NASA/TM—2011-216963

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
Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI Program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NASA Aeronautics and Space Database and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- **TECHNICAL PUBLICATION.** Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- **TECHNICAL MEMORANDUM.** Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- **CONTRACTOR REPORT.** Scientific and technical findings by NASA-sponsored contractors and grantees.

- **CONFERENCE PUBLICATION.** Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.

- **SPECIAL PUBLICATION.** Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- **TECHNICAL TRANSLATION.** English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include creating custom thesauri, building customized databases, organizing and publishing research results.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at [http://www.sti.nasa.gov](http://www.sti.nasa.gov)

- E-mail your question via the Internet to help@sti.nasa.gov

- Fax your question to the NASA STI Help Desk at 443–757–5803

- Telephone the NASA STI Help Desk at 443–757–5802

- Write to:
  NASA Center for AeroSpace Information (CASI)
  7115 Standard Drive
  Hanover, MD 21076–1320
Acknowledgments

NASA's Exploration Technology Development Program supported this work, conducted by the Energy Storage Project. Many people contributed to this work. Special thanks to NASA ESMD: Chris Moore and John Warren, NASA ETDP: Frank Peri and Diane Hope, NASA Constellation: David Westheimer, Rob Button, Pat George, Lisa Kohout, Josh Freeh, James Fincannon, Barb Mc Kissock, and Patricia Loyselle, NASA Technical Staff: Ratnakumar Bugga, Judy Jeevarajan, Koroosh Araghi, S.R. Narayan, Bill Bennett, Marshall Smart, Ken Burke, and Ian Jakupca, NASA Management Staff: John Scott, Michelle Manzo, and Subbarao Surampudi, NASA Contractors: Infinity Fuel Cell and Hydrogen, Inc./Bill Smith; Saft, America/Bob Staniewicz; UT Austin/ Arumugam Manthiram; PSI/Christopher Lang; NEI Corp/Ganesh Skandan; Lockheed Martin/Justin Golightly; GeorgiaTech/ Gleb Yushin; Giner/Robert McDonald; and Yardney Technical Products/Boris Ravdel.

Level of Review: This material has been technically reviewed by technical management.

Available from

NASA Center for Aerospace Information
7115 Standard Drive
Hanover, MD 21076–1320

Available electronically at http://www.sti.nasa.gov

National Technical Information Service
5301 Shawnee Road
Alexandria, VA 22312
Energy Storage Project
Final Report

Carolyn R. Mercer, Amy L. Jankovsky, Concha M. Reid,
Thomas B. Miller, and Mark A. Hoberecht
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

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

Common Airlock With Lander

ISRU Oxygen Production Plant

ATHLETE
Long-distance Mobility System (2)

Small Pressurized Rover (SPR)
(Facilitates SPR docking & charging)

Unpressurized Rover

Communication/Navigation

NASA/TM—2011-216963
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 IMCB-5</td>
<td>Mobility</td>
<td>Enabling</td>
<td>High Specific-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-Density PEM Fuel Cell Systems – Need light weight, 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-Density EVA Suit 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 for a 20 kW 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>Sd5</td>
<td>Required specific energy not achievable with current batteries</td>
</tr>
<tr>
<td>Cx TPP 606</td>
<td>Surface Systems, Orion and LSS</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 #06</td>
<td>Low mass, highly reliable fuel cell for Lunar Lander power generation.</td>
</tr>
<tr>
<td>Cx TPP 465</td>
<td>Lander</td>
<td>Critical LT #107</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 #111</td>
<td>High specific energy power for Lunar Rovers</td>
</tr>
<tr>
<td>Ares V Risk #2366 Cx TPP 525</td>
<td>Area IV</td>
<td>Sd5</td>
<td>Solid Rocket Booster Throat Vector Control Power Source require high power, primary batteries</td>
</tr>
</tbody>
</table>

Updated 4/21/08
### 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**
### 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** (@ 3 kW)</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</td>
<td>RFC (without tanks)</td>
<td>49 W/kg</td>
<td>44 W/kg</td>
<td>88 W/kg</td>
</tr>
<tr>
<td></td>
<td>Fuel Cell</td>
<td>n/a</td>
<td>n/a</td>
<td>25 W/kg</td>
<td>36 W/kg</td>
</tr>
<tr>
<td></td>
<td>Fuel Cell Stack power density</td>
<td>n/a</td>
<td>51 W/kg</td>
<td>107 W/kg</td>
<td>231 W/kg</td>
</tr>
<tr>
<td></td>
<td>Fuel Cell Balance-of-plant mass</td>
<td>n/a</td>
<td>2 kg</td>
<td>21 kg</td>
<td>9 kg</td>
</tr>
<tr>
<td>Lunar Surface Systems: TBD kW for 15 days continuous operation</td>
<td>MEA efficiency @ 200 mA/cm²</td>
<td>For Fuel Cell</td>
<td>73%</td>
<td>72%</td>
<td>73%</td>
</tr>
<tr>
<td></td>
<td>Individual cell voltage</td>
<td>0.90 V</td>
<td>0.89 V</td>
<td>0.90 V</td>
<td>0.92 V</td>
</tr>
<tr>
<td></td>
<td>For Electrolysis</td>
<td>n/a</td>
<td>83%</td>
<td>84%</td>
<td>85%</td>
</tr>
<tr>
<td></td>
<td>Individual cell voltage</td>
<td>n/a</td>
<td>1.48</td>
<td>1.46</td>
<td>1.44</td>
</tr>
<tr>
<td></td>
<td>For RFC (Round Trip)</td>
<td>n/a</td>
<td>60%</td>
<td>62%</td>
<td>64%</td>
</tr>
<tr>
<td>Rover: TBD</td>
<td>System efficiency @ 200 mA/cm²</td>
<td>Fuel Cell</td>
<td>71%</td>
<td>64%</td>
<td>71%</td>
</tr>
<tr>
<td></td>
<td>Parasitic penalty</td>
<td>2%</td>
<td>8%</td>
<td>2%</td>
<td>1%</td>
</tr>
<tr>
<td></td>
<td>Regenerative Fuel Cell***</td>
<td>n/a</td>
<td>n/a</td>
<td>43%</td>
<td>54%</td>
</tr>
<tr>
<td></td>
<td>Parasitic penalty</td>
<td>n/a</td>
<td>n/a</td>
<td>10%</td>
<td>5%</td>
</tr>
<tr>
<td></td>
<td>High Pressure penalty</td>
<td>n/a</td>
<td>n/a</td>
<td>20%</td>
<td>10%</td>
</tr>
</tbody>
</table>

*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

### 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)
  - Pyrolitic 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
- Liquid feed system draws significant parasitic power for pumps and water/gas separators
- 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
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
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.

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.

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-Thru Stack.

The 6-Cell fuel cell stack has been fully assembled.

The integrated FC stack is to be tested at Teledyne in August 2008.

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

**MEA Testing**
- Nafion 115
- 4.0 mg/cm² Pt unsupported cathode
- ~65% RH @ inlet
- 70 °C
- 300 kPa abs H₂/O₂
- Narayan et al, STAIF 2007

**MEA Testing**
- Nafion 111
- 0.5 mg/cm² Pt supported cathode
- 60% RH @ inlet
- 85 °C
- 100 kPa abs H₂/O₂

**MEA Testing**
- Nafion 111
- 0.5 mg/cm² Pt supported cathode
- 60% RH @ inlet
- 85 °C
- 100 kPa abs H₂/O₂
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

![Graph showing MEA performance comparison]

<table>
<thead>
<tr>
<th>Efficiency (%)</th>
<th>Fuel Cell MEA</th>
<th>JPL N115</th>
<th>Vendor 1 N115</th>
</tr>
</thead>
<tbody>
<tr>
<td>86%</td>
<td>72%</td>
<td>(86%)(72%) = 62% round-trip RFC stack efficiency @ 200 mA/cm²</td>
<td></td>
</tr>
</tbody>
</table>

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

Partners: Hamilton Sundstrand, NASA

**MEA and Electrolysis Technology: Recent Progress**

**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.

**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.

![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.

<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>

Representative mass allocation for 3 kW fuel cell

[Image: derivative of Gemini fuel cell technology]

**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
- Motorized centrifugal separators or passive membrane separators for water separation

[Image: 50 cm² Lab Stack #1 Integrated with Balance-of-Plant]

Packaging Concept for Non-Flow-Through System
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

![3D Packaging Concept Model of Balance-of-Plant Components](image)

---

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](image)
WBS 3.2.1.1 Baseline Stacks  
Milestone 3.2.1.1-1 Lab Stack #2 Unit Delivery  

**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

<table>
<thead>
<tr>
<th>Milestone/Event</th>
<th>Date</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.2.1.1-2 Lab Stack #3 Unit Delivery</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.2.2.2-4 BOP for Lab Stack #3 Complete</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.2.2.2-5 Lab Stack #3 System Testing Complete</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.5-1 Lab Stack #3 MEA Delivery</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**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.

---

### 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

---

**Partners:** Infinity Fuel Cell and Hydrogen, NASA

**Non-Flow-Through Fuel Cell Technology: Recent Progress**

---

**Lab-scale non-flow-through fuel cell stack under test**

---

**Schematic image of future 3 kW non-flow-through fuel cell stack**
Non-Flow-Through Fuel Cell: Common Test Bed

- Configurable to test stacks provided by multiple vendors
- Capable of testing total output power of 1 kW
- 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

URFC System

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>Instrumentation/controllers used to prevent unsafe conditions. There is no non-flammable electrolyte in SSA</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>
<td></td>
</tr>
<tr>
<td>Specific energy</td>
<td>Battery-level specific energy* [Wh/kg]</td>
<td>50 Wh/kg at C/10 &amp; 30 °C; 83 Wh/kg at C/10 &amp; 0 °C (MER rovers)</td>
<td>180 at C/10 &amp; 30°C (UHE)</td>
<td>135 Wh/kg at C/10 &amp; 0°C “High-Energy”***</td>
<td>150 Wh/kg at C/10 &amp; 0°C “Ultra-High Energy”***</td>
</tr>
<tr>
<td></td>
<td>Cell-level specific energy [Wh/kg]</td>
<td>130 Wh/kg at C/10 &amp; 30 °C; 118 Wh/kg at C/10 &amp; 0 °C</td>
<td>190 at C/10 &amp; 23°C (UHE)</td>
<td>165 Wh/kg at C/10 &amp; 0°C “High-Energy”***</td>
<td>180 Wh/kg at C/10 &amp; 0°C “Ultra-High Energy”***</td>
</tr>
<tr>
<td></td>
<td>Cathode-level specific capacity [mAh/g]</td>
<td>180 mAh/g</td>
<td>252 mAh/g at C/10 &amp; 25 °C; 190 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>
</tr>
<tr>
<td></td>
<td>Anode-level specific capacity [mAh/g]</td>
<td>280 mAh/g (DOMO)</td>
<td>320 @ C/10 &amp; 0 °C (HE); 1200 mAh/g @ C/10 &amp; 0 °C for 15 cycles (UHE)</td>
<td>600 mAh/g at C/10 &amp; 0°C “Ultra-High Energy”</td>
<td>1000 mAh/g at C/10 &amp; 0°C “Ultra-High Energy”</td>
</tr>
<tr>
<td>Energy density</td>
<td>Battery-level energy density</td>
<td>250 Wh/l</td>
<td>n/a</td>
<td>270 Wh/l “High-Energy”</td>
<td>320 Wh/l “Ultra-High Energy”</td>
</tr>
<tr>
<td></td>
<td>Cell-level energy density</td>
<td>320 Wh/l</td>
<td>n/a</td>
<td>385 Wh/l “High-Energy”</td>
<td>460 Wh/l “Ultra-High Energy”</td>
</tr>
<tr>
<td>Operating environment</td>
<td>Operating Temperature</td>
<td>-20 to 40 °C</td>
<td>0 to 30 °C</td>
<td>0 to 30 °C</td>
<td>0 to 30 °C</td>
</tr>
</tbody>
</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

*** Over-temperature up to 110 °C; reversal 150% excess discharge @ 1C; pass external and simulated internal short tests; overcharge 100% @ 1C for Goal and 80% @ C/5 for Threshold Value.

---

### Energy Storage Project Cell Development for Batteries

<table>
<thead>
<tr>
<th>Li(LINMC)O₂</th>
<th>NASA Cathode</th>
<th>Ultra-High Energy Cell</th>
<th>Conventional Carbonaceous Anode</th>
<th>Si-composite NASA Anode</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>High Energy Cell</strong></td>
<td>Baseline for EVA and Rover</td>
<td>Lithiated-mixed-metal-oxide cathode/Graphite anode</td>
<td>Li(LINMC)O₂/Conventional carbonaceous anode</td>
<td>150 Wh/kg (100% DOD) @ battery-level 0 °C C/10 80% capacity retention at ~2000 cycles</td>
</tr>
<tr>
<td><strong>Ultra-High Energy Cell</strong></td>
<td>Upgrade for EVA and Altair, possibly Rover</td>
<td>Lithiated-mixed-metal-oxide cathode/Silicon composite anode</td>
<td>Li(LINMC)O₂/Silicon composite</td>
<td>220 Wh/kg (100% DOD) @ battery-level 0 °C C/10 80% capacity retention at ~200 cycles</td>
</tr>
</tbody>
</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

*** Over-temperature up to 110 °C; reversal 150% excess discharge @ 1C; pass external and simulated internal short tests; overcharge 100% @ 1C for Goal and 80% @ C/5 for Threshold Value.
Lithium-Ion Battery Master Schedule

FY09 FY10 FY11 FY12 FY13 FY14 FY15
Q4 Q3 Q4 Q3 Q4 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 H1 H2 H1 H2 H1 H2 H1 H2

Component Development

- Screen, scale-up, cell design
- Scale-up and Cell Build
- Integrated Component Down-select
- NASA TRL 5/6 Testing
- Environmental Testing Complete
- High Energy Battery
- Lightweight Cell A

Lithium-Ion Battery Master Schedule

FY09 FY10 FY11 FY12 FY13 FY14 FY15
Q4 Q3 Q4 Q3 Q4 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 H1 H2 H1 H2 H1 H2 H1 H2

Component Development

- Screen, scale-up, cell design
- Scale-up and Cell Build
- Integrated Component Down-select
- NASA TRL 5/6 Testing
- Environmental Testing Complete
- Ultra-High Energy Battery
- Lightweight Cell B

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: LiPF6 in EC:EMC:TPP:VC

- Layered Li/NMC|O2 cathode particle
- Varying composition and morphology to improve capacity and charge/discharge rate
- Safety Coating for Thermal Stability
- Li-Metal-PO4

- 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[Li_xNi_yMn_zCo_{1-x-y-z}]O_2 to improve capacity

- Porous, elastomeric binder allows ionic transport and accommodates large volume changes during charge/discharge cycling
- Functionalized nanoparticles adhere to binder without blocking reactive silicon surface area

- Collector
- Coating
- Separator
- Cathode
- Anode
- Charged Load

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

Silicon-based anodes: Specific capacity vs. cycles for three materials at C/10 and 23 °C in coin cell half cell.

---

**Anode Development**

NASA Contract # NNC08CB02C

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

COTR: Concha Reid, NASA GRC

"Advanced Nanostructured Silicon Composite Anode Program"

PI: Dr. Justin Golightly, Lockheed Martin

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

**Approach:**
- Functionaize 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.

Preliminary results for unoptimized materials are shown. Materials were tested at NASA in coin cell half cells.

**Challenge:**
Anode specific capacity fade rates are still too high to meet the goal of 200 cycles at the cell level.
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 at:
- University of Texas at Austin
- NEI Corporation
- JPL

Objective:
Develop Li(NMC) 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).
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
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 show 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

Self-extinguishing time (SET) flammability tests show excellent flame retardance in JPL and Yardney/URI electrolytes.
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
Project: ETDP Energy Storage Project – Space-rated Lithium-ion Batteries
COTR: Judy Jeevarajan, NASA JSC
NASA Contract # NNC09CA04C

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

Approach:
• Coat LiCoO$_2$ 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% LiCoPO$_4$ 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 LiCoO$_2$ 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 manufacturing process.
- 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.

### Options 1 and 2 Table

<table>
<thead>
<tr>
<th>Basic (34 months)</th>
<th>Option 1 Flightweight Cell Fabrication (18 months)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>High Energy Cell</strong></td>
<td>Fabrication and delivery of 12-48 (TBR) High Energy, ~35 Ah (TBR) flightweight cells that incorporate cell-level safety components.</td>
</tr>
<tr>
<td><strong>Ultra High Energy Cell</strong></td>
<td>Fabrication and delivery of 12-48 (TBR) Ultra High Energy, ~35 Ah (TBR) flightweight cells that incorporate cell-level safety components.</td>
</tr>
</tbody>
</table>
  - Component screening and evaluation for manufacturing suitability
  - Component material scale-up
  - Electrode optimization
  - Fabrication and delivery of evaluation screening cells
  - Flightweight cell design

### 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

<table>
<thead>
<tr>
<th>KPP at 0 °C</th>
<th>model at 3 V cutoff</th>
</tr>
</thead>
<tbody>
<tr>
<td>threshold</td>
<td>goal</td>
</tr>
<tr>
<td>Baseline</td>
<td>150</td>
</tr>
<tr>
<td>HE</td>
<td>165</td>
</tr>
<tr>
<td>UHE</td>
<td>180</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.
Energy Storage Risk Assessment: Overall Project – Open Risks
Summary Since December 2007 Major Re-plan

<table>
<thead>
<tr>
<th>Risk ID</th>
<th>Description</th>
<th>Likelihood, Consequence Mitigation</th>
<th>Risk Mgt Approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (ES-14)</td>
<td>Poor integrated cell performance due to potential incompatibility of the best selected cathodes, anodes, electrodes, separators, and their associated unique manufacturing processes to function together as a complete lithium-ion cell design.</td>
<td>Preliminary assessment = 3 / 5. Individual development of advanced components for lithium-ion cells may fail to meet all of the enhanced performance metrics for human-rated batteries. Impact: Additional investigative investigations with added costs will need to be conducted to meet the compatibility issues and safety for human-rating.</td>
<td>Integrate candidate materials together in a laboratory to screen for compatibility and guide selection of frost components. Manufacture evaluation cells with different combinations of candidate component materials and conduct performance, safety and abuse testing to determine the best performing chemistries.</td>
</tr>
<tr>
<td>2 (ES-13a, ES-13b)</td>
<td>Scale-up of critical materials to meet performance goals may not be compatible with existing manufacturing techniques or may require multiple re-qualifications.</td>
<td>There is uncertainty of the load profile and energy requirements within the Constellation Program.</td>
<td>Define the power load profiles and mission requirements as early as possible.</td>
</tr>
<tr>
<td>3 (ES-15)</td>
<td>IPP/SBIR electrolysis funding not stable.</td>
<td>IPP/SBIR funding likely to remain stable in FY09 and FY10. If not, high pressure electrolysis will not be ready for integration further impacting LSS schedule.</td>
<td>Focus SBIR solicitations on Energy Storage needs.</td>
</tr>
</tbody>
</table>

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>Rank/ Trend</th>
<th>Description</th>
<th>Likelihood/Consequences</th>
<th>Risk Mgt Approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (ES-14)</td>
<td>There is uncertainty of the load profile and energy requirements within the Constellation Program.</td>
<td>There is a risk that once the lithium-ion cell design has been baselined, the suppliers may alter their manufacturing process and impact performance or necessitate re-qualification of the lithium-ion cell.</td>
<td>Define the power load profiles and mission requirements as early as possible.</td>
</tr>
<tr>
<td>2 (ES-13a, ES-13b)</td>
<td>Scale-up of critical materials to meet performance goals may not be compatible with existing manufacturing techniques or may require multiple re-qualifications.</td>
<td>The aerospace lithium-ion battery market is small in comparison with the commercial market sector and the commercial market drives the manufacturing process.</td>
<td>Contract with Industry Partner to evaluate advanced materials for their manufacturability. Factor results into component downselection decisions.</td>
</tr>
<tr>
<td>3 (ES-15)</td>
<td>Poor integrated cell performance due to potential incompatibility of the best selected cathodes, anodes, electrodes, separators, and their associated unique manufacturing processes to function together as a complete lithium-ion cell design.</td>
<td>Preliminary assessment = 3 / 5. Individual development of advanced components for lithium-ion cells may fail to meet all of the enhanced performance metrics for human-rated batteries. Impact: Additional investigative investigations with added costs will need to be conducted to meet the compatibility issues and safety for human-rating.</td>
<td>Integrate candidate materials together in a laboratory to screen for compatibility and guide selection of frost components. Manufacture evaluation cells with different combinations of candidate component materials and conduct performance, safety and abuse testing to determine the best performing chemistries.</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.

---

NASA/TM—2011-216963 30
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</th>
<th>Mitigation</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 development is not successful, mass/vol and reliability requirements won’t be met for Lander &amp; LSS.</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>
</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>

1. Non-flow-through stacks built and tested, initial feasibility demonstrated.
2. NFT BOP built and tested, initial feasibility demonstrated.
3. Initial electrolysis work promising, but too early to reduce likelihood a level.
4. Same
5. Same

Top 10 Battery Lower-Level Risks

<table>
<thead>
<tr>
<th>Risk Category</th>
<th>Risk Stmt</th>
<th>Rank</th>
<th>Mitigation</th>
<th>Mitigation 1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

NASA/TM—2011-216963 31
## TRL Status

<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></td>
<td></td>
<td></td>
<td>3-4 Years</td>
</tr>
<tr>
<td>“Ultra High Energy” lithium-ion battery cell</td>
<td>2/3</td>
<td>Component development</td>
<td>$19M*</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>6 Years</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>ETDP</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>
</tr>
<tr>
<td>RFC</td>
<td>Regenerative Fuel Cell</td>
</tr>
<tr>
<td>R.T.</td>
<td>Room Temperature</td>
</tr>
<tr>
<td>SBIR</td>
<td>Small Business Innovative Research</td>
</tr>
<tr>
<td>SPPR</td>
<td>Small Pressurized Rover</td>
</tr>
<tr>
<td>TAMU</td>
<td>Texas A&amp;M University</td>
</tr>
<tr>
<td>TBD</td>
<td>To Be Determined</td>
</tr>
<tr>
<td>TBR</td>
<td>To Be Reviewed</td>
</tr>
<tr>
<td>TCR</td>
<td>Technical Content Review</td>
</tr>
<tr>
<td>TPP</td>
<td>Technology Prioritization Process</td>
</tr>
<tr>
<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


Conference Presentations and Papers


Nader M. Hagh, Mumu Moorthi, Ganesh Skandan, Shirley Meng, William C. West, Ratnakumar Bugga, Concha M. Reid, and Ganesan Nagasubramanian, “High Energy Density Cathode Materials for Li-ion Battery Applications,” 44th Power Sources Conference, June 2010, Las Vegas, NV.


Boris Ravdel and Brett L. Lucht, “Development of Non-Flammable Electrolytes for Lithium Ion Batteries,” NASA Aerospace Battery Workshop, November 2009, Huntsville AL.


M.C. Smart, F.C. Krause, K.A. Smith, W.C. West, J. Soler, G.K.S. Prakash, and B.V. Ratnakumar, “Electrochemical Characterization of LiNi_{x}Co_{1-x}O_{2} and Li(Li_{0.17}Ni_{0.25}Mn_{0.58})O_{2}–based Li-Ion cells Containing Electrolytes with Reduced Flammability,” International Battery Association (IBA) Meeting, Pacific Power Source Symposium 2010, Waikoloa, Hawaii, January 11–15, 2010.


M.C. Smart, B.L. Lucht, and B.V. Ratnakumar “The Use of Electrolyte Additives to Improve the High Temperature Resilience of Li-ion Cells,” 212th Meeting of the Electrochemical Society, Washington, DC, October 7–12, 2007.


M.C. Smart, B.V. Ratnakumar, and K. Amine, “Electrochemical performance and kinetics of LiCo$_{0.33}$Ni$_{0.33}$Mn$_{0.33}$O$_2$ electrodes in low temperature electrolytes,” IBC-HBA 2006, *Waikoloa, Hawaii, 9–12 January 2006.*


K.A. Smith, M.C. Smart, W.C. West, J. Soler, F.C. Krause, G.K.S. Prakash, B.V. Ratnakumar, L. Yang, and B.L. Lucht, “Evaluation of Electrolytes Containing Flame Retardant Additives in LiNi$_{0.5}$Co$_{0.25}$O$_2$ and Li(Li$_{0.17}$Ni$_{0.25}$Mn$_{0.58}$)O$_2$-Based Li-ion Cells,” 216th Meeting of the Electrochemical Society, Vienna, Austria, Oct. 5, 2009.


W.C. West, J. Soler, M. Smart, and B. V. Ratnakumar, “Li$_2$MnO$_3$-LiMO$_2$ (M=Mn, Co, Ni) Solid Solutions With Surface Coatings to Improve Li-ion Cathode Performance,” Materials Science & Technology Meeting, October 2010, Houston TX.


W.C. West, M.C. Smart, and Ratnakumar V. Bugga, Materials for Improving the Specific energy and Safety of Lithium-ion Cells, International Meeting on Lithium Batteries, Montreal, Canada, June 2010.


W.C. West, M.C. Smart, E. Wong and R.V. Bugga, “Characterization Studies of Li(Li$_{(1/3-2x/3)}$Mn$_{(2/3-x/3)}$Ni$_x$)O$_2$ Cathodes,” Electrochemical Society Meeting, October 2007, Washington, DC.

NASA Published:


Reid, Concha M., “Progress in Materials and Component Development for Advanced Lithium-ion Cells for NASA’s Exploration Missions,” NASA/TM number to be assigned (2010).  


Journal Articles


M.C. Smart, B.L. Lucht, and B.V. Ratnakumar, “Electrochemical characteristics of MCMB and LiNi_{1/3}Co_{1/3}O_2 electrodes from cells containing electrolytes with stabilizing additives and exposed to high temperature,” J. Electrochemical Soc., 155 (8), A557-A568 (2008).

M.C, Smart, B.V. Ratnakumar, and K. Amine, “Electrochemical performance and kinetics of LiCo_{0.33}Ni_{0.33}Mn_{0.33}O_2 electrodes in low temperature electrolytes,” J. Power Sources, 168 (2), 501–508 (2007).

R&T Reports


New Technology Reports


Keith Billings, “Catalyst Spray Technique for Fabrication of Membrane Electrode Assemblies (MEAs) for Fuel Cells and Alcohol Electrolysis Cells,” NTR-NPO 47188.


M.C. Smart, R.V. Bugga, A.S. Gozdz, S. Mani, “Electrolytes designed for improved operation of Li-ion cells at high temperatures,” NTR NPO-46527, (Sept 5, 2008).


M.C. Smart, B.L. Lucht, and B.V. Ratnakumar, “The use of electrolyte additives to improve the high temperature resilience of Li-ion cells,” NTR NPO-44805 (January 16, 2007).

M.C. Smart, and B.V. Ratnakumar, “Optimized carbonate and ester-based Li-ion electrolytes with improved low temperature performance of Li-ion cells,” NTR NPO-44974 (March 13, 2007).


**NASA Contractor Reports**


**Patents and Patent Applications**


**Provisional Patent Applications**


Gleb Yushin, Igor Luzinov, Alexandre Magasinski, and Bogdan Zdyrko, “Polymeric Binder for High-Performance Silicon Anodes for Li-ion Batteries,” Serial No. 61/261,520 (November 16, 2009).
**1. REPORT DATE (DD-MM-YYYY)**
01-01-2011

**2. REPORT TYPE**
Technical Memorandum

**3. DATES COVERED (From - To)**

**4. TITLE AND SUBTITLE**
Energy Storage Project Final Report

**5a. CONTRACT NUMBER**

**5b. GRANT NUMBER**

**5c. PROGRAM ELEMENT NUMBER**

**5d. PROJECT NUMBER**

**5e. TASK NUMBER**

**5f. WORK UNIT NUMBER**
WBS 038957.01.01.03

**6. AUTHOR(S)**
Mercer, Carolyn, R.; Jankovsky, Amy, L.; Reid, Concha, M.; Miller, Thomas, B.; Hoberecht, Mark, A.

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**
National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135-3191

**8. PERFORMING ORGANIZATION REPORT NUMBER**
E-17568

**9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)**
National Aeronautics and Space Administration
Washington, DC 20546-0001

**10. SPONSORING/MONITOR’s ACRONYM(S)**
NASA

**11. SPONSORING/MONITORING REPORT NUMBER**
NASA/TM-2011-216963

**12. DISTRIBUTION/AVAILABILITY STATEMENT**
Unclassified-Unlimited
Subject Categories: 20 and 44
Available electronically at http://www.sti.nasa.gov
This publication is available from the NASA Center for AeroSpace Information, 443-757-5802

**13. SUPPLEMENTARY NOTES**

**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

**16. SECURITY CLASSIFICATION OF:**

<table>
<thead>
<tr>
<th>a. REPORT</th>
<th>b. ABSTRACT</th>
<th>c. THIS PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>U</td>
<td>U</td>
<td>U</td>
</tr>
</tbody>
</table>

**17. LIMITATION OF ABSTRACT**
UU

**18. NUMBER OF PAGES**
54

**19. NAME OF RESPONSIBLE PERSON**
STI Help Desk (email:help@sti.nasa.gov)

**19a. TELEPHONE NUMBER**
443-757-5802