Fuel Cells R&D Overview

Dr. Dimitrios Papageorgopoulos – Fuel Cell Technologies Office

2018 Annual Merit Review and Peer Evaluation Meeting

June 13 – 15, 2018
Fuel Cells: Pillar of H₂ & Fuel Cell Technologies R&D

Focus

Early-stage applied R&D and innovation in hydrogen and fuel cell technologies leading to:

- Energy security
- Resiliency
- Affordability
- Strong domestic economy

H₂ & Fuel Cells Program: Early-Stage R&D Areas

Fuel Cells

Hydrogen

GOAL: Advance fuel cell technologies for transportation, stationary and cross-cutting applications

Making Fuel Cells our Future, Today
Objectives and Targets

1. R&D to enable a direct hydrogen fuel cell power system for transportation competitive with incumbent and alternative technologies on a lifecycle cost basis

2. R&D of efficient, resilient and affordable fuel cell systems for distributed power generation (primary, back up, CHP)

3. Enable fuel cell technology advancements for cross-cutting applications (e.g. APUs, rail, material handling)

**2025 Targets by Application**

**Automotive**
- Fuel Cell Cost: $40/kW
- $30/kW*
- Durability: 5,000 hrs
- Efficiency: 65%

**Stationary**
- Fuel Cell Cost: $1,000/kW**
- $1,500/kW***
- Durability: 80,000 hrs
- Efficiency: 50% †

* Ultimate (Beyond 2030) ** For Natural Gas *** For Biogas † Electrical ‡ CHP

Market-driven targets allow fuel cells to compete with incumbent and advanced alternative technologies

**Fuel Cells MYRD&D Plan**
http://energy.gov/eere/fuelcells/downloads/fuel cell technologies office multi year research development and 22
Challenges and Strategy

**Durability and Cost** are the primary challenges to fuel cell commercialization and must be met concurrently.

Improvements in multiple components are required to meet 2025 targets.

Early-stage materials and components R&D to achieve low-cost, high-performance fuel cell systems.

R&D portfolio focused on PEMFCs, but also includes longer-term technologies (e.g. AEMFCs) & higher temp fuel cells (e.g. MCFCs) for stationary applications.
Challenges and Strategy

Early-stage R&D generates knowledge to foster significant fuel cell technology advances

BARRIERS
- Cost
- Durability
- Performance

STRATEGY
Materials, components R&D to improve durability, reduce cost and enhance performance of fuel cells

FOCUS AREAS
- Stack Components
  - Catalysts
  - Electrodes
  - Membranes
  - MEAs and Cells
  - Gas diffusion media
  - Bipolar plates
- Performance and Durability
  - Mass transport
  - Degradation issues
- BOP Components

Testing and Cost/Technical Assessments

Emphasis on longer-term high-risk research areas
Strategic Analysis Guides Fuel Cell R&D Priorities

**PEMFC Stack Cost Breakdown**

**Catalyst cost is projected to be the largest single component of the PEMFC stack cost**

**Strategy**
- Reduce or eliminate PGM levels in catalysts *
- Improve MEA performance

* PGM elimination mitigates US dependence on precious metal imports
Fuel Cell Cost Improvements

Fuel Cell Cost Status

- $50/kW* for 100,000 units/year
- $45/kW* for 500,000 units/year
- $180/kW* for 1,000 units/year
- $230/kW† for currently commercialized on-road technology at 1,000 units/year

60% cost reduction in the last 10 years

* SA Inc., bottom-up analysis of model system manufacturing cost, high volume manufacturing with next-gen lab technology
† SA Inc., bottom-up analysis of model system based on commercially available FCEVs

Fuel Cell R&D Funding

FY 2017 Appropriation = $32.0 M
FY 2018 Appropriation = $32.0 M

- Catalysts and Electrodes
- Electrolytes/Membranes
- MEAs, Cells, and Other Stack Components
- Fuel Cell Performance and Durability
- Testing and Technical Assessment
- FOA 2018
Current emphasis is on early stage applied R&D in the key areas of fuel cell components and materials, including catalysts and membranes, as well as fuel cell performance and durability.

Funding distribution of all FOA, LAB, SBIR/STTR projects

including number of current projects and % of portfolio funding
**Goal**

Accelerate the deployment of fuel cell systems by replacing platinum-based catalysts with **platinum group metal-free (PGM-free)** catalysts.

**Objectives**

- Streamline access to unique PGM-free catalyst synthesis and characterization tools across national labs
- Develop missing strategic capabilities
- Curate a public database of information

**Core Lab Team**

- Argonne National Laboratory
- Los Alamos National Laboratory
- NREL
- Oak Ridge National Laboratory

**Accomplishments and Next Steps**

- Updated capability set
- Demonstrated significant progress in **(a)** catalyst development, **(b)** active-site characterization, and **(c)** high-throughput PGM-free catalyst modeling and synthesis
- Partnered with 4 newly awarded FOA projects
- Add partners through FY18 FOA

**High-throughput materials discovery, characterization, and testing**

**Design and synthesis of PGM-free catalysts and electrodes, modeling**

[www.electrocat.org](http://www.electrocat.org)
Accomplishment: PGM-Free Mass Activity

Demonstrated MEA performance of 21 mA/cm² at 0.9 V_{IR-free} with H₂/O₂, a 30% improvement over 2016 baseline

Cyanamide (CM)-polyaniline (PANI) precursors for Fe-N-C catalyst; Zn removed during pyrolysis as pore-forming agent

Anode: 0.3 mg_{Pt} cm⁻² Pt/C H₂, 200 sccm, 1.0 bar H₂ partial pressure; Cathode: ca. 4.8 mg cm⁻² O₂, 200 sccm, 1.0 bar air partial pressure;
Membrane: Nafion® 211; Cell: 5 cm²; 80°C
Accomplishment: High-Throughput (HT) Synthesis & Characterization

HT materials with potentially > 5× ORR activity of baseline compositions identified in HT hydrodynamic screening

Baseline materials explored by batch synthesis prior to initiation of combinatorial synthesis task.
ElectroCat FOA Projects Added in 2017

Carnegie Mellon University
Advanced PGM-free Cathode Engineering for High Power Density and Durability

Giner Inc
Durable Mn-based PGM-Free Catalysts for Polymer Electrolyte Membrane Fuel Cells

Greenway, LLC
PGM-free Engineered Framework Nano-Structure Catalysts

Pacific Northwest National Lab
Highly Active and Durable PGM-free ORR Electrocatalysts through the Synergy of Active Sites

U.S. DEPARTMENT OF ENERGY OFFICE OF ENERGY EFFICIENCY & RENEWABLE ENERGY FUEL CELL TECHNOLOGIES OFFICE
Accomplishment: Low Pt-loading alloy catalysts

PtCo/HSC-f: exceeds 8 kW/g_{PGM} target while demonstrating durable performance at high current density

Equivalent performance to current on-road technology with 5x less Pt

Have yet to meet performance and durability targets concurrently
## FC-PAD: Fuel Cell Performance and Durability

### Approach

Couple national lab capabilities with funding opportunity announcements (FOAs) for an influx of innovative ideas and research.

### Objectives

- Improve component stability and durability
- Improve cell performance with optimized transport
- Develop new diagnostics, characterization tools, and models

### Consortium fosters sustained capabilities and collaborations

Core Consortium Team

- Argonne National Laboratory
- Los Alamos National Laboratory
- NREL
- Oak Ridge National Laboratory

Prime Partners

- 3M
- GM
- United Technologies Research Center

### Structured across six component and cross-cutting thrusts

1. Electrocatalysts and Supports
2. Electrode Layer
3. Ionomers, GDL, Bipolar Plates
4. Modeling and Validation
5. Operando Evaluation
6. Component Characterization

### Expands the body of knowledge

Example: JES Focus Issue on PEMFC Durability

www.fcpad.org
Accomplishments: FC-PAD

Novel catalyst layer architectures

Mesostructured electrodes with vertically aligned ionomer channels allow use of 50% less ionomer for H⁺ transport

Improved catalyst conditioning

Conditioning protocol developed demonstrating up to 2-3x difference in mass activity between initial and peak $i_m$ for several commercial Pt and PtCo catalysts
Accomplishments: FC-PAD

Characterization tools used to build catalyst layer microstructural model

Allows for unprecedented, comprehensive view of catalyst layer micro- and nanostructure including heterogeneities across scales.

Secondary pore structure: nano-CT

Resulting microstructure

C particle size: TEM and USAXS

Pt particle size: TEM and USAXS
Accomplishment: Low-PGM Electrospun Catalyst Layers

Electrospun catalyst layers using PtCo catalyst with carrier ionomer improve low humidity performance

- >3x compared to project spray coating baseline at 40% RH
- Max power exceeds **1100 mW/cm²** at 0.1 mgₚt/cm² cathode loading

**MEA details:** 80°C, 200 kPa (abs.)
- **Cathode:** 0.1 mgₚt/cm²
- **Anode:** 0.1 mgₚt/cm² (Espun), J-M 0.4 mgₚt/cm² (Spray)
- **Membrane:** NR 211, **GDL:** SGL 29 BC

<table>
<thead>
<tr>
<th>Sample</th>
<th>100% RH</th>
<th></th>
<th></th>
<th>40% RH</th>
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<tbody>
<tr>
<td></td>
<td>Max Power (mW/cm²)</td>
<td>Power at 0.65 V (mW/cm²)</td>
<td>HFR (mΩ·cm²)</td>
<td>Max Power (mW/cm²)</td>
<td>Power at 0.65 V (mW/cm²)</td>
<td>HFR (mΩ·cm²)</td>
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<tr>
<td>PtCo Spray</td>
<td>652</td>
<td>544</td>
<td>70</td>
<td>315</td>
<td>85</td>
<td>208</td>
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<tr>
<td>Gen-1 PtCo Espun</td>
<td>759</td>
<td>661</td>
<td>76</td>
<td>590</td>
<td>250</td>
<td>219</td>
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<tr>
<td>Gen-2 PtCo Espun</td>
<td>1132</td>
<td>998</td>
<td>56</td>
<td>967</td>
<td>488</td>
<td>120</td>
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*P. Pintauro, et al., Vanderbilt*
Accomplishment: Intermediate Temperature Fuel Cell Membranes

- Peak power density exceeds 1100 mW/cm\(^2\) at 180°C (H\(_2\)/O\(_2\))
- > 20 \times better water tolerance than established PBI system* to allow low-T operation

*measured at P\(_{H_2O}\) = 19.9 kPa, 80°C

MEA details: H\(_2\)/O\(_2\), 285 kPa abs;
membrane: PA-XL-BPN; ionomer: PA-QAPS;
Pt loading 0.6 mg/cm\(^2\) for both electrodes

Y. S. Kim, et al., LANL
Accomplishment: Direct Dimethyl Ether Fuel Cell

- Close to 2x increase in anode specific activity compared to methanol
- Ten-fold decrease in crossover as compared to methanol

<table>
<thead>
<tr>
<th>Key Performance Indicator this period</th>
<th>Current DMFC</th>
<th>Status DDMEFC</th>
<th>Target DDMEFC</th>
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<tbody>
<tr>
<td>Total precious metal loading</td>
<td>5 mg PGM/cm²</td>
<td>4.5 mg PGM/cm²</td>
<td>3 mg PGM/cm²</td>
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<tr>
<td>Anode mass-specific activity</td>
<td>50 A/g measured at 0.5 V(*)</td>
<td>93.8 A/g measured at 0.5 V (PtRu)</td>
<td>75 A/g measured at 0.5 V</td>
</tr>
<tr>
<td>Maximum Power</td>
<td>160 mW/cm²</td>
<td>135 mW/cm² (***)</td>
<td>270 mW/cm²</td>
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<tr>
<td>Crossover</td>
<td>60-120 mA/cm² (**)</td>
<td>6 mA/cm²</td>
<td>&lt; DMFC</td>
</tr>
</tbody>
</table>

(*) By comparison, LT direct DME FC obtained 25 A/g measured at 0.5 V with PtRu.
(**) 60 mA/cm² with 0.5 M MeOH, 80 °C, Nafion® 117; 120 mA/cm² with 1.0M MeOH.
(***) 2.23mg/cm² PtRu anode, 2.3mg/cm² Pt-alloy cathode

E. De Castro, et al., Advent
Reversible Fuel Cells (RFCs)

Research Priorities Include:
- Bifunctional catalysts
- Advanced membranes
- Electrode optimization including effective water management
- Corrosion protection schemes

Viability and cost-competitiveness of RFCs require foundational R&D to improve roundtrip efficiency and meet long-term targets less than $1250/kW capital cost and cycle life of 5,000 cycles.

R&D to focus on innovative concepts for reversible fuel cells to provide easily dispatchable power and flexibility to address resiliency and grid/microgrid needs.

Summary of Current Activities

• **Applied Early-Stage R&D** addresses cost reduction, performance and durability enhancement of materials and stack components, including catalysts and membranes.

• **ElectroCat** coordinates with newly awarded FOA projects to expedite the development of PGM-free catalysts and electrodes.

• **FC-PAD**, including industry/university partners, continues to expand the knowledge base to advance fuel cell performance and durability.
Summary of Upcoming Activities & Milestones

• **Fuel cells** to enable **energy storage** and **resiliency***

• **Innovative R&D projects** through FY18 FOA and FY19 Lab Call

• **Lab-led membrane R&D project working group** to coordinate efforts and leverage activities with other agencies

• **Technical milestones:**
  - Demonstrate **25 mA cm\(^{-2}\)** at 0.9 V (iR-corrected) in an H\(_2\)-O\(_2\) fuel cell (**4Q 2018**)
  - Demonstrate **29 mA cm\(^{-2}\)** at 0.9 V (iR-corrected) in an H\(_2\)-O\(_2\) fuel cell (**4Q 2019**)

*Under ‘Beyond Batteries’ crosscut effort (FY 2019 Budget Request)
Collaborations

Vehicle Technologies Office (VTO)
Small Business Innovation Research (SBIR)

Energy Materials Network

DOE-EERE Fuel Cells Program

INDUSTRY
U.S. DRIVE Partnership: Fuel Cell Tech Team

Technology Validation

National Collaborations (inter- and intra-agency efforts)

DOE - FE
SOFCE Program

DOE - BES
Catalysts and Membranes

DOE - ARPA-E
IONICS & INTEGRATE

NSF
ElectroCat

DOT/FTA
Fuel Cell Buses

DOD
DOD/DOE MOU

DOC/NIST
Neutron Imaging

DOT/FRA
H₂/FC-Rail

Applied R&D is coordinated among a range of organizations
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Questions?
Back Up Slides
R&D Benefits Various Fuel Cell Market Sectors

<table>
<thead>
<tr>
<th>Fuel Cell Application</th>
<th>Cost &amp; Durability Status¹</th>
<th>Cost &amp; Durability Targets (2025)</th>
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<tbody>
<tr>
<td>Backup power (direct hydrogen)</td>
<td>$6,000/kW 8,000 h</td>
<td>$1,000/kW 10,000 h</td>
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<tr>
<td>Medium scale CHP (natural gas)</td>
<td>$1,200-4,500/kW 40,000-80,000 h</td>
<td>$1,000/kW 80,000 h</td>
</tr>
<tr>
<td>APU (diesel, 1-10 kW system)</td>
<td>$2,100/kW 3,000 h</td>
<td>$1,000/kW 20,000 h</td>
</tr>
<tr>
<td>Buses</td>
<td>$893,000² 25,000 h²</td>
<td>$600,000 25,000 h</td>
</tr>
<tr>
<td>Automotive</td>
<td>$50/kW³ $45/kW⁵</td>
<td>$40/kW ($30/kW ultimate) 5,000 h 8,000 h ultimate</td>
</tr>
<tr>
<td>Portable power (100-250 W)</td>
<td>$15/W 2,000 h</td>
<td>$5/W 5,000 h</td>
</tr>
</tbody>
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³ [https://www.nrel.gov/docs/fy18osti/70075.pdf](https://www.nrel.gov/docs/fy18osti/70075.pdf)

⁴ Projected to a production volume of 100,000 units/year, [https://www.hydrogen.energy.gov/pdfs/17007_fuel_cell_system_cost_2017.pdf](https://www.hydrogen.energy.gov/pdfs/17007_fuel_cell_system_cost_2017.pdf)

⁵ Projected to a production volume of 500,000 units/year, [https://www.hydrogen.energy.gov/pdfs/17007_fuel_cell_system_cost_2017.pdf](https://www.hydrogen.energy.gov/pdfs/17007_fuel_cell_system_cost_2017.pdf)

Potential Cost Reduction Strategy

PGM-free catalysts and advancements in key components are key research goals for meeting DOE’s ultimate $30/kW target.
Accomplishments: ElectroCat

Four-fold $H_2$-air performance increase for ZIF-derived catalyst

- ZIF-based Fe-N-C catalyst with no Fe-rich nanoparticles detected
- Fe present in N-coordinated FeN$_x$ sites
- $H_2$-air fuel cell performance at 0.80 V, from 9 mA cm$^{-2}$ to 36 mA cm$^{-2}$ since 2017 AMR

Molecular probe for quantifying active sites

- NO adsorbs on surface Fe sites from a nitrite solution
- Count surface Fe sites by reductive stripping scan
- Developed library of adsorption energy of probes/poisons to Fe-N$_x$ site structures hosted in graphene and zig-zag (ZZ) edges

Active site identification and high-throughput catalyst discovery

- ORR activity of intermediate Fe-content catalyst correlates with FeN$_4$ content
- Catalyst identified with 5X ORR activity versus baseline composition
Accomplishments: HT Synthesis & Characterization

Potential dependence of ORR kinetics

Molecular probe for quantifying active sites

- Fe sites counted by reductive stripping scan to remove NO$_{ads}$
  - $3 \times 10^{12}$ sites/cm$^2$ (0.5 site per surface Fe atom)
- Developed library of probes adsorption energy on Fe-N$_x$ sites in bulk graphene and at edges

ORR kinetics in MEA correlated with potential dependence of active site availability