Lithium-Ion Battery Cells for Ultra High Power and Low Temperature Applications

Chao Lei*, Svetlana Trebukhova, Thomas Barbarich, Boris Ravdel, Frank Puglia
EaglePicher Technologies, LLC
2000 South County Trail
East Greenwich, RI 02818
Chao.Lei@eaglepicher.com

Abstract: *The latest developments in US and global military technologies reinforced the need for a new generation of batteries for the ultra-high-power applications, such as Directed Energy Weapons (DEW), More Electric Aircraft (MEA), and various hybrid systems, etc.*

A successful design must meet greater specific power requirements and often perform at harsher environmental conditions than previous generations. The discharge time for DEW can range from milliseconds up to several minutes, which translates to a rate from 20C to over 300C. There is also a thrust to improve the low temperature performance of the lithium-ion batteries (LIB) and many of the design changes needed to support DEW rates are applicable to low temperature operations.

This paper illustrates the extremely high charge and discharge rates achieved with small pouch cells of the most advanced chemistry and cell design solutions. The projected specific short pulse-power of one 1 Ah cell can reach a breakthrough value of 50 kW/kg! Recharge rates exceeding 100C have also been demonstrated for State of Charge (SOC) changes exceeding 50%. When these cells are combined with EPT's extensive electrolyte development, they demonstrate C/2 discharge performance at temperatures as low as -60 °C.

Keywords: LIB; DEW; MEA; high-rate; ultra-high-power; low temperature;

Introduction

EaglePicher Technologies (EPT) has developed unique battery solutions to fulfill the highly specialized demands of evolving and existing technologies in the defense and aerospace sectors [1]. The demand in power in DEW, MEA and other hybrid systems is consistently increasing. For instance, the military requires more power to operate energy-demanding electronics, radars, and other equipment in MEA. In the case of aircraft applications, battery power requirements can range from 1C to 400C, but more importantly, the operating environment on an aircraft can be very harsh. Typically, battery capable of operating within a wide temperature range of -40 to 70°C is necessary. In this article, we will highlight EPT's recent progress in the design and development of ultra-high-power cells with a rate capability up to 380C discharge and 250C charge, as well as low-temperature electrolyte development with decent cell performance at temperatures as low as -60°C. When combined with EPT's advanced terminal designs and module designs, these cells can provide very high duty cycles to meet current and future extreme requirements.

Ultra-High-Power Pouch Cell

To enhance the rate capability of the cell, it is essential to facilitate the flow of ions and electrons through the cell, particularly through the electrodes and electrode interfaces. EPT has thoroughly selected cell chemistry and each cell component, as well as designed electrode formulation and structure to maximize the power capability. Most of the data presented in this article are based on our single-layer pouch (SLP) or double-layer pouch (DLP) cells with capacity < 0.05Ah. EPT has also manufactured, tested, and delivered to our customers 1.0~2.0Ah prototype cells for use at specific duty cycle profiles with extremely high discharge and charge rates and various temperature conditions.

Discharge rate characterization was performed using the DLP cells at C rate up to 380C and various temperatures. At each temperature, the cells were soaked for at least 6 hours to reach thermal equilibrium. As shown in Figure 1, good discharge rate capability is demonstrated. The cell is able to deliver 72% of 1C room temperature (R.T.) capacity while discharging under 380C at 60˚C, and the average voltage during discharge is only reduced from 3.65V at 1C to 3.27V. At a moderate temperature of 40 ˚C, the cell can deliver >70% of 1C capacity while discharge at 200C, with an average discharge voltage of 3.34V. When the temperature is reduced to 0˚C, the cell can still provide >60% of 1C capacity at a 50C rate.

In addition to the cell's exceptional discharge capability across a broad temperature range, the cell also exhibits excellent recharging capability. Figure 2 shows the charge capacity return from 2.5V to 4.1V at various C-rates and temperatures. At 60˚C and a constant current of 250C, the cell is recharged from 0%SOC to 60%SOC in just 15 seconds, without a constant voltage (CV) hold. Even at a moderate temperature of 40˚C or 20˚C, the cell can reach approximately 60%SOC at a rate of 150C or 50C, respectively. This particular cell design is highly suitable for applications such as DEW, where rapid recharge capabilities are essential.

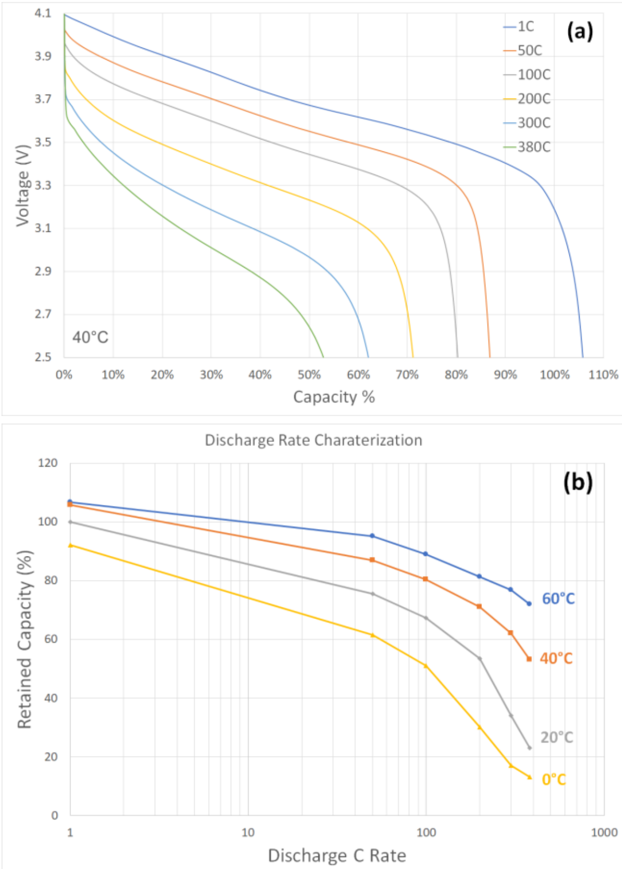

Figure 1. (a) Discharge rate capability at 40°C; (b) Delivered capacity normalized to 1C capacity @20°C, at different C-rates and temperatures.

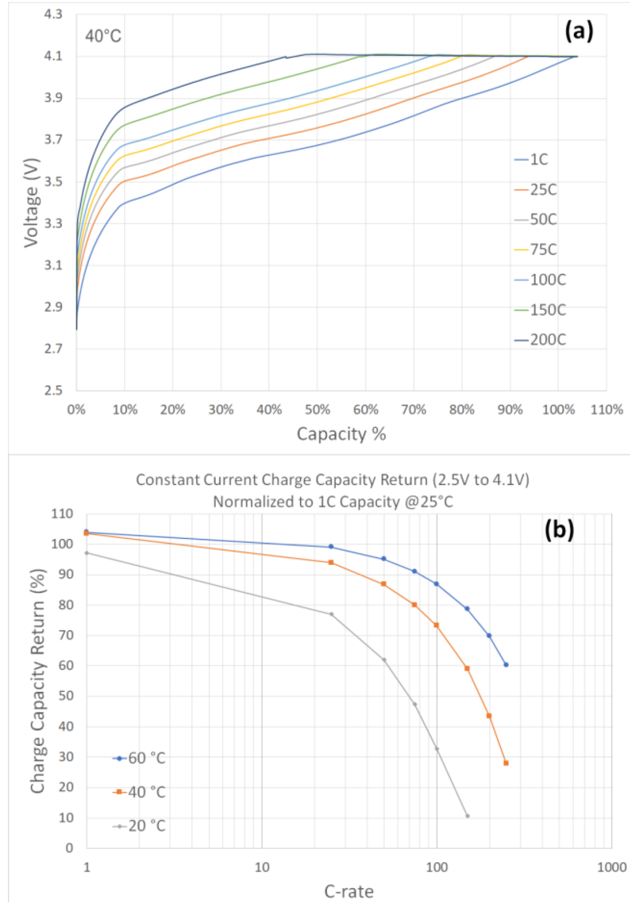

Figure 2. (a) Charge rate capability at 40°C; (b) Charge capacity return at various C-rates charging and temperatures.

To further assess the performance of the DLP cells, they were subjected to cycling at 200C discharge and 150C charge starting at 3.9V, with a 50% depth of discharge (DOD). The results are presented in Figure 3. At 40˚C, the voltage at the end of each discharge (V_{min}) rapidly increased after a few cycles and eventually settled at a relatively constant value of 2.7V. This indicated the cell temperature reached a state of dynamic stability. When the test temperature was elevated to 60˚C, V_{min} was approximately 3.2V and both V_{min} and V_{max} (voltage at the top of charge) remained fairly steady for all cycles. At 40˚C, the energy efficiency (not shown) has risen from 80.4% to a steady state around 82.8%, while at 60˚C, it stayed nearly constant between 88.3% and 89%.

Besides the continuous current tests, the cells were also evaluated for their short pulse capabilities. Figure 4 shows the short pulse discharge test for a SLP cell at 31˚C under a 2V hold. It is found that the current can reach as high as 1288C for milliseconds. For our 1Ah pouch cell, the projected specific short pulse-power density can reach a breakthrough value of 50 kW/kg!

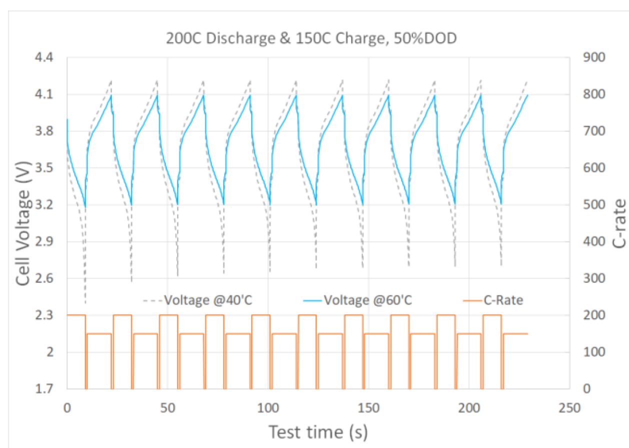

Figure 3. Cell cycling under 200C discharge and 150C charge, 50%DOD

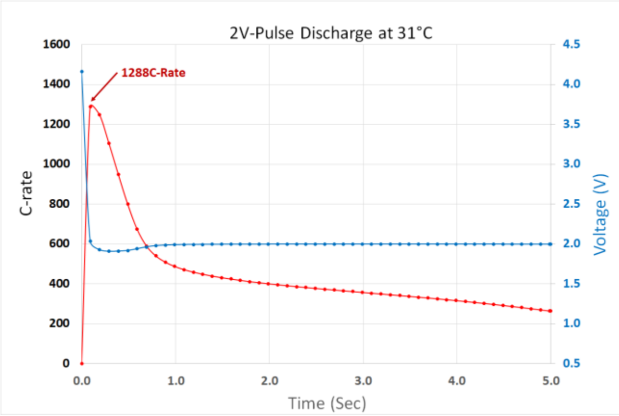

Figure 4. Short pulse discharge test at 31°C under 2V

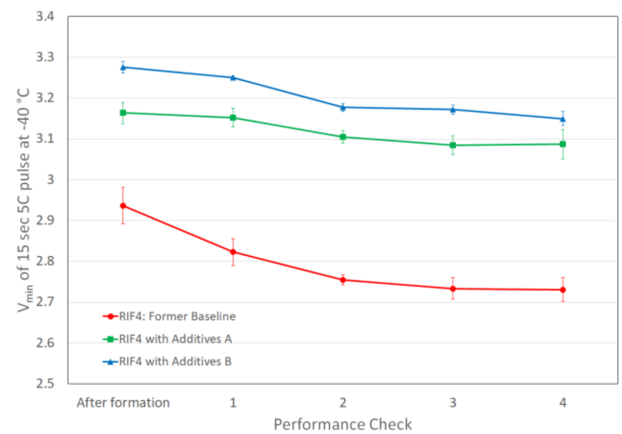

Figure 5. The voltage at the end of discharge (V_{dip}) from a 15 second 5C pulse at -40°C, after thermal aging between each check points

Ultra-Low Temperature Electrolyte Development

Non-standard applications like high-power DEW and MEA that operate in low temperatures pose a challenge for all components of the LIB. In certain situations, batteries intended for use in low-temperature environments may be exposed to high temperatures. In such cases, the battery or cell must exhibit high stability, minimal side reactions at high temperatures, as well as to maintain excellent energy density and power capability in low-temperature conditions. EPT has developed electrolytes with improved high power at temperatures as low as -40°C with improved stability at elevated temperatures (+70°C).

Various additive and additive packages have been developed to improve the life and high-power performance of batteries in low-temperature environments. Figure 5 displays the voltage at the end of discharge (V_{min}) of a 15-second 5C pulse at -40°C. These cells underwent aging between performance checkpoints by cycling at different temperatures ranging from -40°C to +71°C following a temperature histogram, with a total aging time of approximately one month. Compared with our former baseline, the new electrolytes with both additive package A and additive package B have demonstrated significant reductions in cell overpotential during -40°C discharge, as well as slowed cell degradation resulting from thermal cycling.

Figure 6 displays the voltage at the end of discharge (V_{min}) from a 15-second 5C pulse at -40°C. These cells were subjected to calendar aging at 55°C between performance checkpoints. The large error bars of the data points with former baseline indicates the cell performance varies greatly after high temperature exposure. The electrolytes with new additives show more consistent results, implying better thermal stability. Again, compared with our previous baseline, the new electrolytes have shown substantial reductions in cell overpotential during -40°C discharge and improved calendar life at elevated temperatures.

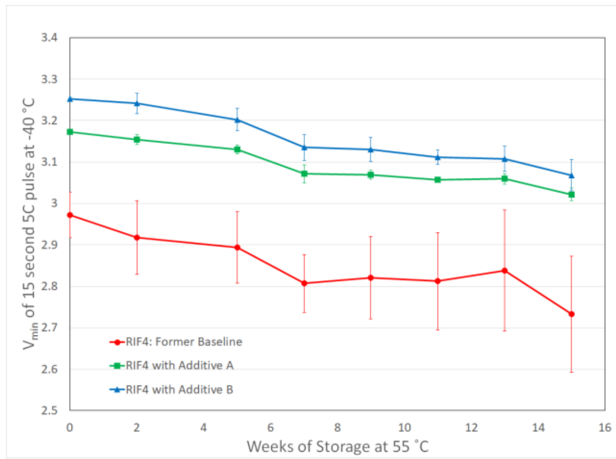

Figure 6. The voltage at the end of discharge (V_{min}) from a 15 second 5C pulse at -40°C, after calendar aging at 55°C between each check points

It is widely believed that ethylene carbonate (EC) is the critical component of the mixed solvent responsible for creating a robust passivation layer on the graphite-based negative electrode, also known as the solid electrolyte interface (SEI) layer. However, the high melting point of EC can result in the solution freezing or phase separation at low temperatures, particularly when the concentration of EC is high.

In response to the challenges posed by extreme-low temperature applications, such as those at -60°C, EPT has developed an "EC-free" electrolyte. As depicted in Figure 7, our baseline EC-based electrolytes can only deliver approximately 40% of the 1C R.T. discharge capacity when discharging at -60°C at C/3. However, with EPT's EC-free electrolytes, the cells can deliver up to 65% capacity at the same rate, representing an improvement of over 60%. Furthermore, after 250 cycles at room temperature, the cells using EC-free electrolyte continue to maintain a relatively high deliverable capacity at -60°C, validating their good cycle life at ambient temperatures.

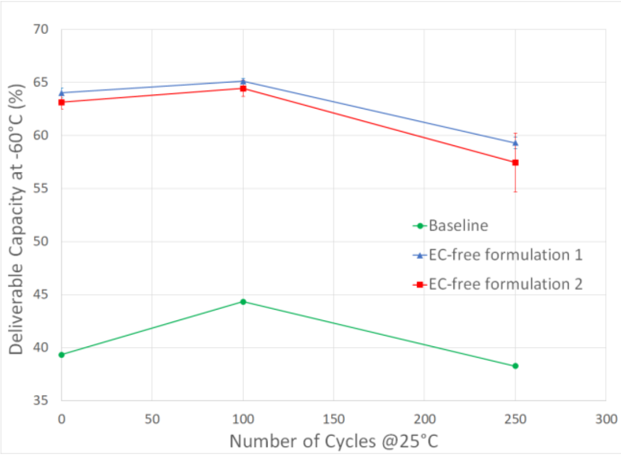

Figure 7. Deliverable capacity percentage at -60°C as a function of cycle numbers

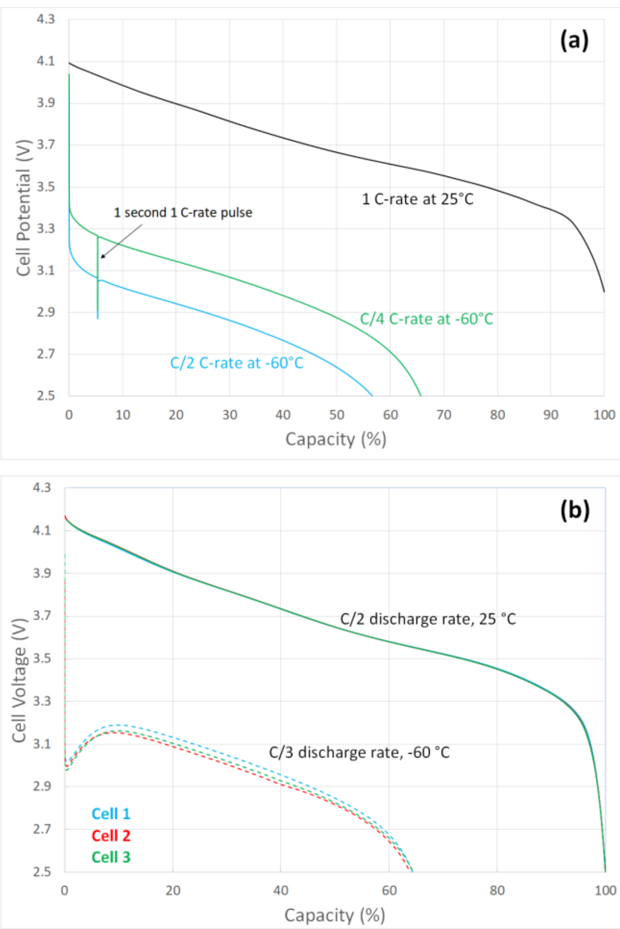

Figure 8. Discharge voltage profile at -60°C for (a) SLP cells and (b) 18650 cylindrical cells

Figure 8 illustrates the discharge voltage profiles of SLP cells and 18650 cylindrical cells at -60°C. At C/4 and C/2 rates, the SLP cells can deliver 66% and 56% of 1C R.T. capacity, respectively. Similarly, the 18650 cells can deliver around 64% of 1C R.T. capacity at C/3. During the discharge, the voltage of the 18650 cells showed a brief recovery at the start, attributed to self-heating. The cell temperature quickly rose by 3-4°C, then stabilized until the end of the discharge. In contrast, due to their small capacity and relatively larger surface area, the SLP cells did not exhibit any significant self-heating.

Conclusions

EPT has developed and demonstrated the impressive charge and discharge capabilities of our small pouch cells, which can deliver continuous power with up to 380C discharge rates. The specific short pulse-power of one 1 Ah cell is projected to reach a groundbreaking 50 kW/kg! These cells can also be recharged from 0%SOC to 60%SOC at a rate exceeding 100C, making them ideal for applications such as DEW and various hybrid systems that require rapid recharge capabilities.

Additionally, EPT has developed electrolytes specifically tailored for non-standard applications such as high-power DEW and MEA that operate in both high and low temperatures. Cells containing the new electrolyte have demonstrated improved high-power performance at temperatures as low as -40°C, with increased stability at elevated temperatures up to +70°C. To address the challenges of extreme-low temperature applications, EPT has also developed an "EC-free" electrolyte that allows the cell to deliver up to 65% of 1C capacity at temperatures as low as -60°C.

Overall, EPT's innovative technologies and solutions are poised to make a significant impact in various fields where high-performance energy storage is essential.

Acknowledgements

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References

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