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Short communication

Pulse power 350 V nickel–metal hydride battery power-D-005-00181

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Abstract

Energy-storage devices are needed for applications requiring very high-power over short periods of time. Such devices have various military (rail guns, electromagnetic launchers, and DEW) and commercial applications, such as hybrid electric vehicles, vehicle starting (SLI), and utility peak shaving.

The storage and delivery of high levels of burst power can be achieved with a capacitor, flywheel, or rechargeable battery. In order to reduce the weight and volume of many systems they must contain advanced state-of-the-art electrochemical or electromechanical power sources. There is an opportunity and a need to develop energy-storage devices that have improved high-power characteristics compared to existing ultra capacitors, flywheels or rechargeable batteries.

Electro Energy, Inc. has been engaged in the development of bipolar nickel–metal hydride batteries, which may fulfil the requirements of some of these applications. This paper describes a module rated at 300 V (255 cells) (6 Ah). The volume of the module is 23 L and the mass is 56 kg. The module is designed to deliver 50 kW pulses of 10 s duration at 50% state-of-charge. Details of the mechanical design of the module, safety considerations, along with the results of initial electrical characterization testing by the customer will be discussed. Some discussion of the possibilities for design optimization is also included.

Keywords: Nickel; Module; Conductivity

1. Introduction

As a departure from classic cylindrical or prismatic battery packaging approaches, EEI is developing a flat, wafer, bipolar design for the nickel–metal hydride chemistry. Fig. 1 shows a sketch of the design concept. Individual flat wafer cells are constructed with outer contact faces with one positive electrode, a separator, and one negative electrode. The contact faces serve to contain the cell and make electrical contact to the positive and negative electrodes. The contact faces are sealed around the perimeter to contain the potassium hydroxide electrolyte. To fabricate a multi-cell battery, identical cells are stacked one on top of each other such that the positive face of one cell contacts the negative face of the adjacent cell making a series connected battery. The current is collected at the ends of the cell stack. Structural integrity for the cell stack is obtained by housing the stack in an outer container, which holds the cells in compression.

This battery design has several advantages. The need for conventional terminals, tabs, current collectors, and cell containers is eliminated. Use of available space is maximized, with the headspace for tabs and terminals required in conventional cells eliminated. The path that current has to move in the electrodes and from cell to cell is minimized, since the current flows normal to the plane of the electrodes. Battery impedance is reduced, making this design particularly effective for high-rate power applications. The wafer stack design has excellent thermal conductivity in the planar direction due to the metal foils in the wafer cell that aid thermal management. Compared to conventional cylindrical and prismatic packaging designs, the use of plastic bonded electrodes offers considerable reduction potential in cost and volume.

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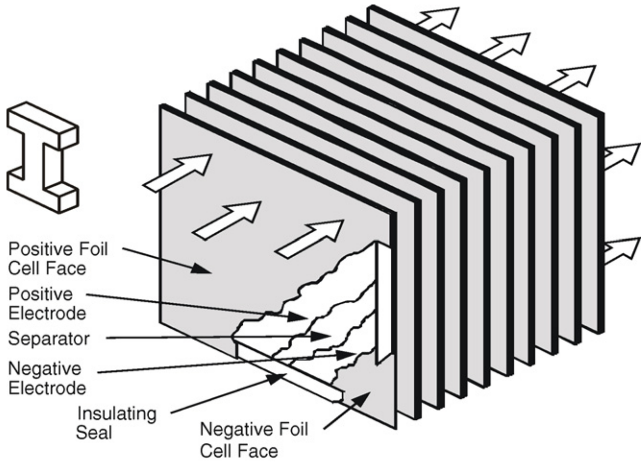

Fig. 1. Schematic depiction of the wafer bipolar battery design.

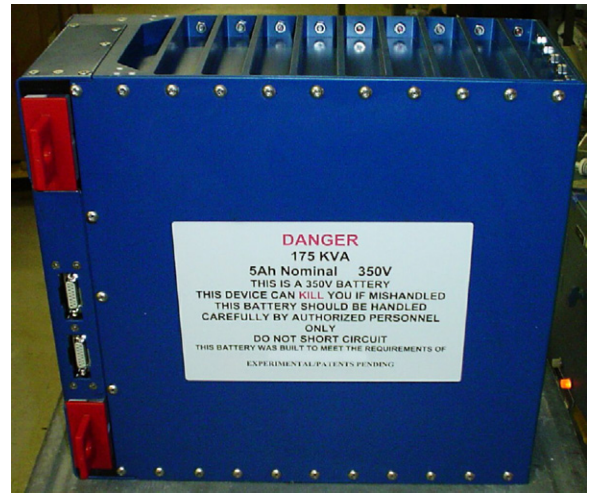

Fig. 3. Photograph of 350 V module.

2. 350 V bipolar NIMh battery

EEI has been developing high-voltage high-power bipolar batteries for the past several years. An example of such a battery was a 350 V (6 Ah) device (rated at 6 Ah), which we recently shipped to a customer. We believe that this battery is representative of current state-of-the-art technology for high-pulse power applications. The battery was intended to be operated by float charging at 350 V, and delivering 100 A pulses at a discharge voltage of about 300 V.

Fig. 2 presents a rendering of the module, while Fig. 3 presents a photograph of the shipped module. A layout drawing of the module is given in Fig. 4. At an operating point of 300 V and 100 A, each module can supply 30 kW of discharge power.

The overall volume of the battery was 23 L, and the weight was 55 kg. The battery contained 255 wafer cells. Each cell used had nominal 6 Ah capacity electrodes that were 6 in. × 12 in. in area.

Fig. 5 displays a discharge after the battery was charged to 100% SOC. A rest period of about 10 min was used after charge. At this point, the battery case was 35 °C (that is, relatively warm). Note that the current was not constant throughout the discharge, a resistive load was used. Immediate voltage loss from resistive components is approximately 40 V, about 10% of the battery voltage. Additional voltage loss for mass transfer and activation is approximately 10 V, about 4% of the OCV. Recovery is immediate for the resistive losses, once the pulse is terminated. The power density at this operating point was approximately (305 V) (125 A) 23 L^{-1}, or 1.66 kW L^{-1}. The specific power can be calculated as (305 V) (125 A) 55 kg^{-1}, or 0.69 kW kg^{-1}.

Fig. 6 shows customer-generated data, and shows a 1 s 100 A discharge after the battery was float charged at 350 V. The battery met expectations.

It should be emphasized that figures, such as power density and specific energy are very dependent on the specific operating point chosen. Parameters, such as temperature, battery SOC, discharge current, and discharge time can have a marked influence on power density measurements. Fig. 7 gives some indication of the relationship. The cell used for this measurement had the same electrode area and capacity, as was used in the larger battery. The measurements in the figure were for a cell, which was brought to 50% SOC, allowed to rest for 1 h, and then discharged. The test was conducted at room temperature (25–28 °C). The power measurements were 1 s into the discharge.

One calculates the battery resistance from the data presented in Fig. 5 as 358–318 V 128 $A^{-1} = 0.312\ \Omega$ ($0.0012\ \Omega$ $cell^{-1}$). From a purely ohmic perspective, it is known that the maximum power point of a battery will occur at a battery voltage of OCV/2. In our case, this would be at 358 V/2 = 179 V. The expected power would be $V^2/R = (179\ V)^2/0.312 =$ 102.7 kW L^{-1}, and the specific power is 1.86 kW kg^{-1}. However, these figures apply only in the limit of a vanishingly small discharge time (probably, 0.1 s or less). Therefore, these power estimates are a probable upper bound on the delivered power capability of this battery.

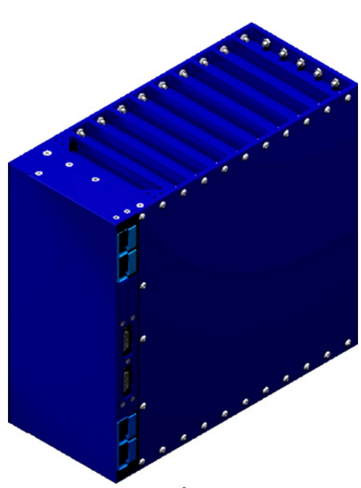

Fig. 2. Isometric rendering of a 350 V module.

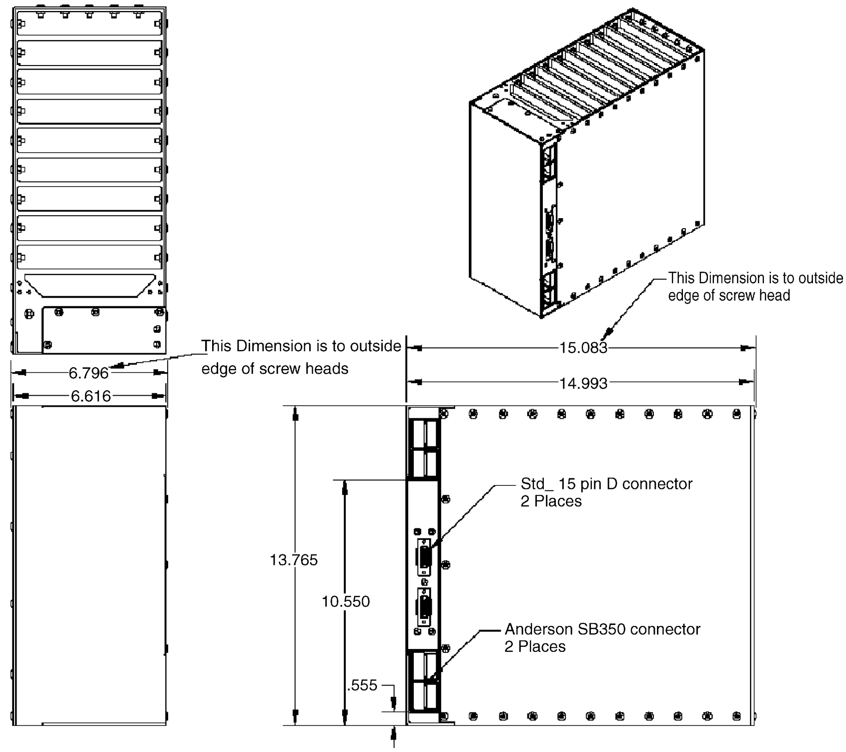

Fig. 4. Layout drawing of 350 V module, showing physical dimensions.

3. Battery-sizing alternatives

In general, to increase the capacity of a battery, one has many options. For instance, one may increase the electrode area at a constant electrode thickness, or alternatively one can increase the thickness of the electrodes while keeping the area constant. A demonstration of these two limiting cases follows.

There is some interest in developing a battery, which will meet automotive needs for a 42 V system. The Department of Energy, under the "Freedom CAR" Initiative, has proposed a set of guidelines to assist system developers. For a "start–stop" type of hybrid vehicle, the requirements are for 250 Wh of available energy (measured at 3 kW discharge power) with a 2.4 kW recharge rate. One of the tests that is specified is known as a "power and energy design verification (PEDV) test".

Using our technology, we can specify that 35 cells from a voltage standpoint will be adequate for the application. What remains to be seen is the appropriate electrode area and thickness for the task at hand.

For a full battery, the test consists of a constant power charge of 2.4 kW, a 1 h rest, and a 3 kW constant power discharge. To return the cell to 0 % SOC requires a discharge at the *C*/2-rate to 0.8 V. Scaling by the factor of 35 leads to

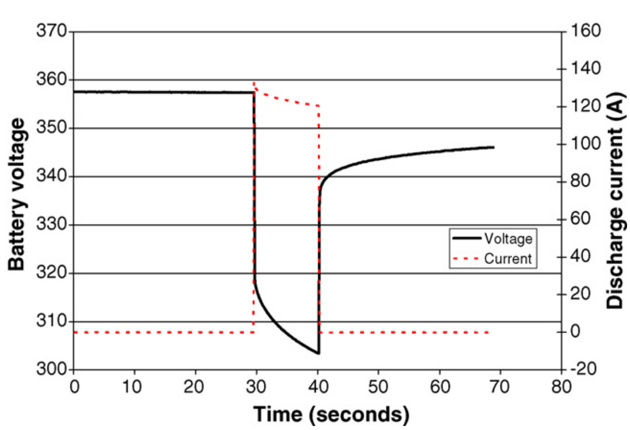

Fig. 5. Nominal 38 kW discharge pulse lasting 10 s.

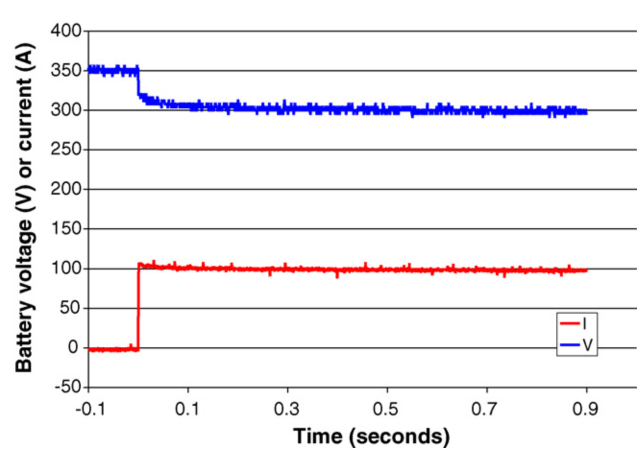

Fig. 6. Customer-generated pulse data.

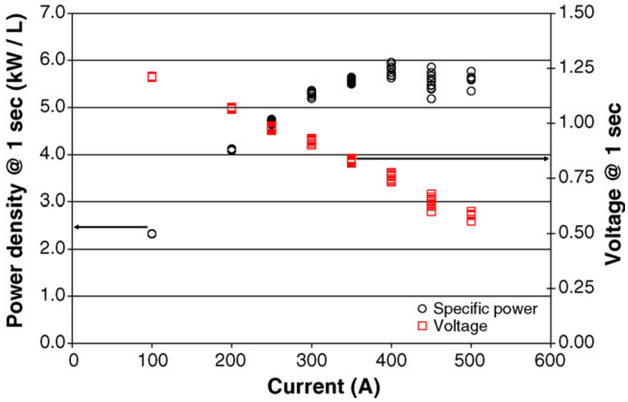

Fig. 7. Current density vs. power density relationship.

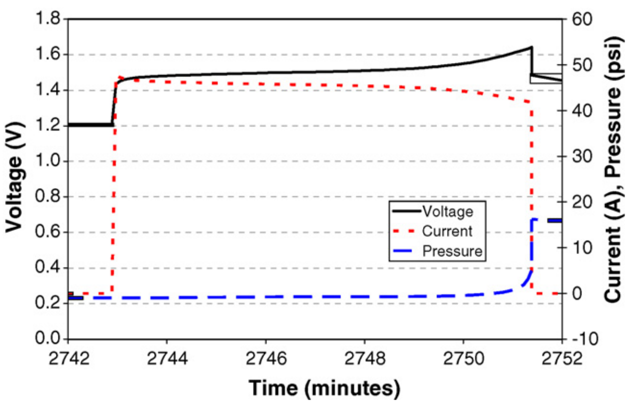

Fig. 8. 6.48 Ah cell charge under a PEDV regime.

a target charge power level of 68.6 W cell^{-1}, and a discharge power level of 85.7 W cell^{-1}.

Figs. 8 and 9 present the charge and discharge profiles for a 6 in. × 12 in. area cell with a theoretical capacity of 6.48 Ah. These are the same as what was contained in the 350 V battery. Figs. 10 and 11 present the charge and discharge profiles for a cell of area 6 in. × 12 in., and a theoretical capacity of 12.96 Ah (the electrodes are twice as thick).

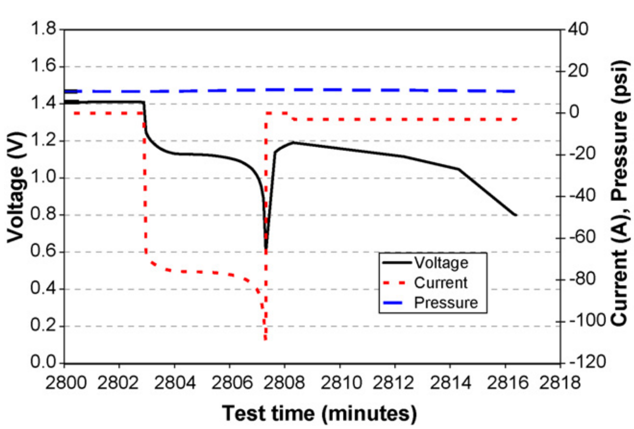

Fig. 9. 6.48 Ah cell discharge under a PEDV regime.

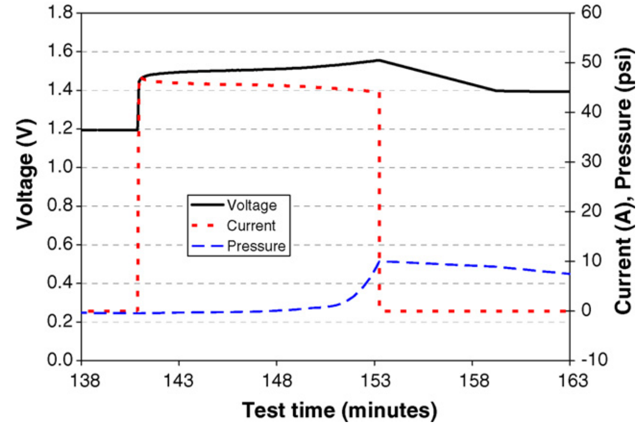

Fig. 10. 12.96 Ah cell charge under a PEDV regime.

Fig. 8 shows that the thinner cell was able to go from from 0% SOC to full charge in about 8.5 min. The plot also indicates that cell pressure was largely unchanged until the very end of charge, at which point it increased rapidly.

Fig. 9 shows the corresponding discharge under a PEDV test; the cell went from a fully-charged condition to discharged in 4.3 min. A slower 3 A discharge to 0.8 V followed, to return the cell to the empty state.

For comparison purposes, Figs. 10 and 11 show that the thicker cell was able to accept charge at the specified rate for 12.3 min, and was able to discharge for 6 min. Also note that there is considerably more residual "low-power" capacity in the discharge for this cell when compared with the thinner cell.

Table 1 summarizes the data. The key figure in the table is the battery capacity for 300 Wh available energy under a 3 kW load. This allows 50 Wh of margin for decay of available energy during life. The data suggest that it, probably, would make more sense to increase the cell area such that the available energy target is obtained rather than increasing the electrode thickness.

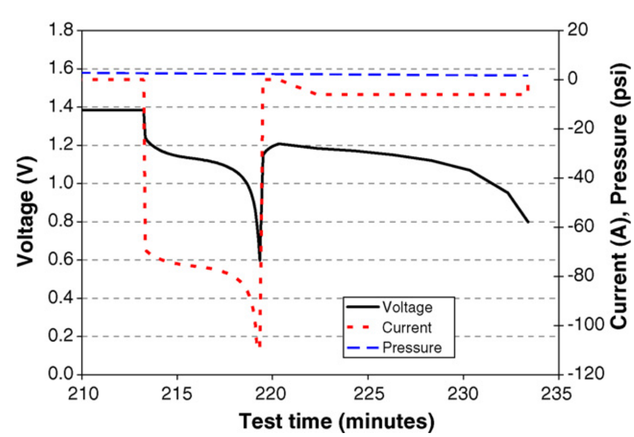

Fig. 11. 12.96 Ah cell discharge under a PEDV regime.

Table 1
Summary data for PEDV testing

Parameter	Cell theoretical capacity	
	6.48 Ah	12.96 Ah
Charge capacity (Ah)	6.42	9.37
Charge energy (Wh)	9.71	14.14
Discharge capacity (Ah)	5.71	7.95
Discharge energy (Wh)	6.31	8.67
Scale factor for 250 Wh	39.6	28.8
Scale factor for 300 Wh	47.5	34.6
Battery capacity for 300 Wh (Ah)	8.8	12.8

Note that the discharge figures are for the high power discharge only.

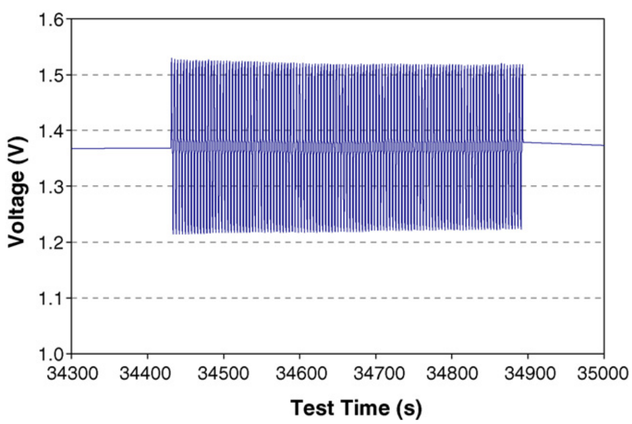

Fig. 12. Pulse cycling of cell S121–3 at 50% SOC.

4. Alternative cycling regimes

Other applications of interest may require a battery, which is capable of accepting and delivering short high-power pulses on an extended basis. Figs. 12 and 13 show the performance of a cell, which is similar in design to those contained within the larger battery described earlier. The cell was brought to the 50% SOC level and then cycled repetitively. The duty cycle employed was a 100 A charge for 1.0 s, rest for 1.0 s, 100 A discharge for 1.0 s, and rest for 1.0 s. Relatively stable charge and discharge voltages were observed, and little or no pressure change was observed during the test.

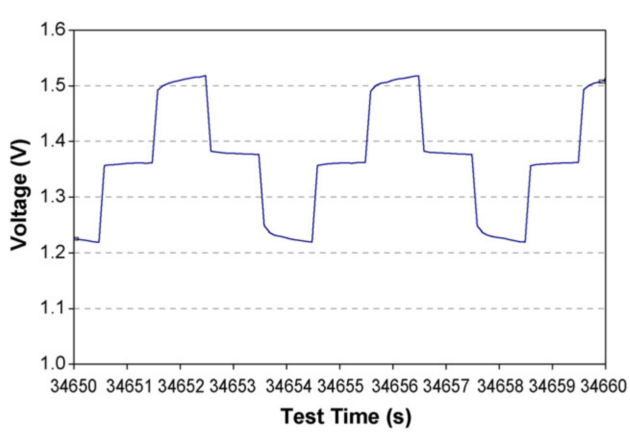

Fig. 13. Pulse cycling of cell S121–3 at 50% SOC.

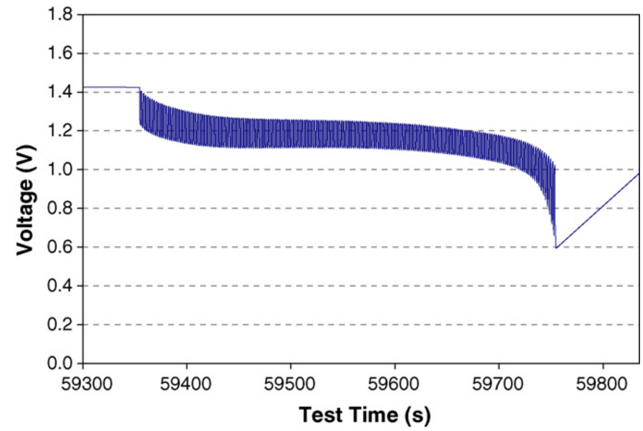

Fig. 14. Pulse discharge of cell S121–3 at 100% SOC.

Other applications may require deep discharge of the battery under pulsed load conditions. Figs. 14 and 15 show the performance of a cell, which was fully charged then discharged according to a duty cycle of a 100 A discharge for 1 s followed by rest for 1 s. The measured delivered capacity of 5.69 Ah is impressive when considering that the cell can deliver about 6.3 Ah at the C/3 rate.

Electro Energy has also successfully integrated this bipolar battery design with lithium ion technology to achieve a multi-cell prototype battery with increased discharge efficiency, reduced weight and volume, more flexible design, and lower manufacturing cost. The bipolar Li-ion (BP Li-ion) cells have the same positive attributes as Electro Energy's bipolar nickel–metal hydride (BP Ni–MH) design,

5. Safety considerations

Although high-voltage/power systems are of great interest many designers do not understand the safety considerations that need to be considered. In general, the higher the energy

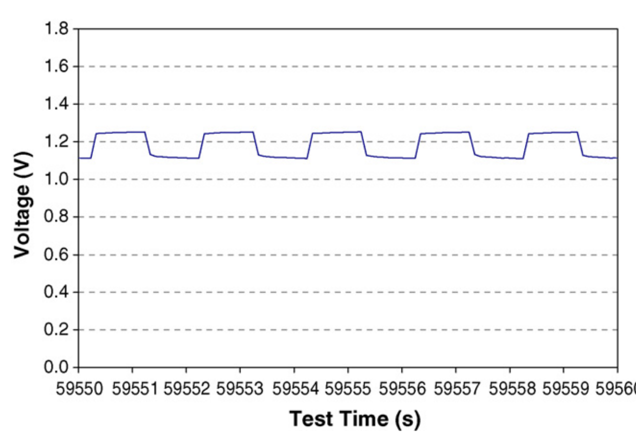

Fig. 15. Pulse discharge of cell S121–3 at 100% SOC.

and power available, the more dangerous the device. The wafer cell design facilitates high-rate discharges but is an exceptionally safe design during failure modes, such as penetration, fire, or other modes of failure.

6. Conclusion

Data related to high-pulse power applications of Electro Energy's bipolar nickel–metal hydride technology were presented. It appears that the technology is capable of both accepting and supplying very high-power density pulses, which could be used in a variety of applications.

Acknowledgements

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