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Robust, Versatile and Safe Lithium-Ion Batteries for Military Vehicle Applications

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ABSTRACT

Rechargeable batteries needed for military applications face critical challenges including performance at extreme temperatures, compatibility with military logistical processes, phasing out of legacy battery technologies, and poor compatibility of COTS lithium-ion batteries with specialized military operational requirements and legacy platforms. To meet these challenges, CAMX Power has developed and is commercializing a lithium-ion battery technology, trademarked CELX-RC®, with high power and rapid charging capability, long life, exceptional performance and charge acceptance capability at extreme low temperatures (e.g., -60 ºC), excellent safety, capability for discharge and storage at 0V, and ability to be implemented in batteries without management systems. This paper describes CELX-RC technology and its implementation in prototype batteries.

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1. INTRODUCTION

Specialized military applications can present performance, robustness and logistical requirements for batteries that may not be readily met by the lithium-ion (Li-ion) battery types that are predominant in the commercial vehicle, portable power and energy storage sectors. Challenges include performance at extreme temperatures, safety and compatibility with military logistical processes, phasing out of legacy battery technologies, poor compatibility of state-of-the-art Li-ion batteries with legacy platforms, and the lack of domestic sources for those Li-ion batteries.

CAMX Power has developed and is commercializing a lithium-ion battery technology that can address these issues, and has trademarked it as CELX-RC®. CELX-RC is much safer and more tolerant of extreme mechanical, electrical and thermal abuse than conventional Li-ion technology. CELX-RC can be discharged to 0V and safely handled, transported, and stored indefinitely in the completely de-energized condition with minimal environmental controls, overcoming problems in the logistical management of many rechargeable batteries including lead-acid and lithium-ion. Unlike conventional lithium-ion battery

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technology, CELX-RC has exceptional performance and charge acceptance capability at extreme low temperatures and can be implemented in batteries without management systems. CELX-RC is also made in the U.S. from CAMX Power's own proprietary GEMX® cathode active material, addressing concerns around the foreign sourcing of Li-ion cells and batteries.[1-2]

2. CELX-RC TECHNOLOGY

CELX-RC implements GEMX cathode materials (licensed to Samsung SDI, LG Energy Solution, EV Metals Group, L&F Co. and Umicore) opposite commercial lithium titanate (LTO) anode in cells with application-designed electrolytes. The GEMX materials platform is based on enriching the grain boundaries of polycrystalline high-nickel-content cathode materials with cobalt [3] and other stabilizing elements such as aluminum.[4] This strategy enables the bulk crystallites' nickel content to be maximized, yielding the highest energy density of any Li-ion cathode materials on the market today together with excellent power delivery and low-temperature performance.

The LTO anode was initially noted for its negligible volume change during electrochemical cycling, earning it designation as a "zero strain material",[5] and giving it exceptional cycling stability. However, at the time of its discovery, its low specific capacity and high potential relative to carbon made it unattractive for the contemporary Li-ion battery applications which all required the highest obtainable energy density. In subsequent years, it was found that the rate capability of nano-structured LTO is exceptionally high, at least in part because of its high potential. Most Li-ion electrolyte solutions are reductively stable at the LTO potential, ~1.55 V vs. Li, and thus do not form the passivating surface films (known as SEI) on LTO that they otherwise form on Li-ion anodes with lower electrochemical potential. Therefore, high surface area LTO can be used without incurring the prohibitive 1st cycle irreversible capacity loss that is encountered when using high surface area SEI-forming carbon-based anode materials. The lack of SEI and its associated impedance further enhances LTO rate capability as well as expanding the options for electrolyte composition. The high LTO potential also enables it to be charged at very high rates and low temperatures without danger of Li metal plating; Li plating limits the charge rates and temperatures that can be used for conventional graphitic carbon anodes because it causes rapid capacity fade and serious safety risks. Furthermore, LTO anode cells are much safer than conventional carbon anode cells because LTO lacks the reactivity with electrolyte that initiates thermal runaway in carbon-anode cells and because LTO is not combustible.[6]

Therefore, the LTO anode, although restricting energy density to about half that achievable with conventional graphite Li-ion anodes, nevertheless enables potentially critical performance attributes that graphite precludes, as listed above and described further here. The 0V tolerance and cycle life of CELX-RC are demonstrated by the pouch cell results shown in Figure 1.

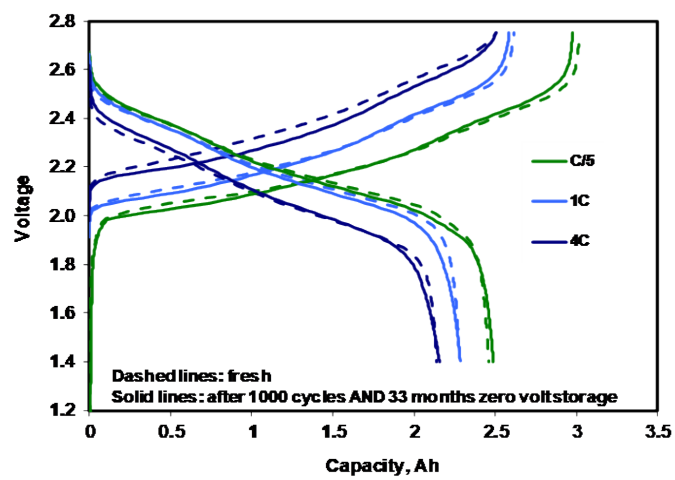

Figure 1: Charge and discharge voltage curves at indicated rates for a 2.5 Ah CELX-RC pouch cell before and after 1,000 full cycles at 1C/1C rate and almost 3 years storage in the 0V condition.

The data in Figure 1 show that the cell's performance was almost unchanged by being cycled through its full depth of discharge 1,000 times and then being stored in the 0V condition for almost 3 years. An important aspect of these results is that the pouch cell used to generate them was free-standing without any externally applied pressure beyond that of the ambient atmosphere. Although elevated-temperature gassing is reputed to be an issue for LTO-anode pouch cells,[7] we have found that careful attention to materials, cell design and cell assembly conditions can prevent any gassing issues.

The performance capabilities of CELX-RC at extreme low temperature are illustrated by the pouch cell cycling data in Figure 2, which show that unlike conventional Li-ion technologies, CELX-RC can be charged as well as discharged at extreme low temperature.

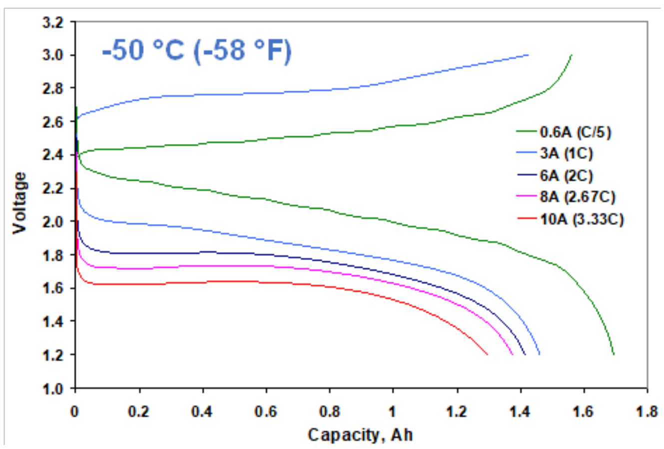

Figure 2: Charge and discharge voltage curves at indicated rates for a 3 Ah CELX-RC pouch cell cycled at -50 °C.

The potential for CELX-RC to be implemented in unmanaged batteries is demonstrated by results for cycling of a bare 11-series-cell stack of small pouch cells, shown in Figure 3. This capability is enabled by the cell technology's unusual tolerance for both overcharge and reversal voltages, and by its excellent safety. Benefits that can be provided by batteries without management electronics may include much reduced radiation susceptibility and more facile implementation as drop-in replacements for nickel-cadmium or lead-acid batteries in legacy platforms.

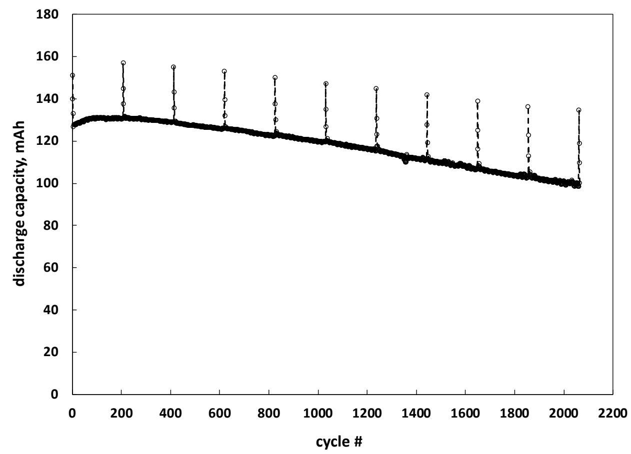

Figure 3: Discharge capacity of an unmanaged 11-S stack of CELX-RC pouch cells cycled 28.5 V to 20 V at 200 mA charge and discharge current, with 20, 50 and 100 mA discharges at 200-cycle intervals.

3. CELX-RC BATTERY EXAMPLES

Several different CELX-RC-based military battery prototypes have been or are being developed by CAMX Power in government-sponsored work. Two of them are described below.

3.1. 0V-Capable 6T Battery

A CELX-RC-based, 0V-capable 6T battery prototype meeting type 1-A55 battery performance requirements of the MIL-PRF-32565C 6T Lithium-ion battery specification was made from 6 parallel 11-series strings of 10 Ah pouch cells. Figure 4 shows the battery's voltage characteristics.

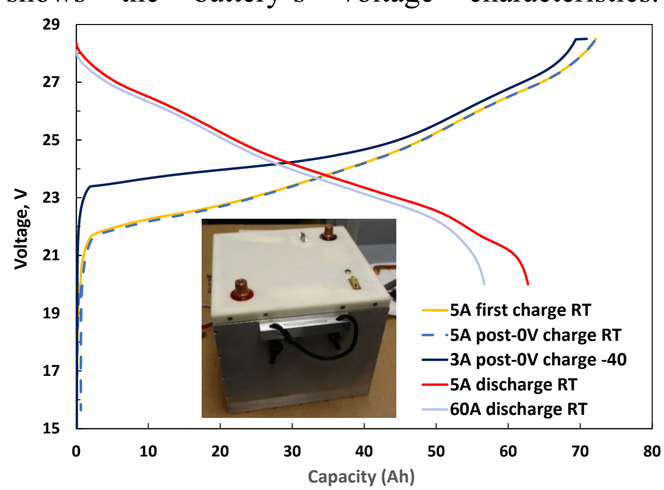

Figure 4: Charge and discharge voltage curves for CELX-RC-based 6T battery prototype (picture is inset).

Figure 4 shows that the battery's post-0V RT recharge characteristic matches its first charge curve, indicating that discharge to 0V essentially returns the battery to its as-made state. Furthermore, Figure 4 shows that the battery can be fully recharged from the 0V condition at -40 °C (-40 °F).

The battery's excellent low-temperature performance was further demonstrated by its cold cranking performance. While meeting the type 1-A55 battery requirement for 30-second 200 A pulse capability above 14.4 V at -40 °C, the battery also met the type 1-B55 requirement for 30-second 400 A pulse capability at -40 °C, as shown in Figure 5.

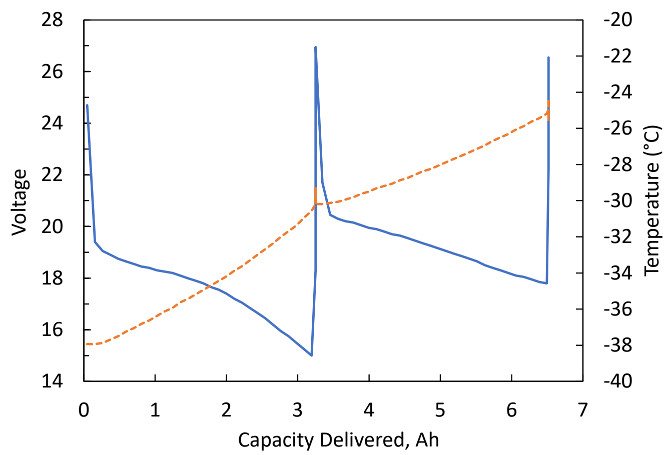

Figure 5: Voltage and internal temperature of CELX-RC-based 6T battery prototype at -40 °C as it was discharged at 400 A in two 30-second pulses with 5 minutes intervening rest.

Figure 5 shows that the battery's ohmic self-heating significantly boosted its low-temperature performance, and this was even more clearly demonstrated by results of discharge testing at -60 °C, shown in Figure 6. The data show that even at such extremely low temperature, the battery delivered over half its capacity when discharged at the 1C rate, with voltage reversal starting after about 2 Ah of charge had passed. The -60 °C discharges shown in Figure 6 were performed in sequence without removing the battery from the -60 °C temperature chamber, and with the battery being recharged to 28.5 V at 3 A rate in the -60 °C chamber, further demonstrating its exceptional low-temperature charging capabilities.

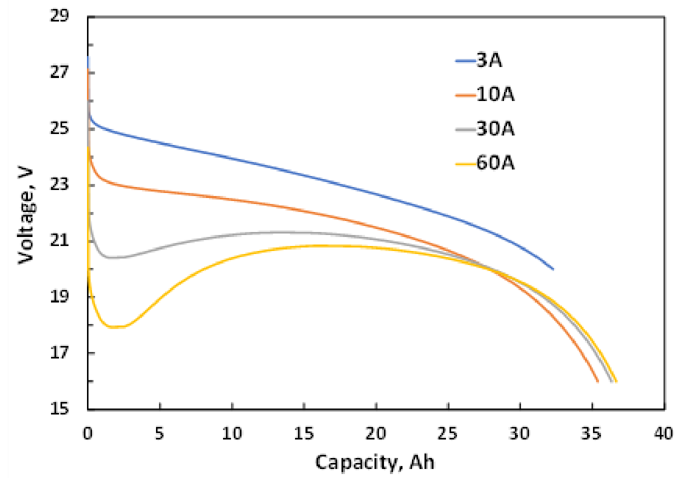

Figure 6: Constant current discharges of CELX-RC-based 6T battery prototype at -60 °C.

A 6T battery of the type described above could provide several unique advantages to meet specialized needs. Its 0V capability and robustness and safety in the fully discharged condition can greatly simplify logistical management. Its exceptional low-temperature performance can be highly advantageous in the emerging Arctic operational theatre. And its excellent safety in the charged condition, addressed in a following section of this paper, can overcome concerns surrounding deployment of Li-ion battery-equipped vehicles by Navy vessels. CAMX Power is continuing to develop this 6T battery technology.

3.2. High-Power Buffering Module

An unmanaged CELX-RC-based module built from a 12-S, 2-P array of 2 Ah pouch cells was developed to address replacement of the MIL-B-11188/2 4HN flooded lead-acid battery. The 4HN is used in the Bradley Fighting Vehicle to stabilize voltage when electrical load transients occur within the vehicle's turret power bus. Flooded lead-acid batteries are being replaced by AGM types, but these do not tolerate high current charge pulses as well as the older flooded batteries do, prompting interest in alternative technologies. Figure 7 shows results for pulse charging of the module when it was already charged to 28.5V and at >90% SOC.

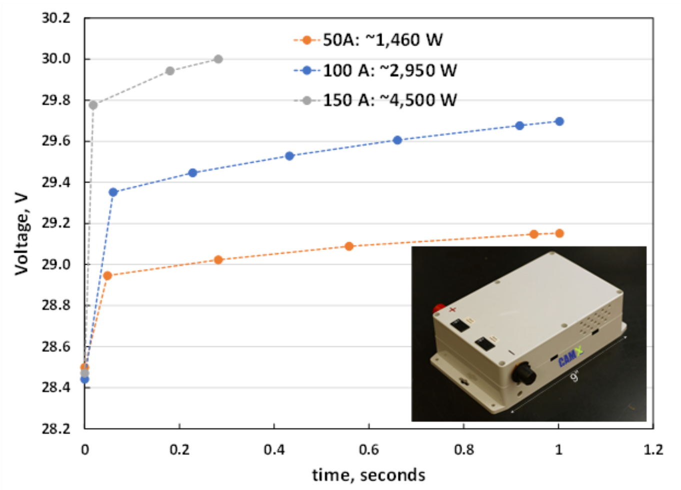

Figure 7: Voltage during constant current charging for 1 sec. or to 30V of CELX-RC-based 2.7 liter, 4.3 Ah, 100 Wh battery module (picture is inset) at indicated currents and corresponding approximate powers, after the module had been charged to 28.5V.

The module accepted charge power of about 4.5 kW before reaching the 30V limit of the cycler used to run the test, and was projected to accommodate initial pulse current up to 530 A (~17.5 kW) and current up to 370 A (~12 kW) for 1 second within the 33 V operating voltage limit of the MIL-STD-1275 28V DC bus interface standard.

The module also demonstrated exceptional high-power and low-temperature discharge performance as shown by the -18 °C pulse discharge and -40 °C continuous discharge results in Figure 8. Although the module is only one third the volume and less than one fifth the weight of a 4HN battery, it met the MIL-B-11188/2 requirement for the 4HN battery to deliver 75 A above 1 V per cell (12 V) at -40 °C for at least 1.75 minutes. In other tests, the module readily performed discharge profiles emulating electrical loads of critical vehicle weapon systems.

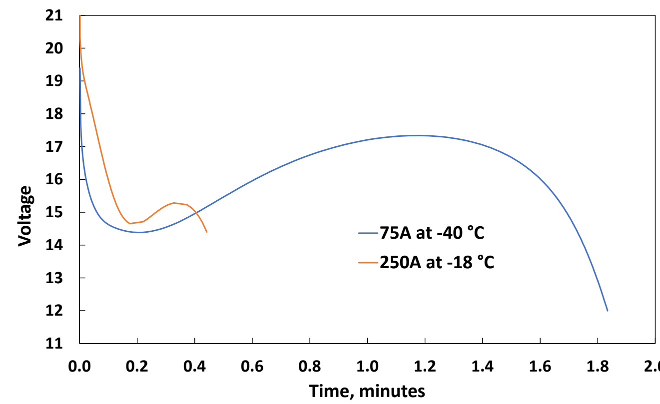

Figure 8: 30-second discharge pulsing at -18 °C and 75 A continuous discharge at -40 °C for CELX-RC-based 4.3 Ah battery module.

Other opportunities for high-power CELX-RC technology are being explored, as for example, applications needing the power density of ultracapacitors but with up to 10 times their energy density.

4. CELX-RC SAFETY

The CELX-RC cell technology's safety and exceptional tolerance to severe mechanical abuse has been demonstrated by tests including nail penetration, round bar crush, impact, and cutting (with shears) of pouch cells up to 6 Ah in size, which at worst have resulted in only mild shorting corresponding to a low-rate discharge. However, even when hard-shorted, the technology is much safer than conventional Li-ion.

Figure 9 shows that when a charged 8 Ah, 28 V 11-series pouch cell-based module was fully shorted by through-penetrating it with a 2 cm diameter nail, the cells vented and limited melting of the polycarbonate case occurred (indicating ~300 °C reached), but no flames or sparks were observed, thus demonstrating SAE J2464 hazard severity level ≤ 4 (as is required for a 1-A55 Li-ion 6T battery per MIL-PRF-32565C).

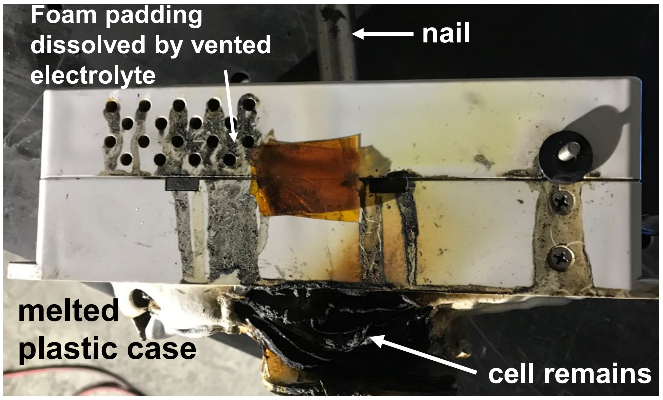

Figure 9: 200 Wh module after charged module was penetrated by 2 cm diameter nail.

A post-mortem tear-down of the module revealed that the cells' electrodes and aluminum current collectors were intact as shown in Figure 10, thus indicating that no thermal runaway had taken place.

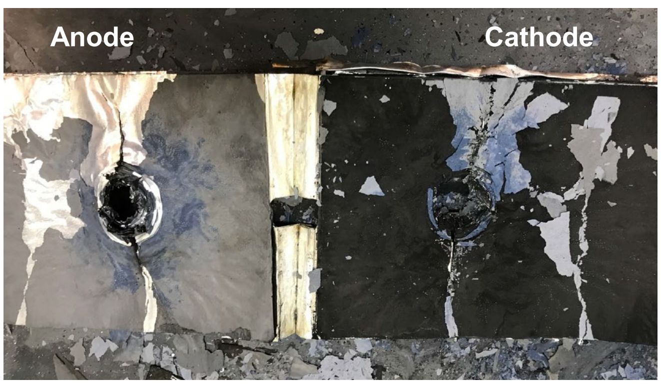

Figure 10: Torn down cell from 200 Wh module following penetration by 2 cm diameter nail.

The safety characteristics of CELX-RC technology under extreme abuse conditions are far superior to those of conventional Li-ion technology and can thus enable its use in military applications where safety concerns have hindered adoption of conventional Li-ion technology. This, together with the excellent performance, robustness and logistical characteristics described above, can make CELX-RC suitable for applications in which these properties are more important than a need for the highest possible energy density provided by conventional Li-ion.

CELX-RC cell and battery development are continuing at CAMX Power and include development of hard-case cylindrical cells and batteries employing them for low-pressure applications such as aircraft and spacecraft. Facilities to manufacture CELX-RC at volumes of up to 1 MWh/year are currently undergoing construction to support production for niche applications and for initial battery qualifications.

5. ACKNOWLEDGEMENTS

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