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40

High-*g* power sources for the US Army's HSTSS programme

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Abstract

Under the Hardened Subminiature Telemetry and Sensor System (HSTSS) programme, the US Army has been developing gun-hardened telemetry devices and subsystems for the testing of smart weapon systems. These devices will be able to withstand accelerations in excess of 100 000 *g* and radial accelerations in excess of 25 000 *g*. Under this programme, rechargeable lithium-ion polymer battery technology and primary lithium/manganese dioxide technology are being developed for ballistic telemetry applications. To date, prototypes of these batteries have survived accelerations well over 100 000 *g*. This report provides the current status of these developments and reviews battery designs and testing regimes.

Keywords: Lithium-ion secondary batteries; Applications/weapons

1. Introduction

The Hardened Subminiature Telemetry and Sensor System (HSTSS) programme has been a technical effort involving the US Army Research Laboratory (ARL) Weapons Technology Directorate (WTD), and the US Army Test and Evaluation Command (TECOM), Yuma Proving Ground. This programme is developing telemetry transmitters, antennas, programmable high-density multichip modules, physical sensors, programmable data acquisition chip sets, and power sources for high-*g* applications [1]. The goal of the programme is to provide low-cost, user configurable telemetry components for making in-flight measurements of smart weapon systems. These new telemetry components are being developed to withstand shock levels in excess of 100 000 *g* and radial accelerations in excess of 25 000 *g*.

This report focusses on the battery development effort with Ultralife Batteries (UK) Ltd. Under a current US Army contract, Ultralife will be providing both primary and secondary batteries for evaluation in ballistic applications. This paper provides the current status of these developments and reviews battery designs, test regimes, and results.

2. Background

An on-board telemetry power source usually consists of several cells connected together to give the desired voltage and capacity. Typically these can be primary (i.e. lithium), secondary (i.e. nickel/cadmium) or reserve batteries. These batteries are of fixed dimensions and often large when compared to other telemetry components. Because these batteries are rigid, the designer has very little flexibility in the package design. If moments of inertia and centre of gravity of the flight body are to be preserved, the job becomes even more challenging. In the past, special order batteries that would meet these requirements have proved to be cost prohibitive.

Safety and performance issues have also been of concern. For example, many types of nickel/cadmium cells degrade in performance when subjected to high-spin rates. Fig. 1 shows this typical behaviour. Depending on the cell's internal structure, this problem may escalate when mounted either on or off the spin axis. Due to design constraints, the power source is often embedded in the projectile and is not removable. In these cases a rechargeable supply is preferred. Typically, before the projectile is launched, it is put through a series of ground tests that allow for the calibration of sensors and electronics. When the calibration procedures require a spinning platform and nickel/cadmium batteries are used,

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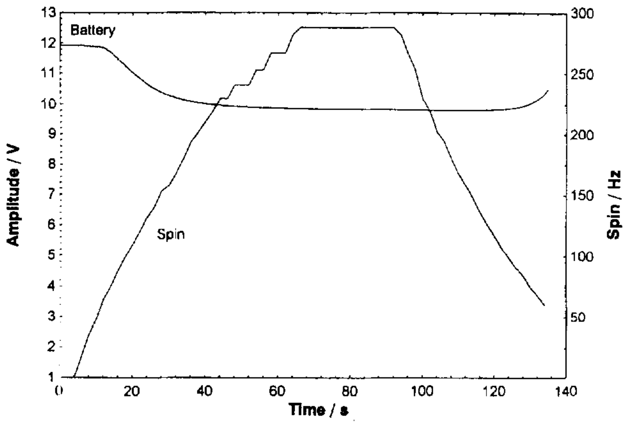

Fig. 1. Typical response of a nickel–cadmium battery during a spin test.

then the number of calibration cycles that should be performed is limited.

Under the HSTSS programme, conformal solid polymer electrolyte and conformal Li/MnO_2 batteries are being developed by Ultralife Batteries (UK) Ltd., for high-*g* applications. This technology is being proposed for telemetry applications where power requirements are not extreme, but where space and packaging is of major concern. It is expected that these technologies will provide the telemetry engineer with an affordable and reliable power source, while allowing more flexibility in the system package design.

2.1. Review of previous contract work

To date, three separate battery development contracts have been conducted under the HSTSS programme. The first contract was with Dowty Batteries (now Ultralife Batteries (UK) Ltd.) for the evaluation and modification of rechargeable Li/V_6O_{13} polymer electrolyte cells. This took place in 1994 and focussed primarily on the survivability issues of the cell structure under high accelerations. This evaluation showed that the basic cell structure could be modified to survive accelerations of 80 000 *g* and radial accelerations of 4300 *g*. Details of this work can be found in Refs. [2,3].

In 1995, a second contract was initiated with Ultralife Batteries (UK) Ltd., to conduct a study on rechargeable lithium-ion solid polymer cells. After making several modifications to the cell structure, it was shown that these cells could survive accelerations of over 100 000 *g* and radial accelerations over 25 000 *g*. The lithium-ion chemistry offers a much better practical energy density (> 100 Wh kg^{-1}) and a higher operating voltage (3.6) than does the Li/V_6O_{13} chemistry. During this study, Ultralife's primary Li/MnO_2 'thin cell' and high-rate cylindrical cells were also evaluated for ballistic applications. Both technologies have applications in high-*g* telemetry and projectile guidance and control systems, and both yielded promising results during these preliminary tests.

2.2. Current contract status

Currently, the HSTSS programme has Ultralife Batteries (UK) Ltd., under a twelve-month, three-part contract to provide batteries for ballistic telemetry applications. This three part contract addresses: (1) solid polymer lithium-ion technology; (2) primary Li/MnO_2 'thin cell' technology; (3) primary Li/MnO_2 high-rate technology. The goals of this contract are as follows:

(i) finalise cell structure for high-*g* survivability;

(ii) develop assembly and fabrication techniques for multiple cell batteries;

(iii) deliver multiple cell batteries for typical munitions test applications.

The remainder of this report focusses primarily on the lithium-ion effort and reviews cell design and specifications, test results, and special application designs. Work being performed on primary 'thin cells' and high-rate cells is also discussed.

3. Rechargeable solid polymer electrolyte lithium-ion cells

3.1. Technology description

This rechargeable technology comprises a carbon anode coupled with a lithiated manganese oxide ($LiMn_2O_4$) cathode. In place of a conventional liquid electrolyte there is a polymer that functions both as a transporting medium for the lithium ions and an electronic insulator that prevents the electrodes from shorting. By incorporating a lithium salt and organic plasticisers into the polymer matrix, high ionic conductivity, good electrochemical stability, and high mechanical strength have been obtained. A basic diagram of the cell structure is shown in Fig. 2.

The batteries are fabricated by laminating the electrode and electrolyte layers by the proper use of heat and pressure. This assembly is contained within a laminated foil package sealed by conventional heat-bonding methods.

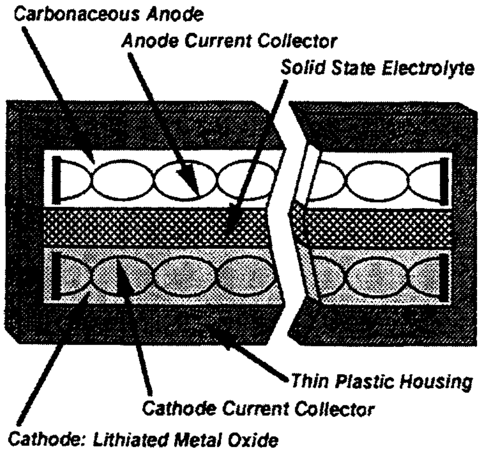

Fig. 2. Cross section of an Ultralife lithium-ion polymer cell.

The polymer battery is configurable in a variety of thin prismatic shapes and possesses high energy density (> 100 Wh kg^{-1}) and excellent cyclability (> 500 cycles to 80% of initial capacity). It is capable of being charged in less than 2.5 h and can be discharged continuously at rates up to 2*C*. As a result of using a polymer electrolyte and the absence of lithium metal, the cells are extremely tolerant to abuse when subjected to short circuit, overcharge, and forced-discharge conditions.

3.2. Review of test data

The following is a review of test data gathered thus far on the solid state lithium-ion cells (contracts 2 and 3). The tests conducted were very similar to those performed under the first contract, which evaluated the lithium/vanadium oxide cell. Details, diagrams, and photographs of all test apparatus can be found in Ref. [3].

The cells provided by Ultralife for shock and spin testing were of a flat rectangular format and measured approximately 46 mm by 36 mm and had a capacity of 20 mAh.

3.3. Shock table data

An impact shock test machine is used to establish cell behaviour for shock levels of 30 000 *g* or less. The batteries are typically tested in two different orientations: (i) mounted with the thin edge along the shock vector (vertically) and (ii) mounted with the thin edge perpendicular to the shock vector (horizontally). The cells are sprayed with mould release, placed into an aluminum test fixture, and encapsulated on all sides. This procedure allows the encapsulated cell to be removed so that a physical inspection of the cells internal components can be performed after the tests. The cells are shock tested whilst under a resistive load and monitored throughout the shock event. An accelerometer, which is mounted on the drop table, is also monitored. Typical data plots can be seen in Figs. 3 and 4.

Numerous cells were tested using this apparatus during the early stages of development. The first step was to shock test the standard commercial cell so that failure mechanisms could be identified and corrected. Fig. 3 shows cell voltage dropping out during and just after shock. Post-shock analysis of these cells revealed the failure modes were due to the tag welds and strength of the tag material [4,5].

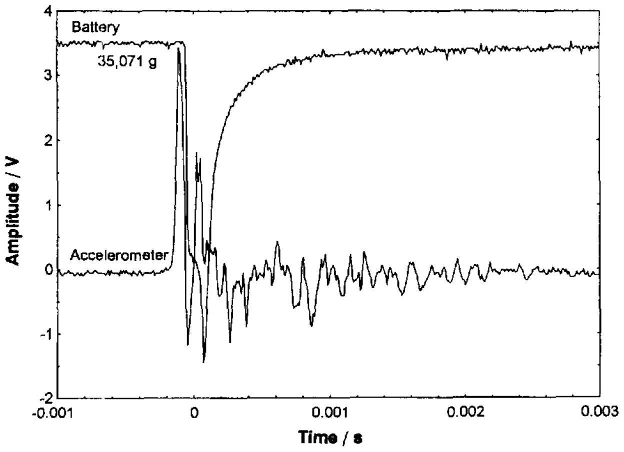

Fig. 3. Response to acceleration of a lithium-ion cell on a 3 mA load (first example).

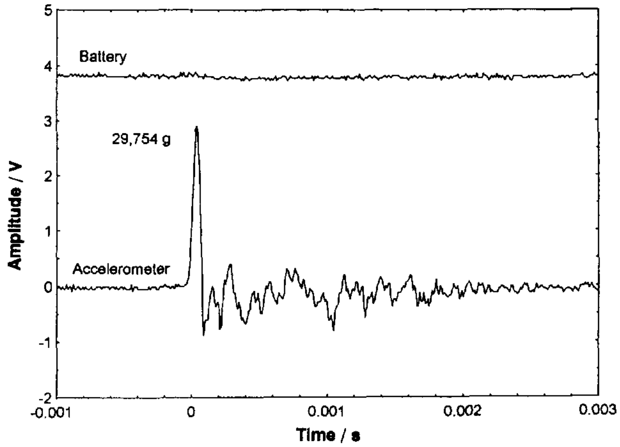

Fig. 4. Response to acceleration of a lithium-ion cell on a 3 mA load (second example).

After switching to ultrasonic welds and changing the tag material, the lithium-ion cells routinely survived accelerations of 30 000 *g* in both the horizontal and vertical positions. Fig. 4 shows an ideal data plot.

3.4. Airgun data

In order to qualify the cells at much higher acceleration levels, a high pressure airgun is used. Test items are fitted into a carrier body and launched by the airgun. After exiting the tube, the carrier impacts a mitigator and momentum exchange mass designed specifically to create a unique deceleration profile. A complete description of this apparatus and its operation is given by Burke et al. [3] and Davis et al. [6].

A typical test regime consists of seven shots, starting at 40 000 *g* (nominal) and progressing to 100 000 *g* (nominal) in increments of 10 000 *g*. Each test includes two cells, one mounted vertically and one mounted horizontally with respect to the shock vector (Fig. 5). The cells are treated with mould release, placed into an oversized mould, and encapsulated [6]. The moulded styrene cast is then machined down to fit snugly into the carrier. Wires that are attached to each cell terminal are also machined flush with the potting and provide a means for testing or charging the cells. The cells cannot be electrically loaded or monitored during impact. Each cell's open-circuit voltage (OCV) is measured and recorded before and after each test. The encapsulated cells are then returned to Ultralife where post-test analysis is performed.

3.5. Airgun results

To date, two series of airgun tests have been performed on the lithium-ion cells. The first tests occurred in Oct. 1995 and

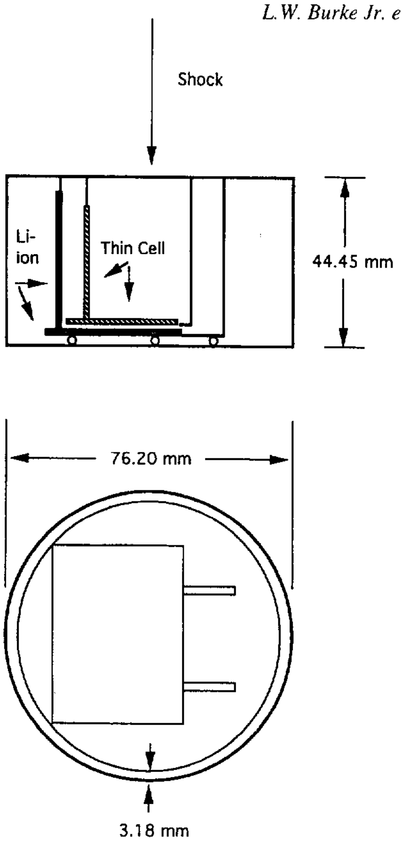

Fig. 5. Cell orientation for airgun testing.

the second group in July 1996. In both cases, decelerations greater than 100 000 *g* were achieved.

3.5.1. *Results from first series*

The cells that were positioned horizontally survived all the tests. The large variation in the OCV was related to the quality of the seal of the foil packaging, which led to the premature discharge of several cells. New sealing procedures have since corrected this problem. Ultralife's Investigation Report No. 3 clearly shows there was no deformation of these cells, even at 115 000 *g* [7].

The cells positioned vertically did not fare as well. Table 1 shows that the only cell to survive the airgun test was at 51 000 *g*. Examination of the cells at Ultralife showed a common mode of failure, this being detachment of electrodes from the tags [7]. However, this appeared to have been caused by swelling of the cell package that resulted in insufficient support for the electrodes. Further investigation revealed that the potting procedure had inadvertently led to encapsulant curing temperatures in excess of 150°C, and that this was responsible for the unexpected behaviour on the airgun tests. It is interesting to note that the majority of the cells retained their charge even after being subjected to a temperature of more than twice their maximum rating for several minutes.

From these data it appears the lithium-ion polymer cells, when mounted in a vertical position and fully supported, are able to survive at least 50 000 *g*. When mounted in the horizontal position, they are capable of over 100 000 *g*.

3.5.2. *Results from second series*

A second series of airgun tests was performed in July of 1996. The test regime was very similar to that just discussed. The cells used for testing were also of the same type with modifications made to the structure and packaging. Vertical cells were present in all five trials. Horizontally positioned cells were not tested at 60, 70 or 80 000 *g*. The results are summarised in Table 2.

With the exception of the cell tested at 60 000 *g* in the vertical plane, all cells survived the shock testing. The cells tested at 60 000, 100 000 and 110 000 *g* were sent to Ultralife for further inspection.

The cause of failure for the cell tested at 60 000 *g* was subsequently shown to be due to the shearing of the anode tag at the boundary of the anode current collector. It is likely that this was the result of damage to the tag during assembly. There was however no evidence of the tag welds failing on either the anode or cathode [8].

Although the OCV readings indicated cell survivability at acceleration levels greater than 100 000 *g*, further examination of the cells revealed some minor deformation. This is attributable to the edge of the cell not being in complete contact with the seal of the packaging. A simple modification to the package design would easily eliminate this problem [8].

Overall, these results were extemely encouraging and showed that the cells could indeed survive shocks in excess of 100 000 *g* in both orientations.

Table 1
Summary of first airgun test

Trial number	Target acceleration $g \times 1000$	Measured acceleration $g \times 1000$	OCV [a] before		OCV [a] after	
			Horz.	Vert.	Horz.	Vert.
1	40	49	3.26	0.42	3.26	0.00
2	50	51	1.24	1.77	1.24	2.04
3	60	58	3.89	3.64	3.89	0.00
4	70	70	3.79	3.69	3.78	0.00
5	80	80	3.68	1.03	3.68	0.00
6	90	95	0.99	0.61	0.99	0.61
7	100	115	3.89	3.54	3.89	0.00

[a] The low open-circuit voltages were due to seal quality and the encapsulant curing temperature being greater than 150°C.

Table 2
Summary of second airgun test

Trial number	Target acceleration $g \times 1000$	Measured acceleration $g \times 1000$	OCV before		OCV after	
			Horz.	Vert.	Horz.	Vert.
1	60	65	N/A	3.99	N/A	0.00
2	70	75	N/A	3.98	N/A	3.97
3	80	89	N/A	4.00	N/A	3.99
4	90	93	3.98	4.03	3.99	4.04
5	100	110	4.00	4.00	4.02	3.98

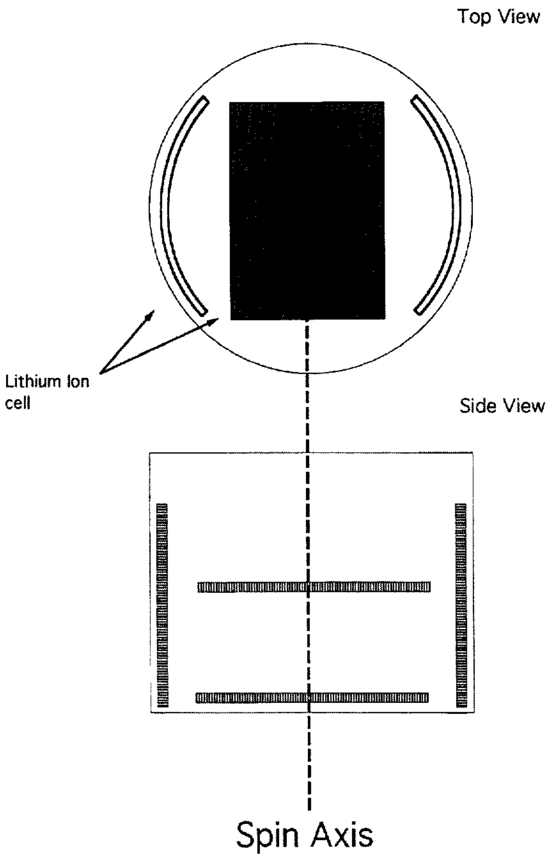

Fig. 6. Cell orientation with respect to spin axis.

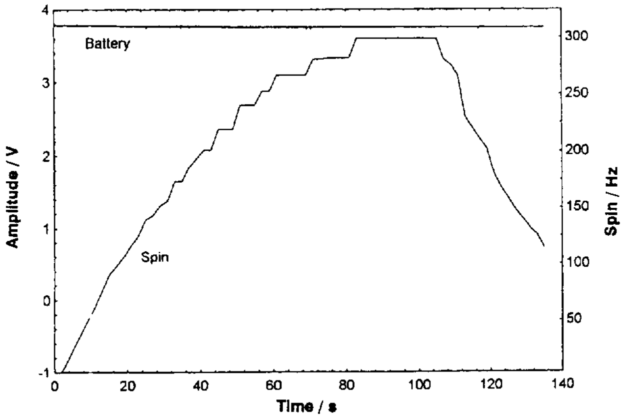

Fig. 7. Response to spin of a lithium-ion cell on a 10 mA load.

3.6. Spin data

The purpose of these tests was to evaluate the electrical performance of the cell when subjected to typical artillery projectile spin rates (up to 300 Hz). The cells tested are of the same type as described previously in the technology description.

The apparatus used to conduct these tests is a three-degrees-of-freedom flight simulator manufactured by the Carco Corporation.

This unique piece of equipment is capable of rotating a 45 kg, 155 mm projectile up to 300 Hz while inducing yaw motion up to 20 Hz. Typically, a set of four batteries is tested under load in the configuration as shown in Fig. 6. A complete description of the test procedure can be found in Ref. [3].

To date, over 25 single cell configurations have been spin tested in both orientations at rates greater than 300 Hz, yielding radial accelerations of more than 24 000 g. No failures have yet been seen, with only minor disturbances occurring that were attributed to the quality of the sealing. Typical spin data are shown in Fig. 7.

3.7. Summary

As a result of the above tests, a solid polymer lithium-ion cell that can reliably perform at extreme accelerations is now available. The modifications made to the standard lithium-ion polymer electrolyte construction to produce cells capable of surviving high shock and spin levels are as follows:

- tag location
- tag material change to improve tag-to-grid weld
- ultrasonic welding of tag to grid
- improved heat-sealing location around perimeter of cell

Only mechanical changes were needed to the original polymer design as the cell chemistry was suitable for high-g applications.

4. Lithium-ion multicell designs

The next step in the programme is to build multiple cell battery packs using the knowledge gained from the previous tests. Under the current HSTSS contract, Ultralife will be

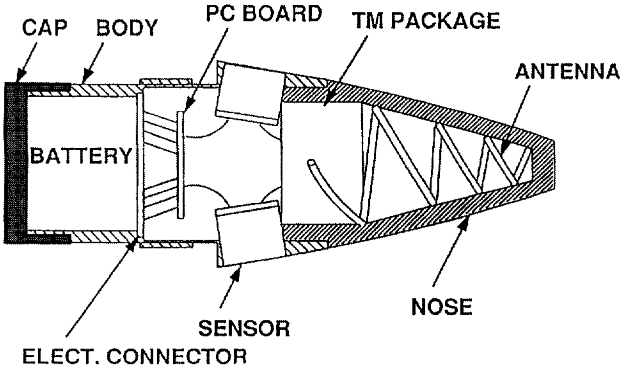

Fig. 8. Fuze-configured yawsonde measurement system.

building two battery packs for flight instrumentation applications. The first will be for an artillery nose fuze configuration and the other for a Navy rocket configuration. At the time of writing, the rocket configuration had not yet been defined; therefore, only the nose fuze application will be discussed in this report.

4.1. Nose fuze application

Fig. 8 shows a diagram of a typical instrumentation package called a 'yawsonde', which is routinely used by ARL for measuring the flight dynamics of a projectile. This telemetry package routinely includes sensors such as photo diodes, accelerometers, an angular rate sensor, and supporting electronics. The battery requirements for this instrumentation package are outlined in the following paragraphs.

The available envelope for this power source is a cylinder of 37 mm diameter and 33 mm long. After making an allowance for encapsulation, this is reduced to 32 mm diameter and 28.5 mm long.

The salient features of the battery specification are that it should deliver a current of 150 mA for 30 min to an end-point voltage of 12.3. The battery is mounted in a horizontal orientation and, while operational, should survive accelerations in the range 25 000–30 000 *g* and spin rates up to 300 Hz.

4.2. Battery design

The rechargeable lithium-ion polymer electrolyte power source used in this application is the same as that described in the technology description section.

4.3. Nose fuze battery

In order to meet the specification, four lithium-ion cells need to be connected in the series arrangement shown in Fig. 9. Each cell has a nominal capacity of 120 mAh. This is achieved by the parallel stacking of discs using a novel design that minimises the number of interconnections and prevents movement of the electrode assembly within the housing. Such an arrangement ensures the survivability of the battery at high-*g* forces and spin rates.

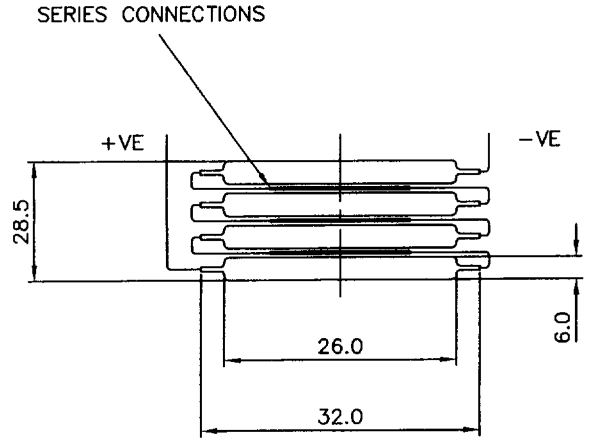

Fig. 9. Design of the 16 V 120 mAh nose fuze battery (dimensions in mm).

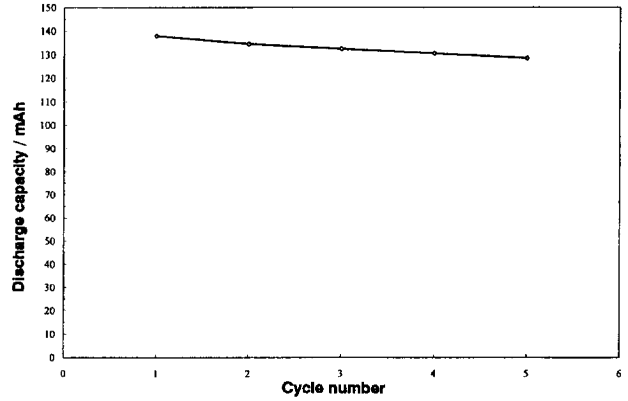

Fig. 10. Cycling performance of the nose fuze cell when discharged at 15 mA ($C/8$).

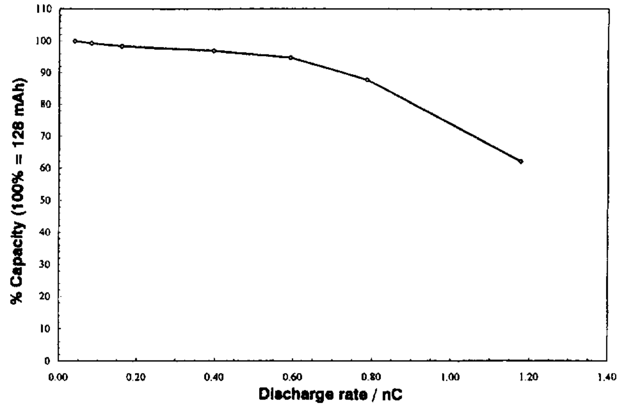

Fig. 11. Capacity obtained against discharge rate for the nose fuze cell.

To date, individual 4 V, 120 mAh cells have been fabricated and tested against the requirement specification. Fig. 10 shows the capacity of a typical cell to be used in the nose fuze battery. Over the period of interest (maximum 5 cycles) in the region of 130 mAh is obtained on a 15 mA ($C/8$) discharge.

Fig. 11 is the power rate curve for a typical 4 V cell. This provides information on the rate capability of the cell and shows that at a current of 150 mA of the order of 63% of the cell capacity is available, viz. 80 mAh. This is equivalent to an operational time in excess of 30 min, the design goal.

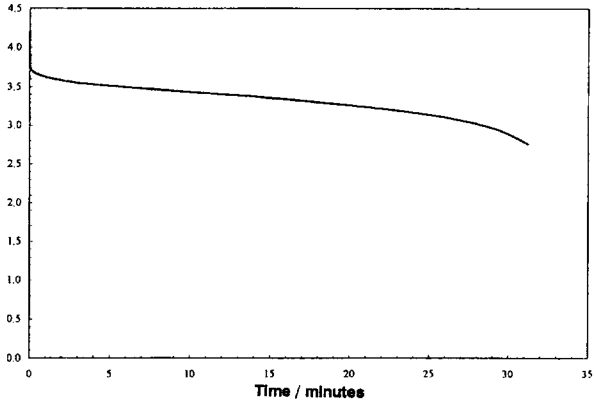

Fig. 12. Discharge curve of the nose fuze cell at 150 mA (1.25*C*).

Fig. 12 depicts the discharge curve of a nose fuze cell under a 150 mA load.

Work is in progress to fabricate 16 V, 120 mAh batteries in order to characterise the electrical performance. Shock, spin, and flight testing will also be performed to confirm the ruggedness of the design.

5. Primary Li/MnO$_2$ 'thin cell' technology

5.1. Description of the technology

Ultralife has developed a 3 V primary lithium/manganese dioxide cell in a flat format trademarked with the name 'thin cell'. This cell design, which is housed in a laminated foil package, allows for an extremely efficient filling of the battery cavities. Cells possess high energy density (> 200 Wh kg^{-1}) and can operate over the temperature range −20 to +50°C.

This battery technology is being evaluated for applications not requiring rechargeability, but needing a greater energy density and packaging flexibility than existing primary batteries. As with the lithium-ion technology, the cells can be layered together to form a multiple cell pack and can also be pre-shaped to fit into unique cavities at a lower cost than other technologies. The 'thin cell' technology is also being developed to survive accelerations of 100 000 *g* and radial accelerations of 25 000 *g*. Multiple cell designs will also be delivered for unique Army applications.

5.2. Shock and spin testing

To date, shock table, airgun, and spin testing have been performed only on the standard commercial cells. These tests were performed to determine any failure mechanisms of the basic cell structure.

With no structural modifications yet made to the cells, preliminary shock table and airgun tests indicate the cells are capable of surviving 110 000 *g* when mounted horizontally, but no more than 20 000 *g* (reliably) when mounted vertically. Preliminary spin testing shows the cells perform well at spin rates up to 300 Hz. Fig. 13 shows the response of a 'thin cell' while under load. Post-analysis of these cells is currently underway.

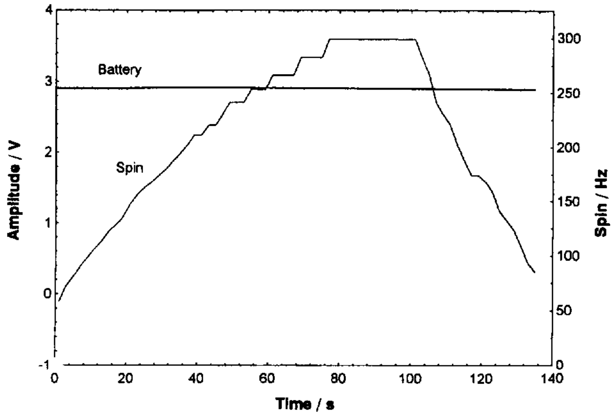

Fig. 13. Response to spin of a Li/MnO$_2$ 'thin cell' on a 10 mA load.

5.3. Summary

Although preliminary data are promising, further work is required to modify the 'thin cell' structure to ensure consistency in surviving high-*g* shocks [9]. Improvements much like those outlined for the solid polymer lithium-ion cells are currently being considered.

6. High-rate cells

6.1. Technology overview

Ultralife's high-rate primary lithium/manganese dioxide cells employ a spirally wound solid cathode construction that maximises electrode surface area, generates low internal resistance, and enables a high discharge rate capability over a wide temperature range. This construction is housed in a hermetically sealed stainless steel container.

Unlike liquid cathode systems, the use of a manganese dioxide cathode ensures the absence of voltage delay following periods of storage. Furthermore, benign behaviour under a range of abusive conditions is achieved by the unique cell design that includes a low-pressure vent and a copper anode current collector.

Ultralife's high rate Li/MnO$_2$ batteries are being modified for lower shock applications where military operating temperatures and high current pulsing are required. Although these batteries do not offer the packaging flexibility of the solid polymer lithium-ion or 'thin cell' formats, they do yield an excellent energy density of better than 200 Wh kg^{-1}. Under the HSTSS programme, these batteries will be modified to function during shock levels of 30 000 *g* and radial accelerations of more than 25 000 *g*. It is expected that these batteries will provide alternatives to more volatile battery chemistries such as thionyl chloride and sulfur dioxide.

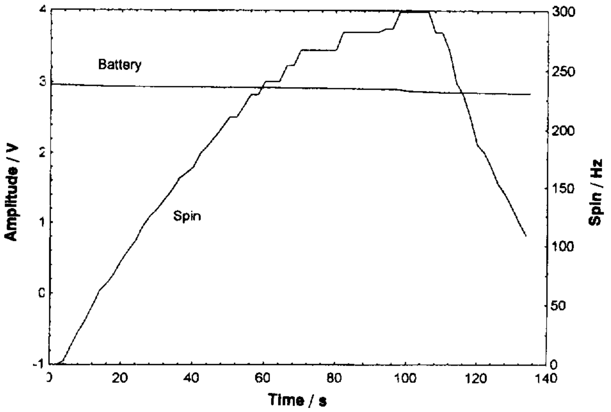

Fig. 14. Response to spin of a high-rate Li/MnO_2 C-size cell on a 100 mA load.

6.2. *Summary*

At the time of writing, the high-rate cell phase of this contract has just been initiated. To date, only preliminary shock table and spin testing have been performed on the standard commercial 'C'-size high-rate cells.

It was observed from preliminary shock testing of high-rate cylindrical Li/MnO_2 cells that under certain conditions, bulging and occasional rupture of the vent cap occurred at shock levels above 5000 *g*. A contributing cause of this was considered to result from small movements of the coil-pack. Although not consistent, venting of the cells also occurred when subjected to radial accelerations greater than 10 000 *g*. It should be noted, however, that even after multiple spins, the cells maintained a voltage while under load. Fig. 14 shows these data.

In order to prevent movement of the coil-pack from occurring, a mandrel is to be inserted into the centre of the coil-pack. At the same time, protection of the vent area of the cell will be increased by incorporating an additional component between the vent cap and the coil-pack. These modifications are currently under way.

7. Conclusions

Under the current contract with Ultralife Batteries, the US Army expects to have both the rechargeable solid polymer lithium-ion and the primary lithium/manganese dioxide 'thin cell' technologies fully qualified for high-*g* telemetry applications by 1998. The reliable performance and packaging flexibility that these technologies possess will have an immediate impact on smart weapons testing. In the future, as operating voltages for telemetry components decrease, these technologies will allow even more flexibility.

Ultralife's primary high-rate lithium/manganese dioxide cylindrical cells are also expected to be qualified for artillery and missile applications by 1998. It is expected that this technology will offer an alternative to applications requiring a specialised reserve battery.

Flight testing of all three technologies is currently scheduled for the summer of 1997.

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