# ADVANCED LITHIUM-ION CELL DEVELOPMENT FOR NASA'S CONSTELLATION MISSIONS

The Energy Storage Project of NASA's Exploration Technology Development Program is developing advanced lithium-ion batteries to meet the requirements for specific Constellation missions. NASA GRC, in conjunction with JPL and JSC, is leading efforts to develop High Energy and Ultra High Energy cells for three primary Constellation customers: Altair, Extravehicular Activities (EVA), and Lunar Surface Systems. The objective of the High Energy cell development is to enable a battery system that can operationally deliver approximately 150 Wh/kg for 2000 cycles. The Ultra High Energy cell development will enable a battery system that can operationally deliver 220 Wh/kg for 200 cycles. To accomplish these goals, cathode, electrolyte, separator, and safety components are being developed for High Energy Cells. The Ultra High Energy cell development adds lithium alloy anodes to the component development portfolio to enable much higher cell-level specific energy. The Ultra High Energy cell development is targeted for the ascent stage of Altair, which is the Lunar Lander, and for power for the Portable Life support System of the EVA Lunar spacesuit. For these missions, mass is highly critical, but only a limited number of cycles are required. The High Energy cell development is primarily targeted for Mobility Systems (rovers) for Lunar Surface Systems, however, due to the high risk nature of the Ultra High Energy cell development, the High Energy cell will also serve as a backup technology for Altair and EVA. This paper will discuss mission requirements and the goals of the material, component, and cell development efforts in further detail.

# Advanced Lithium-Ion Cell Development for NASA's Constellation Missions

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# U.S. Space Exploration Policy

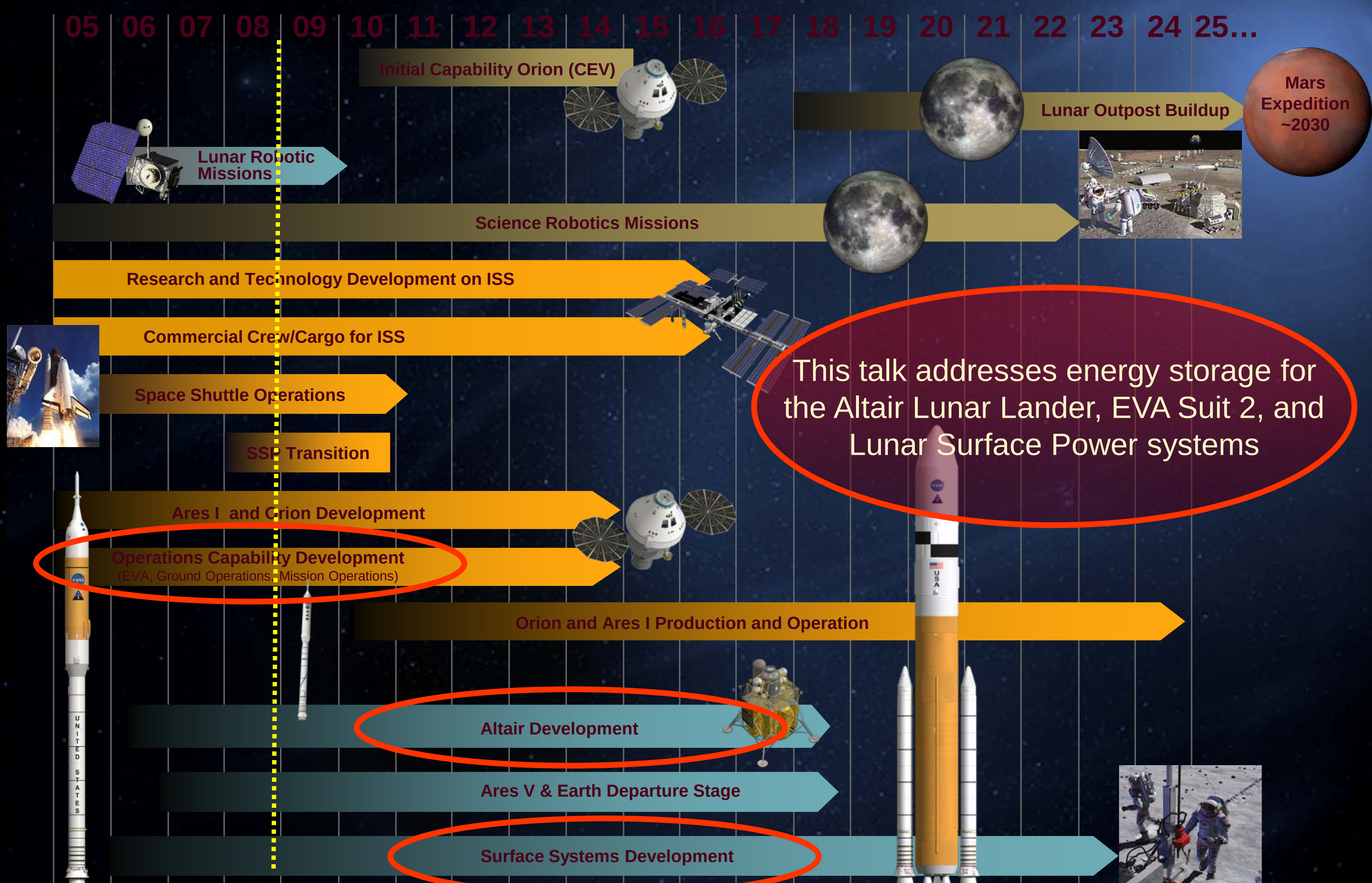
**FUNDAMENTAL GOAL IS TO ADVANCE U.S. SCIENTIFIC, SECURITY, AND ECONOMIC INTEREST THROUGH A ROBUST SPACE EXPLORATION PROGRAM**

## Preparing for Mars Exploration: First Stop, Our Moon

- Use the Moon as a test bed to reduce risk for future human Mars missions
- Advance technology to reduce mission costs and support exploration
- Perform systems testing for reliability in harsh environments
- Expand mission and science surface operations experience
- Build human-machine collaboration to achieve more than either alone
- Break the bonds of dependence on Earth with closed-loop life support
- Develop and test power generation and propulsion
- Invest in common hardware for Moon, Mars, and other Exploration objectives




# NASA's Exploration Roadmap



# Exploration Technology Development Program
# Energy Storage Project

## Exploration Technology Development Program

Multiple focused projects to develop enabling technologies addressing high priority needs for Lunar exploration. Matures technologies to the level of demonstration in a relevant environment – TRL 6

## Energy Storage Project –

Developing electrochemical systems to address Constellation energy storage needs

**Altair - Lunar Lander**

- **Primary fuel cells – descent stage**
- **Secondary batteries – ascent stage**

**EVA**

- **Secondary batteries for the Portable Life Support System (PLSS)**

**Lunar Surface Systems (LSS)**

- **Regenerative fuel cell systems for surface systems**
- **Secondary batteries for mobility systems**

# Li-based batteries have been baselined to provide primary power for EVA, Altair, and LSS

# Altair Lunar Lander Battery

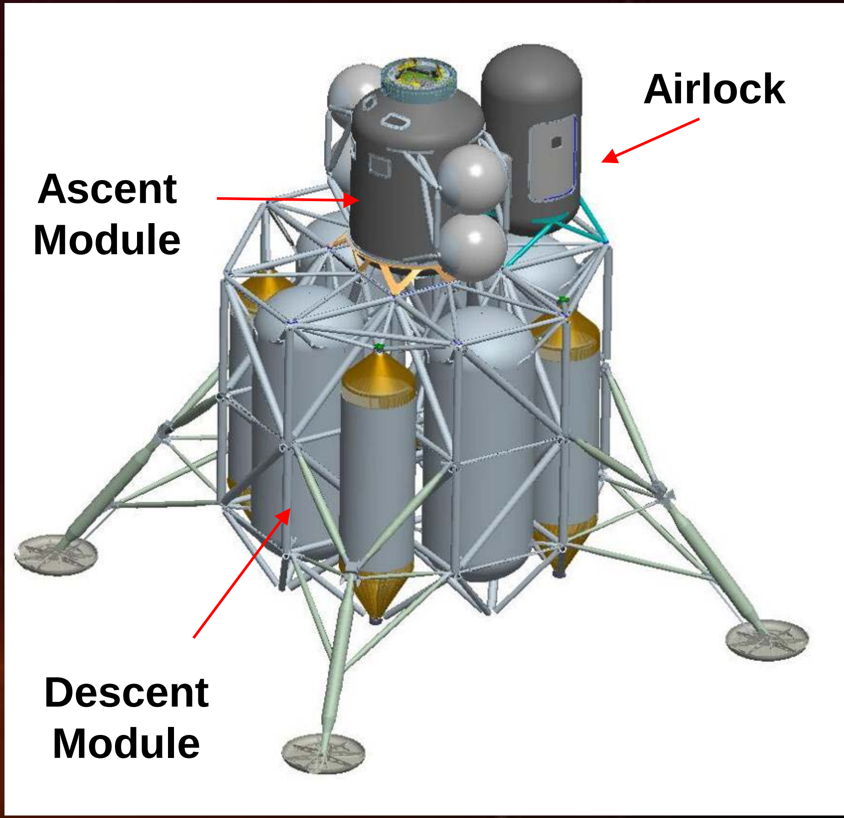
- **Advanced Li-ion batteries are being developed to provide power to the Ascent Module.**
- **Current baseline –$LiMnO_2$ - Lithium primary**
- **Change of baseline to Li-ion battery under consideration due to advantages Li-ion will offer over a primary system**
  - **Contingency power for the descent stage and during translunar insertion**
  - **Greater power capability margins to accommodate growth in peaking power requirements (baselined battery has a maximum discharge rate of approximately C/7)**
  - **Ability to ground test and verify actual mission battery (test-as-you-fly).**

# Altair Ascent Stage Power

## Preliminary Power Requirements:*

**Human safe, reliable operation**

- **14 kWhr energy, delivered**
- **1.67 kW average and 2 kW peak power**
- **Mass allocation:  67 kg**
- **Volume allocation: 45 liters**
- **7 hours continuous operation**
- **1 cycle**
- **Operation over 0 – 30 degrees C**
- **Operation in 0 – 1/6 G**

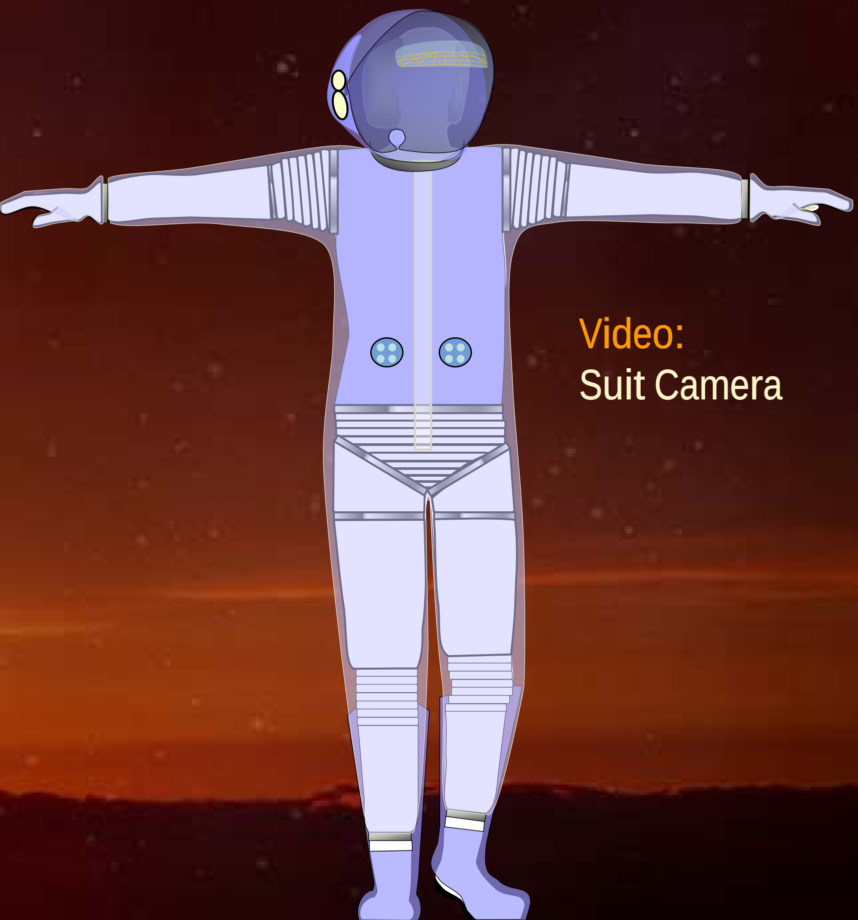



* Minimum capability vehicle design – no redundancy

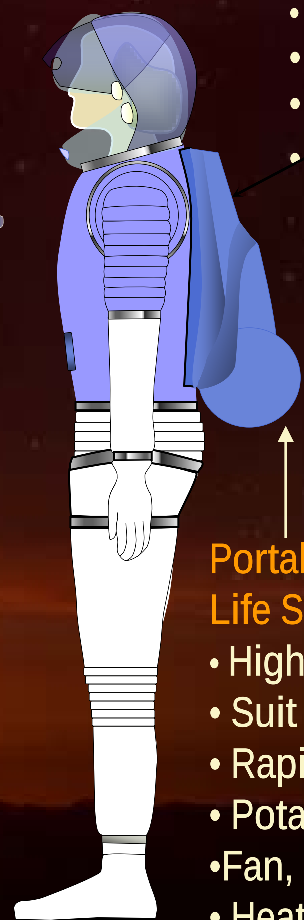
# Lunar EVA Suit: "Configuration 2" Powered Elements

**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



**Enhanced Liquid Cooling Garment:**
- Bio-Med Sensors

**Portable Life Support System (PLSS):**
- High Pressure GOX
- Suit Water Membrane Evaporator
- Rapid Cycle Amine
- Potable Water in PLSS Tank
- Fan, pump, ventilation subsystem processor
- Heater, controllers, and valves

# Lunar EVA Suit Power

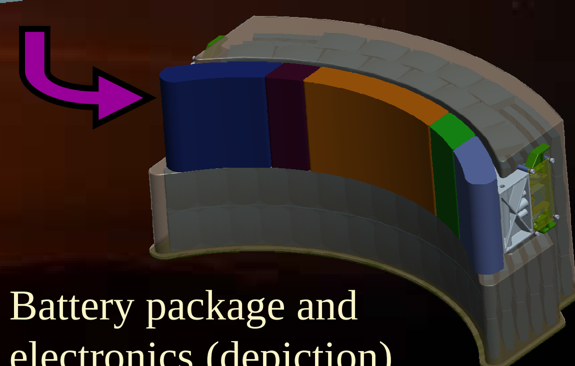
**Advanced Li-ion batteries will be used to provide power for the PLSS, Communications, Avionics, and Informatics system, helmet, heater, camera, and biomedical sensors.**

## Preliminary Power Requirements:

- Human safe, reliable operation
- 1155 Whr energy, delivered
- 145 W average and 233 W peak power
- Mass allocation:  5 kg
- Volume allocation: 1.6 liters
- 8 hour operation per sortie
- 100 cycles (operation every other day for 6 mo
- Operation over 0 – 30 degrees C

## Compared to current PLSS:

- 134% increase in energy requirement
- 106% increase in average power requirement
- 33% increase in peak power requirement
- >7x increase in cycle life requirement
- 25% decrease in mass allocation



Battery package and electronics (depiction)

# Lunar Surface Systems Mobility Systems Rovers


## Preliminary Power Requirements:

**Human safe, reliable operation**

- **>150 Wh/kg delivered**
- **100-1000 cycles**
- **Operation over 0 – 30 degrees C**
- **Maintenance-free operation**

- Actual operating environment can range from 40K in permanently dark craters to +120 deg C at the equator.
- Trade studies underway to assess merit of extending battery operating temperature range to -55 to 60 deg C versus designing the rover thermal system to keep battery within 0 – 30 degrees C.

# Energy Storage Project Lithium-Ion Cell Development

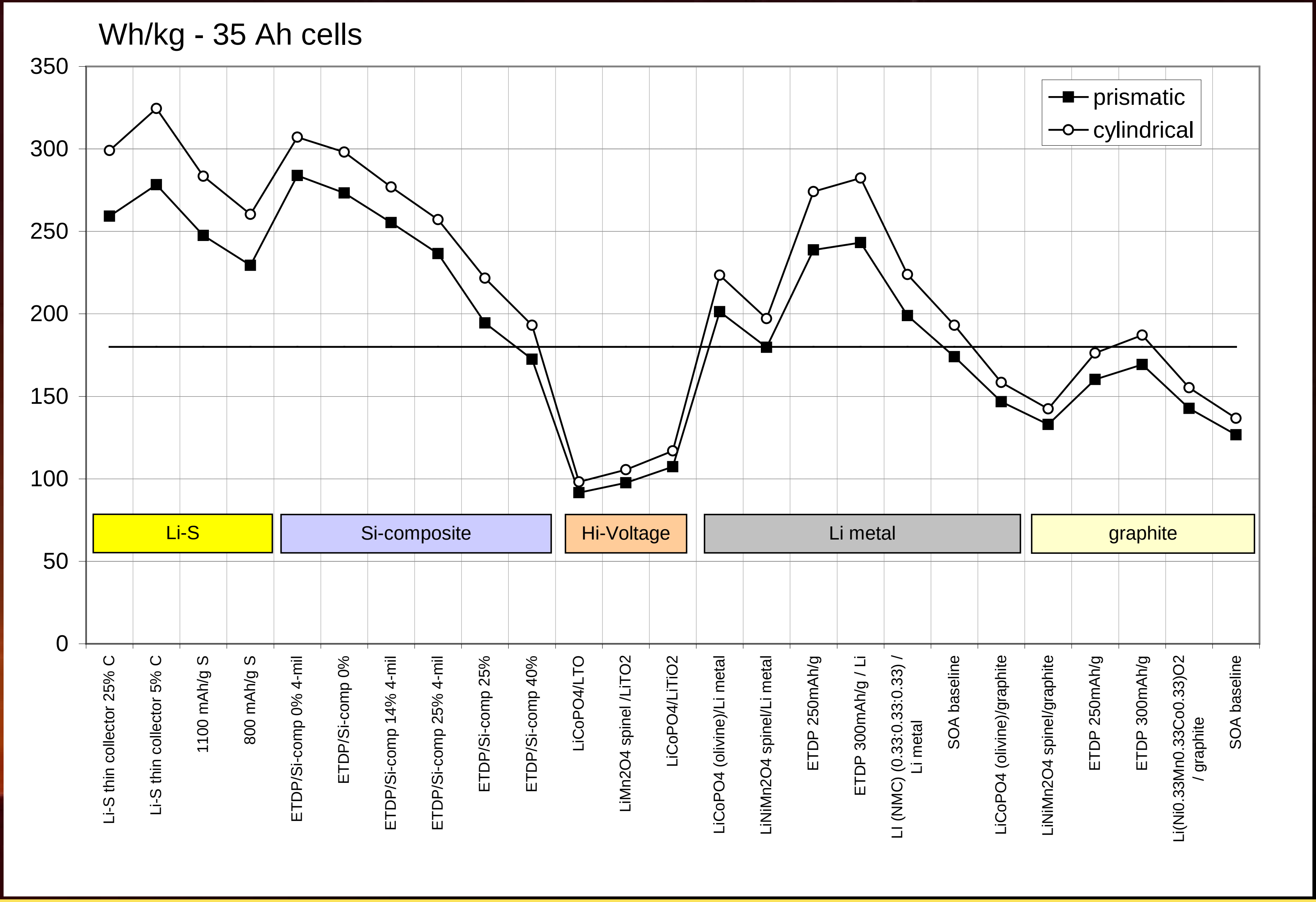
Two parallel cell development approaches to meet Constellation customer requirements

- High Energy Cell Development
  - Safe, reliable Li-ion cell with improved specific energy and energy density over SOA and good cycle life
  - Combination of newly developed cathode, electrolyte, and separator with a carbonaceous anode with known heritage and performance
- Ultra High Energy Cell Development
  - Safe, reliable Li-ion system with greatly improved specific energy and energy density over SOA and low cycle life
  - Very high energy system for applications where mass and volume reduction is enabling and cycle requirements are benign
  - Combination of newly developed anode cathode, electrolyte, and separator
  - Higher developmental risk than High Energy Cell
    - Much higher gains in component level specific capacity over conventional electrode materials required for success
    - Addition of a developmental anode increases risk in areas of electrochemical performance, sufficient maturity by need dates, and scalability and manufacturability.
    - Lithium-alloy anode and higher energy chemistry are inherently less safe – component-level inherent safety features more critical

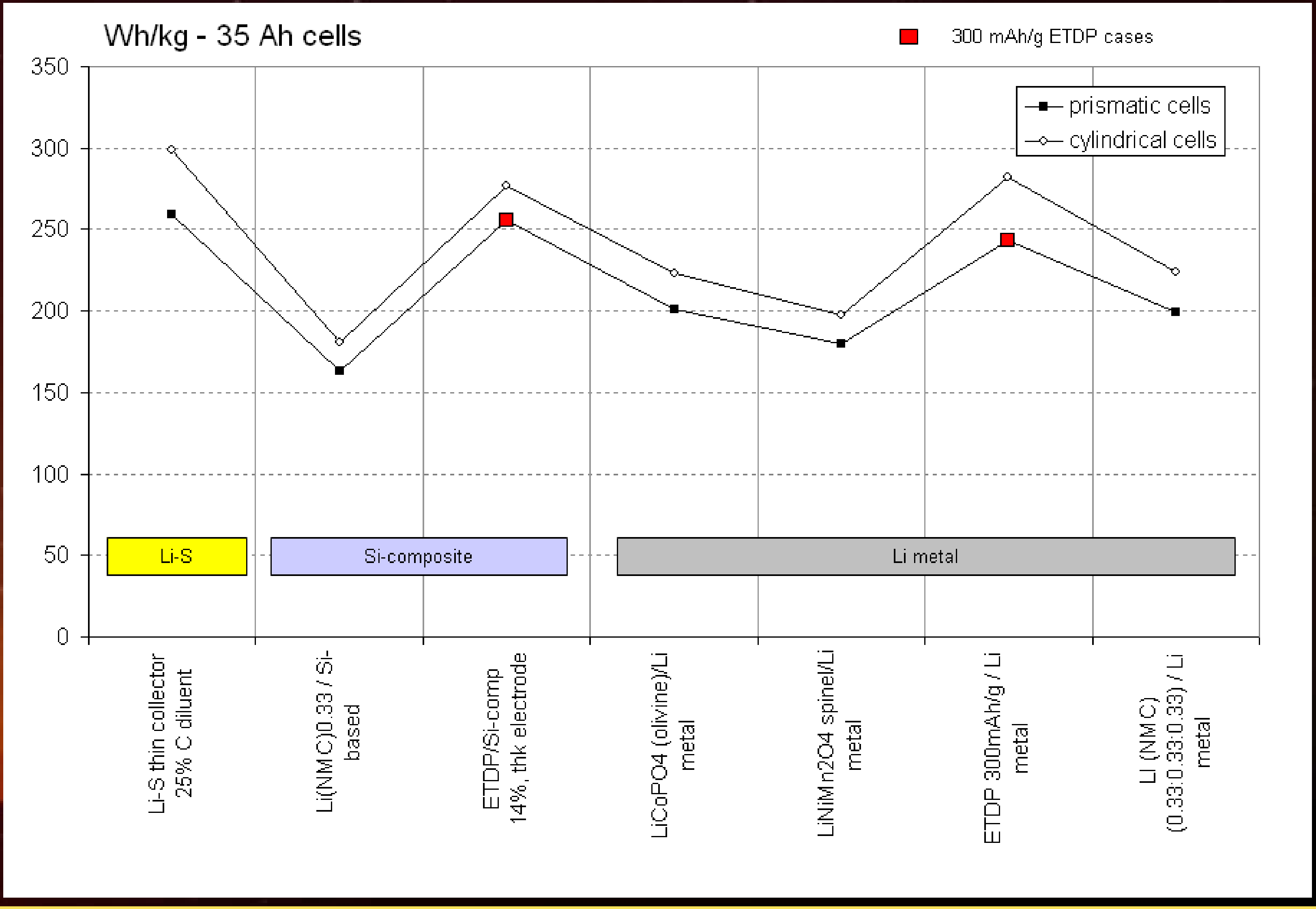
# Key Performance Parameters

| Customer Need | Performance Parameter | State-of-the-Art | Current Value | Threshold Value | Goal |
|---|---|---|---|---|---|
| **Safe, reliable operation** | No fire or flame | Instrumentation/controllers used to prevent unsafe conditions. There is no non-flammable electrolyte in SOA | Preliminary results indicate a moderate reduction in the performance with flame retardants and non-flammable electrolytes | Benign cell venting without fire or flame and reduce the likelihood and severity of a fire in the event of a thermal runaway | Tolerant to electrical and thermal abuse such as over-temperature, over-charge, reversal, and external short circuit with no fire or flame |
| **Specific energy**<br>Lander:<br>150 – 210 Wh/kg<br>10 cycles<br><br>Rover:<br>150 – 200 Wh/kg<br><br>EVA:<br>180 – 230 Wh/kg<br>100 cycles | **Battery-level** specific energy | 90 Wh/kg at C/10 & 30°C<br>83 Wh/kg at C/10 & 0°C<br>(MER rovers) | 130 Wh/kg at C/10 & 30°C<br>120 Wh/kg at C/10 & 0°C | **135** Wh/kg at C/10 & 0°C "High-Energy<br>**150** Wh/kg at C/10 & 0°C "Ultra-High Energy | **150** Wh/kg at C/10 & 0°C "High-Energy"<br>**220** Wh/kg at C/10 & 0°C "Ultra-High Energy" |
| | **Cell-level** specific energy | 130 Wh/kg at C/10 & 30°C<br>118 Wh/kg at C/10 & 0°C | 150 Wh/kg at C/10 & 0°C | **165** Wh/kg at C/10 & 0°C "High-Energy"<br>**180** Wh/kg at C/10 & 0°C "Ultra-High Energy" | **180** Wh/kg at C/10 & 0°C "High-Energy"<br>**260** Wh/kg at C/10 & 0°C "Ultra-High Energy" |
| | **Cathode-level** specific capacity $Li(Li,NiMn)O_2$ | 140 – 150 mAh/g typical | $Li(Li_{0.17}Ni_{0.25}Mn_{0.58})O_2$:<br>240 mAh/g at C/10 & 25°C<br>$Li(Li_{0.2}Ni_{0.13}Mn_{0.54}Co_{0.13})O_2$:<br>250 mAh/g at C/10 & 25°C<br>200 mAh/g at C/10 & 0°C | **260** mAh/g at C/10 & 0°C | **280** mAh/g at C/10 & 0°C |
| | **Anode-level** specific capacity | 320 mAh/g (MCMB) | 320 mAh/g (MCMB)<br>450 mAh/g Si composite | **600** mAh/g at C/10 & 0°C (with Si composite) | **1000** mAh/g at C/10 0°C (with Si composite) |
| **Energy density**<br>Lander: 311 Wh/l<br>Rover: TBD<br>EVA: 400 – 700 Wh/l | **Battery-level** energy density | 250 Wh/l | n/a | **270** Wh/l "High-Energy"<br>**360** Wh/l "Ultra-High" | **320** Wh/l "High-Energy"<br>**420** Wh/l "Ultra-High" |
| | **Cell-level** energy density | 320 Wh/l | n/a | **385** Wh/l "High-Energy"<br>**460** Wh/l "Ultra-High" | **390** Wh/l "High-Energy"<br>**530** Wh/l "Ultra-High" |
| **Operating environment**<br>0°C to 30°C, Vacuum | Operating temperature | -20°C to +40°C | -50°C to +40°C | **0°C** to **30°C** | **0°C** to **30°C** |

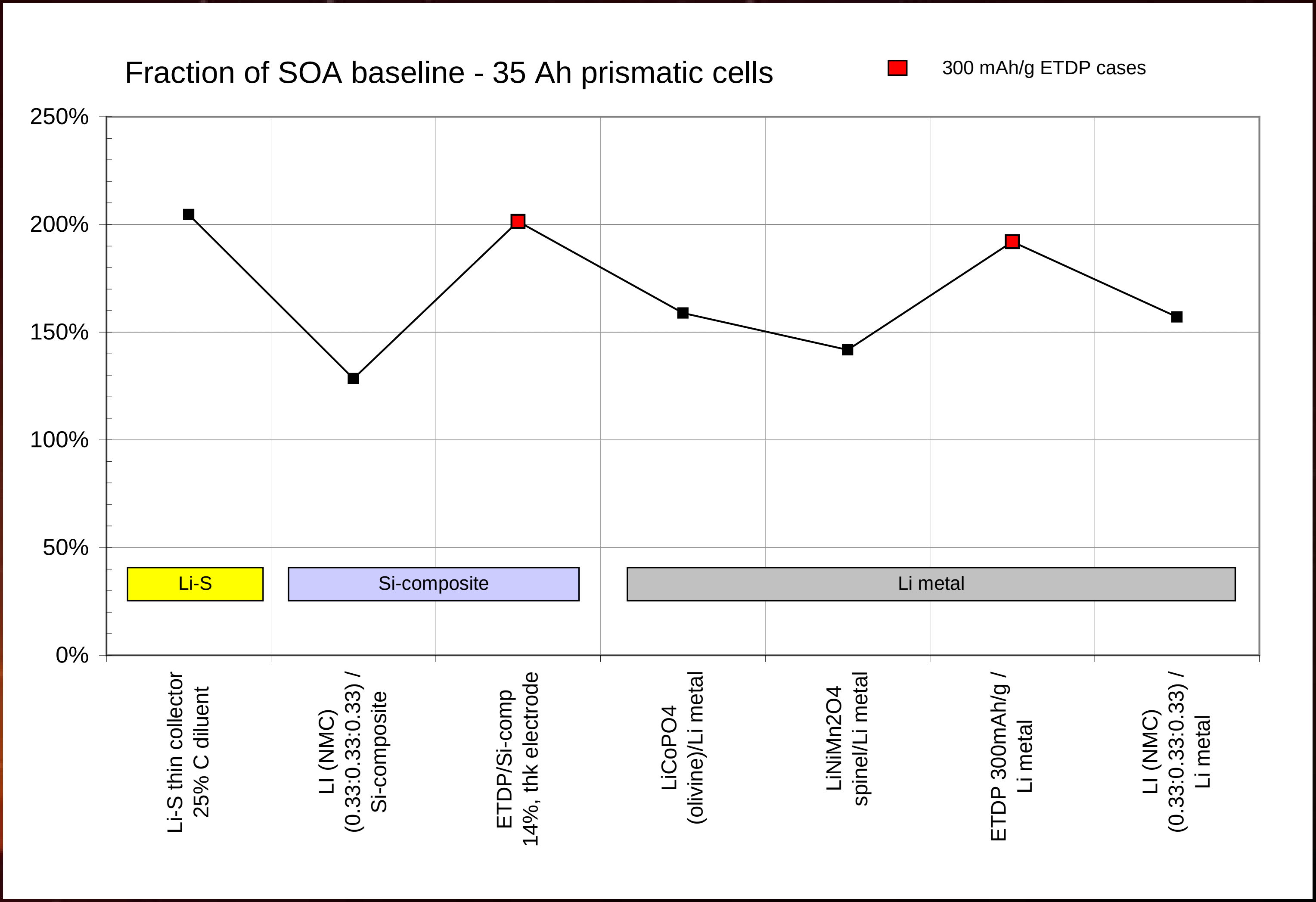
# Cell Level Specific Energy Projections of Expanded Chemistry Options



# Cell Level Specific Energy Projections of Final Chemistry Options



# Projected Improvement in Cell-Level Specific Energy over SOA (based on prismatic cells)



# Energy Storage Project Li-ion Cell Development

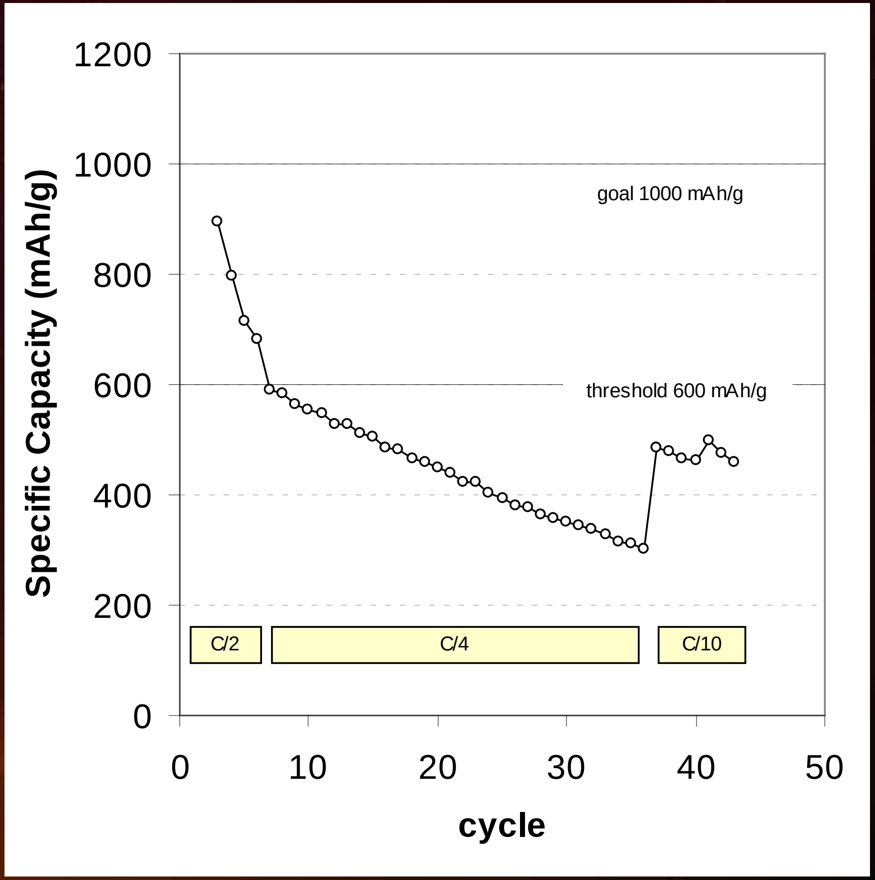
**Component-level goals** will be addressed thorough a combination of NASA in-house materials development efforts, NASA Research Announcement contracts, and grants

- 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 of other government programs (DOD, DOE) for component-level technology

# Anode Development

## Led by NASA GRC (William Bennett, ASRC)

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

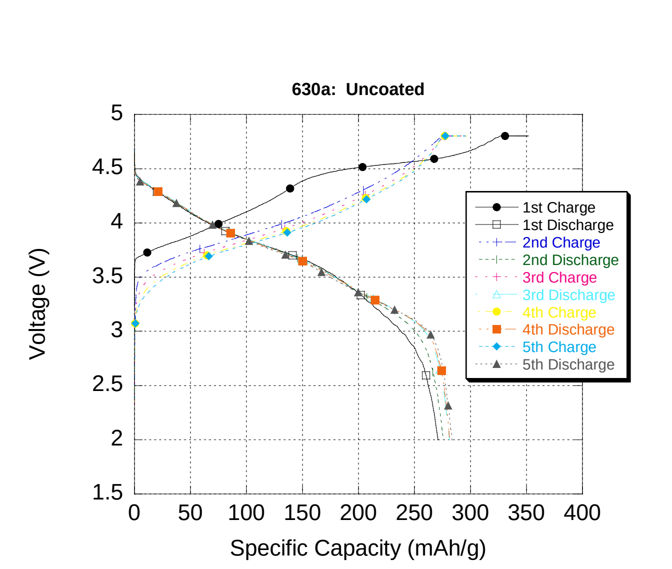


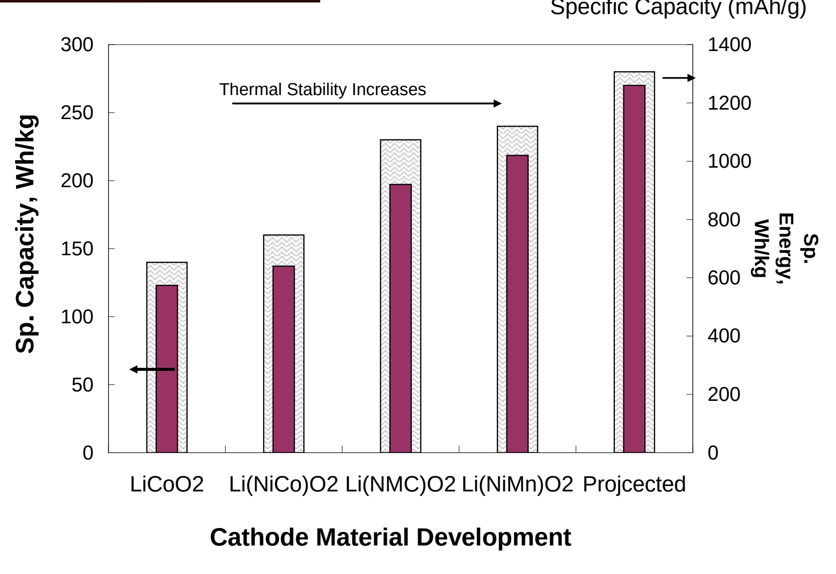

Silicon-based anode: Specific capacity vs. cycles at different discharge rates

# Cathode Development

## Led by NASA JPL (Kumar Bugga)

- Develop Li(NMC) materials
  - Offer enhanced thermal stability over conventional cobaltate cathodes
  - High voltage materials
- Development will focus on:
  - Increasing specific capacity
  - Improving rate capability
  - Stabilizing materials for higher voltage operation
  - Reducing irreversible capacity loss

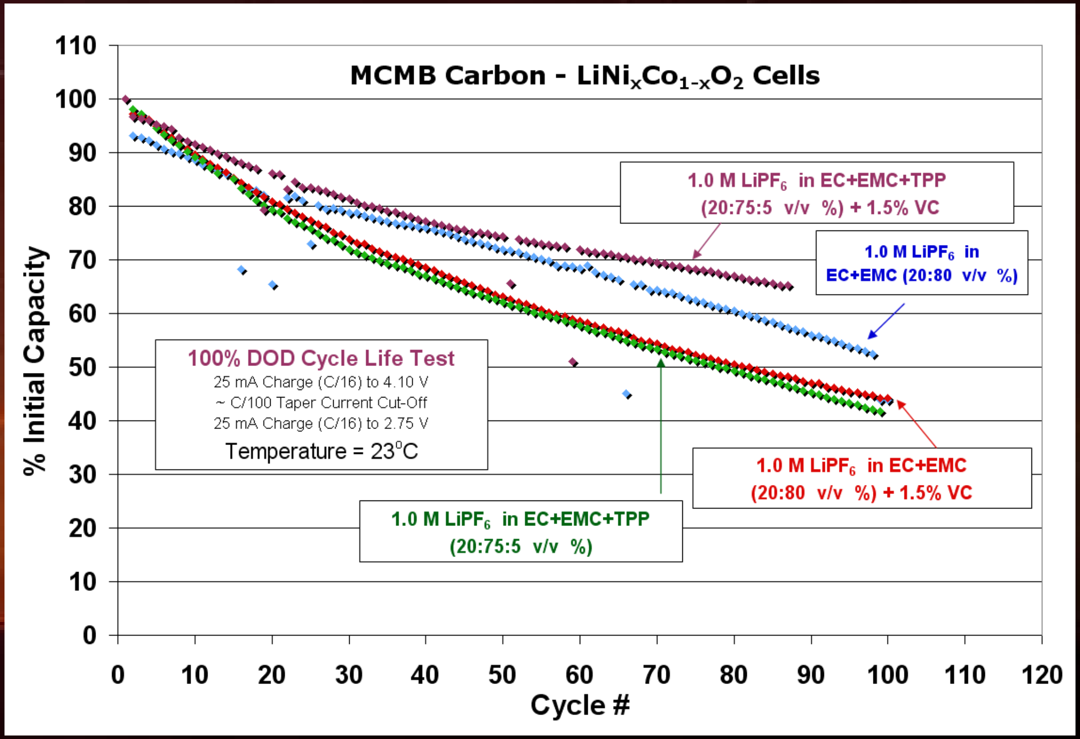


# Electrolyte Development

## Led by NASA JPL (Marshall Smart)

- Develop electrolytes that are compatible with the NASA chemistries
- Develop non-flammable electrolytes and flame retardant additives
- Develop electrolytes that are stable at potentials up to 5V



# Separators and Safety Components

## Separator Development

**Led by NASA GRC (Richard Baldwin)**

- Separators with improved safety
- Shutdown separators

## 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

# NASA Research Announcement NNC08ZP022N
# Research and Development of Battery Cell Components

- **Contracts Awarded**
  - Georgia Tech Research Corp. & Clemson University, “Design of Resilient Silicon Anodes”
- **Proposals Selected for Award**
  - Lockheed Martin Space Systems Company, “Advanced Nanostructured Silicon Composite Anode Program”
  - 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”

# Energy Storage Project Li-ion Cell Development

**Cell-level goals** will be achieved through contracted efforts with an aerospace Li-ion cell developer. NASA will enlist industry participation via a multi-year contract to:

- Screen components for scalability and manufacturability
- Scale-up materials
- Optimize components
- Build small production cells consisting of candidate developmental materials to enable performance and safety evaluations of integrated components in full cells
- Design and develop space-quality cells that meet NASA's requirements - incorporate lightweight cell-level hardware and packaging to further improve specific energy and energy density while considering battery-level impacts
- Manufacture TRL 4 flightweight cells

- NASA will perform performance, safety, and environmental testing to bring cells to TRL 6
- Battery development will occur under EVA, Altair, or LSS flight development programs or through follow-on tasks

# Target Customers for Technologies and Risk Mitigation

## High Energy Cell

- Primary technology for Lunar Surface Systems Mobility Systems
- Back-up technology for EVA and Altair

## Ultra High Energy Cell

- Primary technology for EVA and Altair

## Risk mitigation strategies

- High Energy Cell is a back-up technology for the Ultra High Energy target customers
- Multiple parallel component development efforts
- Involvement of cell manufacturer early in process to participate in the evaluation and selection of the best candidate materials and to scale-up materials and components
- Builds of small production cells to perform integrated testing
- Optimizing cell design and packaging while also considering battery packaging ensures cell level specific energy gains are maintained to fullest extent at battery level

# Summary

- NASA is developing High Energy and Ultra High Energy Li-ion cells for EVA, Altair, and Lunar Surface Systems customers in conjunction with companies and universities
- Efforts span from materials-level development through TRL 6 flightweight cell hardware
- High risk development is being mitigated through multiple paths