Battery and Fuel Cell Development Goals for the Lunar Surface and Lander

Carolyn R. Mercer

Presented at the Space Power Workshop, April 23, 2008, Huntington Beach, California.

Abstract

NASA is planning a return to the moon and requires advances in energy storage technology for its planned lunar lander and lunar outpost. This presentation describes NASA’s overall mission goals and technical goals for batteries and fuel cells to support the mission. Goals are given for secondary batteries for the lander’s ascent stage and suits for extravehicular activity on the lunar surface, and for fuel cells for the lander’s descent stage and regenerative fuel cells for outpost power. An overall approach to meeting these goals is also presented.
Battery and Fuel Cell Development Goals for the Lunar Surface and Lander

Carolyn R. Mercer, Ph.D.
National Aeronautics and Space Administration

Space Power Workshop
April 23, 2008
Huntington Beach, California
This talk addresses energy storage for the Altair Lunar Lander, EVA Suit 2, and Lunar Surface Power systems.
Altair Lunar Lander

Ascent Module

Descent Module
Altair Lunar Lander

Preliminary information from “minimally functional” DAC1 design (zero fault tolerant)
Abort and contingency scenarios still to be addressed

• **Ascent Module and Airlock**
  – Single primary battery, LiMnO₂ chemistry, 14.2 kW-hr capacity
  – Secondary battery desirable to provide instantaneous power for ascent in case descent stage is ejected during abort; and to provide make-up power during shadow phase of TLI.

• **Descent Module**
  – PEM fuel cell, 5.5 kW peak production
  – Provides ascent and descent module power for LLO and surface operations
    • Orion provides 1.5 kW when docked
  – Propulsion residuals provide reactants for surface operations

Key mission requirements:
Human-safe, reliable operation; high energy density; architecture compatibility
Converting Constellation Architecture into Tech Development Goals
Example: Lunar Ascent Stage (nominal mission)

Mission requirements drive capacity, self-discharge rates, specific energy, and energy density technology development goals.
Lunar EVA Suit: “Configuration 2”

Greatly increased electronic capability (HDTV, communications node, displays, etc…) drives need for high energy batteries in small, low-mass package. Very high specific energy and energy density with 8-hour, human-safe operation drives technology development.

**Power / Communications, Avionics & Informatics (CAI):**
- Lithium Ion Batteries
- Cmd/Cntrl/Comm Info (C3I) Processing
- Expanded set of suit sensors
- Advanced Caution & Warning
- Displays and Productivity Enhancements

**Portable Life Support System (PLSS):**
- High Pressure GOX
- Suit Water Membrane Evaporator
- Rapid Cycle Amine
- Potable Water in PLSS Tank

**Preliminary Battery Requirements:**
- ~ 900 W-Hr energy, delivered
- ~ 100 W average and 175 W peak power
- Current mass allocation: 5 kg
- Current volume allocation: 1.6 liter
- 100 cycles (operation every other day for six months)

Power to support 8 hour EVA provided by battery in PLSS

Prioritized mission requirements:
- Human-safe operation; 8-hr duration;
- high specific energy; high energy-density.
Lunar Surface Systems

**Goal:** Continuous human presence on surface
Plan for polar site, but keep capability to go anywhere

- Modular power system
- ~20-40 kW lunar daytime power level
- ~10-20 kW lunar nighttime power level
- 5,000 hr operational life at poles
- >10,000 hr operational life beyond poles
- 5-10 year calendar life
- 100-1000+ discharge/recharge cycles
- Thermal, dust, launch/landing, vacuum environments
- Autonomous control and operation
- Human-rated
- Low mass and volume
- Little or no maintenance needs

**Potential Requirements**

**Energy Storage: Regenerative Fuel Cells**

- ~250 kWh\(_{\text{net}}\) energy storage module
  - Equals ~2 kW\(_{\text{net}}\) minimum fuel cell continuous power at Shackleton Crater
- ~36 cell fuel cell stacks,
  ~18 cell electrolyzer stacks
  - Based on ~30 Vdc bus voltage
- Cryogenic vs Gaseous reactant Storage

**Prioritized mission requirements:**
Reliable, long-duration maintenance-free operation; human-safe operation; architecture compatibility; high specific-energy; high system efficiency.
Converting Constellation Architecture into Tech Development Goals
Example: Surface Mobility Systems (nominal missions)

4 classes of rover missions:
- Short duration outpost traverse (Chariot)
- Long duration pressurized crewed sortie (Small Pressurized Habitat + Chariot)
- Long duration habitat transport (ATHLETE)
- Science/ISRU platforms

Power profiles differ for each, but each include some subset of the following functions:
- Pre-sortie vehicle check-out, transport to site(s), return transport, post-sortie checks and shutdown;
- Ingress/egress time for each EVA, boots-on-surface time, crew time in rover;
- Robotic lifting, connecting, emplacement, testing, processing.

Example: Short- and long-term pressurized rover

<table>
<thead>
<tr>
<th>Length of Sortie (days)</th>
<th>Sorties per year</th>
<th>Energy per sortie per rover (kW-hr)</th>
<th>Energy from Fuel Cell (per sortie, per rover) (kW-hr)</th>
<th>Energy from Battery (per sortie, per rover) (kW-hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>48</td>
<td>22</td>
<td>-</td>
<td>22</td>
</tr>
<tr>
<td>3</td>
<td>12</td>
<td>104</td>
<td>-</td>
<td>104</td>
</tr>
<tr>
<td>7</td>
<td>10</td>
<td>307</td>
<td>250</td>
<td>57</td>
</tr>
<tr>
<td>14</td>
<td>6</td>
<td>557</td>
<td>500</td>
<td>57</td>
</tr>
</tbody>
</table>


Human-safe operation; reliable, maintenance-free operation; architecture compatibility; high specific-energy.
RFC fuel-cell reactant tank Depth-of-Discharge over the course of a month for Electrolysis power = 2kW (blue), 2.375kW (red), and 3.7kW (green)

<table>
<thead>
<tr>
<th>Customer Need</th>
<th>Performance Parameter</th>
<th>State-of-the-Art</th>
<th>Current Value</th>
<th>Threshold Value</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safe, reliable operation</td>
<td>Electrolyte flammability</td>
<td>Controllers used to prevent unsafe conditions. There is no non-flammable electrolyte in SOA</td>
<td>Preliminary results indicate a moderate reduction in the performance with non-flammable additives</td>
<td>Non-flammable electrolyte that will minimize thermal runaway</td>
<td>Tolerant to mild abuse, overcharge and over-temperature</td>
</tr>
<tr>
<td>Specific energy</td>
<td>Battery-level specific energy*</td>
<td>90 Wh/kg at C/10 &amp; 30°C 83 Wh/kg at C/10 &amp; 0°C (MER rovers)</td>
<td>105 Wh/kg at C/10 &amp; 30°C 95 Wh/kg at C/10 &amp; 0°C</td>
<td>135 Wh/kg at C/10 &amp; 0°C &quot;High-Energy*** 150 Wh/kg at C/10 &amp; 0°C &quot;Ultra-High Energy&quot;***</td>
<td>150 Wh/kg at C/10 &amp; 0°C &quot;High energy&quot; 220 Wh/kg at C/10 &amp; 0°C &quot;Ultra-High Energy&quot;</td>
</tr>
<tr>
<td>Lander: 150 – 200 Wh/kg (14KWhr, 67 kg, 45L, 10 cycles)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rover: 150 – 200 Wh/kg</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EVA: 200 – 300 Wh/kg 100 cycles</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cell-level specific energy</td>
<td>130 Wh/kg at C/10 &amp; 30°C 118 Wh/kg at C/10 &amp; 0°C</td>
<td>150 Wh/kg at C/5 and 0°C</td>
<td>165 Wh/kg at C/10 &amp; 0°C &quot;High Energy&quot; 180 Wh/kg at C/10 &amp; 0°C &quot;Ultra-High Energy&quot;</td>
<td>180 Wh/kg at C/10 &amp; 0°C &quot;High energy&quot; 260 Wh/kg at C/10 &amp; 0°C &quot;Ultra-High Energy&quot;</td>
<td></td>
</tr>
<tr>
<td>Cathode-level specific capacity Li(Li,NiMn)O₂</td>
<td>140 – 150 mAh/g typical</td>
<td>Li(Li₀.₁₇Nι₀.₂₅Mι₀.₅₈)O₂: 240 mAh/g at C/10 &amp; 25°C Li(Li₀.₁₃Nι₀.₁₃Mι₀.₅₄Cι₀.₁₃)O₂: 250 mAh/g at C/10 &amp; 25°C 200 mAh/g at C/10 &amp; 0°C</td>
<td>260 mAh/g at C/10 &amp; 0°C</td>
<td>280 mAh/g at C/10 &amp; 0°C</td>
<td></td>
</tr>
<tr>
<td>Anode-level specific capacity</td>
<td>320 mAh/g MCMB 450 mAh/g Si composite</td>
<td></td>
<td>600 mAh/g at C/10 &amp; 0°C With Si composite</td>
<td>1000 mAh/g at C/10 0°C With Si composite</td>
<td></td>
</tr>
<tr>
<td>Energy density</td>
<td>Lander: TBD Rover: TBD EVA: ~400 Wh/l</td>
<td>Battery-level energy density</td>
<td>250 Wh/l</td>
<td>n/a</td>
<td>270 Wh/l &quot;High Energy&quot; 360 Wh/l &quot;Ultra-High&quot; 320 Wh/l &quot;High Energy&quot; 420 Wh/l &quot;Ultra-High&quot;</td>
</tr>
<tr>
<td>Battery-level energy density</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cell-level energy density</td>
<td>320 Wh/l</td>
<td>n/a</td>
<td>385 Wh/l &quot;High Energy&quot; 460 Wh/l &quot;Ultra-High&quot;</td>
<td>390 Wh/l &quot;High Energy&quot; 530 Wh/l &quot;Ultra-High&quot;</td>
<td></td>
</tr>
<tr>
<td>Operating environment</td>
<td>0°C to 30°C, Vacuum</td>
<td>Operating temperature</td>
<td>-20°C to +40°C</td>
<td>-50°C to +40°C for all carbonate- and ester-blend electrolytes in prototype cells</td>
<td>0°C to 30°C</td>
</tr>
</tbody>
</table>

Assumes prismatic cell packaging. Goal values assume lightweight battery construction.

* Battery values are assumed at 100% DOD, discharged at C/10 to 3,000 volts/cell, and at 0 degrees C operating conditions

** "High-Energy" = NASA-developed Li(Li,NMn)O2 cathode with MCMB graphite anode

"Ultra-High Energy" = NASA-developed Li(Li,NMn)O2 cathode with Silicon composite anode
Cell 1: Li(NMn)/MCMB-150 “High Energy”
Baseline for EVA and Rover
Lithiated-mixed-metal-oxide cathode / Graphite anode
Li(Li,NMn)O₂ / Commercial mesocarbon microbead
150 Wh/kg @ battery-level 0°C C/10, ~2000 cycles at 100% DOD

Cell 2: Li(NMn)/Si-220 “Ultra-High Energy”
Upgrade for EVA and Altair, possibly Rover
Lithiated-mixed-metal-oxide cathode / Silicon composite anode
Li(Li,NMn)O₂ / silicon composite
220 Wh/kg @ battery-level 0°C C/10, ~200 cycles 100% DOD

Cell 3: Li(NMC)/Si-160 (virtually no-cost option)
Lithiated-mixed-metal-oxide cathode / Silicon-composite anode
Commercial Li(Li,NMC) / Silicon composite anode
160 Wh/kg @ battery-level 0°C C/10, ~200 cycles 100% DOD

4/28/08
Proton Exchange Membrane Fuel Cell
Design Options

“Flow-Through”
Conventional design. Used widely in terrestrial applications because venting is required to purge non-O2 air constituents. Pump and separator are life-limiting elements of this design.

“Non-Flow-Through”
Membrane wicks water through; eliminates external pumps and separators. This design was used on the Gemini capsule.

Representative mass allocation for 3 kW fuel cell

<table>
<thead>
<tr>
<th></th>
<th>FT</th>
<th>NFT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stack</td>
<td>16 kg</td>
<td>13 kg</td>
</tr>
<tr>
<td>BOP</td>
<td>21 kg</td>
<td>9 kg</td>
</tr>
<tr>
<td>Total</td>
<td>37 kg</td>
<td>22 kg</td>
</tr>
</tbody>
</table>
### Key Performance Parameters for Fuel Cell Technology Development
**Derived Values Based on Customer Requirements**

<table>
<thead>
<tr>
<th>Customer Need</th>
<th>Performance Parameter</th>
<th>SOA (alkaline)</th>
<th>Current Value</th>
<th>Threshold Value</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lander: 3 kW for 220 hours continuous, 5 kW peak.</td>
<td>System power density @ nominal power (3 kW)</td>
<td>49 W/kg n/a</td>
<td>33 W/kg n/a</td>
<td>65 W/kg</td>
<td>88 W/kg</td>
</tr>
<tr>
<td></td>
<td>Flow-Through Fuel Cell</td>
<td>97 W/kg n/a</td>
<td>132 W/kg n/a</td>
<td>97 W/kg</td>
<td>107 W/kg</td>
</tr>
<tr>
<td></td>
<td>Non-Flow-Through Fuel Cell</td>
<td>n/a</td>
<td>n/a</td>
<td>30 kg</td>
<td>21 kg</td>
</tr>
<tr>
<td></td>
<td>RFC (without tanks)</td>
<td>n/a</td>
<td>n/a</td>
<td>30 kg</td>
<td>21 kg</td>
</tr>
<tr>
<td>Lunar Surface Systems: TBD kW for 15 days continuous</td>
<td>Stack power density @ nominal power (3 kW)</td>
<td>30 kg n/a</td>
<td>70%</td>
<td>71%</td>
<td>73%</td>
</tr>
<tr>
<td></td>
<td>Flow-Through Fuel Cell</td>
<td>n/a</td>
<td>70%</td>
<td>71%</td>
<td>73%</td>
</tr>
<tr>
<td></td>
<td>Non-Flow-Through Fuel Cell</td>
<td>n/a</td>
<td>67%</td>
<td>71%</td>
<td>73%</td>
</tr>
<tr>
<td>Rover: TBD</td>
<td>Balance-of-plant mass (3 kW system)</td>
<td>n/a</td>
<td>n/a</td>
<td>30 kg</td>
<td>21 kg</td>
</tr>
<tr>
<td><strong>Stack efficiency values assume 200 mA/cm² operation.</strong></td>
<td>Stack efficiency**</td>
<td>n/a</td>
<td>73%</td>
<td>71%</td>
<td>73%</td>
</tr>
<tr>
<td></td>
<td>Flow-Through Fuel Cell</td>
<td>n/a</td>
<td>70%</td>
<td>71%</td>
<td>73%</td>
</tr>
<tr>
<td></td>
<td>Non-Flow-Through Fuel Cell</td>
<td>n/a</td>
<td>67%</td>
<td>71%</td>
<td>73%</td>
</tr>
<tr>
<td></td>
<td>System efficiency</td>
<td>RFC</td>
<td>n/a</td>
<td>46%</td>
<td>56%</td>
</tr>
<tr>
<td>Maintenance-free lifetime Lander: 220 hours (primary) Surface: 10,000 hours (RFC)</td>
<td>Fuel cell system maintenance-free operating life</td>
<td>RFC</td>
<td>n/a</td>
<td>5,000 hrs</td>
<td>10,000 hrs</td>
</tr>
<tr>
<td></td>
<td>Flow-Through Fuel Cell</td>
<td>2500 hrs n/a</td>
<td>1000 hrs n/a</td>
<td>5,000 hrs</td>
<td>10,000 hrs</td>
</tr>
<tr>
<td></td>
<td>Non-Flow-Through Fuel Cell</td>
<td>n/a</td>
<td>n/a</td>
<td>5,000 hrs</td>
<td>10,000 hrs</td>
</tr>
</tbody>
</table>
## Constellation Program Summary Schedule
### Lunar Capability Content
### PMR ‘07 Baseline – 10/19/07

<table>
<thead>
<tr>
<th>Phase A/B</th>
<th>Phase C</th>
<th>Phase D</th>
<th>Level I</th>
<th>Level II-C</th>
<th>Level II-N</th>
<th>Level III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre Phase A</td>
<td>▲ 100% Complete</td>
<td>▲ 0% Complete</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Altair Lander
- **Unpressurized Rover**
- **SRR**
- **PDR**
- **CDR**

### EVA
- **(Suit 2 Config)**
- **SRR**
- **PDR**
- **CDR**

### EVA PLSS
- **(Suit 2 Config)**
- **SRR**
- **PDR**
- **CDR**

### Lunar Surface Systems

#### Batteries
- **High Energy**
  - **TRL4 Cell**
  - **TRL6 Cell**
  - **TRL 6 Battery: 150 Whr/kg at 0C, C/10, safe**

- **Ultra High Energy**
  - **TRL4 Cell**
  - **TRL6 Cell**
  - **TRL 6 Battery: 200 Whr/kg at 0C, C/10, safe**

#### Fuel Cells
- **Primary Fuel Cell**
  - **TRL5**
  - **TRL6 Primary Fuel Cell: 10,000 hrs**

- **Regenerative Fuel Cell**
  - **TRL5**
  - **TRL6 Regenerative Fuel Cell: 10,000 hours**
LAT-1 and LAT-2 identified regenerative fuel cells and rechargeable batteries as enabling technology, where enabling technologies are defined as having: "overwhelming agreement that the program cannot proceed without them."

**Surface Systems**

**Surface Power:**
- Maintenance-free operation of regenerative fuel cells for >10,000 hours using ~2000 psi electrolyzers.
- Power level TBD (2 kW modules for current architecture).
- Reliable, long-duration maintenance-free operation; human-safe operation; architecture compatibility; high specific-energy, high system efficiency.

**Mobility Systems:**
- Reliable, safe, secondary batteries and regenerative fuel cells in small mass/volume.
- 200 W-hr/kg assumed; 150 W-hr/kg may be sufficient.
- Human-safe operation; reliable, maintenance-free operation; architecture compatibility; high specific-energy.

**EVA**

- Portable Life Support System (PLSS); and Power, Communications, Avionics, and Informatics (PCAI) Subsystem:
- 200 – 300 W-hr/kg; ~400 Wh/liter
- Human-safe operation; 8-hr duration; high specific energy; high energy-density.

**Lunar Lander**

**Ascent Stage:**
- Rechargeable battery capability for ascent operations and to support emergency lander/surface operations. Nominally 14 kWh in 67 kg, 45 liter package.
- Human-safe, reliable operation; high energy-density.

**Descent Stage:**
- Functional primary fuel cell with 5.5 kW peak power.
- Human-safe reliable operation; high energy-density; architecture compatibility.
Acknowledgements

The following people contributed data, images, text and/or ideas to this presentation:

Michelle Manzo
Mark Hoberecht
Concha Reid
Tom Miller
Dave Hoffman
Joe Nainiger
Rob Button
Diane Linne
Diane Malarik