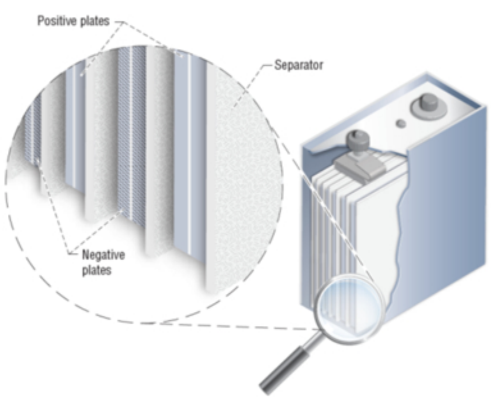
High Efficiency Space Power Systems Project
Advanced Space-Rated Batteries

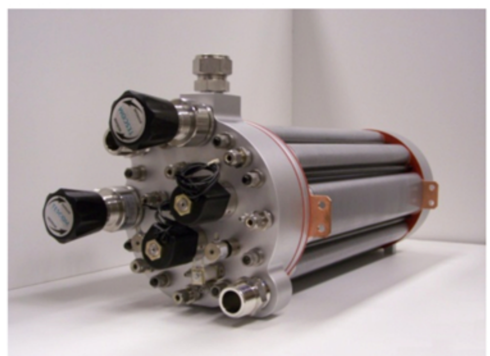
Case Western Reserve University (CWRU) has an agreement with China National Offshore Oil Corporation – New Energy Investment Company, Ltd. (CNOOC), under the United States-China EcoPartnerships Framework, to create a bi-national entity seeking to develop technically feasible and economically viable solutions to energy and environmental issues. Advanced batteries have been identified as one of the initial areas targeted for collaborations. CWRU invited NASA Glenn Research Center (GRC) personnel from the Electrochemistry Branch to CWRU to discuss various aspects of advanced battery development as they might apply to this partnership. Topics discussed included: the process for the selection of a battery chemistry; the establishment of an integrated development program; project management/technical interactions; new technology developments; and synergies between batteries for automotive and space operations. Additional collaborations between CWRU and NASA GRC's Electrochemistry Branch were also discussed.

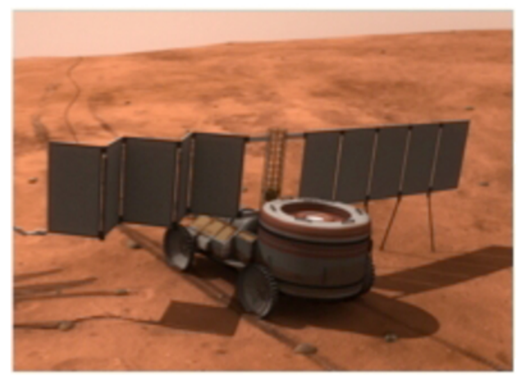
High Efficiency Space Power Systems Project

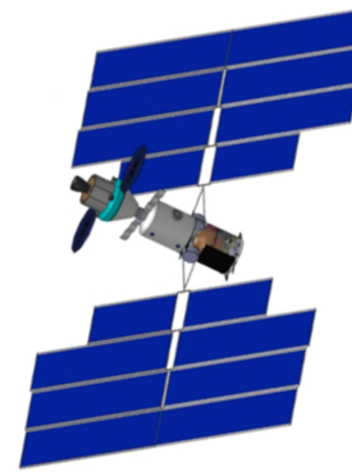
Advanced Space-Rated Batteries

Providing technology for abundant and low-cost power where it is needed







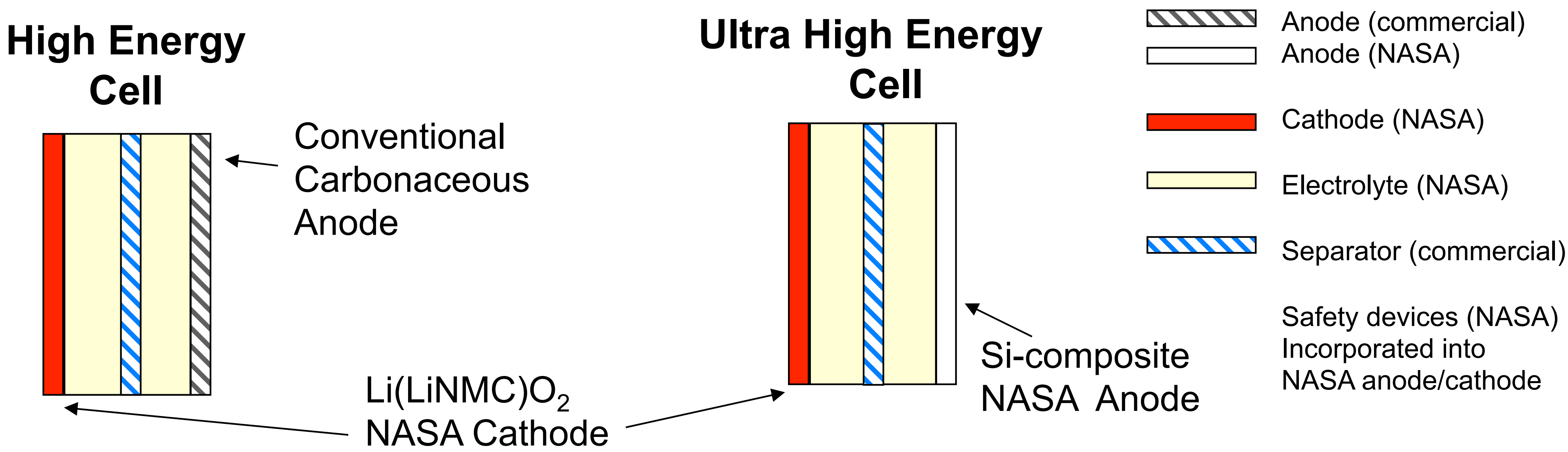


Presentation to Case Western Reserve University

April 6, 2011

NASA GRC/Concha Reid, co-PI for Batteries

Advanced Li-ion Cell Development



High Energy Cell

•Development targeted for Lunar Surface Systems (Lunar Electric Rover, Portable Utility Pallet)
•Lithiated mixed-metal-oxide cathode / Graphite anode

•Li(LiNMC)O_2 / Conventional carbonaceous anode
•**180** Wh/kg (100% DOD) @ cell-level, 0^0C and C/10
80% capacity retention at ~**2000** cycles

Ultra High Energy Cell

•Development targeted for EVA spacesuit and Altair Lunar Lander
•Lithiated-mixed-metal-oxide cathode / Silicon composite anode
•Li(LiNMC)O_2 / silicon composite
•**260** Wh/kg (100% DOD) @ cell-level, 0^0C and C/10
80% capacity retention at ~**200** cycles

Preliminary system requirements given in, "Reid, Concha, M., Miller, Thomas B., Manzo, Michelle A., and Mercer, Carolyn M., "Advanced Li-ion Cell Development for NASA's Constellation Missions", NASA Aerospace Battery Workshop, Huntsville, AL, Nov. 2008.

Feasibility Study to Determine Ultra High Energy Chemistry

Customers' top priority is safety.

Based on customer requirements, team determined safety goals:
No fire or thermal runaway at the component level

No chemistry exists that can meet customers' aggressive specific energy goals. Desire for a safer chemistry presents a set of conflicting objectives – Safer chemistry combined with ultra high specific energy

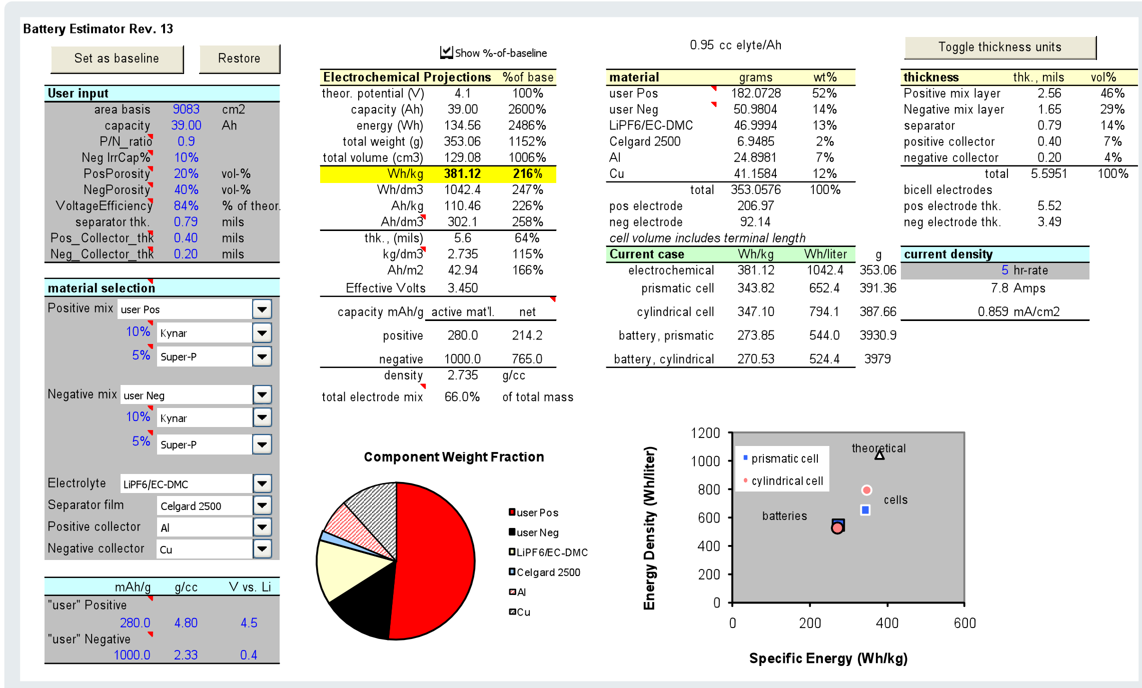
Feasibility study was initiated to determine the best advanced chemistry to meet EVA and Altair's requirements on the established schedule (in time for customer System Design Reviews) and within available resources.

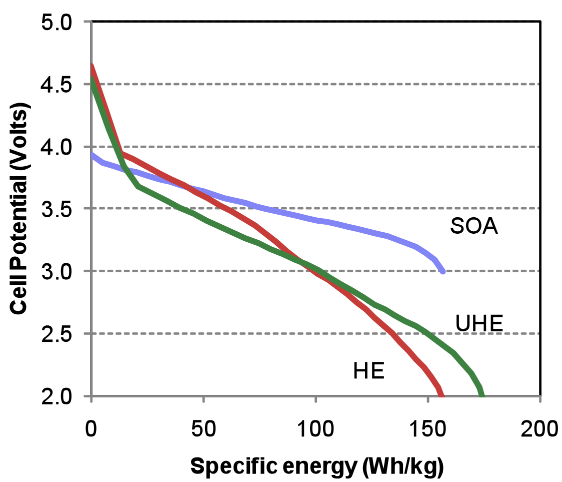
Goal of Feasibility Study:
Determine the best advanced chemistry to develop for EVA and Altair who require safe, reliable energy storage systems with extremely high specific energy as compared to today's state-of-the-art (SOA) batteries.

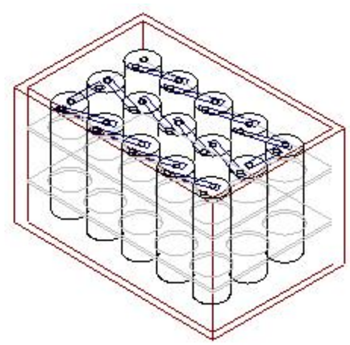
Advanced chemistries were researched and evaluated against attributes that characterized each of the chemistries

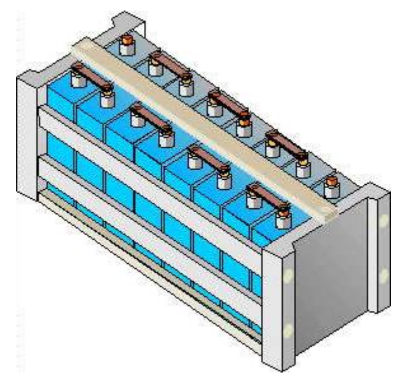
Modeling

- Spreadsheet-based models project cell and battery level characteristics
- Tool for “what if?” analysis
- Rate performance can be estimated from laboratory data for electrodes under relevant conditions



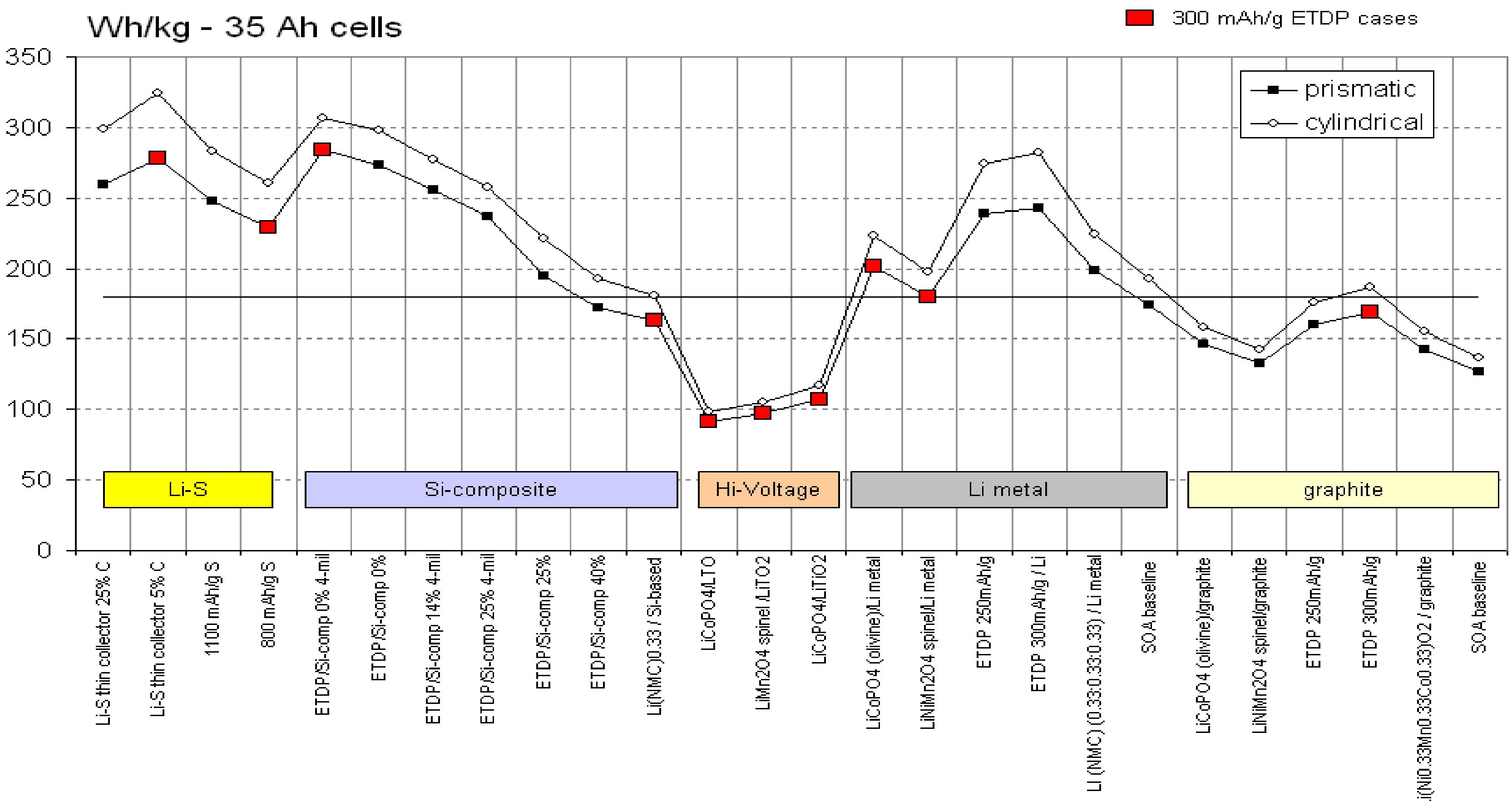






Ultra High Energy Battery Chemistry Determination

Study Goal:
Determine the best advanced chemistry to develop for EVA and Altair who require safe, reliable energy storage systems with extremely high specific energy as compared to today's state-of-the-art (SOA) batteries.
Safety target: No fire or thermal runaway at the component level.
Specific energy target: 160-220 watt-hours per kilogram delivered at the battery level at C/10 and 0° C.
Process: Assessed 31 chemistries, selected 7 as feasible, ranked those 7 using an Analytical Hierarchy Process (pairwise comparison against 10 weighted attributes)



Goal and Important Attributes to Achieve the Goal

- Goal: Determine the best advanced chemistry to develop for customers who require safe, reliable energy storage systems with extremely high specific energy as compared to today's state-of-the-art batteries.

Attribute	Definitions	Weights
Cost to TRL 6	The cost to develop the technology to TRL 6, including costs attributed to costly manufacturing processes or processes that cannot be automated	6.5
Cycle Life	Projected cycle life of the technology	3.8
Energy Density	Projected energy density of the technology (calculated under a standard set of conditions)	10.2
Manufacturability	The projected level of ease or difficulty associated with working with materials, scaling up batches of materials, and manufacturing cells of practical capacity made from these components, and the projected adaptability of materials to large scale processing	8.3
Rate Capability up to C/5	Likelihood that the technology can meet a C/5 continuous discharge rate	15.6
Rate Capability up to C/2	Likelihood that the technology can meet a C/2 continuous discharge rate	2.5
Safety	The likelihood that a cell made from these components can be made to be safe. Included safety under normal operation and abuse conditions	17.9
Schedule	Likelihood that TRL 6 cells can be delivered by March 2104	8.0
Specific Energy	Projected specific energy of the technology (calculated under a standard set of conditions)	15.0
Storage and Calendar Life	Projected storage + calendar life, where calendar life includes the operating time plus periods at open circuit between active charging and discharging	12.2

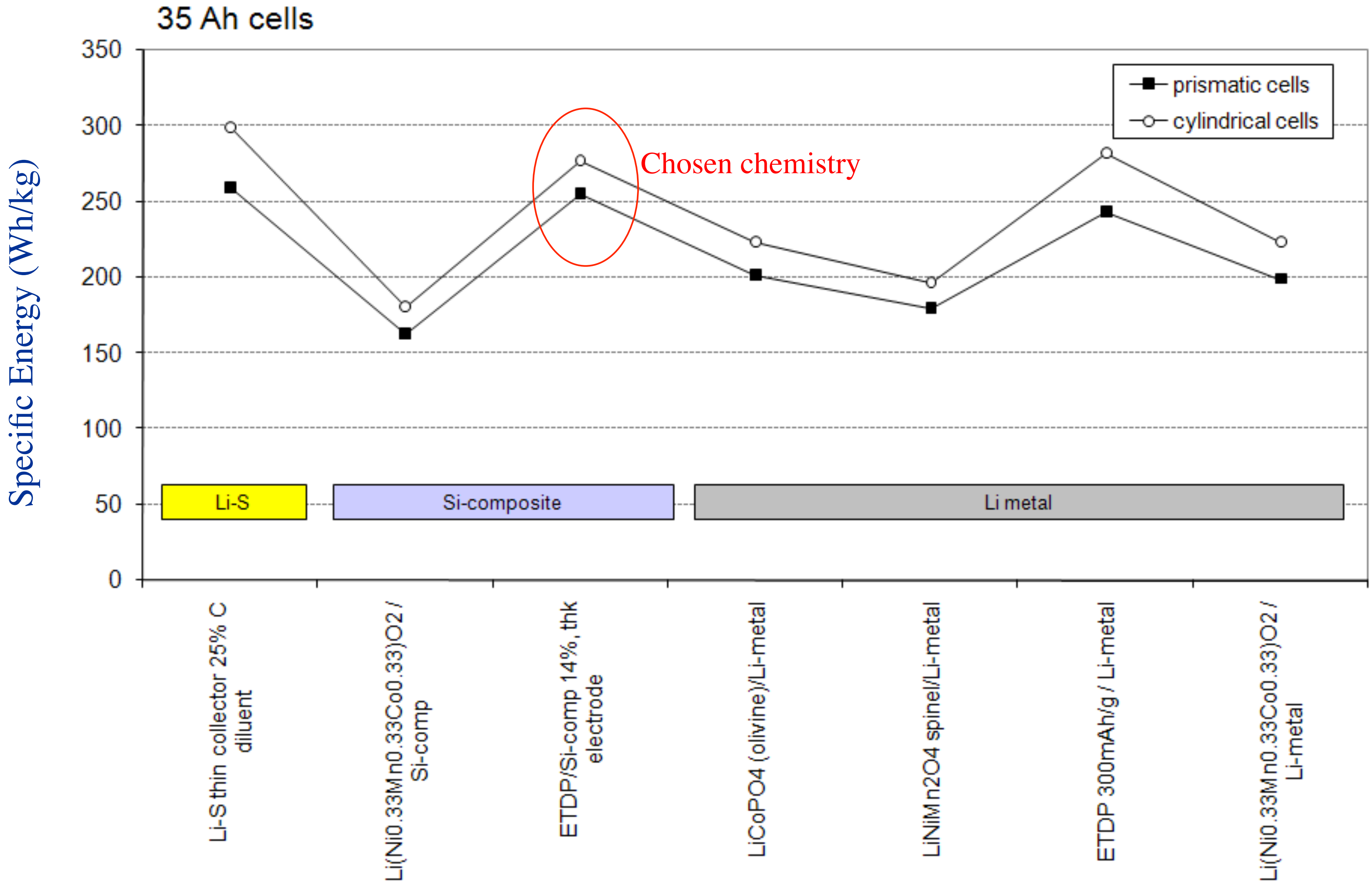
Advanced Chemistry Options and Ranking

Cathode	Anode	Rank
$Li(Ni_{0.33}Mn_{0.33}Co_{0.33})O_2$	Si-based Composite	20.2
$Li(LiNMC)O_2$ (ETDD)	Si-based Composite	17.0
$LiNiMn_2O_4$	Li metal	15.3
$Li(Ni_{0.33}Mn_{0.33}Co_{0.33})O_2$	Li metal	13.9
$Li(LiNMC)O_2$ (ETDD)	Li metal	13.1
$(Li_2)S$	Li metal	11.5
$LiCoPO_4$	Li metal	9.1

- Li(NMC) cathode with Si-based composite anode offers:
  - Higher safety, manufacturability and rate capability
  - Lower specific energy
- ETDD cathode with Si-based composite anode offers:
  - Higher specific energy
  - Lower safety, manufacturability and demonstrated rate capability

✓ETDD cathode with Si-based composite anode chosen as Ultra High Energy chemistry due to its potential to achieve much higher specific energy.

Projected Specific Energy for Final Options



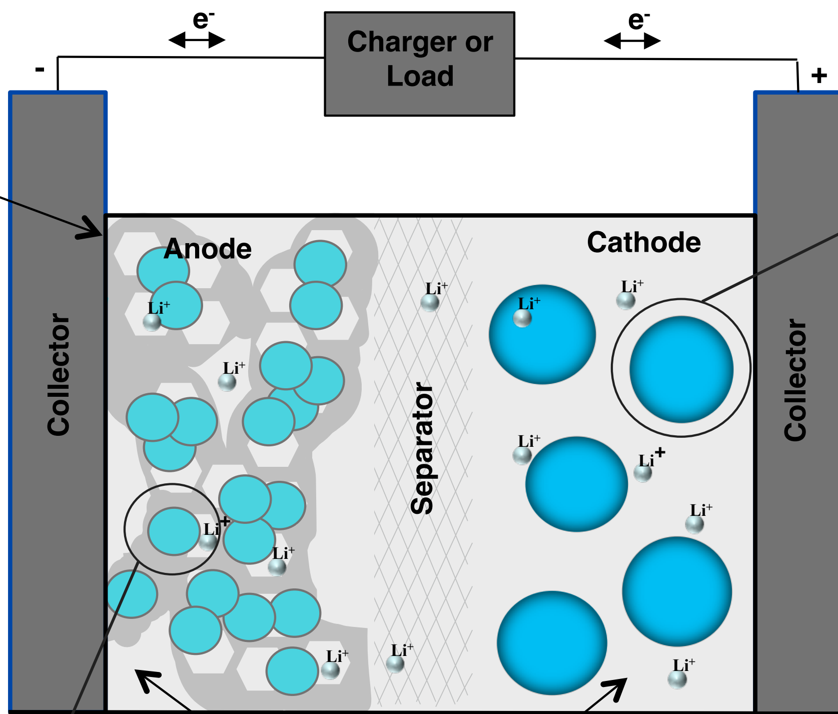
Key Performance Parameters

Performance Parameter	State-of-the-Art	Current Value	Threshold Value[a]	Goal[a]
No fire or flame	Instrumentation/controllers used to prevent unsafe conditions. There is no non-flammable electrolyte in SOA	Preliminary results indicate a small reduction in performance using safer electrolytes and cathode coatings	Tolerant to electrical and thermal abuse such as over-temperature, over-charge, reversal, and short circuits with no fire or thermal runaway[c]	Tolerant to electrical and thermal abuse such as over-temperature, over-charge, reversal, and short circuits with no fire or thermal runaway[c]
Battery-level specific energy[b] [Wh/kg]	90 Wh/kg at C/10 & 30°C 83 Wh/kg at C/10 & 0°C (MER rovers)	160 at C/10 & 30°C (HE) 170 at C/10 & 30°C (UHE) 80 Wh/kg at C/10 & 0°C (predicted)	**135** Wh/kg at C/10 & 0°C "High-Energy" **150** Wh/kg at C/10 & 0°C "Ultra-High Energy"	**150** Wh/kg at C/10 & 0°C "High-Energy" **220** Wh/kg at C/10 & 0°C "Ultra-High Energy"
Cell-level specific energy [Wh/kg]	130 Wh/kg at C/10 & 30°C 118 Wh/kg at C/10 & 0°C	199 at C/10 & 23°C (HE) 213 at C/10 & 23°C (UHE) 100 Wh/kg at C/10 & 0°C (predicted)	**165** Wh/kg at C/10 & 0°C "High-Energy" **180** Wh/kg at C/10 & 0°C "Ultra-High Energy"	**180** Wh/kg at C/10 & 0°C "High-Energy" **260** Wh/kg at C/10 & 0°C "Ultra-High Energy"
Cathode-level specific capacity [mAh/g]	180 mAh/g	252 mAh/g at C/10 & 25°C 190 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 [mAh/g]	280 mAh/g (MCMB)	330 at C/10 & 0°C (HE) 1200 mAh/g at C/10 & 0°C for 10 cycles (UHE)	**600** mAh/g at C/10 & 0°C "Ultra-High Energy"	**1000** mAh/g at C/10 0°C "Ultra-High Energy"
Battery-level energy density	250 Wh/l	n/a	**270** Wh/l "High-Energy" **360** Wh/l "Ultra-High"	**320** Wh/l "High-Energy" **420** Wh/l "Ultra-High"
Cell-level energy density	320 Wh/l	n/a	**385** Wh/l "High-Energy" **460** Wh/l "Ultra-High"	**390** Wh/l "High-Energy" **530** Wh/l "Ultra-High"
Operating Temperature	-20°C to +40°C	0°C to +30°C	**0°C** to **30°C**	**0°C** to **30°C**

Revised 03/22/10

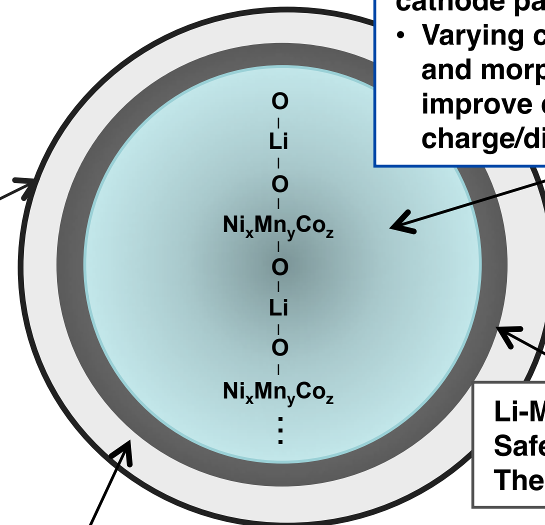
a Assumes prismatic cell packaging for threshold values. Goal values include lightweight battery packaging.
b Battery values are assumed at 100% depth-of-discharge (DoD), discharged at C/10 to 3.0 volts/cell, and at 0˚C operating conditions.
c Over-temperature up to 110˚C; reversal 150% excess discharge at 1C; pass external and simulated internal short tests; overcharge 100% at 1C for Goal and 80% at C/5 for Threshold Value.

Lithium Ion Battery Technology Development
Advanced Cell Components



Nano-particle based circuit breaker

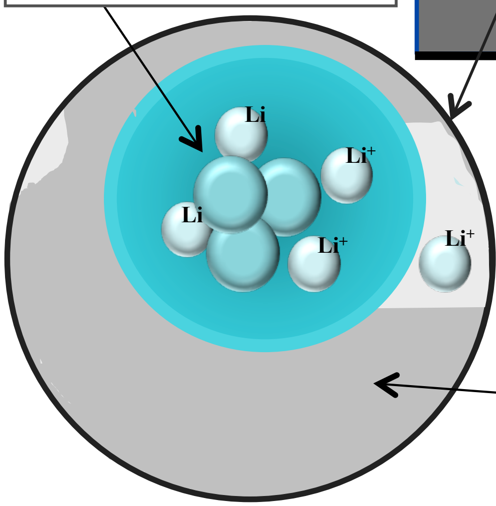
Layered $Li(NMC)O_2$ cathode particle
- Varying composition and morphology to improve capacity and charge/discharge rate



Li-Metal-PO_4 Safety Coating for Thermal Stability

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

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: $LiPF_6$ in EC+EMC+TPP+VC

- 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

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*