ABSTRACT

Lecture for IEEE Hydrogen Economy Forum
Washington DC  19-20 April 2004

The fuel cell uses a catalyzed reaction between a fuel and an oxidizer to directly produce electricity. Its high theoretical efficiency and low temperature operation made it a subject of much study upon its invention ca. 1900, but its relatively high life cycle costs kept it as "solution in search of a problem" for its first half century. The first problem for which fuel cells presented a cost effective solution was, starting in the 1960's, that of a power source for NASA's manned spacecraft. NASA thus invested, and continues to invest, in the development of fuel cell power plants for this application. However, starting in the mid-1990's, prospective environmental regulations have driven increased governmental and industrial interest in "green power" and the "Hydrogen Economy." This has in turn stimulated greatly increased investment in fuel cell development for a variety of terrestrial applications. This investment is bringing about notable advances in fuel cell technology, but these advances are often in directions quite different from those needed for NASA spacecraft applications. This environment thus presents both opportunities and challenges for NASA's manned space program.
The Development of Fuel Cell Technology for Electric Power Generation

From Spacecraft Applications to the Hydrogen Economy

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Fuel Cell Fundamentals

Cell Electrochemical Reaction

$2\text{H}_2 + \text{O}_2 \rightarrow 2\text{H}_2\text{O}$

$(2\text{CO} + \text{O}_2 \rightarrow 2\text{CO}_2)$

Nernst Equation (Hydrogen Anode): $E = E^\circ + \frac{RT}{2F}\ln\left(\frac{P_{\text{H}_2}}{P_{\text{H}_2\text{O}}}ight) + \frac{RT}{2F}\ln\left((P_{\text{O}_2})^{1/2}\right)$
Fuel Cell Fundamentals

Power Plant Elements

Hydrocarbon Fuel → Electrolyzer → Electric power

Sulfur & other → Fuel Processor (Reformer)
• Steam Reforming
• Partial Oxidation
• Water-Gas Shift

Fuel Cell Stack

ANODE: 
- Pure H₂
- H₂ reformate (+CO₂+CO)

CATHODE:
- Pure O₂
- Air

Fuel Cell Stack → DC power

Inverter

Water (PEM):

Water (SOFC, Alkaline):

AC power
## Basic Fuel Cell Power Plant Characteristics

<table>
<thead>
<tr>
<th>Chemistry</th>
<th>Alkaline</th>
<th>PEM</th>
<th>SOFC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Electrolyte</strong></td>
<td>Concentrated KOH in asbestos matrix</td>
<td>Ion exchange membrane</td>
<td>Ceramic - Solid nonporous metal oxide (Y_{2}O_{3}ZrO_{3})</td>
</tr>
<tr>
<td><strong>Catalyst</strong></td>
<td>Pt</td>
<td>Pt</td>
<td>Ni-ZrO_{3}</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Co-ZrO_{3}</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Sr-LaMnO_{3}</td>
</tr>
<tr>
<td><strong>Fuel Capability</strong></td>
<td>Pure H\textsubscript{2}</td>
<td>H\textsubscript{2} from clean reformate</td>
<td>CO and H\textsubscript{2} from dirty reformate</td>
</tr>
<tr>
<td><strong>Operating Temperature</strong></td>
<td>~90 C</td>
<td>~80 C</td>
<td>800-1000 C</td>
</tr>
<tr>
<td><strong>Water Production</strong></td>
<td>Fuel side (two phase)</td>
<td>Oxidant side (two phase)</td>
<td>Fuel side (vapor)</td>
</tr>
<tr>
<td><strong>Operating Life Drivers</strong></td>
<td>Operating Time</td>
<td>Humidity Control</td>
<td>Thermal Cycles</td>
</tr>
<tr>
<td><strong>Thermodynamic Efficiency (Fuel Tank to AC Power Bus)</strong></td>
<td>50-55%</td>
<td>30-40%</td>
<td>45-60%</td>
</tr>
</tbody>
</table>
Commercial/Military Power Systems:

- Emissions Reduction ($\text{NO}_x$, $\text{CO}_x$, noise)
- Specific Power (kW/kg)
- Production cost ($/\text{kW}$)

Constraint: Public Safety
Design Drivers for Electric Power Systems

Spacecraft Power Systems:

- Specific Energy (kWh/kg)
- Specific Energy (kWh/kg)
- Specific Energy (kWh/kg)

Constraint: Mission Reliability
Fuel Cell Development Roadmaps

Transportation  Distributed Generation

Solid Oxide  PEM

Aeronautics  DOT  DOD  DOE

“Hydrogen Economy”  “Green Power”

SEPA United States Environmental Protection Agency

mid-1990’s


Advanced PEM (late 1990’s)

Shuttle Alkaline (1970’s)

Apollo Alkaline (late 1960’s)

Gemini PEM (early 1960’s)

Spacecraft

W. Nernst 1899

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17 April 2004
NASA Spacecraft Fuel Cell Technology Roadmap

**Power System Mission Drivers**
- Duration?
- Solar availability?
  - Flux?
  - Surface area?
- Heat rejection capability?
- Launch mass limits?

**Fuel Cell Requirements:**
- Pure O₂ oxidant stream
- Load following (e.g. 6:1 in 200 ms)

**Development toward improved:**
- Fluid commonality with propulsion, life support, thermal control, etc
- Mission reliability
- Life cycle cost
- Power/energy density

**Planetary Rovers:**
- PEM fuel cell power plant
- Steam reforming of fuel from planetary resources
  - Methane (CH₄), or
  - Ethanol (C₂H₅OH)
  - Methanol (CH₃OH)
- Oxidant (O₂) from planetary resources (e.g., electrolysis)

**Advanced Exploration:**
- Gravity independence
- Regenerative fuel cells
- Electrolysers
- H₂O propulsion

**1970’s Space Shuttle**
- Alkaline fuel cell power plant
- Gravity-independent water management
  - (0-g, multi-g, vibration)
- Full mission reactant storage
- Reactant grade O₂ (supercritical)
- Propulsion grade H₂ (supercritical)

**Next Generation Launch Technology and Crew Exploration Vehicle**
- Proton Exchange Membrane (PEM) fuel cell power plant
- Gravity-independent water management
  - (0-g, multi-g, vibration)
- Full mission reactant storage
- Propulsion grade O₂ (liquid)
- Propulsion grade H₂ (supercritical)

**1990’s Shuttle Upgrades**
- Long Life Alkaline Fuel Cell

**H₂ reformed on-board (<10 ppm CO) from C₅H₁₂OH fuel (common fuel with propulsion)**

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Fuel Cells for Planetary Exploration

Common Technologies & Fluids Maximizes
Benefits, Flexibility, & Affordability

In-Situ Production Of
Consumables for Propulsion,
Power, & ECLSS

Core Technologies

- CO₂ & N₂ Acquisition & Separation
- Sabatier Reactor
- RWGS Reactor
- CO₂ Electrolysis
- Methane/HC Reforming
- H₂O Separators
- H₂O Electrolysis
- H₂O Storage
- Heat Exchangers
- Liquid Vaporizers
- O₂ & Fuel Storage
  (0-g & reduced-g)
- O₂ Feed & Transfer Lines
- O₂/Fuel Couplings
- Fuel Cells
- O₂/Fuel Igniters & Thrusters

Life Support Systems for
Habits & EVA

Water – H₂/O₂ Based
Propulsion

Non-Toxic O₂-Based
Propulsion

Fuel Cell Power for
Rovers & EVA

0-g & Reduced-g
Propellant Transfer
The Primary Challenge for NASA’s Space Program

New Space Exploration Vision

On January 14, 2004 the President announced a new vision for NASA

- Implement a sustained and affordable human and robotic program to explore the solar system and beyond;

- Extend human presence across the solar system, starting with a human return to the Moon by the year 2020, in preparation for human exploration of Mars and other destinations;

- Develop the innovative technologies, knowledge, and infrastructures both to explore and to support decisions about the destinations for human exploration; and

- Promote international and commercial participation in exploration to further U.S. scientific, security, and economic interests.
The Hydrogen Economy

Toward a More Secure and Cleaner Energy Future for America

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 2-3, 2002

November 2002

United States Department of Energy

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 15-16, 2001

February 2002

United States Department of Energy
The Major Challenge to the Hydrogen Economy
The Hydrogen Economy: its impact on the future of electricity

19-20 April, 2004
JW Marriott Hotel, Washington, DC

April 19, 2004
7:30-8:30am  Registration / Breakfast Snack Buffet
8:30-10:00am  Opening Session

- Greeting / Introductions
- Opening Presentation - What is a hydrogen economy?
- Keynote Address - Understanding the challenge: The Honorable Robert Walker, Chairman, Wexler and Walker Public Policy Associates

10:00-10:30am  Break
10:30-12:15pm  Electric Energy and Hydrogen Links

- The Development of Fuel Cell Technology for Electric Power Generation: John H. Scott, NASA Lyndon B Johnson Space Center
- Lessons learned from Automotive Applications: TBD
- Fuel Cells for Stationary Power Application: TBD
- Sources of Hydrogen, How much is needed?: TBD
- Q&A Session

12:15-1:45pm  Lunch
1:45-3:30pm  Hydrogen Infrastructure - Challenges

- Large-Scale H2 Production and Distribution: Guenter Conzelmann, Argonne National Laboratory
- Values of Electricity Storage in a Hydrogen Based Electrical System: Ali Nourai, AEP
- Q&A Session

3:15-3:45pm  Break
3:45-5:30pm  International Experience


April 20, 2004

7:30-8:30am  Breakfast Buffet / Late Registration
8:30-10:15am Managing Major Technology Transition
   • A Technology Roadmap for Hydrogen: Robert Schainker, EPRI
   • Economical Energy Conversion: TBD
   • Commercialization Challenges: David Parekh, Georgia Tech
   • Q&A Session
10:15-10:30am Break
10:30-12:00pm Public and Private Decision Points
   • Formulating and Implementing Public Policy for Hydrogen: Clint Andrews, Rutgers University
   • Lessons from the National Academy of Engineers Hydrogen Study: Antonia Herzog, Natural Resources Defense Council
   • The “Value Proposition” of Hydrogen: Scott Weinste Esq., Rutgers University
   • Q&A Session
12:00-1:15pm Lunch
1:15-3:00pm Closing Session
   • The Hydrogen Economy: The creation of the worldwide energy web and the redistribution of power on earth: Jeremy Rifkin, author of “Hydrogen Economy”, President of the Foundation on Economic Trends
   • Meeting Review Comments
   • Closing Remarks
   • Next Steps/Action Items
3:00pm Meeting Adjourned

19-20 April, 2004; JW Marriott Hotel, Washington, DC