1999-01-2447

Mars Rover 2003 Battery Charger

Frank Deligiannis, Richard Ewell and James Gittens
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, CA 91109

ABSTRACT

The Jet Propulsion Laboratory Mars Exploration Program Office is currently planning a series of exciting missions to the Red Planet. During each launch opportunity, the missions to Mars will include a Rover mission. During the earlier Rover missions to Mars such as the Mars Pathfinder mission carrying the Sojourner Rover in 1997, the main rover power source was a solar array. The power subsystem of the Sojourner Rover included a solar panel for power during the day, a non-rechargeable lithium battery for power during the night, and a power electronics board for power conditioning and distribution. Starting with the year 2003 the rover missions to Mars will incorporate a rechargeable energy storage device rather than a non-rechargeable power source. Included in the power electronics board, will be a battery controller/charger. The battery controller/charger will be able to monitor and control three parallel 4-cell battery strings. It will also incorporate a cell bypass circuit to ensure that the individual cells within a battery string are at the same state-of-charge. During the design phase of the power subsystem a breadboard version of a one 4-cell string battery charger was fabricated using discrete electronic components on a circuit board. The breadboard was to be used as proof of concept and was not optimized for weight or volume. The breadboard was tested initially using nickel cadmium cells and subsequently using commercial lithium ion rechargeable cells. In this paper a description of the single string charger and the breadboard setup will be presented along with the performance data of the bypass circuit.

INTRODUCTION

The Mars Rover 2003 also known as the Athena Rover 2003 is part of JPL's Mars Surveyor Program (MSP). The MSP has planned a series of missions to conduct surface and orbital studies to expand our knowledge of the Red Planet and enable the selection of samples for return to Earth. The scientific goals of the program are to understand the climate, resources and potential for life on Mars. The science strategy includes the completion of the global reconnaissance of the planet, surface exploration, and sample return missions. The Mars Surveyor 2003 lander and rover, and the Mars Surveyor 2005 orbiter, lander and rover projects are also jointly referred to as the Mars Sample Return mission. The Mars Surveyor 2003 Lander will carry a rover and a Mars ascent vehicle. The Athena Rover 2003 carried on the Mars Surveyor Lander will be approximately 3-4 times the size of the very popular Mars Pathfinder Rover 'Sojourner'. The Athena Rover '03 will be designed and built by the Jet Propulsion Laboratory. It will be launched in May 2003 and after a short 7-month cruise it will be deployed on the Martian surface in December 2003. The main objective of the Athena Rover is to document, select and collect Martian rock and soil samples. Consequently these samples will be deposited in the sample canister mounted on the Lander for future return to Earth. The Athena Rover will conduct this mission within 90 days of landing on the Martian surface.

POWER SUBSYSTEM

The Athena Rover '03 power subsystem consists of the components listed below:

- Gallium Arsenide (GaAs) solar panel for primary power
- Shunt radiator for radiating excess power
- Lithium ion rechargeable battery for energy storage
- Non-rechargeable battery for powering the real time clock
- DC/DC converters to provide conditioned power to engineering components
- Charge control electronics board to manage battery charging

Unlike the power subsystem on the 'Sojourner' rover, which incorporated non-rechargeable lithium batteries, the Athena Rover carries rechargeable batteries and consequently a charge control unit (battery charger). Using rechargeable batteries will extend operations during the night portion of the Martian day. However, the main power source will be a solar array, which provides load power and battery charging during the day portion of the Martian day. The solar panel will provide approximately 300-500Whr (beginning-of-mission) @ 14V to 18V assuming nominal operating conditions. The shunt radiator will be sized to radiate approximately 90 W of energy, which is the projected solar array peak power capability. The rechargeable lithium ion battery system will have capacity of 15 Ah @ 12-16.4 V and will be used for communications, nighttime operation and backup. The non-rechargeable battery will power the real time clock during the cruise period and after the rechargeable lithium ion battery is depleted. The regulated power-supplies will provide +5.0 V and ±15 V output voltage. The output voltage regulation will be maintained over an input voltage range of 11- 18 V. The battery charger portion of the power subsystem will manage the charging and discharging of the battery system while also providing individual cell monitoring & protection.

LITHIUM ION BATTERIES

Lithium ion chemistry has been utilized in the commercial consumer electronic industry for several years now. The commercial consumer electronic industry has been providing consumers with lithium ion battery packs for laptop computers, camcorders and cellular phones. The electronic industry quickly recognized the need to closely monitor and control individual lithium ion cells in batteries. Intel Corp. and Duracell Inc. proposed the System Management Bus (SMBus) and the Smart Battery System (SBS) Specification utilizing the I^2C bus for an interface. According to the SBS Specification the definition of a Smart Battery is: "A battery equipped with specialized hardware that provides present state, calculated and predicted information to its SMBus Host under software control" (**Ref. 1**). In addition to safety, the primary motive behind the SBS Spec effort was to notify laptop computer (or other electronic device) users of the true remaining run time. As 'smart' batteries become more popular in the commercial world, the lithium ion chemistry is also making its way into the aerospace industry. As the aerospace users are making the transition from the nickel based battery chemistries to lithium ion, they are now beginning to adapt and make the appropriate changes in the electronics to accommodate the specifics of the lithium ion chemistry.

The Athena Rover battery system consists of 3 batteries in parallel providing approximately 15 Ah of energy storage capability. Each battery has 4 cells in series thus providing a voltage range of 12 to 16.4 V. The battery system is designed in such a way as to be able to provide ample energy during the nighttime operations and during excess load drains during the day with only two batteries, thus the third battery serves as a redundant unit. Lithium ion batteries were chosen for their higher specific energy, which is approximately 100 Wh/Kg as opposed to the nickel chemistries, which have specific energies ranging between 25 and 70 Wh/Kg. Lithium ion batteries were also attractive because of the wider operating temperature range over the nickel-based batteries. However, the lithium ion chemistry has no overcharge protection, thus individual cells within a battery are required to be monitored and controlled. The lithium ion cell voltage is not allowed to exceed a set voltage in order to avoid premature cell degradation. Nickel-based space batteries and charge control units have been utilized in space applications for several decades now. The NASA standard battery system used in the Modular Power System was three 50Ah 22-cell NiCd batteries in parallel. No cell voltage monitoring was required. The charging unit monitored only the battery voltages and half-battery voltages. The battery charge was controlled by battery voltage limits, which were temperature compensated. This simpler type charge control unit could not be used with lithium ion batteries. A redesign of the traditional aerospace charge control unit was necessary. To date several lithium ion battery management techniques exist in the industry, most of which are tailored for commercial applications and maximizing run time during one cycle. The Athena Rover 2003 charge control electronics board performs battery management for an aerospace power system with lithium ion batteries.

CHARGE CONTROL ELECTRONICS

The Athena Rover charge control unit combines the functions of a traditional battery charge control unit and the functions of a lithium ion cell bypass unit. The charge control electronics board includes:

- a shunt limiter
- a mission clock
- heater control
- a microcontroller based on an 8051-processor
- two power converters
- a serial RS-422 data interface.

The charge controller can be powered by the solar array, lander power, ground support equipment power or lithium ion battery power. It has the capability to monitor twelve cell voltages, 3 battery currents, a source current, bus current, bus voltage and battery temperatures. The microcontroller is a high density interconnect multi-chip module containing an 8051 central processing unit. This advanced low power, small volume microcontroller was part of a development effort of another JPL project - the New Millenium Deep Space 2 Microprobe project (**Ref. 2**). The microcontroller monitors all critical battery parameters and acts as the backup to the hardware control. The charger hardware has the capability of controlling the charge of three batteries in parallel, with each battery containing four cells in series. An initial breadboard charger was designed and fabricated having the capability of controlling a single string battery with four cells in series. The breadboard battery charger was tested for functionality prior to the design and fabrication of the brassboard version, which will have the capability to control 3 batteries in parallel. Results from the breadboard version are discussed in the next section. The charger monitors individual cell voltages, however, can only control the charging mode at the battery level. The charger also incorporates a cell bypass circuit within a battery string. The charging technique implemented is a pseudo-constant current charge to a selectable bus voltage and continuation with constant voltage charge. The constant voltage level is controlled by the shunt limiter settings at the power bus level. The shunt limiter has five selectable bus voltage levels ranging from 17.2 to 16.4 V.

The cell bypass logic is based on monitoring the individual cell voltages. The charger unit has a series of set and selectable voltages, which are described below:

- **The maximum charge voltage (Vch).** This voltage is the upper limit/not to exceed voltage. The maximum charge voltage has 3 selectable levels (4.1, 4.0 and 3.9 V/cell).
- **The end-of-bypass voltage (Vebp).** This voltage is used to determine whether a cell is removed from the bypass mode. There are 3 selectable end-of-bypass voltage levels, which are a function of the maximum

charge voltage levels. Each of the three Vebp settings is 150mV below each respective Vch setting.

- **The bypass voltage (Vbp).** This is used to determine whether a cell is placed in the bypass mode. There are 3 selectable bypass voltage levels, which are a function of the maximum charge voltage levels. Each of the three Vbp settings is 50mV below each respective Vch setting.
- **The end-of-discharge voltage (Vd).** This is the voltage when reached the discharge is terminated and the battery string is removed from discharge. This voltage has only one setting (3.0 V/cell).

When the charger is in the nominal charging mode and a cell within the battery pack reaches the maximum charge voltage and at least one other cell is below the bypass voltage the cell which reached the maximum charge voltage is bypassed. When a cell is bypassed, a resistor is connected in series and the cell begins to discharge slightly. When a bypassed cell reaches the end-of-bypass voltage limit, it is then placed back into the main battery string and allowed to charge again. Charging is terminated when a cell has reached the maximum charge voltage and the remaining cells are above the bypass voltage. Charging continues as long as one cell remains below the bypass voltage. During discharge the cell voltages are monitored and discharge is terminated when a cell reaches the end-of-discharge voltage. During implementation of the mission, under nominal conditions the day-night cycles and the variation in solar array voltage will control the charge and discharge modes. Under nominal mission conditions the battery will be used to a 50% Depth-of-Discharge (DOD) and for approximately 180 cycles.

TEST RESULTS

Figure 1 exhibits the charge/discharge voltage and current profiles of four 'D' size prototype aerospace lithium ion cells connected in series. The four cells were purposely discharged to various state-of charge levels prior to battery assembly. An unbalanced battery was desired for the sole purpose of testing the functionality of the cell bypass portion of the charger. The four cells were discharged at 1.0 A and charged at 500 mA. The 4-cell battery was charged with a constant current of 500 mA up to a bus voltage of 16.8 V, subsequently the charging continued at a constant voltage rate. After 320 minutes of charging cell #1 reached the maximum charge limit of 4.1 V and was bypassed. Subsequently, cell #4 reached the maximum charge voltage and it was bypassed. The remaining two cells continued to charge and as the next cell reached 4.1 V and the other three cells were above the bypass voltage, the charger went into the discharge mode. During the discharge as soon as the first cell reached the end-of-discharge voltage the charger went into the charging mode.

Figure 2 exhibits the charge/discharge voltage and current profiles of a string of 4 commercial lithium ion cells cycled under nominal conditions. The 4 cells used in the battery pack were previously cycled under various conditions. The previous history of cycle life and cycling conditions was not recorded or logged. The cells were randomly selected and assembled into a battery pack with the objective of testing the functionality of the battery charger breadboard. The figure exhibits three consecutive charge/discharge cycles. The charging was at a constant current 500 mA rate until the bus voltage of 16.8 V, subsequently the charging continued at a constant voltage mode. The discharge rate was 500 mA constant current. During the cycling operations, implementing the conditions described above, the battery charger bypass circuit was not activated. This type of operation is expected

Figure 1. Charge/Discharge Cycle of an Aerospace Prototype 4-cell Lithium Ion Battery

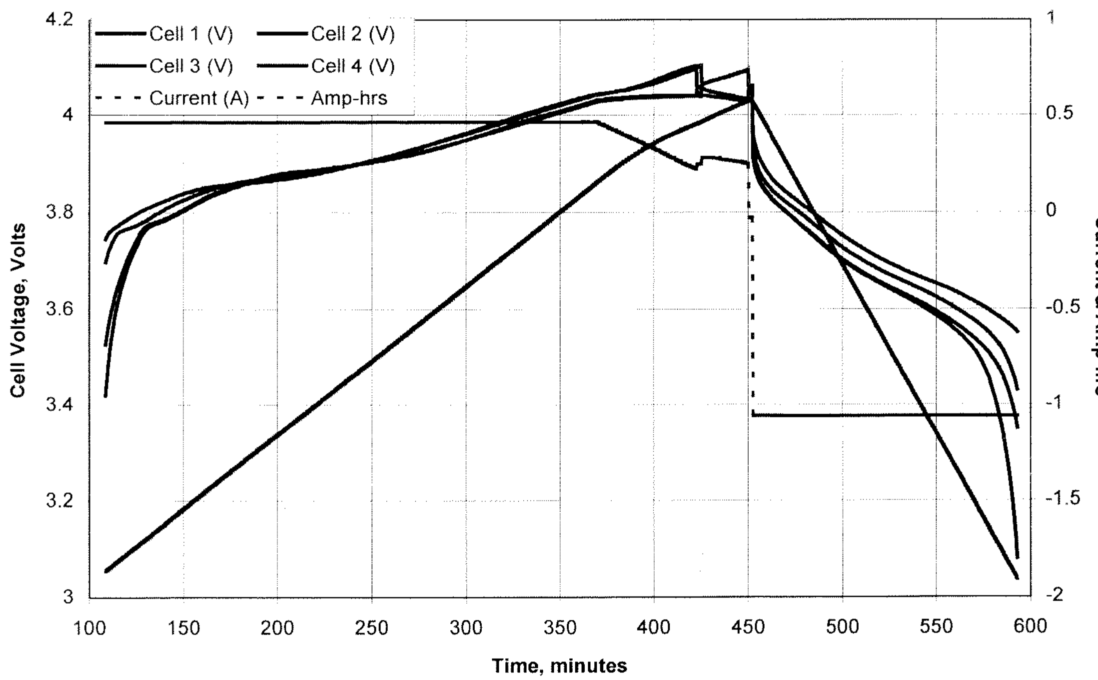
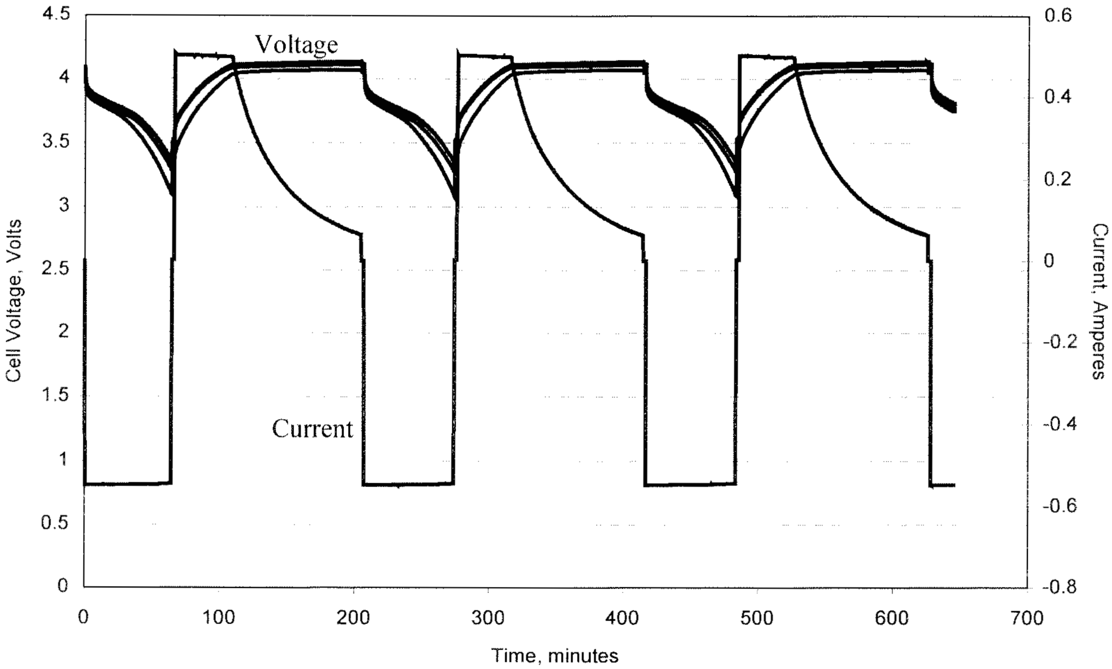


Figure 2. Charge/Discharge Cycles of a Commerical 4-cell Lithium Ion Battery



during nominal surface operations. The Athena Rover power system is designed to use only 50% of the available battery capacity, therefore, nominal operating conditions do not require to "top-off" the batteries to 100% state-of-charge. A lower state-of-charge of over 95% is acceptable and provides for a simpler charging method. However, the capability to charge the batteries to 100% SOC does exist, if it becomes necessary during any fault protection modes.

SUMMARY

The Athena Rover 2003 has incorporated a rechargeable battery in the power subsystem, in order to prolong surface operations. The lithium ion chemistry was selected over the traditional nickel chemistries for it's higher specific energy and it's wider operating temperature range. Despite the advantages the lithium ion chemistry offers, the lithium ion battery requires an elaborate battery management system for controlling the charging process. The lithium ion battery charger is required to monitor and control the charging process of individual cells. The first version (breadboard unit) charge control unit for the Athena Rover 03 was designed and tested at the Jet Propulsion Laboratory. The breadboard version has the capability of controlling 4 lithium ion cells in series. The breadboard also incorporates a cell bypass circuit as a method of controlling overcharge on individual cells. Test results using commercial lithium ion cells and prototype aerospace cells exhibited the proper operation of the breadboard unit. Plans are to move to the next battery charger version, the brassboard unit. This unit will provide the ability to monitor and control a total of 12 lithium ion cells (three 4-cell batteries in parallel). In addition, the brassboard charger will incorporate a microcontroller, which was developed in a joint effort among the AFRL & JPL for a previous JPL mission – Deep Space 2. The microcontroller will provide additional fault protection and will be the interface with the flight computer.

ACKNOWLEDGMENTS

The work described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

REFERENCES

1. Smart Battery Data Specification, Revision 1.1, SBS-Implementers Forum, December, 1998.

2. "Ultra-Miniature Instrument Control Processor for Space Application" James Lyke and Dave Alexander, Digest of Papers, Government Microcircuit Applications Conference, vol. XXIV, March 8-11, 1999, Monterey, CA