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# Lithium-ion batteries for hearing aid applications
## II. Pulse discharge and safety tests

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## Abstract

Rechargeable lithium-ion batteries were designed to meet the power requirements of hearing aid devices (HADs). The batteries were designed in a 312-button cell size, compatible with existing hearing aids. The batteries were tested to evaluate the design and the electrochemical performance, as they relate to a typical hearing aid application. The present report covers the pulse capabilities, cycle life and preliminary safety tests. The results are compared with other battery chemistries: secondary lithium-alloy and nickel–metal hydride batteries and primary Zn–air batteries. The cell AC impedance was stable over the frequency range between 1 and 50 kHz, ranging between 5 Ω at the higher frequency and 12 Ω at the lower extreme. Pulse tests were consistent with these values, as the cells were capable of providing a series of 100 mA pulses of 10-s duration. The safety tests suggest that the design is intrinsically safe with respect to the most common types of abuse conditions. © 2000 Elsevier Science S.A. All rights reserved.

*Keywords:* Li-ion button cell; Hearing aid cell; Hearing aid; Safety

## 1. Introduction

The objective of this paper is to report on the further characterization of a new-design lithium-ion battery for hearing aid device (HAD) applications. The new-design battery (Model 312A) was proven to perform in a consistent manner when compared with the larger commercial-size lithium-ion batteries, in terms of specific energy and energy density [1].

During the past 10 years, laboratories around the world have actively developed rechargeable lithium-based battery technologies to satisfy the ongoing demand of electronic consumer products for more energy in smaller packages. However, no lithium-based rechargeable cells are available in hearing aid sizes. Most of the commercially viable cells are based on the lithium-ion concept, which does not contain metallic lithium. In this type of cell, lithium ions are shuttled between two intercalation compounds through a supported liquid or a gel electrolyte (i.e., a semisolid, solvent-loaded polymer electrolyte) [1–3].

Lithium-ion batteries are well established in the market. Due to their superior performance compared to other battery chemistries, the lithium-ion battery market is experiencing rapid growth [4]. The price of lithium-ion batteries is expected to come down because of increased production volumes and economies of scale, which will make them more price competitive, and lead to increased demand throughout the next decade. Commercial batteries based on the Li-ion concept have been in production by Sony since 1990 [3]. These cells have a specific energy of 110 W h/kg and an energy density of 250 W h/l. Their cycle life has been demonstrated out to beyond several hundred full, 100% DOD cycles. Today, several multinational companies produce lithium-ion batteries for commercial purposes [4,5]. All systems are based on carbonaceous materials (graphite or amorphous carbons) as the negative electrode and lithiated cobalt, nickel or Co–Ni mixed oxides as the positive electrode. The electrodes are separated by one or more layers of plastic film, made of micro-porous polyethylene and/or polypropylene that are impregnated with an electrolytic solution. A comparison of five commer-

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cially available (18650 size) lithium-ion batteries from different producers (Sony, Sanyo Electric, Matsushita Electric Industrial, Moli Energy and A&T Battery), has recently been published [6].

In a previous work [1], the authors demonstrated the feasibility of lithium-ion batteries for HAD applications. The batteries developed had typical lithium-ion chemistry with the common structure that may be depicted as:

$$(-)\mathrm{Cu}/\mathrm{C(graphite)}\|1\,\mathrm{M\,LiAsF_6\ in\ EC} \\ -\mathrm{DMC}\,50{:}50\|\mathrm{LiCoO_2}/\mathrm{Al}(+).$$

The batteries fulfilled the requirements for HAD applications in terms of capacity, rate performance and cycle life [1]. In this paper we report the results on the characterization of the pulse capability of this battery from the point of view of a typical HAD application. A typical cycle for a HAD battery consists of a low power (1 mW) discharge for 16 h (normal waking period). Power pulses as high as 6 mW and as long as 1 s, superposed on the low power discharge, are required for high level sound amplification. The total capacity required for a day of operation is about 18 mW h. The daily discharge is followed by an overnight charge of 1 to 8 h at the respective power levels of 18 to 2 mW. The pulse requirement is very stringent. A HAD battery must be able to supply the required power without any dramatic change of the output voltage. The use of a battery chemistry that provides an average output voltage of 3.6 V gives the advantage of reducing the pulse current by a factor of three as compared to the commercially available 1.2 V cells.

In this paper, we also report the results of preliminary safety characterization. The safety of lithium-ion batteries is a very important issue. From a thermodynamic point of view, lithiated carbonaceous materials are as reactive as metallic lithium. Fully lithiated graphite and amorphous carbon electrodes exhibit potentials that are within a few millivolts of metallic lithium. Although some characteristics of carbonaceous materials make them intrinsically safer than lithium metal, e.g., the high melting point of $\mathrm{LiC_6}$ (> 700°C) as compared to that of pure metallic lithium (180°C), it is clear that safety is a key issue that must still be taken into account for carbon-based, rechargeable lithium ion batteries. Thermal runaway is one of the most-likely modes of accidental failure. Overheating during normal cell operation (charge and discharge) or because of mechanical, electrical or thermal abuse will cause pressure build-up in the cell. If such an event is not controlled, it could result in the accelerated leakage of flammable liquids and/or gases.

Several pre-pilot HAD batteries were used for the present tests. For comparison purposes, commercial cells based on the lithium-alloy anode/ vanadium oxide, zinc/air (Zn–air) and nickel/metal hydride (Ni–MH) chemistries were also tested. The latter two were hearing aid cell designs whereas the lithium cell was a low rate, rechargeable coin cell.

## 2. Experimental

The 312A cell design [1] was developed to meet the power and shape requirements of a typical hearing aid battery. A complete description of the 312A battery, including the container, the battery stack and other components, as well as the assembly procedure are given elsewhere [1,7]. The battery is a typical squat, cylindrical cell (button cell) with a diameter of 7.95 mm and a height of 3.6 mm. The total (external) cell volume was about 0.18 $\mathrm{cm}^3$. These dimensions are very close to those of the standard 312 HAD batteries. The approximate weight of the 312A battery was about 0.45 g ($\pm$0.02 g). The case and the lid were the two terminals of the battery. The case, electrically connected to the cathode by the cathodic tab, was the positive pole of the battery while the lid, electrically connected to the anode by the anodic tab, was the negative pole.

The electrochemical tests were run with a fully computerized battery cycler (Arbin) and EGG potentiostat/galvanostat (model 273). A frequency response analyzer (Solartron FRA model 1260) was used in conjunction with a potentiostat (Solartron ECI model 1287) to perform the impedance measurements.

To perform the safety tests, the batteries were placed in a stainless steel tube, 2 in. wide and 6 in. long, with one end sealed. The hot plate test was performed by placing the battery directly on a hot plate. Omega thermocouples connected to an A/D card on a Macintosh computer were used to measure the temperature of the batteries during the tests. The temperature-measurement system was calibrated in ice/water (0°C) and boiling water (100°C). The calibration gave accuracy on the temperature measurements of about ±2°C with a fast response (a few seconds) upon temperature changes of 100°C.

## 3. Results & discussion

### 3.1. AC impedance measurements

Impedance measurements were performed on the 312A and the reference batteries (Ni–MH, Li-alloy and Zn–air) to evaluate the impedance in the audio frequency range (50 kHz–1 Hz).

The results are shown in Fig. 1, which displays the impedance modulus vs. the frequency (panel A) and the imaginary component vs. the real component of the impedance (panel B). The batteries were first discharged to about 10% depth of discharge (DoD) before the tests. The 312A battery impedance was quite stable throughout the whole frequency window. In fact, it ranged from 5 Ω at 50 kHz to 12 Ω at 1 Hz. The low frequency value is in good agreement with the calculated instantaneous DC impedance (described in later sections of this paper). The impedance of the commercial size 1620 coin cell that ranged from 20

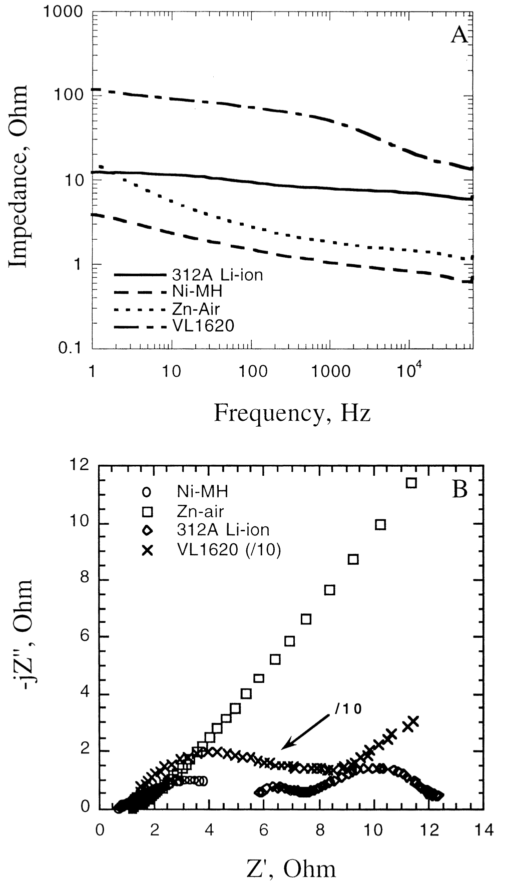

Fig. 1. Impedance vs. frequency (panel A) and real vs. imaginary plot (panel B) of 312A cell and reference batteries. The batteries were discharged to 10% DoD prior to testing. Amplitude of sinusoidal signal: 10 mV. To fit all spectra in the same plot window (panel B), the real and the imaginary parts of the impedance of the VL1620 battery have been divided by a factor of 10.

to 110 Ω over the same frequency window. On the other hand, both the Zn–air and the Ni–MH cells showed smaller impedance at 50 kHz. At lower frequencies, the impedance of the Zn–air cell increased to end above the impedance of the 312A cell. Such a steep change may be associated with the diffusion of an electroactive specie (oxygen) into the electrode, as indicated by the straight line with a 45° slope seen in the plot of Fig. 1B. In contrast, the Ni–MH battery did not show any diffusional impedance contribution and its impedance modulus always remained smaller than that of the 312A battery. As indicated by the difference in the high frequency intercepts of the impedance on the real axis (Fig. 1B), this is mostly due to the higher conductivity of the aqueous electrolyte ($R = 0.6\ \Omega$) of the Ni–MH battery when compared with the organic electrolyte ($R = 5.9\ \Omega$) of the 312A battery.

### 3.2. Pulse discharge characterization

Several pulse discharge tests were performed to evaluate the capability of the 312A batteries to perform as a rechargeable power source for HADs. A hearing aid cell needs to supply power pulses during normal discharge at a current equivalent to 0.3–1 mA (at 1.25 V). Both constant current and constant resistive load tests were performed.

Table 1
High power pulses (step 5) on constant current discharge (step 4) test schedule. The rates quoted are calculated with the capacity delivered by the battery during the first discharge (step 2)

| Step | Current, mA | *C* rate | Time limit, s | Iteration | Voltage cut-off V |
|---|---|---|---|---|---|
| (1) Charge | 3 | *C*/2.5 | none | no | 4.1 |
| (2) Discharge | 2 | *C*/3.7 | none | no | 2.75 |
| (3) Charge | 3 | *C*/2.5 | none | no | 4.1 |
| (4) Discharge | 2 | *C*/3.7 | 8 | no | 2.75 |
| (5) Pulse | 10 | 1.3*C* | 2 | step 4 | 1.5 |

### 3.2.1. Constant current 10 mA pulses during 2 mA background discharge

The test schedule, composed of five steps, is summarized in Table 1. For comparison purposes, the schedule included a full constant-current cycle (steps 1 and 2). The *C* rate quoted in the table was calculated from the delivered capacity of 7.5 mA h determined in the first discharge cycle (step 2).

The performance of the 312A button cell during pulse discharge is illustrated in Fig. 2. For comparison purposes a 2 mA discharge of the same cell is also reported in the figure. The most important result of the test is easily seen in the figure: the capacity delivered by the battery during the pulse discharge test coincides with the capacity delivered during the constant current discharge. This clearly indicates that the 312A button cell can sustain 10 mA pulses without any major change of performance in terms of delivered capacity. The delivered energy during the pulse discharge was 25.8 mW h, almost 96% of the energy delivered in the constant current cycle and about 45% more than the energy required by an HAD for a full day of operation.

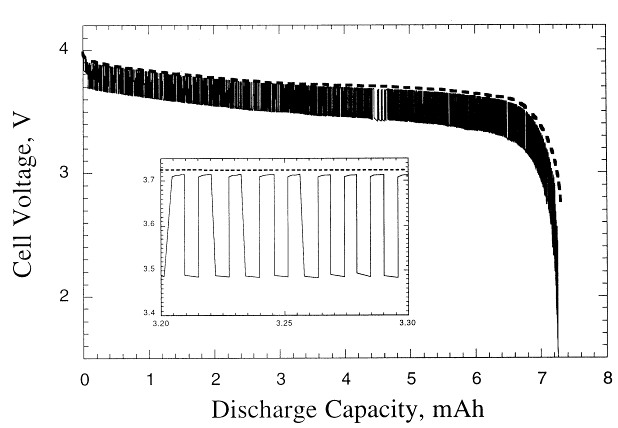

Fig. 2. Constant current pulse test. Cell voltage vs. delivered capacity for a 312A cell during a 10 mA pulse discharge (solid line) and a 2 mA constant current discharge (dashed line). The inset shows a magnification of the curves. For test details see Table 1.

In Fig. 2 is also shown a magnification of the cell voltage at about 40% DoD. A voltage drop of about 200 mV is associated with the 10 mA pulses. This corresponds to an internal resistance of approximately 20 Ω, in reasonable agreement with the impedance measurements. Further, as shown by the IR drop in Fig. 2, the cell internal resistance does not change greatly throughout the discharge. The voltage behavior during the current pulse is almost flat, thus indicating the absence of diffusional limitations in the electrodes on the time scale of the current pulse (2 s). During the pulse-off time, the cell voltage recovered to within a few millivolts of the value measured during the constant current discharge.

The results of this test clearly indicate the capability of the 312A battery to supply high rate pulses on top of a low level background load. The 312A button cell was able to sustain the test with very good performance in terms of the delivered capacity, the energy output and the internal impedance.

### 3.2.2. *High rate pulse test with resistive load*

The test consisted of alternately loading and unloading the 312A battery with a constant ohmic load. The battery, initially in open circuit conditions, was connected to the ohmic load (30 or 70 Ω) for 10 s and then it was left to relax on open circuit for 15 s. These latter two steps were repeated four times. The results of the test, illustrated in Fig. 3, clearly show the capability of the battery to sustain repeated current pulses of as high as 100 mA (3 V output over 30 Ω load) for 10 s. This current corresponds to a discharge rate of greater than 10 C. The load voltage during such high current pulses decreased less than 1 V, relative to the open circuit potential.

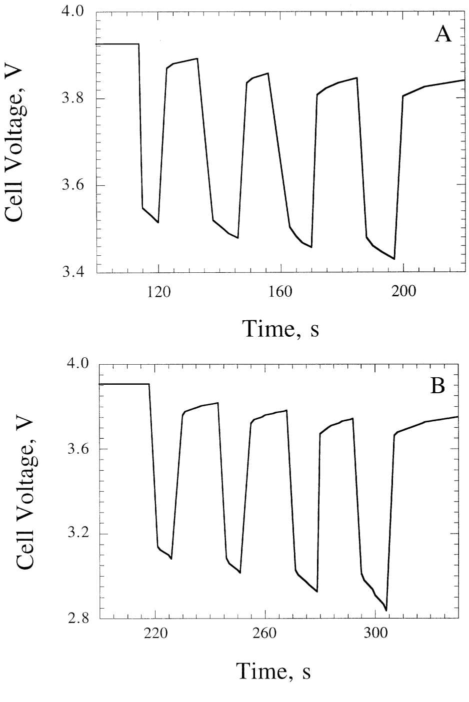

Fig. 3. Constant resistance pulse tests. 312A cell voltage behavior during nominal 50 and 100 mA pulse discharge (10 s) on 70 Ω constant load (panel A) and 30 Ω constant load (panel B). The 10-s pulses were alternated with open circuit rest periods of 15 s.

Table 2
Pulse-train test schedule

| Step | Current, mA | Time limit, s | Iteration |
|---|---|---|---|
| (1) Background discharge | 0.5 | 1800 | no |
| (2) 1st pulse | 2.0 | 10 | no |
| (3) Background discharge | 0.5 | 10 | no |
| (4) 2nd pulse | 5.0 | 10 | no |
| (5) Background discharge | 0.5 | 10 | no |
| 6. 3rd pulse | 10 | 10 | step 1 |

### 3.2.3. *Pulse-train test*

This test consisted of discharging the battery by repeatedly applying a train of pulses on a low background discharge. Each train of pulses was composed of six steps as shown in Table 2. The pulse train was repeated until the cell voltage hit the lower voltage cut-off limit. The battery was then recharged at a constant current (3 mA). The charge voltage limit was selected at 4.0 V. This resulted in a reduction of the delivered capacity to a maximum of 6.5 mA h, i.e., still larger than the requirement for hearing aid applications (5 mA h).

The 312A battery was able to deliver the current pulses throughout the whole discharge. The cell voltage behavior during the current pulses remained almost constant up to 6 mA h of delivered capacity. A magnification of the pulse load behavior for the 312A cell at a 50% DoD is shown in the upper plot of Fig. 4. The voltage drop is proportional to the current. The ratio between these two quantities, i.e., the instantaneous DC resistance, is approximately 10 Ω. In the same figure are also reported the cell pulse load behavior for a Ni–MH and a Zn–air hearing aid cell. The Zn–air battery exhibited some difficulty in delivering the current pulses. The high voltage drops seen in the figure correspond to an instantaneous DC resistance of 20 Ω for this cell. On the other hand, the Ni–MH battery showed the best capability to deliver the current pulses with an instantaneous DC resistance of only about 6 Ω. These results are in full agreement with the impedance measurements.

### 3.2.4. *Constant power pulse discharge test*

This test was performed to compare the pulse performance of the 312A cell with the reference batteries in terms of delivered energy at the same power. It consisted of the application of high constant power pulses on a low power background discharge. The test consisted of two discharge steps. The first step consisted of the application of a 0.6 mW background load for 585 s followed by (2nd step) a 4.7 mW pulse load for 15 s. The two steps were

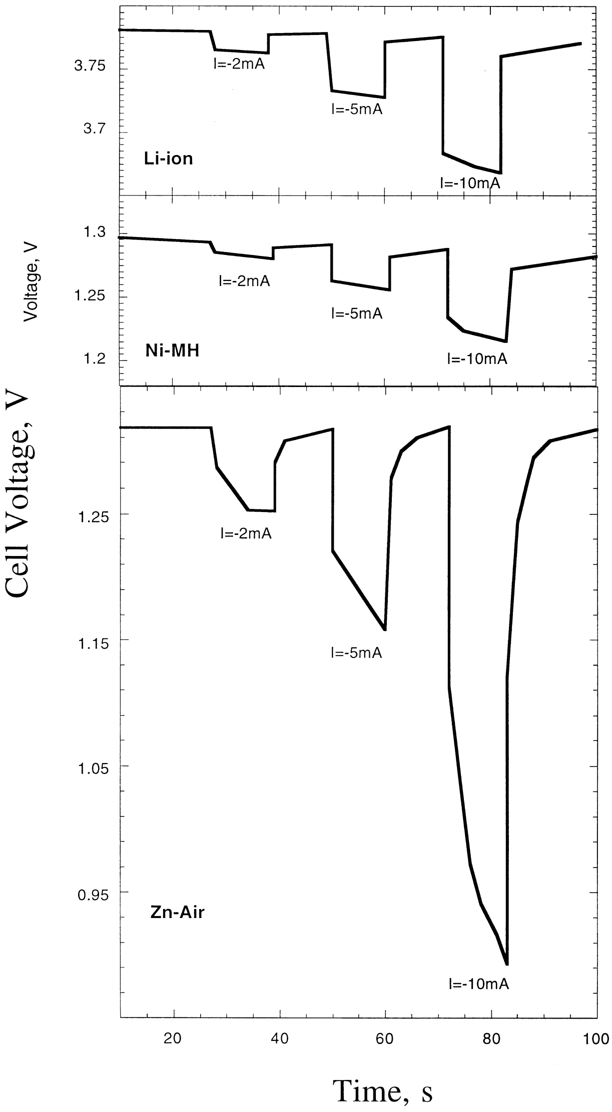

Fig. 4. Constant current pulse tests. Comparison of the cell voltage upon pulse discharge for the 312A cell and the reference batteries (Ni–MH and Zn–air). Details of the test schedule are given in Table 2.

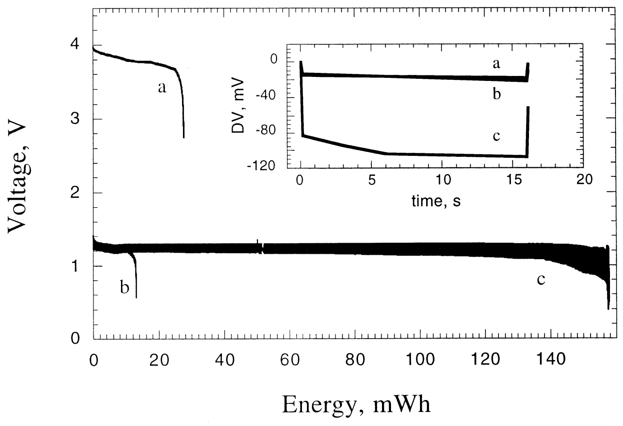

Fig. 5. Constant power pulse tests. Comparison of the voltage vs. delivered energy for the 312A cell and the reference batteries (Ni–MH and Zn–air) at equivalent power levels. Low power step: 0.6 mW for 585 s. High power step: 4.7 mW for 15 s.

repeated until the battery was fully discharged, i.e., the low voltage limit was reached.

The results of this test on the 312A cell as well as on the Ni–MH and Zn–air batteries are shown in Fig. 5. In this figure, the cell voltage is plotted vs. the delivered energy (for a single cycle). The width of each curve is proportional to the voltage drop during the high power pulses. Magnifications of the voltage drop occurring in the three batteries upon a single pulse at 50% DoD is reported in the inset. Both figures show that the Zn–air battery had a larger voltage drop when delivering the high power pulses. The 312A Li-ion cell and the Ni–MH cell performed very well without any substantial difference. The comparison shows the importance of the battery output voltage. Although the 312A battery has a larger impedance than the Ni–MH one (see earlier), the discharge current needed to provide a fixed power pulse with a higher voltage output is smaller, thus substantially reducing the effect of the ohmic drop on the cell voltage.

### *3.2.5. Pulse discharge cycle life*

The cycle life of the 312A cells during a pulse discharge was investigated on two batteries. The test consisted of discharging the batteries with a 1-mA background current ($C/9$) on top of which 10 mA current pulses were applied. The discharge cycle was terminated when the battery delivered 5 mA h or the battery voltage hit the cathodic cut-off limit. A detailed description of the test schedule is given in Table 3. The delivered capacity (5 mA h) corresponded to about 60% of the full capacity of the batteries used in the test. The batteries were then charged with a constant current of 3 mA ($C/3$) up to a 4.0 V cut-off voltage. The low voltage cut-off was chosen to prevent electrolyte or cathode decomposition. The intensity of the pulses is approximately five times larger than the required value for normal operation in a hearing aid. Such high rate pulses are extremely stressful to the cell, as required for an accelerated life test. In addition, the overall charge/discharge procedure used corresponds to at least an acceleration of the normal cycle of a HAD battery by a factor of about four. Four simulated daily cycles were completed in 24 h. With an average cell discharge voltage

Table 3
Pulse discharge over a constant current background test schedule used for the 312A-battery life evaluation

| Step | Current, mA | $C$ rate | Time limit, s | Iteration | Voltage cut-off, V |
|---|---|---|---|---|---|
| (1) Charge | 3 | $C/3$ | none | no | 4.0 |
| (2) Discharge | 1 | $C/9$ | 600 | no | 2.75 (step 4) |
| (3) Pulse | 10 | 1.1$C$ | 10 | step 2 (26) | 2.75 (step 4) |
| (4) Charge | 3 | $C/3$ | none | step 2 | 4.0 |

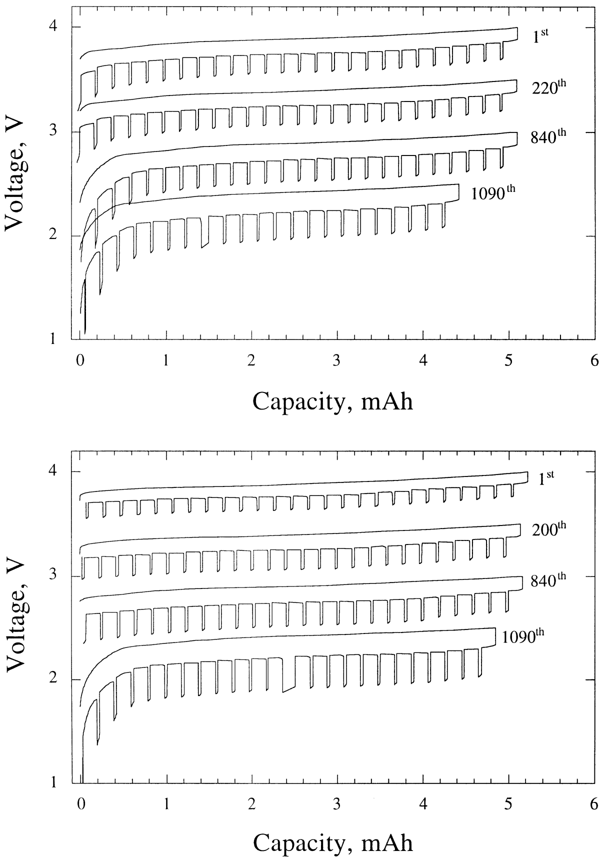

Fig. 6. Cell voltage vs. capacity plots of two 312A batteries in four different cycles (see legend). Details of the test schedule are given in Table 3. For clarity, the voltage values of the succeeding cycles are displaced. End-of-charge voltage was always 4.0 V for each charge cycle.

of 3.7 V (see first cycles in Fig. 6), this capacity corresponds to more than 18 mW h, i.e., the daily energy requirement of a typical HAD.

The two 312A batteries were tested for over a year. Since the discharge capacity of the batteries is fixed, important information can be obtained only by comparing the behavior of the cell voltage during the full charge and discharge cycle. In Fig. 6 is shown the cell voltage vs. capacity behavior of the 312A batteries in four different cycles during the test. (The plotted voltages for the three later cycles of each cell are displaced in voltage for clarity. All of the charge curves terminate at the same voltage of 4.0 V). The two batteries performed very well. They were able to deliver the requested capacity (5 mA h) without any problem even beyond 800 cycles. Upon further cycling the cells behaved differently by showing a substantial decrease of the end-discharge and initial-charge voltages. This indicates that the cell was not fully recharged within the charge cut-off limit selected. The insufficient charge cut-off voltage is in agreement with the results seen earlier [1]. Unfortunately, when the long-term cycle test was started the other information on the 312A batteries was not available.

It is worth noting that in this test the 312A batteries were charged in less than 2 h. Such a fast charge time is certainly significant for hearing aid applications. In only 10 min, it is possible to charge the 312A battery sufficiently to allow 2–3 h of normal operation. Thus, if the hearing aid users had neglect to charge the hearing aid at night, they could charge it in the morning and in 30 min put in enough capacity for about 6 h of use.

### 3.3. Safety evaluation

Preliminary safety tests were performed on the rechargeable, lithium-ion 312A batteries. The tests were oriented to characterize the response of the batteries to the most common misuses. Although the tests performed were only a fraction of those required to verify the safety of a lithium-ion battery for commercial purposes, the results illustrated in this paper can be used to partly assess the safety of the 312A batteries.

### 3.3.1. Safety evaluation test specifications

Table 4 summarizes the tests devoted to the evaluation of the response of the 312A batteries to the most common misuses. The list of tests is not exhaustive.

*3.3.1.1. Hot plate*. This test is intended to demonstrate the behavior of the battery during overheating. It consists of placing a 312A battery on a hot plate at 150°C and following the temperature profile of the battery.

*3.3.1.2. Overcharge*. Overcharge tests demonstrated the behavior of the 312A batteries as a result of an accidental overcharge. The first test consisted of applying a constant

Table 4
Safety evaluation tests performed on 312A batteries

| Test | Test type | Action | Observations |
|---|---|---|---|
| 1 | Thermal | Hot plate (150°C) | Integrity of the cell temperature |
|  | Electrical | Overcharge |  |
| 2 |  | 100 mA | Integrity of the cell, voltage, current, temperature |
| 3 |  | 10 V | Integrity of the cell, voltage, current, temperature |
|  | Electrical | Overdischarge |  |
| 4 |  | − 100 mA | Integrity of the cell, voltage, current, temperature |
| 5 |  | − 10 V | Integrity of the cell, voltage, current, temperature |
| 6 | Electrical | Short circuit | Integrity of the cell, voltage, current, temperature |

current of 100 mA to the batteries. The second test consisted of the application of a constant voltage (+10 V).

*3.3.1.3. Overdischarge.* Two tests were performed to verify the behavior of the 312A batteries as a result of an accidental overdischarge. The first test consisted of applying a constant current of 100 mA to the battery. The second test consisted of the application of a constant voltage (−10 V).

*3.3.1.4. Short circuit.* This test was performed by connecting the 312A battery to a potentiostat at 0 V. This is equivalent to shorting the battery through a very small resistance (0.1 Ω).

All tests were executed in a safe environment under a fume hood. The batteries were placed in a stainless steel tube, 2 in. wide and 6 in. long, with the exception of the hot plate test that was performed by placing the battery directly on a hot plate. The temperature of the batteries under test was recorded by using thermocouples connected to an A/D card on a Macintosh computer. The temperature-measuring system was characterized by a fast response (a few seconds) to temperature changes of up to 100°C.

### 3.3.2. Safety evaluation test results

*3.3.2.1. Hot plate test.* In Fig. 7 is reported the temperature profile of a 312A battery subjected to the hot plate test. The battery temperature rose quickly from RT to 70°C and then more slowly up to 140°C. The increase in temperature caused a build-up of internal pressure that resulted in the spontaneous disassembly of the battery after 110 s. The lid with the gasket and the battery stack were expelled.

*3.3.2.2. Overcharge tests*

*Constant current (100 mA).* In Fig. 8 are reported the voltage and the temperature of a 312A battery during a prolonged overcharge at the 12*C* rate. A constant current of 100 mA was applied to the cell. The battery voltage reached a plateau at about 5 V in a few minutes. After about 3 h, the voltage decreased to 4.4 V. A substantial temperature change was detected during the experiment. The temperature went up to 63°C in the initial 3 h and then stabilized at about 57°C. At the end of the experiment, the lid and the gasket were out of the battery case. The weight loss was approximately 28 mg. The battery did not show any voltage but still maintained an infinite DC resistance. This indicated that the battery was not in short circuit.

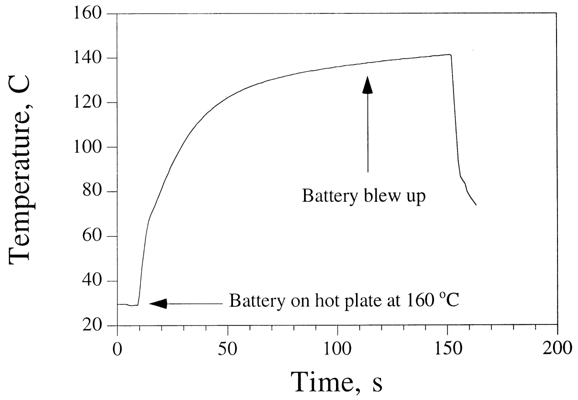

Fig. 7. Temperature behavior of a 312A battery during the hot plate test.

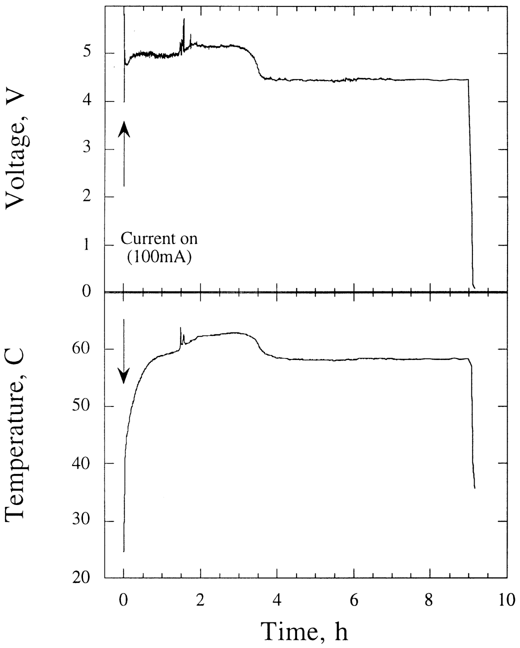

Fig. 8. Voltage and temperature of a 312A battery during the 100 mA constant current overcharge test.

*Constant voltage (10 V).* In Fig. 9 are reported the current and the temperature as recorded on a 312A battery during a prolonged overcharge at a constant potential of 10 V applied to the cell. At the beginning of the test, the current was about 300 mA and then it decreased to a plateau of about 50 mA in 30 min. After about 3 h, the test was stopped. A substantial temperature change was detected during the experiment. The temperature went up to 85°C within a few minutes of the start of the test and it stabilized at about 65°C after 1 h. At the end of the experiment, the battery did not show any external damage. The weight loss was approximately 37 mg. At the end of the experiment, the battery showed an open circuit voltage of about 0.2 V with an almost infinite DC resistance. This indicated that the battery was not in short circuit.

*3.3.2.3. Overdischarge tests*

*Constant current (−100 mA).* In Fig. 10 are reported the voltage and the temperature as recorded on a 312A battery during an overdischarge. A discharge current of

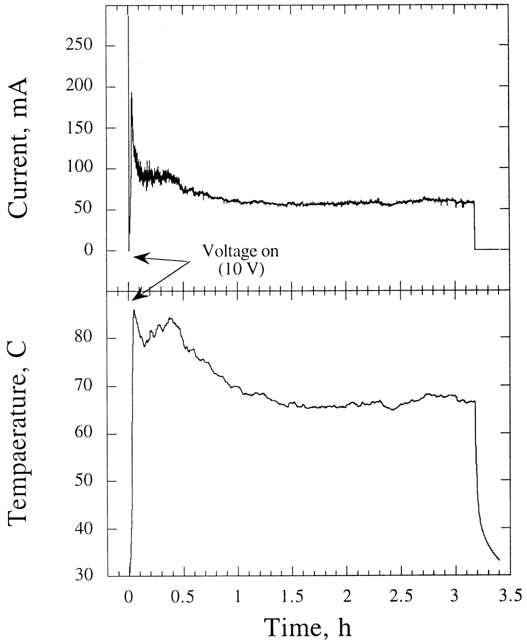

Fig. 9. Current and temperature of a 312A battery during the 10 V constant voltage overcharge test.

−100 mA was maintained through the cell. The battery voltage reached −7 V in a few seconds and then it slowly decreased to −2 V. In a similar way, the temperature went up to 51°C in 2 min and then slowly decreased towards room temperature. At the end of the experiment, the lid and the gasket were out of the battery case. The weight loss was approximately 5 mg. At the end of the experiment, the battery did not show any voltage and a 300 Ω DC resistance. This indicated that the battery was in short circuit.

*Constant voltage (−10 V).* In Fig. 11 are shown the current and the temperature of a 312A battery during an overdischarge test. A constant potential of −10 V was applied to the battery. At the beginning of the test, the current showed a few peaks as high as −1500 mA. The electrical contact inside the cell went off and on a few times until a short circuit took place within the battery. The current stabilized at −1100 mA that corresponded to the maximum current the equipment could supply in steady state condition. A substantial temperature change was detected during the experiment. The temperature went up to 80°C in 1 min from the beginning of the test and then it increased more slowly because of the Joule effect. At the end of the experiment, the battery did not show any external damage. The weight loss was approximately 14 mg. The cell did not show any voltage and exhibited a DC resistance of 3000 Ω. This indicated that the battery was in short circuit.

*3.3.2.4. Short circuit test.* The current and the temperature of a 312A battery during a short circuit test are shown in Fig. 12. The cell was shorted through a low impedance (0.1 Ω) current meter. At the beginning of the test, the current was about −850 mA and then it decreased to reach a plateau at about −50 mA in 5 min. A small temperature change was detected during the experiment.

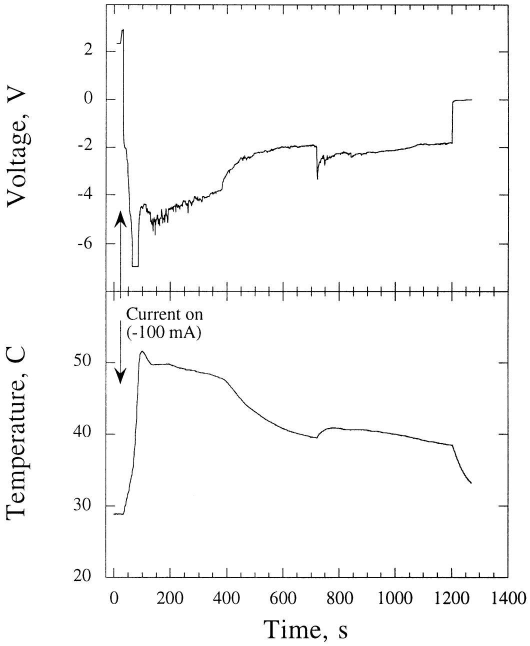

Fig. 10. Voltage and temperature of a 312A battery during the −100 mA constant current overdischarge test.

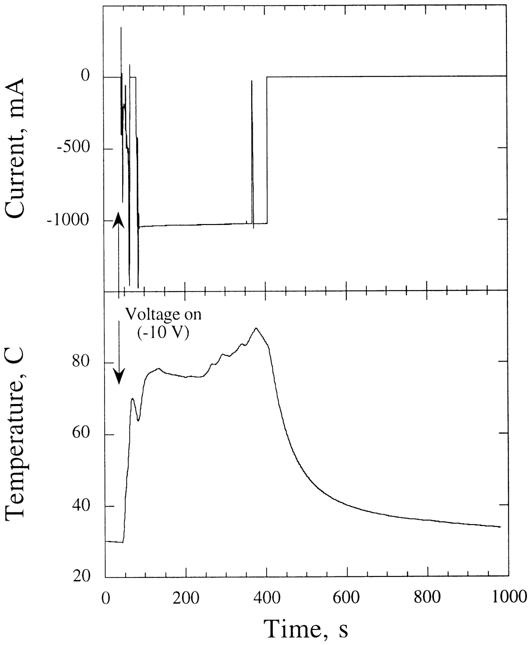

Fig. 11. Current and temperature of a 312A battery during the −10 V constant voltage overdischarge test.

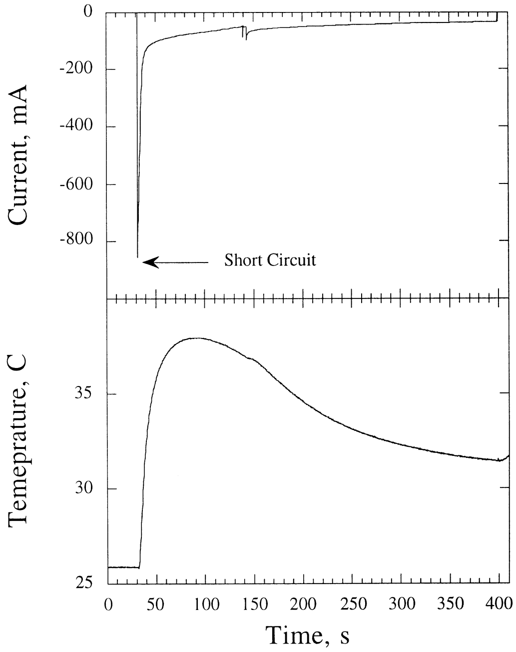

Fig. 12. Current and temperature of a 312A battery during the short circuit test.

The temperature went up to 38°C within a few seconds from the start of the test and then it decreased towards room temperature. At the end of the experiment, the battery did not show any external damage and no weight loss was detected. The battery showed an open circuit voltage of about 2.5 V with an almost infinite DC resistance.

### *3.3.3. Summary of safety evaluation tests*

The results of these preliminary safety tests indicate that the 312A battery design is intrinsically safe with respect to the most common types of abuse. None of the batteries under test went on fire or exploded with fragments. The fast ejection of the case and the lid was observed only during the hot plate test. Even in this case no fire was seen. The short circuit test did not cause any damage to the case or the gasket. The battery voltage recovered after the test and no weight loss was detected.

In all the other tests, the gas evolving from the electrolyte decomposition was released through the sealing gasket without any major deformation of the battery case. In a few cases, the lid assumed a dome-like shape and this facilitated the release of the internal pressure.

## 4. Conclusions

The 312A lithium-ion cell that has been recently developed exhibited very good performance during pulse-discharge tests. The batteries satisfied all of the requirements for powering HADs, including the battery life under operating conditions.

With respect to safety, the preliminary test results indicate that the 312A battery design is intrinsically safe with respect to the most common types of abuse. None of the batteries under test caught on fire or exploded with fragmentation. The fast ejection of the case and the lid was observed in only one test (hot plate). Even in this case no fire was seen.

The overall conclusion from this evaluation of the pulse discharge behavior and the abuse testing of the 312A Li-ion cell is that the cell meets the requirements of a rechargeable hearing aid. No commercial rechargeable Li-ion hearing aids are available although Li-ion batteries are in use in many consumer products such as camcorders, cellular phones and notebook computers. The battery technology is now available to enable the realization of greatly improved rechargeable hearing aids that would combine higher safety, ease of use, cost savings and improved performance.

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