Overview

### Timeline
- Project Start: 28 June 2012
- Project End: 13 Aug 2015
- Percent complete: 45%

### Budget
- Total Funding Spent*: $413,000
- Total Project Value: $1,150,000
- Cost Share Percentage: 0% (SBIR)

### Barriers
- G. Capital Cost

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Units</th>
<th>2011 Status</th>
<th>2015 Target</th>
<th>2020 Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen Levelized Cost (Production Only)</td>
<td>$/kg</td>
<td>4.2\textsuperscript{d}</td>
<td>3.9\textsuperscript{d}</td>
<td>2.3\textsuperscript{d}</td>
</tr>
<tr>
<td>Electrolyzer System Capital Cost</td>
<td>$/kg</td>
<td>0.70\textsuperscript{e,f}</td>
<td>0.50\textsuperscript{f}</td>
<td>0.50\textsuperscript{f}</td>
</tr>
<tr>
<td>$/kW</td>
<td>430\textsuperscript{e,f}</td>
<td>300\textsuperscript{f}</td>
<td>300\textsuperscript{f}</td>
<td>300\textsuperscript{f}</td>
</tr>
<tr>
<td>System Energy Efficiency (% (LHV))</td>
<td>kWh/kg</td>
<td>67</td>
<td>72</td>
<td>75</td>
</tr>
<tr>
<td>Stack Energy Efficiency (% (LHV))</td>
<td>kWh/kg</td>
<td>74</td>
<td>76</td>
<td>77</td>
</tr>
</tbody>
</table>

2012 MYRDD Plan

### Partners
- Brookhaven National Lab
Relevance: Leveraging Fuel Cell Advancements in Electrolyzers

- Significant investment made in PEM fuel cells
- Electrolyzer platform can benefit with incremental investment
  - Similar chemistry but different operating requirements
  - Not always a drop in but shows promise – need some adaptation
- Core-shell catalysts: developed by various groups including BNL/Adzic group
  - High activities and durability demonstrated
  - Even more benefit in reduction of electrolyzer loadings
Relevance: Renewable Fuels

- Hydrogen from electrolysis is the carbon-free solution
- Germany already at 20-40% stranded wind power
  - Changes economics for $/kg production
Relevance: Hydrogen Energy Storage

- Flexibility of hydrogen enables additional options for lower cost across applications
  - Also impacts fueling through biogas applications

Germany highly invested in H₂ option for energy storage
Relevance: System Scale-Up Needs

- System cost improves considerably with scale
- Reduction of PGM content needed to manage price volatility and high volume needs
Relevance: Capital Cost Reduction

- MEA is a large fraction of overall stack cost
- Current cost roughly equivalent between membrane, catalyst, and manufacturing/labor
- New manufacturing methods and ultra-low PGM loading will reduce capital costs significantly and enable scale
Insertion to MW Scale

- Stack platform already in verification stages
- Manufacturing processes must be scalable to required active area
Top Level Approach

• Task 1.0 Cathode Catalyst
  – Technology transfer
  – Scale-up

• Task 2.0 Cathode Manufacturing
  – Deposition verification
  – Manufacturing development

• Task 3.0 Anode Catalysts
  – Synthesis of Ru nanoparticles on TiO₂
  – Coating Ir metal/metal oxide on Ru cores
  – Evaluation of synthesized catalysts

• Task 4.0 Anode Electrode
  – Ink formulation for anode catalysts
  – Anode GDE fabrications
  – Structural and component characterization

• Task 5.0 Cell Development and Testing
  – Anode GDL development
  – Cathode GDE incorporation
  – Durability and post-operation assessment

• Task 6.0 Cost Analysis
Phase I Summary

- Equivalent cathode performance at low loadings (<0.1 mg/cm²)

- Reduction on anode to <0.5 mg/cm²
- Manual application processes used in Phase 1
Approach: Phase II Project Objectives

- Translate catalyst synthesis to a manufacturable process at Proton.
- Develop technique for manufacturable electrodes.
- Demonstrate feasibility for 80% cost reduction in OER catalyst.
- Downselect promising anode electrode configurations to achieve >100 hrs durability.
- Achieve 500 hours of operation with cathode GDE.
- Evaluate the cost benefits of new materials.
### Approach: Year 1 Project Milestones

<table>
<thead>
<tr>
<th>Task #</th>
<th>Milestone Description</th>
<th>Due Date / Completion</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>Project Kick-off: Proton, BNL</td>
<td>8/30/2013 (100%)</td>
</tr>
<tr>
<td>1</td>
<td>Demonstrate successful cathode catalyst synthesis and electrode manufacture at Proton</td>
<td>12/31/2013 (100%)</td>
</tr>
<tr>
<td>3</td>
<td>Complete study of TiO$_x$-supported Ru@Ir catalysts in solution electrochemical cells.</td>
<td>12/31/2013 (100%)</td>
</tr>
<tr>
<td>4</td>
<td>Demonstrate uniform and robust catalyst layer on Ti GDLs</td>
<td>4/30/2014 (20%)</td>
</tr>
<tr>
<td>1</td>
<td>Complete scale up synthesis of cathode catalysts to 10 – 100 g batch level</td>
<td>6/30/2014 (20%)</td>
</tr>
<tr>
<td>5</td>
<td>Complete cell design analysis for cathode configuration</td>
<td>7/15/2014 (0%)</td>
</tr>
</tbody>
</table>

Cell design analysis shifting due to resource availability and priority of task
<table>
<thead>
<tr>
<th>Task #</th>
<th>Milestone Description</th>
<th>Due Date / Completion</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Downselect optimal cathode material and process for reliable production</td>
<td>8/30/2014 (20%)</td>
</tr>
<tr>
<td>4,5</td>
<td>Demonstrate improved activity and durability of selected anode GDE samples in cell</td>
<td>8/30/2014</td>
</tr>
<tr>
<td>6</td>
<td>Provide initial cost assessment via H2A model</td>
<td>8/30/2014</td>
</tr>
<tr>
<td>2,4,5</td>
<td>Identify key issues for enhancing durability</td>
<td>11/30/2014</td>
</tr>
<tr>
<td>4,5</td>
<td>Achieve &gt;100 hours durability of developed anode catalyst/GDE</td>
<td>4/30/2015</td>
</tr>
<tr>
<td>2,4,5</td>
<td>Demonstrate process capability for large active area electrodes</td>
<td>6/30/2015</td>
</tr>
<tr>
<td>2,4,5</td>
<td>Achieve 500 hours of operation at 89 cm² cell level</td>
<td>7/30/2015 (50%)</td>
</tr>
<tr>
<td>6</td>
<td>Evaluate the benefits of selected anode catalysts/electrodes over the baseline in cost reduction or efficiency boost.</td>
<td>8/30/2015</td>
</tr>
<tr>
<td>6</td>
<td>Complete Final Reporting</td>
<td>8/30/2015</td>
</tr>
</tbody>
</table>
Approach: Low Catalyst Loading Concept

- Increase the Pt specific surface area by synthesizing sized-controlled, core-shell nanocatalysts
- Translates into a >98% reduction of Pt
- Strategy: translate and scale up process for manufacturing

Previous methods produced imperfect structure and mixing.
Defect-induced partial alloying eliminated.

Atomically coated structures process shown by TEM (right) using a simple process.
Approach: Manufacturing and GDL Selection

- Ultrasonic spray deposition identified as possible approach for high-throughput and low labor
- Phase 1: MPLs result in better distribution of catalyst near membrane
- Stable anode supports need to be identified
- Strategy:
  - optimize deposition technique and GDL selection
  - explore TiO₂ as initial anode support

Ultrasonic spray deposition¹

¹SPIE Newsroom. DOI: 10.1117/2.1200903.1555
Technical Accomplishments

• Demonstrated successful cathode catalyst synthesis and electrode manufacture at Proton

• Completed study of TiO$_x$-supported Ru@Ir catalysts in solution electrochemical cells

• Downselect optimal cathode material and process for reliable production
  – Showed feasibility for ultrasonic spray deposition for cathode manufacturing

• Showed > 500 hrs durability with ultra-low loaded Proton-made cathode in production quality hardware
Technical Accomplishments

• Task 1.0 Cathode Catalyst Development
  – Installed safety-qualified equipment and procedures
  – Established quality metrics at critical process points: solution color, pH, and product weight

Color transformation of solution should proceed from dark brown to green

Safety-qualified hydrogen reducing furnace
Technical Accomplishments

- **Task 1.0 Cathode Catalyst Development**
  - Achieved equivalent cathode performance at 1/10 the loading using Proton-made catalyst and GDE

[Graph showing potential vs. current density with Proton-made Cathode GDE, GDE Baseline, MEA Baseline lines]

Alternate GDE used due to unavailability; showed poorer wetting, further optimization likely possible.
Technical Accomplishments

- **Task 2.0 Cathode Manufacturing Development**
  - Achieved nearly equivalent performance using a spray-deposited cathode (<0.15 mg/cm²)

Ultrasonic printer used to make GDE.
Technical Accomplishments

• Task 3.0 Develop Anode Catalysts
  – BNL synthesized and characterized Ru-Ir “core-shell” nanocatalysts on TiO$_2$ supports

• Ru-Ir particles were 2.4 and 6.8 nm in diameter respectively before and after annealing, while TiO$_2$ particles are $\sim$30 nm.

• Performances were similar to unsupported catalysts.

• Interaction with Ti GDL may be more important.

XRD measurements confirm nanocatalyst synthesis
Technical Accomplishments

• Made uniform and stable catalyst coating on Ti GDL and OER catalyst for anode

3D SEM image of a Ti GDL average roughness 20 µm

Photos and optical images of catalyst-coated Ti GDLs with 3.4, 1.5, 0.8, and 0.3 mg cm$^{-2}$ IrOx

• Uniform change in catalysts’ loading by ten-fold.
Technical Accomplishments

• Established IrOx baseline measured in solution electrochemical cell using standalone GDE strips.

iR-corrected polarization for IrOx on Ti measured after 20 min stabilization at 200 mA cm\(^{-2}\) in 0.5 M H\(_2\)SO\(_4\) solution.

Kinetic current at 1.6 V (right axis) and mass activity (left axis) as a function of IrOx loading.
Technical Accomplishments

• **Task 5.0 Cell Development and Testing**
  – Proton-made cathode shows durability for >500 hr

![Graph showing cell potential over run time](image)
Future Work

• **Task 1: Cathode Development**
  – Scale up process to relevant production lot quantity

• **Task 2: Cathode Manufacturing**
  – Identify optimum spraying parameters and equipment

• **Task 3: Develop Anode Catalysts**
  – Improve the durability of Ru-Ir core-shell catalysts or leverage new approach being explored in parallel by BES-supported research project

• **Task 4: Anode Electrode Fabrication**
  – Explore and develop ways to enhance catalyst-Ti interaction
  – Study the impact of Ti GDLs on OER performance
Future Work

• **Task 5: Cell Development and Testing**
  – Identify optimum cathode GDL material to increase efficiency and maintain durability
  – Identify promising anode GDL materials and test performance/durability

• **Task 6: Cost Analysis**
  – Utilize H2A model and Proton’s electrochemical interface model to refine the impact of design changes developed in Tasks 1-5 on the $/kg of H₂
Collaborators

- **Brookhaven National Lab**
  - Synthesis and characterization of core shell catalyst materials
  - Development of electrode formulations and application methods on gas diffusion layers for low catalyst loading
Summary

- **Relevance:** Reduces stack capital cost for lower hydrogen production cost
- **Approach:**
  - Optimize anode catalyst utilization for >80% reduction in PGM loading
  - Identify optimum configuration for manufacturable, ultra-low loaded cathode
- **Technical Accomplishments:**
  - Achieved equivalent cathode performance at <1/10 loading
  - Showed feasibility for ultrasonic spray deposition for cathode manufacturing
  - TiO$_x$-supported Ru@Ir catalysts manufactured and characterized
  - Showed > 500 hrs durability with ultra-low loaded Proton-made cathode
- **Collaborations:**
  - Brookhaven National Labs – catalyst and formulation development
- **Proposed Future Work:**
  - Scale up cathode manufacturing
  - Identify optimum ultrasonic spraying parameters and equipment
  - Carry out MEA tests to identify key issues for anode catalyst durability
  - Identify optimum anode and cathode GDL materials for final design
  - Perform cost analysis
Acknowledgments

The Proton Team

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• Chris Capuano
• Luke Dalton
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• Mike Niedzwiecki
• Mike Parker
• Julie Renner
• Andy Roemer

Our Collaborators

• Jia Wang
• Yu Zhang