How to Progress on Low Temperature PEM Fuel Cells

outlook, challenges, future research directions and needs, and future developments

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Joint European Summer School for Fuel Cell and Hydrogen Technology
Outline

- Status (what do we know, what has been done so far)
- Why don’t we have more fuel cell products on the market
- Trends (what still needs to be done, what we still have to learn)
- Bigger picture
PROCESSES INSIDE A FUEL CELL

1 gas flow
2 gas diffusion
3 electrochemical reaction
4 proton conduction
5 electron conduction
6 water drag and diffusion
7 water flow
8 2-phase flow
9 heat transfer (convection and conduction)
Membrane

Functions
• Conducts protons
• Does not conduct electrons
• Separates H₂ and O₂

Properties
• Proton conductivity
• Water content
• Electroosmotic drag
• H₂ and O₂ permeability
• Mechanical strength
• Chemical stability

Material
• Nafion™
• Copolymer of tetrafluoroethylene ("Teflon") and various perfluorosulfonate monomers.
• Thickness 0.025-0.125 mm
• Roughly 1 nm diameter hydrophilic pores.

\[
- [(CF₂ - CF₂)_m - CF - CF₂]n -
\]

- \(m = 5 \text{ to } 13.5\)
- \(n = 1,000\)
- \(z = 1,2,3...\)

When \(m = 5\), EW = 950
Catalyst/Catalyst Layer

Functions
- Oxygen reduction
- Hydrogen oxidation
- Conducts electrons

Properties
- Good catalyst
- Chemical stability
- Electrical conductivity

Material
- Platinum
- Finely dispersed (3-5 nm) on high surface area carbon
- Loading: 0.1-1.0 mg/cm²

Chemical Equations:

\[ \text{H}_2 \rightarrow 2e^- + 2\text{H}^+ \]
\[ \text{O}_2 + 2e^- + 2\text{H}^+ \rightarrow \text{H}_2\text{O} \]
Gas Diffusion Layer

Functions
• Supplies reactants to the catalyst site
• Conducts electrons
• Electrical contacts
• Takes the product water away
• Structural support to the membrane

Properties
• Porosity
• Electrical conductivity
• Hydrophobicity
• Mechanical strength
• Compressibility
• Chemical stability

Materials
• Carbon fiber paper
• Carbon cloth
• Non-woven materials
• Metallic screens
• Foams
Bi-polar plates

**Functions**
- separates gases
- connects cells electrically
- houses flow fields
- supports MEAs
- seals
- provides structural rigidity
- conducts heat

**Properties**
- permeability
- electrical conductivity
- comformability
- manufacturability
- mechanical strength
- chemical stability
- thermal conductivity

**Materials**
- graphite
- graphite/polymer mixtures
- graphoil
- metallic with coating
- composite

**Processes**
- machining
- compression molding
- injection molding
- embossing
- stamping
Hierarchy of structures in PEM fuel cells

M. Eickerling, 2007
Tehnological challenges in fuel cell development

- Membrane material
- Catalyst
- Catalyst layer structure
- Interactions between layers
- Water management
- Heat transfer
- Cell and stack design
- System design
- Manufacturing processes

Performance
Durability
Cost
Technological Challenges in PEM Fuel Cells

- **Membrane material**
  - other (non-PSA) cheaper materials
  - high temperature membranes

- **Catalyst**
  - reduced loadings
  - binary & ternary alloys
  - non precious metal catalysts

- **Catalyst layer & GDL structure**
  - improved water removal
**Goals**

- Uniform reactant distribution to each cell
- Uniform reactant distribution inside each cell
- Required temperature distribution inside each cell

**Methods**

- Modeling of processes
- Experiments with single cell
- Diagnostics
- Experiments with short stack
- Evaluation of full size stack
Oxygen molar fraction
conventional flow field vs. interdigitated flow field

Current density (A/cm$^2$) distributions at $I_{\text{avg}} = 1.2$ A/cm$^2$; stationary conditions

Current density (A/cm$^2$) distributions at $I_{\text{avg}} = 0.8$ A/cm$^2$; automotive conditions

Fuel Cell Diagnostic Methods

Electrochemical techniques
- Polarization curve
- Current interruption
- Electrochemical Impedance Spectroscopy
- Cyclic Voltammetry
- CO Stripping Voltammetry
- Linear Sweep Voltammetry

Species Distribution Mapping
- Pressure Drop Measurements
- Gas Composition Analysis
- Neutron Imaging
- Magnetic Resonance Imaging
- X-ray Imaging
- Optically Transparent Fuel Cells
- Embedded Sensors

Current Distribution Mapping
- Partial MEA
- Segmented Cells

Temperature Distribution Mapping
- IR Transparent Fuel Cells
- Embedded Sensors
Segmented bipolar plates

- local current density measurement
dynamic > 2000 measurement /s
- local temperature measurement
- local electrochemical impedance spectroscopy (EIS)
neutrons can ‘see’ water in fuel cells

normalization of images: water distribution map

original radiography

water distribution

arrow:
ratio:
water filled cell
/empty cell

100 mm
Liquid water distribution in PEMFC by neutron imaging at Penn State University

Goals

- Uniform reactant distribution to each cell
- Uniform reactant distribution inside each cell
- Required temperature distribution inside each cell
- Minimal resistive losses
  - Good electrical contacts
  - Choice of materials
- Take into account thermal expansion
- No hydrogen or oxygen leaks
- Minimal required pressure drop (reactants and coolant)
- Eliminate possibility for water accumulation
- Design for manufacturing/design for assembly
MEAs demonstrate high performance under non-ideal (cool, wet) conditions.
Recent Trends in Fuel Cell R&D

- High temperature membrane
- Self-humidifying membrane
- Alternative non-noble metal catalysts
- Gas diffusion layer characterization
- Corrosion and properties of bi-polar plates
- Diagnostics and modeling
- Understanding of water transport
- Miniature fuel cells
- Direct-borohydride fuel cells
- Bio fuel cells
- Flow field configuration
- System simplification and optimization
- Durability
- Application-specific topics
Fuel Cell R&D - Metrics

Fuel Cell R&D is focused on a broad range of applications, using a variety of technologies and fuels.

**KEY TARGETS:**

**Distributed Power**:  
- $750/kW by 2011  
- 40,000-hour durability by 2011  
- 40% efficiency by 2011

**Transportation**:  
- $45/kW by 2010; $30/kW by 2015*  
- 5,000-hour durability by 2015  
- 60% efficiency

**APUs**:  
- Specific power of 40 W/kg by 2015  
- Power density of 35 W/L by 2015

**Portable Power**:  
- Energy density of 1,000 W-h/L by 2013

Performance metrics being tracked will help form materials handling and backup power targets

*Targets are currently under review

Source: US DOE 09/2010
Projected high-volume cost of fuel cells has been reduced to $51/kW (2010)*

- More than 15% reduction since 2009
- More than 80% reduction since 2002
- 2008 cost projection was validated by independent panel**

As stack costs are reduced, balance-of-plant components are responsible for a larger % of costs.

*Based on projection to high-volume manufacturing (500,000 units/year).
**Panel found $60 – $80/kW to be a “valid estimate”:
http://hydrogendoedev.nrel.gov/peer_reviews.html

Source: US DOE 09/2010
Catalysts and Supports

Challenges:
- Platinum (Pt) cost is ~34% of total stack cost
- Catalyst durability needs improvement

Four Strategies for Catalysts & Supports R&D:
- Lower PGM Content
  - Improved Pt catalyst utilization and durability
- Pt Alloys
  - Pt-based alloys with comparable performance to Pt and cost less
- Novel Support Structures
  - Non-carbon supports and alternative carbon structures
- Non-PGM catalysts
  - Non-precious metal catalysts with improved performance and durability

Stack Cost - $26/kW

Source: US DOE 09/2010

DTI, 2009 analysis, scaled to high volume production of 500,000 units/yr
Used $1100/Troy Ounce for Pt Cost
High-Activity Binary PtNi Alloy Catalyst

- Screening of multiple new alloys at 3M revealed anomalously high ORR activity for Pt$_x$Ni$_y$ at high Ni content.
- Dramatic and sharp mass activity peak at Pt$_3$Ni$_7$ (gravimetric) vs 60at% Ni and 76at% Ni by EMP and XRF respectively.
- Definite gains in kinetic performance but not a practical catalyst yet due to performance limitations above 1 A/cm$^2$.

Next Steps: Improve high current density performance

M. Debe, 2010 DOE Hydrogen Program Review

Source: US DOE 09/2010
Nano-segregated Cathode Catalysts

Argonne National Laboratory approach: Materials by design to characterize, synthesize, and test nanosegregated multi-metallic nanoparticles and nanostructured thin metal films

Next Steps: Evaluate in-cell durability, scale-up

PtNi/Pt core/shell catalyst has 7X activity over same size Pt/C

N. Markovic, 2010 DOE Hydrogen Program Review
2010 Progress & Accomplishments

Non-PGM catalyst activity increased

- High ORR activity reached with several non-PGM catalysts by LANL, including cyanamide-Fe-C catalyst (shown)
- Fuel cell performance improved by more than 100× since 2008
- Catalyst activity exceeds DOE 2010 activity target of 130 A/cm³ at 0.80 V

Source: US DOE 09/2010
Challenges:

- Membranes account for 48% of stack cost at low volume
- Limits on operating range
- Chemical and mechanical durability

Membrane R&D:

- High-Temperature, Low Humidity Conductivity
  - Phase segregation (polymer & membrane)
  - Non-aqueous proton conductors
- Hydrophilic additives
- High Conductivity and Durability Across Operating Range with Cycling
  - Mechanical support or membrane reinforcement
  - Chemical stabilization (additives, end-group capping)
  - Polymer structure (side chain length, grafting, cross-linking, backbone properties, blends, EW)
  - Processing parameters (temperature, solvents)
  - New materials

Stack Cost - $137/kW

DTI, 2009 analysis, production of 1,000 units/yr

Used $453/m² for membrane Cost

Source: US DOE 09/2010
Membranes achieve high conductivity for high temperature applications

CWRU: Frozen-in Free Volume

(a) Homopolymer
   Chains can pack closely

(b) Copolymers with angled comonomers

(c) Copolymers with linear, bulky comonomer

3M: Low-EW PFSA and Multi-Acid Side Chains

Low-EW PFSA has highest conductivity, but poor mechanical properties
Multi-acid side chain ionomer achieves high conductivity while retaining better mechanical properties

- Latest rigid-rod polyelectrolytes show outstanding conductivity at 80 °C
- 120 °C testing in progress

Source: US DOE 09/2010
3M Nanostructured Thin Film (NSTF) catalyst

MEAs demonstrate high performance under non-ideal (cool, wet) conditions

First time standard NSTF CCM has ever hit 1.5 to 2 A/cm² at 30 to 35°C

3M’s use of specific anode operating conditions and modification of anode diffusion media allows high performance operation under challenging conditions – temperature as low as 30 °C

NSTF meets major performance and durability targets
- High power at low PGM loading – 0.18 gPGM/kW (single cell), 0.19 gPGM/kW (stack) – DOE 2010 target: 0.3 gPGM/kW
- Membrane Durability Test - 5000 hours with cycling (single cell) – DOE 2010/2015 target: 5000 hours
We’ve greatly increased durability—including more than doubling the demonstrated durability of transportation fuel cells.

**Transportation Fuel Cell System Durability**
(based on durability observed under real-world conditions, projected to 10% degradation)

*5000 hrs corresponds to approximately 150,000 miles of driving*

**Demonstrated >7,300-hour durability**
This exceeds our target for MEA durability, in single-cell testing—and has the potential to meet the 2010 target for MEAs in a fuel cell system.

**Durability of Automotive Membrane Electrode Assembly (MEA) (in the lab)**

Source: US DOE 09/2010
**RECENT ACCOMPLISHMENTS**

**Vehicles & Infrastructure**
- Fuel cell durability
  - 2,500 hours projected (nearly 75K miles)
- Over 2.8 million miles traveled
- Over 114 thousand total vehicle hours driven
- Fuel cell efficiency 53-59%
- Vehicle Range: ~196 – 254 miles
- Over 134,000 kg of H₂ produced or dispensed
- 152 fuel cell vehicles and 24 hydrogen fueling stations have reported data to the project

**Buses**
- DOE is evaluating real-world bus fleet data (DOT collaboration)
  - H₂ fuel cell buses have a range of 39% to 141% better fuel economy when compared to diesel & CNG buses

**Forklifts**
- Forklifts at Defense Logistics Agency site have completed more than 18,000 refuelings

**Recovery Act**
- NREL is collecting operating data from deployments for an industry-wide report

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*Not all hydrogen produced is used in vehicles*
# Summary – Key Performance Metrics

## Vehicle Performance Metrics

<table>
<thead>
<tr>
<th></th>
<th>Gen 1 Vehicle</th>
<th>Gen 2 Vehicle</th>
<th>2009 Target</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fuel Cell Stack Durability</strong></td>
<td></td>
<td></td>
<td>2000 hours</td>
</tr>
<tr>
<td>Max Team Projected Hours to 10% Voltage Degradation</td>
<td>1807 hours</td>
<td>2521 hours</td>
<td></td>
</tr>
<tr>
<td>Average Fuel Cell Durability Projection</td>
<td>821 hours</td>
<td>1062 hours</td>
<td></td>
</tr>
<tr>
<td>Max Hours of Operation by a Single FC Stack to Date</td>
<td>2375 hours</td>
<td>1261 hours</td>
<td></td>
</tr>
<tr>
<td><strong>Driving Range</strong></td>
<td>103-190 miles</td>
<td>196-254 miles</td>
<td>250 miles</td>
</tr>
<tr>
<td><strong>Fuel Economy (Window Sticker)</strong></td>
<td>42 – 57 mi/kg</td>
<td>43 – 58 mi/kg</td>
<td>no target</td>
</tr>
<tr>
<td><strong>Fuel Cell Efficiency at ¼ Power</strong></td>
<td>51 - 58%</td>
<td>53 - 59%</td>
<td>60%</td>
</tr>
<tr>
<td><strong>Fuel Cell Efficiency at Full Power</strong></td>
<td>30 - 54%</td>
<td>42 - 53%</td>
<td>50%</td>
</tr>
</tbody>
</table>

## Infrastructure Performance Metrics

<table>
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<tr>
<th></th>
<th>2009 Target</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>H₂ Cost at Station (early market)</strong>*</td>
<td>On-site natural gas reformation $7.70 - $10.30</td>
</tr>
<tr>
<td>Average H₂ Fueling Rate</td>
<td>0.77 kg/min</td>
</tr>
</tbody>
</table>

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*DOE independent panels concluded at 500 replicate stations/year: Distributed natural gas reformation at 1500 kg/day: $2.75-$3.50/kg (2006) Distributed electrolysis at 1500kg/day: $4.90-$5.70 (2009)

Source: US DOE 09/2010
For More Information

**Fuel Cell Program Plan**
Outlines a plan for fuel cell activities in the Department of Energy
Replacement for current Hydrogen Posture Plan
→ To be released in 2010

**Annual Merit Review Proceedings**
Includes downloadable versions of all presentations at the Annual Merit Review
→ Latest edition released June 2009
www.hydrogen.energy.gov/annual_review09_proceedings.html

**Annual Merit Review & Peer Evaluation Report**
Summarizes the comments of the Peer Review Panel at the Annual Merit Review and Peer Evaluation Meeting
→ Latest edition released October 2009
www.hydrogen.energy.gov/annual_review08_report.html

**Annual Progress Report**
Summarizes activities and accomplishments within the Program over the preceding year, with reports on individual projects
→ Latest edition published November 2009
www.hydrogen.energy.gov/annual_progress.html

2010 Annual Merit Review & Peer Evaluation Report and Annual Progress Report will be issued in November 2010

www.hydrogenandfuelcells.energy.gov and www.hydrogen.energy.gov

Source: US DOE 09/2010
## Fuel Cell Technology:

### Obstacles for Commercialization

<table>
<thead>
<tr>
<th>Application</th>
<th>Key Obstacle(s)</th>
</tr>
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<tbody>
<tr>
<td>Space</td>
<td>reliability</td>
</tr>
<tr>
<td>(Sub)marine</td>
<td>reliability</td>
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<tr>
<td>Marine (propulsion)</td>
<td>cost, fuel</td>
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<tr>
<td>Automotive, cars</td>
<td>cost, fuel availability</td>
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<tr>
<td>Automotive, buses</td>
<td>durability, cost</td>
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<tr>
<td>Niche transportation</td>
<td>durability, cost</td>
</tr>
<tr>
<td>Stationary Power</td>
<td>durability, cost</td>
</tr>
<tr>
<td>Portable Power</td>
<td></td>
</tr>
<tr>
<td>Battery Replacement</td>
<td>cost, fuel practicality</td>
</tr>
</tbody>
</table>

- **Space**: reliability
- **(Sub)marine**: reliability
- **Marine (propulsion)**: cost, fuel
- **Automotive, cars**: cost, fuel availability
- **Automotive, buses**: durability, cost
- **Niche transportation**: durability, cost
- **Stationary Power**: durability, cost
- **Portable Power**: 
- **Battery Replacement**: cost, fuel practicality
Summary about fuel cells:

- **Fuel cells are:**
  - versatile (many possible applications)
  - efficient
  - clean (when use hydrogen as fuel)
  - modular

- **Fuel cells are close to commercialization**
  - niche market opportunities

- **Few technical challenges, but no show-stoppers**
  - performance
  - durability
  - cost

- **There is a room and need for improvements**

- **Fuel cells using hydrogen as fuel need hydrogen supply infrastructure**
What will an energy system of the future look like?

What would be a role of hydrogen in it?

How do we get there from here?
Hydrogen Energy and Fuel Cells
A Vision of Our Future

Summary

In 2050:
- Oil will likely no longer be cheap
- Europe’s internal reserves will be exhausted
- Increasing proportion of primary energy production will be drawn from “CO₂-lean” resources:
  - Renewables – solar, wind, hydro and biomass
  - Nuclear
- Hydrogen will be one of the three energy vectors (besides electricity and biofuels)
  - It can be produced from variety of primary energy sources
  - It can be used in a variety of applications
  - It can be stored more effectively than electricity
- Fuel cells will be mature technology and cost competitive (other technologies will include turbines and ICE)
- Fuel cells will be used in transport, stationary and portable applications
- Fuel cells are likely to predominantly consume hydrogen, but should be fuel flexible

Quote:
By 2050, competitively priced hydrogen is expected to be widely available in industrial nations. It will not only serve as a major transport fuel but complement electrical power from renewable energy sources in order to match stochastic energy generation and demand.
U.S. DOE Hydrogen Activities
Hydrogen, Fuel Cells and Infrastructure Technologies Program

Vision

Strategy

Toward a More Secure and Cleaner Energy Future for America

A National Vision of America’s Transition to a Hydrogen Economy – To 2030 and Beyond

Based on the results of the National Hydrogen Vision Meeting
Washington, DC
November 13-16, 2001

February 2002

United States Department of Energy

NATIONAL HYDROGEN ENERGY ROADMAP

Production • Delivery • Storage • Conversion
• Applications • Public Education and Outreach

Based on the results of the National Hydrogen Energy Roadmap Workshop
Washington, DC
April 25, 2002

November 2002

United States Department of Energy

HYDROGEN POSTURE PLAN

AN INTEGRATED RESEARCH, DEVELOPMENT, AND DEMONSTRATION PLAN

February 2004

United States Department of Energy
Countries that have adopted hydrogen strategy or a roadmap:

- United States
- European Union
- Canada
- Japan
- China
- India
- Malaysia
- South Africa
- Australia
- Argentina
In which context is there a future for hydrogen?

- There should be an imminent shift in global energy supply from an unsustainable system based on fossil fuels to a new sustainable system.
- Renewable energy sources may result in a sustainable energy system.
- Renewable energy sources need energy carriers:
  - electricity and hydrogen.
- In such a system hydrogen will have a role:
  - solving the problem of variable intensity.
  - as fuel for transportation sector.
  - as fuel where electricity cannot be used.
Renewable energy: solar, wind, hydro, biomass ...

Hypothetical Future Energy System Based on Renewable Energy

Role of hydrogen

useful energy

heat

transport

electricity

industrial

residential
How to change an entire energy system?

- There should be no competition – there should be transition
- Transition requires vision and commitment
- Transition may cause economic hardship
- It is not simply a replacement – transition will require a major shift in our mind sets, priorities, culture and life style
  - shift from the goals of continuous growth to the goals of sustainable development!
  - promote energy and resources conservation!
  - give priorities to the protection of the environment!
  - new operating system – Capitalism 3.0!
Future of Hydrogen

Future of hydrogen is tightly related to the pace of global energy shift/transition to sustainable (renewable) energy.

Difficulties in transition:
- renewables do not need hydrogen for initial penetration in the energy market.

Outside the context of global energy shift/transition, individual hydrogen technologies may be applied only:
- where they are economically competitive,
- where they bring advantage which is more important than immediate financial effect, or
- as curiosity in various demonstrations.