Battery and Fuel Cell Development for NASA’s Constellation 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.

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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

- 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
Constellation Leverages Unique Skills and Capabilities Throughout NASA Centers

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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**
  - Ares V (Cargo Launch Vehicle, CaLV) - EDS
  - Precursor and Robotics Program (LPRP)
  - Lunar Surface Access Module (Altair)
  - 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
  - **Alt 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)
    - 3 16AH Li-Ion Batteries
  - **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
    - *Primary Fuel Cell*
      - Opportunity for commonality with Orion 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

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**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

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**Lunar Extravehicular Activity Suit**

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

**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)

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**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**
  - 669 kg dry vehicle mass, >100 km range, upgradeable 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: ~65 kg (dry), ~300 kg (full)
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
- >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

Preliminary Fuel Cell/Regenerative Fuel Cell Design Parameters
- 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

Preliminary Battery Design Parameters
- 10-hour discharge and 10-hour charge
- 2000 discharge/recharge cycles
- Temperature controlled to 0 – 30°C
- 5 year calendar life

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 lightweight 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

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 reactive processing technologies for integrated electrolyzer/fuel cell.

Energy Storage Project Cell Development for Batteries

High Energy Cell
- L/Li(NiMn)O_2
- NASA Cathode
- Conventional Carbonaceous Anode
- 180 Wh/kg @ cell level
- 150 Wh/kg @ battery-level
- At 0°C C/10
- ~2000 cycles to 80% of original capacity at 100% DOD

Ultra-High Energy Cell
- L/Li(NiMn)O_2
- NASA Cathode
- Si-composite NASA Anode
- 260 Wh/kg @ cell level
- 220 Wh/kg @ battery-level
- At 0°C C/10
- ~200 cycles to 80% of original capacity at 100% DOD

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/controls used to prevent unsafe conditions. There is no flammable electrolyte in SEI.</td>
<td>Preliminary results indicate a moderate reduction in the performance with flammable electrolytes and non-flammable electrolytes.</td>
<td>Design 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, overcurrent, reverse, and external short circuit with no fire or flame.</td>
</tr>
</tbody>
</table>

**Specific energy**
- Lead-acid: 150-200 Wh/kg 10 cycles
- NiCd: 180-240 Wh/kg 200 cycles

**Battery-level specific energy**
- 90 Wh/kg at C/10 & 30°C
- 65 Wh/kg at C/10 & 0°C (MEH review)

**Cell-level specific energy**
- 130 Wh/kg at C/10 & 30°C
- 150 Wh/kg at C/10 & 0°C

**Cathode-level specific capacity**
- LiNi0.5Mn1.5O4 180 mAh/g
- LiNi0.5Mn1.5O4, LiCoO2 240 mAh/g at C/10 & 30°C
- LiNi0.5Mn1.5O4, LiCoO2 250 mAh/g at C/10 & 20°C
- 200 mAh/g at C/20 & 0°C

**Anode-level specific capacity**
- 385 mAh/g (MCMB) 350 mAh/g (NC111)
- 450 mAh/g (Si composite)

**Energy density**
- Lander: 311 Wh/l
- Rover: 180 Wh/l
- EX/VE: 400 Wh/l

**Operating environment**
- -20°C to +40°C
- 50% to 70% RH

Assumes pretzel cell packaging for threshold values. Goal values include lightweight battery packaging.

- Battery values are assumed at 100% SOH, discharged at C/10 to 1,000 cycles, and at IPC operating condition.
- "High-Energy" = Exploration Technology Development Program cathode with MCMB graphite anode
- "Ultra-High Energy" = Exploration Technology Development Program cathode with silicon composite anode

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**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/engines 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 wicking

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**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 (some 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.
## 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><strong>Altair:</strong></td>
<td>System power density</td>
<td>49 Wh/kg</td>
<td>n/a</td>
<td>99 Wh/kg</td>
<td>136 Wh/kg</td>
</tr>
<tr>
<td><strong>3 kW for 220 hours continuous, 3.5 kW peak</strong></td>
<td>RFC (without tanks)</td>
<td>n/a</td>
<td>25 Wh/kg</td>
<td>36 Wh/kg</td>
<td></td>
</tr>
<tr>
<td><strong>Fuel Cell Stack power density</strong></td>
<td>n/a</td>
<td>n/a</td>
<td>107 Wh/kg</td>
<td>231 Wh/kg</td>
<td></td>
</tr>
<tr>
<td><strong>Fuel Cell Balance-of-plant mass</strong></td>
<td>n/a</td>
<td>n/a</td>
<td>21 kg</td>
<td>9 kg</td>
<td></td>
</tr>
<tr>
<td><strong>Lunar Surface Systems:</strong> TBO kW for 15 days continuous operation</td>
<td>MEA efficiency @ 200 mA/cm²</td>
<td>73%</td>
<td>0.90V</td>
<td>0.95V</td>
<td>0.92V</td>
</tr>
<tr>
<td><strong>Power: TBO</strong></td>
<td>For Fuel Cell</td>
<td>73%</td>
<td>0.95V</td>
<td>0.98V</td>
<td></td>
</tr>
<tr>
<td><strong>Based on limited small-scale testing</strong></td>
<td>Individual cell voltage</td>
<td>73%</td>
<td>0.95V</td>
<td>0.98V</td>
<td></td>
</tr>
<tr>
<td><strong>System efficiency @ 200 mA/cm²</strong></td>
<td>n/a</td>
<td>n/a</td>
<td>62%</td>
<td>62%</td>
<td>64%</td>
</tr>
<tr>
<td><strong>Electric power flow through with liquid MEA</strong></td>
<td>System efficiency @ 200 mA/cm²</td>
<td>71%</td>
<td>0.95V</td>
<td>0.98V</td>
<td></td>
</tr>
<tr>
<td><strong>Regenerative Fuel Cell</strong>*</td>
<td>Parasitic penalty</td>
<td>2%</td>
<td>0.95V</td>
<td>0.98V</td>
<td></td>
</tr>
<tr>
<td><strong>Parasitic penalty</strong></td>
<td>n/a</td>
<td>n/a</td>
<td>10%</td>
<td>10%</td>
<td>5%</td>
</tr>
<tr>
<td><strong>High Pressure penalty</strong></td>
<td>n/a</td>
<td>n/a</td>
<td>43%</td>
<td>43%</td>
<td>54%</td>
</tr>
<tr>
<td><strong>Maintenance-free lifetime</strong></td>
<td>Maintenance-free operating life</td>
<td>2500 hrs</td>
<td>13,500 hrs</td>
<td>5,000 hrs</td>
<td>10,000 hrs</td>
</tr>
<tr>
<td><strong>Altair: 220 hours (primary)</strong></td>
<td>Fuel Cell MEA</td>
<td>n/a</td>
<td>n/a</td>
<td>5,000 hrs</td>
<td>10,000 hrs</td>
</tr>
<tr>
<td><strong>Surface: 10,000 hours (RFC)</strong></td>
<td>Electrolysis MEA</td>
<td>n/a</td>
<td>n/a</td>
<td>5,000 hrs</td>
<td>10,000 hrs</td>
</tr>
<tr>
<td><strong>Fuel Cell System (for Altair)</strong></td>
<td>n/a</td>
<td>n/a</td>
<td>220 hrs</td>
<td>220 hrs</td>
<td></td>
</tr>
<tr>
<td><strong>Regenerative Fuel Cell System</strong></td>
<td>n/a</td>
<td>n/a</td>
<td>5,000 hrs</td>
<td>10,000 hrs</td>
<td></td>
</tr>
</tbody>
</table>

### 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

### 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