The Use of Nanomaterials to Achieve NASA’s Exploration Program Power Goals

J. Jeevarajan, Ph.D.

NASA-JSC, Houston, TX
Outline

• Power Needs (Customers) for Exploration
• Technology Programs to Achieve Safe and High Energy Power Goals
• Summary and Conclusions
Exploration Program

Courtesy: NASA Ambassador package

J. Jeevarajan, Ph.D. / NASA-JSC
Our Exploration Fleet
What Will the Vehicles Look Like?

Earth Departure Stage

Ares V
Cargo Launch Vehicle

Orion
Crew Exploration Vehicle

Altair
Lunar Lander

Ares I
Crew Launch Vehicle
Lunar Surface Systems (Mobility)
Pressurized Rover

Preliminary Power Requirements:
Safe, reliable operation
>150 Wh/kg at battery level
~ 500 cycles
Operation Temp: 0 to 30 °C
Maintenance-free operation

J. Jeevarajan, Ph.D. / NASA-JSC
Lunar Surface Systems (Mobility) / Lunar Outpost

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

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-m diam Orion-class solar array
• Energy Storage: 10 kWh (Li-ion batteries)
• Mass: 708.9 kg (dry), 963.4 kg (wet)

Outpost Power Needs
• ~20-40 kW lunar daytime power level
• ~10-20 kW lunar nighttime power level
• Modular systems with 5-10 year calendar life
• Reliable, human-rated operation in thermal, dust, launch/landing, vacuum environments
• Low mass and volume
• Autonomous control and operation

Battery Needs
• 10-hour discharge and 10-hour charge
• 2000 discharge/recharge cycles
• Temperature controlled to 0 to +30 °C
• 5 year calendar life

J. Jeevarajan, Ph.D. / NASA-JSC
Altair Lunar Lander Ascent Module

Ascent Module:
- Secondary Batteries are considered critical for the Ascent Stage.
- LDAC-3 recommended a 121.6 kg, 22.7 kW-hour primary battery, sized for an ascent underburn.
- Key risks associated with primary batteries:
  1. Inability to verify proper battery function in-flight before critical use;
  2. Probable large mass impact when peak/average power ratios defined;
  3. 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.
  - Nominally ten 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 to +30 °C and zero to 1g.

J. Jeevarajan, Ph.D. / NASA-JSC
Extravehicular Activity (EVA) Suit
Lunar EVA 2nd Configuration

Enhanced Helmet Hardware:
- Lighting
- Heads-Up-Display
- Soft Upper Torso (SUT) Integrated Audio

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

Video: Suit Camera

PLSS:
Fan, pump, ventilation subsystem processor; Heater, controllers, and valve

Enhanced Liquid Cooling Garment:
- Bio-Med Sensors

- Power to support 8-hour EVA provided by battery in Portable Life Support System
- Preliminary battery design goals:
  - Human-safe operation
  - 144 W (average) and 233 W (peak) power
    Assumes 1% connector loss and 30% margin for growth in power requirements
  - No more than 5 kg mass and 3 liter volume
  - 100 cycles (use every other day for 6 months)
  - 8-hour discharge to at most 85% depth-of-discharge
  - Temperature controlled to 0 to +30 °C
- Secondary batteries are considered critical for EVA Suit 2.

Current Suit Batteries:
EMU: 20.5 V; min 26.6 Ah (7 hr EVA), 9A peak, 5 yr, <15.5 lbs, 30 cycles
SAFER: 42 V; 4.2 Ah (in emergency only)
REBA: 12.5 V, 15 Ah, (7 hr EVA); 5 yr, ~6 lbs
EHIP: 6 V, 10.8 Ah; (7 hr EVA); 5 yr, ~1.8 lbs
Exploration Technology Development Program (ETDP)
Energy Storage Battery Development Schedule for Constellation

PDR: Preliminary Design Review
CDR: Critical Design Review
SRR: System Requirements Review
TRL: Technology Readiness Level

TRL 4 — components integrated but not tested
TRL 5 — Performance testing complete
TRL 6 — Environmental testing complete

J. Jeevarajan, Ph.D. / NASA-JSC
<table>
<thead>
<tr>
<th>Customer Need</th>
<th>Performance Parameter</th>
<th>State-of-the-Art</th>
<th>Current Value</th>
<th>Threshold Value</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safe, reliable operation</td>
<td>No fire or flame</td>
<td>Instrumentation/controls used to prevent unsafe conditions. There is no non-flammable electrolyte in 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, over-charge, reversal, and external short circuit with no fire or flame</td>
</tr>
<tr>
<td>Specific energy</td>
<td>Lander: 150 – 210 Wh/kg 10 cycles</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rover: 150 – 200 Wh/kg</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>EVA: 200 – 300 Wh/kg 100 cycles</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy density</td>
<td>Lander: 311 Wh/l</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rover: TBD</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>EVA: 240 – 400 Wh/l</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operating environment</td>
<td>0°C to 30°C, Vacuum</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Battery-level specific energy**: 90 Wh/kg at C/10 & 30°C, 83 Wh/kg at C/10 & 0°C (MER rovers)

**Cell-level specific energy**: 130 Wh/kg at C/10 & 30°C, 118 Wh/kg at C/10 & 0°C

**Cathode-level specific capacity**: Li(Li_{0.17}Ni_{0.25}Mn_{0.58})_O_2

**Anode-level specific capacity**: 320 mAh/g (MCMB)

**Battery-level energy density**: 250 Wh/l

**Cell-level energy density**: 320 Wh/l

**Operating temperature**: -20°C to +40°C

**Threshold Value**

- **High-Energy**: 135 Wh/kg at C/10 & 0°C
- **Ultra-High Energy**: 150 Wh/kg at C/10 & 0°C

**Goal**

- **High-Energy**: 150 Wh/kg at C/10 & 0°C
- **Ultra-High Energy**: 220 Wh/kg at C/10 & 0°C

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 volts/cell, and at 0°C operating 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 06/02/2008
ETDP Li-ion Cell Development

- **Component-level goals** are being addressed through a combination of NASA in-house materials development efforts, NASA Research Announcement contracts (NRA), and grants.
- Materials developed will be delivered to NASA and screened for their electrochemical and thermal performance, and compatibility with other candidate cell components.
- Other activities funded through NASA can be leveraged – NASA Small Business Innovative Research (SBIR) Program and Innovative Partnership Program (IPP).
- Leveraging off other government programs (DOD, DOE) for component-level technology.
- Leveraging off other venues through Space Act Agreements (SAA) that involve partnerships with industry partners such as Exxon; non-profit organizations such as Underwriters Laboratory (UL), etc.
“High Energy” Cell
Baseline for EVA and Rover
Lithiated-mixed-metal-oxide cathode / Graphite anode
Li(LiNMC)O₂ / Conventional carbonaceous anode
150 Wh/kg (100% DOD) @ battery-level 0°C C/10
80% capacity retention at ~2000 cycles

“Ultra-High Energy” Cell
Upgrade for EVA and Altair, possibly Rover
Lithiated-mixed-metal-oxide cathode / Silicon composite anode
Li(LiNMC)O₂ / silicon composite
220 Wh/kg (100% DOD) @ battery-level 0°C C/10
80% capacity retention at ~200 cycles

J. Jeevarajan, Ph.D. / NASA-JSC
Anode Development
Led by NASA GRC (William Bennett, ASRC)

- **Goal:** 1000 mAh/g at C/10 (10 hour discharge rate) and 0°C
  - Over 3 times the capacity of SOA Li-ion anodes
  - Threshold value = 600 mAh/g at C/10 and 0°C

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

J. Jeevarajan, Ph.D. / NASA-JSC
**Cathode Development**  
*Led by R. Bugga (JPL)*

**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 1\textsuperscript{st} cycle irreversible capacity loss and irreversible oxygen loss | • Surface modification via coatings to improve cathode-electrolyte interfacial properties  
  • Improves capacity retention  
  • Reduces capacity fade |

J. Jeevarajan, Ph.D. / NASA-JSC
Safety Component Development
Led by NASA JSC (Judy Jeevarajan)

- Development of internal cell materials (active or inactive) designed to improve the inherent safety of the cell
  - Approach 1: Develop a high-voltage stable (phosphate type) coating on cathode particles to increase the safe operating voltage of the cell and reduce the thermal dissipation by the use of a high-voltage stable coating material. (Nanosized material)

- Approach 2: Develop a composite thermal switch to shutdown cell reactions safely using coatings on the current collector substrates (nanoparticle metals)
SBIR

Phase I:
TDA Research: Si/C composite anode (nanomaterials)
TH Chem: Improved cathodes – Polymer/S type

Phase II: Yardney Technical Products
• In Phase I, high-rate capability with Cu nanorod and Fe$_3$O$_4$ anodes was demonstrated.
• Phase II has several facets:
  – Baseline Li titanate anode (NTP) with LiNiCoO$_2$ cathode
  – High voltage cathode LiCoPO$_4$
  – Nanoengineered anode of Fe$_3$O$_4$ with Cu nanorods
  – Carbon nanotubes (CNT) with Al current collector and Fe$_3$O$_4$ anode
• 6 Other SBIR Phase I at other Centers
• FY10: Reviewed nanotechnology related proposals for both batteries and capacitors.
Summary

• Exciting Future Programs ahead for NASA
• Power is needed for all Exploration vehicles and for the missions.
• For long term missions as in Lunar and Mars programs, safe, high energy/ultra high energy batteries are required.
• Nanomaterial usage also increases the energy density of the cells apart from increasing the power density.
Acknowledgment

Coworkers in Power Systems Branch