300-Watt Power Source Development at the Jet Propulsion Laboratory

Presented by:
Thomas P. Valdez

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Presentation Outline

- DMFC Overview
- Program Discussion
- Overview of Power Source Design
- System Performance
- Analysis of System Performance
- Program Conclusions

Fuel Cell Team

- Program Managers
  - T. Durand (Power Systems Manager)
  - W. Scott (Program Manager)
- Technical Team
  - J. P. Valdez (Principal Investigator)
  - R. B. Bertsch (Advanced Fuel Cell Technology Development Manager)
  - A. K. G. (Subsystem Design)
  - J. B. (Packaging)
  - M. A. (Mechanical Design)
  - W. V. (Electrical Engineering)
  - M. A. (Systems Integration)
  - R. G. (Chemical Materials Processing)
  - J. D. (Thermal and Fluids Engineering)
  - J. L. (System Design/Engineering Support)
  - T. D. (Subsystem/Testing)

Industry Partners

- Clearfix/DL System, LLC
  - C. Coppley
- FuelCell, Inc.
- Donahoe Company Inc.
  - J. Clapper
- JPL
  - J. G. (Program Development)
- JPL Industries
  - J. J. (Program Management)

DMFC Overview
**The Direct Methanol Fuel Cell**

Direct Methanol Fuel Cell Reaction:
- Acid: \( \text{CH}_3\text{OH} + H_2O \rightarrow \text{H}^+ + \text{H}_2 + \text{CO}_2 \)
- Catalyse: \( \text{H}_2 + \text{O}_2 \rightarrow \text{H}_2\text{O} \)
- **Cell:** \( \text{CH}_3\text{OH} + \frac{3}{2} \text{O}_2 \rightarrow \text{CO}_2 + 3\text{H}_2\text{O} \)

**DMFC Advantages:**
- Safety of handling a liquid fuel versus compressed gas fuel tank (i.e. Hydrogen)
- Low methanol concentration (<5%) in the ‘working’ fuel loop

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**The Benefits of a DMFC Power Source**

<table>
<thead>
<tr>
<th>Battery Configuration</th>
<th>4 Battery Configuration</th>
<th>2 Battery Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mass (lb)</strong></td>
<td>3015</td>
<td>167</td>
</tr>
<tr>
<td><strong>Volume (l)</strong></td>
<td>2.6</td>
<td>1.4</td>
</tr>
<tr>
<td><strong>Energy (times)</strong></td>
<td>4800</td>
<td>3600</td>
</tr>
</tbody>
</table>

- Substantial reduction in mass
- Increased energy capacity
- Increased operating time

*Comparison based on information from TESCO using a 4-battery and 2-battery cell configuration without recharging.*

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**JPL Direct Methanol Fuel Cell Program Description**

**Objective, Background and Requirements**

**Objective:**
- Develop direct methanol fuel cell technology and demonstrate a 300-Watt prototype power source.

**Background:**
- The Army currently uses four deep cycle marine batteries to provide auxiliary power to armored vehicle external power applications. The batteries weigh 135 kg (300 lb) and are limited to 8 hours of operation without recharging.

**Summary of Requirements:**
- Power: 300 W (Continuous)
- Run Time: 100 h (Continuous)
- Energy: 30,000 Wh
- Target Mass: 36 kg (80 lb) (including Fuel)
- Other Attributes:
  - Rapid Startup
  - Field Refueling for Extended Operation
  - No Recharge Time
  - Quiet
  - Low Thermal Signature
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**Summary of Accomplishments**

**Goal:**
Develop a 300 Watt DMFC Power Source for powering test instrumentation on Armored Vehicles

**Integrated DMFC Unit**

- Developed a 300-Watt DMFC based power source delivered to the Jet Propulsion Laboratory and integrated.
- The DMFC system met the power output of 300 Watts for the specific power density and volumetric power density requirements.
- Test profile from 25°C to 85°C cell temperature was achieved.
- A flow cell stack has been tested for 60 hours, and was characterized to decrease 35% during the test.
- Sequential fueling using a real-time measurement of the hydrogen uptake and cell temperature was performed.
- The system was operated continuously at a set output of 30 Watts for 2 hours.
- Operational test instrumentation baseline (44 to 50 Watts) for 11 hours.

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**Future Development**

- A 300-Watt DMFC system design has been completed.
- The functionality of this system was demonstrated.
- System design challenges and issues have been identified.
- Industry partners should develop this system into a pre-production prototype.
- JPL's future role will be to assist the US Army with technical support to facilitate the delivery of a pre-production prototype power source.

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**Overall DMFC System Design**

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**Requirements**

- **Power Source:**
  - Power: 300 W (Continuous)
  - Input Voltage: 100 V
  - Energy: 30,000 Wh
  - Nominal Voltage: 48 V
  - Starting Margin: 60% (Including 30% buffer)
  - Starting Margin: 60% (Including 30% buffer)
  - Minimum operating temperature: 5°C (41°F)
  - Maximum operating temperature: 40°C (104°F)
  - Field installability:

- **Environmental Conditions:**
  - Ambient temperature: -10°C to 40°C
  - Relative Humidity: 25% to 95%
  - Shock and Vibration:
    - Vibration: A-weighted crest factor
    - Shock: A-weighted shock spectrum

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Technical Challenges

- Key Technical Challenges
  - Meeting environmental requirements
  - Corrosion operation in thermal and water balance
  - System size and volume with contained heat
  - Raggedness operation
  - Safety of system handling

- Challenges to be addressed
  - Cost Effective Membrane
  - Electrochemical Fabrication
  - Power Source Longevity
  - Ambient Innovation Operation
  - Raggedness Operation

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Challenges Resulting from Environmental Temperature

- Power Source Environments
  - Operating Temperature and Humidity: 45°C, 95% RH
  - At 95% RH, MEA operating inactivity will define system volume
  - An airflow stoichiometry in the range of 1:1 to 1.3 is required for a PEMFC stack, operating at 60°C, without an exhaust conditioner, to operate in water balance at 9% RH
  - The smaller the temperature difference between the systems' operating temperatures and ambient temperature, the larger the radiator surface area required for cooling
  - A PEMFC-based power source operating at 60°C in an ambient environment of 45°C allows for only a 7°C differential in temperature and results in an increased radiator size.

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Stack Design Challenges

- Operating Temperature
  - Heat rejection: Environmental temperature 45°C
  - Water balance: MEA operation at low airflow is required to maintain a water balance without the use of a condenser

- Orientation Sensitivity
  - Efficient product water removal is required during operation
  - Stack pressure drop, specifically, the cathode pressure drop should be minimized to reduce auxiliary power demand

- Stack Cooling
  - Sized to required power output, system ancillaries and power conditioning
  - Stack operating voltage should be oriented to match with a higher efficiency power converter

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Electronics Subsystem Challenges

- Monitored Concentration Control
  - Operation from 09:00
  - "in-field" refueling required
  - Active concentration control via a monitored sensor is suggested

- System Startup
  - Instant startup
  - System startup from 9°C acceptable

- Power Management
  - Power source is required to back load following
  - Stack voltage should be controlled from spiking to prevent electronics

- Ancillary power demand
  - Must reduce power required by ancillary to increase system operating efficiency

- Electronics Survivability
  - Electronics should be designed to operate at the maximum power source mixture operating temperature
  - A maximum temperature of 60°C is suggested
  - Electronics reconfiguration

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System Integration

- Gas Expander
- Heat Exchanger
- Methanol Storage
- Fuel Tank
- Circ. Pump
- Exhaust Blower
- 50 Cell DMFC Stack

Component Percent of Power Source Mass

- The fuel mass and moisture represent 89% of the power source mass.
- A DMFC power source can achieve the highest energy density when the fuel mass represents a large fraction of the total system mass.

Component Percent of Power Source Volume

- System operating temperature and operating environment have a clear impact on volume.

System Demonstration
System Demonstration Summary

- After the system demonstration, the program focused on performance recovery.
- Fault-tree analysis was performed on the system.
- The fault-tree analysis revealed that cathode flooding was the primary reason for system performance decline.
- The experiments performed for the fault-tree analysis were:
  - Stack test stand testing
  - Stack tear down
  - Advanced single cell MEA testing
- The conclusions from the analysis of system performance defined by the fault tree are:
  - Fluid accumulation in the stack to be addressed by design changes
  - Stack leakage attributed to poor sealing
  - System performance decline was caused by cathode flooding
  - Electrolyte migration from the anode to the cathode of the MEAs contributed itself as cathode flooding
  - Commercial platinum-based catalyst appeared to be stable during field cell operation

Results and Observations from the System Demonstration

- During the demonstration, the power source operated autonomously with the operating logic being driven by an external computer.
- The system started up in 18 minutes during the system demo.
- The stack output power was over 155 Watts and the system delivered an output power of 50 Watts for over 8 hours. The power output was lower than expected.
- After 4 hours of operation, ACMS system electronics consumed approximately 70 Watts, were operated for half an hour.
- During the 8.5-hour continuous test, the system consumed approximately 1.8 L of pure methanol resulting in a fuel to electrical energy conversion efficiency of 7%. This value of system efficiency is to be expected considering that the system was not operating at its optimum power output and that 50% of the output from the stack was consumed in running the auxiliary.
- Water accumulation was noticed in the stack exhaust manifold. The water accumulation was a result of the air diffuser on the stack exhaust side saturating with water and a stack leak rate that was greater than the designed volumetric pumping speed of the pump pumps. The test was concluded because of water accumulation in the stack exhaust manifold.

Analysis of System Performance

Stack Testing
Analysis of System Performance

Stack Tear Down

Discolored MEAs

MEA Mounted in Stack Electronics

MEA Stored in Plastic Bag

Discolored MEA Testing

Observations on MEAs from the 80-cell stack

- Cathode of MEAs from the stack exhibited increased reactivity compared to a "new" MEA.
- Particles of dark grey "deposit" found on various parts of the cathode.
- The area with dark deposits were more reactive than the lighter areas.
- Several representative MEAs showed the same type of cathode changes.
- Areas under the flow field (not) remained "non-reactive".
- Flow field penetration were light and did not appear to damage the cathode paper.

No impact on MEA performance is apparent for discolored MEAs.
EDAX Analysis

Diffuser Cloth
Brownish black ruthenium oxide precipitated at the cathode is washed down by water and absorbed on diffuser.

Impact of Stack Performance Decline on Stack Output Power

Analysis of System Performance
Advanced MEA Studies
Advanced MEA Studies

- Objective: To determine the stability of platinum-ruthenium catalyst and effect of carbon paper Teflon content for DMFC operation
  - MEA Compositions:
    - MEA# 012005, Anode: JPL, Cathode 15% Teflon
    - MEA# 012905, Anode: Johnson Matthey, Cathode 15% Teflon
    - MEA# 012805, Anode: Reduced Johnson Matthey, Cathode 15% Teflon
    - MEA# 012905, Anode: Johnson Matthey, Cathode 5% Teflon (Standard)

All MEAs were fabricated with the same pasting technique, catalyst loadings and bio-press conditions.

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Post 250-hr Durability Testing Performance Summary

| MEA Number | Formulation                  | Performance Decay [%] | Rate of Decay [kT/sec] | MEA Analysis - MEA 012005, JPL Anode, 15 Cathode
|------------|------------------------------|-----------------------|------------------------|---------------------------------------------------
|            |                              | OCV [mV]              | iR [mV]                | 60C, 0.5M MeOH, 1 LPM, 9FEG, Air                  |
| MEA# 012005| Anode: JPL, Cathode 15% Teflon| 10                    | 13                     |                                                   |
| MEA# 012905| Anode: Johnson Matthey, Cathode 15% Teflon | 10                  | 13                     |                                                   |
| MEA# 012805| Cathode: 15% Teflon          | 20                    | 40                     |                                                   |
| MEA# 012905| Cathode: 5% Teflon (Standard)| 2                     | 36                     |                                                   |

- MEAs fabricated with the commercial Johnson Matthey catalyst showed the least performance decline.
- The MEA fabricated with the reduced Johnson Matthey anode catalyst, MEA# 012905, performed similar to the MEA fabricated with the JPL catalyst, MEA# 012005.
- The test standard, MEA# 012905, performed the best during the durability experiment.
- The rate of voltage decay for all MEAs tested is similar to values observed in the past.

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Re-Migration Studies, 250-hr Durability Test 60C, 0.5M MeOH, 60mA/cm², High Flow Rate, Air
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**MEA Analysis - IRK Anode Polarization**
60C, 0.5M MeOH

*Anodes stable after 250 hours of testing*

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**MEA Analysis - Half Cell Analysis**
MEA 012805, JPL-04001, 15C Cathode
60C, 0.5M MeOH, 1 LPM, 95% RH, Air

*Cathode degradation after 250 hours of testing*

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**Typical View of an MEA After the 250-hr durability Test**

Pin cushion pattern

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**Cathode Hydrophobic Characterization - Water Droplet Experiment**

Slight change in hydrophobicity after 250 hours of testing

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Durability Test Summary

- Four MEAs have completed durability testing in excess of 250 hours.
- The cells were disassembled and individually tested in the single cell test stand.
- Testing in the single cell test stand has revealed irreversible voltage decay on the cells.
- The voltage decay rate was found to be in the range of 0.9006 to 0.9002 V/hr at 100 mA/cm², which is in the range previously determined for MEAs fabricated in a similar fashion.
- The voltage decay resulted in an average decline of cell power of 20% at a 100 mA/cm².
- FEAX analysis performed on the MEAs has shown that the commercial platinum-ruthenium catalyst is stable during DMFC operation.

Program Conclusions

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Power Source Testing Conclusions

- A 300W DMFC based power source design that can deliver 100 hours of continuous operation has been designed and fabricated.
- The CBE figures of merit for this power source are 540 W/kg and 243 Wh/1, for the specific power density and volumetric power density respectively.
- A five-cell stack has been scaled up to 80 cells and was demonstrated to deliver 370W.
- Demonstrated autonomous operation capability of a complete fuel cell system in a box.
- Operated continuously at a net output of 50 Watts for 8 hours.
- Operated test instrumentation hardware for 0.5 hours.
- Stock performance decline due to cathode flooding and ruthenium dissolution and thus limited power source output.

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Recommendations

- **MEA:** DMFC Membrane Electrode Assembly (MEA) should be developed that can operate for durations greater than 500 hours with less than a 10% decline in power output.
- **Stack, Substrate:** A stack should be designed that can address reactant availability to the MEA's electrodes during operation and limit short currents:
  - Integrate nanoscale scale-down designs limited extension sensitivity, coupled laser film deposition, or MEA assembly suppression of oxygen through the anode.
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  - Enhance anode to fuel cell integration with integrated fuel cell support structures.
- **Fuel System:** The gas flow separator (GFS) should be designed to allow for better gas bubble (fuel, air, and liquid flow) interaction:
  - The GFS design limited the fuel flow by reducing fuel flow gas to gas interaction.
  - The GFS design limited the fuel flow by reducing fuel flow gas to gas interaction.
- **Electronics Substrate:** Purchase or fabricate power converter with an input voltage range that spans the stack operating voltage range:
  - The system power converter had a limited input voltage range of 18 to 36 Vdc.
  - The stack voltage could rise as high as 40 Vdc during fuel reduction.

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