner for synthesis due to the importance of ALD reactions and reactors. Small business interactions involving NWs for related applications have included. Small Business Voucher program: Oorja; SBIR program: Giner, pH Matter – pH Matter is getting trained to synthesize NWs and has been approached about licensing options. Large business interactions: Includes OEMs and component suppliers.
Summary

• **Relevance:** Focused on overcoming the cost, performance and durability barriers for fuel cell commercialization by increasing Pt mass activity and durability.

• **Approach:** Developing durable, high mass activity extended surface Pt catalysts, and optimize MEA performance/durability for these materials.

• **Accomplishments and Progress:** The project has demonstrated the ability to achieve high performance of ALD synthesized PtNi NWs in reasonable scale (up to 10g batches) and reproducibility. Pt/Ni co-deposition by ALD has been demonstrated. Post-treatment has allowed significant gains in performance and removed Ni leaching concerns. MEAs now demonstrate mass activity above DOE targets 440 mA/mg\(_{\text{Pt}}\). MEA optimization has shown potential to improve high current density performance.

• **Collaborations:** We have a diverse team of researchers including 3 universities, and an industrial participant.

• **Proposed Future Research:** See previous slide.
Technical Back-Up Slides
Accomplishments and Progress
ALD compared to SGD (Pt on Ni NWs)

<table>
<thead>
<tr>
<th></th>
<th>Bond</th>
<th>N</th>
<th>R(Å)</th>
<th>σ²x10³</th>
<th>R-Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>SGD</td>
<td>As synth</td>
<td>Pt-Pt</td>
<td>12</td>
<td>2.74</td>
<td>7.97</td>
</tr>
<tr>
<td></td>
<td>H₂ 250℃</td>
<td>Pt-Pt</td>
<td>5.7</td>
<td>2.69</td>
<td>7.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pt-Ni</td>
<td>5.7</td>
<td>2.56</td>
<td>5.4</td>
</tr>
<tr>
<td></td>
<td>H₂ 400℃</td>
<td>Pt-Ni</td>
<td>10.4</td>
<td>2.55</td>
<td>4.7</td>
</tr>
<tr>
<td>ALD</td>
<td>As synth</td>
<td>Pt-Pt</td>
<td>11.2</td>
<td>2.74</td>
<td>6.5</td>
</tr>
<tr>
<td></td>
<td>H₂ 250℃</td>
<td>Pt-Ni</td>
<td>10.5</td>
<td>2.57</td>
<td>6.8</td>
</tr>
</tbody>
</table>

- SGD samples require higher annealing temp (400℃) to form full PtNi alloy.
- ALD wires are easier to alloy (lower T).
  - Visible in homogeneous coating on wire.
Accomplishments and Progress
Platinum nickel Alloying with Cobalt Template

<table>
<thead>
<tr>
<th>Sample</th>
<th>Bond</th>
<th>$N$</th>
<th>$R$(Å)</th>
<th>$\sigma^2 x 10^3$</th>
<th>$R$-Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Co23</td>
<td>Pt-Ni</td>
<td>11.08</td>
<td>2.57</td>
<td>9.4</td>
<td>0.021</td>
</tr>
<tr>
<td>Co23_A</td>
<td>Pt-Ni</td>
<td>11.06</td>
<td>2.57</td>
<td>8.8</td>
<td>0.011</td>
</tr>
<tr>
<td>WM20</td>
<td>Pt-Pt</td>
<td>11.2</td>
<td>2.74</td>
<td>6.5</td>
<td>0.011</td>
</tr>
<tr>
<td>WM20_A</td>
<td>Pt-Ni</td>
<td>10.45</td>
<td>2.57</td>
<td>6.8</td>
<td>0.008</td>
</tr>
</tbody>
</table>

- Co23 as prepared sample already shows full PtNi alloy, due to annealing step during ALD synthesis.
- Both annealed samples show full PtNi alloy.
- Co23 shows similar PtNi CN in as prepared sample, higher CN for annealed sample.
Accomplishments and Progress
Incorporated Carbon to Improve Mass Transport  Constant I:C

This work is progressing towards 3D reconstructions.

2D TXM data:
- Energy: 8355 eV (right above Ni K edge, both Pt and Ni absorb here).
- As expected, less dense amounts of wires as ratio goes down.
- Wires look most distributed in 2:1 ratio; and this was the best performer.
**Accomplishments and Progress**

*Platinum Nickel and Nafion interactions*

- Consistent observations of correlation between metal (Pt and Ni) maps with S map.
- Correlations between S and Ni are stronger than for Pt.
- Need alternative electrode fabrication process: PtNi NWs, C+ionomer deposited separately.
Accomplishments and Progress
Acid leaching studies: electrodes

Wires (0.1M HNO₃ leached)

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>R(Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pt-Pt</td>
<td>6.4</td>
<td>2.72</td>
</tr>
<tr>
<td>Pt-Ni</td>
<td>3.7</td>
<td>2.58</td>
</tr>
</tbody>
</table>

Unleached electrode

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>R(Å)</th>
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<tbody>
<tr>
<td>Pt-Pt</td>
<td>6.4</td>
<td>2.72</td>
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<td>3.7</td>
<td>2.58</td>
</tr>
</tbody>
</table>

1M H₂SO₄ at 25°C

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>R(Å)</th>
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<tr>
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<td>2.71</td>
</tr>
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<td>Pt-Ni</td>
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<td>2.60</td>
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1M H₂SO₄ at 80°C

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<tr>
<th></th>
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<th>R(Å)</th>
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<tbody>
<tr>
<td>Pt-Pt</td>
<td>7.5</td>
<td>2.70</td>
</tr>
<tr>
<td>Pt-Ni</td>
<td>2.2</td>
<td>2.60</td>
</tr>
</tbody>
</table>

• Acid leaching preferentially removes bulk Ni
• But alloyed Ni is also removed
• Motivates further studies of acid leaching

Note: these are SGD samples.
Although MeCpPtMe$_3$ Precursor is currently high cost (~4x Pt), at even modest production volume (100’s of kg/yr), we project cost to only be a few % higher than Pt cost.
Estimated Production Costs: Rotary Blender Reactor (ALDN)

<table>
<thead>
<tr>
<th>Production Rate</th>
<th>1</th>
<th>10</th>
<th>100</th>
<th>Tons/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor Size</td>
<td>2</td>
<td>9</td>
<td>20</td>
<td>ft³</td>
</tr>
<tr>
<td>Required MeCpMe₃Pt</td>
<td>1750</td>
<td>17500</td>
<td>175000</td>
<td>Kg/yr</td>
</tr>
<tr>
<td>Required H₂</td>
<td>44</td>
<td>441</td>
<td>4410</td>
<td>Kg/yr</td>
</tr>
<tr>
<td>Production Cost (excluding MeCpMe₃Pt)</td>
<td>665</td>
<td>623</td>
<td>618</td>
<td>$/kg Product</td>
</tr>
</tbody>
</table>

ALD reactor costs and post-processing costs (annealing and acid leaching) are projected to be low as well. Pt would be used very efficiently and recycled in this operation at scale.

Resulting catalyst processing cost would be >10% than the cost of Pt.