Li-Ion Cells for Terrestrial Robots

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SAFT prismatic wound 5 Ahr MP series cells were evaluated for potential application in a lithium ion battery designed for Tactical Mobile Robots (TMR). In order to satisfy battery design requirements, a 10 Ahr battery containing two parallel 8-cell strings was proposed. The proposed battery has a weight and volume of approximately 3.2 kg and 1.6 liters, respectively. Cell qualification procedures include initial characterization, followed by charge/discharge cycling at 100% DOD with intermittent EIS measurements at various state of charge. Certain cells were also subjected to extreme operational temperatures for worst-case analysis. Excellent specific energy (>130 Whr/kg) was obtained with initial characterization cycles. Even at abusive thermal conditions, the cell capacity fade was less than 1 Ahr after 300 cycles. Rate characterization showed good cell discharge behavior with minimal decrease in capacity. At various state of charge, impedance measurements suggest that the cathode play a more significant role in capacity fade than the anode.

INTRODUCTION

Lithium ion batteries offer significant advantages, in terms of mass of volume, compared to the conventional Ni-Cd and Ni-H_2. Accordingly, numerous efforts are underway to develop appropriate Li ion batteries, to evaluate various performance characteristics such as cycle life, calendar life, extreme temperature performance (-20°C > T > 30°C) etc, and to demonstrate the readiness of these technologies for a variety of NASA's robotic planetary exploration missions, including planetary rovers, landers and orbiters.[1] At JPL, the transition to Li ion batteries for landers and rovers was facilitated by the development of low temperature batteries, primarily via a modification of the electrolyte solvent, to achieve low viscosity and high ionic conductivity at low temperatures, combined with good film-forming capability to provide the desired electrochemical stability.[2] Li ion batteries, utilizing this electrolyte mixture, were qualified for the 2001 Mars Lander mission,[3] which was later cancelled, as well as on the current Mars Exploration Rover mission.[4] Other research efforts at JPL also resulted in quaternary mixture electrolytes with enhanced performance at low temperatures down to –40°C.[5] Li ion cells containing these electrolytes exhibited resilience at ambient and moderately warm temperatures, up to 40°C, as well as at low temperatures.

Apart from the robots for planetary exploration, JPL is also interested in robots for terrestrial applications as well. The environments for such applications are equally challenging, with operating temperature as high as 55°C. In addition, these unmanned vehicles are highly maneuverable as well as portable, and, therefore, require high specific energy batteries. The state of art battery system is Ni-Cd, which has considerable penalty on mass and volume, not to mention the high self-discharge at high operating temperatures. At these high operating temperatures for Li ion cells, there would be problems associated with the instability of salt $LiPF_6$, solubility of cathodes and enhanced oxidation of electrolyte.[6]

In an effort to qualify Li ion technology for military mobile robotics and other robotic applications, we have undertaken a detailed evaluation of lithium ion cells. The preliminary results of this study are promising and establish the feasibility of Li-ion technology for terrestrial robots requiring high specific energy at elevated temperatures.

MISSION BACKGROUND

The main purpose of the tactical mobile robot (TMR) is to serve as the "point man" for military combat operations, surveying enemy terrain with high agility and maneuverability. A design example of the robot design is shown on Figure 1. Within the tactical vehicle contains real-time navigation and intelligent sensor systems. The vehicle is also easily deployable and, therefore, is no more the 16" in length and is light enough to be carried by a single individual. The operational environment of the vehicle is relatively extreme, ranging from temperatures as low as –20°C to as high as 55°C. Along with high durability and reliability, the operational life of the vehicle is between 4 to 6 month.

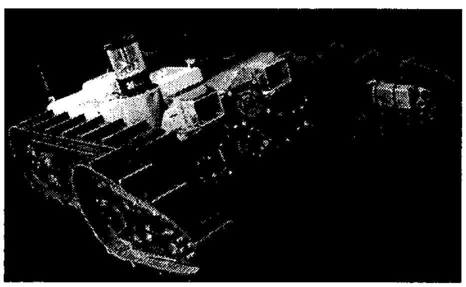

Figure 1 – Design Example of TMR Design by I-robot

BATTERY DESCRIPTION

The strict operational and design requirements of the mission vehicle dictate an extremely advanced battery (Table 1). During climbing mode, the power load of the vehicle is as high as 350 Watts at 10% duty cycle. The energy requirement for the TMR battery is 720 Whr, with operating time beyond 6 hours continuous. The weight and volume of the TMR battery are less than 7 Kg and 4.6 liters, respectively. Thus, the TMR battery not only process high specific energy and energy density, but also high rate capabilities with moderate cycle life capable of operating at extreme thermal environments.

Table 1- Battery Design Requirements for TMR Battery

Parameter	Value
Power Loads*	
Watch mode:	80W (45% d.c)
Running Mode:	120W (45% d.c.)
Climbing Mode:	350W (10% d.c.)
Energy Content	720 Whr
Operating Time	> 6 Hours continuous
Weight	< 7 Kg
Volume	< 4.6 Liters
Mass	155 g

*d.c. – duty cycle

Lithium ion technology is the chemistry of choice to fulfill these unique and challenging battery requirements. For the TMR, proposed battery is a 10 Ahr lithium ion. The battery is comprised of two parallel strings of eight cells (16 cells total). The operating voltage range of the TMR battery is 24 to 32 volts, with a nominal power output of approximately 280 Whr.

SAFT prismatic wound 5 Ahr MP series cells (Figure 2) were selected for the TMR battery. These cells are nearly commercial off the shelf (COTS), and, therefore, relatively inexpensive. The cell properties are listed in Table 1. The rated capacity of SAFT MP series cells is 5 Ah, with a nominal voltage of 3.6 V. Considering a cell mass of 155 gm with a typical mass factor of 1.4 for battery packaging, the total mass of the TMR battery is estimated at 3.2 kg or 8 lbs. The estimated volume of the battery is only 1.6 liters.

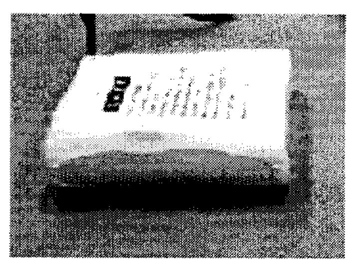

Figure 2 – SAFT 5 Ah MP Series Cells

Table 2- SAFT 5 Ah MP Series Cell Properties

Parameter	Value
Rate Capacity	5 Ah
Nominal Voltage	3.6 V
Length	6.2 cm
Width	5.8 cm
Height	1.4 cm
Mass	155 g

EXPERIMENTAL FOR CELL EVALUATION

In order to qualify the lithium ion cells for the TMR battery, a 4000 series MACCOR cycler was used to perform cell cycling. Initially, each cell was subjected to five characterization cycles. Following, certain cells were randomly chosen to cycle at extreme conditions of 100% DOD and at various temperatures, using Tenny environmental chambers. Additionally, a single cell was selected for abuse testing at 100% DOD and 55°C in order to determine the cell behavior at worst-case scenario. The capacity rate characterization analysis was performed prior cycle life testing at various temperatures. Additionally, C/10, C/5, C/2.5, and C discharge rate characterization was also performed after each 100 cycles of 100% DOD at 23°C temperature.

To investigate the effect of cell impedance growth as a function of capacity fade, EIS (electrochemical Impedance Spectroscopy) measurements were also performed as a function of states of charge as well as cycle life. The impedance measurements were completed after each 100 cycles of 100% DOD using a model 273A EG&G potentiostat/galvanostat interfaced with a 1055 frequency analyzer and PC running PowerSuite software.

CELL EVALUATION RESULTS AND DISCUSSION

Cell Characterization Results – Figure 3 and 4 show the discharge capacity and specific energy of SAFT MP series test cell after initial five characterization cycles. In terms of capacity, the test cells exhibited excellent uniformity, ranging between 5.5 to 6.0 Ahr. The MP series cells also demonstrated excellent specific energy. From Figure 4, the average specific energy from the characterization cycles for each test cells exceeded 130 Whr/kg. Therefore, the estimated energy from lithium ion battery containing SAFT MP series cells could easily fulfill the TMR energy requirement.

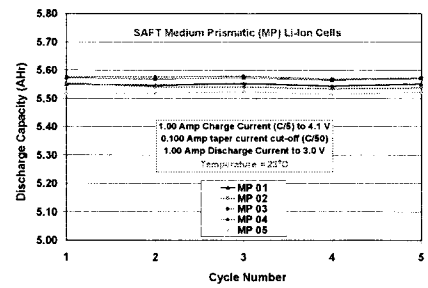

Figure 3 – Discharge Capacity of MP cells after Characterization Cycles.

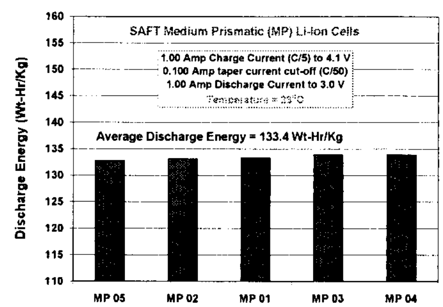

Figure 4 – Specific Energy of MP cells after Characterization Cycles.

Cycle Life Results – In terms of cell capacity and specific energy, positive results ~~was~~ were also obtained from cycle life testing at extreme conditions. The capacity retention at worst-case scenario (100% DOD and 55°C) still exceeded 90% of initial capacity after 300 cycles, which is more than adequate for TMR operational life requirement (Figure 5). The corresponding specific energy exhibited from cycle life testing at 100% DOD and at various temperatures were approximately 120 Whr/kg or above (Figure 6).

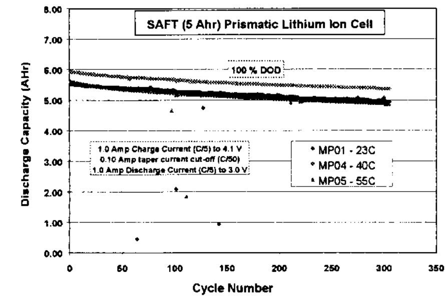

Figure 5 – Capacity as a Function of Cycle Life at Various Temperatures.

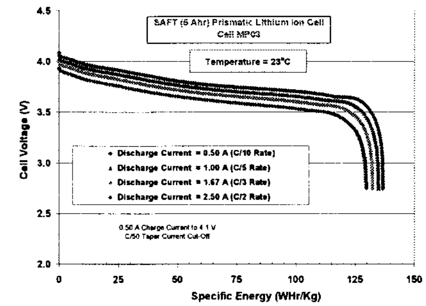

Figure 7 – Specific Energy at Various Discharge Rates at 25°C.

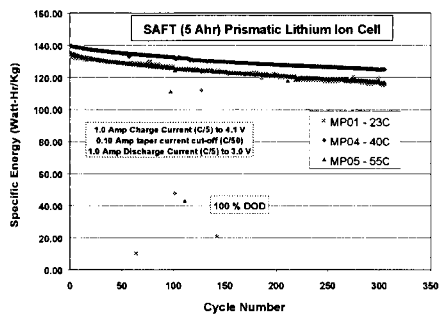

Figure 6 – Specific Energy as a Function of Cycle Life at Various Temperatures.

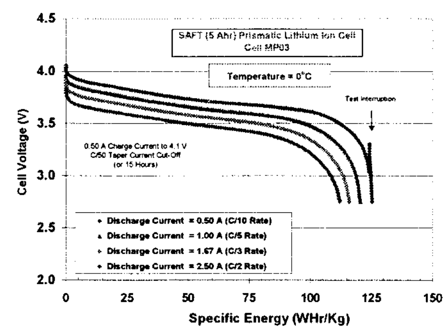

Figure 8 – Specific Energy at Various Discharge Rates at 0°C.

Discharge Rate Characterization Results – The results from rate characterization at various temperatures and at various cycle life also support SAFT MP series cells for TMR application. As shown on Figures 7 and 8, high specific energy was exhibited at various discharge rates and temperatures. At 25°C, the specific energy at various discharge rates was 130 Whr/kg or greater. Even at 0°C, the specific energy was as high as 125 Whr/kg at C/10 discharge rate. Though specific energy decreased more significantly with increase in discharge rate at 0°C, the cell still maintain excellent discharge behavior at various discharge rates.

The affect of cycle life on discharge rates is summarized in Figures 9 through 11. After 300 cycles at 100% DOD and 23°C, the capacity only decreased approximately 0.5 Ahr at C rate. The polarization effects from the increase in discharge rate was negligible. Even at the worst-case scenario of 300 cycles at 100% DOD and 55°C, the capacity decreased less than 1 Ahr, with no significant decrease in capacity with increase in discharge rate. These results are very encouraging for lithium ion technology in TMR applications.

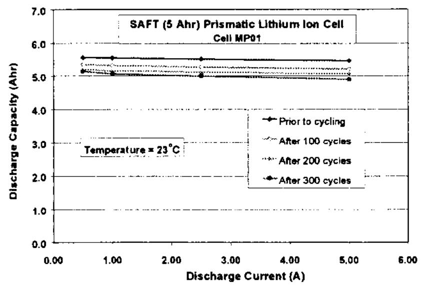

Figure 9 – Discharge Capacity as a Function of Cycle Life (100% DOD 23°C) at Various Discharge Rates.

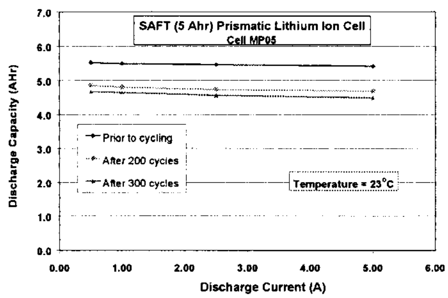

Figure 10 – Discharge Capacity as a Function of Cycle Life (100% DOD 55°C) at Various Discharge Rates.

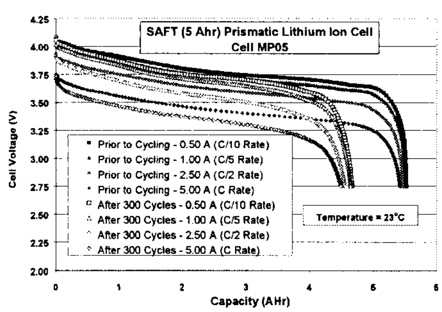

Figure 11 – Discharge Curves Prior to and After 300 Cycles (100% DOD 55°C) at Various Discharge Rates.

Impedance Measurement Results – Impedance measurements after 300 cycles at 100% DOD are shown in Figure 12. No significant difference in impedance was observed for the cell subjected to cycling at 55°C as compared to cells cycled at milder temperatures. An increase in impedance was observed with increase in cycle life. Figure 13 and 14 compare the impedance profiles at various state of charge at 25°C and 55°C after 300 cycles. It is apparent that low frequency charge-transfer resistance increase with decrease in SOC due to the de-intercalation of lithium from the cathode into the anode.[7] The series resistance, on the other hand, shows insignificant change as a function of SOC compared the cathode charge-transfer resistance. This strongly suggests that the cathode play a more significant role in cell capacity fade than the anode.

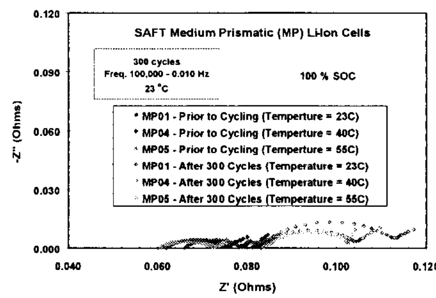

Figure 12 – Nyquist Plots at 100% State of Charge after 300 Cycles.

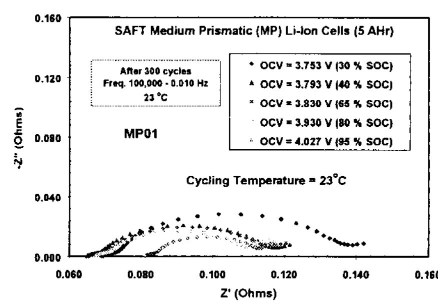

Figure 13 –Nyquist Plots at Various State of Charge after 300 Cycles (100% DOD and 25°C).

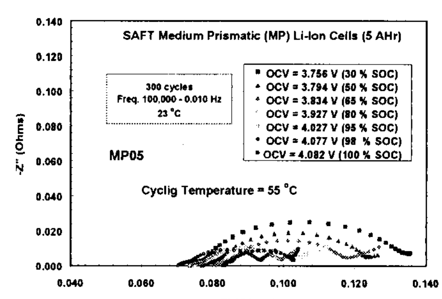

Figure 14 –Nyquist Plots at Various State of Charge after 300 Cycles (100% DOD and 55°C).

CONCLUSIONS

A 10 Ahr lithium ion battery containing SAFT 5 Ahr prismatic wound MP series cells was proposed to fulfill the power requirements of the TMR. The weight and volume of the battery is approximately 3.2 Kg and 1.6 Liters, respectively. Initial characterization of the SAFT MP series cells resulted in an average specific energy exceeding 130 Whr/kg. Cycle life testing characterization show minimal capacity fade after 300 cycles (100% DOD) even at extreme operational temperatures. Rate characterization indicates minor decrease in capacity with discharge rate as high as C rate. EIS measurements indicate a substantial increase in charge-transfer resistance as compared to ohmic resistance at various state of charge, suggesting the cathode appears to have a more significant role in capacity fade than the anode.

ACKNOWLEDGEMENT

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