### Electrical Characteristics

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>BP 380</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Power (Pmax)</td>
<td>80W</td>
</tr>
<tr>
<td>Voltage at Pmax (Vmp)</td>
<td>17.6V</td>
</tr>
<tr>
<td>Current at Pmax (Imp)</td>
<td>4.55A</td>
</tr>
<tr>
<td>Warranted minimum Pmax</td>
<td>75W</td>
</tr>
<tr>
<td>Short-circuit current (Isc)</td>
<td>4.8A</td>
</tr>
<tr>
<td>Open-circuit voltage (Voc)</td>
<td>22.41V</td>
</tr>
<tr>
<td>Temperature coefficient of Isc</td>
<td>(0.065±0.015)%/° C</td>
</tr>
<tr>
<td>Temperature coefficient of Voc</td>
<td>-(80±10)mV/° C</td>
</tr>
<tr>
<td>Temperature coefficient of power</td>
<td>-(0.5±0.05)%/° C</td>
</tr>
<tr>
<td>NOCT</td>
<td>47±2ºC</td>
</tr>
<tr>
<td>Maximum series fuse rating</td>
<td>20A (U,H versions) 15A (S,L versions)</td>
</tr>
<tr>
<td>Maximum system voltage</td>
<td>600V (US, NEC &amp; IEC 61215 rating)</td>
</tr>
<tr>
<td></td>
<td>1000V (TUV Rheinland rating)</td>
</tr>
</tbody>
</table>
Portable Battery and Fuel Cell Technology Overview

Cheh, Huk Yuk

Samuel Ruben-Peter G. Viele Professor Emeritus of Electrochemistry Columbia University
Main Messages

• Definitions
• Battery Technology
  – Classification
  – Current R&D Trends
• Fuel Cell Technology
  – Clarification
  – Key Enabling Technologies
Definitions

**Battery and Fuel Cell:** Devices that convert chemical energy of materials into electrical energy

**Capacity (Ampere Hours):** The amount of electrical charge that is stored inside a battery or in a fuel container

**Energy (Watt Hours):** The amount of capacity a battery or fuel cell is able to provide at the voltage level the battery or fuel cell can support

**Power (Watts):** The rate at which the electrical energy is withdrawn from the battery or fuel cell
At first sight, the options for novel materials which determine the battery chemistry appear to be endless.
Electrochemical Energy Conversion

Batteries
- Primary
- Rechargeable

Fuel Cells
- Direct Hydrogen
- Direct Hydrocarbon
- Indirect Hydrogen
Battery Chemistry Criteria

- All materials for consumer batteries must pass key criteria to be successful

- Environmental Acceptability
- Safety
- Voltage Compatibility
- Performance
- Shelf Life
- Cost
Successful Consumer Batteries

- **PRIMARY**
  - Zinc Chloride
  - Alkaline
  - Zinc Nickel Oxyhydroxide
  - Lithium Manganese Dioxide
  - Zinc Air
  - Lithium Iron Disulfide
  - Zinc Silver Oxide

- **RECHARGEABLE**
  - Nickel Cadmium
  - Nickel Metal Hydride
  - Lithium Ion
  - Lithium Polymer
  - Lead Acid
Successful Battery Chemistries

Primary Chemistries

1.5 Volt
  - Round Cell
    - Zinc Chloride
    - Alkaline
    - Ni-Zn
    - Lithium FeS2
  - Button Cell
    - Zinc Air
    - Silver
    - Alkaline

3.0 Volt
  - Round
    - Li-MnO2
  - Button
    - Li-MnO2

1.5 Volt and 3.0 Volt are voltages measured across the terminals of the battery.
Successful Battery Chemistries

- **Rechargeable Chemistries**
  - **1.2 Volt**
    - Cylindrical Wound
    - Button
    - Prismatic
    - NiCd
  - **3.6 Volt**
    - Cylindrical Wound
    - Button
    - Prismatic
    - Lilon
    - Li Polymer
Energy and Power density: Cap-xx
### Energy Density

<table>
<thead>
<tr>
<th>Battery Type</th>
<th>Cell Voltage</th>
<th>Energy Density (Wh/liter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vented lead-acid</td>
<td>2.0V</td>
<td>25</td>
</tr>
<tr>
<td>Vented Ni-Cd</td>
<td>1.2V</td>
<td>27</td>
</tr>
<tr>
<td>VRLA</td>
<td>2.0V</td>
<td>54</td>
</tr>
<tr>
<td>Ni-MH</td>
<td>1.2V</td>
<td>135</td>
</tr>
<tr>
<td>Li-polymer</td>
<td>2.5V</td>
<td>117</td>
</tr>
<tr>
<td>Li-ion</td>
<td>3.6V</td>
<td>230</td>
</tr>
</tbody>
</table>
## High Power

<table>
<thead>
<tr>
<th></th>
<th>Ni-MH 100Ah</th>
<th>Li Ion HE-44Ah</th>
<th>Li Ion DM-30Ah</th>
<th>Li Ion HP-12Ah</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy</strong></td>
<td>133</td>
<td>308</td>
<td>220</td>
<td>150</td>
</tr>
<tr>
<td><strong>Power</strong></td>
<td>320</td>
<td>642</td>
<td>2100</td>
<td>2900</td>
</tr>
<tr>
<td><strong>Ratio</strong></td>
<td>2.4</td>
<td>2.1</td>
<td>9.5</td>
<td>19.3</td>
</tr>
</tbody>
</table>

*Energy Storage Association*
Cycling

Energy Storage Association
Discussion

• Lead-acid for cars vs for solar apps
• DoD vs life cycle
• Cost vs energy density and power density
from Vechy, Energysys

<table>
<thead>
<tr>
<th>Property</th>
<th>Lead Acid</th>
<th>Ni-Cd</th>
<th>Ni-MH</th>
<th>Li-Ion</th>
<th>Li Polymer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Density Wh/kg</td>
<td>40</td>
<td>50</td>
<td>80</td>
<td>125</td>
<td>110</td>
</tr>
<tr>
<td>Energy Density Wh/l</td>
<td>100</td>
<td>120</td>
<td>300</td>
<td>300</td>
<td>250</td>
</tr>
<tr>
<td>Cycle Life</td>
<td>800</td>
<td>1000</td>
<td>500</td>
<td>600</td>
<td>600</td>
</tr>
<tr>
<td>Power Density W/kg</td>
<td>400</td>
<td>300</td>
<td>300</td>
<td>300</td>
<td>100</td>
</tr>
<tr>
<td>Relative Cost Wh/$ (100 = Best)</td>
<td>100</td>
<td>40</td>
<td>25</td>
<td>20</td>
<td>15</td>
</tr>
<tr>
<td>Recycling Rating (100 = Best)</td>
<td>100</td>
<td>60</td>
<td>20</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Safety Rating (100 = Best)</td>
<td>100</td>
<td>60</td>
<td>65</td>
<td>20</td>
<td>20</td>
</tr>
</tbody>
</table>
Energy-Power Diagrams for Primary Battery Systems (AA Size)

For illustration only, data not current
Energy-Power Diagrams for Rechargeable Battery Systems (AA Size)

For illustration only, data not current
Bobbin Cell
Alkaline, ZnCl, Ni-Zn

Advantages:
- High Energy Content
- High Volume Manufacturing

Cell Design

- Anode Collector
- Anode
- Separator
- Cathode
- Cathode Collector
- Electrolyte
Wound Cell
LiMnO$_2$, LiFeS$_2$, NiMH, NiCd, Li Ion

Advantage:
- High Power
Cell Design

Button Cell
LiMnO₂, Zn Air, Zn/Ag₂O

Advantage:
- Small form factor
Cell Design

Prismatic
Li Ion, Li Polymer, NiMH, NiCd

Advantages:
- Energy Efficient
- Form Factor
- High Power
Fuel Cell Attributes

• High Theoretical Energy Content

• Fuel Replenishable

• Potentially, High Rate Capabilities
Portable Fuel Cell Chemistry

**Hydrogen / Oxygen Fuel Cell**

Anode: \[ 2H_2 + 4OH^- \rightarrow 4H_2O + 4e^- \]

Cathode: \[ O_2 + 2H_2O + 4e^- \rightarrow 4OH^- \]

Overall: \[ 2H_2 + O_2 \rightarrow 2H_2O \]

**Direct Methanol / Oxygen Fuel Cell**

Anode: \[ CH_3OH + H_2O \rightarrow CO_2 + 6H^+ + 6e^- \]

Cathode: \[ 1.5O_2 + 6H^+ + 6e^- \rightarrow 3H_2O \]

Overall: \[ CH_3OH + 1.5O_2 \rightarrow CO_2 + 2H_2O \]
H₂ Fuel Cell Requirements

• Reliable power
  – Robust operation vs. temperature, humidity conditions
  – Fast startup
  – Long lifetime
  – Orientation independent operation

• Miniature size
  – Enables total fuel cell system (stack/system and cartridge) to provide power and energy comparable or better than batteries

• Good consumer value
  – Against alternative power sources
H₂ Fuel Cartridge Requirements

• Long runtime
• Reliable
  – Orientation independent
  – Consistent fuel delivery vs. depth of discharge
  – Long shelf life
• Good consumer value
  – Against alternative power sources
• Convenient
  – Cartridge is disposable
Energy Generation

- **Hydrogen / Oxygen Fuel Cells**
  - Energy per mole of hydrogen = 65.9 WH (2 gm hydrogen)
  - Pressure for a 10cc vial containing 2 gm hydrogen = 2,446 atm

- **Direct Methanol / Oxygen Fuel Cells**
  - Energy per mole of methanol = 195 WH (32 gm methanol)
  - Energy in a 10cc vial of pure methanol = 48.15 WH
Runtime Considerations for Fuel

Fuel cells can give longer runtime than LiIon (especially in larger devices) if technical challenges are solved.

![Graph showing runtime considerations for fuel cells vs. LiIon](chart.png)
Status of Portable Hydrogen Fuel Cells

- Several organizations active in developing miniaturized H$_2$ fuel cell systems
  - Current status of power densities: 50 to 200 W/l for full system (includes stack and balance of plant; does not include fuel)

- Device classes that could use portable fuel cells:

<table>
<thead>
<tr>
<th></th>
<th>Nikon 3100 DCamera</th>
<th>Dell Axim PDA</th>
<th>Samsung i700 PIA</th>
<th>Portable DVD Player</th>
<th>Dell M50 Laptop</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Current battery volume</strong></td>
<td>22 cc</td>
<td>35 cc</td>
<td>39 cc (ext. pack)</td>
<td>100 cc</td>
<td>250 cc</td>
</tr>
<tr>
<td><strong>Average Power</strong></td>
<td>5 W</td>
<td>0.62 W</td>
<td>1.9 W</td>
<td>10 W</td>
<td>25 W (hybrid)</td>
</tr>
<tr>
<td><strong>Typical Energy</strong></td>
<td>7.5 Wh</td>
<td>5.0 Wh</td>
<td>7.4 Wh</td>
<td>25 Wh</td>
<td>66 Wh</td>
</tr>
<tr>
<td><strong>Methanol fuel cells?</strong></td>
<td>✗</td>
<td>✓</td>
<td>✓</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td><strong>Hydrogen fuel cells?</strong></td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>
Load-characteristics

![Graph showing efficiency vs. percentage of load for PEM fuel cell system, Diesel engine, and Otto engine.](image-url)
Key Enabling Technologies

• Hydrogen Storage Density
  - Technologies that enable high density storage and release of hydrogen fuel
  - Safe, convenient technologies - consumer use

• Methanol Crossover
  - Technologies that enable high MeOH concentrations without significant crossover/ degradation

• Catalysts Development
  - Dispersed noble metal systems
  - Transition metal / oxides

• Fluid Management Systems
  - Flow of fuel, water, CO2
Summary

- Hydrogen fuel cells are attractive for portable power
  - Could provide longer runtime, “instant recharge” power technology to some categories of consumer devices
- Successful commercialization will require advances in fuel cell stack/system technology, fuel storage and delivery
  - Stack/system power densities must increase to enable broad utilization in consumer devices
  - High power capable cartridge technology must be developed that provides safety, reliability and long runtime