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Lithium batteries for aerospace applications: 2003 Mars Exploration Rover

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Abstract

Future NASAs planetary exploration missions require batteries that can operate at extreme temperatures and deliver high specific energy and energy densities. Conventional aerospace rechargeable battery systems, such as Ni–Cd, Ni–H_2 and Ag–Zn, are inadequate to meet these demands. Lithium ion rechargeable batteries were therefore chosen as the baseline for these missions. The 2003 Mars Exploration Rover (MER) mission plans to deploy twin rovers onto Mars, with the objectives of understanding its geology, climate conditions and possibility of life on Mars. The spacecraft contain various batteries, i.e. primary batteries on the lander, thermal batteries on the back shell and rechargeable batteries on the Rovers. Significant among them are the Li ion rechargeable batteries, which are being utilized for the first time in a major NASA mission. The selection of the Li ion battery has been dictated by various factors, including mass and volume constraints, cycle life, and its ability to operate well at sub-zero temperatures (down to −30 °C), at moderate rates. This paper describes the selection criteria, design and performance of the three battery systems on 2003 MER mission.

Keywords: Mars Exploration Rover; Martian rocks; Mars Pathfinder

1. Introduction

The Jet Propulsion Laboratory/NASA is planning to launch a twin-Rover mission to Mars, termed as Mars Exploration Rover (MER) in 2003. Designed to operate over a primary mission life of 90 sols and perform in situ geological science data collection, the Rovers are aimed at detecting the possibility of water, understanding the mineralogy of Martian rocks, and demonstrating the long-range traverse capabilities of Rovers containing mobile science platforms, as well as, the capabilities of the orbiting Mars communications infrastructure.

Each Rover Flight System consists of: (1) a cruise stage and entry, descent and landing (EDL) system with inheritance from the Mars Pathfinder (MPF); (2) a lander to carry the Rover; and (3) a rover based upon the Athena Rover and Athena Science Package.

Each of the rovers will have several instruments, including a Panoramic camera, two remote sensing instruments, in the form of a mini-thermal emission spectrometer (mini-TES) and a mid-IR point spectrometer, and different in situ pay-load elements, including a Mossbauer spectrometer, an alpha-particle X-ray spectrometry (APEX), a microscopic imager and a rock-abrasion tool located on a robotic arm. Compared with the previous rover, Sojourner, on the Mars Pathfinder mission, the MER Rover is more than 10 times heavier (173 g versus 11 kg) and six times taller (142 cm versus 25 cm) (Fig. 1). The pay-load, anticipated mission life, and the total distance traversed are proportionately an order of magnitude higher than Sojourner.

The MER mission will have three different batteries: primary, rechargeable, and thermal batteries [1]. The primary batteries are located on the Lander, which carries the Rover and releases it on the Martian surface. The primary batteries will support the entry, descent and landing operations and will also support the initial deployments on Mars. The thermal batteries, located on the back shell, will power pyro events during the descent phase of the mission, including opening of parachute. The rechargeable batteries will aid in the launch, correct anomalies during cruise, and support surface operations. In the latter phase, the rechargeable batteries will augment the primary power source for the MER Rovers, a triple-junction GaInP/GaAs/Ge cell deployable solar arrays, and support nighttime experiments. In order to maintain the rechargeable battery at moderate temperatures, i.e. from −20 to +30 °C, the Rover is provided with an aerogel-insulated warm electronics box, radioisotope heating units (RHUs), and a battery thermal switch heat rejection system.

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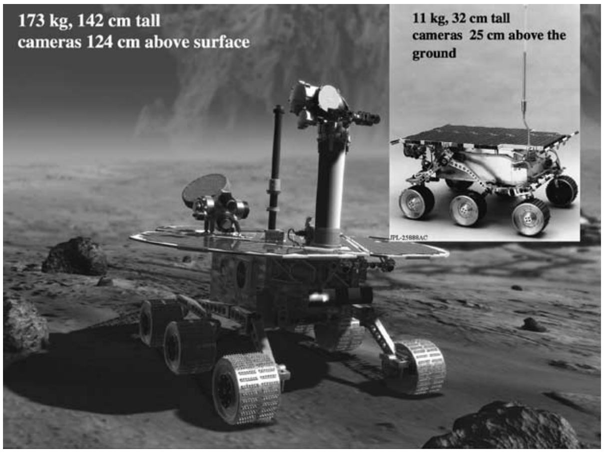

Fig. 1. Comparison of the MER Rover with the Mars Pathfinder Sojourner Rover.

2. Rechargeable batteries

The requirements for the rechargeable battery include an operating voltage of 24–36 V, to provide energy of 220 Wh during launch, and 160 Wh for supporting any fault induced attitude excursion from the sun point until reacquisition of the sun point during cruise, and 283 Wh/sol at 0 °C for surface operations. The battery should also provide a cycle life of at least 270 cycles at 50% DOD at 0 °C. In addition, the rechargeable batteries need to support multiple pulses of 30 A for 50 ms, both at ambient and low temperatures. As dictated by the mass and volume restrictions, it is imperative that the battery system is compact and lightweight. Lithium ion batteries, in general, have high specific energy, good low temperature performance, low self-discharge, and high coulombic and energy efficiencies. These attributes, especially the high sp. energy and good low temperature performance, make the Li ion system an attractive option, i.e. the mass and volume of the Li ion MER battery would be half of that of the aerospace Ag–Zn and one-fifth of either Ni–Cd or Ni–H_2 batteries. Specifically, several aerospace Li ion prototype cells, fabricated by domestic manufacturers under the cognizance of a NASA-DoD consortium and being evaluated at JPL [2–6], have displayed several desirable attributes, listed below. Data presented here represent the performance of either 7 or 25 Ah prismatic cells from Yardney Technical Products, Pawcatuck, CT, USA. The cells contain mixed nickel cobalt oxide cathode, MCMB graphitic anode and a low temperature electrolyte with a ternary solvent mixture of ethylene carbonate, diethyl carbonate and dimethyl carbonate [7].

2.1. High specific energy and energy density

At the cell level, all the prototype tests have shown specific energies of over 120 Wh/kg and about 300 Wh/l.

2.2. Good low temperature performance

Good low temperature performance is made possible in these prototype cells via the use of optimal solvent mixtures, ternary or quaternary mixtures, or with appropriate film-forming, solvent-additives [7–11]. Capacities in excess of 65% of room temperature values were realized at −20 °C, at a moderate discharge rate of *C*/5.

2.3. High discharge rate capability

Over 85% of the low-rate capacity is accessible at rapid discharge rate of *C* at 25 °C). Similarly, high discharge rates approximating *C*/2 do not reduce the capacity appreciably even at −20 °C.

2.4. Long cycle life

The cells showed impressive cycle life over 1000 cycles to 80% of initial capacity both at ambient and low temperatures (Fig. 2). These cycles were performed at charge rates of *C*/5 (*C*/10 at −20 °C to avoid lithium plaiting) to 4.1 V, followed by a taper at 4.1 V to either a current of *C*/50 or for 3 h, whichever comes first. The discharge was carried out at *C*/5 to 3 V.

It should be borne in mind, that the low temperature cycling involves a low temperature charging as well as low temperature discharge, at −20 °C. If the charging were to be made at room temperature, the low temperature capacity would be better. As may be seen from the figure, the capacity fade rate during cycling is low and is diminished with reduction of temperatures.

2.5. Storage life

In addition to good low temperature performance and cycling characteristics, lithium ion cells have impressive storage characteristics, as illustrated in Table 1. Cells were stored at three different states of charge at temperatures simulating mission cruise, typically around 10 °C the first

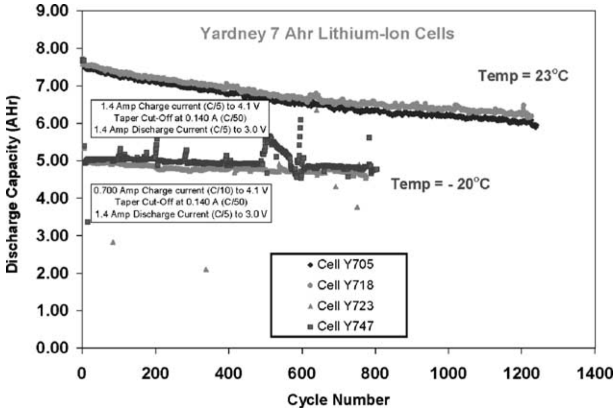

Fig. 2. Cycle life of Li ion cells at 25 and −20 °C.

Table 1
Characteristics of 25 Ah Li ion cells during on-buss storage at 0 °C

Cell number	SOC on buss	Capacity at −20 °C prior to buss storage (second cycle)	Capacity at 23 °C after 2 years buss storage (fifth cycle)	Percentage of initial capacity at 23 °C after 2 years buss storage	Percentage of initial capacity at 23 °C after 2 years buss storage	Capacity at −20 °C after 2 years buss storage (third cycle)	Capacity at −20 °C after 2 years buss storage as percentage of initial capacity at −20 °C prior to buss storage
Y003	30	34.0201	21.8307	33.5936	98.7464	20.9120	95.79
Y004	50	33.9624	22.4870	32.8729	96.7922	20.7299	92.19
Y005	70	33.4789	–	33.5205	100.1242	19.2257	–

10 months and later at 0 °C and discharged both at ambient and low (−20 °C) temperatures. As may be seen from the table, excellent capacity retention of over 95% is shown by the cells at all the three states of charge and even under low temperature discharge conditions, which are usually more sensitive to impedance growth.

2.6. *Good pulse capability*

Finally, the cells have good pulse capability to support pyro events at currents comparable to 2*C*–3*C* under all conditions of states of charge and temperatures (at low temperatures and low states of charge, however, the voltage drops below 3 V).

Based on the fact that the prismatic cell, as produced by Yardney, has demonstrated high packing efficiency in a rectangular envelope, which translates into a higher capacity, we selected the Yardney lithium ion battery for MER applications. In addition, the Yardney batteries have the advantages of MSP01 Lander heritage, with the batteries successfully qualified and also well supported by subsequent mission simulation tests [12,13].

Based on the energy needs, the battery system has been designed to be a 30 V, 600 Wh system, with two parallel batteries, for some degree of redundancy, each of eight 10 Ah cells in series. The battery will be housed in a warm electronics box of the rover and will be supported by boron epoxy struts for thermal insulation purposes.

The design of the battery assembly unit requires that the cells and batteries be inverted either during pre-launch/launch for a duration of 3 months or during the entire surface operation on Mars, i.e. for 3–12 months at reduced gravity. We chose the former option, to avoid extended cycling at the inverted position. Subsequently we found there to be little concern over cycling in the inverted condition from the following tests on four cells, with two cells cycled at ambient and at high temperatures (40 °C) in the inverted mode and two cells float-charged at 4.1 V at ambient and high temperatures (55 °C). Under all these conditions, we have baseline data with the cells in the normal upright position. Figs. 3 and 4 show performance of Li ion cells in the inverted mode during cycling at 40 °C and during float-charge at 25 °C, respectively. As may be seen from these figures, the lithium ion cells seem to perform adequately for the MER mission even in the inverted mode.

Fig. 5 gives a schematic representation of the Rover Battery Assembly Unit (RBAU), which consists of two eight-cell batteries in parallel. This design ensures that the two batteries are independent of each other in terms of preload, a requisite for prismatic cells.

After performing the initial characterization cycles at different temperatures and establishing that the batteries gave adequate capacities and with minimal cell to cell voltage dispersion (batteries resistively balanced otherwise), we carried out mission profiles tests to simulate conditions during launch, cruise and surface operations on each of the

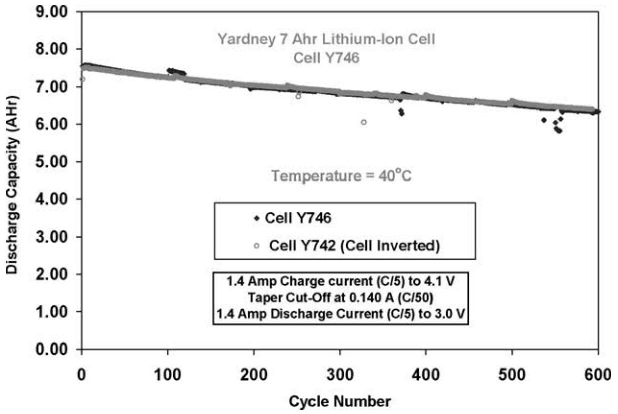

Fig. 3. Cycling of a prismatic Li ion cell in the inverted and normal terminal-up mode at 40 °C.

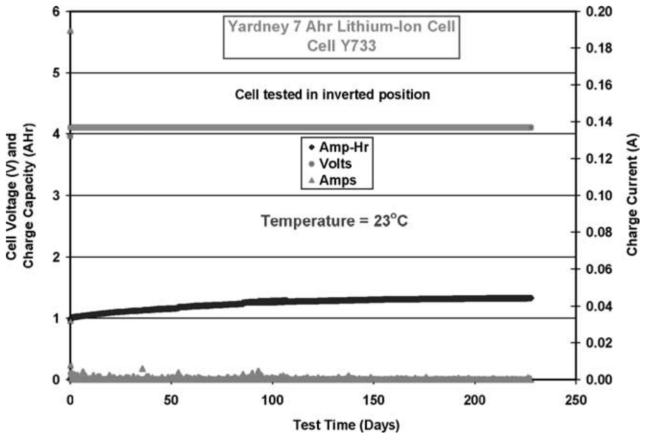

Fig. 4. Behavior of a prismatic Li ion cell in the inverted mode on 4.1 V float charge at 25 °C.

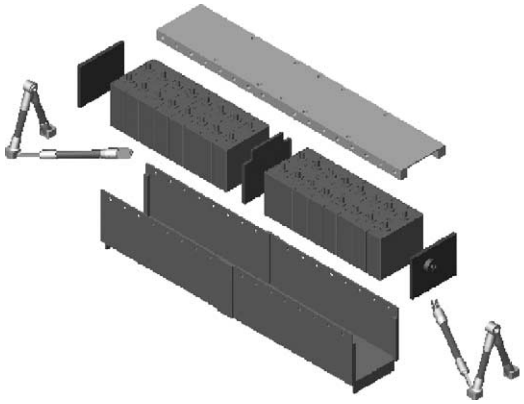

Fig. 5. Li ion Rover Battery Assembly Unit.

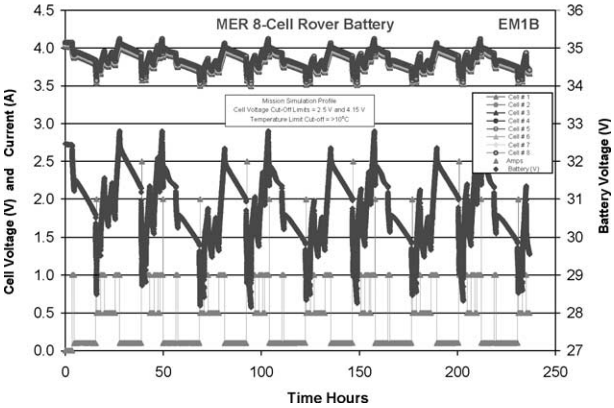

Fig. 6. Simulation of surface operations of the MER Rover Battery Assembly Unit.

batteries in the engineering RBAU. On the spacecraft, the charge and discharge processes of the batteries will be controlled with an in-house designed Battery Control Board that provides individual cell monitoring and control and maintains cell balance through the use of partial by-pass shunts for each individual cell. Fig. 6 shows the typical performance of the RBAU under a simulation profile for surface operations, simulated by a Maccor Battery Test system. The state of charge varies from 90% to slightly lower than 50% on each Martian sol.

3. Primary batteries

Unlike the rechargeable batteries, the function of the primary batteries will be fulfilled within 1.25 h of initial discharge. In this short duration, the batteries shall supply 27.1 A h at the 15 A rate @ 0 °C even with one battery non-functional, from 5 min prior to turn to entry (TTE) until the completion of the critical EDL deployment sequence (includes standup) on Sol 1. The desirable battery characteristics include: (a) high rate discharge capability; (b) low heat generation because of the absence of active cooling and near-adiabatic discharge conditions; (c) high specific energy and energy density; and (d) good shelf life. Various battery systems, including Li–$SOCl_2$, Li–SO_2, Li–BCX were considered for the initial trade-off studies. The absence of active cooling coupled with high discharge rates required that the initial battery temperature would have to be low (e.g. −10 °C for Li–BCX and Li–$SOCl_2$ and 0 °C for Li–SO_2) to avoid the final temperatures exceeding 60 °C. The Li–BCX system showed particularly inconsistent performance at these low temperatures and high rates. From a comparison of the available options, Li–SO_2 emerged as the most viable system, considering the performance characteristics and the availability of technology.

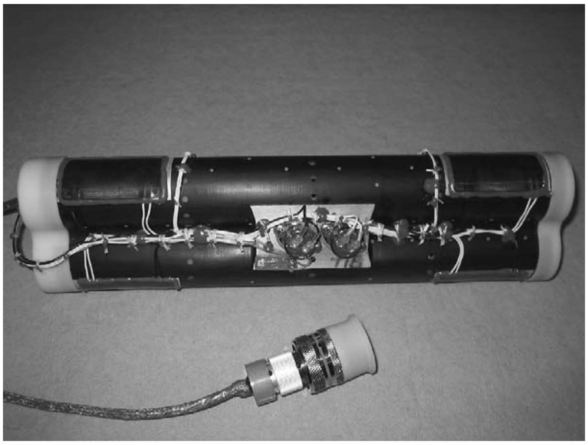

Fig. 7. Lander battery (36 V, 6.8 Ah), one of the five parallel units on MER Lander.

Between the three available cell design options of Li–SO_2, i.e. LO265X, LO265HX and LO255HX from SAFT America, the high rate designs (LOSHX), have heritage in terms of Stardust and Genesis missions, but have limited low temperature performance. The low-rate version, LO26SX, on the other hand, has good low temperature performance, owing to blended cathode of acetylene black and Ketjen black, and was thus chosen for MER applications. The lander battery assembly thus consists of five parallel strings of 12 D-size cells each to produce a 36 V, 34 Ah (∼1200 Wh) power source. The cells are stacked in three tubes, which are machined from a single piece of Al (Fig. 7).

Each such three-tube, a 12-cell stack, is bolted onto the pedals of Lander with Ti brackets.

4. Thermal batteries

The MER mission also requires thermal batteries to support the pyro events during descent and EDL events including opening of parachute. Each MER has two thermal batteries, for the sake of redundancy, located on the back shell, each capable of firing simultaneous three NSIs (NASA Standard Initiators for pyro events, each with a load of 10 A). The thermal battery chosen is an Eagle Picher Li–FeS_2 battery EAP 12137, that was used in several missions in the past, including Mars Pathfinder, Mars 98 and

Fig. 8. MER Li–FeS_2 thermal battery, fabricated by Eagle Picher Technologies.

Mars Odyssey (Fig. 8). While some of the dynamic requirements and pulse currents were marginally high for this battery, qualification tests showed that they met the MER environments and pulse loads.

5. Conclusions

The twin Mars Exploration Rovers, to be launched in the summer of 2003, will have Li–FeS_2 thermal batteries for supporting various pyro events during descent and EDL, primary batteries for supporting the entry, descent and landing operations, and Li ion rechargeable batteries for the surface operations. The use of lithium ion batteries for surface operations will help to extend mission life, beyond what was possible with the earlier Sojourner Rover mission on Mars Pathfinder, which contained Li–$SOCl_2$ primary batteries. Excellent performance characteristics were exhibited by the lithium ion prototype cells at low temperature, during cycling and on storage. The cells also functioned well as required by the design of Rover Battery Assembly Units. Protoflight batteries of Lander, thermal and Rover batteries are now being tested in conjunction with other components on the spacecraft.

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References

[1] B.V. Ratnakumar, M.C. Smart, G. Halpert, A. Kindler, H. Frank, S. Distefano, R. Ewell, S. Surampudi, in: Proceedings of the IEEE 17th Annual Battery Conference on Applications and Advances Lithium Batteries for 2003 Mars Exploration Rover, Long Beach, CA, 15–18 January 2002, pp. 47–52.

[2] M.C. Smart, B.V. Ratnakumar, L. Whitcanack, S. Surampudi, L. Lowry, R. Gitzendanner, C. Marsh, F. Puglia, J. Byers, R. Marsh, in: H. Croft, B. Staniewicz, M.C. Smart, B.V. Ratnakumar (Eds.), Proceedings of the 35th Intersoc. Energy Conv. Engg. Conf. (IECEC), Las Vegas, NV, 24–28 July 2000.

[3] R.A. Marsh, S. Vukson, S. Surampudi, B.V. Ratnakumar, M.C. Smart, M. Manzo, P.J. Dalton, J. Power Sources 97–98 (2001) 25.

[4] B.V. Ratnakumar, M.C. Smart, R. Ewell, S. Surampudi, R. Marsh, in: Proceedings of the 34th Intersoc. Energy Conv. Engg. Conf. (IECEC) on Performance Characteristics of Lithium-Ion Cells for Mars Sample Return Athena Rover, Vancouver, BC, 1999.

[5] M.C. Smart, B.V. Ratnakumar, L. Whitcanack, S. Surampudi, R. Marsh, in: Proceedings of the 2000 SAE Power Systems Conference on Performance Testing of Lithium Ion Cells at JPL for Future NASA Aerospace Applications, San Diego, CA, October 2000.

[6] B.V. Ratnakumar, M. C. Smart, R. Ewell, S. Surampudi, R.A. Marsh, in: Proceedings of the NASA Aerospace Battery Workshop on Performance Characteristics of Lithium Ion Prototype Cells for 2003 Mars Sample Return Athena Rover, Huntsville, AL, 17 November 1999.

[7] M.C. Smart, B.V. Ratnakumar, S. Surampudi, J. Electrochem. Soc. 146 (1999) 486.

[8] M.C. Smart, B.V. Ratnakumar, S. Surampudi, H. Croft, D. Tice, B. Staniewicz, in: Proceedings of the 200th Electrochemical Society Meeting on Improved Low Temperature Performance of Lithium Ion Cells with Low Ethylene Carbonate (EC) Content Electrolytes, Washington DC, October 2001, Ext. Abstr.

[9] M.C. Smart, B.V. Ratnakumar, S. Surampudi, J. Electrochem. Soc. 149 (4) (2002) A361–A370.

[10] M.C. Smart, B.V. Ratnakumar, L. Whitcanack, K. Chin, S. Surampudi, H. Croft, D. Tice, R. Staniewicz, in: Proceedings of the 11th International Meeting on Li Batteries on Improved Low Temperature Performance of Lithium Ion Cells with Quaternary Carbonate-Based Electrolytes, Monterey, 24–29 June 2002, J. Power Sources 00 (2003).

[11] E.J. Plichta, M. Hendrickson, R. Thomas, G. Au, W.K. Behl, M.C. Smart, B.V. Ratnakumar, S. Surampudi, J. Power Sources 94 (2001) 160.

[12] M.C. Smart, B.V. Ratnakumar, L. Whitcanack, S. Surampudi, J. Byers, R. Marsh, IEEE Aerospace Electron. Syst. Mag. 14 (11) (1999) 36–42.

[13] M.C. Smart, B.V. Ratnakumar, L. Whitcanack, S. Surampudi, J. Byers, R.A. Marsh, in: Proceedings of the NASA Aerospace Battery Workshop on Performance Characteristics of Lithium-Ion Prototype Batteries for Mars Surveyor Program 2001 Lander, Huntsville, AL, 17 November 1999.