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Primary batteries for implantable pacemakers and defibrillators

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Abstract

The lithium-iodine battery is established as the standard system for low-rate implantable applications, namely pacemakers because of its excellent volumetric energy density. Within defibrillators/cardioverters lithium-silver-oxovanadium (SVO) and lithium-manganese-dioxide (MDX) high-rate batteries are in use. The concept of a hybrid system which makes use of a high-rate battery and a low-rate battery within one application is described. Experimental results obtained from a MDX battery and a lithium-iodine battery, both with the same dimensions, are showing that MDX batteries of that size are able to combine excellent volumetric energy density and medium power ratings. Energy densities of 650 mWh/cm^3 for the MDX battery with a lode of 30 kΩ to an end voltage of 2.5 V have been confirmed. These results show the potential of lithium-manganese-dioxide batteries to be used as low-rate and medium-rate sources within implantable applications. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Manganese-dioxide; Defibrillator; Cardioverter; Implantable power supply; Pacemaker; Lithium-iodine battery; Battery

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Currently, all primary batteries for implantable medical devices contain a lithium anode. Defibrillators/cardioverters are powered either by lithium–silver–vanadium-oxide (SVO) or lithium–manganese-dioxide (MDX) double-cells. Development, production, and use of MDX batteries within implanted ICD's in the last few years have confirmed the ability of MDX batteries to comply with extremely high pulse power requirements. For the use within ICDs, the two basic requirements of the power source are high power and longevity, whereas pacemakers require longevity at low-rate currents. A hybrid system consisting of an MDX battery plus a lithium–iodine cell has been further improved in order to increase pulse power capabilities and energy density of the system. Recent results are presented below. The development of batteries suitable to comply with extended electrical requirements of future devices, e.g. pacemakers with increased functionality, neurostimulators and implantable micromechanical devices, has to evaluate the performance of MDX and other systems under the specific conditions and requirements of implantable batteries. As a result of this work, the electrical performance data of a medium rate MDX cell is presented.

In general, three categories of power capabilities (low-rate, medium-rate and high-rate) are used to categorize battery performances. Although the differences are not strictly defined, these terms may be applied in the following situations. Low-rate batteries are able to supply up to 100 μA of constant current. High-rate batteries with a volume of about 10 cm^3, should be able to provide a pulse power of at least 5 W for about 10 s. The remaining gap is served by medium-rate batteries. Pacemakers require low current drain; neurostimulators, micromechanical devices and drug pumps need medium-rate currents, and implantable defibrillators/cardioverters (ICDs) are devices with extremely high pulse power and additional longevity requirements. Within the next 10 years, low-rate batteries will have to be able to supply intermediately-increased power outputs. Medium-rate applications may be powered by different systems. Currently, available systems are lithium–silver–vanadium-oxide (SVO), lithium–thionyl–chloride batteries and cells with CFx cathodes [1,2], which are also suitable for pacemaker applications. Development and performance of a medium-rate battery with a lithium–manganese-dioxide (MDX) cathode is described below.

At the present time, defibrillators and cardioverters are either powered by 3 V SVO cells [3], SVO double-cells [4], or 6 V lithium–manganese-dioxide double-cells [5]. The development, production, and use of MDX batteries in implanted ICDs during the last few years have confirmed the capabilities of the batteries; they are able to comply with the ICDs' extremely high pulse power requirements. One approach to overcome the difficulties in designing a battery with high power plus high energy density makes use of a 6 V

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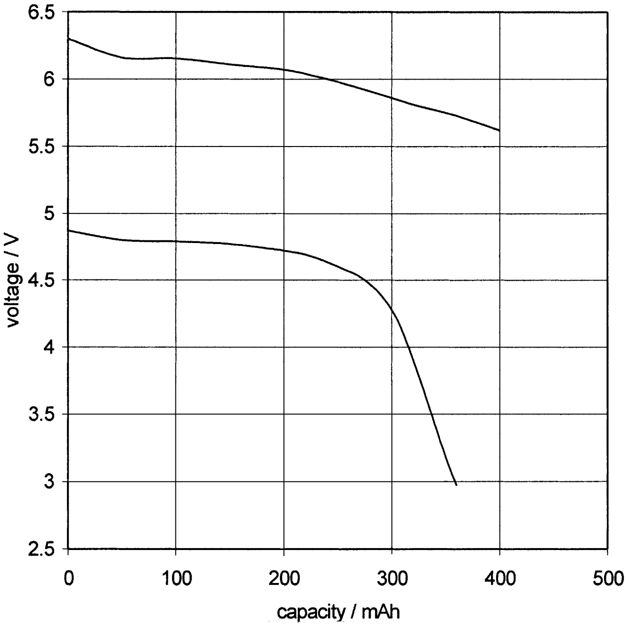

Fig. 1. LiS 32125/K6+ pulsetrain discharge. End voltage of 1 A pulses, voltage at background load 600 kΩ.

MDX double-cell, plus a lithium–iodine cell in order to increase pulse power capabilities and energy density of the system [6]. Improvements in the performance of this hybrid system lead to an improvement of the pulse power performance. The results of a pulse discharge regime, which illustrate the high power capability of the improved design, are presented in Fig. 1.

The power density of the battery was greater than 660 W/dm^3 at the middle of life (MOL), and the low-rate energy density was 410 Wh/dm^3 (at a background load of 600 kΩ). The pulse discharge regime consisted of a sequence of pulse trains. Each pulse train consisted of four pulses at a 9 s constant current (1 A), with an interval of 15 s at an open circuit. After each train a 30 min rest interval was applied.

The capacity of the corresponding lithium–iodine cell was 0.68 Ah across 174 kΩ to an end voltage of 2.5 V. Within the ICD, the iodine battery supplied pacing and sensing until it reached its end of service (EOS). Battery replacement was indicated and the power for the background load was provided by the MDX double-cell. A lithium–iodine battery as small as the battery described above (2.7 cm^3) approaches the limits of the iodine system with respect to the reasonable minimum size of an implantable lithium–iodine cell. Because of the reduced achievable energy density, implantable lithium–iodine cells with a volume less than 3 cm^3 will barely achieve 800 mWh/cm^3. MDX cells may offer equal or better performance at a lower cost.

Taking into consideration the increasing power demands of advanced devices and the limitations of the lithium–iodine system, another hybrid battery system has been selected to demonstrate the capabilities of an MDX cell replacing a lithium–iodine battery (see Fig. 2). In that hybrid system, the lithium–iodine cell provides 0.87 Ah over across 174 kΩ to an end voltage of 2.5 V, and delivers 1.05 Ah to 1.8 V. The MDX battery with identical outer dimensions delivers 0.83 Ah to 2.5 V over across 174 kΩ due to the higher mean discharge voltage; however, the energy output of the MDX cell is larger. The volumetric energy density of the MDX battery is 650 mWh/cm^3, which is an increase of 6% over the lithium–iodine battery. An EOS indication will be accompanied by switching the whole power supply to the 6 V battery. The capacity of the 3 V battery can be fully utilized, which makes a battery-internal EOS indication, given in the form of a suitable discharge property at EOS, obsolete.

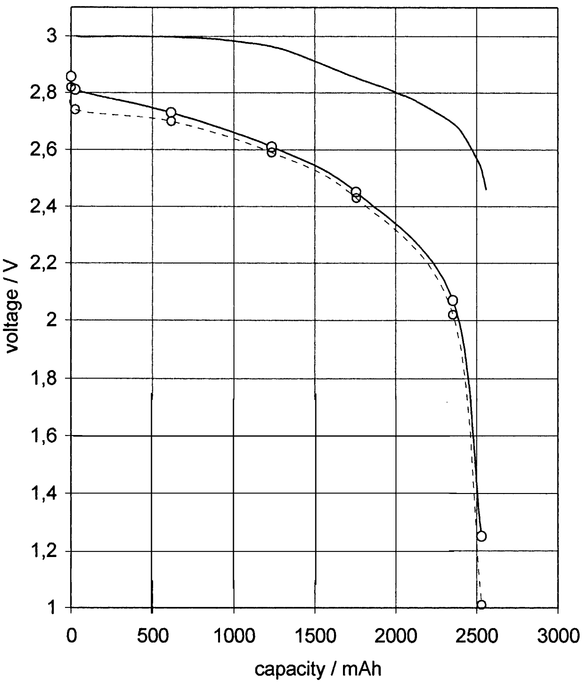

Fig. 2. LiS 4087 pulsetrain discharge. End voltages at first and fourth pulses, voltage at background load 820 Ω.

Various applications, namely neurostimulators, drug pumps and other micromechanical devices, need significantly more power than a pacemaker and cannot be powered by lithium–iodine cells. The requirements of power sources for such devices do show a wide range, but they may be recalculated to current demands in the range of 0.5–50 mA, for instance. In addition, some devices may need pulse discharges with currents up to several hundred mA.

The calculations of the energy consumption and minimum lifetime requirements of a neurostimulator resulted in a projected capacity of more than 2 h. MDX cells can be specifically designed to meet high-energy output, and a battery with a capacity of 2 Ah will be able to provide pulse currents of more than 300 mA for 10 s with only a small voltage drop. To determine the ability of the Li/MDX system to comply with this requirement, a battery with the following performance data has been developed (Table 1).

The stainless steel case negative battery design includes one central lithium anode, and a cathode on each side.

Table 1
LiS 4087, medium rate MDX cell

Volume (cm^3)	10.5
Mass (g)	20.5
Capacity 3 kΩ/2.5 V (Ah)	2.5
Mean discharge voltage 3 kΩ (V)	2.75
Energy density	
Volumetric (Wh/cm^3)	0.588
Gravimetric (Wh/g)	0.149

Electrical tests of the battery demonstrated a pulsing capability, which allowed for pulse currents up to 0.4 A. The pulse discharge regime consists of a sequence of pulse trains. Each pulse train consists of four pulses of a 10 s constant current (0.2 A) with an interval of 15 s at open circuit. After each train, a 30 min rest interval is applied. A pulse capacity of 2.5 Ah can be discharged until the end voltage of 1.5 V is reached (the background load of 820 Ω was chosen to complete the test within 30 days and has only little reference to a real application).

When pulsing with 0.2 A, the voltage drops only 10 mV; the cell can supply pulse currents up to 0.4 A. Potential swelling of implantable batteries has to be investigated carefully. Parasitic chemical reactions of the cathode and/or anode with the electrolyte contribute to the swelling [7]. Basically, the gamma-MDX modification oxidizes and the lithium anode reduces parts of the electrolyte which contains propylene carbonate, ethylene carbonate, and dimethoxyethane. The reaction products increase the internal pressure of the cell, which may result in swelling. At the anode, traces of water are reduced and hydrogen is formed. Additionally, a passivation layer of lithium salts is formed on the anode's surface, and propylene and ethylene are also formed. The gamma-MDX content of the cathode increases cell voltage of up to 3.5 V. The results of one approach to reduce electrolyte oxidation are given in Fig. 3.

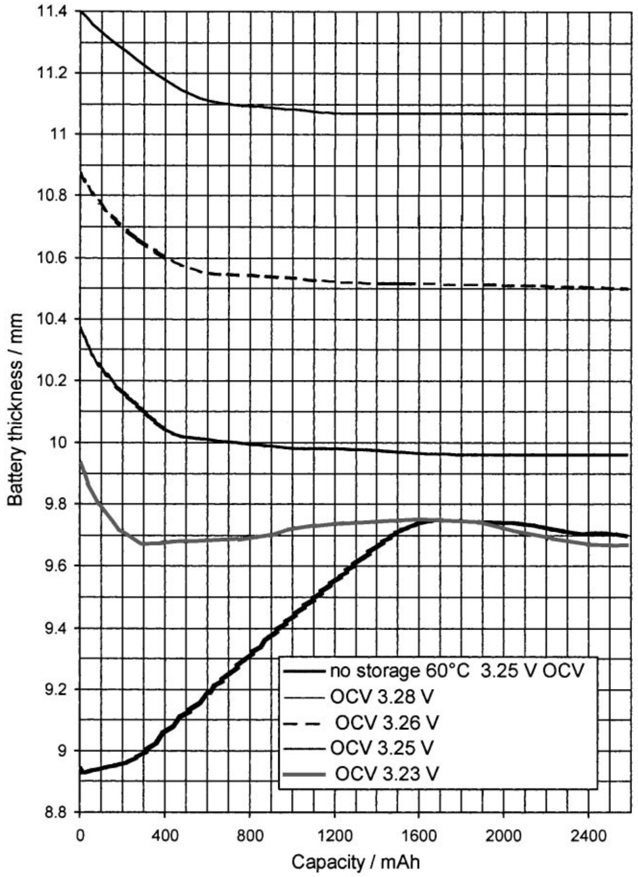

Fig. 3. LiS 4087, discharge over 820 Ω after 8 weeks storage at 60°C.

The result of different predischarge procedures show different impacts on swelling of the battery. A series of batteries were predischarged immediately after activation, down to 3.28, 3.26, 3.25 and 3.23 V OCV. Accelerated aging was performed by storing the predischarged cells at 60°C for 40 days, except on one series, which was not subjected to accelerated aging. Finally, the cells were discharged across 820 Ω and the thickness of the batteries was measured over the discharge time. After aging, all cells showed the same response: the thickness at the beginning of the discharge is was a function of the voltage at BOL. This reflected the amount of electrolyte oxidized and reduced. The thickness decreased to a steady level, which was determined by the cell's BOL voltage, and thus the voltage to which the cell was predischarged. The initial decrease in internal pressure and thickness could be partially caused by hydrogen consumption at the anode [8]. The cells that were predischarged to 3.23 V, showed a slight increase in thickness due to cathode swelling.

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