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HSTSS Battery Development for Missile and Ballistic Telemetry Applications

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Abstract

The rapid growth in portable and wireless communication products has brought valuable advancements in battery technology. No longer is a battery restricted to a metal container in cylindrical or prismatic format. Today's batteries (both primary and secondary) can be constructed in thin sheets and sealed in foil/plastic laminate packages. Along with improvements in energy density, temperature performance, and environmentally friendly materials, these batteries offer greater packaging options at a significantly lower development cost. Under the Hardened Subminiature Telemetry and Sensor System (HSTSS) Program, these battery technologies have been further developed for high-g telemetry applications. Both rechargeable solid-state lithium-ion polymer and primary lithium manganese dioxide (Li/MnO_2) batteries are being developed in conjunction with Ultralife Batteries, Inc. Prototypes of both chemistries have been successfully tested in a ballistic environment, while providing high constant rates of discharge, which is essential to these types of applications. Electrical performance and environmental data are reported.

Acknowledgments

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1. Introduction

The Hardened Subminiature Telemetry and Sensor System (HSTSS) Program is currently developing state-of-the-art telemetry components and subsystems for missile and ballistic applications. The goal of the program is to provide lower cost, user-configurable telemetry components for making in-flight measurements of smart munitions. Along with these telemetry components comes the need for a power source, which cannot only fit into the constrained dimensions available on a munition but also perform under extreme conditions such as high-g acceleration and spin. The HSTSS Program has identified recent advancements in battery technology, which will provide possible power sources for future telemetry systems. Development with Ultralife Batteries is ongoing in an effort to adapt their commercial technologies to the high-g military environment. This paper reviews the current status of these developments, the battery technologies, battery designs, and test results.

2. Background

An onboard telemetry power source usually consists of several cells connected together to give the desired voltage and capacity. Typically, these batteries fall into the following categories: secondary (rechargeable), primary (nonrechargeable), and reserve (activated upon some condition, i.e., spin). These batteries are of fixed dimension, are comprised of free electrolyte, and are 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 center of gravity 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.

Under the HSTSS Program, both secondary solid polymer electrolyte lithium-ion batteries and primary lithium manganese dioxide (Li/MnO_2) batteries are being developed for ballistic applications. Both technologies are available in conformal foil/plastic laminate packaging and can be rapidly prototyped for most applications. These technologies are being proposed for applications where power requirements are not extreme but where space and packaging flexibility 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.

The HSTSS Program started evaluating these technologies nearly 5 yr ago, while under the test technology and demonstration phase of the program. During this period, numerous development contracts have been executed. The early contracts focused on survivability issues of the basic cell structure under high setback and radial accelerations. Research has also been conducted in the areas of assembly and fabrication techniques of multicell batteries and improved energy densities and temperature performance. Basic cell structures of both chemistries have been shown to survive accelerations in excess of 80,000 g's. These works are summarized in Burke, Faulstich, and Newnham [1] and Burke et al. [2, 3]. Since initial evaluations, the technology has matured dramatically. Currently, the HSTSS Program is building demonstration batteries for several munition applications in both the lithium-ion and Li/MnO_2 chemistries.

3. Rechargeable Solid Polymer Lithium-Ion Technology

Lithium-ion technology was first commercialized in 1991 by Sony and is based on a carbon anode, a lithium metal oxide cathode, and a liquid electrolyte. However, since these early liquid-based systems had the need to contain the liquid in a metal can, there were limitations to the applications in which liquid-based systems could be used. In order to overcome these limitations, Ultralife Batteries (and others) has developed a solid polymer lithium-ion battery. In place of the conventional liquid electrolyte 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 plasticizers into the polymer matrix, high ionic conductivity, good electrochemical stability, and high mechanical strength have been obtained. A basic schematic of the cell construction is shown in Figure 1.

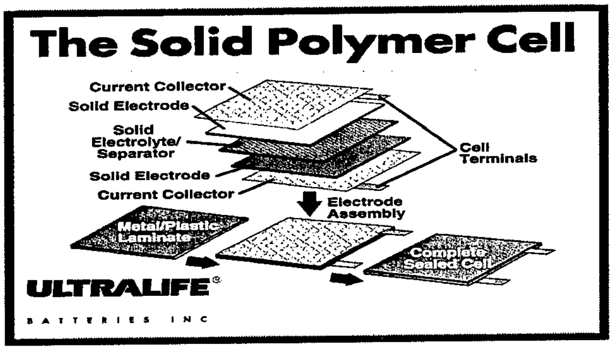

Figure 1. Schematic of a Lithium-Ion Polymer Cell Structure.

The batteries are fabricated by laminating the electrode and electrolyte layers with the proper application of heat and pressure. The whole assembly is contained within a foil laminate package sealed by conventional heat-bonding methods. Due to the nature of the electrode layers, and the use of foil laminate packaging material, the polymer battery can be configured in a variety of thin prismatic shapes, while maintaining a higher energy density than other prismatic battery chemistries (Figure 2). The foil laminate package also allows the cells to be made as thin as 3 mm, compared to 6 mm, when a metal casing is used. Depending on the configuration, energy densities as high as 130 Wh/kg can be achieved, while maintaining a high cycle life (>500 cycles to 80% of initial capacity). The polymer battery is capable of being fully charged in approximately 2.5 hr and can be continuously discharged at 2C (rated capacity), with very little loss in capacity. Higher constant currents can also be sustained, but larger losses in capacity will occur. As a result of using a polymer electrolyte, and the absence of lithium metal, the cells are extremely tolerant of abuse when subjected to short-circuit, overcharge, and forced-discharge conditions. The cells meet the CSA950, IEC950, and UL1950 safety standards for mobile computing systems and pass all Japan Storage Battery Association safety tests.

4. Li/MnO_2 Thin Cell Technology

Ultralife Batteries has developed a line of thin, flat, primary Li/MnO_2 batteries called "Thin Cell." Like the solid polymer lithium-ion cells, these cells are packaged in a foil laminate and can be rapidly prototyped in a range of sizes and shapes, as seen in Figure 3. The internal construction of the Thin Cell is a wound solid cathode structure. However, the electrode stack is

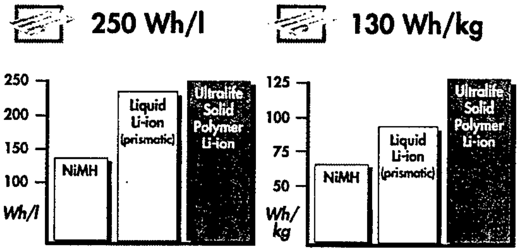

Figure 2. Comparison of Energy Densities for Various Prismatic Battery Chemistries.

Figure 3. Typical Cells Constructed Using Thin Cell Technology.

made thinner and the number of winds is increased in order to increase the surface area and battery performance under high current loads, as compared to commercial cylindrical batteries of this type. The electrode stack can be made as thin as 0.2 mm. Power densities of 500 W/liter (or 250 W/kg) have been demonstrated. Recently, optimization of the electrolyte composition has improved the performance of the cells over the temperature range of −20° C to +70° C. The Thin Cell technology is proposed for applications not requiring rechargeability, but needing a greater energy density and package flexibility than existing primary batteries.

5. Applications

To further qualify these technologies for ballistic applications, Ultralife Batteries has been contracted by the HSTSS Program to build batteries for actual munition instrumentation systems. Batteries for artillery, rocket, and kinetic energy (KE) munitions are currently being built and are reviewed in the remaining sections.

6. Artillery Nose Fuse Battery

One of the most common applications for ballistic instrumentation is the artillery nose fuse (Figure 4). If given the entire fuse cavity, the volume available for an instrumentation package is roughly 147 cm^3. An artillery projectile can experience setback accelerations as high as 30,000 g's and spin rates up to 300 rps, yielding radial accelerations as high as 25,000 g's, depending on payload location. Both maximum acceleration and spin are achieved in less than 15 ms. The range of a typical artillery projectile is 20 km.

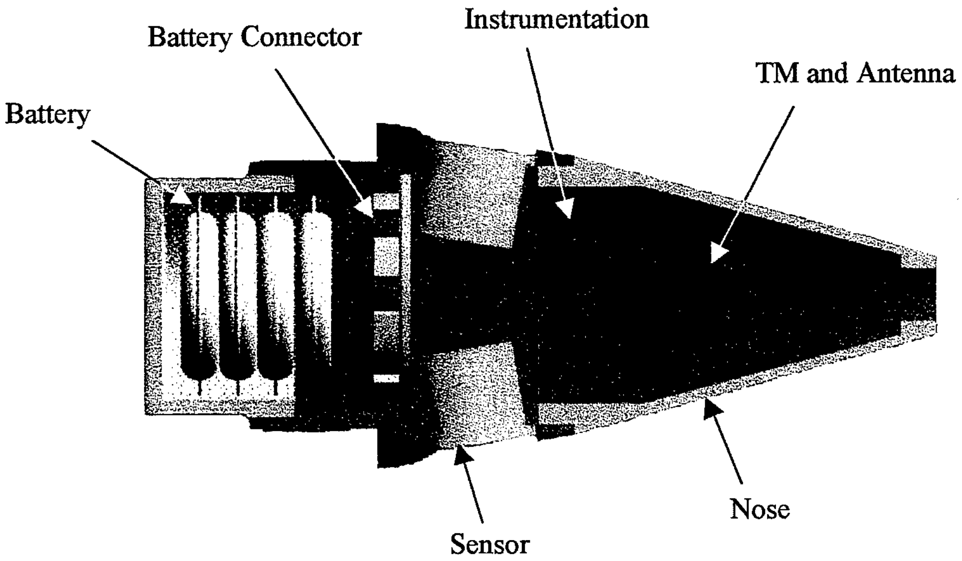

Figure 4. Typical Artillery Nose Fuse Instrumentation System.

7. Solid Polymer Lithium-Ion Nose Fuse Battery

A solid polymer lithium-ion nose fuse battery is being developed for projectile test and evaluation applications. The battery is to be located in the rear of the nose fuse cavity, as shown in Figure 4. The specifications for this battery are summarized in Table 1.

Table 1. Specifications for a Solid Polymer Lithium-Ion Nose Fuse Battery

Battery Type	Rechargeable Solid Polymer Lithium Ion
Dimension (Outside Diameter × Height)	37.0 mm × 37.0 mm
Minimum Voltage	12.3 V
Maximum Voltage	16.8 V
Constant Current Drain	150 mA
Minimum Duration	30 min (to Minimum Voltage)
Shock Survivability	30,000 g's
Spin Rate	300 rps
Operational Temperature	0° C to +50° C

The nose fuse battery design consists of four lithium-ion cells connected in series. Each disk-shaped cell has a nominal voltage of 4.2 V and a nominal capacity of 120 mAh. The cells are constructed using multiple parallel layers, which minimize the number of interconnections and prevent movement of the electrode assembly within the housing [3]. The stack of cells is then inserted into a prefabricated mold and encapsulated, as shown in Figure 5. This arrangement ensures the survivability of the battery at high-g forces and spin rates, while still providing enough power to meet the electrical requirements of the application. Figure 6 shows a typical electrical discharge curve of a single 4.2-V nose fuse cell under the specified current drain of 150 mA.

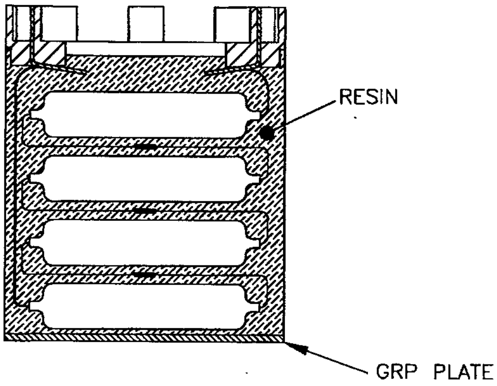

Figure 5. Lithium-Ion Nose Fuse Battery.

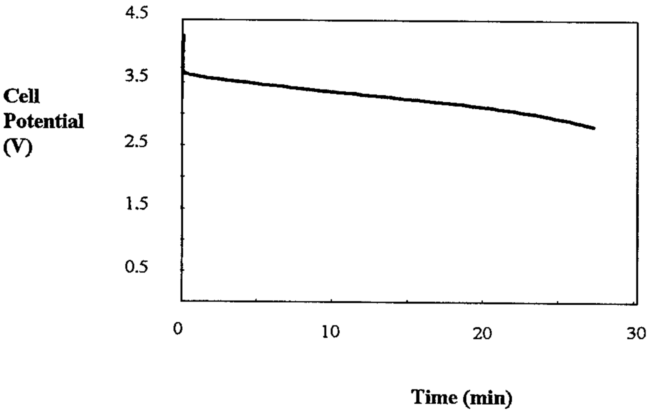

Figure 6. Lithium-Ion Cell Discharge at 150 mA.

Single cells of this type have been successfully shock-tested to over 30,000 g's, while under load, and up to 100,000 g's, with no load [2]. To date, only prototype batteries have been supplied for environmental testing. Initial shock table testing of these batteries, while under load, showed a small reduction in the battery voltage due to shock (Figure 7). Post-analysis of the tested batteries indicated a possible movement of the cell structure inside the foil package. To correct this problem, the packaging process has been modified to provide a tighter and more efficient package. Initial spin testing was performed up to 300 rps and showed no voltage dropout (Figure 8).

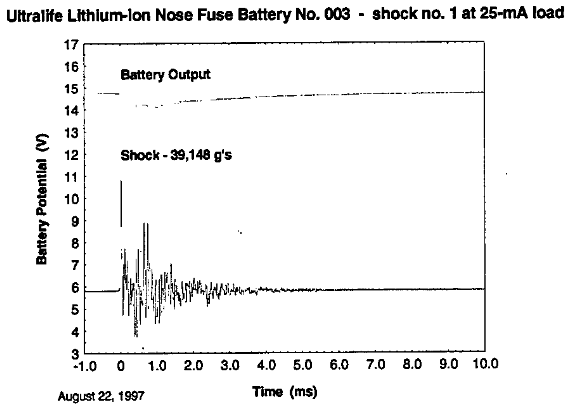

Figure 7. Shock Testing of a 16-V Lithium-Ion Nose Fuse Battery.

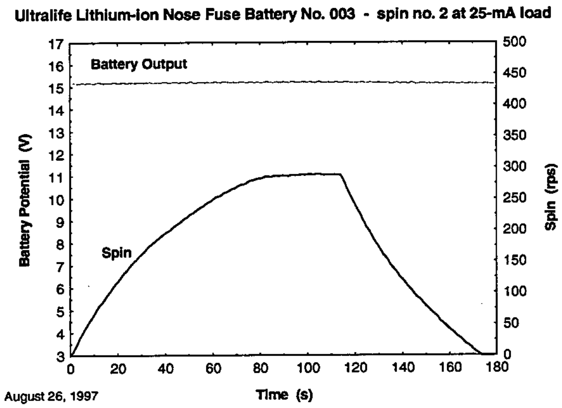

Figure 8. Spin Testing of a 16-V Lithium-Ion Nose Fuse Battery.

8. Primary Li/MnO$_2$ Nose Fuse Battery

A primary Li/MnO$_2$ nose fuse battery has been built for applications requiring a higher rate of discharge. The battery has been designed to fit into the same cavity and meet the same specifications as described in Table 1, but it provides more current (250 mA) over a -20° C to +70° C temperature range (Figure 9). The battery design consists of eight square-shaped cells. These cells are constructed using a solid winding process that employs a very thin electrode material (0.152-mm cathode and 0.076-mm anode). Each cell has a nominal voltage of 3.0 V and a nominal capacity of 166 mAh. The cells are connected in series and encapsulated to ensure high-g force and spin survivability (Figure 10).

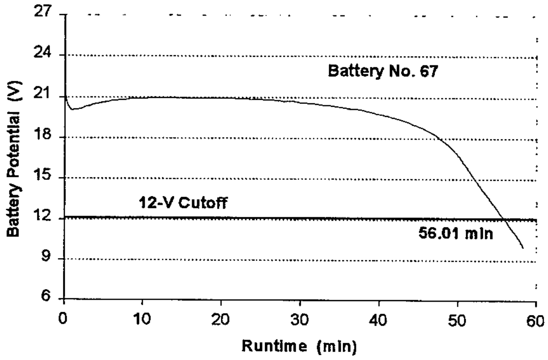

Figure 9. Li/MnO$_2$ Nose Fuse Battery Discharge at 250 mA.

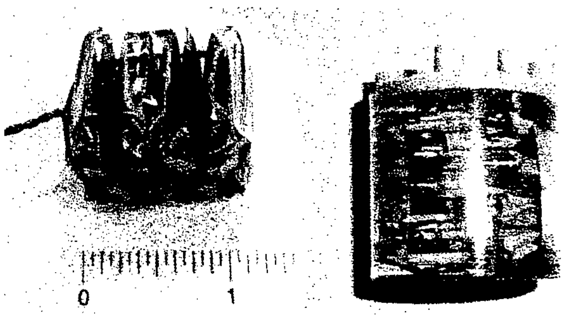

Figure 10. Unencapsulated and Encapsulated Li/MnO$_2$ Nose Fuse Batteries.

Li/MnO$_2$ nose fuse batteries have been shock-tested under load up to 30,000 g's with a high rate of success. They have also been spin-tested under load up to 300 rps, with only a minimal decrease in voltage (approximately 1 V due to radial acceleration [Figure 11]). This decrease was due to movement of the electrolyte, and changes to the electrolyte chemistry are being considered in order to limit this behavior. The batteries have also been flight-tested on an M483 artillery projectile where they were used to power a U.S. Army Research Laboratory (ARL) yawsonde instrumentation package. The battery output was monitored in flight with a multichannel telemetry system. The system load on the battery was estimated to be 130 mA, and the battery run time prior to launch was estimated at 15 min. Setback acceleration and spin were estimated at 14,000 g's and 265 rps, respectively. The flight time was roughly 52 s. Figure 12 shows the battery output in correlation with the subcarrier oscillator over the duration of the flight.

9. KE Projectile Battery

A KE projectile is a long, thin, solid rod that is used to defeat tanks in the battlefield. The only available space for instrumentation is located in the tracer-well cavity of the fins, and possibly in the nose. The volume available in a tracer-well cavity is less than 8 cm^3, and the environment for this projectile is extreme with launch accelerations over 60,000 g's and propellant flash temperatures over 2,500° C.

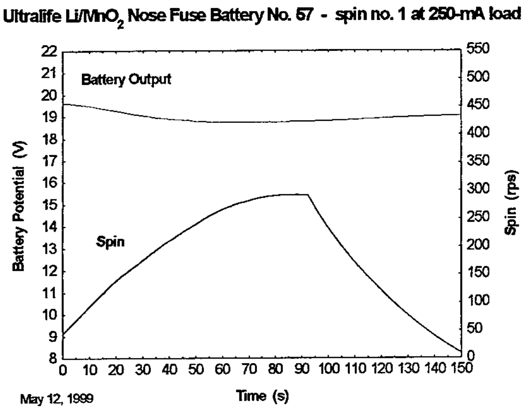

Figure 11. Spin Test of a 24-V Li/MnO$_2$ Nose Fuse Battery.

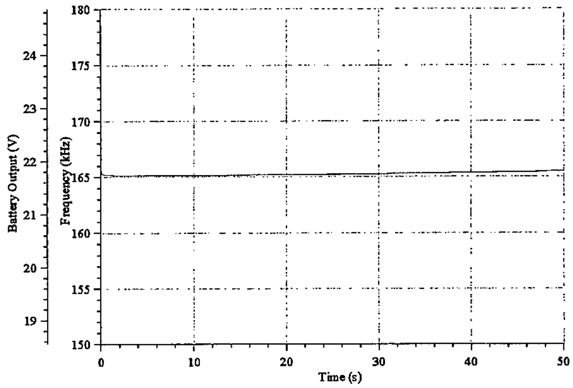

Figure 12. Flight Data of an Li/MnO$_2$ Nose Fuse Battery on an M483 Projectile.

A primary Li/MnO$_2$ battery has been developed for powering instrumentation systems on-board these projectiles. The battery has been designed to fit into the tracer-well cavity of the projectile and still meet all of the remaining design requirements shown in Table 2. After several iterations, the battery has been optimized to yield a minimum capacity of 2.5 mAh at 150 mA at room temperature and an 8-mAh minimum capacity at 80 mA at room temperature [4]. Electrical discharge testing has also been performed to verify the electrical performance of the batteries (Figure 13).

Table 2. Specifications for a Tracer-Well Battery

Battery Type	Primary Li/MnO$_2$
Dimension (Length × Width × Height)	15.5 mm × 15.5 mm × 8.9 mm
Minimum Voltage	6 V
Maximum Voltage	12.8 V
Constant Current Drain	150 mA
Minimum Duration	6 s (to Minimum Voltage)
Shock Survivability	100,000 g's
Spin Rate	100 rps
Operational Temperature	0° C to +50° C

The Li/MnO_2 tracer-well battery has been successfully flight-tested in an M735 105-mm KE projectile. The battery was used to power a telemetry system, which measured the spin history of the projectile. An exploded view of the package design is shown in Figure 14. The battery and electronic assembly were encapsulated to form a stand-alone module that could be inserted into the projectile while in the field (Figure 15). The system transmitted spin history from the projectile for about 2 s when gun-tested at Yuma Proving Ground (YPG). The system was exposed to propellant flash temperatures greater than 2,500° C and setback accelerations greater than 40,000 g's.

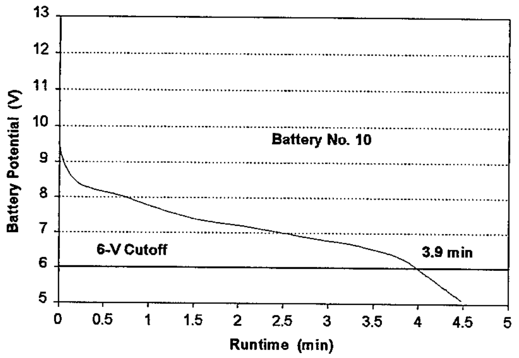

Figure 13. Li/MnO_2 Tracer-Well Battery Discharge at 150 mA.

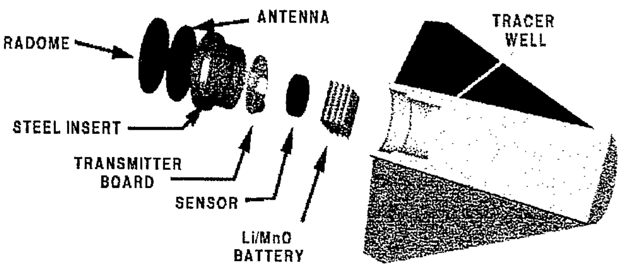

Figure 14. Package Design of an M735 105-mm KE Projectile.

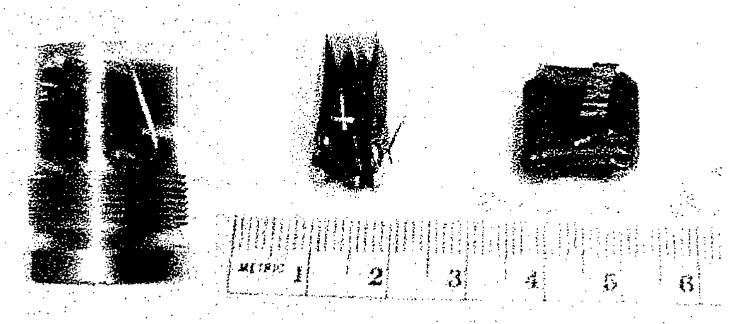

Figure 15. Encapsulated Tracer-Well Assembly and Unencapsulated Tracer-Well Batteries.

10. 2.75-in Rocket Battery

The Naval Air Warfare Center at China Lake, CA, required a rechargeable power source for their Advanced Missile Instrumentation Package (AMIP) Program. This instrumentation system consisted of a multichannel pulse code modulation (PCM) telemetry system and an ARL-designed inertial measurement unit (IMU). This instrumentation package, which is about the size of a soda can, fits into a standard 2.75-in rocket. The battery requirements are summarized in Table 3. No commercial batteries could be found to meet both the electrical and mechanical requirements. After estimating the cost of developing a custom battery using standard battery technologies, the HSTSS Program Office was contacted.

Table 3. Specifications for a 2.75-in Rocket Battery

Battery Type	Rechargeable Solid Polymer Lithium Ion
Dimension (Length × Width × Height)	31.75 mm × 86.36 mm × 10.16 mm
Minimum Voltage	11.5 V
Maximum Voltage	24 V
Constant Current Drain	700 mA
Minimum Duration	30 s (to Minimum Voltage)
Shock Survivability	500 g's (Maximum)
Spin Rate	50 rps
Operational Temperature	−10° C to +70° C

Two batteries have been designed to meet the AMIP specification. The first design used rechargeable solid polymer lithium-ion technology. This was an aggressive design for this technology because of the high rate of current required. Initial electrical testing of these cells was promising, but, over a short period of time (weeks), the cells would no longer meet the specification. It was discovered that this failure was due to an internal impedance growth problem, which caused the cells to lose capacity over time. Modifications to the processing procedures are currently being addressed to correct this problem.

In order to meet the AMIP Program deadlines, the HSTSS Program funded the development of a Li/MnO$_2$ version of the battery, shown in Figure 16. Electrical testing of these batteries was performed to verify their performance. The discharge profile for this application included 12 predischarges at 25 mA and then a primary discharge of 700 mA (Figures 17 and 18). Since operation over temperature is also very important for this application, the cells have been tested at – 10° C and +70° C and have met the specification [4].

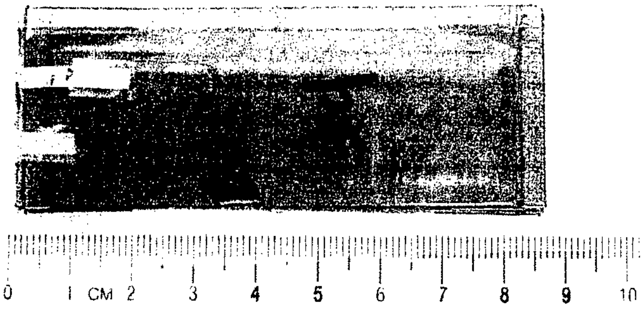

Figure 16. 2.75-in Rocket Battery.

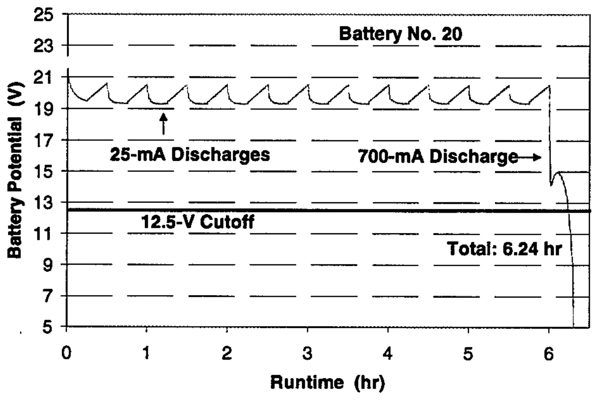

Figure 17. Li/MnO$_2$ 2.75-in Rocket Battery With 12 25-mA Discharges and a 700-mA Discharge.

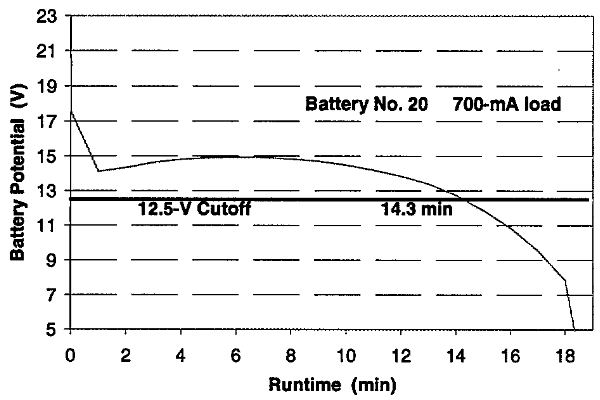

Figure 18. Exploded View of an Li/MnO$_2$ 2.75-in Rocket Battery Discharge at 700 mA.

11. Conclusion

Rechargeable, solid polymer lithium-ion batteries are being developed for ballistic telemetry applications. Prototype batteries for artillery nose fuse and rocket applications are currently being built and evaluated. Future work on this technology includes improving capacity and run time, optimizing process parameters, and modifying the electrolyte for low-temperature performance. Solid polymer lithium-ion is still a young technology and is not readily available on the commercial market.

Primary Li/MnO_2 batteries using the Ultralife Thin Cell technology are also being developed for ballistic telemetry applications. Prototype batteries have been built and successfully flight-tested on KE and artillery projectiles. Batteries are also being built for rocket applications. Future work on this technology includes improving shelf life, modifying the electrolyte for improved performance in high-spin applications, and designing internal safety features such as a shut-down separator.

The prototype batteries described in this paper have been designed for use with existing commercial telemetry subsystems. Typical working voltages for these products range from 12 to 24 V. Future HSTSS products are being designed to operate at much lower voltages (3 to 5 V). This will allow for more efficient battery designs that can fully utilize the packaging flexibility of both battery technologies.

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13. ABSTRACT *(Maximum 200 words)*

The rapid growth in portable and wireless communication products has brought valuable advancements in battery technology. No longer is a battery restricted to a metal container in cylindrical or prismatic format. Today's batteries (both primary and secondary) can be constructed in thin sheets and sealed in foil/plastic laminate packages. Along with improvements in energy density, temperature performance, and environmentally friendly materials, these batteries offer greater packaging options at a significantly lower development cost. Under the Hardened Subminiature Telemetry and Sensor System (HSTSS) Program, these battery technologies have been further developed for high-g telemetry applications. Both rechargeable solid-state lithium-ion polymer and primary lithium manganese dioxide (Li/MnO_2) batteries are being developed in conjunction with Ultralife Batteries, Inc. Prototypes of both chemistries have been successfully tested in a ballistic environment, while providing high constant rates of discharge, which is essential to these types of applications. Electrical performance and environmental data are reported.

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