“A DARPA Perspective on Small Fuel Cells for the Military”

Presented at the SOLID STATE ENERGY CONVERSION ALLIANCE (SECA) WORKSHOP

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Performance Shortfall for Today’s Power Sources

- Batteries
- Micro Air Vehicles
- Micro Climate Cooling
- Robots
- Exoskeletons
- Soldier Power

Specific Energy, Whr/kg vs. Specific Power, W/kg graph

- Specific Energy and Specific Power values for batteries, micro air vehicles, micro climate cooling, robots, and exoskeletons.

- A timeline from 2005 to 2018-25 is indicated with targets for improved performance.
Energy Conversion Technologies Considered For Portable Power Applications

**Electrochemical** $\varepsilon \approx 100\%$
- Fuel Cells

**Heat Engines** $\varepsilon = [(1 - T_L/T_H) \times 100] \%$

*Dynamic Systems*
- Piston
- Turbines
- Stirling

*Static Systems*
- Thermoelectrics
- Thermionics
- Alkali Metal Thermal to Electric Conversion
- Thermophotovoltaics

Fuel cells promise earliest but not only opportunity
DoD Compact Fuel Cell Evolution

1992 – H₂ Stack
- 15 W
- 5 pounds

1996 – H₂ System
- 40 W / 90 Wh
- 3.5 pounds
- Metal Hydride

1998 – H₂ System
- 50 W / 2 Kw-hr
- 7.5 lbs
- Compressed Hydrogen

2000 – DMFC Stack (2001 - System)
- 70 W
- 2.2lbs (goal)

Future - SOFC

The Fuel is the Issue
MILITARY EXERCISE

COST ESTIMATE FOR ONE DAY, ONE RETRANS SITE

• BA5590 BATTERIES = $900
• FUEL CELLS = $26
Fuel cells operating laptop
Computers, battery chargers
In the CMOC area

Hybrid Fuel Cell, photovoltaic,
Battery system operating a Ham
Radio at the refugee camp
Hydrogen Sources Comparison
For Portable PEM Fuel Cells

- 4500 psi H₂
  - 289 Wh/kg
  - 1.7% Storage

- NH₃ + LiAlH₄ → H₂ + Solid Products
  - 1000 Wh/kg
  - 6% Storage

50 W PEM Fuel Cell (2.7 kg)
30-Cell Direct Methanol Fuel Cell Stack

Los Alamos National Laboratory

![Image of fuel cell stack]

![Graph of Voltage and Power vs. Current]

![Bar chart of cells in stack]

- **Voltage (V):** 5 to 30
- **Current (A):** 0 to 6
- **Power (W):** 0 to 100
- **Cell # in stack:** 1 to 30
Lithium Battery / Fuel Cell Comparison

- **Lithium ion Battery**
- **Lithium SO₂ Battery**
- **Fuel Cells**
  - Compressed Hydrogen
  - Hydrogen Generator
  - Direct Methanol
Palm Power Program

Program Goal

20 Watts
(10-20 X Batteries)

High Energy Content Fuel

Electric Power

Materials Development

Thermal Management

System Integration

- Fabrication
- Cascading Systems

Exoskeletons

Robots

Soldiers

High T

Low T
The Holy Grail? - Direct Conversion of Hydrocarbon Fuels

**DIRECT OXIDATION**

- Hydrocarbons
- Liquid Fuel
- Fuel Cell

**CHALLENGES**
- Increase Performance
- Catalysts
- Thermal management
- Liquid Fuels

**Power Density (W/cm²)**

- \( \text{C}_4\text{H}_{10} \)
- \( \text{C}_7\text{H}_8 \)
- \( \text{C}_4\text{H}_{10} \)
- \( \text{CH}_4 \)
- \( \text{C}_2\text{H}_6 \)
- \( \text{C}_4\text{H}_8 \)

**Time (x10³ sec)**

**Voltage = 0.4V**

Recent work:
Thermal Management Opportunities

Superthermal Conductors and Heat Exchangers

Aerogel Insulators

\[ K_{\text{solid, Aerogel}} = 0.002 \text{ W/mK @ 300K} \]
\[ K_{\text{solid, Silica}} = 1.4 \text{ W/mK @ 300K} \]
Thermal Integration Opportunities

Cascading Systems

- Thermally integrate multiple technologies
  - Design
  - Fabrication

SOLID OXIDE FUEL CELL
1000 - 650 °C

THERMOELECTRICALS
1000 - 100 °C

*Integrated Efficiency* >> Σ *Individual Efficiencies*
Palm Power Goals

- **2,000 Wh/kg goal for 3 day system**
- **3,000 Wh/kg goal for 10 day system**
- **1,000 Wh/kg goal for 3 hour system**

**Current SOA Batteries (Primary & Secondary)**
<table>
<thead>
<tr>
<th>Period</th>
<th>Technology</th>
<th>Specific Power</th>
<th>Revolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Early 1700’s</td>
<td>Steam engines</td>
<td>0.005 W/g</td>
<td>‘Industrial’</td>
</tr>
<tr>
<td>1890-1960</td>
<td>Steam turbines</td>
<td>0.05-1.0 W/g</td>
<td>‘Transportation’</td>
</tr>
<tr>
<td></td>
<td>IC engines</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1950-2000</td>
<td>Turbojets</td>
<td>10 W/g</td>
<td>‘Aviation’</td>
</tr>
<tr>
<td></td>
<td>Turbofans</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2000-?</td>
<td>Microcombustors</td>
<td>100 W/g</td>
<td>Use imagination</td>
</tr>
</tbody>
</table>

Information from Prof Alessandro Gomez, Yale University
The Bottom Line

Photo by Sarah Underhill