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Preliminary evaluation of rechargeable lithium-ion cells for an implantable battery pack

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Abstract

A preliminary evaluation of the performance characteristics of 1.08 Ah lithium-ion cells was undertaken utilizing operating conditions similar to that required for an implanted medical device, such as a ventricular assist device or total artificial heart, in order to determine their potential usefulness for this application. The major parameters studied at 22 or 37 °C were discharge-rate capability, specific energy and energy density, surface temperature, self-discharge and cycle life. The discharge loads used in the cycle-life study were either constant or pulsatile, with the constant discharge load being equivalent to the average of the pulsatile load. The lithium-ion cells showed high discharge-rate capability up to 1.5 A at 37 °C, with over 74% of their rated capacity being obtained and a midpoint voltage of over 3.3 V (> 72% of rated capacity and > 3.3 V for up to 1.0 A discharges at 22 °C), before the first indication of cell polarization was noticed. The specific energy and energy density of cells discharged at 0.88 A to 2.5 V at 37 °C was 73 Wh/kg and 190 Wh/l, respectively (64 Wh/kg and 167 Wh/l at 22 °C). The internal resistance of the cells was calculated to be 198 mΩ at 37 °C (316 mΩ at 22 °C), which resulted in a relatively high, 8.0 °C, increase in surface temperature under a 0.88 A discharge load. The self-discharge of the cells at 37 °C was relatively low, with only a 1.3% loss in capacity being observed after 24 h. The lithium-ion cells yielded longer cycle lives at 37 °C (2 239 cycles) compared with 22 °C operation (1539 cycles) under similar 0.88 A discharge loads. The cells performed slightly better under constant discharge loads than under pulsatile loads of equivalent average current (0.83 A average) with cycles lives of 2279 cycles versus 1941 cycles and operating times were 1.6 ± 1.1 min (mean) longer. Preliminary indications are that these lithium-ion cells would be suitable for use in a rechargeable battery pack capable of powering implanted medical devices.

Keywords: Rechargeable lithium-ion cells; Implantable devices

1. Introduction

The reported high specific energy (99 Wh/kg) and energy density (236 Wh/l), as well as long cycle life (> 1200 cycles), of the recently commercialized lithium-ion battery cells [1] has generated interest for their use in small, lightweight, rechargeable battery packs capable of powering implanted medical devices such as a ventricular assist device (VAD) and total artificial heart (TAH). These devices, and VADs in particular, are nearing commercialization with reliability, animal and human trials presently being undertaken [2–6].

The operating conditions and requirements of an implanted, rechargeable battery pack are unique and are not normally part of the specifications published by the manufacturer. These requirements are as follows:

(i) safe, stable cell chemistry at 37 °C that can be hermetically enclosed;
(ii) high specific energy and energy density;
(iii) high discharge rate capability at 37 °C;
(iv) high capacity, i.e. long operating time, at 37 °C;
(v) long cycle life at 37 °C;
(vi) low self-discharge at 37 °C;
(vii) low internal resistance and surface temperature at high discharge rates;
(viii) state-of-charge detection capability;
(ix) quick charging capability with good 'full charge' detection point;
(x) high quality, uniform (i.e. capacity, internal resistance, etc.) cells, and
(xi) forewarning of premature cell failure.

The objective of this preliminary evaluation of lithium-ion cells is to determine if rechargeable lithium-ion cells would be useful as a potential power source for implanted medical

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devices. In particular, the cycle life, capacity (i.e. operating time) and surface-temperature studies have been designed so as to test the lithium-ion cells under the discharge loads and operating conditions projected for a 12 V battery pack powering a typical VAD [7,8]. The concerns regarding the first nine items on the above list of requirements for an implantable, rechargeable battery pack will be directly dealt with in this paper. The last two requirements on the list will be commented on but require further testing of single cells and multicell battery packs.

2. Experimental

The battery cells used in this preliminary evaluation were 1.08 Ah, 'C'-size, lithium-ion cells (Model US-61, 20500) obtained from Sony Energytec Inc., Tokyo, Japan. Before their delivery, the manufacturer had cycled each cell once at 23 °C using a maximum charging current of 1.0 A and voltage of 4.1 V during the 2.5 h charging period and a 0.2 A discharge current to a 2.5 V cutoff. The rated mean capacity of the cells used in this study was 1.00 Ah with no cell having a capacity beyond ±1.3% of the mean. Two lithium-ion cells were used for each type of study and, although the results for each cell pair were relatively similar, only the best results from one of the cells are reported.

Unless otherwise stated, the test equipment, conditions and protocols, as well as the correction of cell-capacity loss due to cycling in the discharge rate and self-discharge studies, are similar to those used previously [8,9]. The lithium-ion cells were evaluated at ambient room temperature (22±3 °C) or at 37±1 °C, representing human body temperature. In this evaluation, the cycle life (CL_{50}) of the lithium-ion cells is defined as the number of charge/discharge cycles that a cell undergoes while retaining its capacity above one half of its original or first cycle value.

The lithium-ion cells were standardized before use by cycling them five times at 22 °C using a 0.5 A discharge to 2.5 V and a two-phase charge consisting of a constant-charging current of 0.5 A to a 4.1 V cutoff followed by maintaining the cell at 4.1 V for a 1 h period. This charging regime was selected as it is similar to that used by the manufacturer and it is more easily carried out by the automated cycler used in this evaluation. A lower charging current (0.5 A) was used, instead of the 1.0 A current used by the manufacturer, in order to mimic the relatively limited amount of power that may be left to charge the implanted battery pack during operation of the medical device. This two-phase charging regime was used throughout this evaluation of the lithium-ion cells, as was the 2.5 V discharge termination voltage.

The discharge currents of 0.83 and 0.88 A were used in the cycle life, capacity (i.e. operating time) and surface-temperature studies. These discharge currents were selected so as to test the lithium-ion cells under the power loads (10.0–10.5 W) projected for a 12 V battery pack powering a typical VAD [7,8]. In addition, VADs also typically operate in a pulsatile manner, as do some TAHs [10], which results in a pulsatile load being placed on the battery pack [8,9,11]. In one of the cycle-life and capacity studies, two cells were cycled having pulsatile discharges that consisted of a baseline current of 0.42 A for 0.4 s and a total pulse current of 1.67 A for 0.2 s. This pulsatile discharge cycle represented an average discharge current of 0.83 A, which was repeated until the cell reached its 2.5 V discharge termination voltage. A discharge current of 0.20 A was used in the self-discharge studies.

3. Results and discussion

3.1. General

There was no indication of gases or electrolyte being released from the safety vents in any of the lithium-ion cells used in this preliminary evaluation. In addition, the results obtained were relatively similar for cells tested under similar conditions, albeit a limited number of cells were used. This similarity of results indicates, at least to some degree, the high quality and relative uniformity (i.e. capacity, internal resistance, etc.) of the cells.

3.2. Discharge current versus capacity and voltage

Fig. 1 shows the effect of discharge current on the capacity of the lithium-ion cell both at 22 and 37 °C. The capacity of a cell normally decreases with cycling. As this study required several cycles to complete, the cell capacities shown in this Figure were corrected for their natural capacity fade in order to obtain values that more accurately reflected the effect of the different discharge rates. At both temperatures, the cells show an inversely linear relationship between capacity and discharge current up to a current of about 1.5 A. However, the capacity of the cells dropped off at a quicker rate at higher discharge currents due to increased polarization within the

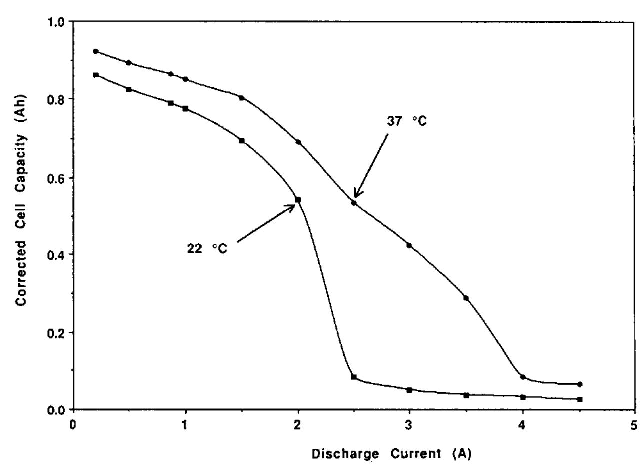

Fig. 1. Comparison of discharge capacity, corrected for cycling capacity fade, vs. discharge current for a lithium-ion cell at two different temperatures.

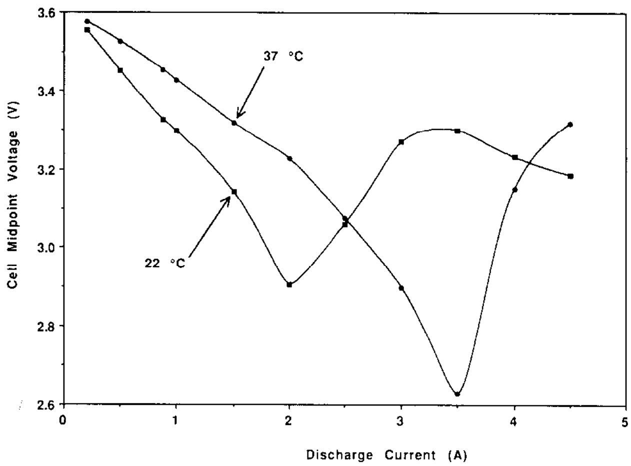

Fig. 2. Comparison of midpoint voltage (MPV) vs. discharge current for a lithium-ion cell at two different temperatures.

cells. This drop in the capacity was more rapid for the 22 °C cell. The 22 °C cell becomes totally polarized at a discharge current of about 2.5 A, while the cell at 37 °C becomes totally polarized at a discharge current of about 4.0 A. Since VADs require an average current of about 0.83 or 0.88 A and operate at 37 °C, these lithium-ion cells have sufficiently high capacities under high discharge currents to be useful as an implanted power source for a VAD.

The midpoint voltage (MPV) of a cell is defined as the cell voltage at one half of the cell's discharge capacity and can be determined from the cell's discharge voltage–time profile. Fig. 2 shows the effect of discharge currents on the MPV of the lithium-ion cells both at 22 and 37 °C. The cells at 37 °C show an inversely linear relationship between MPV and discharge current up to a current of 2.0 A and up to 1.5 A at 22 °C. However, at higher discharge currents the MPV of the cells dropped off at a quicker rate due to increased polarization within the cells, with the drop in the MPV of the 22 °C cell being more rapid than of the 37 °C cell. The 22 °C cell showed that it is totally polarized at about 2.5 A when its MPV begins to rebound, while the 37 °C shows that it is totally polarized at about 4.0 A. The MPV for a 0.88 A discharge at 37 °C (i.e. required for a VAD) was found to be 3.46 V (see Fig. 2 and Table 1), resulting in the need for only four lithium-ion cells to form a 12 V battery pack. Therefore, these lithium-ion cells have sufficiently high voltages under the discharge currents required by a VAD.

3.3. *Specific energy and energy density*

Table 1 shows the specific energy and energy density for the lithium-ion cells, which was calculated based on the weight and volume of the cells, respectively, as well as their capacity and MPV while being discharged at a typical load (0.88 A) required to operate a VAD. The lower values found for the capacities and MPVs of the 22 °C discharged cell, as seen in Figs. 1 and 2, result in a lower specific energy and energy density compared with the 37 °C discharged cell. However, more accurately, cylindrical cells within a battery pack occupy a larger rectangular prismatic volume, which, when used to calculate the 'effective' energy density of the lithium-ion cells, results in a lower value (i.e. in parentheses in Table 1) being obtained. Based on the high MPV for the lithium-ion cells, as well as their high specific energy and effective energy density, the weight and volume of an unencapsulated, four cell, 12 V battery pack would be about 164 g and 80 cm^3, respectively. This compares very favourably with a 12 V battery pack comprised of ten, 0.7 Ah, 'AA'-sized, nickel/cadmium cells [12] having a weight and volume of about 270 g and 101 cm^3, respectively.

3.4. *Internal d.c. resistance and surface temperature*

For discharge currents below about 1.5 or 2.0 A, the curves in Fig. 2 show that the MPV of the lithium-ion cells decrease linearly as the discharge current is increased. This linear relationship shows that normal ohmic polarization within the cells is occurring and is resulting in the observed voltage drop. The internal d.c. resistance of the 22 and 37 °C cells at

Table 1
Performance characteristics of lithium-ion "C"-size cells at different temperatures under a constant 0.88 A discharge load

Characteristics	22 °C operation	37 °C operation
Capacity (Ah)	0.79	0.86
Percent of rated capacity (%)	73	80
Midpoint voltage (V)	3.33	3.46
24 h capacity loss (%)	not done	1.3
Operating time (min)	54	59
Internal d.c. cell resistance at mid-discharge (R_{50}, mΩ)	316	198
Maximum surface temperature increase on discharge (°C)	not done	8.0
Cycle life to 50% of initial capacity (CL_{50}, cycles)	2239	1539
Cell weight (g)	40.9	40.9
Cell volume (cm^3) [a]	15.7 (20.0)	15.7 (20.0)
Specific energy (Wh/kg)	64	73
Energy density (Wh/l) [a]	167 (131)	190 (149)

[a] The values in parentheses are effective cell volumes and effective energy densities, which are calculated based upon cylindrical cells occupying a rectangular prismatic volume, as would occur within a battery pack.

the 50% capacity point (R_{50}) can be obtained from the slopes of these lines and are given in Table 1. The lower internal resistance calculated for the cell at 37 °C is due mainly to the increased conductivity of the electrolyte at this temperature. This increased conductivity manifests itself through improved cell performance by yielding higher capacities and MPVs than cells at 22 °C.

The internal resistance of a cell has a major effect on the amount of heat generated within the cell and on its resultant surface temperature, with a greater temperature being produced with higher internal resistances at high discharge currents. Previous investigations have shown that body tissue can withstand long-term exposure to temperatures no greater than about 43 °C [13,14]. Therefore, it is preferred that the internal resistance of the cells used in an implanted medical application be as low as possible in order to maintain a safe operating temperature.

Fig. 3 shows the insulated surface temperature of a lithium-ion cell during its two-phase charge, discharge (0.88 A to 2.5 V) and open-circuit periods, as well as the ambient oven temperature near the cell. During the first, constant-current phase of the charge, the temperature initially decreases indicating an endothermic process is taking place. A slight increase in temperature above ambient occurs near the end of the first phase of charging. The second, constant potential phase of the charge results in little difference between the temperature of the oven and the cell's surface. During discharge, the electrochemical process is exothermic with the surface temperature of the cell reaching about 8.0 °C above the ambient oven temperature. The cell's surface temperature quickly drops once it is placed on open circuit. For an implanted battery, a temperature increase of this magnitude would result in surface temperatures within the human body of about 45 °C, which is too high for a safe, chronic implant. However, this problem with the lithium-ion cells may be eliminated by insulating the cells from their titanium enclosure or by not fully discharging the battery pack.

Fig. 3 also shows that these lithium-ion cells can be fully charged within 2.5 h with the use of the two-phase charge and its initial 0.5 A charge current. This implies that these cells can be charged quickly, which may be useful for the patient in the case of an emergency.

3.5. Self-discharge

A low self-discharge rate is desirable for implantable applications, as this results in better charge acceptance and longer operating times after cessation of the charge. Fig. 4 shows the discharge capacity (0.20 A current) of a lithium-ion cell after imposing open-circuit periods of various lengths on the fully charged cell. The cell capacities shown in this Figure were corrected for their natural capacity fade due to cycling. The cell showed only a 0.012 Ah (1.3%) decrease from its initial capacity after 24 h at 37 °C. This small amount of self-discharge over this period of time would have little effect on the operating time of an implantable battery pack.

3.6. Cycle life

Fig. 5 shows the operating time at each discharge cycle for lithium-ion cells cycled at either 22 or 37 °C with a discharge

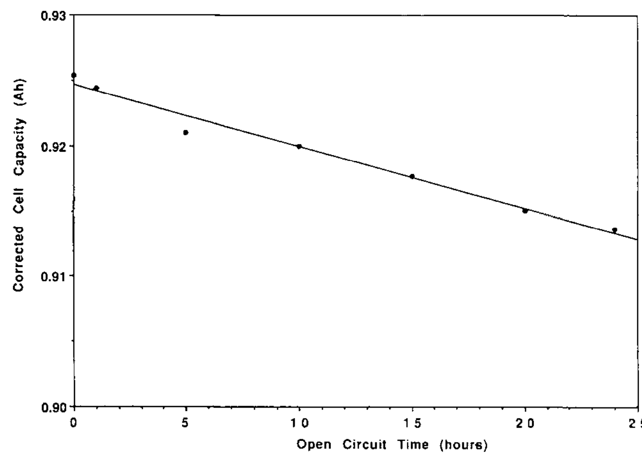

Fig. 4. Discharge capacity, corrected for cycling capacity fade, vs. open-circuit time showing the amount of self-discharge for a lithium-ion cell at 37 °C.

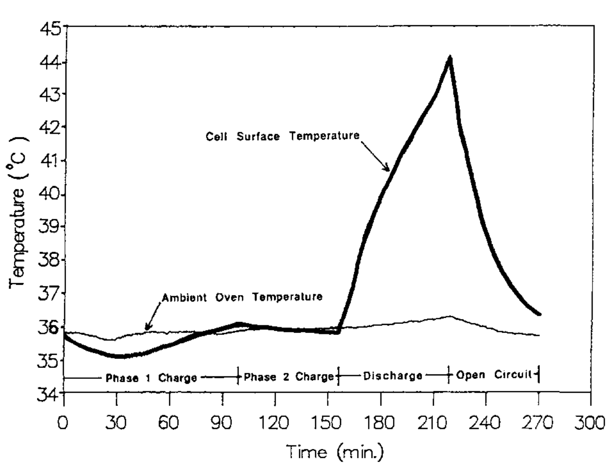

Fig. 3. Surface temperature vs. time profile for a lithium-ion cell during charge, discharge and open circuit at 36 °C.

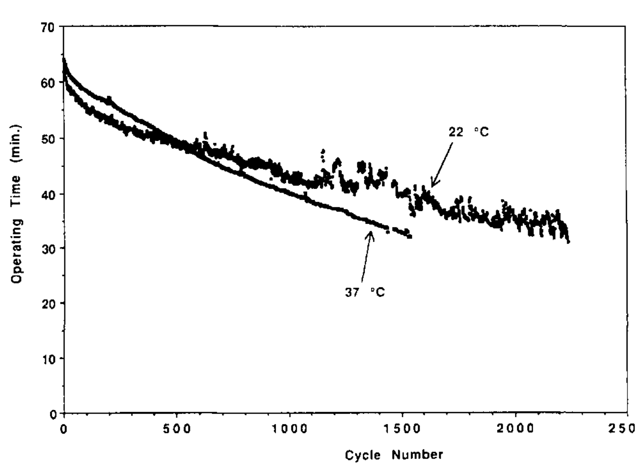

Fig. 5. Comparison of operating time vs. cycle number for lithium-ion cells under constant-current discharge (0.88 A) at two different temperatures.

current of 0.88 A. The overall trend in the capacity fade of the two cells is similar. However, there is a greater fluctuation in the observed operating times with the 22 °C cell, due to the fluctuations of the ambient room temperature (i.e. 22 ± 3 °C). The cell operated at 22 °C had a longer cycle life ($CL_{50} = 2239$ cycles) than the 37 °C cell ($CL_{50} = 1539$ cycles). The operating time of the 37 °C cell was 2.1 ± 1.1 min (mean) greater on each cycle than the 22 °C cell for approximately the first 550 cycles. Above about 550 cycles, the operating time of the 37 °C cell was 4.3 ± 2.6 min (mean) lower on each cycle than the 22 °C cell.

Fig. 6 compares two lithium-ion cells tested under both pulsatile and constant-current discharge conditions at 37 °C. The discharge currents used represent an average load of 10.0 W (0.83 A) for a 12 V implanted battery that could power a VAD. The overall trend in the capacity fade of the two cells is similar. The cell operated under the constant-current discharge load had a somewhat longer cycle life ($CL_{50} = 2279$ cycles) than the pulsatile discharged cell ($CL_{50} = 1941$ cycles). Throughout the cycle life of the two cells, the operating time of the constant-current discharged cell was 1.6 ± 1.1 min (mean) greater on each cycle than the pulsatile discharged cell. This characteristic of shorter cycle life and lower operating time of the lithium-ion cells under pulsatile discharge, as compared with constant-current discharge, has previously been reported in both nickel/cadmium [15] and lithium metal-based [8] cell chemistries.

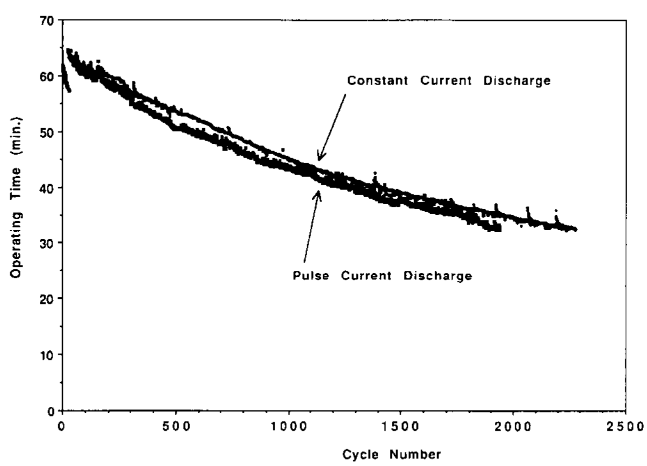

Fig. 6. Comparison of operating time vs. cycle number for lithium-ion cells under constant-current (0.83 A) and pulsatile discharge loads (0.83 A average) at 37 °C.

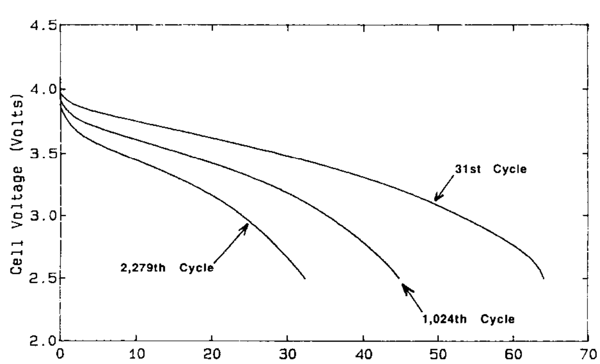

Fig. 7. Comparison of discharge voltage vs. operating time at three different points in the cycle life of a lithium-ion cell under constant-current discharge (0.83 A) at 37 °C.

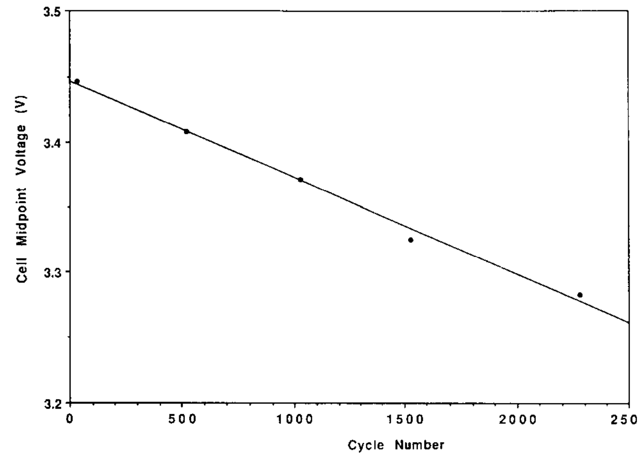

Fig. 8. Midpoint voltage vs. cycle number for a lithium-ion cell under constant-current discharge (0.83 A) at 37 °C.

It is anticipated that an implanted battery pack will only be used once per day to operate the implanted device, with the majority of the operating time and power coming from an external power source. If one takes as a worse case cycle life for the lithium-ion cells to be 1539 cycles, as shown in Fig. 5, then this represents an implant time of 1539 days or over 4.2 years. The cycle lifes found for the lithium-ion cells are acceptable for an implanted battery pack and are considerably greater than the 423 to 730 cycles found for nickel/cadmium cells [9,11,15] and the 44 to 188 cycles found for the lithium metal-based cell chemistries [8] previously tested under similar conditions.

Fig. 7 shows the discharge voltage–time curves at three different points in the cycle life of the constant-current discharged cell shown in Fig. 6. The representative discharges after 31, 1024 and 2279 cycles had observed operating times of 64.2, 44.8 and 32.3 min, respectively. The sloping trend of the discharges are similar and are approximately linear. This decrease in discharge voltage may be of use in monitoring the state-of-charge of the battery pack.

Fig. 8 shows the MPV at various points in the cycle life of the same cell shown in Figs. 6 and 7 and shows a small, linear decrease of the MPV (0.17 V or 4.8%) throughout the cell's cycle life. This linear decrease in the MPV represents a linear increase in the cell's internal resistance with cycling, which may be a useful diagnostic for the detection of premature cell failure within a battery pack. Additional studies are required.

4. Conclusions

Preliminary results indicate, as summarized in Table 2, that the lithium-ion cells examined in this study could be used

Table 2
Summary of results on the evaluation of rechargeable lithium-ion cells for use in an implantable battery pack

Item No.	Requirement at 37 °C	Summary rating [a]
1	Safe, stable chemistry (hermetic)	+
2	High specific energy/energy density	+ / +
3	High discharge rate capability	+
4	High capacity	+
5	Long cycle life	+ +
6	Low self-discharge	+
7	Low internal resistance/surface temperature	− / −
8	State-of-charge detection capability	+
9	Quick charging capability	+
10	High quality, uniform cells	+ (?)
11	Forewarning of premature cell failure	?

[a] (−) Unsuitable; (+) suitable; (+ +) excellent; (?) questions remain.

in a rechargeable, implanted battery pack to provide power to an implanted device, such as a VAD. The ratings were made by comparing the results for the lithium-ion cells with those of the nickel/cadmium [9,11,15,16] and lithium metal-based [8,16] cell chemistries previously evaluated under similar conditions. The Table shows that these cells operate safely at 37 °C and have good performance characteristics for the first nine requirements of an implantable, rechargeable battery pack, except number seven. The seventh requirement, which is a low surface temperature during discharge, was not satisfied by these cells, but may be rectified with the use of insulation or a lower depth-of-discharge. Additional studies on single cells and multi-cell battery packs need to be carried out in order to determine if the last two requirements can be met by these lithium-ion cells.

The capacity of the Sony lithium-ion cells studied here have since been increased to 1.35 Ah, a 25% increase [17], which would result in a similar increase to the operating time observed under our conditions. The increased capacity and operating time of these cells make their use even more attractive.

Acknowledgements

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