Tailored High Performance Low-PGM Alloy Cathode Catalysts

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Materials Science Division
Argonne National Laboratory

Project ID#
FC140

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**Timeline**
- Project start: 10/2015
- Project end: 10/2018

**Budget**
- Total Project funding: $3.25M
- Total DOE funds spent: $2.93M
- Funding for FY18: $900K

**Overview**

**Barriers to be addressed**
- ~ 30-40% (!!!)
- Cathode kinetics

1. **Durability** of fuel cell stack (<40% activity loss)
2. **Cost** (total loading of PGM $0.125 \text{ mg}_{\text{PGM}} / \text{ cm}^2$)
3. **Performance** (mass activity @ 0.9V 0.44 A/mg_{Pt})

**Partners:**
- Argonne National Laboratory – MERF - CSE – Greg Krumdick, Debbie Myers
- Oak Ridge National Laboratory – Karren More
- National Renewable Energy Laboratory – Kenneth Neyerlin

**Project Lead:**
- Argonne National Laboratory - MSD – V. Stamenkovic / N. Markovic
**Objectives** The main focus of ongoing DOE Hydrogen & Fuel Cell Program is development of highly-efficient and durable Pt-Alloy *catalysts* for the ORR *with low-Pt content*.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Units</th>
<th>2011 Status</th>
<th>2020 Targets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Platinum group metal total content (both electrodes)</td>
<td>g / kW (rated)</td>
<td>0.19&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.125</td>
</tr>
<tr>
<td>Platinum group metal (pgm) total loading&lt;sup&gt;a&lt;/sup&gt;</td>
<td>mg PGM / cm&lt;sup&gt;2&lt;/sup&gt; electrode area</td>
<td>0.15&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.125</td>
</tr>
<tr>
<td>Loss in initial catalytic activity&lt;sup&gt;c&lt;/sup&gt;</td>
<td>% mass activity loss</td>
<td>48&lt;sup&gt;b&lt;/sup&gt;</td>
<td>&lt;40</td>
</tr>
<tr>
<td>Electro catalyst support stability&lt;sup&gt;d&lt;/sup&gt;</td>
<td>% mass activity loss</td>
<td>&lt;10&lt;sup&gt;b&lt;/sup&gt;</td>
<td>&lt;10</td>
</tr>
<tr>
<td>Mass activity&lt;sup&gt;e&lt;/sup&gt;</td>
<td>A / mg Pt @ 900 mV&lt;sub&gt;ir-free&lt;/sub&gt;</td>
<td>0.24&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.44</td>
</tr>
<tr>
<td>Non-Pt catalyst activity per volume of supported catalyst&lt;sup&gt;f&lt;/sup&gt;</td>
<td>A / cm&lt;sup&gt;2&lt;/sup&gt; @ 800 mV&lt;sub&gt;ir-free&lt;/sub&gt;</td>
<td>60 (measured at 0.85 V&lt;sub&gt;f&lt;/sub&gt;)</td>
<td>165 (extrapolated from &gt;0.85 V&lt;sub&gt;f&lt;/sub&gt;)</td>
</tr>
</tbody>
</table>

*Source:* Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan
Materials-by-design approach - to design, characterize, understand, synthesize/fabricate, test and develop tailored high performance low platinum-alloy nanoscale catalysts

**Approach**

- Rational synthesis based on well-defined systems
- Activity boost by lower surface coverage of spectators
- Addition of the elements that hinder Pt dissolution
- Prevent loss of TM atoms without activity decrease

**ANL**

PEMFC Cathode Catalysts Development
- well-defined systems, fundamental principles, chemical and thin film synthesis, structural and RDE & MEA characterizations

<table>
<thead>
<tr>
<th>Task</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1°</td>
<td>LEIS, AR-XPS, AES, UPS, LEED, STM</td>
</tr>
<tr>
<td>2°</td>
<td>Magnetron Sputtering</td>
</tr>
<tr>
<td>3°</td>
<td>Electrochemical Cell</td>
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<tr>
<td>4°</td>
<td>Electrochemical ICP/MS</td>
</tr>
<tr>
<td>5°</td>
<td>LEIS, AR-XPS, AES, UPS, LEED, STM</td>
</tr>
</tbody>
</table>

**ANL - Synthesis**

- PtMN: well-defined bulk and thin film surfaces of PtMN: -single crystalline and polycrystalline systems -structure/composition vs. activity/durability (UHV, PVD, STM vs. RDE, STM, ICP/MS)
- synthesis of nano-, meso- and thinfilm- PtMN catalysts: -shape/size/composition control -intermetallics; core/interlayer/shell; thin-film systems (colloidal chemical synthesis, PVD, HRTEM/STEM)
- electrochemical characterization of catalysts: -optimization: ionomer/carbon/propanol/catalyst ink -temperature effect; Ionic Liquid evaluation -activity/durability in RDE vs. 5-50cm²/MEA; HRTEM
- fine tuning of performance through catalyst-support: -Carbon based materials
- scaling-up of the most promising catalysts: -gram scale single batches

**Inter Lab Collaborators**

- Project Lead: AIO 4A Low-PGM
- ANL - Catalyst Synthesis
- ORNL - Electron Microscopy
- NREL - 50cm² MEA testing
- ANL - ES - Carbon nano/m tubes
- ANL - ES - Support of Scaling-Up
**Approach**

- Single Crystals
- Solid Nanoparticles
- NPs with Skin Surfaces
- Core-Shell Nanoparticles
- Shaped Particles
- Meso-S Thin Films
- Nanoframes and Nanowires

**Project Management**

<table>
<thead>
<tr>
<th>Table 1</th>
<th>FY16</th>
<th>FY17</th>
<th>FY18</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active Task</td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
</tr>
<tr>
<td>T1 WDS</td>
<td>Jan</td>
<td></td>
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<tr>
<td>T2 SYN</td>
<td></td>
<td></td>
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<tr>
<td>T3 ECC</td>
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<tr>
<td>T4 SUP</td>
<td></td>
<td></td>
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<tr>
<td>T5 SCA</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

- Task 1 - Well-Defined Systems (WDS)
- Task 2 - Synthesis of Materials (SYN)
- Task 3 - Electrochemical Characterization (ECC)
- Task 4 - Novel Support/Catalyst (SUP)
- Task 5 - Scaling Up of Materials (SCA)

- From fundamentals to real-world materials
- Simultaneous effort in five Tasks
- Go-No Go evaluation
- Progress measures are quarterly evaluated
**Task 1**  

**Accomplishments:** *RDE-ICP/MS of Pt/C Nanoparticles*

![Diagram of Electrochemical Cell and In-Situ RDE-ICP/MS setup]

**Surface Structure**

<table>
<thead>
<tr>
<th></th>
<th>Pt(111)</th>
<th>Pt(100)</th>
<th>Pt(110)</th>
<th>Pt-poly</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dissolved Pt per cycle [µML]</td>
<td>2</td>
<td>7</td>
<td>83</td>
<td>36</td>
</tr>
</tbody>
</table>

**Detection Limit:** 0.8 µML of Pt

**In-Situ RDE-ICP/MS**

- Monodisperse 20% Pt/C NPs 3 and 5nm

**Correlation between Surface Structure - Activity – Dissolution**

- Average size = 2.7 +/- 0.5 nm
- Average size = 5.1 +/- 0.5 nm

*ACS Catalysis, 6 (4), 2536-2544, 2016*
Task 1  Accomplishments and Progress:  \textbf{RDE-ICP/MS of Pt/C Nanoparticles}

- Surface Structure:
  - Pt(111)
  - Pt(100)
  - Pt(110)
  - Pt-poly

- Dissolved Pt per cycle [\(\mu\text{ML}\)]:
  - 2
  - 7
  - 83
  - 36

Detection Limit: 0.8 \(\mu\text{ML}\) of Pt

\textbf{Dissolution Rates}

CV up to 1V @ 50mVs\(^{-1}\)

- Wide Particle Size Distribution
  - +/- 2nm

- Monodisperse Particles
  - +/- 0.5nm

Control of particle size distribution have important role for dissolution rate
Task 1 Accomplishments and Progress: **EC-ICP-MS Pt-Surfaces effect of substrate**

- **Pt-Au system**
  - Pt 4ML over GC forms a non-continuous film, full of small nanoparticles (~2nm)
  - Pt 4ML over Au thin layer) shows the Pt with Au structure, favoring (111) surface

**Potential range:** 0.05 to 1.0 V

**0.1M HClO₄**
Task 2 Accomplishments and Progress: Pt$_3$Au synthesis and characterization

in collaboration with K.L. More, ORNL

**High-Precision Synthesis** monodisperse NPs with uniform compositional profile

Pt shell Au core nanoparticles:
- Monodisperse ~5 nm
- Uniform Pt shell
Task 1-2 Accomplishments and Progress: EC-ICP-MS Pt$_3$Au nanoparticles

- Dissolution of Pt completely diminished up to 1.0 V
- Stability improvement retains at higher electrode potentials
- Up to 10 times more stable above 1.2V

Potential range: 0.05 to 1.0 V
**Task 2**

Accomplishments:  
**Pt$_3$Co catalysts Structures**

*in collaboration with K.L. More, ORNL*

### Annealing sequence of Pt$_3$Co NP

### HAADF at different T and t(min)

### HAADF and EDS elemental mapping

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**Dynamic of structural and chemical evolution at the atomic scale of Pt$_3$Co NPs during in-situ annealing**

Distinct behavior at critical stages:

- $\{111\}$, $\{110\}$, $\{100\}$ facets play different roles during the evolution of structure
- formation of a Pt-Skin shell with an alloyed disordered core;
- the nucleation of ordered domains;
- the establishment of an ordered L1$_2$ phase followed by pre-melting

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Task 1 Accomplishments and Progress: In-Situ EC-ICP-MS Pt-Alloys Intermetallic

Annealing at 700°C = Intermetallic Phase

- Decreases dissolution of both Pt and Co
- Improvement in ORR activity

**PtCo-As Sputter**

**PtCo Intermetallic**

**Composition 1:1**

Potential range: 0.05 to 1.0 V

[Pt] (ngL⁻¹)

0.1M HClO₄

Benefit of intermetallic phase:

- Decreases dissolution of both Pt and Co
- Improvement in ORR activity
Task 2-3 **Selected Nanostructures:** *Pt-Alloys, Solid, Porous and Hollow Structures*

**Nanopinwheels**
- ANL, ORNL
- Improvement vs. Pt/C
- RDE @ 0.95V
  - SA: 10
  - MA: 5

**Nano Multi Skin**
- ANL, ORNL
- Improvement vs. Pt/C
- RDE @ 0.95V
  - SA: 7
  - MA: 4

**Nanocages**
- ANL, ORNL
- Improvement vs. Pt/C
- RDE @ 0.95V
  - SA: 9
  - MA: 6

**Excavated Nanoframes**
- LBNL, ANL, ORNL
- Improvement vs. Pt/C
- RDE @ 0.95V
  - SA: 13
  - MA: 7

*in collaboration with Karren More, ORNL*
**Task 5  Accomplishments:**  
*Process R&D and Scale Up*

collab. with Greg Krumdick, ANL -MERF

| Timeline & Milestones |  
|-----------------------|---------------------------------------------------------------|
| **Research Chemistry** | M 1-2 1) **Hot-injection** was avoid using one-pot synthesis.  
2) Benzyl ether as solvent. **No Go** |
|                       | M 3 3) **Phenyl ether** as solvent.  
4) **Best synthesis condition** was established.  
5) **Reproducibility** was confirmed. **Go** |
| **1st stage scale up** | M 4 6) 1st stage scale up (1 g / batch) was **successful**.  
7) **New method** to load PtNi nanoparticles on carbon and its separation from solvent was developed.  
8) **Reproducibility** of 1st stage scale up was confirmed.  
9) Pre-annealing process applied.  
10) **Acid leaching process was modified. Go** |
| **2nd stage scale up** | M 8-9 11) The 2nd stage scale up (5 g / batch) was **successful**.  
12) **Acid leaching process** was established.  
13) The 2nd stage scale up is **reproducible. Go** |
|                       | M 10 14) MEA performance; New IP application; Sample send out; Manuscript submitted. |
**Task 5  Accomplishments:**

**Process overview: 0.1 g vs. 5 g**

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**PtNi synthesis: 0.1 g Scale**

1. **Pre-heat mixture to 200 °C.**
   - Nickel acetate tetrahydrate (0.1667 g)
   - 1,2-Tetradecanediol (0.085 g)
   - Oleic acid (0.4 ml) & Oleylamine (0.4 ml)
   - Diphenyl ether (20 ml) or Dibenzyl ether (20 ml)

2. **Inject preheated Pt solution (~80 °C).**
   - Platinum(II) acetylacetonate (0.13 g)
   - In 1,2-Dichlorobenzene (1.5 ml)

3. **Hold T at 200 °C for 1 h.**

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**Loading on carbon: 0.1 g Scale**

1. **Mix and sonicate in Hexane or Chloroform.**
2. **Evaporation of solvent.**
3. **Precipitate PtNi/C with Hexane.**
4. **Filtration.**

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**Acid leaching: 0.1 g Scale**

1. **Sonicate and soak PtNi/C in 0.1 M HClO₄.**
2. **Centrifuge.**

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**One-pot 5 g Scale**

- **200 °C 30 min**
  - Nickel acetate tetrahydrate (2.5 g)
  - 1,2-Tetradecanediol (1.28 g)
  - Oleic acid (7.5 ml) & Oleylamine (7.5 ml)
  - Diphenyl ether (300 ml)
  - Platinum(II) acetylacetonate (1.95 g)
  - 1,2-Dichlorobenzene (45 ml)

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**5 g scale**

- **Safer ➤ Easier ➤ Scalable ➤ Reproducible**

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**Target: mono-disperse 5 nm PtNi**

- **Loading**
- **Annealing**
- **Leaching**
- **Multilayered Pt-skin NPPtNi nanoparticles**
Task 3-5 Accomplishments and Progress: Scale-up of Excavated Nanoframes 0.3g

Nanoframe

Excavated nanoframe

Particle larger than small scale

Excavated nanoframe—Further reducing Ni precursor amount

Pt$_1$Ni$_3$

Pt$_3$Ni$_1$

@ 0.95V
Task 3-5  Accomplishments and Progress:  

Scale up of Nanopinwheels 0.4 g

5X scaled up PtNi Nanopinwheels keep the same morphology

5X scaled up PtNi Nanopinwheels maintain high performance

<table>
<thead>
<tr>
<th></th>
<th>2017 @0.90 V</th>
<th>2017 @0.95 V</th>
<th>2018 0.90 V</th>
<th>2018 0.95 V</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8.2</td>
<td>1.14</td>
<td>8.8</td>
<td>1.3</td>
</tr>
<tr>
<td>5X scale up</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nanopinwheels</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

@0.90 V
@0.95 V
**Task 3-5 Accomplishments and Progress:**

**Scale up of nanocages 0.6g**

- **One-pot synthesis-0.1 g / batch**
  - Pt$_1$Ni$_6$
  - PtNi Nanocages

- **Scale up-0.6 g / batch**
  - Batch 1
  - Batch 2

**Graphs:**
- 0.9 V vs. RHE
- 0.95 V vs. RHE
Task 5  Accomplishments and Progress:  Scale up-Flow reactor

Flow reactor at MERF, ANL

- Fast mass and heat transfer.
- Rapid optimization of reaction parameters.
- Easy scalability.

> Accurate control of reaction temperature and duration.
> Low usage of reagents in the optimization process.
> Capability for online monitoring.

PtNi Nanoparticles

Batch synthesis

Flow reactor

20 nm

20 nm
Task 4-5  Accomplishments and Progress:  Different Supports & Loadings

As synthesized

On Vulcan xc-72

On C2

On C3

On C4

On C5

On C6

On C7

Same loading but different particle densities  ↔  Different accessible carbon surface areas
Task 3, 4, 5

Accomplishments and Progress: Different Supports & Loadings

On XC-72

After 400°C annealing

G 15ul RW105-C1-185-A1-185-400

Jk / mA cm²

0.9 V vs. RHE

Pt/C

JACS

On XC-72

After 400°C annealing

Jk, Pt (A/mg)

0.95 V vs. RHE

TKK

JACS

On XC-72

Jk, Pt (A/mg)
Task 4-5  Accomplishments and Progress:  *Particle deposition on carbon support*

*in collaboration with K.L. More, ORNL*

All (100%) of the particles are on the exterior of the carbon support, mainly at nanocarbon junctions.
Task 2-3  Accomplishments and Progress:  scaled PtNi in 50 cm$^2$ MEA

in collaboration with K.L. More, ORNL
Cathode Loading:
0.03 mg-Pt/cm²
I/C = 0.8,
H₂/O₂ (or Air),
80°C, 150 kPa(abs)
100%RH

After acid treatment an increase on the MEA performance
Activation condition, held certain constant voltage for more 12 hours
until reach the best performance

(H₂-O₂, 80C, 100%RH, 150kPa(abs)) from high-low current

Mass activity at 0.9V: ~0.5 A/mg with 0.03 mg/cm² Pt loading
Task 3  
**Accomplishments and Progress:**  
scaled PtNi in 50 cm² MEA 

*in collaboration with Kenneth Neyerlin, NREL*

- 150 kPa, 100% RH, 80°C H₂/O₂, 50 cm², N211
- Ultrasonic spray coated at NREL 0.9 I:C
- Cathode loading 0.046 mgPt/cm²

- 150 kPa, 100% RH, 80°C H₂/Air, 50 cm²,

- Developed PtNi/HSC: \( i_m^{0.9V} \sim 500 \text{ mA/mg}_{\text{Pt}} \) vs. to \( \sim300 \text{ mA/mg}_{\text{Pt}} \) for 50 wt% Pt/HSC (TKK)

- PtNi/HSC: \( i_s^{0.9V} \ 920 \mu\text{A/cm}^2_{\text{Pt}} \) vs. 480 \( \mu\text{A/cm}^2_{\text{Pt}} \) for Pt/HSC (TKK)

- PtNi/HSC shows improved performance at high current density / Improved non-Fickian transport

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*see FCPAD talk for other relevant baselines*
Task 3  
**Accomplishments and Progress:**  
*scaled PtNi in 50 cm² MEA*

*in collaboration Neyerlin, NREL*

- 150 kPa, 100% RH, 80°C H₂/Air, 50 cm², N211

- PtNi/HSC shows improved performance
  - Both at high and low potential
  - For both raw cell voltage and HFR-corrected cell voltage
- Performance improvement is significant at low potential (transport limited regime) when normalized to ECSA
- Suspect improved non-fickian transport
Task 3  
Accomplishments and Progress: scaled PtNi in 50 cm² MEA
in collaboration with Kenneth Neyerlin, NREL

Improved Non-Fickian Transport Resistance

- By first synthesizing the nanoparticles then supporting them on HSC, the particles are preferentially located on the surface of the carbon

![Graph showing CO stripping as a function of RH]

CO stripping as a function of RH reveals that the majority of Pt sites are located on the carbon surface

![Graph showing non-Fickian transport resistance]

Limiting current measurements indicate that PtNi/HSC has significantly reduced non-Fickian transport resistance relative to other highly active electrocatalysts (PtCo/HSC)

- Reduced non-Fickian transport resistance
Task 3  
Accomplishments and Progress: scaled PtCo/Vulcan in 50 cm² MEA

in collaboration with Kenneth Neyerlin, NREL

150 kPa, 100% RH, 80°C H₂/O₂, 50 cm²  
Ultrasonic spray coated at NREL 0.5 I:C  
Cathode loading 0.035 mgPt/cm²

PtCo/Vulcan: \( i_m^{0.9V} \approx 700 \text{ mA/mgPt} \)

Pt/Vulcan: \( i_m^{0.9V} \approx 200 \text{ mA/mgPt} \)

Pt/Vulcan only shows about 0.2 A/mg mass activity at 0.9 V
Task 3: Accomplishments and Progress:

in collaboration with Kenneth Neyerlin, NREL

**scaled PtCo/Vulcan in 50 cm² MEA**

- 150 kPa, 100% RH, 80°C H₂/Air, 50 cm²
- Ultrasonic spray coated at NREL 0.5 I:C
- Cathode loading 0.035 mgPt/cm²

- PtCo/Vulcan shows improved performance
- Both at high and low potential region
- For both raw cell voltage and HFR-corrected cell voltage
- Performance improvement is significant at low potential (transport limited regime)
Responses to some reviewers comments

Question 1: Approach to performing the work
- The approach is both aggressive (multiple tasks in parallel) and well designed, since it strives to address many potential risks (in a highly complex system) at early stages.
- The project team uses world-leading resources and capabilities to design catalysts from a fundamental point of view.

Question 2: Accomplishments and progress toward DOE goals
- This project had impressive results in the past year in all key areas. (1) Fundamentals: The previous development of the RDE-inductively coupled plasma mass spectrometry (ICP-MS) was a great contribution, and it is great to see the group using this tool effectively on these new catalysts, with interesting results. (2) Synthesis: The core team has continued to make excellent progress in developing new nanostructures. (3) Scale-up: The progress here is especially impressive. It is unclear whether this new one-pot process can be used to make nanoframes as well as nanoparticles. (4) MEA performance: It is also great to see MEA results, which are impressive when one considers how challenging it is to make a good MEA with a new catalyst.
- A year later, they have even more new catalysts, more evidence of their potential, and more poor fuel cell performance. More effort should have been put into demonstrating that RDE results can translate into MEA results, and if not, why not.

Much more has been accomplished over the last year in testing of our catalysts in 50cm² MEAs. All of them exceeded DOE technical target and labeling our performance with “poor” has more to do with the reviewer’s ability to perform an unbiased review.

Question 3: Collaboration and coordination with other institutions
- The collaboration with the Fuel Cell Consortium for Performance and Durability to obtain the MEA results is especially commendable.
- The catalyst community position should simply be that RDE is a good screening tool and that they would welcome improved methods to translate this into MEA performance projections by those who can contribute to this challenging task.

The project has constant interaction among the participants including the OEMs, which does not necessarily mean that all results can be disclosed. During the TechTeam meetings much more has been shared.

Project weakness
- Activity of the catalyst in MEAs is approximately 10 times below RDE activity. Apparently, there is limited work on MEA-level testing and characterization. MEA testing was a project weakness.

We are making constant progress in MEA testing and understanding similarities and differences between RDE and MEA.

Recommendations for additions/deletions to project scope
- More MEA work should be planned.
- The project should look for new collaboration at the international level

Additional MEA testing are confirming improvement in performance and more international collaborations are being launched.
Challenges and Barriers

- **Differences** between RDE and MEA, surface chemistry, ionomer catalyst interactions
- **Temperature** effect on performance activity/durability
- **High current density** region needs improvements for MEA
- **Support** – catalyst interactions
- **Scale-up** process (one pot and flow reactor) for the most advanced structures

1) **Durability** of fuel cell stack (<40% activity loss)

2) **Cost** (total loading of PGM 0.125 mg\(_{\text{PGM}}\) / cm\(^2\))

3) **Performance** (mass activity @ 0.9V 0.44 A/mg\(_{\text{Pt}}\))
Future Work

- **Alternative** approaches towards highly active and stable catalysts with low PGM content
- **Tailoring** of the structure/composition that can optimize durability/performance in Pt-alloys
- **Synthesis** of tailored low-PGM practical catalysts with alternative supports
- **Structural** characterization (in-situ XAS, HRTEM, XRD)
- **Resolving** the surface chemistry in MEA
- **Electrochemical** evaluation of performance (RDE, MEA)
- **In-situ** durability studies for novel catalyst-support structures (RDE-ICP/MS)
- **Scale-up** of chemical processes to produce gram quantities of the most promising catalysts

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

- **United States Patent**
  - **Stamenkovic et al.**
  - **Patent No.:** US 7,871,738 B2
  - **Date of Patent:** Jan. 18, 2011

- **MEAs**
  - **Auto OEMs**
  - **T2M**

- **Catalysts Scale Up**

- **FY18**
  - **2 NDA signed**

- **Constant build up of IP portfolio**
  - **6 issued patents, 5 pending**

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**Catalysts Scale Up**

- **Add Pt**
- **T = 200°C**
- **Nickel acetate
  L,3-Tetradecanediol Oleic acid Oleylamine ether**

- **MEA**

- **H2**
- **O2**
- **anode**
- **PEM**
- **cathode**
- **H+**
- **H+**
- **H+**
- **H+**
- **H+**

- **Argonne National Laboratory**
SUMMARY

Approach
- From fundamentals to real-world materials
- Focus on addressing DOE Technical Targets
- Link between the performance measured in RDE vs. MEA
- Rational design and synthesis of advanced materials with low content of precious metals

Accomplishments
- Dissolution of Pt for different particle size distributions of Pt/C: the advantage of monodisperse
- Resolved the mechanism of diminished Pt dissolution for Au subsurface
- Designed of highly durable NPs: Applied the knowledge from well-defined surfaces to nanoparticles
- “No-Dissolution” Proof of Concept in Highly Durable NPs: Synthesis and Characterization of Pt$_3$Au/C NPs
- Well-Defined Pt-Alloy intermetallic systems are more active and durable vs. solid-solution Pt-Alloys
- Scaled four nanoarchitectures at the gram level quantities
- Applied different carbon supports
- Effective placement of particles exclusively on the high surface area carbon surface – no buried particles
- PtNi with multilayered Pt-Skin and Nanopinwheels exceeded DOE 2020 Technical Target for mass activity in MEA
- Two patent application in FY18, 2 articles submitted and 6 presentations at conferences

Collaborations
- Collaborative effort among the teams from four national laboratories is executed simultaneously in five tasks
- Ongoing exchange with Auto-OEMs and stake holders
- Numerous contacts and collaborative exchanges with academia and other national laboratories
Publications and Presentations

3 Publications
3 Presentations
2 patent applications