

## LITHIUM BATTERIES FOR AEROSPACE APPLICATIONS: 2003 MARS EXPLORATION ROVER

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### ABSTRACT

Future NASA planetary exploration missions require batteries that can operate at extreme temperatures and with high specific energy and energy densities. Conventional aerospace rechargeable battery systems, such as Ni-Cd, Ni-H<sub>2</sub> and Ag-Zn, are inadequate to meet these demands. Lithium ion rechargeable batteries are therefore being chosen as the baseline for these missions. The 2003 Mars Exploration Rover 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  $-30^{\circ}\text{C}$ ), at moderate rates. This paper describes the selection criteria, design and performance of the three battery systems on 2003 MER mission.

### 1.0 INTRODUCTION

The Jet Propulsion Laboratory / NASA is planning to launch a twin-Rover mission to Mars, termed as Mars Exploration Rover 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 system (EDL) 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 payload elements, including a Mossbauer spectrometer, an alpha-particle X-ray spectrometry (APEX), a

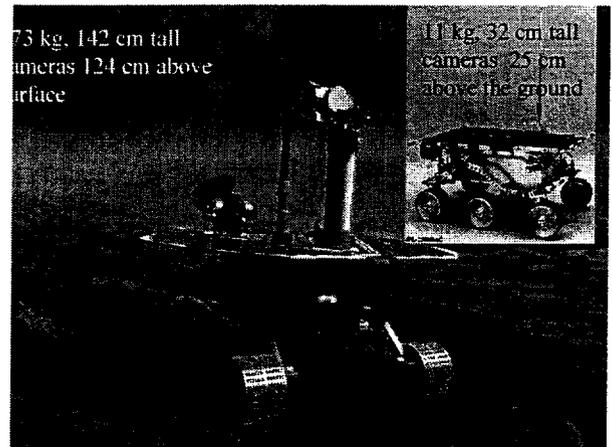


Fig1 : Comparison of the MER Rover with the Mars Pathfinder Sojourner Rover

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 ten times heavier (173 g vs. 11 Kg) and six times taller (142 cm vs. 25 cm), (Fig. 1). The payload, anticipated mission life, and the total distance traversed are proportionately an order of magnitude higher.

The MER mission will have three different batteries: primary, rechargeable and thermal batteries.<sup>(1)</sup> The primary batteries are located on the on Lander, which carries the Rover and releases it on the Martian surface. The primary batteries will support the Entry, Descent and Landing (EDL) Operations and will also support the first day's operations on Mars. The thermal batteries, located on the back-shell, will power pyro events that will enable the cruise stage separation. 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  $+30^{\circ}\text{C}$ , the Rover is provided with an aerogel-insulated warm electronics box, radioisotope heating units (RHUs), and a battery thermal switch heat rejection system.

## 2.0 RECHARGEABLE BATTERIES

The requirements for the rechargeable battery include an operating voltage of 24-36 V, with an energy of 220 Wh during launch, about 160 Wh for supporting any fault induced attitude excursion from sun point until reacquisition of sun point during cruise, and about 260 Wh/sol for surface operations. The battery should also provide a cycle life of at least 300 cycles at 50 % DOD at  $0^{\circ}\text{C}$ . In addition, the rechargeable batteries need to support multiple pulses of 25 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 has to be 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- $\text{H}_2$  batteries. Specially, several aerospace Li ion prototype cells, fabricated by domestic manufacturers under the cognizance of NASA-DoD consortium and being evaluated at JPL<sup>(2-6)</sup> have displayed several desirable attributes, listed below.

*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.

*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.<sup>(7-11)</sup> Capacities in excess of 65% of room temperature values were realized at low temperatures  $-20^{\circ}\text{C}$ , at a moderate discharge rate of C/5.

*High discharge rate capability* : Over 85 % of the low rate capacity is accessible at rapid discharge rate of C @  $25^{\circ}\text{C}$ . Similarly high discharge rates approximating C/2 do not reduce the capacity appreciably even at low temperatures of  $-20^{\circ}\text{C}$ .

*Long cycle life*: The cells showed impressive cycle life over 1000 cycles to 80% of initial capacity both at ambient and low temperatures. These cycles were performed at charge rates of C/5 (C/10 at  $-20^{\circ}\text{C}$  to avoid lithium plating) to 4.1 V, followed by a taper at 4.1 V to either C/50 A or for three hours. The discharge was carried out C/5 to 3 V.

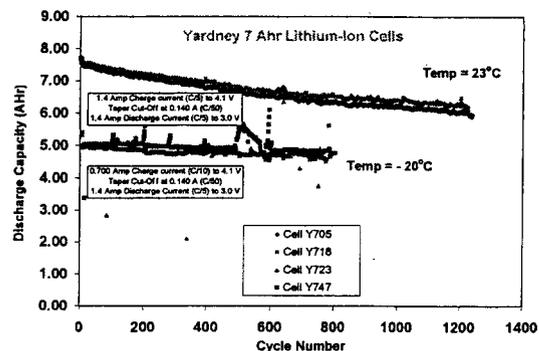


Fig. 2 : Cycle life of Li ion cells at 25 and  $-20^{\circ}\text{C}$ .

It should be borne in mind, that the low temperature cycling involves a low temperature charging as well at  $-20^{\circ}\text{C}$ . 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 even lower at low temperatures.

*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  $0^{\circ}\text{C}$  and discharged both ambient and low ( $-20^{\circ}\text{C}$ ) 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.

Cell Number	SOC on Bus	Capacity Prior To Bus Storage at $-20^{\circ}\text{C}$ (2nd Cycle)	Capacity After 2 Years Bus Storage $-20^{\circ}\text{C}$ (3rd Cycle)	% of Initial Capacity Prior to Bus Storage $-20^{\circ}\text{C}$			
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
Y028	70%	33.4789	—	33.5205	100.1242	19.2257	

Table 1: Characteristics of Li ion cells during on-buss storage at  $0^{\circ}\text{C}$ .

*Good Pulse capability:* Finally, the cells have good pulse capability to support pyro events at currents comparable to 2C-3C 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 a prismatic cell, as produced by Yardney, would have 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.<sup>(12,13)</sup> 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 three months or during the entire surface operation on Mars, i.e., for three to twelve months at reduced gravity. We chose the former option, instead of cycling cells for extended periods, albeit at low gravities. In this context, we designed a set of tests on four cells, with two cells cycled at ambient and at high temperatures ( $40^{\circ}\text{C}$ ) in the inverted mode and two cells float-charged at 4.1 V at ambient and high temperatures ( $55^{\circ}\text{C}$ ). Under all these conditions, we have baseline data with the cells in the normal upright position. Fig. 3 and 4 show performance of Li ion cells in the inverted mode during cycling at  $40^{\circ}\text{C}$  and during float charge at  $25^{\circ}\text{C}$ , 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.

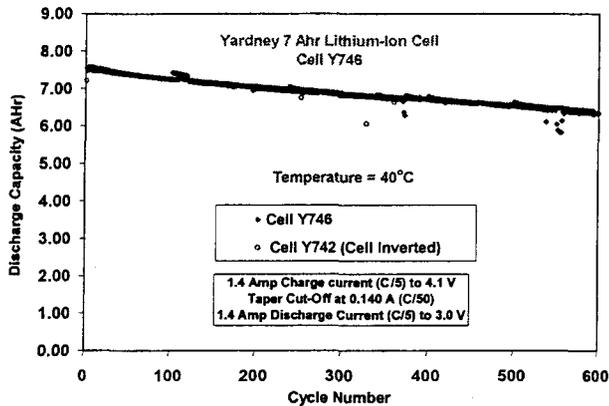


Fig.3 Cycling of a prismatic Li ion cell in the inverted and normal terminal-up mode at 40°C.

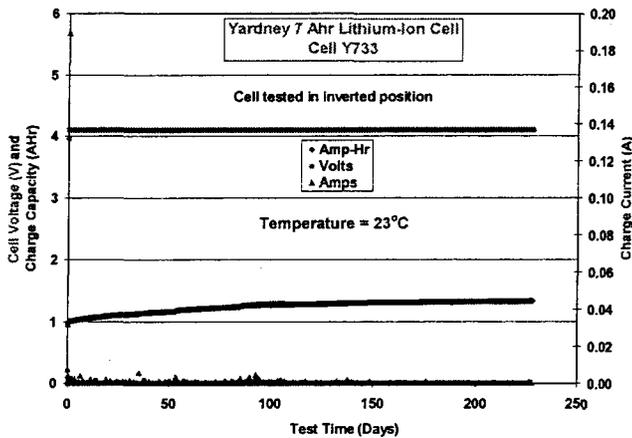


Fig.4: Behavior of a prismatic Li ion cell in the inverted mode on 4.1 V float charge at 25°C.

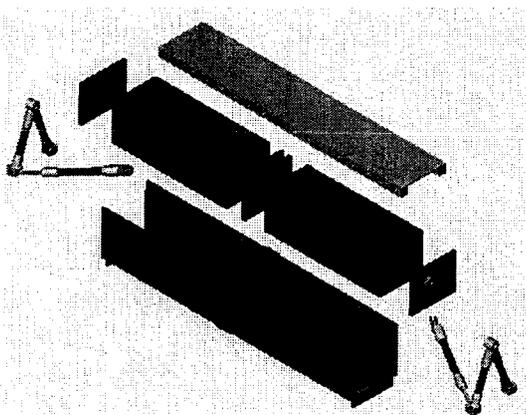


Fig. 5: Li Ion Rover Battery Assembly Unit (RBAU)

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 simulation profile test during launch, cruise and surface operations on each of the 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 monitor and control and prevents overcharge by pass shuts at the selected charge voltages. 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.

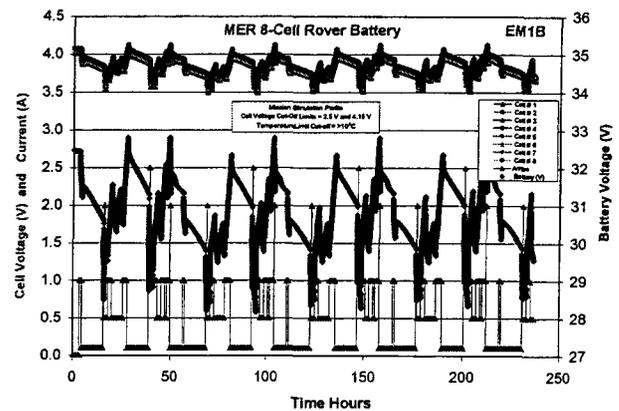


Fig. 6: Simulation of surface operations of the MER Rover Battery Assembly Unit (RBAU).

### 3.0 PRIMARY BATTERIES

Unlike the rechargeable batteries, the function of the primary batteries will be fulfilled within 1.25 hours of discharge. In this short duration, the batteries shall supply 650 Wh at a peak power of 250 W, from 5 minutes 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 good shelf life. Various battery systems, including Li-SOCl<sub>2</sub>, Li-SO<sub>2</sub>, 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<sub>2</sub> and 0°C for Li-SO<sub>2</sub>) 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<sub>2</sub> emerged as the most viable option, considering the performance characteristics and technological availability.

Between the three available options of Li-SO<sub>2</sub>, i.e., LOSX26, LiOSHX26 and LOSHX25 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, LOSX26, 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 get 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).

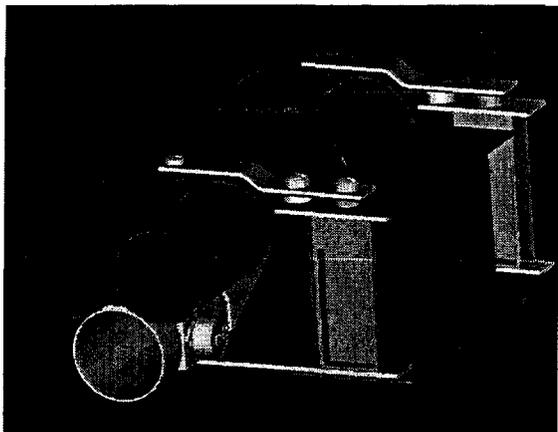


Fig. 7. Lander battery (36 V, 6.8 Ah), one of the five parallel units on MER Lander.

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

#### 4.0 THERMAL BATTERIES

The MER mission also requires thermal batteries to support the pyro events leading to cruise stage separation. Each MER has two thermal batteries, for the sake of redundancy, located on the back shell, each capable of firing simultaneous 6 NSI's (NASA Standard Initiators for pyro events, each with a load of 6 A). The thermal battery chosen is an Eagle Picher Li-FeS<sub>2</sub> battery EAP 12137, that was used in several missions in the past, including Mars Pathfinder, Mars 98 and Mars Odyssey. There are, however, some uncertainties, i.e., the dynamic environments as well as the pulse loads are marginally high. The prototypes that were tested met the MER environments and pulse loads.

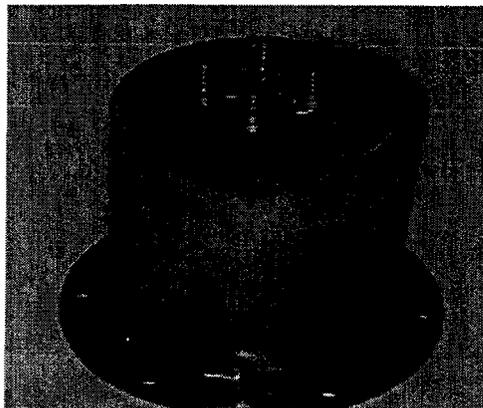


Fig. 8: MER Li-FeS<sub>2</sub> Thermal Battery, fabricated by Eagle Picher Technologies.

#### 5.0 CONCLUSIONS

The twin Mars Exploration Rovers, to be launched in the summer of 2003, will have Li-FeS<sub>2</sub> thermal batteries for supporting various pyro events during cruise stage separation, primary batteries for supporting the Entry Descent and Landing (EDL) operations, and Li ion rechargeable batteries for the surface operations. The use of lithium ion 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<sub>2</sub> 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.

## 6.0 ACKNOWLEDGEMENTS

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