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Development of a BB-2590/U rechargeable lithium-ion battery

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Abstract

PolyStor has teamed with Hawker Eternacell (US) to develop a BB-2590/U rechargeable lithium-ion battery under contract with the US Army CECOM (Ft. Monmouth, NJ, USA). The concept involves using commercially available ICR-18650 cylindrical lithium-ion cells. The individual cells have a high specific energy of 135 Wh kg^{-1} and an energy density of 335 Wh dm^{-3}. Electronic circuitry was developed to provide pack protection, charge equalization and battery management (fuel gauging). PolyStor's rechargeable BB-2590/U battery provides 4.5 Ah at 28 V nominal or 9.0 Ah at 14 V nominal, translating into 108 Wh kg^{-1} and 150 Wh dm^{-3}. The key developments are discussed in this paper. © 1999 Elsevier Science S.A. All rights reserved.

Keywords: Applications/military portable equipment; Lithium-ion secondary batteries Charge control; Safety devices

1. Introduction

PolyStor has teamed with Hawker Eternacell (US) to develop the next-generation battery for one of the most common type in the US Army battery series listed in MIL-B 49436, a type currently using both primary and secondary technologies. These batteries are currently used in over 50 different transceivers including, but not limited to, AN/PSC-5, AN/PRC-117, AN/LST-5, MST-20 also known as AN/PSC-7), AN/PRC-113, AN/URC-200, AN/PRC-138, AN/PRC-104 and the very popular AN/PRC-119 (commonly known as SINCGARS) [1]. This new-generation battery is fully rechargeable, lighter and provides longer run-times than other rechargeable systems.

PolyStor's concept is to use commercially available lithium-ion cylindrical cells as the energy source to provide the highest performance system with the best value. The cylindrical cells used, ICR-18650, are the most popular size with over 150 million cells produced in 1998 by at least six manufacturers in North America and Japan. This factor drives the price of the cells down and provides a low-cost end product. The strong commercial market, primarily for notebook computers, has led manufacturers to improve the product performance to keep up with increasing power demands of today's high performing notebooks, some matching the performance of desktop systems. The use of existing lithium-ion cell technology provides the best performance at the lowest possible price.

The BB-2590/U rechargeable lithium-ion battery is being developed as a replacement for the existing BB-XX90/U batteries used today. Current primary systems include Li/SO_2, $Li/SOCl_2$ and Li/MnO_2. Common rechargeable systems use nickel/cadmium and lead-acid. New systems are being developed with the nickel/metal hydride couple, but these batteries are meeting resistance from the end-users due to inferior performance. PolyStor's lithium-ion battery is being developed to provide the low weight of the primary versions but with significant capacity improvements over the rechargeable versions.

2. Development process

2.1. Lithium-ion cells

PolyStor had previously developed an ICR-18650 lithium-ion cylindrical cell. These cells are approximately 18 mm in diameter and 65 mm in height. Lithium-ion cells are cycled between 4.2 V and 2.5 V, with an average discharge voltage of 3.7 V at the C/5 rate. Since their introduction, ICR-18650 cells have been enhanced every year, with their capacity increasing from 1.0 Ah in 1993 to over 1.5 Ah today. 1.8 Ah cells are forecast for the end of 1999.

Individual ICR-18650 lithium-ion cells were tested for discharge, temperature and charging characteristics, and for cycle life. Testing individual cells gives an indication of the performance to expect in multi-cell battery packs.

The ICR-18650 lithium-ion cell has a relatively flat discharge profile as shown in Fig. 1 at rates from C/5 (5-h discharge) to 2 C (0.5-h discharge). Discharge curves at

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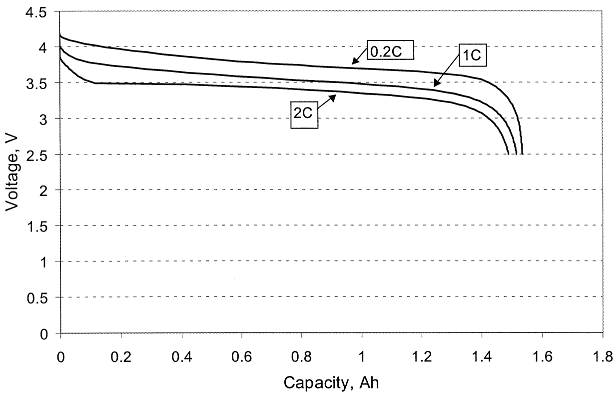

Fig. 1. Discharge curves at the C/5, 1 and 2 C rates for the ICR-18650 cell at 23°C.

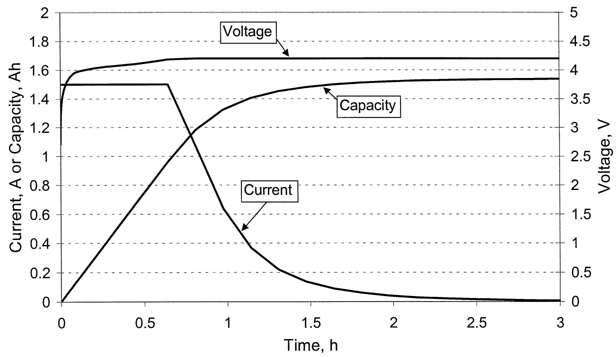

Fig. 3. Charging characteristic at 23°C of an ICR-18650 cell at constant current (limited to 1.5 V) to 4.2 V, then constant voltage.

the C/5 rate are shown in Fig. 2. At temperatures ranging from −20°C to +40°C. These commercial lithium-ion cells perform adequately to −20°C; however, special designs of cells are required for operation at temperatures as low as −40°C.

Lithium-ion cells are charged using a constant current limited to C rate or less with the voltage limited to 4.2 V per cell, as shown in Fig. 3. The charging starts in the constant current mode, then switches to the constant voltage mode when the cells reach 4.2 V. In the constant voltage mode, the charge current tapers downward as less current is required to maintain the 4.2 V limit with increasing time-into-charge. Charge can be terminated either by time, a pre-set low current, or a combination of both.

Cells were tested at both 23°C and 40°C for cycle lives and results are shown in Figs. 4 and 5. The discharge sequence used at both temperatures involved a 1 C rate to 2.5 V, followed by a 5-min rest, then a C/5 rate to 2.5 V. Multi-step discharge sequences provide useful information on the remaining capacity at both high and low rates as a function of cycle life.

The ICR-18650 lithium-ion cells cycled well at both temperatures, with over 70% of the C/5 rated capacity remaining after 500 cycles. The cells actually cycled better at 40°C as the cells exhibited a smaller increase in internal impedance (seen as the difference in capacity at C and C/5 rates) than the cells cycling at 23°C. Lithium-ion cells have a typically useful lifetime of over 1000 cycles, as the cells exhibit a gradual loss of capacity each cycle due to increased cell impedance. The sudden capacity loss as seen in nickel/cadmium and metal hydride systems is not a typical failure mechanism.

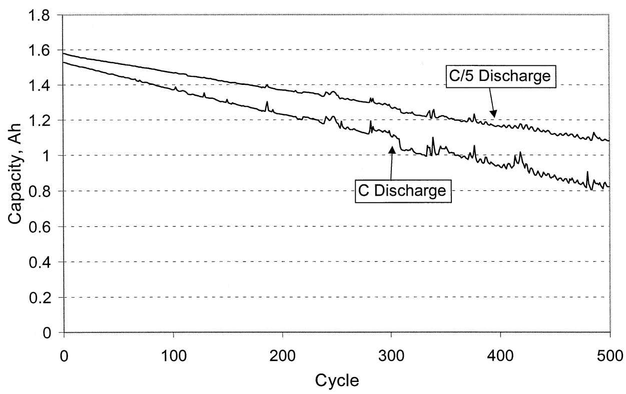

Fig. 4. 500 cycles at 23°C of an ICR-18650 cell. Charged as Fig. 3. Discharge sequence: 1 C rate to 2.5 V, 5 min on open-circuit, then C/5 rate to 2.5 V.

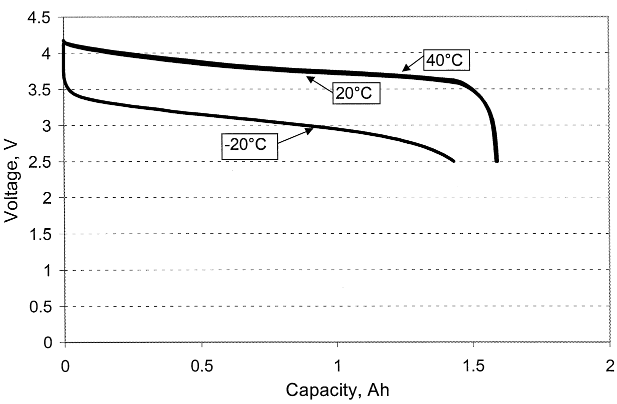

Fig. 2. Discharge curves at the C/5 rate for the ICR-18650 cell at −20, 20 and 40°C.

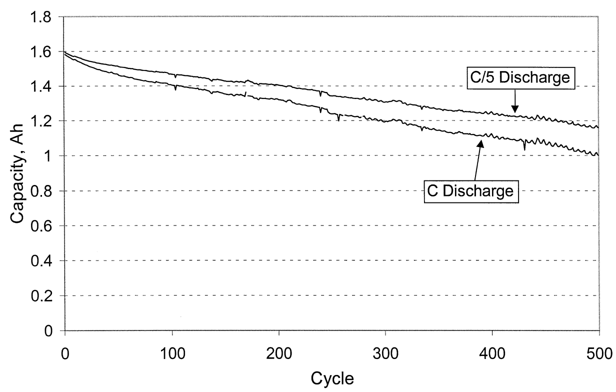

Fig. 5. 500 cycles at 40°C of an ICR-18650 cell. Charged as Fig. 3. Discharge sequence: 1 C rate to 2.5 V, 5 min on open-circuit, then C/5 rate to 2.5 V.

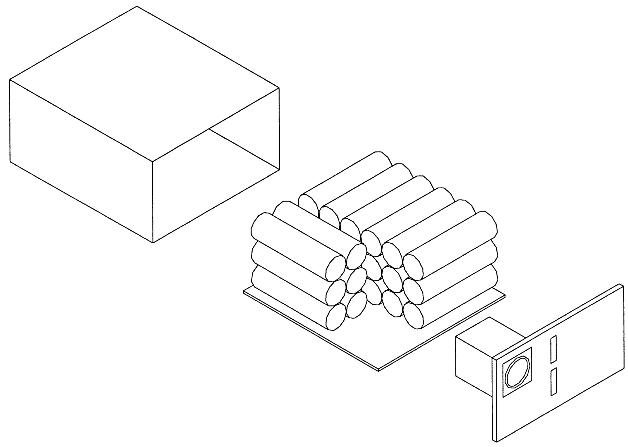

Fig. 6. Layout of cells within the BB-2590 battery.

2.2. Battery design

The battery was designed to accommodate 24 ICR-18650 lithium-ion cells as two 12-cell modules. Each 12-cell module was configured in a three parallel by four series arrangement, providing 4.5 Ah at an average voltage of 14.8 V. The 12-cell modules were designed to be used either in parallel or in series, depending on the application. Unlike nickel/cadmium or metal hydride, lithium-ion cells work very well when connected in parallel as they balance each other continuously through the interconnections. Cells are paralleled first, and then the parallel strings are connected in a series configuration. The mechanical arrangement of the cells within the plastic enclosure is detailed in Fig. 6.

2.3. Electronics

Electronic circuitry was utilized to provide maximum safety and reliability. Pack protection, charge equalization and battery management (or fuel gauging) were three of the functions designed into the pack electronics. The electronics for each 12-cell module were configured independently but designed to work together. A block diagram of the circuitry in one module is shown in Fig. 7.

2.4. Pack protection

Individual cells must be protected from overcharge, over discharge, and excessive discharge current (short

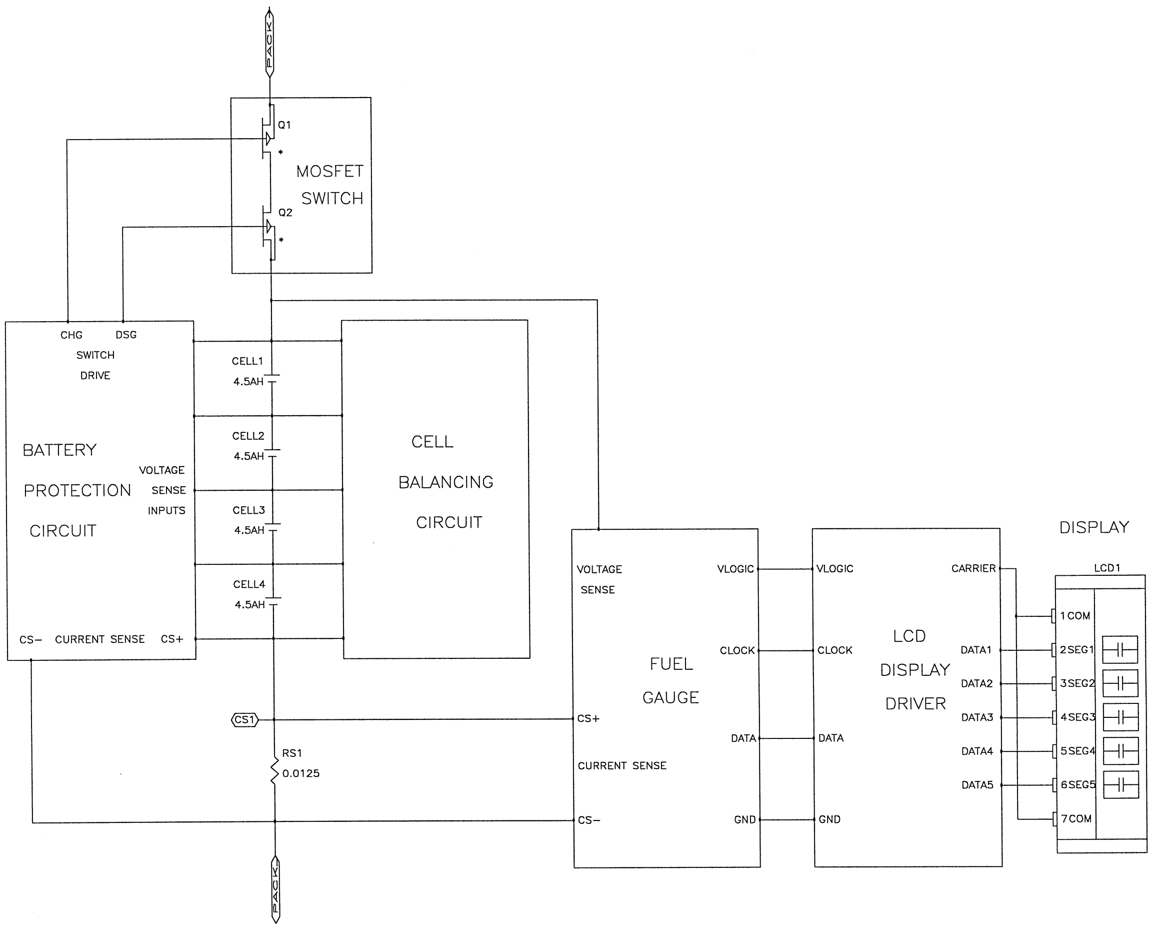

Fig. 7. Block diagram of the circuitry associated with one of the modules in a BB-2590 battery.

Table 1
Protection voltage thresholds and delay times

Symbol	Parameter	Units	Minimum	Typical values	Maximum
V_{OV}	Over-voltage threshold	V	4.25	4.30	4.35
V_U	Under-voltage threshold	V	2.10	2.25	2.40
V_{OC}	Over-current sensing voltage	mV	130	160	190
t_{OVD}	Over-voltage delay time	ms	570	950	1330
t_{UVD}	Under-voltage delay time	ms	570	950	1330
t_{OCD}	Overcharge delay time	ms	7.2	12	16.8

circuit). The protection circuit utilizes a Benchmarq bq2058 control IC and a series connected high-side switch to accomplish these functions. The bq2058 IC samples the individual cell voltages and compares them to precept overcharge and over-discharge voltage limits. The cell voltages must exceed these limits for greater than 950 ms for a fault to register. This programmable delay performs a filtering function that prevents the circuit from triggering on transient voltage spikes that may appear on the cells. The discharge current limit also has a delay, 12 ms, in this battery. The battery current is measured in each module. The fuel gauge and the protection circuit both measure the voltage across a precision (1%) series resistor to determine the current. The protection circuit also measures the voltage drop across a portion of the high-side switch, which serves as a secondary current limit. The maximum continuous current trip point is set at 12.5 A.

The protection thresholds are summarized in Table 1. below and apply from 0°C to 70°C:

The protection switch consists of two IRF-4905S, p-channel MOSFETs, connected in series with opposed drains. These devices were selected for their high current handling capability and breakdown characteristics. The breakdown for the protection switch must be at least 50 V, to enable the two three-by-four cell configurations to be operated in series. In such an arrangement, the switch may have to withstand the full 33.6 V battery voltage or the output of a high voltage charger. The total supply current for the protection circuit is 40 μA maximum. The supply current drops too less than 1 μA if the battery is over-discharged (i.e., average cell voltage less than 2.25 V).

2.5. Charge equalization (cell balancing)

A simple op-amp circuit corrects for any small differences in cell state-of-charge within the battery. This function is frequently referred to as cell balancing. In each battery string of four cell groups in series, an autonomous circuit continuously computes the average battery voltage and provides an incremental current that drives the individual cells toward the average voltage. A current limiting resistor is added inside the loop of each operational amplifier to create a fixed transconductance. Viewed another way, this resistor simply limits the output current of the op-amps. The maximum correction current is only 8.4 mA; hence, any state-of-charge correction will occur slowly and continuously until balance is achieved. Drive connections to the amplifier are decoupled with resistors to further limit the current if the amplifier were to fail.

The cell balancing circuit imposes a parasitic drain on each group of three parallel-connected cells. The maximum quiescent current drawn from each cell is 40 μA. This current is of no practical significance, since it is equivalent to approximately the four-year discharge rate.

2.6. Battery management (fuel gauge)

A Benchmarq bq2040 coulometric fuel gauge is used to compute the state-of-charge of each module. The circuit continuously monitors current flow through the battery, as well as the voltage across the four-cell string. The integrated current over time is recorded in a counter and the difference between the total charge added to the battery and the total charge removed from the battery is used to determine the battery's absolute state of charge. The ratio of the absolute state of charge to a programmed design capacity is the battery's relative state of charge. The bq2040 uses a computational algorithm that has corrections for charge and discharge rate, temperature, and self-discharge. The data described here are organized in a database that conforms to standards set forth by the SBS Smart Battery Association [2].

The use of this arrangement is advantageous, because the battery can be charged from standard Smart Chargers. In fact, the Smart Battery can communicate to the Smart Charger the required charge method, current and voltage.

The maximum total supply current for the fuel gauge is 300 μA. The supply current drops to less than 5 μA in the over-discharged state (i.e., average cell voltage less than 2.25 V).

A separate microcontroller on the display module polls the bq2040 fuel gauge to determine the battery's relative state of charge. Using the data, the microcontroller creates the AC signals required to drive a simple LCD bar code display. Each of the five segments in the display represents a 20% capacity increment.

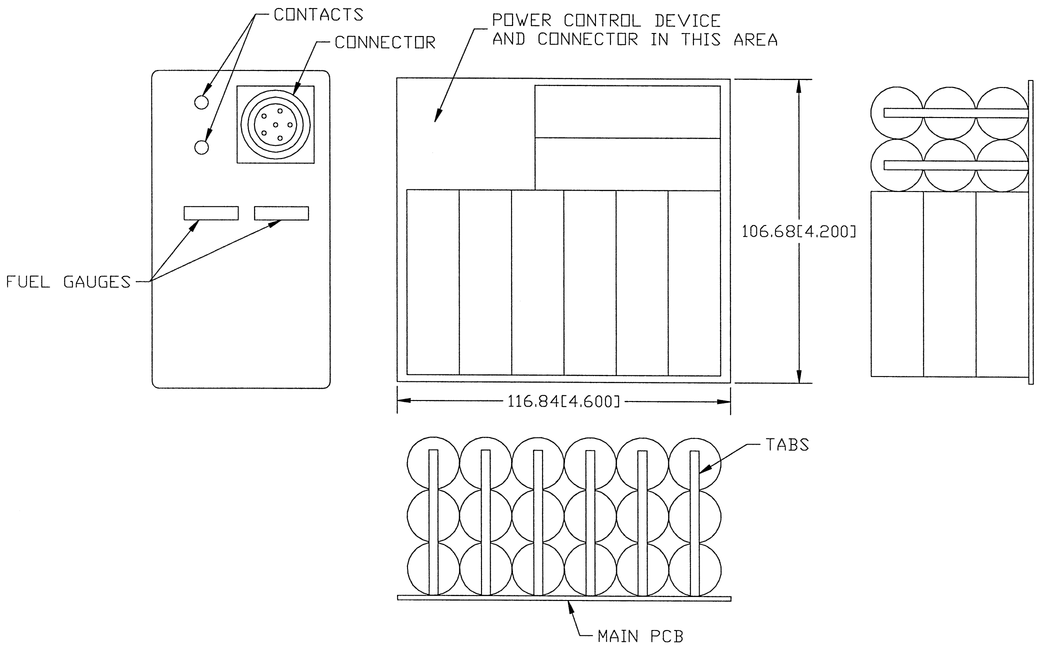

Fig. 8. Layout of the BB-2590 battery.

2.7. Circuit boards

Two circuit boards were developed for this battery. The main board contains the major circuit functions and the daughter board contains the state-of-charge indicator.

The main board is approximately 117 mm × 107 mm and includes the pack protection, charge equalization and battery management functions. The board was designed with 16 slots for soldering the positive and negative tabs of the eight, three-cell, parallel strings. Core pack assembly simply involves tabbing eight, three-cell strings and soldering the tabs to the board. The core pack is then ready for insertion into the battery case. The design of this board resulted in a simplified assembly procedure, as shown in Fig. 8.

Two identical daughter boards containing an LCD panel and microcontroller are used in the battery pack, one for each module. These boards are attached to the end cap with the LCDs visible through clear plastic windows.

2.8. Hardware

The hardware used in the development of the BB-2590/U was initially designed for the BB-390/U nickel/metal hydride battery pack. The hardware was designed to be waterproof and has two slots for LCD panels, one for each module. The plastic case is a solid piece except for one end where an end cap is ultrasonically welded to provide increased waterproof capability, as opposed to the clam shell designs used in some primary versions. In production of the lithium-ion battery pack, the venting system required to prevent hydrogen explosions in the nickel/metal hydride version is eliminated. It is not required for lithium-ion. cells, as they are sealed and do not vent gases, except under certain extreme conditions of abuse.

The six-pin connector is wired to allow for either a 14 V or 28 V output, depending on how the application device is connected. Future versions for new applications will be available with additional pins that bring out the clock and data lines of the Smart Battery Management System. Battery information can then be communicated to the host application and battery charger, following the Smart Battery protocol.

3. Test results

As part of this BB-2590/U development contract, PolyStor and Hawker Eternacell will be performing First Article Testing, Underwriters Laboratories safety and abuse tests and a series of performance and reliability tests.

3.1. Performance

BB-2590/U lithium-ion battery packs were tested for discharge and charge characteristics. Cycle life testing was not available at the time of writing.

The pack has a relatively flat discharge profile at rates from C/5 (5 h discharge) to 2 C (0.5 h discharge), as shown in Fig. 9. Note that at 2 C or 9 A, the battery is discharging at a constant power of approximately 230 W.

Tests are underway to determine the maximum continuous discharge rate and maximum pulse rate for the battery. Cell and pack design, including circuitry, will dictate the maximum discharge rates. Commercial ICR-18650

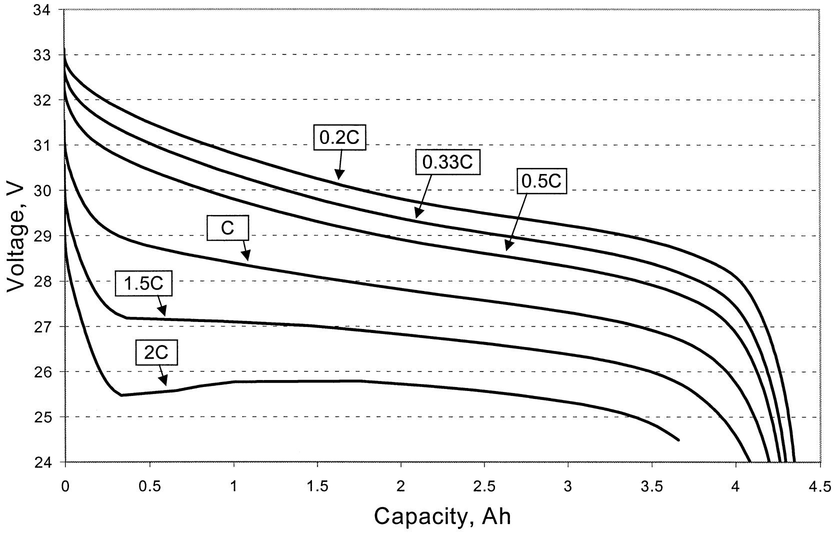

Fig. 9. Discharge curves at various rates between C/5 and 2 C for the BB-2590 battery at 23°C.

lithium-ion cells have an internal PTC device to protect them against short circuit. Using known cell impedances, we calculated that there is a power dissipation from the cells of 21.4 W during a 9 A discharge. At this current output, the MOSFETs on the pack protection board can add an additional 6.5 W and the sense resistors can add 1 W, to give a total of 28.9 W. Despite this relatively large power dissipation, the overall efficiency is very good:

$$\varepsilon = (\text{power delivered})/(\text{total power}) \times 100\%$$
$$= (\text{power delivered} @ 9\,\text{A})$$
$$/(\text{power delivered} @ 9\text{A} + \text{power loss}) \times 100\%$$
$$= (230)/(230 + 28.9) \times 100\% = 88.8\%$$

PolyStor is currently investigating the use of non-standard ICR-18650 cells without PTC devices and modifications to the pack protection circuit that will dramatically lower the heat dissipation within the battery pack under very high current loads.

Charging the BB-2590/U battery pack can be accomplished either at 16.8 V (with the two modules in parallel) or at 33.6 V (with the modules in series). Both methods use the constant current–constant voltage method, with the 33.6 V option shown in Fig. 10. Note the short charge time for the battery pack of 1 h to 83% full charge or 2.25 h to full charge.

3.2. Safety and abuse

PolyStor and Hawker Eternacell are currently evaluating the safety and abuse tolerance of the BB-2590/U battery described in this paper. Preliminary testing has shown the pack protection circuitry to activate as designed,

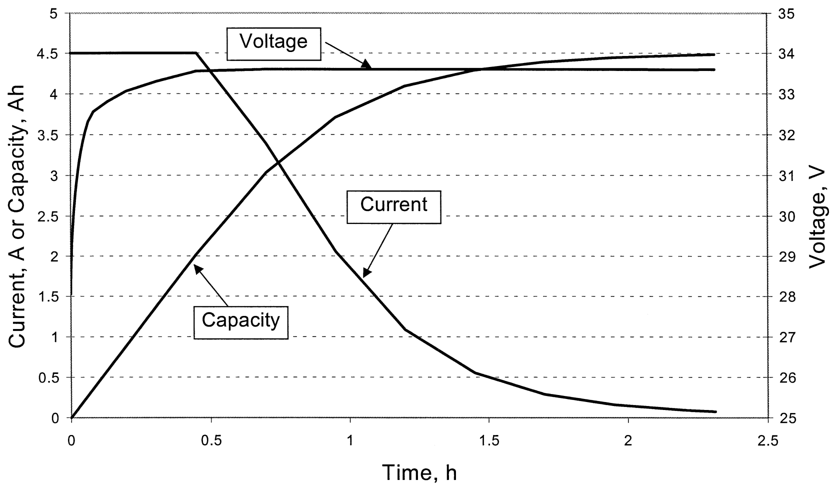

Fig. 10. Charging characteristic at 23°C of a BB-2590 battery at constant current (limited to 4.5 A) to 33.6 V, then constant voltage.

Table 2

	Model number	Chemistry	Capacity (Ah)	Voltage (V)	Weight (g)
Primary	BA-5590	Lithium/sulfur dioxide	8.0	24	1022
Secondary	BB-390	Nickel/metal hydride	3.6	24	1750
	BB-490	Lead–acid	1.8	24	1589
	BB-590	Nickel/cadmium	2.3	24	1750
	BB-690	Lead–acid	1.8	28	1680
	BB-X90	Lithium–polymer elect.	4.0	28	1046
	BB-2590	Lithium-ion	4.5	28	1230

and so protect the cells during short circuit, overcharge and over discharge conditions. Mechanical testing remains.

4. Comparison with other batteries

PolyStor's BB-2590/U rechargeable lithium-ion battery compares very well with the existing primary and rechargeable versions. Although the primary versions have higher capacity, the life-cycle cost is very high compared to lithium-ion batteries that can be cycled at least 500 times. PolyStor's lithium-ion battery outperforms all rechargeable batteries, including the newest lithium-ion polymer batteries currently under development [3].

Table 2 compares some of the existing batteries that have been designed in this format with new systems under development.

5. Conclusions

Military personnel around the world need superior performance, lightweight, cost-effective rechargeable batteries to provide power to a wide range of man-portable radios. PolyStor has developed a state-of-the-art BB-2590/U lithium-ion battery to replace the existing BB-590/U nickel/cadmium and BB-390/U nickel/metal hydride batteries. PolyStor's BB-2590/U is significantly lighter and provides longer operating times than existing rechargeable batteries.

Acknowledgements

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