

## A 65 A h RECHARGEABLE LITHIUM MOLYBDENUM DISULFIDE BATTERY

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### Summary

The design of a rechargeable 65 A h, spirally wound, lithium molybdenum disulfide cell is described as a scale up of a "C" size cell. The results of battery testing are described in which a gravimetric energy density of 94 W h kg<sup>-1</sup> was achieved at the lowest rate. The cycle life of the battery is greater than 100 cycles and peak power densities of 128 W kg<sup>-1</sup> were demonstrated. Directives for further improvements are discussed.

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### 1. Introduction

Moli Energy Limited has, during the past seven years, developed rechargeable lithium molybdenum disulfide batteries which have a number of superior performance characteristics including a high energy density, a high power density, and a long charge retention time. The first cell sizes developed include a "C" size cell and an "AA" size cell whose performance characteristics have been discussed elsewhere [1].

Over the last two years, a project to demonstrate the feasibility of the scale-up of this technology to a "BC" size cell with 65 A h capacity has been undertaken. The objective of the project was to develop, build, and test a 0.6 kW h storage battery consisting of 6 "BC" cells in series.

### 2. Battery design

The design of the "BC" cell was based on concepts developed for "C" size cells. Both cell sizes were of a jelly roll type (spirally wound) construction and the scale up was achieved by increasing the electrode area by a factor of 22 to a total of 16 700 cm<sup>2</sup> without changing the thickness of the electrodes. The capacity was calculated to 65 A h using a linear scale factor.

Figure 1 shows an exploded view of the "BC" cell design. The anode was a 125 μm thick lithium foil connected with six nickel tabs to the negative terminal. These tabs were positioned along the anode strip at equidistant intervals. The cathode consisted of the cathode powder bonded to a metal foil current collector which was connected to the positive terminal with six

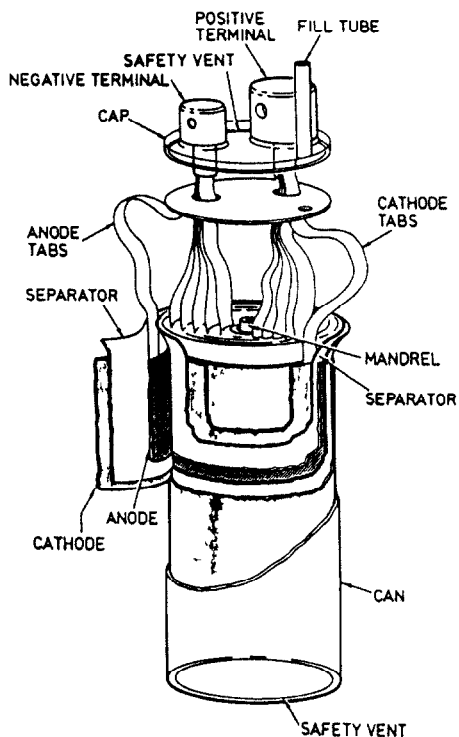


Fig 1 Exploded view of a "BC" cell

nickel tabs. A glass-to-metal seal was used to insulate the positive terminal from the case. The two electrodes were separated by a microporous polypropylene separator. The separator and the porous cathode were impregnated with an electrolyte consisting of a 1 molar solution of  $\text{LiAsF}_6$  in a mixture of organic solvents. The cell case was hermetic with a safety vent in the cell bottom.

The 0.6 kW h battery consisted of six cells connected in series and held together by two rigid plates tied together with bolts. The battery hardware was not optimized with respect to weight or volume. Table 1 gives the specifications for this battery.

TABLE 1

Specifications for 6 cell "BC" battery

Battery dimension	25 cm × 16 cm × 21 cm
Battery weight	7.3 kg
Nominal battery voltage	10.8 V
Nominal battery capacity	65 A h
Charging	5 A constant current
Voltage cut-off on charging (standard charge)	14.4 V

### 3. Single cell performance testing

Tests on single cells were performed after recharging at 21 °C with a constant current of 5 A to a cell voltage of 2.4 V. For some tests, cells were charged to a voltage of 2.6 V, a condition which will be referred to as “supercharged”. The discharges were performed at constant current and the cell voltage was used to determine the endpoint. Figure 2 shows the voltage profile for a single cell cycle consisting of a charge half cycle followed by a discharge at 15 A to a cell voltage of 1.3 V. The shape of the voltage profiles is characteristic of the  $\text{Li}_x\text{MoS}_2$  intercalation compound used in these batteries [2].

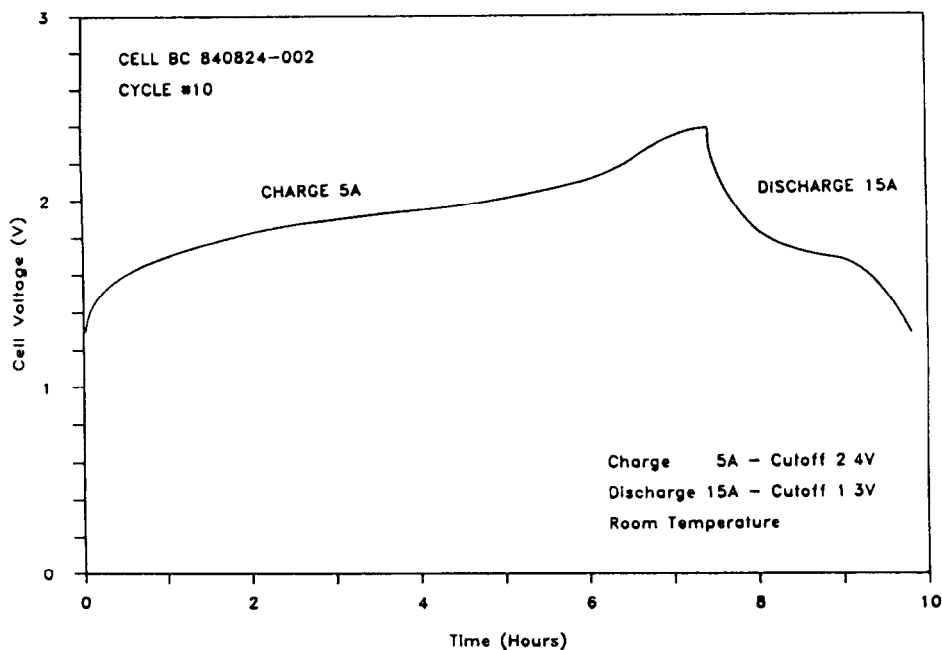


Fig 2 Charge and discharge voltage profile of a “BC” cell Charge 5 A, cutoff 2.4 V, discharge 15 A, cutoff 1.3 V

Figure 3 shows the capacity as a function of cycle number for two cells cycled under different conditions. Cell #001 was supercharged and then discharged to 1.1 V, cell #002 was charged under standard conditions and then discharged to 1.3 V. The first cell achieved a first cycle capacity of 66 A h at 15 A. This capacity is slightly higher than the nominal capacity. The second cell achieved a first cycle capacity of 42 A h. These capacities are approximately equal to the values expected from a linear scale-up of the “C” cell performance. Both tests were terminated voluntarily, cell #002 after achieving 107 cycles at an average capacity of 32.5 A h.

The impedance of the “BC” cell was determined over a wide frequency range using a frequency response analyzer. The results are displayed in Fig. 4

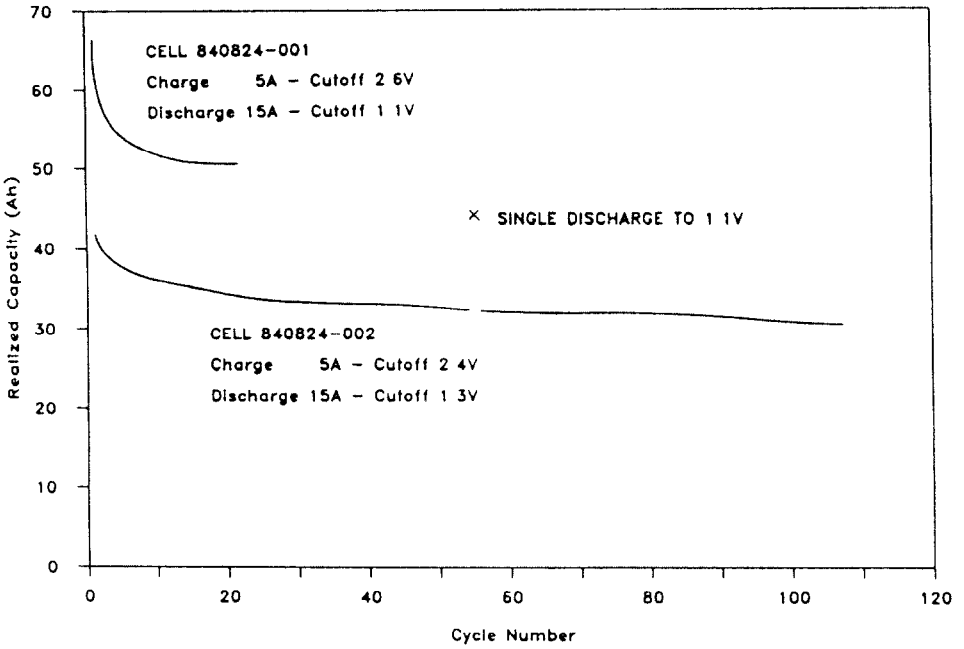


Fig. 3 Cycle life plots for two "BC" cells Cell 001 charge 5 A, cutoff 2.6 V, discharge 15 A, cutoff 1.1 V Cell 002 charge 5 A, cutoff 2.4 V, discharge 15 A, cutoff 1.3 V

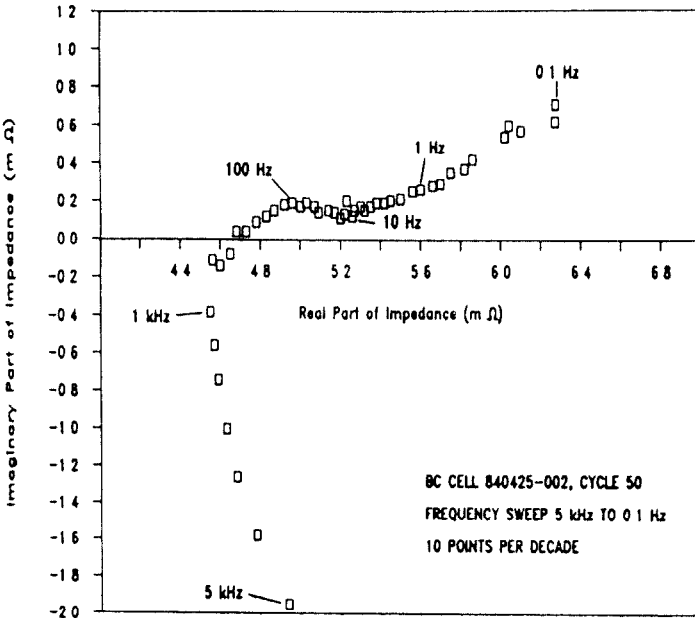


Fig. 4 Cole-Cole plot of the impedance of a "BC" cell

in the form of a Cole-Cole plot. The impedance at a frequency of 1 kHz is approximately 4.6 mΩ. This measured value is approximately double the value calculated from "C" cell measurements using the linear scale factor of

22. This discrepancy is due to the relatively large resistance of the electrode terminals and the connections of the electrodes to the terminals. For frequencies higher than 1 kHz the cell impedance is dominated by an inductance which is due to the wound nature of the electrode assembly. For frequencies below 1 kHz, the impedance of the electrochemical interfaces and the mass transport of ions in the electrolyte determine the shape of the plot [3]

#### 4. Battery performance testing

Performance testing of the 6 cell battery was conducted under conditions similar to the cell performance testing with the battery voltage being used to determine the endpoints of charge and discharge. No attempt was made to equalize the state of charge between individual cells once the testing began. Figure 5 gives the realized battery capacity as a function of cycle number. With exemption of the special tests performed around cycle 30, the battery was cycled between 14.4 V and 7.8 V. These voltages correspond to a single cell voltage ranging from 2.4 V to 1.3 V. The average energy delivered by the battery was 360 W h per cycle with an average capacity of 33.5 A h. The test was terminated voluntarily at cycle 110. A comparison with the single cell cycle test (Fig. 3) shows no difference between single cell cycle life and battery cycle life under these conditions.

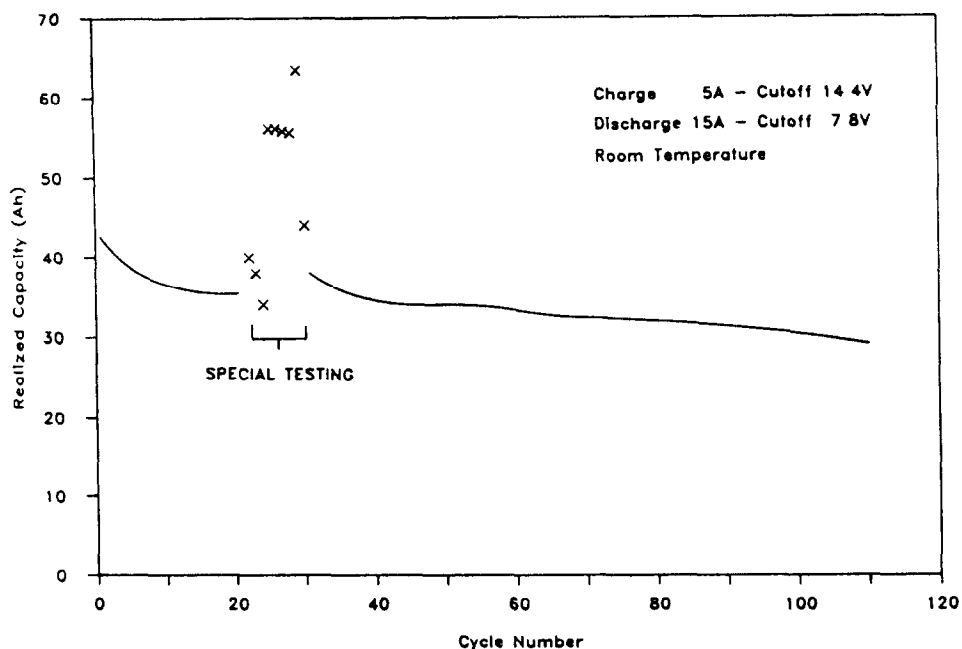


Fig 5 Cycle life plot for a 6 cell "BC" battery Conditions for all cycles except those marked special testing charge 5 A, cutoff 14.4 V, discharge 15 A, cutoff 7.8 V

The sustained power capability of the battery was assessed by discharging the battery to a fixed voltage limit at various currents. Figure 6 shows the realized capacity as a function of the drain current for three different temperatures. Prior to the discharges, the battery was given a standard charge at 21 °C. Cutoff voltage on discharge was 1.3 V per cell. At 20 °C and 0 °C the battery delivered about 50% of its low current capacity at a 50 A rate. At -20 °C, the rate capability is reduced significantly. The average power delivered during the 50 A discharge at room temperature was 510 W

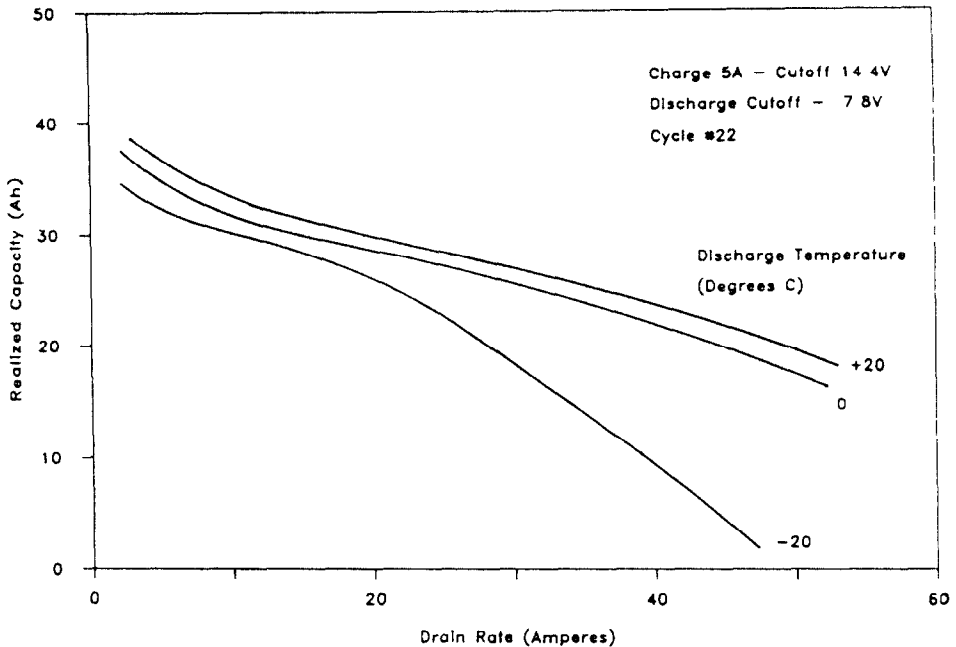


Fig 6 Realized capacity as a function of drain rate for a 6 cell "BC" battery charge 5 A, cutoff 14.4 V, discharge 15 A, cutoff 7.8 V

The realized capacity of the battery can be increased for all drain rates by supercharging and by using a discharge cutoff of 1.1 V per cell. Figure 7 shows the realized capacity for the battery at a temperature of 20 °C under these conditions. The capacity increase is about 58% compared with the condition represented in Fig. 6. The energy delivered by the battery at the lowest rate was 686 W h, corresponding to a gravimetric energy density of 94 W h kg<sup>-1</sup>.

The results presented in Figs. 6 and 7 are a measure of the sustained power capability of the battery. The peak power capability of a supercharged battery was determined by discharging the batteries at various rates for a duration of 5 s. After each discharge, the battery was rested on open circuit for about 1 min. Figure 8 shows the power output at the end

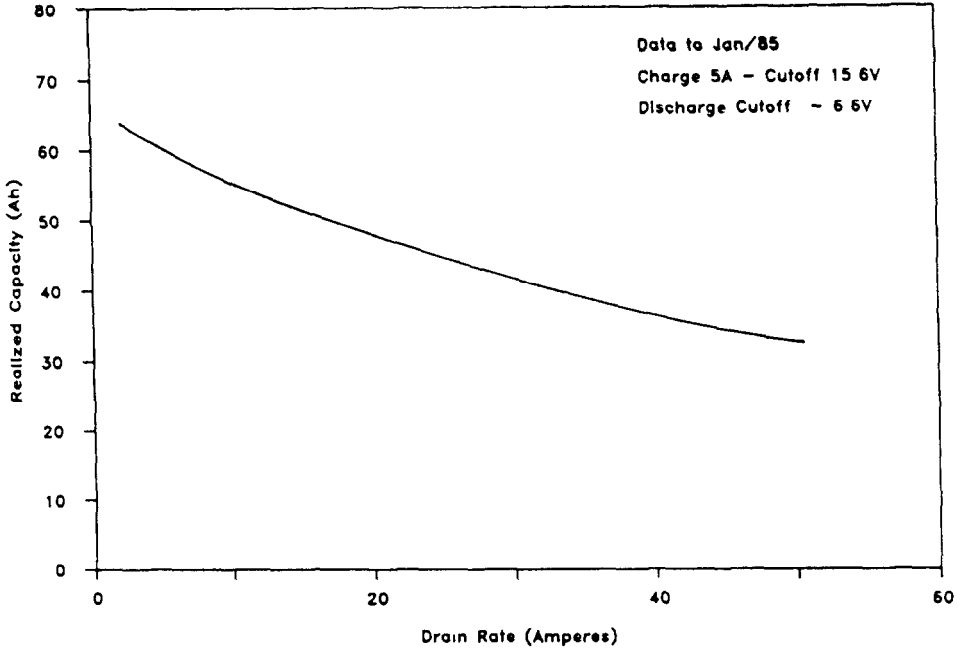


Fig 7 Realized capacity as a function of drain rate for a supercharged 6 cell "BC" battery

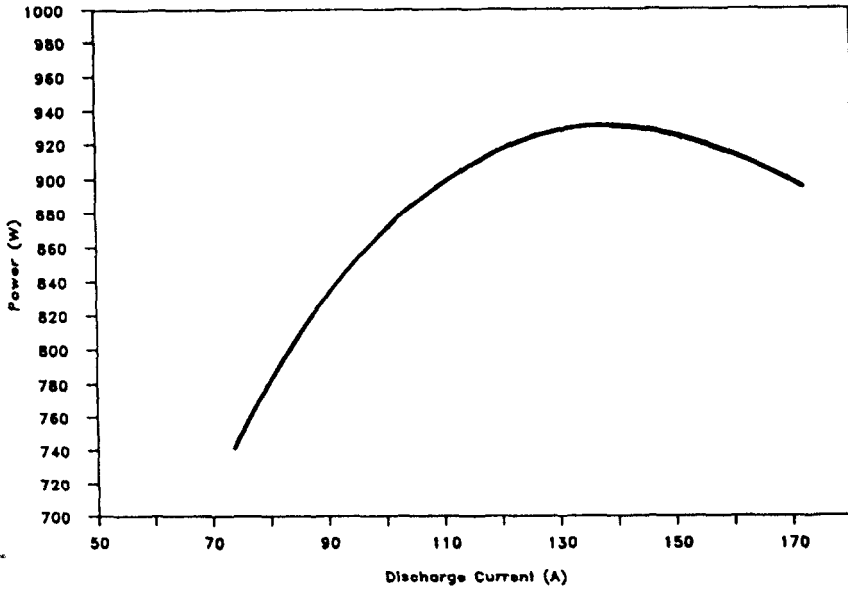


Fig 8 Power output of a 6 cell "BC" battery for various pulse currents. Pulse duration 5 s

of each discharge pulse as a function of the discharge current. The peak power was 932 W, which corresponds to a peak power density of  $128 \text{ W kg}^{-1}$ .

## 5. Conclusion

The results of the "BC" battery performance testing can be best summarized in a Ragone plot which shows the relationship between power density and energy density (Fig 9). A comparison with the Ragone plot for a "C" cell shows the effects in scaling. At lower power densities, the larger cells show an increased energy density due to a reduction of the fraction of the non-active material of the total cell weight. However, the relatively large resistive losses in the current carrying elements of the "BC" cells cause a significant reduction in the power capability.

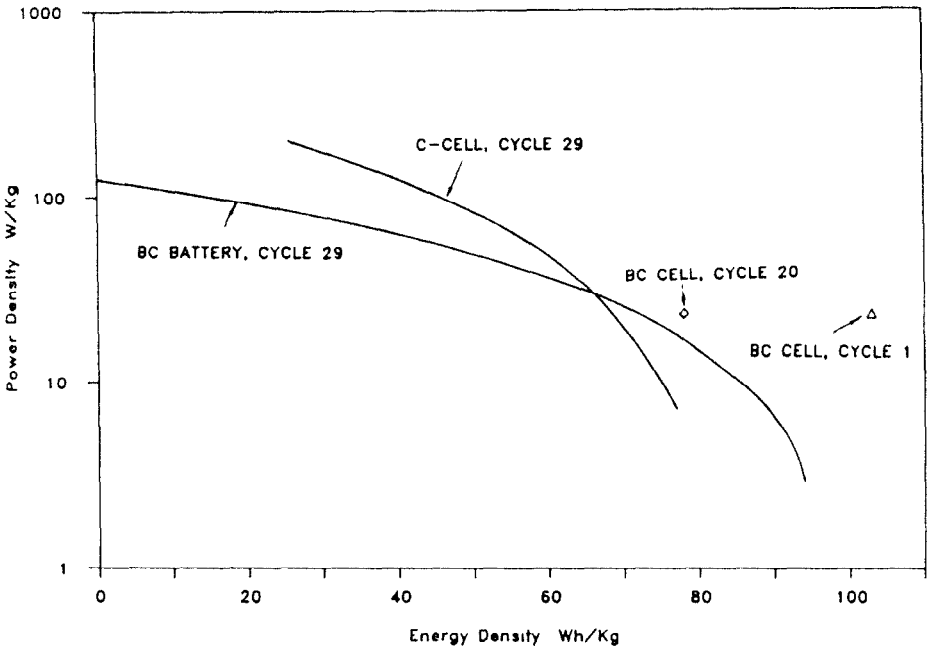


Fig 9 Ragone plot for a 6 cell "BC" battery, single "BC" cells, and "C" cells

The cycle life of this battery is in excess of 100 cycles. No reduction in battery performance relative to cell performance, which might be caused by capacity mismatch or charge imbalance between cells, was observed.

This analysis shows that substantial improvements to the battery performance in the area of power density are possible by improvements to the cell design. Peak power densities of the order of  $200 \text{ W kg}^{-1}$  should be obtainable. Initial tests of a new generation of "BC" cells presently under development that incorporates improved current collectors support this extrapolation.



Improvements in energy density, however, will only be minor unless the lithium insertive capacity of the cathode can be improved. The maximum energy density of batteries using current cathode technology is  $100 \text{ W h kg}^{-1}$ . Improved cathodes will be used in the future to break this barrier.

## References

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- 2 R. R. Haering, J. A. R. Stiles and K. Brandt, *US Pat 4,224,390*, September 23, 1980
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