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Constant and pulse power capabilities of lead-acid batteries made with thin metal film (TMF®) for different applications

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Abstract

Conventional power sources are able to deliver high energy, but high-power demands can be met only with advanced electrochemical or heavy battery devices. BOLDER Technologies has developed a high-power cell (86 g, 1.0 A h, 2 V) based on patented Thin Metal Film (TMF®) Technology which is capable of delivering very high constant or pulse power for several applications. Six cells in a 0.5–1 kg pack are capable of delivering 1 to 1000 A with a stiff voltage plateau of 12 V for periods ranging from 1 h to a few milliseconds, respectively, and constant power not provided by any other battery chemistry. The BOLDER TMF® cells are made of thin lead foil and PbO active material, which gives enormous cost advantages compared with existing lead-acid batteries or with competing battery systems. This paper presents the high constant-power and pulse-power delivery characteristics of batteries made with TMF technology. The new concept of developing hybrid power sources with proton exchange membrane fuel cells (PEMFCs) or other battery types for electronic communication and turbine-starting applications is also discussed.

Keywords: High power; Hybrid power; Lead-acid battery; Low impedance; Pulse application

1. Introduction

An energy-storage device requires different performance capabilities in different applications. For pulsing applications, the battery must able to deliver a high current for significant periods of time, preferably with a stable voltage. The time response must be very rapid and the distortion of the wave-form voltage must be minimal, even at high currents and frequencies. The low-frequency duty cycle of a typical flash camera requires at least 400 to 500 high current pulses so that the camera can be operated without charging the battery for 12 to 24 h. Engine or turbine starting consumes reasonable amounts of specific energy at extremely high levels of specific power.

The performance levels described above are usually sought from supercapacitors or advanced electrochemical energy-storage devices, i.e., batteries. Present-day supercapacitors and conventional batteries suffer the following drawbacks: they are expensive, low on specific energy, in an early developmental stage, unsafe, unstable, and/or unsuitable with regard to space and weight. The ideal candidate would be an existing battery technology which is capable of delivering extremely high currents with good voltage performance. An added bonus would be a rapid-recharge capability so that, once depleted, the battery could be back in operation in a short time without any temperature excursion. The BOLDER valve-regulated lead-acid cell (1.0 Ah, 2 V) has been built to meet, or exceed, many of the these requirements [1–4]. In addition to being valve-regulated, it differs from conventional lead-acid technology in that it has been developed primarily to deliver and accept extremely high power levels. The design and construction attributes of the cell have been presented in detail elsewhere [5,6] and, thus, will not be elaborated in detail here. The high current-carrying efficiency is propagated beyond the plates by continuous foil contact with the top lead, as opposed to the tab arrangement available in most lead-acid batteries. By virtue of the continuous foil contact, the cylindrical design, and the head-to-tail plate winding configuration (i.e., opposite-end current collection), the voltage distortion on load, due to inductive effects, is minimal. Such a design for high-current discharge is also ideal for ultra-fast recharging because the high plate areas and the proximity of the elec-

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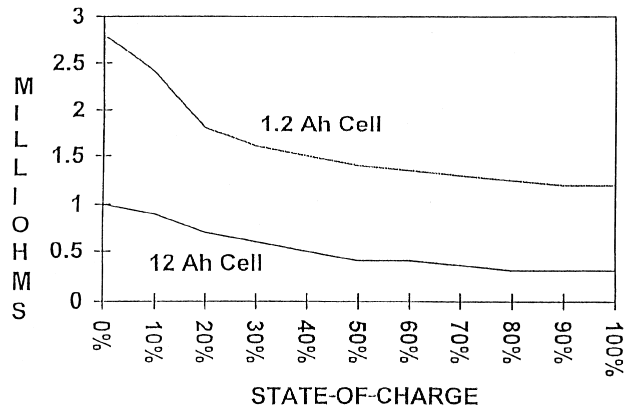

Fig. 1. Impedance of BOLDER cell as a function of state-of-charge.

trolyte reservoir to the plate reaction sites ensure very high charge efficiency.

2. Discharge time and voltage under load

The ability of a cell or battery to deliver reasonable amounts of specific energy at extremely high specific power levels is the most important characteristic for most power-related and pulse applications. This capability depends upon the chemistry and the design/construction of the cell. To deliver significant amounts of energy at high power, the electrolyte should be in close proximity to the plate pores and the cell must have low internal impedance so that the voltage under load is only slightly depressed from the open-circuit value. The impedance of the BOLDER cell as a function of state-of-charge (SoC) is shown in Fig. 1. The cell has an impedance of 1.2 mΩ at 100% SoC which does not increase significantly even at 100% depth-of-discharge (DoD). This endows the BOLDER cell with power characteristics which are superior to those of other battery technologies.

Voltage–time discharge curves for the BOLDER 2-V, 1.0 Ah cell at currents of 1 and 80 A are presented in Fig. 2. The results for high discharge currents of 100 to 270 A have been presented and discussed in earlier reports [7–9]. The data in Fig. 2 show that there is minimal voltage separation between the two discharge curves; this is due to the low cell impedance. Remarkably, the BOLDER cell has a flat voltage plateau at the 80C rate, i.e., at 80 A discharge. This plateau is very similar to that at the 1C rate, a performance which is not achievable by any other battery or electrochemical cell. At even higher currents of 270 A, the same behaviour persists. This is the outstanding characteristic of the BOLDER cell—the ability to deliver reasonable amounts of specific energy at extremely high specific power.

The discharge performance of a 12-V, 1.0 Ah battery under different loads and at different temperatures is given in Fig. 3. The voltage plateau at 50 and 100 A discharge is flat and the drop in voltage from the initial value (without load) is only 8 to 10%—this again demonstrates the remarkable characteristics of thin-film technology. Similar behaviour occurs with 50 and 100 A discharge at -18°C, which is unusual for a lead-acid battery. It is noteworthy that at the highest discharge current employed, viz. 270 A, the cell delivers 7.2 W h kg^{-1} at a specific power level of 4.4 kW kg^{-1} (specific energy and specific power are calculated from a cell weight of 82 g, a volume of 30 cm^3, and the average voltage from the constant-current curve).

3. High-current pulse discharge

The general pulsing capabilities of TMF® technology have been presented previously [10,11]. The high current pulsing of a 6-V BOLDER battery at a 100 A s^{-1} dis-

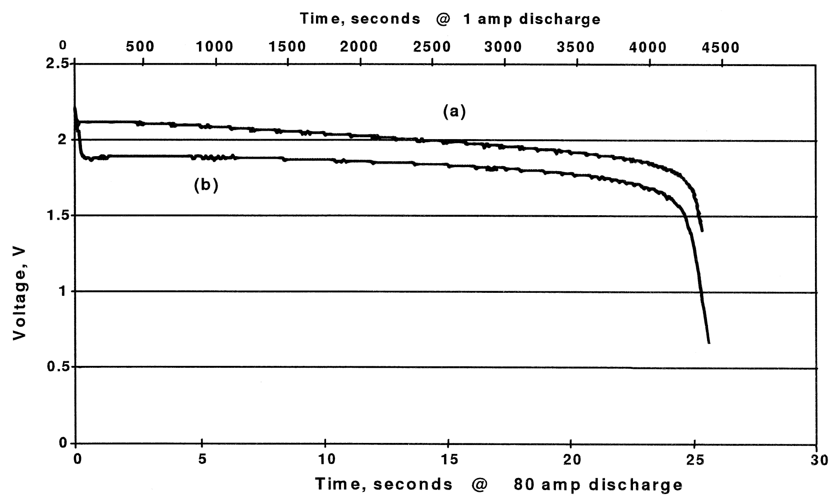

Fig. 2. Voltage of BOLDER cell during constant-current discharge: (a) 1 A; (b) 80 A.

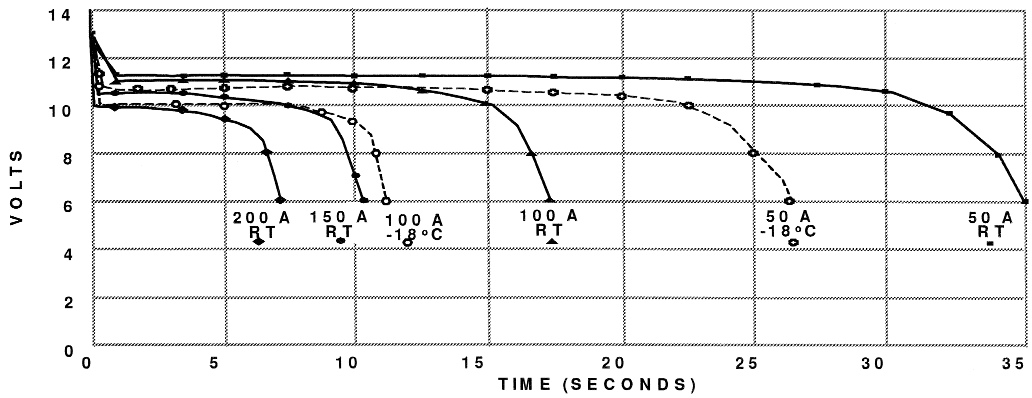

Fig. 3. Discharge of BOLDER cells at different loads and temperatures.

charge followed by a 1-s rest, for a 50% 'on duty' cycle are demonstrated in this paper. The high current pulsing was continued until the battery voltage under load dropped below 1.0 V $cell^{-1}$. The battery was then recharged at the 1C rate and a constant-current discharge at 100 A was performed for comparison. The pulsed-discharge data are given in Fig. 4. At 100-A, the battery will deliver a 16-s run time on a constant-current discharge; this is equal to a capacity of 0.44 A h. In the pulse duty cycle, eighteen 100 A second pulses were obtained; these amount to 0.5 A h of capacity. This is excellent performance for pulsing at the 100C rate. The shape of the wave form is very good in terms of voltage stability during discharge pulses. In addition, the voltage following and recovery upon discharge termination are excellent.

BOLDER does not have the facility for routine pulsed-discharge testing at higher currents in the range of 1000 A. Thus, in order to explore the upper discharge limit for pulsing currents, a modified 'dead short' experiment was conducted using solenoids and a large shunt. The peak rate/rise time curve for a single cell is shown in Fig. 5. This indicates a very fast current response (< 1 μs) and a peak of about 1800 A in 16 μm.

The voltage–current response of a 6-V BOLDER battery as a function of time was also tested; the results are presented in Fig. 6. The peak current is ~ 830 A at a voltage of just under 3 V. As expected, the current and voltage collapse after 1 s into the discharge. Nevertheless, the attainment of this peak current and extrapolation of the Peukert curve both indicate that short-duration (ms) pulsing at 1000 A or higher is achievable. The corresponding Peukert curve is presented in Fig. 7.

4. Flash camera application

The BOLDER cell was tested at low frequencies for flash camera applications. The results were encouraging. The flash discharge was a 10-s pulse train with 10 A for 790 ms and then the remainder of the 10 s at rest (6 pulses min^{-1}), i.e., a 7.9% duty cycle. A single pulse profile for

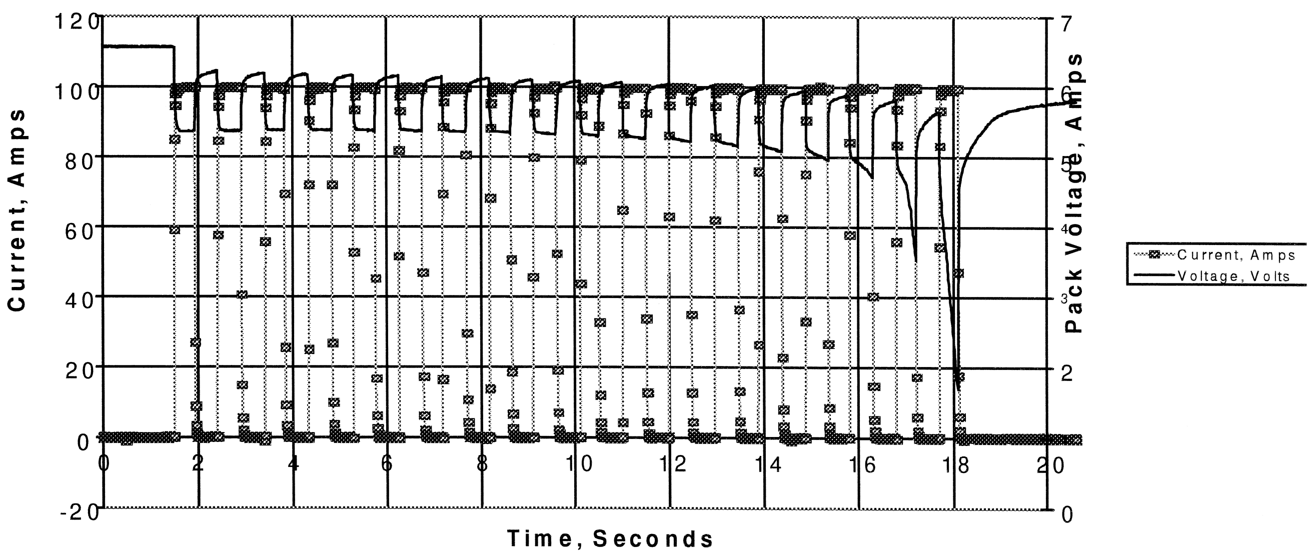

Fig. 4. 100-A pulse discharge of 6-V BOLDER battery; 1-s pulses, 50% duty cycle.

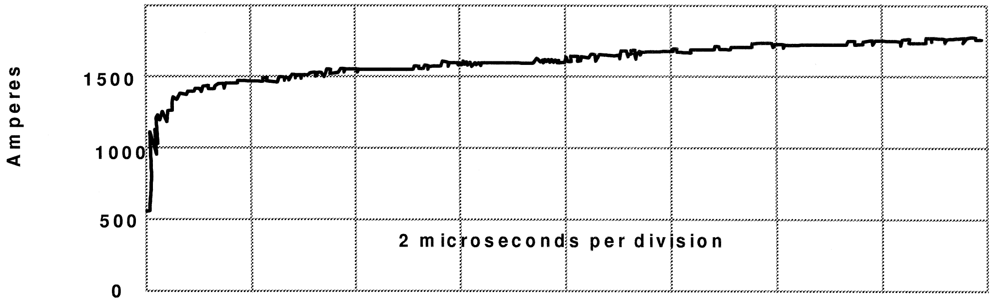

Fig. 5. Peak rate/rise time curve for BOLDER cell.

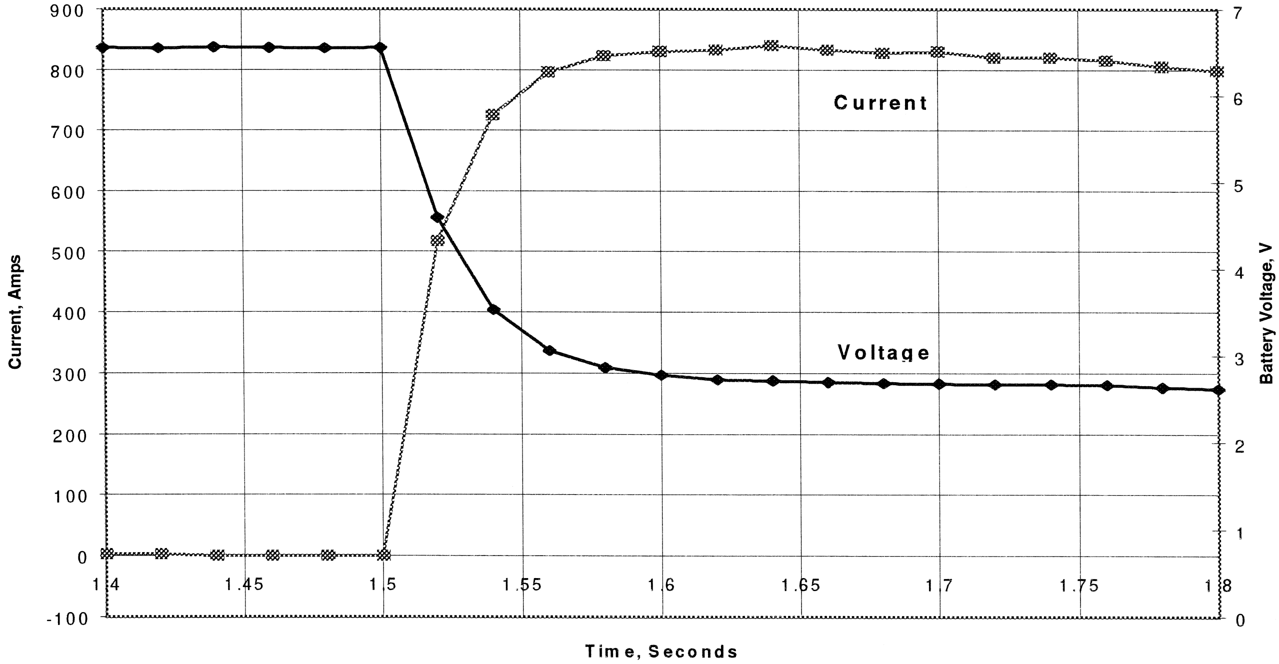

Fig. 6. Voltage–current response of a BOLDER 6-V battery.

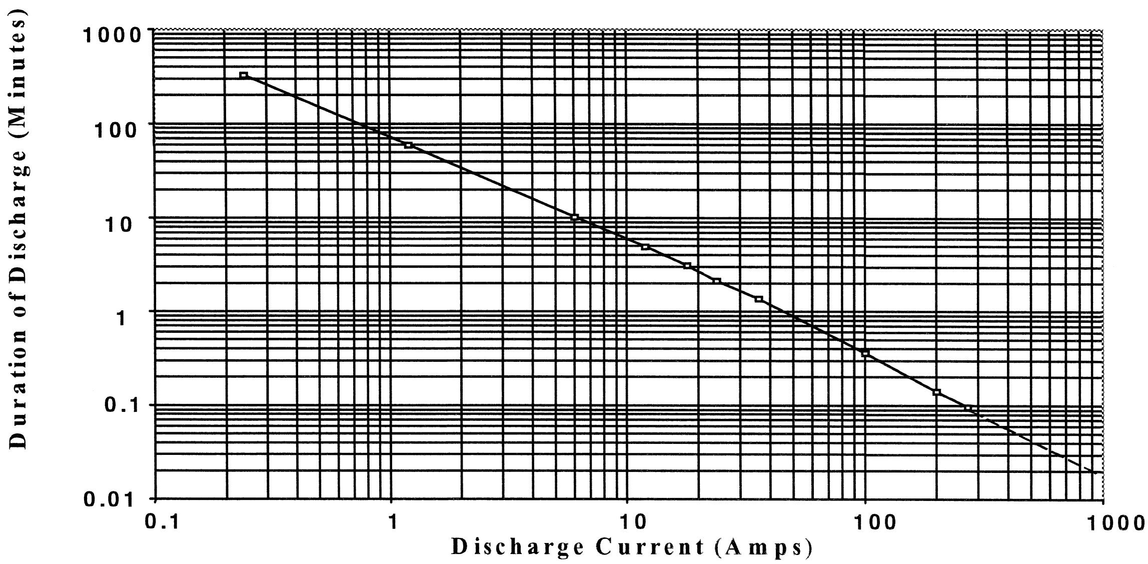

Fig. 7. Peukert curve for BOLDER battery.

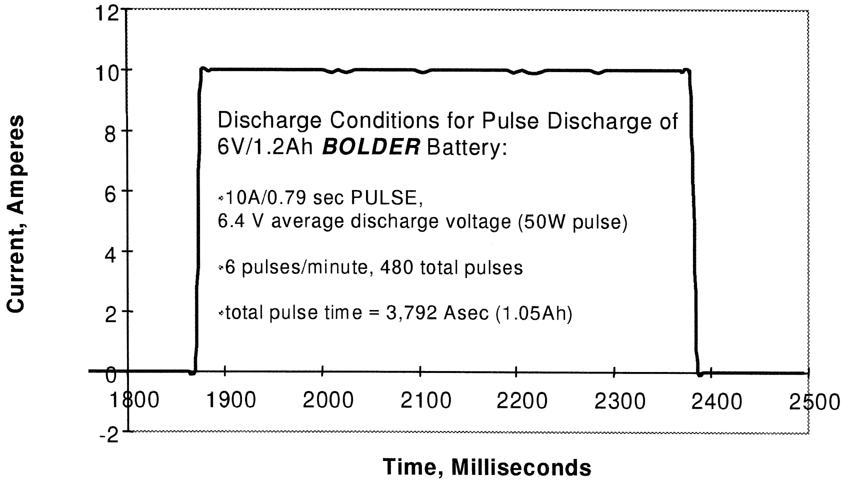

Fig. 8. Single-pulse profile, 10-A/0.79-s pulse.

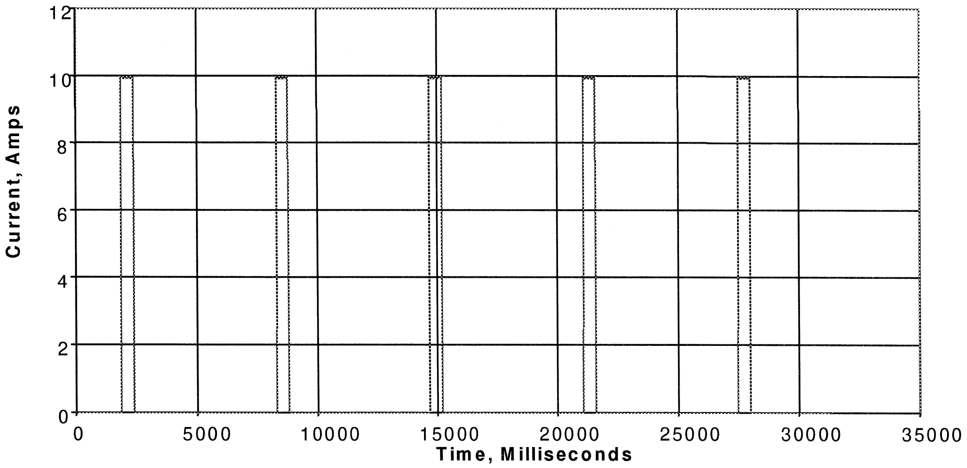

Fig. 9. Pulse train with 7.9% duty cycle.

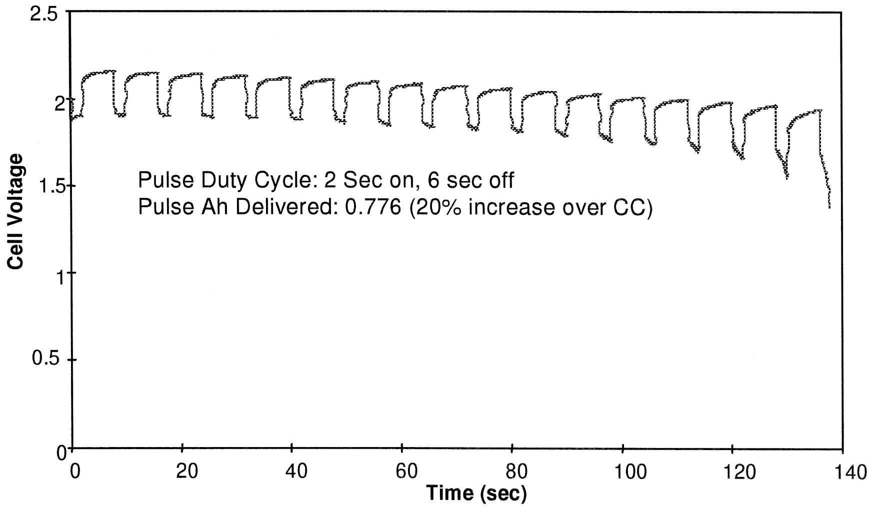

Fig. 10. Voltage as a function of 80-A pulses for 2 s.

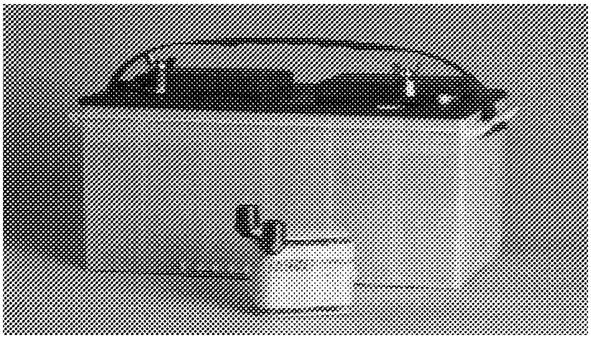

Fig. 11. Size difference between a BOLDER battery and a conventional automotive battery.

this test is shown in Fig. 8, and the results are given in Fig. 9. Since the nominal 6-V battery showed a load voltage of 6.3 V, the pulses were 50 W. The 6-V, 1.0 Ah battery delivered 480 pulses, which equates to a capacity delivery of 1.05 A h, or 100% of the rated value.

In an another experiment, pulses of 80 A for 2 s (25% duty cycle) were applied, followed by a rest of 6 s. The results are given in Fig. 10. Note that, a remarkably flat voltage plateau at this high-rate pulsing is demonstrated by the BOLDER cell and is unachievable by any other battery.

5. Engine start application

A BOLDER battery with six cells weighs around 0.6 kg and can provide the starting power of a 18-kg automotive battery. The size difference between a BOLDER battery and a conventional battery is illustrated in Fig. 11.

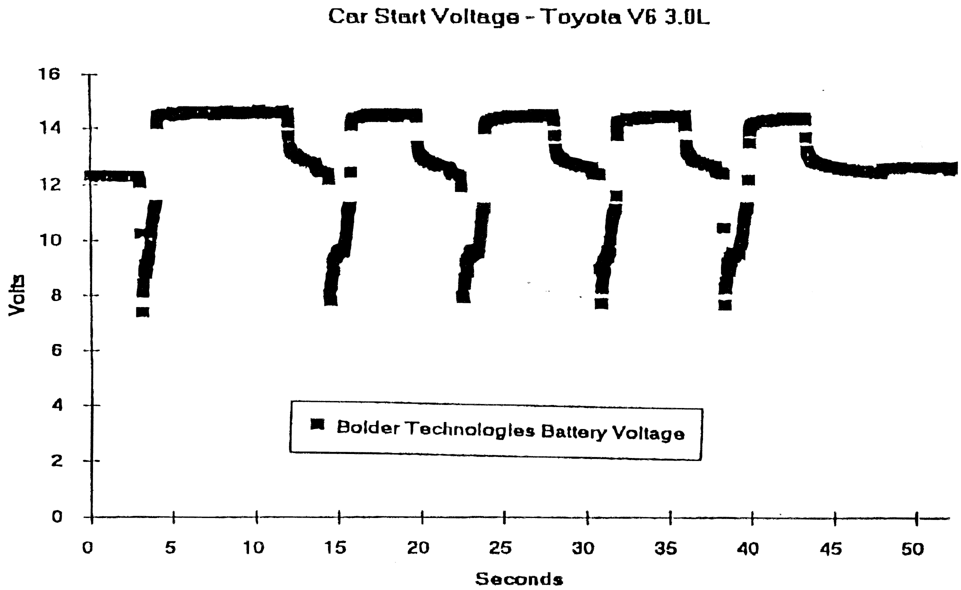

Fig. 12. Battery voltage during starting a V6, 3-l Toyota engine.

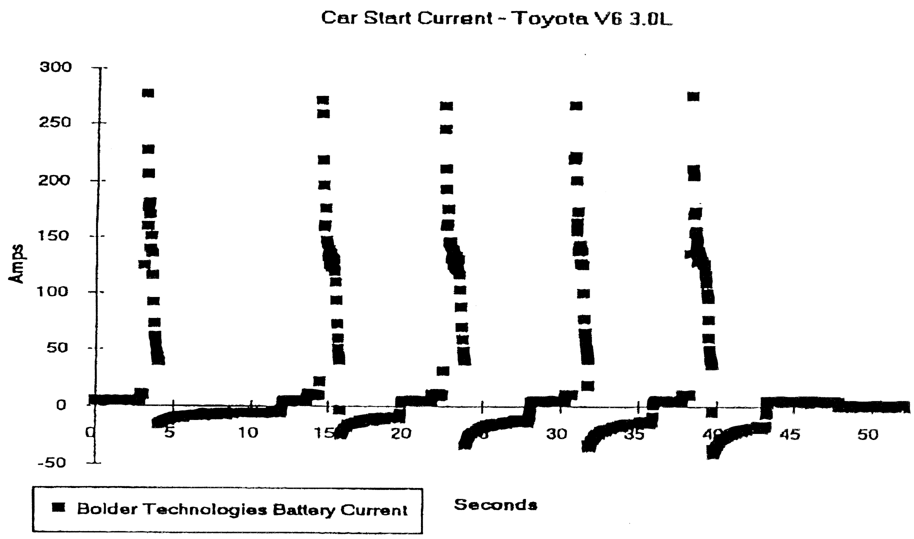

Fig. 13. Battery current during starting a V6, 3-l Toyota engine.

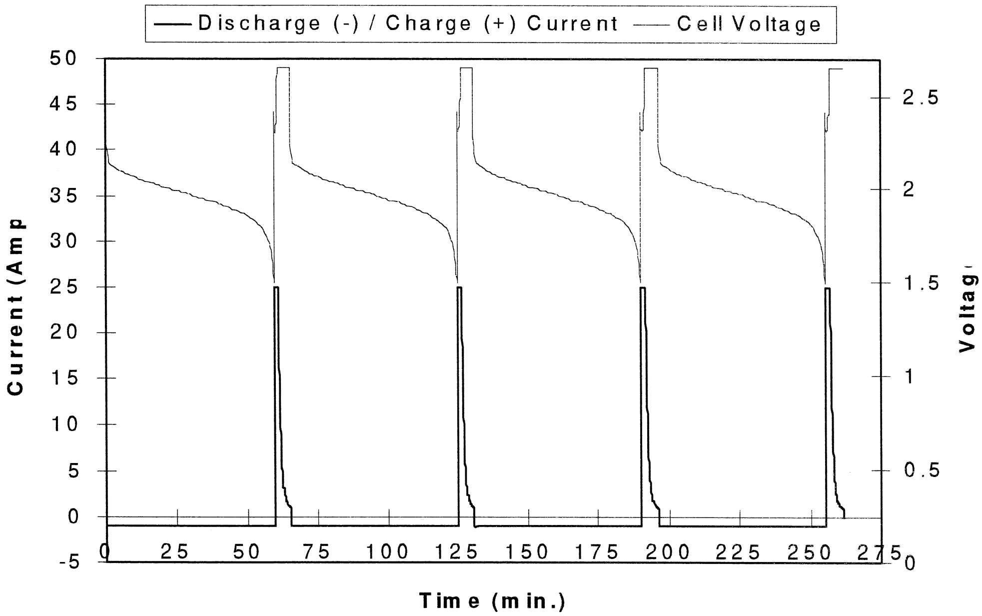

Fig. 14. Voltage and current for a 1.0-A discharge/2.65-V, 6-min recharge cycle.

A 12-V BOLDER battery was used to start a 3-L engine and could start the engine 30 times without recharging. The voltage and current of the BOLDER battery during starting a Toyota V6 3-L engine are shown in Figs. 12 and 13, respectively. The voltage of the battery was fairly constant for 30 starts. The remarkable performance of the 0.6-kg BOLDER battery for engine starts could be an attractive option for several starting applications required by the US Military and Air Force.

6. Hybrid approach for military applications

The BOLDER battery is capable of delivering very high power at a constant-current mode or for a pulse power application. The specific energy of the battery is, however, below that required by several military applications. The Army Communication Electronics Research Division has recently demonstrated the concept of utilizing the energy of a PEMFC fuel cell and the power of a BOLDER cell [12]. The testing was performed on a two-cell assembly with a nominal rating of 4.0 V and 1.2 A h. This assembly of two cells was connected in parallel to the PEMFC stack to form the hybrid. At the start of all the tests, the lead-acid cells were fully charged via a constant-current, two-step process of 1 A to 2.6 V, then 0.1 A to 2.6 V.

All testing was conducted at room temperature. Initially, the limit of the PEMFC stack alone at 18 W (transmit) continuous power was quantified. Performance

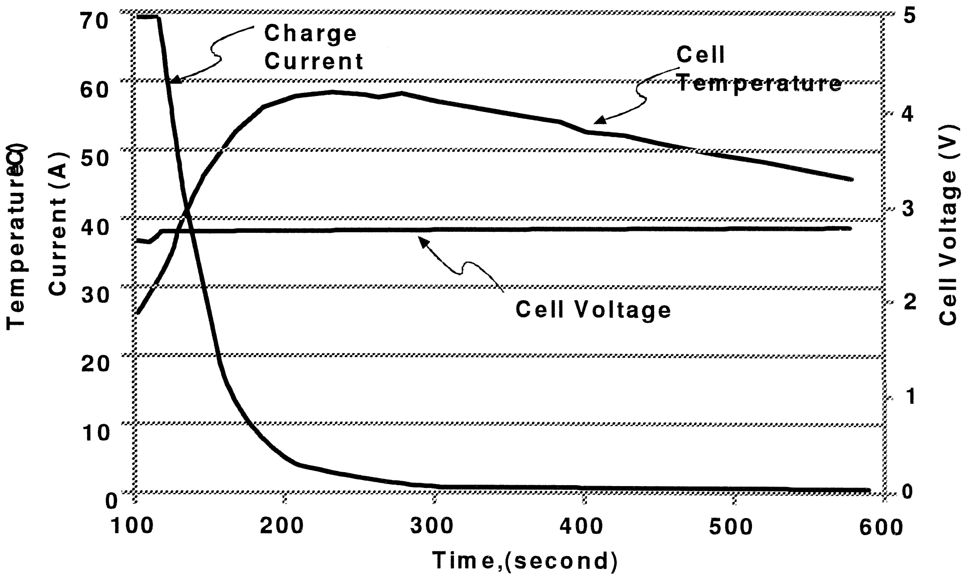

Fig. 15. Temperature, voltage and current during constant-voltage charge.

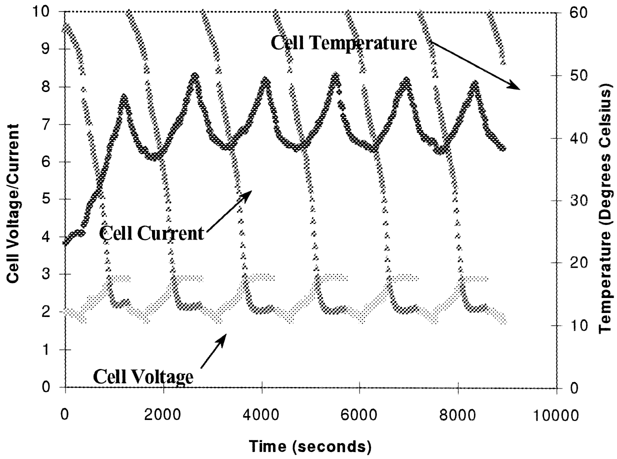

Fig. 16. Current, voltage and temperature during 10-A discharge followed by 15-min fast charge.

of the hybrid was measured at various simulated radio transmit and receive durations. The transmit/receive ratio testing included 3/4.5, 6/9, 12/18, and 24/36; each ratio represents a cyclic regime of transmits duration in minutes followed by receive length in minutes. For example, the 3/4.5 ratio represents a cyclic regime of 3-min transmits (18 W), followed by 4.5-min receive (2.5 W). In addition, the hybrid and the lead-acid assembly alone were tested with a 18.0 W continuous transmit which ranged from 15.0 to 1.5 min; the BOLDER battery assembly was then electrically disconnected from the stack.

The PEMFC stack alone could not power the high load pulse of the high/low power cyclic regime. The operating potential dropped immediately. Within 12 s, the potential of the fuel-cell stack fell to zero volts. The hybrid successfully powered various pulse-power load simulations synonymous with electronics and communications equipment. Once stabilized, the system produced a flat voltage potential under all the transmit/receive ratios described above. This is especially important during transmit (18 W) where the battery voltage is critical. Throughout all runs, the operating voltage never dropped below 3.9 V. The test report clearly demonstrates that the capability of the BOLDER battery in the power assistance of fuel-cell stacks where the energy density advantage of fuel cells and the voltage stability during high-power output of the battery can be successfully utilized.

In a further hybrid approach, a turbine-starting application was tested by utilizing a high-specific-energy battery with a high-power BOLDER battery. The required initial current of 600 A was supplied by a BOLDER battery followed by 200 A from a Hawker 17 A battery. The turbine was started twice without additional charge.

7. Ultrafast charge and temperature

It is apparent that a desirable property of energy-storage devices for most applications is the ability to recharge rapidly so that the device, once depleted, can be brought back to full power in a short time. This is particularly germane in military applications. The BOLDER cell fulfils all the requirements for fast charging, e.g., favourable diffusion kinetics, low cell impedance, and high current-carrying capability. These characteristics allow for extremely efficient charge-acceptance. In Fig. 14, data is presented from a test conducted at a 1.0 A discharge for 60 min (1C rate) followed by a 6-min recharge at a constant voltage of 2.65 V.

The results of a fast-recharge experiment are given in Fig. 15. In this experiment, a BOLDER cell, following a 100% DoD at the 1C rate, was recharged at a constant voltage of 2.65 V with a current limit of 68 A. Data for

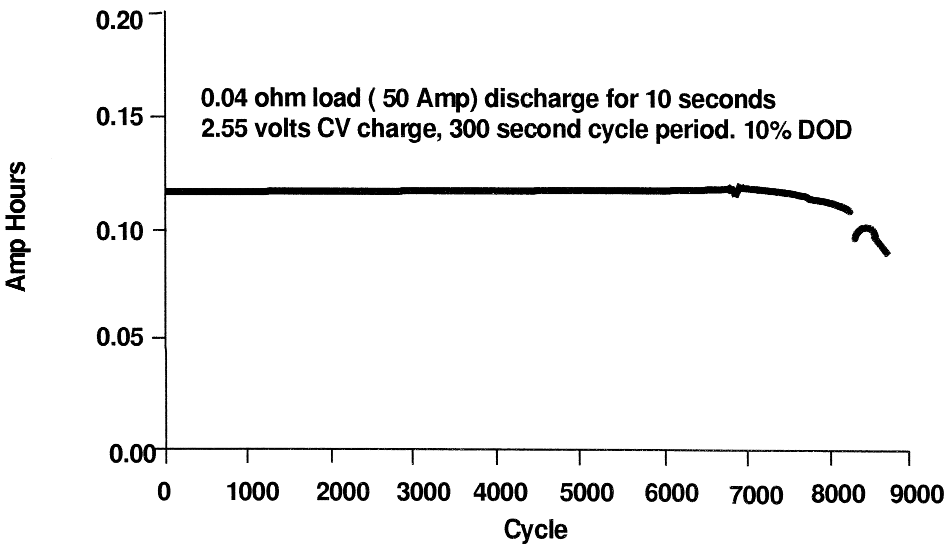

Fig. 17. Number of cycles for 50-A discharge with a 4.8-min charge.

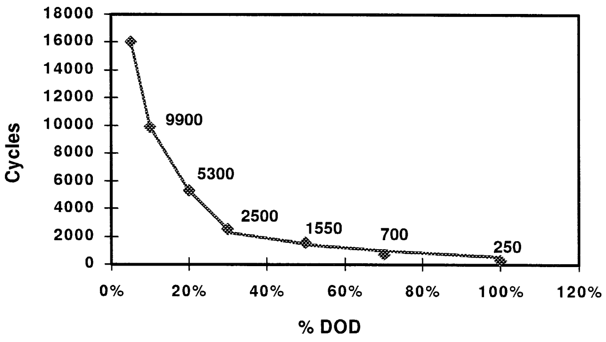

Fig. 18. Cycle-life as a function of depth-of-discharge.

temperature, voltage and current are presented. The cell is about 97% recharged within about 5 min; but due to the nature of constant-voltage charging, it requires another 5 min to complete the recharge. While the temperature rises to a high level of $\sim 58°C$ (but not a level that will damage the cell), it is only there for a matter of seconds and, then, due to the good heat-dissipation properties of the cell, drops rapidly.

In order to test whether such temperatures are harmful to the cell, an experiment was carried out and involved simulation of the duty cycle of a professional power tool. A cell was discharged at the 10-A rate and then recharged in 15 min. Under these conditions, the temperature of the cell skin 'spiked' at $\sim 50°C$ towards the end of each recharge cycle and then dropped quickly. The temperature, cell voltage and cell current during this duty cycle are shown in Fig. 16. In spite of this temperature, the cell delivered over 1500, 100% DoD cycles to 80% of initial capacity.

8. Pulse discharge / charge cycle test

The number of cycles obtained from a BOLDER cell depends on the time and the amount of current withdrawn, in other words, the DoD during pulse application or constant-current discharge. For most pulse applications, the discharge currents may be very high but the time required may vary from a few milliseconds to several seconds. The results of cycle testing at a discharge of 50 A for 10 s with a constant-voltage (2.55 V) charge is shown in Fig. 17. This is equivalent to a 10% DoD for the 1.0 Ah cell. Clearly, the BOLDER cell is capable of delivering 9900 cycles at a discharge of 50 A for 10 s with rapid recharge.

The average number of cycles obtained at a discharge of 50 A and a recharge of 5 min with different DoDs is shown in Fig. 18. The curve shows exponential behaviour for the number of cycles obtained as a function of DoD. This remarkable behaviour indicates the excellent pulse-power life of the BOLDER cell, which is not matched by any other battery chemistry.

9. Summary

The high-rate discharge and pulsing characteristics of the described BOLDER cells and battery are exceptional in terms of current achievable, response times, and high 'stiff' voltage plateaux. It has been shown that the BOLDER battery can sustain discharge currents of up to 300 A or more, and can be recharged in 5 to 7 min or less following a full 1C rate discharge. The duty cycle at low frequencies for flash camera operation indicates that the camera can be operated 400 to 500 times without charging the cell. The new concept of hybridizing a BOLDER battery with a PEMFC has been demonstrated and appears to be suitable for different pulse power sources.

Acknowledgements

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