Safe, High Energy and High Power Li-ion Batteries for Army Multi-domain Operations

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I. Introduction

The mobile power and energy (P&E) technologies are fundamental for all US Army capabilities, and Li-ion batteries provide a ubiquitous solution in this regard due to their comparatively high energy/power density and reduced life cycle cost. However, the current state-of-the-art Li-ion battery systems will not fulfill the performance demands required for the Army to transform into multi-domain operations (MDO) force as existing cell chemistries and designs are incapable of delivering high energy/power output (e.g. > 450 Wh/kg at C/5 rate) safely under degraded/hostile conditions. Specifically, electrode materials in current commercial Li-ion battery systems have low specific capacities, and traditional organic carbonate-based electrolytes are highly flammable and possess narrow thermodynamic stability window, thus limiting the employment in Army mobile P&E needs for future MDO. The American Lithium Energy (ALE) Team has successfully demonstrated a Li-ion energy storage solution with performance greatly exceeding that of current state-of-the-art designs and has been extensively developing its next-generation cell systems to address future performance challenges of MDO. This white paper is intended to introduce current generation of ALE Li-ion battery technology and provide insight into future generations.

II. High Energy, High Power Li-ion Battery

ALE has developed proprietary, high energy/power Li-ion battery technology based on nano-Si anode and high-voltage oxide cathode. Table 1 and 2 shows the cell-level characteristics of current and future generations of ALE Li-ion battery technology. The cell-level specific energy density of both 18650 and pouch format cells significantly exceeds the current commercial specific energy densities (< 300 Wh/kg), and this provides foundation for the development of next generations to satisfy the future energy demand for MDO. Figure 1 shows charge and discharge curves of ALE's 4.4 Ah 18650 cell (Gen 1).

Table Error! No text of specified style in document.**: Characteristics of ALE 18650 cell**

Metric	Gen 1	Gen 2	Gen 3
Specific energy (Wh/kg)	>330	>350	>450
Capacity (Ah)	4.4	4.8	6
Operational voltage (V)	3.5	3.65	>4

Table 2: Characteristics of ALE pouch cell

Metric	Gen 1	Gen 2	Gen 3
Specific energy (Wh/kg)	>350	>400	>500
Capacity (Ah)	3.7	>4	>4.5
Operational voltage (V)	3.5	3.65	>4

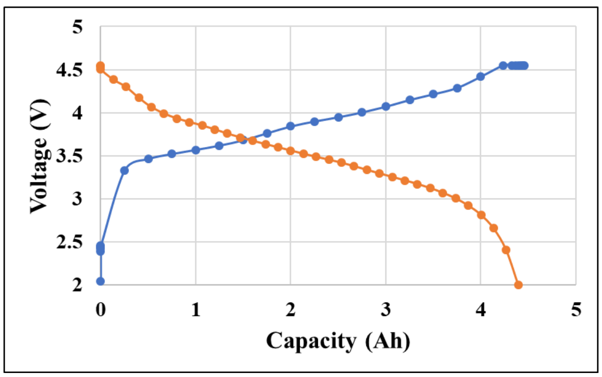

Figure 1. Charge-discharge profiles of ALE's 4.4 Ah 18650 cell (Gen1)

ALE's high energy/power Li-ion battery technology is an achievement of combination of both material and cell engineering development. As mentioned previously, the current generation (Gen 1) employs nano-Si and high-voltage oxides as anode and cathode materials respectively and their properties are listed in Table 3.

Table 3: Properties of Cell Active Materials

Cell Component Metric	Gen 1	Gen 2	Gen 3
Cathode active material specific capacity (mAh/g)	>210	>220	>270
Positive cut-off potential (V vs. Li/Li^+)	4.6	4.8	5.2
Anode active material specific capacity (mAh/g)	>1300	>1500	>2000

Silicon (Si) has been studied for decades as an anode material because of its high specific capacity (~ 4200 mAh/g), which is a several order of magnitude greater than that of the conventional graphite anodes (~ 370 mAh/g). However, extremely high volume expansion of Si-alloy anode results in loss of contact with the current collector, and continuous fracturing and reformation of solid electrolyte interface (SEI) layer leading to rapid degradation of cell discharge capacity during cycling. Moreover, low electrical conductivity of Si is not ideal for high power applications. Nano-structuring of Si provides a solution to alleviate the mechanical stress due to high volume expansion. However, high surface-to-volume ratio of nano-Si contributes to extensive SEI formation during first charge and this causes larger irreversible capacity loss, which effectively reduces the benefit of high-capacity nano-Si electrode. The American Lithium Energy (ALE) Team has successfully addressed this issue by means of utilizing low-cost pre-lithiated nano-Si negative material with significantly better first-cycle coulombic efficiency. Furthermore, cycle life has been improved via creating an innovative strass-tolerant nano-Si electrode yielded by electrode formulations using advanced conductive additives and polymer binders. The superior conductivity, which resulted from enhanced conductive network in both anode and cathode electrodes, together with advanced cell engineering have afforded high power performance in a wide temperature range (-40 to 60°C) for ALE Gen 1 Li- ion cells (Figure 2).

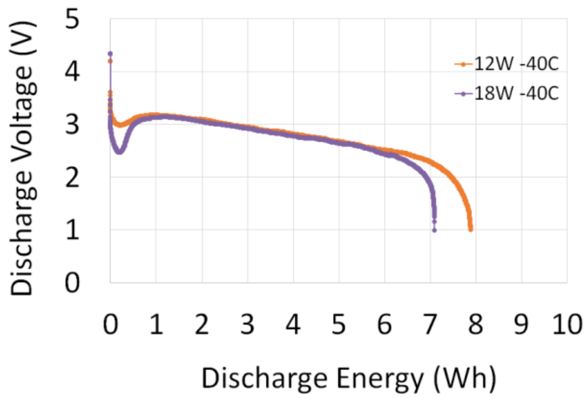

Figure 2. The discharge voltage profiles at -40 °C and at 12W and 18W, respectively for ALE Gen 1 4Ah 18650 cell specially designed for superior power down to -40 °C

III. Excellent Performance in Hazardous Environments and under Shock or Damage

In order to perform MDO, the mobile P&E technologies should provide excellent performance in complex terrain under hazardous conditions. The conventional carbonate-based organic electrolytes are highly flammable and exhibit poor performance at temperature below -20 °C or above 50 °C. A unique electrolyte system is necessary to satisfy the safe battery operation at wide temperature range (-40 °C – 60 °C). The high-concentration electrolytes (HCE's) offer a wide electrochemical window and improved thermal stability enabling stable operation at wide temperature range. Moreover, anion-derived cathode and anode interfaces enable long-term cycle life stability and rate capability. However, the high viscosity of HCE's presents a major challenge for practical cell fabrication by dramatically extending electrolyte wetting time. The Localized High-Concentration Electrolytes (LHCE's) invented by PNNL [1-3] provides a solution for this issue via a dilution strategy to overcome the drawbacks of HCE's while maintaining their merits. In this strategy, non-solvating solvent that cannot dissolve lithium is used to reduce the salt concentration in the final electrolyte in order to improve the wettability (Figure 3a). The non-solvating solvent can be selected from hydrofluoroethers (or partially fluorinated ethers) that are typically nonflammable or have high flash points. When the solvating solvents are chosen from nonflammable solvent systems, then the final electrolytes will be nonflammable as well [4-7]. ALE has successfully employed LHCE's to improve the performance of ALE Gen 1 Li ion cells.

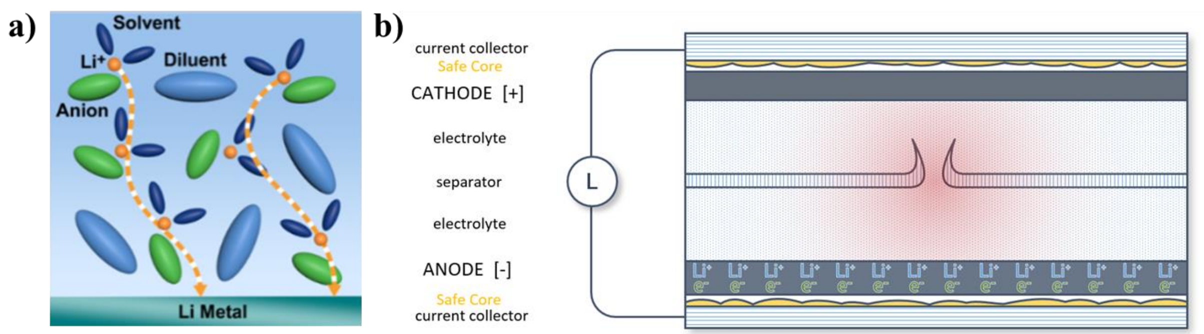

Figure 3. Schematic representation of working principle of a) nonflammable localized high-concentration electrolyte (LHCE); b) SafeCore technology

ALE has also invented a new concept of safety mechanism called SafeCore into the Li-ion cell [8-9]. The SafeCore is a layer within the cell that creates a delamination of the electrode from the current collector when the battery is overcharged or internally shorted or thermally abused. Figure 3b demonstrates the working mechanism of the activated SafeCore layer. By creating a gap between the electrode and current collector, the internal resistance of the cell is effectively increased by several orders of magnitude preventing thermal runaways. Table 4 illustrates the safety performance metrics of current and future generations of ALE cells that employed LHCEs and SafeCore technology, and Figure 4 shows successful completion of overcharge and 130 ^{o}C hot box test for Gen 1 cells. The fully charged cell was charged to 20V at 2A until the overcharge current went to zero during overcharge test, and the fully charged cell was placed in an oven and heated to 130°C at 4°C per min, and hold at 130°C for 60 minutes during the 130 °C hot box test.

Table 4: Cell Performance for Gen I and Targets for Gen II and Gen III

Performance Metric	Gen 1	Gen 2	Gen 3
Operating temperature range	-40 – 60 °C	-40 – 60 °C	-40 – 60 °C
Shock tolerance (Survivability)	Good	Good	Good
Altitude operating	Yes	Yes	Yes
Overcharge up to 2C	No fire	No fire	No fire
Thermal stability at 130°C	No fire	No fire	No fire
Crush	No fire	No fire	No fire

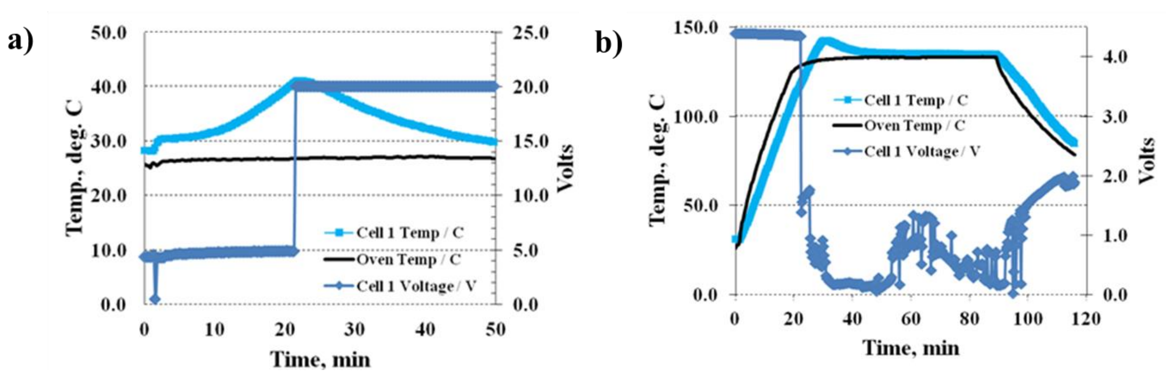

Figure 4. The cell voltage and temperature profiles vs time during a) overcharge test; b) 130 °C hot box test.

IV. Domestic Manufacturing and Development of ALE Next Generation Li-ion Batteries

1 Domestic Manufacturing

The objective is to build a cell production capability with 2 to 5 million cell output per year to serve the domestic military needs and other niches markets.

ALE's next generation of its 4Ah 18650 cell and high energy pouch cell have generated a strong interest among the leading defense companies including Raytheon, Northrop Grumman, General Dynamic, and Bren-Tronics and etc.. Some companies have validated the performance at cell level while others have placed trial orders. The market prospect for ALE's next generation of lithium ion batteries is very good, which forms a good base from a market point of view to build a domestic cell manufacturing capability.

Further, ALE is technically ready for expanding their production facility. **ALE,** founded in 2006, is an AS 9100D certified, advanced lithium-ion battery company with R&D and manufacturing capabilities located in our Carlsbad, CA facilities. ALE's existing instrumentation and physical facilities are capable to make several million electrodes per year. Therefore we anticipate no new equipment purchases in the electrode coating. Our state-of-the-art electrode coater is show in Figure 5. To complete the domestic cell production capability, only some assembly equipment such as automatic winder, electrolyte filling machine, slitting machine and electrode compaction machine need to be purchased, which can be done fairly quickly (six month to a year maximum).

Figure 5. Images of a) ALE facility in Carlsbad, CA; b) AS 9100D certificate; c) Production scale electrode coater

2 Product Developments

ALE's plan is to implement a structured engineering development methodology to develop advanced Li-ion 18650 and pouch cells, and batteries to meet the increased demand in power, energy density and safety. Specifically, ALE would like to develop the following products:

(1) High energy and safe wearable batteries

The objective is to develop a conformal battery with >400 Wh/kg specific energy. The cell-level specific energy in the battery pack will be >500 Wh/kg. The battery will offer high safety operation with the potential to sustain M762 bullet penetration without fire and explosion.

(2) High energy and high power batteries for drones

The objective is to develop a high power and high energy battery to extend the drone's range by 50 or 100% compared to the current Li-ion batteries.

(3) High energy and high power BB2590 batteries

The objective is to develop nano-Si cells for BB2590 battery with >350 Wh/kg specific energy. The battery will have superior low temperature performance from -40 to 60 ^{o}C at 0.5C rate.

(4) High power and high energy batteries for vertical lift

The objective is to develop a safe nano-Si-based battery with 5C power and >300 Wh/kg cell-level specific energy.

V. Conclusions

ALE's current nano-Si battery technology uses advanced electrodes and electrolytes, and adopts innovative cell designs and safety mechanisms. The future generations of ALE batteries are on track to achieve >500 Wh/kg specific energy at cell level and yet very safe to operate. ALE's nano-Si battery technologies will set up a new standard for future Army applications.

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