Battery and Fuel Cell Development for NASA’s Exploration Missions

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NASA’s return to the moon will require advanced battery, fuel cell and regenerative fuel cell energy storage systems. This paper will provide an overview of the planned energy storage systems for the Orion Spacecraft and the Aries rockets that will be used in the return journey to the Moon. Technology development goals and approaches to provide batteries and fuel cells for the Altair Lunar Lander, the new space suit under development for extravehicular activities (EVA) on the Lunar surface, and the Lunar Surface Systems operations will also be discussed.
Battery and Fuel Cell Development for NASA's Exploration Missions

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- Introduction
- Constellation Projects
  - Ares I Crew Launch Vehicle (CLV)
  - Orion Crew Exploration Vehicle (CEV)
  - Altair Lunar Lander
  - Ares V Cargo Launch Vehicle
  - Extra Vehicular Activity (EVA) Suits
  - Lunar Surface Systems
- Technology Development
  - Exploration Technology Development Program
    Energy Storage Project
    - Li-ion Batteries
    - PEM Fuel Cells
    - PEM Regenerative Fuel Cells
- NESC Battery Working Group
U.S. Space Exploration Policy

- Safely fly the Space Shuttle until 2010
- Complete the International Space Station (ISS)
- Develop a balanced program of science, exploration, and aeronautics
- Develop and fly the Orion Crew Exploration Vehicle (CEV)
- Land on the Moon no later than 2020
- Promote international and commercial participation in exploration

"The next steps in returning to the Moon and moving onward to Mars, the near-Earth asteroids, and beyond, are crucial in deciding the course of future space exploration. We must understand that these steps are incremental, cumulative, and incredibly powerful in their ultimate effect."

- NASA Administrator Michael Griffin
- October 24, 2006

NASA's Exploration Roadmap

05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25...

- Initial Capability Orion
- Lunar Robotic Missions
- Research and Technology Development on ISS
- Commercial Crew/Cargo for ISS
- Space Shuttle Operations
- SSP Transition
- Ares I and Orion Development
- Operations Capability Development (EVA, Ground Operations, Mission Operations)

- Orion and Ares I Production and Operation
- Altair Development
- Ares V & Earth Departure Stage
- Surface Systems Development

- Lunar Outpost Construction
- Mars Exploration 2030
Constellation Leverages Unique Skills and Capabilities Throughout NASA Centers

Dryden
- Lead Abort Flight Test Integration/Operations
- Lead Test crew/procurement
- Flight Test Article
- Development/Integration

JPL
- Thermal Protection System support

Ames
- Lead Thermal Protection System AQP
- Aero-Avionics database
- Ares Abort simulations
- Software and CN&C support

Langley
- Lead Launch Abort System integration
- Lead landing system AQP
- Ares I/I-1 vehicle integration
- Ares aerodynamics lead
- SES Support

Kennedy
- Home for Ground Ops Project
- Ground operations
- Launch operations
- Recovery operations

Johnson
- Home for Program
- Home for Projects, Orion, Mission Ops, EVA, Lunar Lander
- Lead Crew Module integration
- Orion Spacelab Integration
- ISS projects management
- Flight Test Program

Glenn
- Lead Service Module and Spacelab Adapter integration
- Flight Test Article "Pathfinder" fabrication
- Ares I/I-1 upper stage simulator lead
- Ares power, TPS and sensors lead
- ISS, Altair, LM, space testing
- Flight Support
- JSC Telecommunications, Avionics, and Informatics Lead

Goddard
- Communications Support

NASA Exploration Mission Energy Storage Systems

Near-term
- Orion (Crew Exploration Vehicle, CEV)
- Ares I (Crew Launch Vehicle, CLV)
- Ares V (Cargo Launch Vehicle, CaLV)

Lithium-ion baselined for Ares I and Orion

Far-term
- Lunar Precursor and Robotics Program (LPRP)
- Lunar Surface Access Module (Altaire)
- Rovers, Habitats and EVA

Battery, fuel cell, regenerative fuel cell energy storage technologies under development
Orion - Crew Exploration Vehicle Li-Ion Battery

- Operational Requirements
  - 120 Volt system
  - 6000 LEO Cycles at 20% DOD, 14 cycles at 100% DOD
  - Mission length – 235 days
  - 50-68°F – Operating range, excursions 30 day cumulative to 104°F

Yardney - battery manufacturer

Crew Module
- 32 cells, 30AH NCP25-1 (Mars Lander Cells)
- 4 batteries
- Target mass 88 lbs
- Volume allocation 13.6 in. width, 17.6 in length, and 13.4 in height

Service Module
- 32 cells, 7 AH
- 2 batteries
- Target mass 35 lbs
- Volume allocation - 12.4 in width, 16.8 in length, and 11 in height

Ares I Upper Stage Batteries

- Upper Stage – (Single Failure Tolerant)
  - Instrument Unit (IU):
    - Two Power Busses (1 kW average per Bus)
    - Two 16 A-Hr Li-Ion Batteries for EPS
  - Aft Skirt:
    - Two Power Busses (3.4 kW average per Bus)
    - Two 16 A-Hr Li-Ion Batteries
  - Flight (Range) Safety System:
    - Silver Zinc Batteries (heritage)
  - Interstage
    - Three Power Busses (500 W average per Bus)
  - First Stage:
    - 55 A-Hr Silver-Zinc Batteries (heritage)

Common US Battery Line Replaceable Unit Concept
16 Amp-Hr, 22 lbs
Ares V Electrical Power

- Earth Departure Stage (EDS)
  - Design Drivers:
    - Electrical Power for Earth orbit loiter
    - Electrical power transfer to Altair Lunar Lander
    - Launch through trans-lunar injection (TLI) burn
  - Design Alternatives:
    - Solar Array & Lithium-Ion Battery
      - Provides for indefinite loiter times
      - Lower heat rejection requirements
      - Opportunity for commonality with Orion systems
    - Primary Fuel Cell
      - Opportunity for commonality with Lander systems
      - Performance not impacted by vehicle attitude during loiter
      - No significant mechanisms required
      - TLI loads should not be an issue

- Core Stage Systems
  - Batteries & Power Distribution Units – Common with Ares I
  - Flight (Range) Safety System Batteries

- Solid Rocket Booster (SRB)
  - Thrust Vector Control: electro-hydrostatic actuators (EHAs) under consideration
  - May require high-voltage battery

Altair Energy Storage Requirements

Descent Module: Baseline – Primary PEM Fuel Cell
- 3 kW nominal, 6 kW peak, 220 hours continuous
  - Sortie: Power Lander for 9 days continuous (7 days surface)
  - Outpost: 3 days continuous power (1 day on surface)
- Should operate until all residual propellants converted to water/power
- Must operate with expected fuel and oxidant contamination levels of residual lander propellants.
- Must remove dissolved gases from water by-product during all phases of the mission, including in 0-g.
- Human-safe operation from 0 – 30°C and 0 – 1 G

Ascent Module: Baseline Primary LiMnO2 Battery
- Baseline battery 121.6 kg, 22.7 kW-hour sized for an ascent underburn
- Human-safe operation from 0 – 30°C and 0 – 1 G.

LDAC-3 design
Assumes no single-point failures, and 2-string redundancy on battery to minimize LOC. Baselines primary battery
Altair Energy Storage System Options

- Replacing primary battery for ascent stage with very high energy, low cycle secondary will address key risks associated with primary batteries:
  - Inability to verify proper battery function in-flight before critical use;
  - Probable large mass impact when peak/average power ratios defined;
  - Increased mass and volume to address potential Altair need for power in excess of the 1500 W power transfer requirement from Orion & EDS identified in LDAC3

- Rechargeable batteries can eliminate these risks; but mass should not increase appreciably
  - 160 – 200 W-hr/kg at the battery level may be sufficient.
  - Nominal 15 recharge cycles are required with 1.67 kW nominal power and 2 kW peak power, operating for 7 hours continuously.
  - Human-safe operation from 0 – 30°C and 0 – 1 G.

Lunar Extravehicular Activity Suit

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

Preliminary Battery Requirements:
- Human-safe operation
  - ~ 1155 W-Hr energy
  - 8 hours continuous operation
  - ~ 144 W average power
  - 233 W max power
- Current mass allocation: 5 kg
- Current volume allocation: 3 liters
- 100 cycles (operation every other day for six months)

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

Scenario-Based Planning:
Rechargeable batteries and/or regenerative fuel cells for power & support unit, portable utility pallet, and/or mobility systems

- **Power & Support Unit**
  - Mass: PSU 2,867 kg / SSU 680 kg
  - Energy storage: 720 kWh Regenerative Fuel Cells
  - Power generation: 11.2 kW net, 9 meter solar array
  - Power consumables storage: 337 kg oxygen, 43 kg hydrogen; 450 kg water x 2
    (power and scavenge)

- **Crew Mobility Chassis Specifications**
  - 969 kg dry vehicle mass, >100 km range, upgradable with PUPs
  - 0-5 kph low gear, 0-20 kph high gear
  - 20 kWh onboard energy storage (Li-ion battery)
  - 5.9 kW peak power, 1.15 kW average power and 125 W standby power.
  - Nominal drive time is 87 hours and stand-by time is 800 hours.

- **Portable Utility Pallet**
  - Logistics: 25 kg Oxygen, 90 kg Water, 90 kg Wastewater
  - Power Generation: 4.4-kW, 5.5-meter Orion-class array
  - Energy Storage: 10 kWh (Li-ion batteries)
  - Mass: 705.9 kg (dry), 903.4 kg (wet)

Lunar Surface Systems

Potential Requirements

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

Fuel Cell / Regenerative Fuel Cell Needs

- 5,000 hr operational life at poles
- >10,000 hr operational life beyond poles
- 100-1000+ discharge/recharge cycles
- Compatible with H2/O2 tanks at 2000 psi

Battery Needs

- 10-hour discharge and 10-hour charge
- 2000 discharge/recharge cycles
- Temperature controlled to 0 – 30°C
- 5 year calendar life
**Exploration Technology Development Program**

**Energy Storage Project**

**Project Objective:** Reduce risks associated with the use of batteries, fuel cells, and regenerative fuel cells for *Altair, Lunar Surface Systems, and EVA.*

**Project TRL-6 Deliverables:**
- Primary fuel cell for *Altair* Descent Stage
- Regenerative fuel cell for Lunar Surface Power Units and Mobility Systems
- Rechargeable battery cells for *Altair* Ascent Stage, EVA Suit 2, Lunar Surface Mobility Systems

**Lithium-based Battery Technology:**
Develop Lithium-based cells for human-rated, reliable operation with very high specific energy.

**Fuel cell technology:**
Develop proton-exchange-membrane stack and balance-of-plant technology to increase system lifetimes and reduce mass, volume and parasitic power.

**Regenerative fuel cell technology:**
Develop balanced high-pressure electrolyzers and thermal management and reactant processing technologies for integrated electrolyzer/fuel cell.

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**Li-Ion Battery Development**

**Objectives:** Develop Flight Qualified, Human-Rated Li-Ion cells with increased reliability and mass and volume reductions

**Approach:**
- Identify chemistries most likely to meet overall NASA goals and requirements within allotted development timeframe
  - "High energy" and "ultra high energy" cells targeted to meet customer requirements.
- Utilize in-house and NRA Contracts to support component development
  - Develop components to increase specific energy (anode, cathode, electrolyte)
  - Develop low-flammability electrolytes, additives that reduce flammability, battery separators and functional components to improve human-safety;
  - Charge methodology
- Engage industry partner - multi year contract
  - Provide recommendations for component development / help screen components
  - Scale-up components (core)
  - Manufacture evaluation and screening cells
  - Design and optionally manufacture flightweight cells that address NASA's goals
- Complete TRL 5 and 6 testing at NASA
  - Leverage outside efforts
    - Utilize SBIR/IPP efforts
    - Leverage work at DoE and other government agencies

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Cell development TRL definitions:
- TRL 4: Advanced cell components integrated into a flight design cell
- TRL 5: Performance testing on integrated cell shows goals met
- TRL 6: Environmental testing on cell (vibration, thermal) shows robust 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/controllers used to prevent unsafe conditions. There is no non-flammable electrolyte in SOA</td>
<td>Preliminary results indicate a moderate reduction in the performance with flame retardants and non-flammable electrolytes</td>
<td>Benign cell venting without fire or flame and reduce the likelihood and severity of a fire in the event of a thermal runaway</td>
<td>Tolerant to electrical and thermal abuse such as over-temperature, overcharge, reversal, and external short circuit with no fire or flame</td>
</tr>
<tr>
<td>Specific energy</td>
<td>Battery-level specific energy*</td>
<td>90 Wh/kg at C/10 &amp; 30°C</td>
<td>130 Wh/kg at C/10 &amp; 30°C</td>
<td>135 Wh/kg at C/10 &amp; 0°C</td>
<td>&quot;High-Energy&quot;</td>
</tr>
<tr>
<td></td>
<td>Cell-level specific energy</td>
<td>130 Wh/kg at C/10 &amp; 30°C</td>
<td>150 Wh/kg at C/10 &amp; 0°C</td>
<td>165 Wh/kg at C/10 &amp; 0°C</td>
<td>&quot;Ultra-High Energy&quot;</td>
</tr>
<tr>
<td></td>
<td>Cathode-level specific capacity Li(LiMnMn)O₂</td>
<td>180 mAh/g</td>
<td>Li(LiMnMn)O₂ 240 mAh/g at C/10 &amp; 25°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 (MCMB)</td>
<td>280 mAh/g</td>
<td>350 mAh/g (MPG-111)</td>
<td>600 mAh/g at C/10 &amp; 0°C (with Si composite)</td>
<td>1000 mAh/g at C/10 &amp; 0°C (with Si composite)</td>
</tr>
<tr>
<td></td>
<td>Battery-level energy density</td>
<td>250 Wh/l</td>
<td>N/A</td>
<td>270 Wh/l &quot;High-Energy&quot;</td>
<td>320 Wh/l &quot;High-Energy&quot;</td>
</tr>
<tr>
<td></td>
<td>Cell-level energy density</td>
<td>320 Wh/l</td>
<td>N/A</td>
<td>385 Wh/l &quot;High-Energy&quot;</td>
<td>430 Wh/l &quot;Ultra-High&quot;</td>
</tr>
<tr>
<td>Operating environment</td>
<td>Operating temperature</td>
<td>-20°C to +40°C</td>
<td>-5°C to +40°C</td>
<td>0°C to 30°C</td>
<td>0°C 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 3.000 voltaic cell, and at 0°C operation conditions.

** "High-Energy" = Exploration Technology Development Program cathode with MCMB graphite anode

"Ultra-High Energy" = Exploration Technology Development Program cathode with Silicon composite anode

Revised 5/19/09
Lithium-Based Battery Master Schedule

ULTRA-HIGH ENERGY SYSTEMS

Component Development
- NRA contracts & in-House
- Screen, scale-up, cell design
- Scale-up and Cell Build
- Integrated Component Down-select
- NASA TRL 5/6 Testing
- Environmental Testing Complete
- Flightweight Cell A
- Flightweight Cell B

BASIC A
- Screen, scale-up, cell design
- Scale-up and Cell Build #1
- Integrated Component Down-select 1 & 2

BASIC B
- Screen, scale-up, cell design
- Scale-up and Cell Build #2
- Scale-up and Cell Build #3

High Energy Battery

Ultra-High Energy Battery

Safety, Packaging and Control

Rev 05/26/09

Ultra High Energy Battery Feasibility Study

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Final Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safety</td>
<td>17.9</td>
</tr>
<tr>
<td>Rate Capability up to C/5</td>
<td>15.6</td>
</tr>
<tr>
<td>Specific Energy</td>
<td>15.0</td>
</tr>
<tr>
<td>Storage and Calendar Life</td>
<td>12.2</td>
</tr>
<tr>
<td>Energy Density</td>
<td>10.2</td>
</tr>
<tr>
<td>Manufacturability</td>
<td>8.3</td>
</tr>
<tr>
<td>Schedule</td>
<td>8.0</td>
</tr>
<tr>
<td>Cost to TRL 6</td>
<td>6.5</td>
</tr>
<tr>
<td>Cycle Life</td>
<td>3.8</td>
</tr>
<tr>
<td>Rate Capability up to C/2</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Chemistry Options

<table>
<thead>
<tr>
<th>Cathode</th>
<th>Anode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li(LiNMC)O₂ (ETDP)</td>
<td>Si-Based Composite</td>
</tr>
<tr>
<td>Li(Ni₀.₃₃Mn₀.₃₃Co₀.₃₃)O₂</td>
<td>Si-Based Composite</td>
</tr>
<tr>
<td>Li(Ni₀.₃₃Mn₀.₃₃Co₀.₃₃)O₂</td>
<td>Li Metal</td>
</tr>
<tr>
<td>Li(LiNMC)O₂ (ETDP)</td>
<td>Li metal</td>
</tr>
<tr>
<td>LiNiMn₂O₄</td>
<td>Li metal</td>
</tr>
<tr>
<td>LiCoPO₄</td>
<td>Li metal</td>
</tr>
<tr>
<td>(Li₂)S</td>
<td>Li metal</td>
</tr>
</tbody>
</table>
**Cell Level Specific Energy Projections of Final Chemistry Options**

The graph shows the specific energy projections for different cell designs, with options for prismatic and cylindrical cells. The chemistry selected for development is highlighted.

**Advanced Chemistry Options and Final Weights**

<table>
<thead>
<tr>
<th>Cathode</th>
<th>Anode</th>
<th>Final Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li(Ni$<em>{0.33}$Mn$</em>{0.33}$Co$_{0.33}$)O$_2$</td>
<td>Si-based Composite</td>
<td>20.2</td>
</tr>
<tr>
<td>Li(LINMC)$_2$O$_2$ (ETDP)</td>
<td>Si-based Composite</td>
<td>17.0</td>
</tr>
<tr>
<td>LiNiMn$_2$O$_4$</td>
<td>Li metal</td>
<td>15.3</td>
</tr>
<tr>
<td>Li(Ni$<em>{0.33}$Mn$</em>{0.33}$Co$_{0.33}$)O$_2$</td>
<td>Li metal</td>
<td>13.9</td>
</tr>
<tr>
<td>Li(LINMC)$_2$O$_2$ (ETDP)</td>
<td>Li metal</td>
<td>13.1</td>
</tr>
<tr>
<td>(Li$_2$)S</td>
<td>Li metal</td>
<td>11.5</td>
</tr>
<tr>
<td>LiCoPO$_4$</td>
<td>Li metal</td>
<td>9.1</td>
</tr>
</tbody>
</table>

- **Li(NMC) cathode with Si-based composite anode offers:**
  - Higher safety, manufacturability and rate capability
  - Lower specific energy
- **ETDP cathode with Si-based composite anode offers:**
  - Higher specific energy
  - Lower safety, manufacturability and demonstrated rate capability
NASA Research Announcement NNC08ZP022N
Research and Development of Battery Cell Components

♦ Contracts Awarded

- Georgia Tech Research Corp. & Clemson University, “Design of Resilient Silicon Anodes”
- University of Texas at Austin, “Development of High Capacity Layered Oxide Cathodes”
- NEI Corp., “Mixed Metal Composite Oxides for High Energy Li-ion Batteries”
- Yardney, “Flame-retardant, Electrochemically Stable Electrolyte for Lithium-ion Batteries”
- Giner, “Control of Internal and External Short Circuits in Lithium-Ion Batteries”
- Physical Sciences, “Metal Phosphate Coating for Improved Cathode Material Safety”

Battery SBIRs and STTRs

♦ Phase I SBIRs

- Yardney Technical Products – Advanced Battery Materials for Rechargeable Advanced Space-Rated Li-Ion Batteries
- Superior Graphite Co. – SiLix-C Nanocomposites for High Energy Density Li-Ion Battery Anodes
- Physical Sciences, Inc. – Silicon Whisker and Carbon Nanofiber Composite Anode
- TH Chem, Inc. – New Li Battery Chemistry for Improved Performance
- TDA Research, Inc. – High Capacity Anodes for Advanced Lithium Ion Batteries
- EIC Laboratories, Inc. – Nanoshell Encapsulated Li-Ion Battery Anodes for Long Cycle Life
- Giner, Inc. – Non-Flammable, High Voltage Electrolytes for Lithium Ion Batteries

♦ Phase II SBIR – Yardney Technical Products – Nano-Engineered Anode Materials for Rapid Recharge High Energy Density Lithium-ion Batteries

♦ STTR - NEI Corporation - High capacity and high voltage composite oxide cathode for Li-ion batteries
Anodes

Goal: 1000 mAh/g at C/10 and 0°C; > 3X the capacity of SOA Li-ion anodes

<table>
<thead>
<tr>
<th>Technology Challenges</th>
<th>Current Approaches to Address</th>
</tr>
</thead>
</table>
| Minimize volume expansion during cycling | Pursuing various approaches to optimize the anode structure to accommodate volume expansion with cycling  
  • Nanostructured Si composite absorbs strain, resists active particle isolation on cycling  
  • Incorporation of elastic binders in Si–graphite and Si-C matrices  
  • Improvement of mechanical integrity by fabricating structure to allow for elastic deformation |
| Minimize irreversible capacity loss | Protection of active sites with functional binder additives  
  • Pre-lithiation approaches are possible  
  • Nanostructured Si resists fracture and surface renewal |
| 250 cycles | Loss of contact with active particles reduces cycle life. Addressing volume changes and improvement of mechanical integrity will improve cycle life |

Approach - Pursuing multiple methods to develop Silicon-based composite anodes that will enable the specific energy and cycle life goals. Combination of in-house and NRA development activities

Significant results to date:

- First NRA deliverables from Georgia Tech (ETDP-3 GT)
  • 406 mAh/g after 5 cycles at C/20 and 23°C  
  • Translates to ~368 mAh/g respectively at C/20 and 0°C
- Preliminary results from Lockheed Martin NRA:
  • 1592 mAh/g after 3 cycles at ~C/30 and 23°C  
  • 1st cycle irreversible capacity loss = 306 mAh/g  
  • Translates to ~1433 mAh/g at C/30 and 0°C and
- In-house anode synthesis capability established at GRC
  • Complementary approaches being pursued with deliverables Oct 2009
    • Modified resorcinol/formaldehyde gel  
    • Thin Si film in 3D carbon structure
Cathodes

Goals:
- Specific capacity of 280 mAh/g at C/10 and 0°C to 3.0 V
- High voltage operation to 4.8 V
- Improved thermal stability over conventional Li-ion cathodes

<table>
<thead>
<tr>
<th>Technology Challenges</th>
<th>Current Project Approaches to Address</th>
</tr>
</thead>
</table>
| High specific capacity at practical discharge rates | - Vary stoichiometry to determine optimum chemical formulation  
- Reduce particle size  
- Experiment with different synthesis methods to produce materials with physical properties such that their specific capacity is retained on production scale |
| Low volume per unit mass | - Vary cathode synthesis method to optimize properties that can:  
  - Improve energy density  
  - Improve ability to cast cathode powders  
  - Facilitate incorporation of oxide coatings, which have the potential to increase rate capability and reduce capacity fade to extend cycle life |
| Minimize 1st cycle irreversible capacity loss and irreversible oxygen loss | - Surface modification via coatings to improve cathode-electrolyte interfacial properties  
  - Improves capacity retention  
  - Reduces capacity fade |

Cathodes

Significant Results to date:
- Baselined cathode material compositions/structures that are inherently more thermally stable than conventional Li-ion cathode materials
- Achieved 280 mAh/g at C/20 and room temp between 4.8 and 2.0V in small lab scale testing (Li$_{1.2}$Mn$_{0.54}$Ni$_{0.13}$Co$_{0.13}$O$_2$ with Al$_2$O$_3$ coating  
  - Translates to ~239 mAh/g at C/20 and 0°C to 3.0 V
- Achieved 210-220 mAh/g at C/10 and room temp between 4.8 and 2.0V (Li$_{1.2}$Mn$_{0.54}$Ni$_{0.13}$Co$_{0.13}$O$_2$ uncoated  
  - Translates to ~180-188 mAh/g at C/10 and 0°C to 3.0 V  
  - Successfully synthesized in large batch sizes
- Operation to 4.8V demonstrated with good reversibility  
  - Cathodes tested with several electrolyte formulations (need compatible electrolytes to sustain cyclability)
Separators

 Goals:
 - Identification of Li-ion cell separator materials that are compatible with the ETDP chemistry and provide an increased level of safety over SOA Li-ion cell separators
 - Current efforts are focused on assessment of developmental (i.e., company IRAD materials) and commercial separator materials

 Technology Challenges:
 - No significant technology challenges
 - Design optimization for high porosity and low ionic resistance to facilitate ionic conductivity while maintaining mechanical strength
 - Must “shutdown” cell reactions below 130 degrees C without shrinking or losing mechanical integrity

Separators

 Significant results to date:
 - Baseline separator identified (Tonen E20) and evaluated
   - Physical, thermal, electrical and mechanical properties measured and documented
 - Several promising commercial and IRAD materials identified and evaluated. Procured, obtained, or negotiating for additional samples to evaluate for our purposes
   - Physical Sciences, Inc. - Tonen polyethylene (PE)
   - Exxon Mobil - Celgard polypropylene (PP)
   - Kynar PVDF resins - Celgard PP/PE/PP trilayer
   - Porous Power Technologies Symmetrix separators - Saft America ceramics
 - Example results for Symmetrix PVDF Separators developed by Porous Power Technologies:
   - As compared to baseline, higher porosity, lower ionic resistance, lower internal heat generation, and allows for higher power and rate capability
   - Fiber-reinforced separator material may suppress internal shorts at elevated temperatures by maintaining mechanical integrity
### Electrolytes

**Goal:** Flame-retardant and/or non-flammable electrolytes that are stable up to 5V

<table>
<thead>
<tr>
<th>Technology Challenges</th>
<th>Current approaches to address</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrolyte that is stable up to 5V</td>
<td>Experiment with different electrolyte formulations and additives with potential to improve high voltage stability. Study interactions at both electrodes</td>
</tr>
<tr>
<td>Non-flammable or flame retardant electrolyte</td>
<td>Develop electrolytes containing additives with known flame retardant properties. Perform flame retardance assessments on developments that exhibit suitable electrochemical performance</td>
</tr>
<tr>
<td>High voltage stable, non-flammable or flame retardant electrolyte (combination of both properties in one electrolyte system)</td>
<td>Combine flame retardant additives with electrolyte formulations with high voltage stability. Operate systems to high voltages and investigate impacts on power capability and life.</td>
</tr>
<tr>
<td>Electrolytes possessing the requisite physical properties to ensure good rate capacity (adequate conductivity) and compatibility (wettability).</td>
<td>Develop electrolytes that are not excessively viscous to ensure that the ionic conductivity is sufficiently high over the desired temperature range and the separator wettability is adequate.</td>
</tr>
</tbody>
</table>

### Significant results to date:

- Demonstrated capability of flame-retardant electrolytes in experimental and prototype cells and determined the impact on life and rate capability (i.e., Gen 1 electrolyte observed to have comparable life to baseline system).
- Investigated electrolyte additives to improve high voltage cycling performance
  - No significant impact in high voltage performance cycling stability observed vs. baseline electrolyte
  - Determined baseline electrolyte is compatible with high voltage operation in cells with JPL-developed high voltage cathode, when evaluated in experimental cells using Li metal as anodes.
- Examined the ability of linear carbonate type electrolytes to improve high voltage stability
  - No impact on high voltage performance observed
- Assess the performance of flame-retardant additives in a high voltage system
  - Displayed rate performance between C/10 and C/2
  - Electrolytes with flame-retardant additives displayed some reduced power and life versus systems with the baseline electrolyte (i.e., the FRA-containing electrolyte delivered ~ 95% of the baseline electrolyte using a C/2 discharge rate).
- Many investigations in small laboratory coin cells, may different results in a fully mature cell.
Goal: Cells that are tolerant to electrical and thermal abuse

<table>
<thead>
<tr>
<th>Technology challenges</th>
<th>Approaches to address</th>
</tr>
</thead>
</table>
| Safe Electrodes       | • Develop materials to improve tolerance to an electrical abuse condition  
                        |   • Approach 1: Develop a high-voltage stable (phosphate) coating on a cobaltate cathode particle to increase the safe operating voltage of the cell and reduce the thermal dissipation by the use of a high-voltage stable coating material (cobalt phosphate).  
                        |   • Approach 2: Develop a composite thermal switch to shutdown cell reactions safely using coatings on the current collector substrates |
| Safe electrolyte      | • Development of advanced high voltage, non-flammable/flame-retardant electrolytes (via electrolyte task) |

**Significant results to date:** Cathode particles with a coating display no exotherms up to 300 °C; switching behavior with composite coating on current collector observed at >60 °C.
**PEM Fuel Cell Development**

Objectives:
- Increase system lifetimes and reduce system mass, volume and parasitic power for primary and regenerative proton exchange membrane (PEM) fuel cells, and
- Enable the use of regenerative PEM fuel cells including the use of high pressure (>2000 psi) reactants to reduce tankage mass and volume.

- Focus is exclusively on Proton Exchange Membrane fuel cells and regenerative fuel cell systems

- Technical Approach is to develop:
  - "Non-flow-through" proton exchange membrane stack and customized balance-of-plant technology;
  - Advanced membrane-electrode-assemblys (MEAs) for both fuel cells and electrolyzers,
  - Balanced high-pressure electrolyzers; and
  - Thermal and reactant management technologies for electrolyzer/fuel-cell integration into regenerative fuel cell systems.

**Fuel Cell Technical Approach**

Develop "non-flow-through" proton exchange membrane fuel cell technology for a system improvement in weight, volume, reliability, and parasitic power over "flow-through" technology

Flow-Through components eliminated in Non-Flow-Through system include:
- Pumps or injectors/ejectors for recirculation
- Motorized or passive external water separators

Non-Flow-Through PEMFC technology characterized by dead-ended reactants and internal product water
- Tank pressure drives reactant feed; no recirculation
- Water separation occurs through internal cell
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* (PEM)</th>
<th>Threshold Value** (@ 3 kW)</th>
<th>Goal** (@ 3 kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Altair: 3 kW for 220 hours continuous, 5.5 kW peak</td>
<td>System power density</td>
<td>Fuel Cell</td>
<td>49 W/kg</td>
<td>88 W/kg</td>
<td>136 W/kg</td>
</tr>
<tr>
<td></td>
<td>RFC (without tanks)</td>
<td>n/a</td>
<td>25 W/kg</td>
<td>36 W/kg</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fuel Cell Stack power density</td>
<td>n/a</td>
<td>n/a</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>n/a</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>76%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>individual cell voltage</td>
<td>0.65V</td>
<td>0.89V</td>
<td>0.90V</td>
</tr>
<tr>
<td></td>
<td></td>
<td>For Electrolysis</td>
<td>60%</td>
<td>84%</td>
<td>85%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>individual cell voltage</td>
<td>1.48</td>
<td>1.46</td>
<td>1.44</td>
</tr>
<tr>
<td></td>
<td></td>
<td>For RFC (Round Trip)</td>
<td>n/a</td>
<td>62%</td>
<td>64%</td>
</tr>
<tr>
<td></td>
<td>System efficiency @ 200 mA/cm²</td>
<td>For Fuel Cell</td>
<td>71%</td>
<td>65%***</td>
<td>71%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Parastatic penalty</td>
<td>2%</td>
<td>10%</td>
<td>2%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Regenerative Fuel Cell***</td>
<td>n/a</td>
<td>n/a</td>
<td>43%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Parastatic penalty</td>
<td>n/a</td>
<td>n/a</td>
<td>10%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>High Pressure penalty</td>
<td>n/a</td>
<td>n/a</td>
<td>20%</td>
</tr>
<tr>
<td></td>
<td>Maintenance-free lifetime</td>
<td>Altair: 220 hours (primary)</td>
<td>2500 hrs</td>
<td>13,500 hrs</td>
<td>5,000 hrs</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Surface: 10,000 hours (RFC)</td>
<td>2500 hrs</td>
<td>n/a</td>
<td>220 hrs</td>
</tr>
</tbody>
</table>

**Based on limited small-scale testing.
***Threshold and Goal values based on full-scale (3 kW) fuel cell and RFC technology.
****Teledyne passive flow through with latest MEA.
*****Includes high pressure penalty on electrolysis efficiency 2000 psi.

Maintenance-free operating life
Altair: 220 hours (primary)
Surface: 10,000 hours (RFC)

---

Fuel Cell Master Schedule

May 20, 2009

<table>
<thead>
<tr>
<th>Constellation Project</th>
<th>FY08</th>
<th>FY09</th>
<th>FY10</th>
<th>FY11</th>
<th>FY12</th>
<th>FY13</th>
<th>FY14</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lander - Altair</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>LSS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Regenerative Fuel Cells</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non Flow-Thru Technology (small area)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lab Stack #1 (50 cm²/Cell)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lab Stack #2 (50 cm²/Cell)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lab Stack #3 (50 cm²/Cell)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lab Stack #4 (50 cm²/Cell)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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Progression of Primary Fuel Cell Hardware

<table>
<thead>
<tr>
<th>MEA Infusion</th>
<th>Primary Fuel Cell Hardware</th>
<th>Hardware Description</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Laboratory Units</td>
<td>Laboratory stack is 50 cm² Stainless Steel</td>
</tr>
<tr>
<td></td>
<td>Lab stack #1 is graphite. Deliverable from SBIR contract. 1st Non-Flow-Through stack at NASA.</td>
<td>4 cells, 40 – 80 W 1st balance-of-plant (BOP #1) developed.</td>
</tr>
<tr>
<td></td>
<td>Lab stack #2 incorporates NASA flat plate heat pipes and MEAs. Partially includes innovative assembly technology. Stainless steel plate used to accommodate heat pipe.</td>
<td>4 cells, 40 – 80 W</td>
</tr>
<tr>
<td></td>
<td>Lab stack #3 fully integrates innovative assembly technology.</td>
<td>4 cells, 40 – 80 W</td>
</tr>
<tr>
<td></td>
<td>Lab stack #4 fully integrates innovative assembly technology with reactant pre-humidification and product-water dissolved gas removal</td>
<td>12 cells, 100 – 200 W 2nd balance-of-plant (BOP #2) with autonomous operation</td>
</tr>
<tr>
<td></td>
<td>Large-Area Units</td>
<td>Large-area stack is 150 cm² Stainless Steel</td>
</tr>
<tr>
<td></td>
<td>Large-area cell design based on lab stack test data.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Short stack has 4-cells. Two units will be delivered, both of the same design.</td>
<td>3rd balance-of-plant (BOP #3)</td>
</tr>
<tr>
<td></td>
<td>Breadboard system is a quarter-scale (35–40 cells) stack. This unit will be used for TRL-5 testing.</td>
<td>35 – 40 cells, ~1 kW 4th balance-of-plant (BOP #4), fully autonomous</td>
</tr>
<tr>
<td></td>
<td>Engineering Model</td>
<td>Based on Breadboard design Uses final materials (e.g. Niobium)</td>
</tr>
<tr>
<td>X</td>
<td>Engineering model to be used for TRL-6 testing</td>
<td>150 cm², ~140 cells, 2 – 3 kW</td>
</tr>
</tbody>
</table>

**Integrated Balance-of-Plant**

- 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 only 10 watts of parasitic power to operate the fuel cell system
- A full-scale (3-kw fuel cell system) balance-of-plant will likely operate on only 50 watts or less of parasitic power (same number of components, but some components larger)
- A 2-12 kW flow-thru fuel cell system tested at GRC required over 1000 watts of parasitic power during operation
- That difference in parasitic power means that Altair would need 100-200 kg less reactants over the course of its 2-3 week mission using a non-flow-through fuel cell system vs. a flow-through system
Membrane Electrode Assembly

- 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.

Current density, mA/cm²
(86%)(72%) = 62% round-trip RFC stack efficiency @ 200 mA/cm²

Comparison of JPL's best iridium-doped ruthenium with the latest vendor MEA shows 30mV performance improvement by the NASA material.

Leveraged Activities: Fuel Cells

Fuel Cell Working Group

To facilitate knowledge transfer that will benefit the space power community by ensuring that fundamental knowledge and understanding underpins new technology development. Participants have the opportunity to receive early insights into NASA-funded technical advances, and the opportunity to provide opinions regarding the relevance of NASA-funded research.

IPP Seed Fund Program

- The Boeing Company and Teledyne Energy Systems – Human-Rated Space Power Systems Pallet Demonstrating Fuel Cells, Lithium-Ion Batteries and Advanced Thermal Management Technologies
- Hamilton Sundstrand Space Systems – Advanced High-Pressure Electrolysis System Development for NASA's Explorations Systems Program
Leveraged Activities: Fuel Cells

Phase I SBIRs
- Amsen Technologies – A Novel Heat Pipe Plate for Passive Thermal Control of Fuel Cells
- Thermacore – Titanium Heat Pipe Thermal Plane
- Infinity Fuel Cell and Hydrogen – Advanced Cathode Electrolyzer
- Giner Electrochemical Systems – Static Water Vapor Feed Electrolyzer
- Ridgetop Group – Innovative Fuel Cell Health Monitoring IC

Phase II SBIRs
- ElectroChem. – Advanced Approaches to Greatly Reduce Hydrogen Gas Crossover Losses in PEM Electrolyzers Operating at High Pressures and Low Current Densities
- Giner Electrochemical Systems – Dimensionally Stable Membrane for High Pressure Electrolyzers
- Giner Electrochemical Systems – Electrolyzer for NASA Lunar Regenerative Fuel Cells
- Distributed Energy Systems (Proton Energy) – Closed-Loop Pure Oxygen Static Feed Fuel Cell for Lunar Missions
- Giner Electrochemical Systems – Advanced Composite Bipolar Plate for Unitized Regenerative Fuel Cell/Electrolyzer Systems

SBIRs developing alternative non-flow-through fuel cell technology, balanced high-pressure electrolysis technology, improved MEAs, and advanced balance-of-plant components for electrical and thermal management

NASA Engineering and Safety Center (NESC)
NASA Aerospace Flight Battery Systems Working Group
Addresses critical battery-related performance / manufacturing issues for NASA and the aerospace community

Objectives
- Develop/maintain/provide tools for the validation of aerospace battery technologies
- Accelerate technology readiness and provide infusion paths for emerging technologies
- Enable implementation of critical risk-mitigating test programs
- Disseminate validation/assessment tools, quality assurance and information to the NASA and aerospace battery communities
- Provide problem resolution expertise and capabilities

Working Group Makeup
- NASA Center members on core teams responsible for task implementation
- Partner agencies provide consultation and support for planning/reviewing activities
Binding Procurements – guidelines related to requirements for the battery system that should be considered at the time of contract award

Wet Life of Ni-H₂ Batteries – issues/strategies for effective storage and impact of long-term storage on performance and life

Generic Guidelines for Lithium-ion Safety, Handling and Qualification – Standardized approaches developed and risk assessments
  - Lithium-ion Performance Assessment – survey of manufacturers and capabilities to meet mission needs. Guidelines document generated
  - Conditions Required for using Pouch Cells in Aerospace Missions – focus on corrosion, thermal excursions and long-term performance issues. Document defining requirements to maintain performance and life
  - High Voltage Risk Assessment – focus on safety and abuse tolerance of battery module assemblies. Recommendations of features required for safe implementation
  - Procedure for Determination of Safe Charge Rates – evaluation of various cell chemistries and recommendation of safe operating regimes for specific cell designs

Lithium-ion Battery Source Material Availability – provide additional support for the governmental Title 3 effort aimed at ensuring a constant supply of source material

NASA Aerospace Battery Workshop – government-industry forum focused on battery industry developments and issues (held annually in the Fall)

Concluding Remarks

NASA GRC supports the development of electrochemical systems for NASA’s upcoming Exploration Missions - from fundamental technology development for EVA, Altair and Lunar Surface Systems through flight hardware development for Ares and Orion Flight Programs