# 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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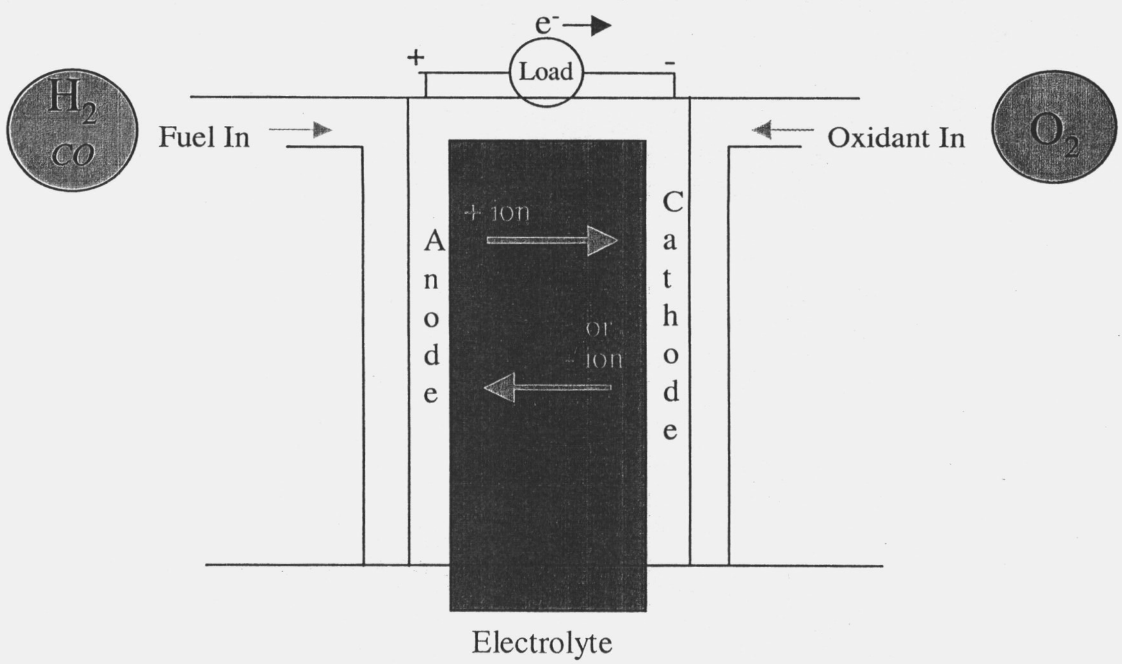
# Cell Electrochemical Reaction

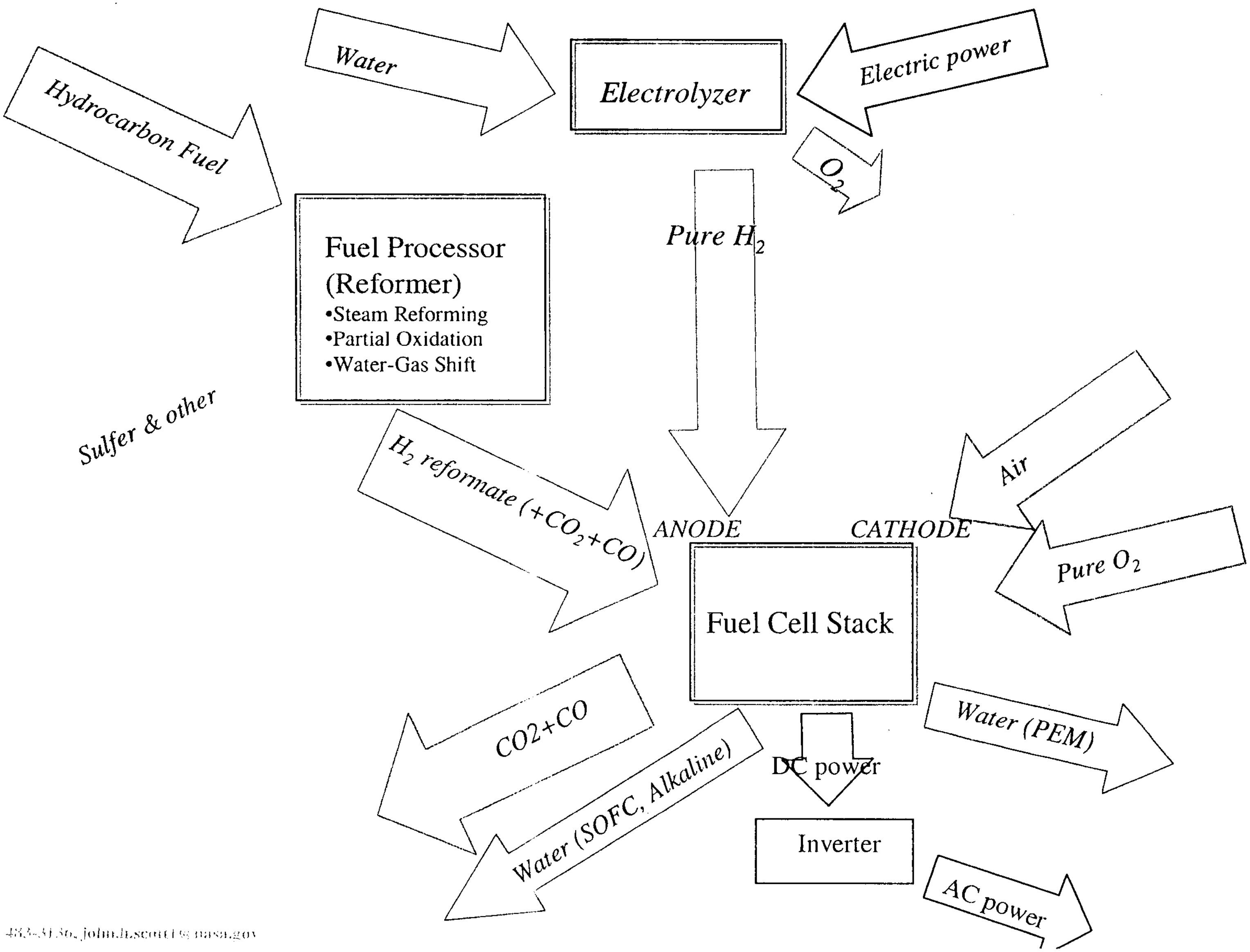
$$2H_2 + O_2 \rightarrow 2H_2O$$

$$(2CO + O_2 \rightarrow 2CO_2)$$




Nernst Equation *(Hydrogen Anode)*: $E = E^o + (RT/2\mathcal{F})\ln(P_{H2}/P_{H2O}) + (RT/2\mathcal{F})\ln[(P_{O2})^{1/2}]$

## Power Plant Elements



# Basic Fuel Cell Power Plant Characteristics

| **Chemistry** | **Alkaline** | **PEM** | **SOFC** |
|---|---|---|---|
| **Electrolyte** | Concentrated KOH in asbestos matrix | Ion exchange membrane | Ceramic - Solid nonporous metal oxide ($Y_2O_3$-$ZrO_3$) |
| **Catalyst** | Pt | Pt | Ni-$ZrO_3$<br>Co-ZrO3<br>Sr-$LaMnO_3$ |
| **Fuel Capability** | Pure $H_2$ | $H_2$ from clean reformate | CO and $H_2$ from dirty reformate |
| **Operating Temperature** | ~90 C | ~80 C | 800-1000 C |
| **Water Production** | Fuel side (two phase) | Oxidant side (two phase) | Fuel side (vapor) |
| **Opeating Life Drivers** | Operating Time | Humidity Control | Thermal Cycles |
| **Thermodynamic Efficiency** (Fuel Tank to AC Power Bus) | 50-55% | 30-40% | 45-60% |

# Commercial/Military Power Systems:

- Emissions Reduction ($NO_x$, $CO_x$, noise)
- Specific Power (kW/kg)
- Production cost ($/kW)

Constraint: Public Safety

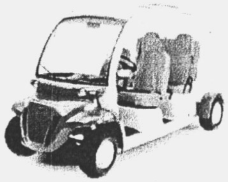
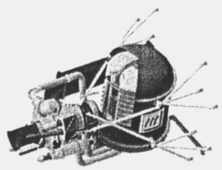
# Spacecraft Power Systems:

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

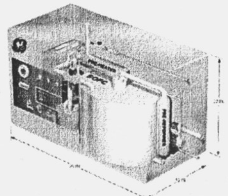
Constraint: Mission Reliabilty

# Fuel Cell Development Roadmaps

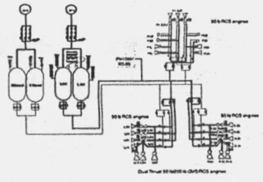


Transportation



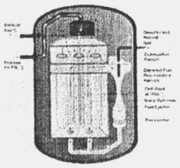
Distributed Generation



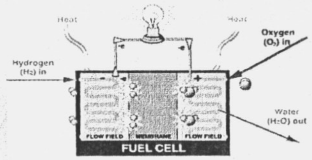
Integrated Regenerative Systems (2000+)

## Solid Oxide

SECA



## PEM




**Aeronautics**

**DOT**

**DOD**

NAVSEA PHILADELPHIA

**DOE**

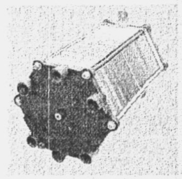
NETL

**"Hydrogen Economy"**

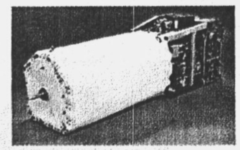
**"Green Power"**

EPA United States Environmental Protection Agency

**mid-1990's**

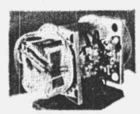


Advanced PEM (late 1990's)



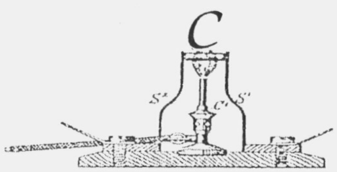
Shuttle Alkaline (1970's)

Apollo Alkaline (late 1960's)



Gemini PEM (early 1960's)

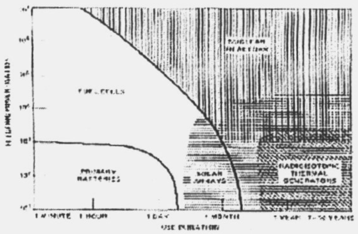
**Spacecraft**




W. Nernst 1899

# NASA Spacecraft Fuel Cell Technology Roadmap

JSC-Energy Systems Division

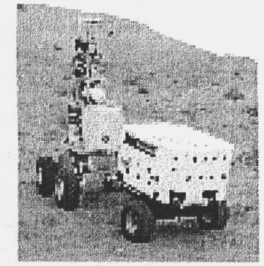


Photovoltaics

Batteries

Nuclear

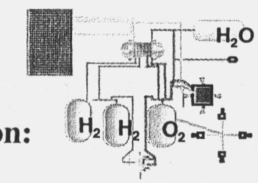
**Planetary Rovers:**
- PEM fuel cell power plant
- Steam reforming of fuel from planetary resources
  - Methane ($CH_4$), or
  - Ethanol ($C_2H_5OH$)
  - Methanol ($CH_3OH$)
- Oxidant ($O_2$) from planetary resources *(e.g., electrolysis)*



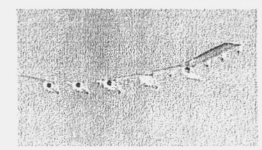
**Power System Mission Drivers**
- Duration?
- Solar availability?
  - Flux?
  - Surface area?
- Heat rejection capability?
- Launch mass limits?

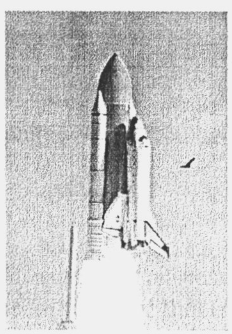
**Fuel Cell Requirements:**
- Pure $O_2$ oxidant stream
- Load following *(e.g. 6:1 in 200 ms)*

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



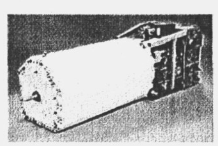

**Advanced Exploration:**
- Gravity independence
- Regenerative fuel cells
- Electrolysers
- $H_2O$ propulsion



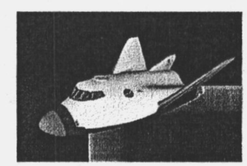


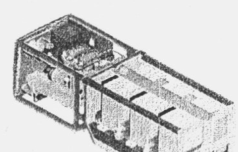
**1970's Space Shuttle**
- Alkaline fuel cell power plant
- Gravity-independent water management *(0-g, multi-g, vibration)*
- Full mission reactant storage
- Reactant grade $O_2$ *(supercritical)*
- Propulsion grade $H_2$ *(supercritical)*

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



**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 $O_2$ *(liquid)*
- Propulsion grade $H_2$ *(supercritical)*





- $H_2$ reformed on-board (<10 ppm CO) from $C_2H_5OH$ fuel *(common fuel with propulsion)*

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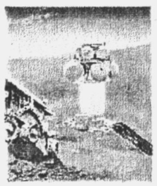
# Fuel Cells for Planetary Exploration

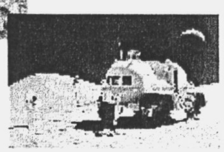


## *Common Technologies & Fluids Maximizes Benefits, Flexibility, & Affordability*

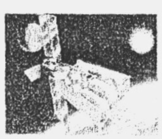
### In-Situ Production Of Consumables for Propulsion, Power, & ECLSS

### Fuel Cell Power for Rovers & EVA

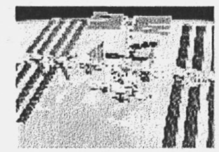
### 0-g & Reduced-g Propellant Transfer

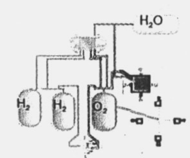
### *Core Technologies*

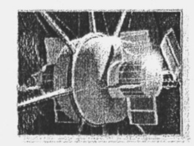
- $CO_2$ & $N_2$ Acquisition & Separation
- Sabatier Reactor
- RWGS Reactor
- $CO_2$ Electrolysis
- Methane/HC Reforming
- $H_2O$ Separators
- $H_2O$ Electrolysis
- $H_2O$ Storage
- Heat Exchangers
- Liquid Vaporizers
- $O_2$ & Fuel Storage (0-g & reduced-g)
- $O_2$ Feed & Transfer Lines
- $O_2$/Fuel Couplings
- Fuel Cells
- $O_2$/Fuel Igniters & Thrusters

### Life Support Systems for Habitats & EVA

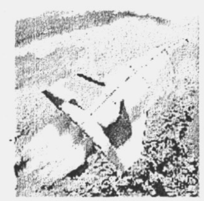
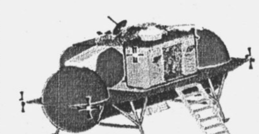



### Water – $H_2/O_2$ Based Propulsion





### Non-Toxic $O_2$-Based Propulsion

# 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

JSC-Energy Systems Division

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

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

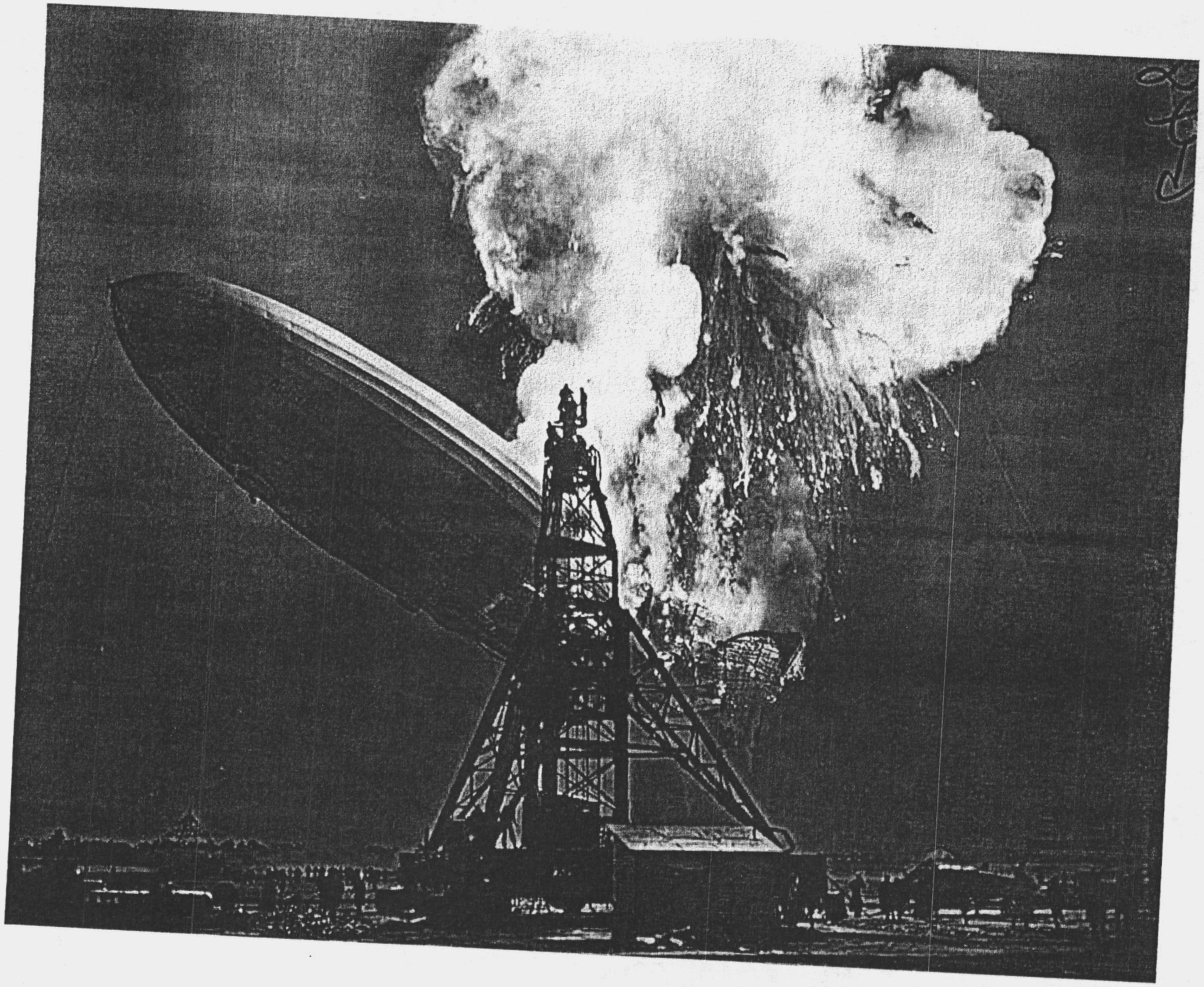
Based on the results of the
National Hydrogen Vision Meeting
Washington, DC
November 15-16, 2001

February 2002

United States Department of Energy

# The Major Challenge to the Hydrogen Economy

JSC-Energy Systems Division



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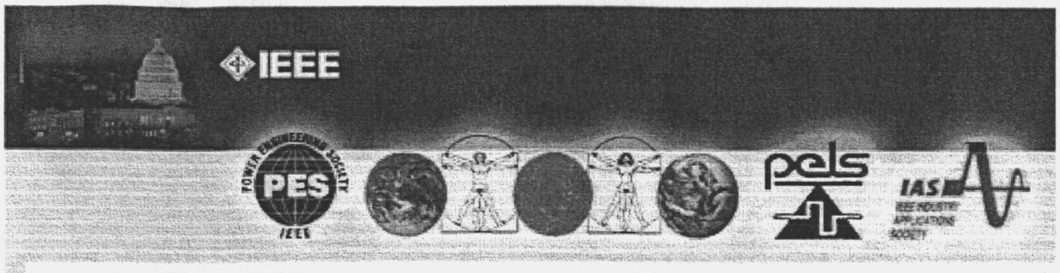
17 April 2004






# *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 Elec Power Generation: John H. Scott, NASA Lyndon B Johnson Space Center
- Lessons learned from Automotive Applications: TE
- Fuel Cells for Stationary Power Application: TBD
- Sources of Hydrogen, How much is needed?: TBD
- Envisioning a Hydrogen Economy - Opportunities Electric Power: Richard Scheer, Energetics, Inc.
- 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 Laborator
- 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**

- International Partnership for the Hydrogen Economy: Robert K. Dixon, Office of Energy

Efficiency and Renewable Energy, US DOE
- European Union: TBD
- Hydrogen for Sustainable Growth and Hydrogen/Fuel Cell Projects in Japan: *Ken-ichiro Ota*, Yokohama National University
- Q&A Session

**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 Engineerin Hydrogen Study: *Antonia Herzog*, Natural Resour Defense Council
- The "Value Proposition" of Hydrogen: *Scott Weine 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 "Hydrog Economy", President of the Foundation on Econor Trends
- Meeting Review Comments
- Closing Remarks
- Next Steps/Action Items

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| 3:00pm | Meeting Adjourned |

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

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