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Energy Storage Project
Final Report

Carolyn R. Mercer, Amy L. Jankovsky, Concha M. Reid, Thomas B. Miller, and Mark A. Hoberecht
Glenn Research Center, Cleveland, Ohio

January 2011
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Abstract

NASA’s Exploration Technology Development Program funded the Energy Storage Project to develop battery and fuel cell technology to meet the expected energy storage needs of the Constellation Program for human exploration. Technology needs were determined by architecture studies and risk assessments conducted by the Constellation Program, focused on a mission for a long-duration lunar outpost. Critical energy storage needs were identified as batteries for EVA suits, surface mobility systems, and a lander ascent stage; fuel cells for the lander and mobility systems; and a regenerative fuel cell for surface power. To address these needs, the Energy Storage Project developed advanced lithium-ion battery technology, targeting cell-level safety and very high specific energy and energy density. Key accomplishments include the development of silicon composite anodes, lithiated-mixed-metal-oxide cathodes, low-flammability electrolytes, and cell-incorporated safety devices that promise to substantially improve battery performance while providing a high level of safety. The project also developed “non-flow-through” proton-exchange-membrane fuel cell stacks. The primary advantage of this technology set is the reduction of ancillary parts in the balance-of-plant – fewer pumps, separators and related components should result in fewer failure modes and hence a higher probability of achieving very reliable operation, and reduced parasitic power losses enable smaller reactant tanks and therefore systems with lower mass and volume. Key accomplishments include the fabrication and testing of several robust, small-scale non-flow-through fuel cell stacks that have demonstrated proof-of-concept. This report summarizes the project’s goals, objectives, technical accomplishments, and risk assessments. A bibliography spanning the life of the project is also included.
Overview

- Project Goals and Objectives
- Summary of Accomplishments
  - Fuel Cells
    - Prior work in flow-through technology
    - Current work in non-flow-through technology
    - Predicted System Performance
  - Batteries
    - Components
    - Cells
    - Predicted System Performance
- Summary
- Bibliography

Energy Storage Technologies for Altair, EVA, and Lunar Surface Systems

Conceptual Lunar Outpost Surface Systems

- 10 kW Array (net)
- 2 kW Array (net)
- Power Support Unit (PSU) (Supports/scavenges from crewed landers)
- Logistics Pantry
- Habitation Element
- Habitation Element
- Common Airlock With Lander
- ISRU Oxygen Production Plant
- Unpressurized Rover
- ATHLETE Long-distance Mobility System (2)
- Small Pressurized Rover (SPR)
- PSU (Facilitates SPR docking & charging)
- Communication/Navigation
The Energy Storage Project’s objective is to reduce risks associated with the use of Lithium chemistry batteries, fuel cells, and regenerative fuel cells for Altair, Lunar Surface Systems, and EVA.

Our deliverables are:

- Primary fuel cell for Altair Descent Stage (TRL 6 by PDR)
- Regenerative fuel cell for LSS (TRL 6 after CDR)
- Rechargeable battery cells for Altair Ascent Stage, EVA Suit 2, and LSS EVA and Altair: TRL 6 cells by PDR; LSS: TRL 6 cells by PDR; All: cells early enough for batteries by CDR

We are addressing the top technology development needs for advanced energy storage:

- Human-rating and increased reliability
- Mass/volume reductions
- High performance components and systems

And we are performing systems analyses to ensure the right approaches are being pursued:

- Cost/benefit analyses based on Constellation mission architectures.

Mechanisms to determine Constellation Requirements:

- Cx Technology Prioritization Process
- Lunar Architecture Team reports
- Exploration Architecture Requirements Document
- Points-of-contact on Lander, Surface Systems, EVA, and Ares I/V projects

**Energy Storage Project**

**Documented Constellation Priorities**

<table>
<thead>
<tr>
<th>Documentation</th>
<th>Project</th>
<th>Criticality</th>
<th>Technology Need</th>
</tr>
</thead>
<tbody>
<tr>
<td>LAT-2 #MOB-5</td>
<td>Mobility</td>
<td>Enabling</td>
<td>High Specific-Energy-Density Power Systems – Need lightweight, long-life rechargeable batteries and need reliable micro-fuel cells to reduce mass of the power system by 30% - 50% to extend life of the power system components, and to reduce cost and frequency of maintenance.</td>
</tr>
<tr>
<td>LAT-2 #POW-1</td>
<td>Surface Systems</td>
<td>Enabling</td>
<td>High Specific-Energy-Density PEM Fuel Cell Systems – Need lightweight, long-life (10,000 hr) regenerative fuel cells, 200 psi electrolyzer, and water separators designed for 1/6 g environment to improve life/reliability, to increase mass to the lunar surface, and to reduce cost.</td>
</tr>
<tr>
<td>LAT-2 #EVA-3</td>
<td>EVA</td>
<td>Enabling</td>
<td>High Specific-Energy-Density EVA Suit PLSS Power – Need lightweight, high energy density rechargeable batteries and micro-fuel cells to increase usable mass to lunar surface, to increase EVA range and mission flexibility.</td>
</tr>
<tr>
<td>LSS TPP – Draft IRMA ID 2380</td>
<td>Surface Systems</td>
<td>Critical</td>
<td>Regenerative fuel cells – Meet energy storage requirements for up to 15 days (360 hours) or more (e.g., for a 20 kWe night time power requirement, this means an energy storage requirement of 7,200 kW-hrs of storage capacity (2 orders of magnitude greater than ISS)) Also highly desirable to have 5 year lifetime.</td>
</tr>
<tr>
<td>IRMA Risk ID 2527</td>
<td>EVA</td>
<td>SxS</td>
<td>Required specific energy not achievable with current batteries</td>
</tr>
<tr>
<td>Cx TPP 606</td>
<td>Surface Systems, Orion and LSS S4</td>
<td>Critical LS #2</td>
<td>Regenerative fuel cell for Lunar Surface Systems</td>
</tr>
<tr>
<td>Cx TPP 466</td>
<td>Lander</td>
<td>Critical LT #38</td>
<td>Low mass, highly reliable fuel cell for Lunar Lander power generation.</td>
</tr>
<tr>
<td>Cx TPP 465 IRMA Risk ID 4796</td>
<td>Lander</td>
<td>Critical LT #47</td>
<td>Low mass rechargeable battery to power the Lunar Lander ascent module during ascent from the lunar surface.</td>
</tr>
<tr>
<td>Cx TPP 544</td>
<td>EVA</td>
<td>Critical LT #12</td>
<td>EVA Suit power</td>
</tr>
<tr>
<td>Cx TPP 661</td>
<td>Surface Systems</td>
<td>Highly Desirable LS #11</td>
<td>High specific energy power for Lunar Rovers</td>
</tr>
<tr>
<td>Area V Risk #2366 Cx TPP 525</td>
<td>Area I/V</td>
<td>SxS Critical LT #16</td>
<td>Solid Rocket Booster Thrust Vector Control Power Source require high power, primary batteries</td>
</tr>
</tbody>
</table>
### Energy Storage Technology Development
#### Mission Requirements Assessment

Lunar Architecture Studies 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 hr 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 desired; 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:

- Human-safe operation; 8-hr duration; high specific energy; high energy-density.

**Lander**

**Ascent Stage:** Rechargeable battery capability for ascent operations and to support emergency lander/surface operations. Nominally 14 kWhr 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 (operate on residual propellants).

### Fuel Cell Systems

- **Goals**
- **Approach**
- **Technology Development**
- **Predicted System Level Performance**
### Summary of Fuel Cell and Regenerative Fuel Cell Technology Development since 2006

#### Flow-Through Fuel Cell Stack Development (Work stopped)
- 13,500 hr of MEA testing complete, passing 10,000 hr life goal through use of Pt-black catalysts
- System characterized, strengths and weaknesses documented

#### Component Development
- Passive components for Flow-Through Balance-of-Plant (Work stopped)
  - Water/gas separators, injectors/ejectors, regulators
  - Devices characterized, strengths and weaknesses documented
- Passive thermal management (Work stopped)
  - Pyrolytic graphite cooling plates and flat plate heat pipes
  - Tested in Flow-Through and Non-Flow-Through fuel cell stacks, respectively
  - Temperature distribution across any single plate and from plate-to-plate stays within 2-3 °C
  - Devices characterized, strengths and weaknesses documented
- MEAs for fuel cells (Work continues)
  - JPL MEAs supplied to Teledyne, Infinity, and Proton
  - 0.89 V at 200 mA/cm² exceeds the performance of vendor cells substantially
  - Work continues
- MEAs for high pressure electrolyzers (Work continues)
  - JPL MEAs supplied to Hamilton Sundstrand
  - Work continues

#### High Pressure Electrolysis (Work continues only under SBIR)
- Hamilton-Sundstrand system modified for high pressure operation; tested at JPL
- Novel concepts under study via SBIR (vapor feed, passive liquid feed)

#### Non-Flow-Through Fuel Cell Stack Development (Work continues)
- Water removal mechanism and advanced manufacturing process brought to TRL 4
- Electrochemical hydrogen pump implemented to provide low-power purge and inert concentration

#### Unitized Regenerative Fuel Cell System (Work stopped)
- System characterized, strengths and weaknesses documented

---

### Key Performance Parameters for Fuel Cell Technology Development

<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** (@ 3 kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Altair: 3 kW for 220 hr continuous, 5.5 kW peak</td>
<td>System power density Fuel Cell RFC (without tanks)</td>
<td>49 W/kg n/a</td>
<td>44 W/kg n/a</td>
<td>88 W/kg 25 W/kg</td>
<td>136 W/kg 36 W/kg</td>
</tr>
<tr>
<td></td>
<td>Fuel Cell Stack power density n/a</td>
<td>51 W/kg</td>
<td>107 W/kg</td>
<td>231 W/kg</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fuel Cell Balance-of-plant mass n/a</td>
<td>2 kg</td>
<td>21 kg</td>
<td>9 kg</td>
<td></td>
</tr>
<tr>
<td>Lunar Surface Systems: TBD kW for 15 days continuous operation</td>
<td>MEA efficiency @ 200 mA/cm² For Fuel Cell Individual cell voltage</td>
<td>73% 0.90 V</td>
<td>72% 0.89 V</td>
<td>73% 0.90 V</td>
<td>75% 0.92 V</td>
</tr>
<tr>
<td></td>
<td>For Electrolysis Individual cell voltage</td>
<td>n/a 1.48</td>
<td>n/a 1.46</td>
<td>n/a 1.44</td>
<td></td>
</tr>
<tr>
<td></td>
<td>For RFC (Round Trip)</td>
<td>n/a 60%</td>
<td>n/a 62%</td>
<td>n/a 64%</td>
<td></td>
</tr>
<tr>
<td>Rover: TBD</td>
<td>System efficiency @ 200 mA/cm² Fuel Cell</td>
<td>71% 64%</td>
<td>71% 64%</td>
<td>74% 64%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Parasitic penalty</td>
<td>2% 8%</td>
<td>2% 8%</td>
<td>1% 8%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Regenerative Fuel Cell*** Parasitic penalty</td>
<td>n/a n/a</td>
<td>n/a n/a</td>
<td>n/a n/a</td>
<td></td>
</tr>
<tr>
<td></td>
<td>High Pressure penalty</td>
<td>n/a n/a</td>
<td>n/a n/a</td>
<td>n/a n/a</td>
<td></td>
</tr>
</tbody>
</table>

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<table>
<thead>
<tr>
<th>Maintenance-free lifetime</th>
<th>Maintenance-free operating life</th>
</tr>
</thead>
<tbody>
<tr>
<td>Altair: 220 hr (primary)</td>
<td>Fuel Cell MEA 2500 hr 13,500 hr</td>
</tr>
<tr>
<td>Surface: 10,000 hr (RFC)</td>
<td>Electroylsis MEA n/a n/a</td>
</tr>
<tr>
<td></td>
<td>Fuel Cell System (for Altair) 2500 hr 13,500 hr 10,000 hr</td>
</tr>
<tr>
<td></td>
<td>Regenerative Fuel Cell System n/a n/a 5,000 hr 10,000 hr</td>
</tr>
</tbody>
</table>

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*Based on non-flow-through test hardware with 4-cells and heavy end plates, scaled to 3 kW

**Threshold and Goal values based on full-scale (3 kW, 300 cm²) fuel cell and RFC technology.

***Includes high pressure penalty on electrolysis efficiency 2000 psi
3.2.1 Flow-Through Primary PEMFC Development

**Key Accomplishment:**
- Initiated testing of Teledyne multi-kW flow-through PEMFC breadboard system
- Achieved several hundred hours of testing through multiple simulated Shuttle load profiles

**Significance:**
- Passive reactant recirculation and water separator components replace active components; reduced mass and volume, lower parasitic power, increased reliability, longer life
  - Initial performance testing has identified limitations and control issues with reactant recirculation system using ejectors and solenoid valves
  - Initial testing has shown performance of membrane water separators to be comparable to active water separators
- Successfully passed 10,000 hr life goal through use of Pt-black catalysts on MEA (13,500 hr)
- Establishes the basis for all future MEA advancements

---

**FC Recent Accomplishments: GRC Passive Water/Gas Separators**
*Reduce Mass and Parasitic Power Without Compromising Performance*

<table>
<thead>
<tr>
<th>Water/Gas Separators</th>
<th>Passive Water/Gas Separators: no performance degradation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Active</strong></td>
<td><strong>Passive</strong></td>
</tr>
<tr>
<td>5.67 kg each</td>
<td>0.45 kg each</td>
</tr>
<tr>
<td>100 W parasitic loss each</td>
<td>0 W parasitic loss each</td>
</tr>
<tr>
<td>11 kg</td>
<td>1 kg</td>
</tr>
<tr>
<td>200 W</td>
<td>0 W</td>
</tr>
</tbody>
</table>

---

**Flow Resistance Design Target:**
- 13.8 inches of water at 20 slpm

**Flow Resistance Performance:**
- 2.3 inches of water at 50 slpm

---

**NASA MEA Life Testing - September 2004 to July 2006**

**Cell Voltage and Current Density vs. Time**

**Teledyne multi-kW flow-through PEMFC Breadboard**
**Flow-Through Primary PEMFC Development**

**Key Accomplishment/Deliverable/Milestone:**
- Completed testing of GRC membrane water separator
- Accepted delivery of Lockheed meniscus water separator

**Significance:**
- Passive water separators replace active mechanical water separators; reduced mass and volume, lower parasitic power, increased reliability, longer life
  - Testing has shown performance of GRC membrane water separator to be comparable to active water separators
  - Initial assessment of Lockheed meniscus water separator is not promising because of gravity dependency
  - Initial assessment of Texas A&M gas-driven vortex water separator is not promising because of insufficient momentum for consistent operation

---

**Flow-Through Primary PEMFC Development**

**Key Accomplishment/Deliverable/Milestone:**
- Completed initial assessment of combined reactant recirculation and water separator concepts at NASA JSC/Texas A&M

**Significance:**
- Passive reactant recirculation and water separator components replace active components; reduced mass and volume, lower parasitic power, increased reliability, longer life
  - Initial testing has shown performance of Tescom integrated ejector/pressure regulator to be comparable to active pumps
  - Initial testing has shown performance of two-stage membrane contactor and de-bubbler (both tubular) to be comparable to active water separators
  - Initial testing has shown gas-driven vortex separator to lack sufficient momentum for consistent operation
  - Initial testing has shown liquid-driven vortex separator connected to pumped coolant loop to be comparable to active water separators
Recent Accomplishments: Fuel Cells

**Key accomplishment:** Completed fab of passive cooling plates for Teledyne and Infinity short stacks

**Significance:** Passive cooling plates replace active pumped-liquid cooling loop; reduced mass and volume, lower parasitic power, increased reliability, longer life

- Testing has shown pyrolytic graphite cooling plates to have 4x the conductivity of copper
- Testing has shown flat-plate heat pipes to have 30-40x the conductivity of copper

### Conventional Fuel Cell with Pumped Loop Thermal Management

- Fuel Cell Stack
- Heater
- Bypass Valve
- Pump
- Accumulator

### Fuel Cell with Passive Thermal Management

- Fuel Cell Stack
- Thermostat Valve

---

**Recent Accomplishments:** Passive Cooling Reduces System Mass and Complexity Without Degrading Performance (1/2)

- Four Graphite Cooling Plates slid into the HX Interface Plate & Cooling Channel. Pad heaters simulate FC heat.

- Exploded View Showing Graphite Cooling Plates & HX Interface Plate

- Temperature Distribution Across Pyrolytic Graphite Cooling Plates In 6-Cell Sub-kW Flow-Through Stack

- Testing shows the temperature distribution across any single plate and from plate-to-plate stays within 2-3 °C which is very acceptable.

- Temperature control uses a thermostatic valve to modulate the cooling flow through the HX.

### Thermal Conductivity Tests in VF-15

- Heat Pipes and Pyrolytic Graphite have high enough thermal conductivity to be acceptable lightweight cooling plates for fuel cells while copper does not.

### Testing has shown flat-plate heat pipes to have 30-40x the conductivity of copper

---

**Recent Accomplishments:** Passive Cooling Reduces System Mass and Complexity Without Degrading Performance (2/2)

- Simulated fuel cell stack testing with identical graphite cooling plates underway at GRC.

The graphite cooling plates, HX Interface Plate, and HX Cooling Channel have been fabricated and delivered to Teledyne Energy Systems for integration into a 6-cell Flow-Through Stack.

The 6-Cell fuel cell stack has been fully assembled. The integrated FC stack is to be tested at Teledyne in August 2008.
Recent Accomplishments:
Passive Cooling (2/2)

- The Ti heat pipes have been fabricated and tested at GRC. Their thermal conductivity ranged from 3500 to 6300 w-m/K. (copper is 400 w-m/K)
- The Ti heat pipes were delivered to Infinity Fuel Cells for integration into the non-flow-through stack
- The HX Interface plate hardware has been fabricated and will be delivered to Infinity for final stack assembly
- The integrated FC stack is to be delivered to GRC by Fall 2008 for testing.
- Preparations are being made for this testing to occur in the GRC Bldg 309 Fuel Cell Laboratory

Milestone Accomplishment:
MEA Testing Shows Substantial Improvement Over SOA

Single Cell Polarization Curves (as measured)

Jet Propulsion Laboratory
Nafion 115
4.0 mg/cm² Ptunsupported cathode
~65% RH @ inlet
70 °C
300 kPaabs H2/O2
Narayan et al, STAIF 2007

Nafion 111
0.5 mg/cm² Pt-supported cathode
60% RH @ inlet
82 °C
100 kPaabs H2/O2

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Membrane Electrode Assembly Accomplishments:
MEA Performance Exceeds Minimum Success Criteria

- NASA fuel cell and electrolysis MEA performance exceeds best performance of industry vendors
  - JPL MEAs supplied to Teledyne, Infinity, and Proton Energy

JPL MEAs performing at 0.89 V at 200 mA/cm² exceed the performance of Vendor cells substantially.

Comparison of JPL’s best iridium-doped ruthenium with the latest vendor supplied MEA shows substantially better (30 mV) performance by the NASA material.

**Membrane Electrode Assembly Accomplishments:**

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Comparison of JPL’s best iridium-doped ruthenium with the latest vendor supplied MEA shows substantially better (30 mV) performance by the NASA material.

**Key Accomplishment:**
- JPL-developed MEA 86% efficient at 1.48 V
- Hamilton Sundstrand modified existing International Space Station electrolyzer (liquid-feed) for high-pressure operation.
- Testing at JPL showed good voltage performance to 2000 psi H₂ and 1000 psi O₂ with Nafion MEA.

**Significance:**
- Advanced electrolysis MEAs will deliver more H₂ and O₂ gases with less electrical power input, reducing the required size of a solar array for a regenerative fuel cell system.
- Balanced high-pressure operation permits operation within an architecture having smaller tanks, reducing launch mass and volume requirements.

**Future Work:**
- Vapor-feed and passive liquid-feed electrolyzers are being investigated to reduce the significant parasitic power draw of the pumps and water/gas separators required for liquid feed systems.

**Objective:**
Develop balanced high-pressure (≥ 2,000 psi) electrolysis technology for Exploration missions.
Incorporate advanced membrane-electrode-assemblies (MEAs) with better electrical performance into high-pressure electrolyzers.

**High-pressure electrolyzer in test stand**

83 cm² MEA with platinum-black catalyst on hydrogen side and iridium oxide catalyst on oxygen side

**Partners:** Hamilton Sundstrand, NASA

**MEA and Electrolysis Technology: Recent Progress**

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**High-pressure electrolyzer in test stand**

83 cm² MEA with platinum-black catalyst on hydrogen side and iridium oxide catalyst on oxygen side
**Background:**
Flow-Through PEMFC technology is characterized by recirculating reactants and external product water separation

- Recirculation requires pumps or injectors/ejectors
- Water separation requires motorized centrifugal separators or passive membrane separators

Non-flow-through PEMFC technology is characterized by dead-ended reactants and internal product water removal

- Tank pressure drives reactant feed; no recirculation
- Water separation occurs through internal cell wicking

**Selection:**
Non-flow-through PEM fuel cell technology selected for further development

**Justification:**
Flow-through PEMFC technology is at a higher TRL, but non-flow-through technology offers advantages in efficiency, weight, volume, parasitic power, reliability, life, and cost.

### 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>

**Recent Accomplishments:**
Non-Flow-Through System Testing Begun

Non-flow-through PEMFC technology is characterized by dead-ended reactants and internal product water removal

- Tank pressure drives reactant feed; no recirculation required
- Water separation occurs through internal cell wicking

Components eliminated in NFT system include:

- Pumps or injectors/ejectors for recirculation [X]
- Motorized centrifugal separators or passive membrane separators for water separation [X]

**Packaging Concept for Non-Flow-Through System**

50 cm² Lab Stack #1
Integrated with Balance-of-Plant

derivative of Gemini fuel cell technology
Non-Flow-Through Primary PEMFC Development

**Key Accomplishment/Deliverable/Milestone:**
- Completed testing of non-flow-through PEMFC single cell at Phase II SBIR contractor infinity technologies
- Completed 3D modeling of balance-of-plant components at NASA GRC

**Significance:**
- Successful steady-state operation in dead-ended mode demonstrated; achieved current densities > 1,000 mA/cm²
- Establishes the basis for future non-flow-through technology advancements
- All ancillary components can be mounted on circuit boards attached to stack end plates, significantly reducing mass and volume of non-flow-through PEMFC systems

![Infinity Single Cell Test Article](image1)

---

WBS 3.2.2 Balance of Plant and System Testing
MS 3.2.2-1 Lab Stack #1 System Testing Complete

**Objective:**
Develop non-flow-through fuel cell technology at baseline stack vendor Infinity Fuel Cells and Hydrogen, Inc. for Exploration missions. Integrate Infinity Lab Stack #1 (4-cell, 50 cm²) with a GRC-developed balance-of-plant and conduct performance evaluation testing at GRC.

**Key Accomplishment/Deliverable/Milestone:**
- Partners: Infinity Fuel Cell and Hydrogen, GRC
- 11/30/08 – Infinity Lab Stack #1 System Testing Complete
- The fabrication and testing of this small-area (50 cm²) short-stack (4 cells) using JPL MEAs with a GRC-developed balance-of-plant is one of several non-flow-through fuel cell system tests used to evaluate the performance of a stack integrated with a balance-of-plant.

**Significance:**
- The milestone represents the first successful testing at the system level of a non-flow-through fuel cell stack integrated with a balance-of-plant.

![Shown: Infinity Lab Stack #1 integrated with GRC balance-of-plant](image2)
Objective:
Develop non-flow-through fuel cell technology at baseline stack vendor Infinity Fuel Cells and Hydrogen, Inc. for Exploration missions. Incorporate GRC-developed passive flat-plate heat pipe technology and JPL-developed membrane-electrode-assembly (MEA) technology into Infinity fuel cell stacks for performance evaluation.

Key Accomplishment/Deliverable/Milestone:
- Partner: Infinity Fuel Cell and Hydrogen
- 4/30/09 – Lab Stack #2 Unit Delivery from Infinity to GRC
- This small-area (50 cm²) short-stack (4 cells) delivery is one of several stack deliveries used to evaluate the development progress of non-flow-through fuel cell technology from baseline fuel cell vendor Infinity Fuel Cells and Hydrogen, Inc. This stack also incorporates NASA-developed technology in the form of passive flat-plate heat pipes (GRC) and advanced MEAs (JPL).

Significance:
- Passive flat-plate heat pipes are an alternative to pumped-liquid cooling loops in fuel cells, and offer the potential of better heat transfer, higher reliability, and lower parasitic power.
- Advanced fuel cell MEAs with better electrical performance will deliver more power from a fixed quantity of hydrogen and oxygen reactants.

Energy Storage Project Recent Accomplishments:
Integrated Balance-of-Plant Components for Fuel Cells

- Integrated balance-of-plant demonstrated in conjunction with the laboratory scale fuel cell stacks
- During this testing, the balance-of-plant ran on a battery source consuming less than 10 W of parasitic power to operate the fuel cell system
- A full-scale (3-kW fuel cell system) balance-of-plant will likely operate on less than 50 W of parasitic power (same number of components, but some components larger)
- A 2-12 kW flow-thru fuel cell system tested at GRC required several hundred watts of parasitic power during operation
- That difference in parasitic power means that Altair would need almost 100 kg less reactants over the course of its 2-3 week mission using a non-flow-through fuel cell system versus a flow-through system
Milestone Accomplishments

3.2.1.1-2 Lab Stack #3 Unit Delivery
3.2.2.2-4 BOP for Lab Stack #3 Complete
3.2.2.2-5 Lab Stack #3 System Testing Complete
3.5-1 Lab Stack #3 MEA Delivery

Objective:
Develop non-flow-through fuel cell technology at baseline stack vendor Infinity Fuel Cells and Hydrogen, Inc. for Exploration missions. Incorporate advanced membrane-electrode-assemblies (MEAs) with better electrical performance into fuel cell stacks. Integrate Infinity Lab Stack #3 (4-cell, 50 cm²) with a GRC-developed balance-of-plant and conduct performance evaluation testing at GRC.

Key Accomplishment/Deliverable/Milestone:
• Partners: Infinity Fuel Cell and Hydrogen, JPL, GRC
• 3/25/09 – Lab Stack #3 MEA Delivery from JPL to Infinity
• 3/31/09 – Lab Stack #3 Unit Delivery from Infinity to GRC
• 3/31/09 – Balance-of-Plant for Lab Stack #3 Complete
• 4/30/09 – Infinity Lab Stack #3 Testing Complete
• The fabrication and testing of this small-area (50 cm²) short-stack (4 cells) using JPL MEAs with a GRC-developed balance-of-plant is one of several non-flow-through fuel cell system tests used to evaluate the performance of a stack integrated with a balance-of-plant.

Significance:
• System testing of Lab Stack #3 revealed several additional stack design modifications and balance-of-plant procedure adjustments which are both needed to resolve system performance deficiencies.
• These changes will be implemented in subsequent hardware builds and evaluated through additional testing.

Non-Flow-Through Fuel Cell Technology: Recent Progress

Objective:
Generate data showing performance of a non-flow-through fuel cell stack having a full-size active area.

Key Accomplishments:
• Delivery of 4-cell, 150 cm² non-flow-through fuel cell stack incorporating advanced manufacturing process.
• First successful continuous testing of a non-flow-through fuel cell for 100 hr.
• Test data showed successful operation, with performance exceeding all prior small area stacks.
• Innovative Hydrogen Pump used to increase operation time between purges

Significance:
• Demonstrates the feasibility of non-flow-through fuel cell technology for Exploration missions
• Eliminates a substantial program risk associated with scale-up of non-flow-through fuel cell technology from a laboratory size to the final flight hardware active area.
• Validates the decision to develop non-flow-through fuel cell technology over the previous flow-through technology.
• The 150 cm² cell size is optimum for full-size stacks anticipated for 120 VDC Exploration applications such as Altair and Lunar Surface Systems.

Future Work:
• Build ¼-scale breadboard, then 3-kW Engineering Model
• Build non-flow-through fuel cell stack under test
• Schematic image of future 3 kW non-flow-through fuel cell stack

Partners: Infinity Fuel Cell and Hydrogen, NASA
Non-Flow-Through Fuel Cell: Common Test Bed

- Configurable to test stacks provided by multiple vendors
- Capable of testing total output power of 1 kWe
- Capable of testing stacks up to 40 cells
- Capable of conducting un-attended life testing
- Developed and built using COTS hardware

Infinity Non-Flow-Through Fuel Cell Stack Progression
Fuel Cell Technology Progression to Simpler Balance-of-Plant

PEMFC System Comparison (cont'd)

1-kW Flow-Through PEMFC System

3-kW Non-Flow-Through PEMFC System (mock-up)
Fuel Cell Predicted Performance

- Test data shows that even with existing heavy endplates, power density of current hardware nearly matches that of SOA Shuttle alkaline flight hardware:
  - 59 kg non-flow-through stack (endplates 17 kg) + 10 kg BoP @ 3 kW = 44 W/kg
  - SOA Shuttle alkaline @ 6 kW = 49 W/kg

- Note: KPP threshold and goal power density values are based on 300 cm$^2$ hardware (for 30 V systems), which is more mass efficient than smaller 150 cm$^2$ hardware (for 120 V systems). Our current expectations for 3 kW performance are based on test results from 4-cell stacks, and assume a 4-screen design, 4 kg lightweight endplates, and a 10 kg BoP. The expected 3 kW performance ranges from:
  - 66 W/kg for the stack and 54 W/kg for the system, assuming a 4-chamber cell (separate cavities for coolant and product water); to
  - 125 W/kg for the stack and 88 W/kg for the system, assuming a 3-chamber cell (combined water/coolant cavity) and additional mass optimization.

- Next steps are to build successively taller stacks to move toward 1/4 scale breadboard (40 cells, 1 kW, 150 cm$^2$) while retaining the excellent power density

- Voltage, lifetime, and some mass KPP’s not specifically addressed in current fiscal year
  - Optimization for voltage not in current year scope, although some conductive coatings will be investigated
  - Lifetime testing not in current year scope
  - Mass optimization not in current year scope, although replacing metallic porous plate with Supor membrane for mass reduction will be investigated

WBS 3.2.1.2 Alternative Stacks
Milestone 3.2.1.2-1 SBIR Stack Delivery

Objective:
Develop non-flow-through fuel cell technology at alternative stack vendor ElectroChem, Inc. for Exploration missions. Integrate this ElectroChem stack with a GRC-developed balance-of-plant and deliver to JSC for performance evaluation testing.

Key Accomplishment/Deliverable/Milestone:
- Partners: ElectroChem, GRC, JSC
- 4/30/09 – ElectroChem Alternative Stack Delivery to GRC
- This small-area (50 cm$^2$) short-stack (4 cells) delivery will be used to evaluate the development progress of non-flow-through fuel cell technology from alternative fuel cell vendor ElectroChem, Inc.

Significance:
- Several fuel cell stack vendors are developing non-flow-through fuel cell technology as an alternative to the baseline stack technology under development. This approach increases competition and reduces risk.

Shown: ElectroChem alternative non-flow-through fuel cell stack (4-cell short stack)
3.4 Regenerative Fuel Cell Technology Development

Key Accomplishment/Deliverable/Milestone:
• Completed testing of single-cell unitized regenerative fuel cell (URFC) system in NASA GRC test facility
• Accepted delivery of 10-cell URFC stack from Proton Energy Systems

Significance:
• URFC performs both fuel cell and electrolysis functions in a single stack; reduced RFC stack mass and volume, but higher system mass and volume due to lower efficiency in both fuel cell and electrolysis operating modes

Plans for FY’08 and beyond:
• Conduct performance testing of 10-cell URFC system in NASA GRC test facility
• Perform study/design of reactant management integration hardware required for RFC system with separate fuel cell and electrolysis stacks

Batteries

• Goals
• Approach
• Component Development
• Cell Development
• Predicted Cell Level Performance
### Key Performance Parameters for Battery Technology Development

<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>No fire or flame</td>
<td>Instrumentation controls used to prevent unsafe conditions. There is no non-flammable electrolyte in SSO</td>
<td>Preliminary results indicate a small reduction in performance using safer electrolytes and cathode coatings</td>
<td>Tolerant to electrical and thermal abuse such as over-temperature, over-charge, reversal, and short circuits with no fire or flame***</td>
<td>Tolerant to electrical and thermal abuse such as over-temperature, over-charge, reversal, and short circuits with no fire or flame***</td>
</tr>
</tbody>
</table>

### Specific Energy

<table>
<thead>
<tr>
<th>Battery-level specific energy* (Wh/kg)</th>
<th>Lander: 150-210 Wh/kg</th>
<th>Rover: TBD Wh/kg</th>
<th>EVA: 220 Wh/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery-level specific energy (Wh/kg)</td>
<td>90 Wh/kg at C/10 &amp; 30 °C (MEV rovers)</td>
<td>100 Wh/kg at C/10 &amp; 0 °C (MER rovers)</td>
<td>118 Wh/kg at C/10 &amp; 0 °C</td>
</tr>
<tr>
<td>Cell-level specific energy (Wh/kg)</td>
<td>130 Wh/kg at C/10 &amp; 30 °C</td>
<td>195 Wh/kg at C/10 &amp; 23 °C (HE)</td>
<td>212 Wh/kg at C/10 &amp; 23 °C (UHE)</td>
</tr>
<tr>
<td>Cathode-level specific capacity (mAh/g)</td>
<td>180 mAh/g</td>
<td>252 mAh/g at C/10 &amp; 25 °C</td>
<td>300 mAh/g at C/10 &amp; 0 °C</td>
</tr>
<tr>
<td>Anode-level specific capacity (mAh/g)</td>
<td>280 mAh/g (MOMB)</td>
<td>330 @ C/10 &amp; 0 °C</td>
<td>400 mAh/g at C/10 &amp; 0 °C</td>
</tr>
</tbody>
</table>

### Energy Density

<table>
<thead>
<tr>
<th>Battery-level energy density</th>
<th>Lander: 235 Wh/l</th>
<th>Rover: TBD Wh/l</th>
<th>EVA: 330 Wh/l</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell-level energy density</td>
<td>250 Wh/l</td>
<td>300 Wh/l</td>
<td>360 Wh/l</td>
</tr>
</tbody>
</table>

### Operating Environment

<table>
<thead>
<tr>
<th>Operating Temperature</th>
<th>0 to 30 °C, Vacuum</th>
<th>0 to 30 °C, Vacuum</th>
<th>0 to 30 °C, Vacuum</th>
</tr>
</thead>
</table>

Assumes prismatic cell packaging for threshold values. Goal values include lightweight battery packaging. * Battery values are assumed at 100% DOD, discharged at C/10 to 3.0 V/cell, and at 0 °C operating conditions. ** “High-Energy” = mixed metal oxide cathode with graphite anode. *** “Ultra-High Energy” = mixed metal oxide cathode with Silicon composite anode.

### Energy Storage Project Cell Development for Batteries

**High Energy** Cell
Baseline for EVA and Rover
Li(NiMnCo)O₂/Conventional carbonaceous anode
150 Wh/kg (100% DOD) @ battery-level 0 °C C/10
80% capacity retention at ~ 2000 cycles

**Ultra-High Energy** Cell
Upgrade for EVA and Altair, possibly Rover
Li(NiMnCo)O₂/Silicon composite
220 Wh/kg (100% DOD) @ battery-level 0 °C C/10
80% capacity retention at ~ 200 cycles

Revised 4/8/10
## Lithium-Ion Battery Master Schedule

<table>
<thead>
<tr>
<th>FY09</th>
<th>FY10</th>
<th>FY11</th>
<th>FY12</th>
<th>FY13</th>
<th>FY14</th>
<th>FY15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
<td>H1</td>
<td>H2</td>
<td>H1</td>
</tr>
</tbody>
</table>

**Component Development**

- Screen, scale-up, cell design
- Scale-up and Cell Build
- Integrated Component Down-select
- NASA TRL 5/6 Testing
- High Energy Battery
- Environment Testing Complete
- Lightweight Cell A
- Lightweight testing of Li-ion cells

## Lithium-Ion Battery Technology Development

### Advanced Cell Components

- **Nano-particle based circuit breaker**
- **Silicon nano-particles alloy with Li during charge, lose Li ions during discharge**
  - Offers dramatically improved capacity over carbon standard

- **Advanced electrolyte with additives** provides flame-retardance and stability at high voltages without sacrificing performance. Example: LiPF$_6$ in EC+EMC+TPP+VC

- **Providing Ultra High Specific Energy**
  - Silicon-composite anodes to significantly improve capacity; elastomeric binders and nanostructures to achieve ~200 cycles
  - Novel layered oxide cathode with lithium-excess compositions Li$_{1+x}$Ni$_x$Mn$_{1-y}$Co$_z$O$_{2}$ to improve capacity

- **Improving Cell-Level Safety**
  - Nano-particle circuit breaker, flame-retardant electrolytes, and cathode coatings to increase the thermal stability of the cell
  - Goal: no fire or flame, even under abuse.

- **Layered Li/NMC|O$_2$** cathode particle
  - Varying composition and morphology to improve capacity and charge/discharge rate

- **Optimized Solid-Electrolyte interface Layer**
  - Mitigates causes of irreversible capacity

---

**Lander - Altair**

- LSS
- EVA (Suit 2 Config)
- Safety, Packaging and Control

---

**Lithium-Ion Battery Technology Development**

**Advanced Cell Components**

- **Charger or Load**
- **Collector**
- **Anode**
- **Separator**
- **Cathode**

- **Layered Li/NMC|O$_2$** cathode particle
- Varying composition and morphology to improve capacity and charge/discharge rate

- **Optimized Solid-Electrolyte interface Layer**
  - Mitigates causes of irreversible capacity

- **Improving Cell-Level Safety**
  - Nano-particle circuit breaker, flame-retardant electrolytes, and cathode coatings to increase the thermal stability of the cell
  - Goal: no fire or flame, even under abuse.

- **Providing Ultra High Specific Energy**
  - Silicon-composite anodes to significantly improve capacity; elastomeric binders and nanostructures to achieve ~200 cycles
  - Novel layered oxide cathode with lithium-excess compositions Li$_{1+x}$Ni$_x$Mn$_{1-y}$Co$_z$O$_{2}$ to improve capacity
Anode Development
Led by William Bennett, ASRC at NASA GRC

- Develop silicon-based carbon composite materials
  - Much higher theoretical capacity than carbonaceous materials
- Development focus on:
  - Decreasing irreversible capacity loss
  - Increasing cycling stability by reducing impact of volume expansion
  - Improving cycle life

- Anode Development at:
  - Georgia Tech Research Institute
  - Lockheed Martin
  - Glenn Research Center

Anode Development

**Objective:**
To develop an optimized silicon nanoparticle anode with a novel elastomeric binder that will mitigate capacity fade and enable long cycle.

**Approach:**
- Functionalize nanoparticles to covalently adhere with binder
- Optimize binder to manage volume changes during cycling
- Optimize anode properties to meet capacity, temperature and life requirements

**Accomplishments:**
- Anode exceeded 1000 mAh/g when tested in a full cell with an NMC cathode (NEI-D) at room temperature. Performance has stayed good through all 5 cycles to date.
- Anode samples demonstrated >1000 mAh/g at C/10 for 40 cycles at room temperature in half cell testing.
- The KPP goal for the anode specific capacity of 1000 mAh/g at C/10 and 0 °C has been demonstrated over more than 10 cycles.
- Anode tested in a full cell with Saft's NCA cathode and tested for 230 cycles at 40% depth of discharge. Long-term cycling stability was demonstrated with this electrode pair, but capacity imbalance between electrodes limited performance.

**Challenge:**
Anode specific capacity fade rates are still too high to meet the goal of 200 cycles at the cell level.
**Anode Development**

**NASA Contract # NNC08CB01C**

**Project:** ETDP Energy Storage Project – Space-rated Lithium-ion Batteries

**COTR:** Richard Baldwin, NASA GRC

**“Design of Resilient Silicon Anodes”**

Dr. Gleb Yushin & Dr. Tom Fuller, Georgia Institute of Technology
Dr. Igor Luzinov, Clemson University

**Objective:**

To address the NASA “ultra-high energy cell” performance metrics, develop a practical silicon-based anode cell component with demonstrated high capacity and cycle life.

**Approach:**

Optimize a (nano)silicon-based anode structure by utilizing a novel elastic epoxidized polybutadiene (EPB) binder so as to permit sufficient elastic deformations during detrimental volume changes associated with lithium-silicon alloying and de-alloying.

**Accomplishments:**

- Anode samples demonstrated >1000 mAh/g at C/10 for 10 cycles at room temperature in half cell testing.

**Challenge:**

Anode specific capacity fade rates are still too high to meet the goal of 200 cycles at the cell level.

---

**GRC In-House Anode Synthesis**

**PI:** Jim Woodworth, NPP, NASA GRC

**Resorcinol Formaldehyde (RF) Gels**

- Resorcinol-formaldehyde resin formed in water
- Formed into monoliths
- Formed into microspheres
- Silicon or other materials may be added to the material
- Materials are freeze dried and pyrolyzed to form the carbonaceous anode material

**Silicon Sputter Coated Carbon Fiber Paper**

- Apply Si to an active support material that is also capable of acting as a current collector
  - 50 nm Si Coating

**Silicon Sputter Coated Copper**

- 50 nm Si coating
- Used to study lithiation of silicon
Cathode Development
Led by Kumar Bugga, NASA JPL

- Develop Li(NMC) materials
  - Offer enhanced thermal stability over conventional cobaltate cathodes
  - High voltage materials

- Development focus on:
  - Increasing specific capacity
  - Improving rate capability
  - Stabilizing materials for higher voltage operation
  - Reducing irreversible capacity loss
  - Increasing tap density

- Cathode Development at:
  - University of Texas at Austin
  - NEI Corporation
  - JPL

---

Cathode Development
NASA Contract # NNC09CA08C

**Objective:**
Develop Li(NMC) cathode materials with high capacity and low irreversible capacity (IRC) loss.

**Approach:**
- Vary composition of base material to maximize discharge capacity with low IRC loss.
- Modify cathode surface with metal oxide coatings to increase capacity and decrease the IRC.
- Dope samples with titanium to increase capacity.

**Accomplishments**
- Surface modified samples demonstrate higher capacity, lower irreversible capacity loss, and more stable cyclability after 25 cycles as compared to unmodified cathode sample.
- Tap density increased to 1.6 g/cc to accommodate Saft’s manufacturing process, but specific capacity degraded (down to ~210 mAh/g from 252 at 3.0 V)

**Challenge:**
0 °C capacity is very poor (~30% reduction). Even at room temperature, the specific capacity remains below 260 mAh/g. High first cycle irreversible capacity loss (~30% at room temperature).
Cathode Development
NASA Contract # NNC09CA07C

“Mixed Metal Composite Oxides for High Energy Li-ion Batteries”
Pl: Dr. Nader Hagh, NEI Corporation

Objective:
Develop a LiNMC cathode material with a unique structure, composition, and a fine-grained particle morphology. Synthesize materials using a scalable and low cost process.

Approach:
• Understand ordering and produce a highly ordered structure
• Ultra fine particle crystallization using solid state reactions
• Structure refinement

Accomplishments:
• Produced several variants of LiNMCO₂ cathode materials
• Demonstrated stability over a wide operating voltage window (4.8 to 2.5 V).
• Successfully synthesized powders with tap densities above 2.0 g/cc.

Challenge:
0 °C performance is very poor (~40% reduction).
High first cycle irreversible capacity loss (~24% at R.T.)

Electrolyte Development
Led by Marshall Smart, NASA JPL

• Develop advanced electrolytes with additives:
  – Non-flammable electrolytes and flame retardant additives
  – Stable at potentials up to 5 V
  – Compatible with the NASA chemistries

• Development focus on:
  – Reducing flammability
  – Stabilizing materials for higher voltage operation
  – Compatibility with mixed-metal-oxide cathodes and silicon composite anodes

• Electrolyte Development at:
  – JPL
  – Yardney Technical Products/University of Rhode Island

Preliminary results of unoptimized materials are shown. Materials were tested at NASA in coin cell half cells.
JPL In-House Electrolyte Development

Led by Marshall Smart, NASA JPL

Objective:
• To develop flame retardant electrolytes for Li-ion cells that are stable up to 5.0 V.

Approach:
• Determine best formulation for low-flammability that is consistent with high-voltage mixed-metal-oxide cathodes, and with graphite and silicon composite anodes:
  • Vary concentration of triphenyl phosphate additives
  • Test both linear and cyclic fluorinated carbonates as non-flammable solvents.

Accomplishments:
• JPL Gen #1 Electrolyte has <50% heat release, <25% pressure rise, and >33% faster flame extinction compared to Saft electrolyte, but showed poor compatibility with NMC cathodes.
• JPL Gen #2 electrolytes (containing LiBOB) now shows good performance with graphite/NMC electrodes, and has lower flammability because of increased TPP content (10%).

Electrolyte Development

NASA Contract # NNC09CA06C

Objective:
• To develop flame retardant electrolytes for Li-ion cells that are stable up to 5.0 V.

Approach:
• Characterize electrochemical stability of baseline electrolyte solution at and above 5 V
• Examine flame retardant properties of baseline electrolyte with additives
• Characterize effect of additives on electrochemical stability
• Analyze performance of cells containing the developed electrolytes

Accomplishments:
• Flame retardant electrolytes were formulated
• Tests performed on 12 Ah cells made with developed electrolyte formulations

Comparable performance was obtained with the JPL Gen #2 electrolytes (containing LiBOB) compared with the baseline solution.

<table>
<thead>
<tr>
<th>Description</th>
<th>Electrolyte</th>
<th>Percentage Flame Retardant Additive (%)</th>
<th>SET (s)</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>JPL Gen #1 Electrolyte</td>
<td>1.0 M LiPF6 + 0.05 M LiBOB + EC+EMC+DMMP (30:55:15 wt %)</td>
<td>25% TPP</td>
<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td>JPL Gen #2 Electrolyte</td>
<td>1.0 M LiPF6 + 0.05 M LiBOB + EC+EMC+DMMP (30:55:15 wt %)</td>
<td>50% TPP</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>Yardney/URI Gen #1 Electrolyte</td>
<td>0.7 M LiPF6 + 0.3 M LiBOB + EC+EMC+DMMP (30:55:15 wt %)</td>
<td>25% TPP</td>
<td>2.4</td>
<td>2.4</td>
</tr>
<tr>
<td>Yardney/URI Gen #2 Electrolyte</td>
<td>0.7 M LiPF6 + 0.3 M LiBOB + EC+EMC+DMMP (30:55:15 wt %)</td>
<td>None</td>
<td>15.9</td>
<td>15.9</td>
</tr>
</tbody>
</table>

Self-extinguishing time (SET) flammability tests show excellent flame retardance in JPL and Yardney/URI electrolytes.

Project: ETDP Energy Storage Project – Space-rated Lithium-ion Batteries
COTR: Richard Baldwin, NASA GRC
TM: Marshall Smart, NASA JPL

“Flame Retardant, Electrochemically Stable Electrolyte for Lithium-Ion Batteries”
PI: Dr. Boris Ravdel, Yardney Technical Products
Collaborator: Dr. Brett Lucht, University of Rhode Island (URI)

Objective:
• To develop flame retardant electrolytes for Li-ion cells that are stable up to 5.0 V.

Approach:
• Characterize electrochemical stability of baseline electrolyte solution at and above 5 V
• Examine flame retardant properties of baseline electrolyte with additives
• Characterize effect of additives on electrochemical stability
• Analyze performance of cells containing the developed electrolytes

Accomplishments:
• Flame retardant electrolytes were formulated
• Tests performed on 12 Ah cells made with developed electrolyte formulations

Rate capability at 23 °C of electrolyte with lowest Self-extinguishing time (left): 0.95 M LiPF6 + 0.05M LiBOB EC+EMC+DMMP (30:55:15 wt %) developed by Yardney Technical Products

(effort completed December 2009)
Separators and Safety Components

Separators
Led by Richard Baldwin, NASA GRC

- Separators with improved safety
- Shutdown separators
- Optimized for ETDP chemistry

Safety Component Development
Led by Judy Jeevarajan, NASA JSC

- Development of internal cell materials (active or inactive) designed to improve the inherent safety of the cell
- Functional components
- Safety Component Development at:
  - Physical Sciences, Inc.
  - Giner

Safety Component Development
NASA Contract # NNC09CA04C

Project: ETDP Energy Storage Project – Space-rated Lithium-ion Batteries
COTR: Judy Jeevarajan, NASA JSC

Objective: Coat metal oxide cathodes with lithium metal phosphate coatings to improve thermal stability.

Approach:
- Coat LiCoO₂ cathodes using 1 and 2% lithium metal phosphate solutions
- Optimize coatings to increase onset temperature of exothermic peak or eliminate peak

Accomplishments:
- Demonstrated no loss in discharge capacity for uncoated cathode compared to cathode with ~1.5% LiCoPO₄ coating (results reported for 1 cycle)
- Demonstrated robust adhesion of coating in half cells for 200 cycles, cycling at C-rate with capacity retention of ~90% of 1st cycle capacity
- Demonstrated to reduce exotherms without reducing performance on high voltage cathodes (Toda).

Preliminary results show complete suppression of exotherm with coated LiCoO₂ cathode.

Next step:
Determine compatibility with MPG-111/NMC full cell.
“Control of Internal and External Short Circuits in Lithium-Ion Batteries”
Pi: Dr. Robert McDonald, Giner Incorporated

**Objective:**
To develop the compositions and fabrication methods for integration of a Composite Thermal Switch into Li-ion cells.

**Approach:**
- Optimize a switch temperature for safe handling of short circuits in Li-ion cells (switch activation causes a resistance increase at surface of coated electrode).
- Build Li-ion cells to demonstrate the concept and effect using externally applied heat and hard shorts.
- Perform electrochemical testing to confirm that safety improvements do not compromise performance.

**Accomplishments:**
- Switch coated on both copper and aluminum substrates
- Coatings deposited in different thicknesses to compare switch behavior as a function of temperature
- Non-uniform switching behavior and resistance observed on samples

**Challenge:**
Repeatable, consistent switching behavior.

---

**Cell Development**
Led by Tom Miller, NASA GRC

- **Assess NASA-developed components**
  - Build and test electrodes and screening cells
  - Provide manufacturing perspective from the start
- **Scale-up NASA-developed components**
  - Transition components from the lab to the manufacturing floor
- **Build and test evaluation cells (10 Ah):**
  - Determine component interactions
  - Determine cell-level performance
- **Design flightweight cells (35 Ah):**
  - Identify high risk elements early
Component screening:

UT Austin increased the tap density of their cathode to provide manufacturability;
Saft modified their electrode processing to be compatible with Giner’s thermal switch;
Georgia Tech will modify their binder additives to be compatible with Saft’s anode
Toda-9100 identified as baseline cathode.
Baseline cells: graphite anode (MPG-111), nickel-cobalt cathode (NCA)
DD cells (10 Ah, cylindrical): fabricated and under test.
34P cells (45 Ah, prismatic): fabricated, activated, and delivered.

Flightweight cells (35 Ah, prismatic): PDR held May, 2010
Flightweight cell design predicted to meet 185 Wh/kg at 25 °C,
and possibly 194 Wh/kg (using a proposed design change in the bussing configuration).
0 °C predictions below current baseline.

<table>
<thead>
<tr>
<th>Basic (34 months)</th>
<th>Option 1 Flightweight Cell Fabrication (18 months)</th>
</tr>
</thead>
</table>

Cell Development

**Objective:**
Develop a cell/battery design tool to aid in component materials assessments

**Key Accomplishment:**
- Spread sheet developed that projects cell/battery level characteristics based on component level materials
- Based on standard design configuration
- Configured to rapidly perform what-if? analyses

**Significance:**
- Aids in quantifying impact of incremental improvements in battery design materials
- Allows identification of critical factors which control cell/battery energy density and specific energy
- Provide engineering-accuracy forecasts of size and mass for cells and batteries
- Rate performance can be estimated from laboratory data for electrodes under relevant conditions
Cell-Level Specific Energy Prediction Results – Using Current Component Data

- Projected discharge profiles for cells using electrode voltage data
  - Based on electrode data at 23 and 0 °C
  - Representative of fresh cell without many cycles

- Cathode low-temperature performance produces very low specific energy at 0 °C
  - Lower than SOA at 0 °C
  - Specific energy at room temperature represents improvement over SOA

### KPP at 0 °C model at 3 V cutoff

<table>
<thead>
<tr>
<th>Baseline</th>
<th>HE</th>
<th>UHE</th>
</tr>
</thead>
<tbody>
<tr>
<td>threshold</td>
<td>150</td>
<td>165</td>
</tr>
<tr>
<td>goal</td>
<td>173</td>
<td>200</td>
</tr>
<tr>
<td>23 °C</td>
<td>199</td>
<td>213</td>
</tr>
<tr>
<td>0 °C</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

Baseline electrodes = MPG-111 and NCA
HE electrodes = MPG-111 and Li(LiNMC)O₂
UHE electrodes = Si-composite and Li(LiNMC)O₂

- Expected performance should improve with further component development

---

Energy Storage Risk Assessment: Overall Project - Closed Risks
Summary Since December 2007 Major Re-plan

**Explanation of risk closure before becoming “green”:**

1. Constellation accepted late delivery of regenerative fuel cell so this project closed it as an Energy Storage risk.
2. Battery performance risk split into more detailed technical risks.

**Consequences:**

<table>
<thead>
<tr>
<th>ID</th>
<th>Risk Title</th>
<th>Risk Statement</th>
<th>Mitigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Constellation accepted late delivery of regenerative fuel cell</td>
<td>This project closed it as an Energy Storage risk.</td>
<td>Ignore</td>
</tr>
<tr>
<td>6</td>
<td>Battery performance risk split into more detailed technical risks</td>
<td>This project closed it as an Energy Storage risk.</td>
<td>Ignore</td>
</tr>
</tbody>
</table>
**Energy Storage Risk Assessment: Overall Project – Open Risks**

Summary Since December 2007 Major Re-plan

<table>
<thead>
<tr>
<th>Risk Mgmt Approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery safety; chemistries may pose unacceptable risks to the crew.</td>
</tr>
<tr>
<td>Less likely with lithium ion chemistry than with lithium metals. Potential consequence is spontaneous ignition causing loss of crew.</td>
</tr>
<tr>
<td>Address electrolyte flammability. Include safety goals in NRA and RFP. Develop fault isolation electronics. Carry &quot;high energy&quot; cell as fall back.</td>
</tr>
</tbody>
</table>

Program

1. Li-ion chemistry selected.
2. Primary fuel cell risk lowered; electrolysis still at low TRL.
3. Management structure of the SBIR program in flux.

**Energy Storage Risk Assessment: Batteries**

Status of Risks as Reported at Last TCR

<table>
<thead>
<tr>
<th>Risk Mgmt Approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regenerative fuel cell life: 10,000 hr reliable operation may not be achieved.</td>
</tr>
<tr>
<td>Highly likely that new system design will have unforeseen problems that could limit life goal.</td>
</tr>
<tr>
<td>Develop non-flow-through technology to eliminate balance-of-plant components (including the highest-failure-rate components) for both primary and regenerative fuel cell systems. Build fuel cell systems out of modular units to prevent single-point failures. Leverage SBIR/IBR for innovation.</td>
</tr>
</tbody>
</table>

1. EVA and Altair have detailed power lists, although still subject to change. LSS working on power profiles.
2. Materials now selected; scale-up not yet begun.
3. Integration not yet begun.
### Energy Storage Risk Assessment: Fuel Cells

**Status of Risks as Reported at Last TCR**

<table>
<thead>
<tr>
<th>Rank</th>
<th>WBS</th>
<th>Description</th>
<th>Likelihood, Consequence Mitigation</th>
<th>Risk Mgmt Approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ES-12</td>
<td>Non-Flow-Through stack development may not be successful.</td>
<td>Non-flow-through stack being developed by experienced vendor personnel team (Gemini, Shuttle fuel cell experience); several leading fuel cell SBIR vendors developing back-up stacks.</td>
<td>Non-flow-through balance-of-plant being developed in-house at NASA by experienced fuel cell team; system integration and testing planned at each succeeding technology readiness level.</td>
</tr>
<tr>
<td>2</td>
<td>ES-12</td>
<td>Non-Flow-Through balance-of-plant development may not be successful.</td>
<td>If Non-Flow-Through balance-of-plant development is not successful, mass/vol and reliability requirements won’t be met for Lander &amp; LSS.</td>
<td>Non-flow-through balance-of-plant being developed in-house at NASA by experienced fuel cell team; system integration and testing planned at each succeeding technology readiness level.</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>High-pressure electrolysis for RFC may not be successful.</td>
<td>If high-pressure electrolysis is not successful, lower pressure electrolysis will be required with mass/vol and parasitic power penalties.</td>
<td>Two parallel development approaches (IPP &amp; SBIR) with leading high-pressure electrolysis vendors. Down-select to follow, leading to TRL 5 &amp; 6.</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>RFC integration of fuel cell and electrolysis technologies may not be successful.</td>
<td>If necessary integration hardware doesn’t work, RFC won’t be available for LSS.</td>
<td>Perform reactant management study/design, followed by hardware development, integration, and testing.</td>
</tr>
<tr>
<td>5</td>
<td>ES-03</td>
<td>10,000 hr. life for primary fuel cells and RFCs may not be achievable.</td>
<td>If 10,000 hr. system life is not achievable, extra redundancy or premature system maintenance or replacement will be required.</td>
<td>Stress long life at component and subsystem levels; perform system life testing at TRL-5 for early awareness of issues; perform at TRL-6 in parallel with system qualification.</td>
</tr>
</tbody>
</table>

### Top 10 Battery Lower-Level Risks

<table>
<thead>
<tr>
<th>Risk Category</th>
<th>Rank</th>
<th>Score</th>
<th>Description</th>
<th>Mitigation 1</th>
<th>Mitigation 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Compliance with contractual requirements</td>
<td>1</td>
<td>9.5</td>
<td>Compliance with contractual requirements</td>
<td>Review contract terms and conditions</td>
<td>Review contract terms and conditions</td>
</tr>
<tr>
<td>2. Cost Overrun</td>
<td>2</td>
<td>9</td>
<td>Cost overrun</td>
<td>Review project scope and budget</td>
<td>Review project scope and budget</td>
</tr>
<tr>
<td>3. Schedule Slippage</td>
<td>3</td>
<td>9</td>
<td>Schedule slippage</td>
<td>Adjust project timeline</td>
<td>Adjust project timeline</td>
</tr>
<tr>
<td>4. Technical Performance Slope</td>
<td>4</td>
<td>8.5</td>
<td>Technical performance slope</td>
<td>Improve technical performance</td>
<td>Improve technical performance</td>
</tr>
<tr>
<td>5. Customer Satisfaction</td>
<td>5</td>
<td>8</td>
<td>Customer satisfaction</td>
<td>Increase customer feedback</td>
<td>Increase customer feedback</td>
</tr>
<tr>
<td>6. Quality Control</td>
<td>6</td>
<td>8</td>
<td>Quality control</td>
<td>Implement quality assurance</td>
<td>Implement quality assurance</td>
</tr>
<tr>
<td>7. Supplier Delays</td>
<td>7</td>
<td>8</td>
<td>Supplier delays</td>
<td>Communicate with suppliers</td>
<td>Communicate with suppliers</td>
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<tr>
<td>8. Intellectual Property Infringement</td>
<td>8</td>
<td>7.5</td>
<td>Intellectual property infringement</td>
<td>Review intellectual property</td>
<td>Review intellectual property</td>
</tr>
<tr>
<td>9. Environmental Impact</td>
<td>9</td>
<td>7</td>
<td>Environmental impact</td>
<td>Minimize environmental impact</td>
<td>Minimize environmental impact</td>
</tr>
<tr>
<td>10. Safety and Health</td>
<td>10</td>
<td>7</td>
<td>Safety and health</td>
<td>Implement safety and health measures</td>
<td>Implement safety and health measures</td>
</tr>
</tbody>
</table>
### Top 10 Fuel Cell & RFC Lower-Level Risks

<table>
<thead>
<tr>
<th>Technology</th>
<th>TRL at end of FY10</th>
<th>Needed to reach TRL 6</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-Flow-Through Fuel Cell System</td>
<td>4</td>
<td>$19M</td>
<td>3 Years</td>
</tr>
<tr>
<td>High Pressure (2000 psi) electrolyzer</td>
<td>2/3</td>
<td>$21M</td>
<td>5 Years</td>
</tr>
<tr>
<td>Regenerative Fuel Cell System</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>“High Energy” lithium-ion battery cell</td>
<td>2/3</td>
<td>Component development</td>
<td>$17M*</td>
</tr>
<tr>
<td>“Ultra High Energy” lithium-ion battery cell</td>
<td>2/3</td>
<td>Component development</td>
<td>$19M*</td>
</tr>
</tbody>
</table>

*Some synergy will allow for cost savings if both High Energy and Ultra-High Energy battery cells are pursued concurrently. These estimates assume a stand-alone task.*
Lessons Learned

1. It is better to try to develop technologies with aggressive goals, aggressive schedules, and no budget margin than not to try, even if the risks are very high.
   • Although we have not met our technical goals for battery components, we made substantial progress and are now positioned to support nearer-term demos.
   • Further development is required, and will continue to be high risk.

2. Down-selecting technologies before TRL-4 is extremely risky – we got lucky on this one for fuel cells.
   • A serious technology development program supporting serious program schedules should not take this risk.
   • It is a testament to the skill of our technical staff that this decision could be made without adequate data on the lower-TRL system.

3. Working closely with Cx and industry at the very beginning had us on a path to cross the "valley-of-death" for technology infusion.
   • Priorities set by EVA, LSS and Altair were essential to keep the technology focused.
   • Feedback provided by Saft, America ensured a sharper focus on manufacturability early on.
   • Close collaboration with Infinity Hydrogen led to success.

Summary

Energy storage technologies were considered critically important for NASA’s Constellation Program.

Advanced batteries are critical
   - Reduces mass/volume and extends mission duration for EVA
   - Extends range and/or functionality of robots/mobility systems
   - Reduces mass or adds functionality for landers

Advanced fuel cells are critical for vehicle power
   - Recent advances make NASA-developed technology extremely attractive for reliability and system mass/volume
   - Provides water for life support

Advanced regenerative fuel cells are critical
   - Provides surface power during the lunar night

Substantial technical progress was made under the Energy Storage Project

Advancements made in Lithium Ion components
   - Li(NMC) cathodes show improved specific capacity at C/10
   - Silicon-composite anodes show improved cycle life
   - Electrolytes show compatibility with high-voltage cathodes and improved self-extinguishing times
   - Cathode coating shows improved thermal stability

Advancements made in PEM fuel cells
   - “Non-flow-through” stack technology demonstrated to TRL-4
   - Flat-plate heat-pipes demonstrated to be effective for thermal management
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>BOP</td>
<td>Balance of Plant</td>
</tr>
<tr>
<td>C</td>
<td>Charge/Discharge Rate</td>
</tr>
<tr>
<td>CDR</td>
<td>Critical Design Review</td>
</tr>
<tr>
<td>Cx</td>
<td>Constellation Program</td>
</tr>
<tr>
<td>DOD</td>
<td>Depth of Discharge</td>
</tr>
<tr>
<td>ETDIP</td>
<td>Exploration Technology Development Program</td>
</tr>
<tr>
<td>EVA</td>
<td>Extra Vehicular Activity</td>
</tr>
<tr>
<td>FC</td>
<td>Fuel Cell</td>
</tr>
<tr>
<td>FT</td>
<td>Flow Through</td>
</tr>
<tr>
<td>GEN</td>
<td>Generation</td>
</tr>
<tr>
<td>GRC</td>
<td>Glenn Research Center</td>
</tr>
<tr>
<td>HE</td>
<td>High Energy</td>
</tr>
<tr>
<td>HX</td>
<td>Heat Exchanger</td>
</tr>
<tr>
<td>IPP</td>
<td>Innovative Partnership Program</td>
</tr>
<tr>
<td>IRC</td>
<td>Irreversible Capacity</td>
</tr>
<tr>
<td>ISRU</td>
<td>In-Situ Resource Utilization</td>
</tr>
<tr>
<td>JPL</td>
<td>Joint Propulsion Laboratory</td>
</tr>
<tr>
<td>JSC</td>
<td>Johnson Space Center</td>
</tr>
<tr>
<td>KSC</td>
<td>Kennedy Space Center</td>
</tr>
<tr>
<td>LAT</td>
<td>Lunar Architecture Team</td>
</tr>
<tr>
<td>LS</td>
<td>Lunar Surface</td>
</tr>
<tr>
<td>LSS</td>
<td>Lunar Surface Systems</td>
</tr>
<tr>
<td>LT</td>
<td>Launch Technology</td>
</tr>
<tr>
<td>MEA</td>
<td>Membrane Electrode Assembly</td>
</tr>
<tr>
<td>NFT</td>
<td>Non-Flow Through</td>
</tr>
<tr>
<td>NMC</td>
<td>Ni-Mn-Co</td>
</tr>
<tr>
<td>NTR</td>
<td>New Technology Report</td>
</tr>
<tr>
<td>PDR</td>
<td>Preliminary Design Review</td>
</tr>
<tr>
<td>PEM</td>
<td>Proton Exchange Membrane</td>
</tr>
<tr>
<td>PEMFC</td>
<td>Proton Exchange Membrane Fuel Cell</td>
</tr>
<tr>
<td>PI</td>
<td>Principal Investigator</td>
</tr>
<tr>
<td>PLSS</td>
<td>Portable Life Support System</td>
</tr>
<tr>
<td>PSU</td>
<td>Power Supply Unit</td>
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<tr>
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<td>Regenerative Fuel Cell</td>
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<tr>
<td>R.T.</td>
<td>Room Temperature</td>
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<td>SBIR</td>
<td>Small Business Innovative Research</td>
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<tr>
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<td>Technical Content Review</td>
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<td>Technology Prioritization Process</td>
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<td>TRL</td>
<td>Technology Readiness Level</td>
</tr>
<tr>
<td>UHE</td>
<td>Ultra-High Energy</td>
</tr>
<tr>
<td>URFC</td>
<td>Unitized Regenerative Fuel Cell</td>
</tr>
</tbody>
</table>
Energy Storage Project Bibliography

Project Summary


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14. ABSTRACT
NASA’s Exploration Technology Development Program funded the Energy Storage Project to develop battery and fuel cell technology to meet the expected energy storage needs of the Constellation Program for human exploration. Technology needs were determined by architecture studies and risk assessments conducted by the Constellation Program, focused on a mission for a long-duration lunar outpost. Critical energy storage needs were identified as batteries for EVA suits, surface mobility systems, and a lander ascent stage; fuel cells for the lander and mobility systems; and a regenerative fuel cell for surface power. To address these needs, the Energy Storage Project developed advanced lithium-ion battery technology, targeting cell-level safety and very high specific energy and energy density. Key accomplishments include the development of silicon composite anodes, lithiated-mixed-metal-oxide cathodes, low-flammability electrolytes, and cell- incorporated safety devices that promise to substantially improve battery performance while providing a high level of safety. The project also developed “non-flow-through” proton-exchange-membrane fuel cell stacks. The primary advantage of this technology set is the reduction of ancillary parts in the balance-of-plant—fewer pumps, separators and related components should result in fewer failure modes and hence a higher probability of achieving very reliable operation, and reduced parasitic power losses enable smaller reactant tanks and therefore systems with lower mass and volume. Key accomplishments include the fabrication and testing of several robust, small-scale non-flow-through fuel cell stacks that have demonstrated proof-of-concept. This report summarizes the project’s goals, objectives, technical accomplishments, and risk assessments. A bibliography spanning the life of the project is also included.

15. SUBJECT TERMS
Lithium batteries; Electric batteries; Storage batteries; Fuel cells; Hydrogen oxygen fuel cells; Regenerative fuel cells; Electrochemical cells; Energy storage

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   b. ABSTRACT
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   c. THIS PAGE
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