Lithium Ion Batteries for Mars Exploration Rovers

Transition from Technology Validation to Flight Insertion

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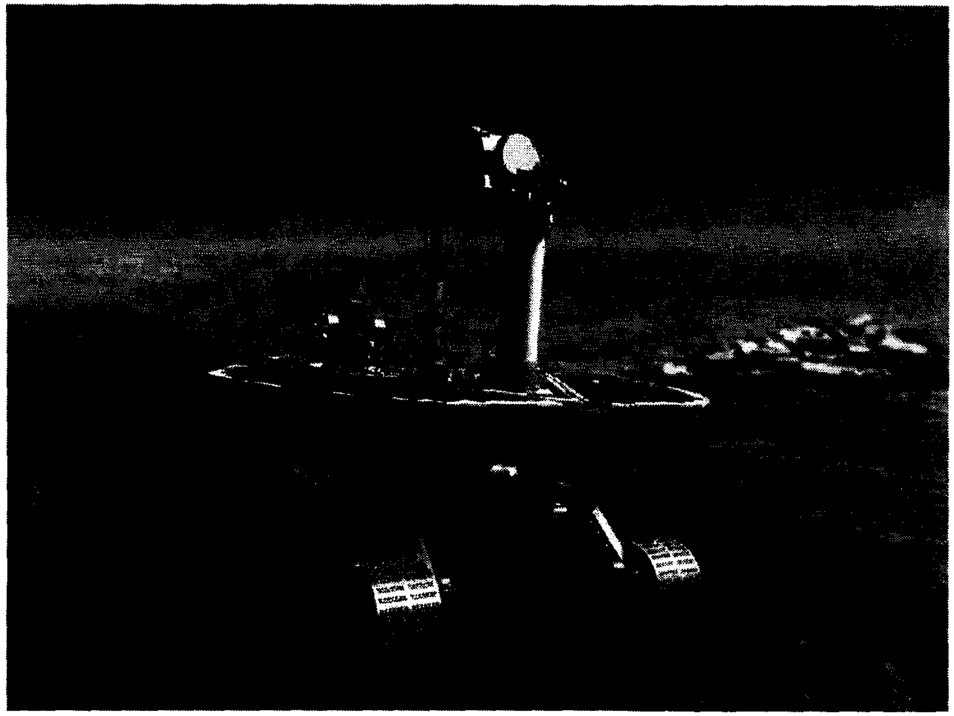
The Mars Exploration Rover
An in situ science mission to Mars

Salient Features

- Two identical landers launched in May-July 2003 on Delta II 7925 Launch vehicle.
- Targeted to two sites on Mars, landing January and February 2004
- Mars Pathfinder lander architecture
- Each delivers a highly capable rover carrying the Athena payload

    On a mast:
        Camera and spectrometer
    On a 5-degree-of-freedom robotic arm:
        Spectrometers, microscopic imager, rock abrasion tool
    On the rover:
        Magnet array, calibration targets



- Two surface missions with an integrated traverse distance of greater than 600 meters over the 90-sol mission lifetime with a possible extended mission.

2003 MER vs. 1996 Sojourner

Mission Objectives

- Science
  - Search for and characterize a diversity of rocks and soils that hold clues to past water activity
  - Investigate landing sites which have a high probability of containing physical and/or chemical evidence of the action of liquid water
  - Determine the distribution and composition of minerals, rocks, and soils
  - Characterize mineral assemblages and textures in the geologic context
  - Identify and quantify iron-bearing minerals indicating aqueous processes
  - Extract clues from geologic investigation related to liquid water to assess whether past environments were conducive for life

- Program
  - Demonstrate long-range traverse capabilities by mobile science platforms
  - Demonstrate complex science operations with two mobile laboratories
  - Validate the standards, protocols, and capabilities of the orbiting Mars communications infrastructure

Science instruments (Athena Heritage)

- **Two remote sensing instruments mounted on Pancam (Panoramic Camera) Mast Assembly to select target.**
  - **Mast mounted Stereo cameras with color filters on pan/tilt gimbal.**
  - **Mini Thermal Emission Spectrometer (Mini-TES) Near and mid-IR point spectrometer for mineralogy of rocks.**

- **In-Situ Payload Elements**
  - **Mossbauer Spectrometer for mineralogy of Fe-bearing minerals in rocks.**
  - **Alpha Particle X-ray Spectrometer (APXS) for elemental chemistry.**
  - **Microscopic Imager (MI) for environmental conditions under which geologic materials formed.**
  - **Rock Abrasion Tool (RAT) to penetrate thro' rock dust and surface alteration.**

- **The front HAZCAMs provide imaging of workspace for ground planning of instrument deployments**

Rover Capabilities

Avionics
- Rad6000 Flight Computer (20Mhz, 128MB DRAM)
- 256MB Non-volatile FLASH data storage
- Analog, digital, serial IO
- Motor control for 36 brushed motors, 4 stepper motors & 4 brushless motors

Power
- Triple-Junction GaInP/GaAs/Ge cell deployable solar arrays
- (2) 8A-hr Li-Ion rechargeable batteries
- Power conversion and distribution

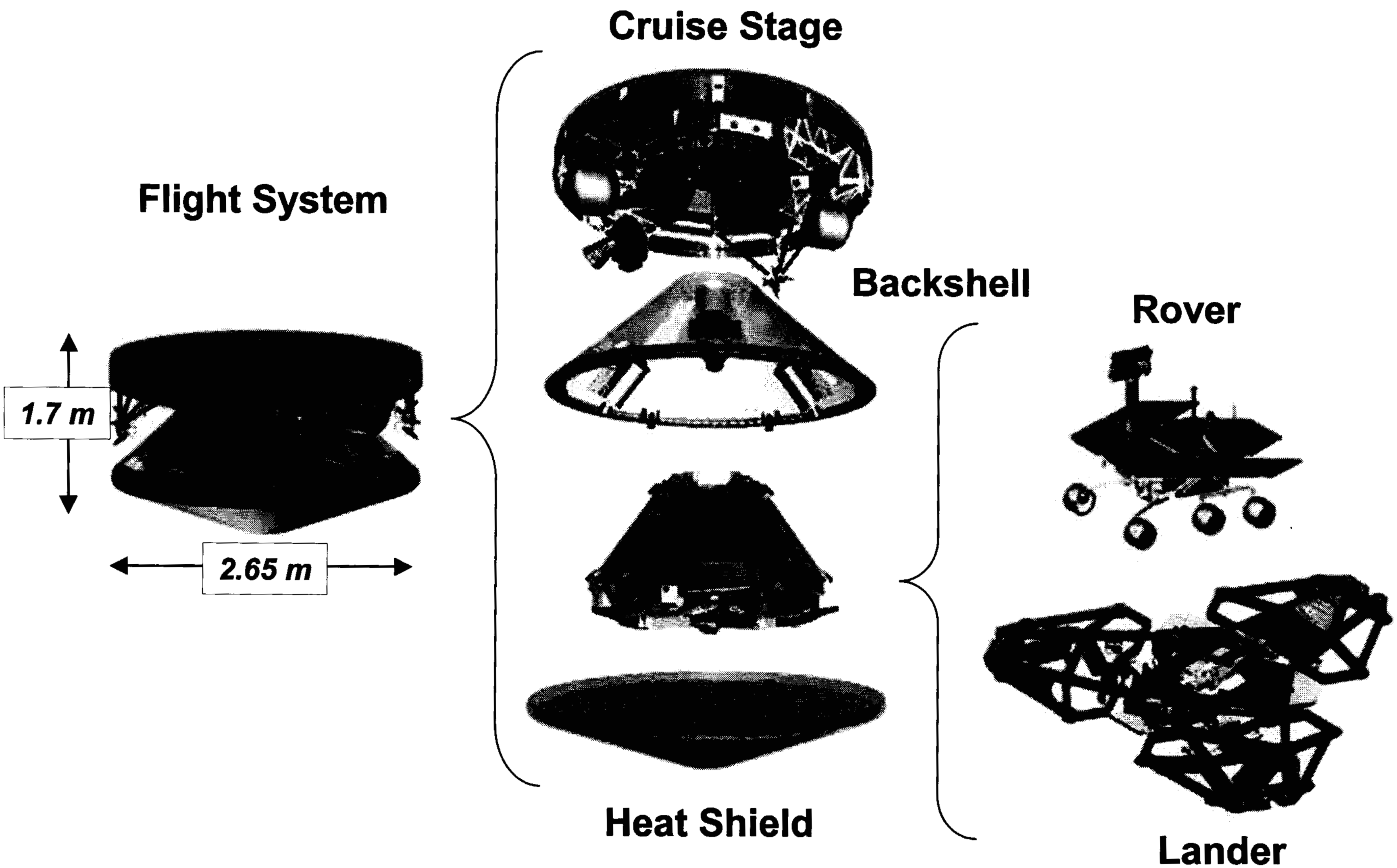
Navigation Sensors
- Mast mounted stereo navigation cameras - NAVCAMs - Front & Rear stereo hazard cameras - HAZCAMs - with 120deg FOV) SUNCAM (mounted on HGA gimbal)
- 6DOF IMU

Telecom
- Direct to Earth Communication (X-band) with fixed Low Gain and gimbaled High Gain Antennas
- Orbiter relay communication (UHF) with fixed monopole antenna

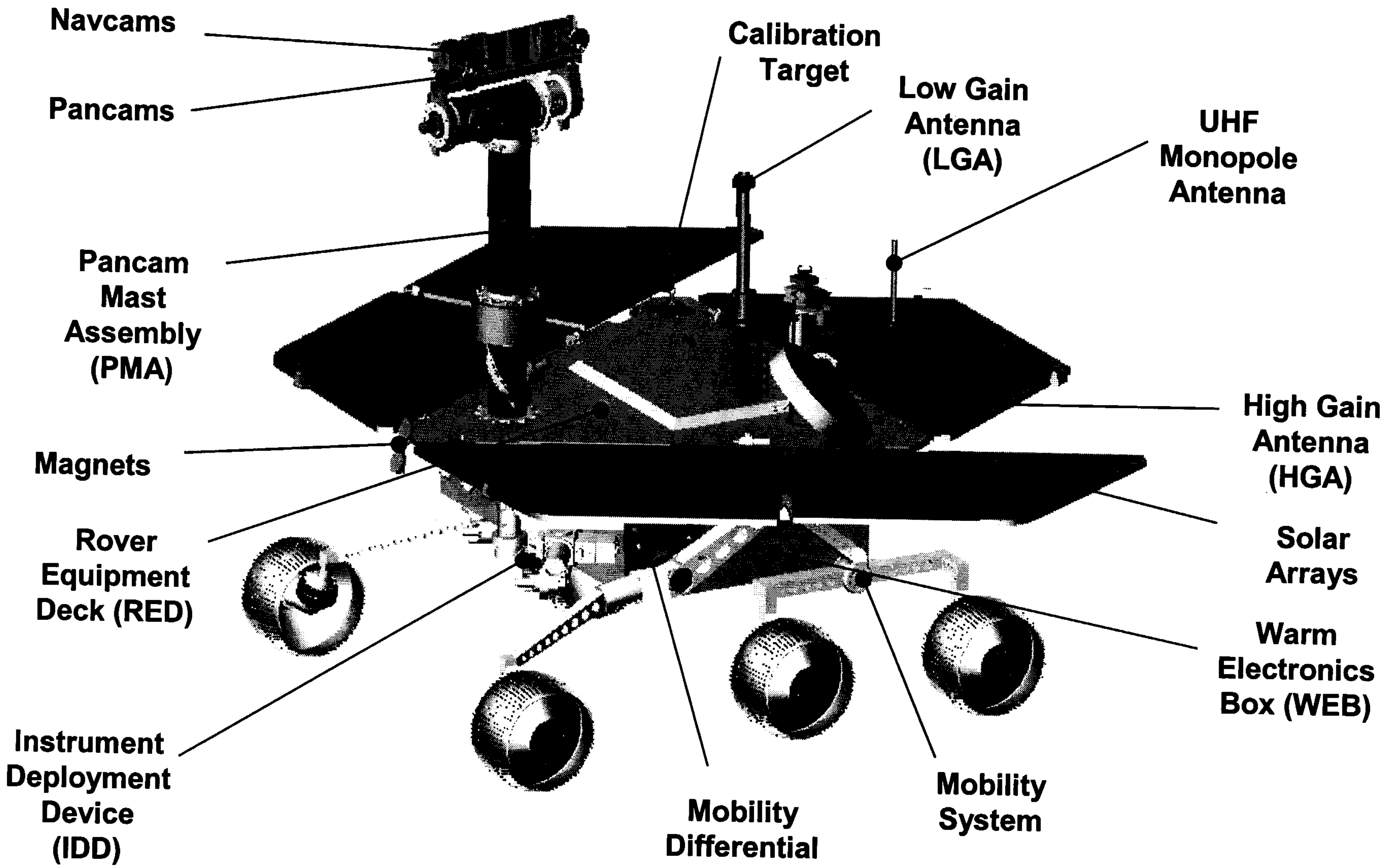
Mobility System
- 6 wheel Rocker-Bogie mechanism with 25cm diameter wheels
- 5cm/s top speed (~0.6m/minute under autonomous navigation)

Thermal
- Aerogel insulated Warm Electronics Box
- Resistive heaters on external motors/cameras and internal components
- Radioisotope heating units (RHUs)
- Battery thermal switch heat rejection system
- SSPA Loop Heat Pipe heat rejection system

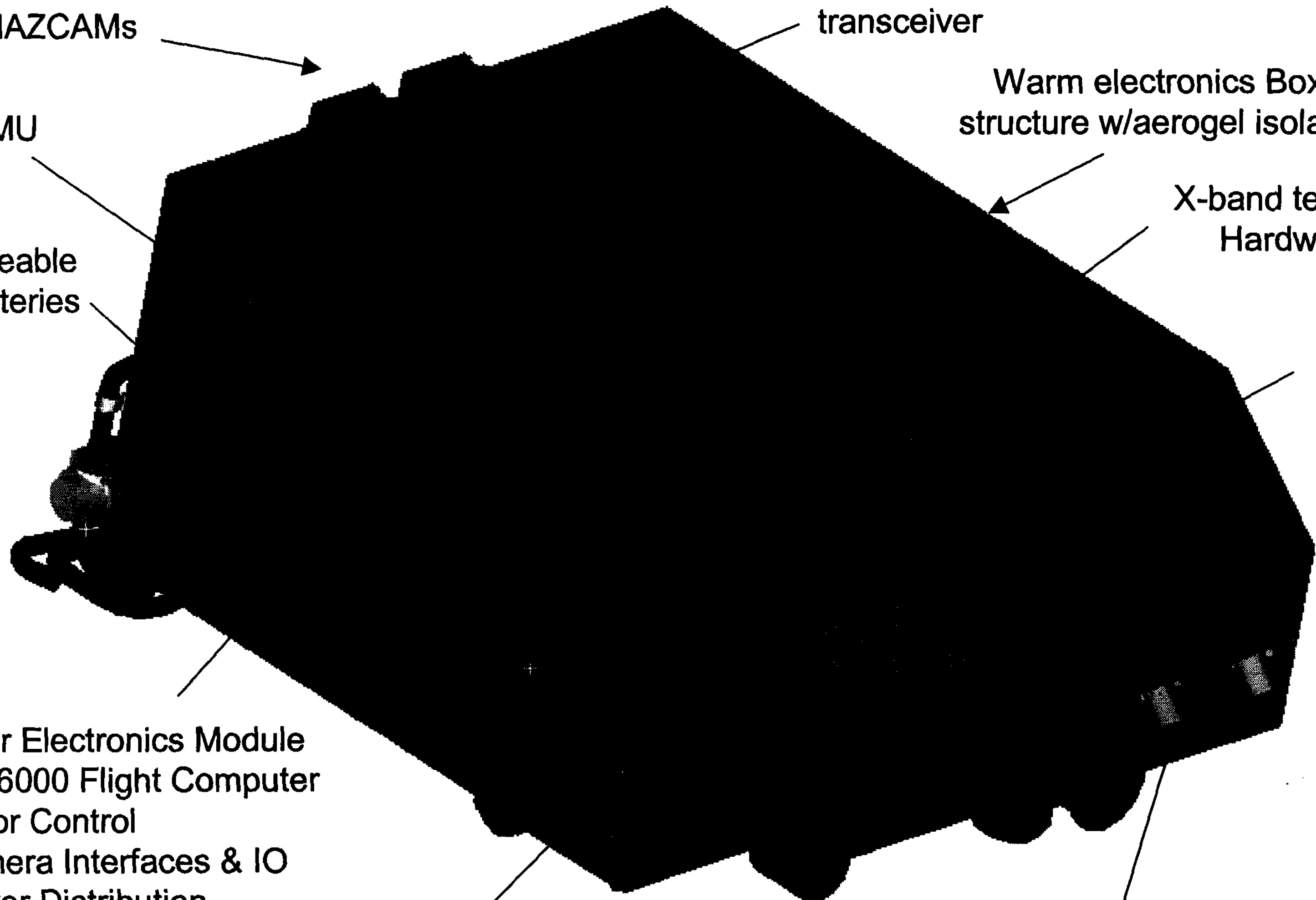
Flight System Configuration



Rover Configuration - Deployed



Rover Warm Electronics Box



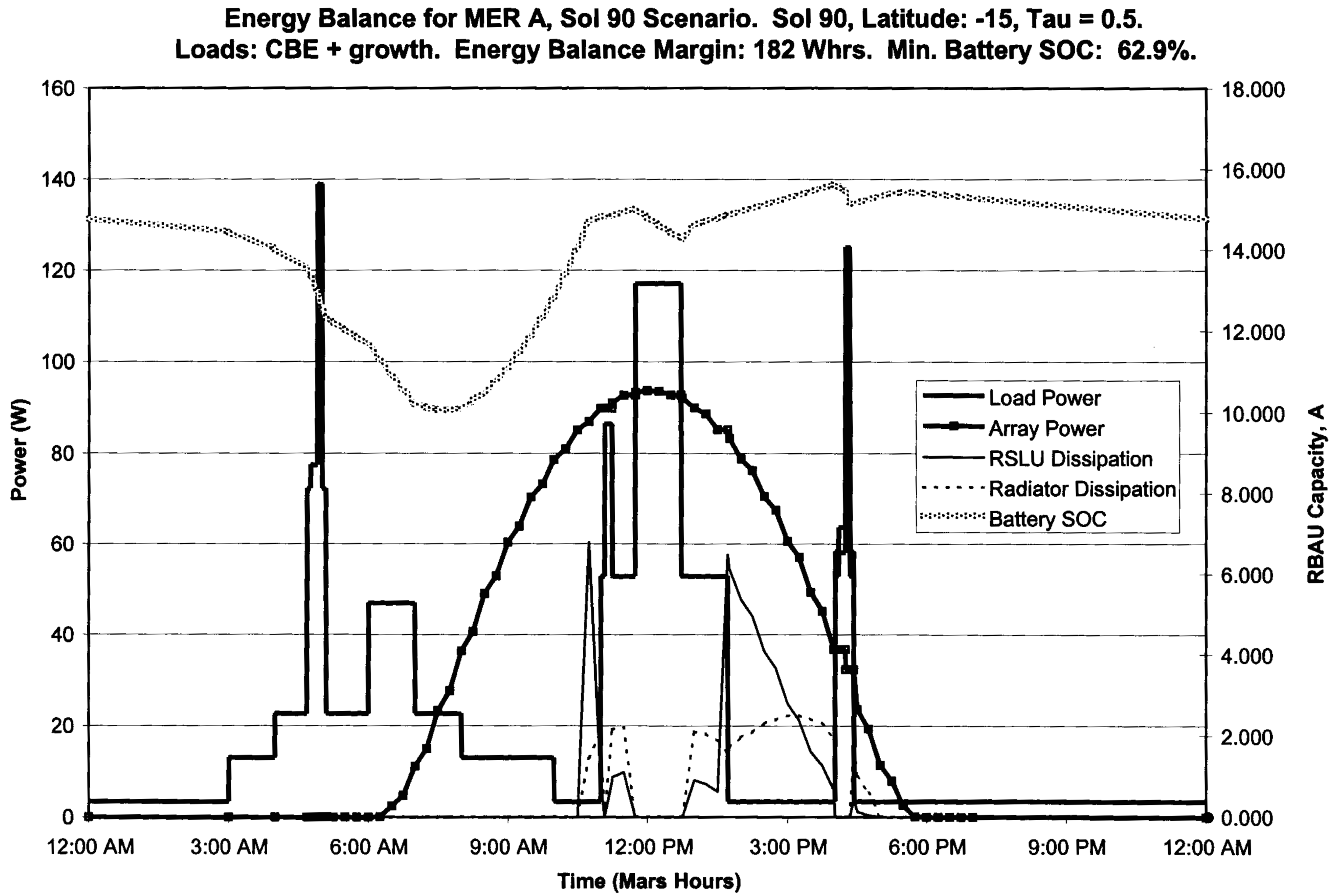
Li Batteries for MER

- **Primary batteries**
  - For Turn to Entry maneuvers, Entry, Descent and Landing (EDL) operations
  - Initial landing operations (Rover regress)
- **Rechargeable Li ion batteries**
  - Launch
  - Cruise anomalies
  - Pyro events
  - Surface operations through Sol 90
- **Thermal Batteries**
  - Support back shell pyros

Rover Battery Assembly Unit –Requirements

- **Voltage : 24- 36 V (Cruise min. 27 V)**
- **Launch: The power subsystem shall be capable of supplying 200 Whrs during launch, from the switch to internal power until spacecraft separation.**
  - **The battery shall be capable of recycling within 30 minutes after an abort of the first opportunity.**
- **Cruise : Some fault cases may leave the spacecraft in a state where the solar arrays are not illuminated. Power shall be capable, at anytime, during cruise to provide 160 Whrs of energy without solar illumination (to a voltage of 27 V min).**
- **Surface Operations: Capable of operating on the surface of Mars for > 90 Sols.**
- **The Rover RBAU shall be capable of providing 283 Whrs of energy on a single charge.**
- **The Rover RBAU shall be capable of 270 cycles at 50 % DOD at 0° C.**
- **The Rover RBAU shall be capable of return to full charge over a 10 hour period**
- **The Power Subsystem shall assure that the loss of one secondary battery or other BCB will not impact the rest of the S/C.**
- **Each battery in the RBAU shall be capable of firing simultaneous three pyros (each with a load of 7 A) with an interval of at least 100 ms.**

Power Profile for Surface Operations- Sol 90



Rover (Rechargeable) Batteries

Criteria for Battery Selection

- **High Specific Energy and Energy Density**
  - **> 100 Wh/kg and > 200 Wh/l at cell level**
- **Good Low Temperature Performance**
  - **> 65% of RT capacity available at -20°C @ C/5 to 3.0 V/cell**
  - **> 70 % of RT capacity accepted during ≥ 0°C charge at > C/10 to 4.1 V/ cell**
- **High Discharge Rate Capability**
  - **> 85% of Low Rate Capacity available at C rate @ 25°C.**
- **Long Cycle Life**
  - **> 90 % of the initial capacity at 20°C available after 300 cycles at 50% DOD at 0°C.**
- **Good Storageability**
  - **> 85 % of the initial capacity realizable after two years of storage (at 0-10°C and 50-70% SOC)**

Rover (Rechargeable) Batteries-Trade off Studies

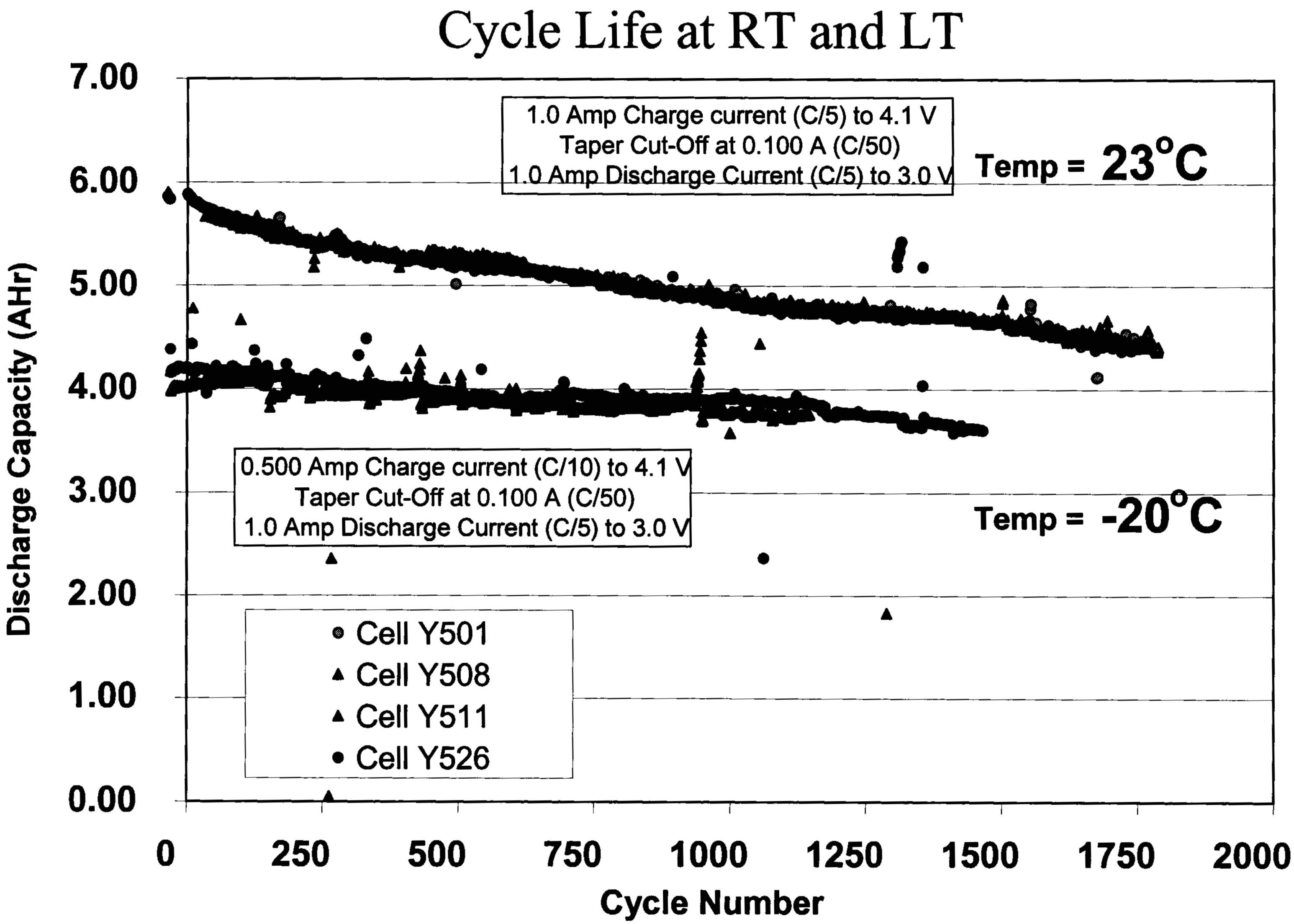
System → Characteristic ↓	Nickel-Cadmium	Nickel-Hydrogen	Silver-Zinc	Lithium-Ion
Specific Energy (Wh/kg)	25	30	~100	>100
Energy Density (Wh/lit)	100	50	~150	>250
Battery Mass for 300Wh MER (kg)	33	28	11	6
Battery Volume for 300 Wh MER (Lit)	9	17	6	2.2
Cycle Life (50% DoD)	>1000	>1000	<100	>1000
Wet life (Storageability)	Excellent	Excellent	Poor	Good
Self-Discharge (per month)	15%	30%	15-20%	<5%
Low temperature Performance (-20°C)	Moderate	Moderate	Moderate	Excellent
Temperature Range, °C	-10- 30	-10- 30	-10- 30	-20 to +40
Charge Efficiency %	80%	80%	70%	~100%

Rover (Rechargeable) Batteries

Lithium - Ion System

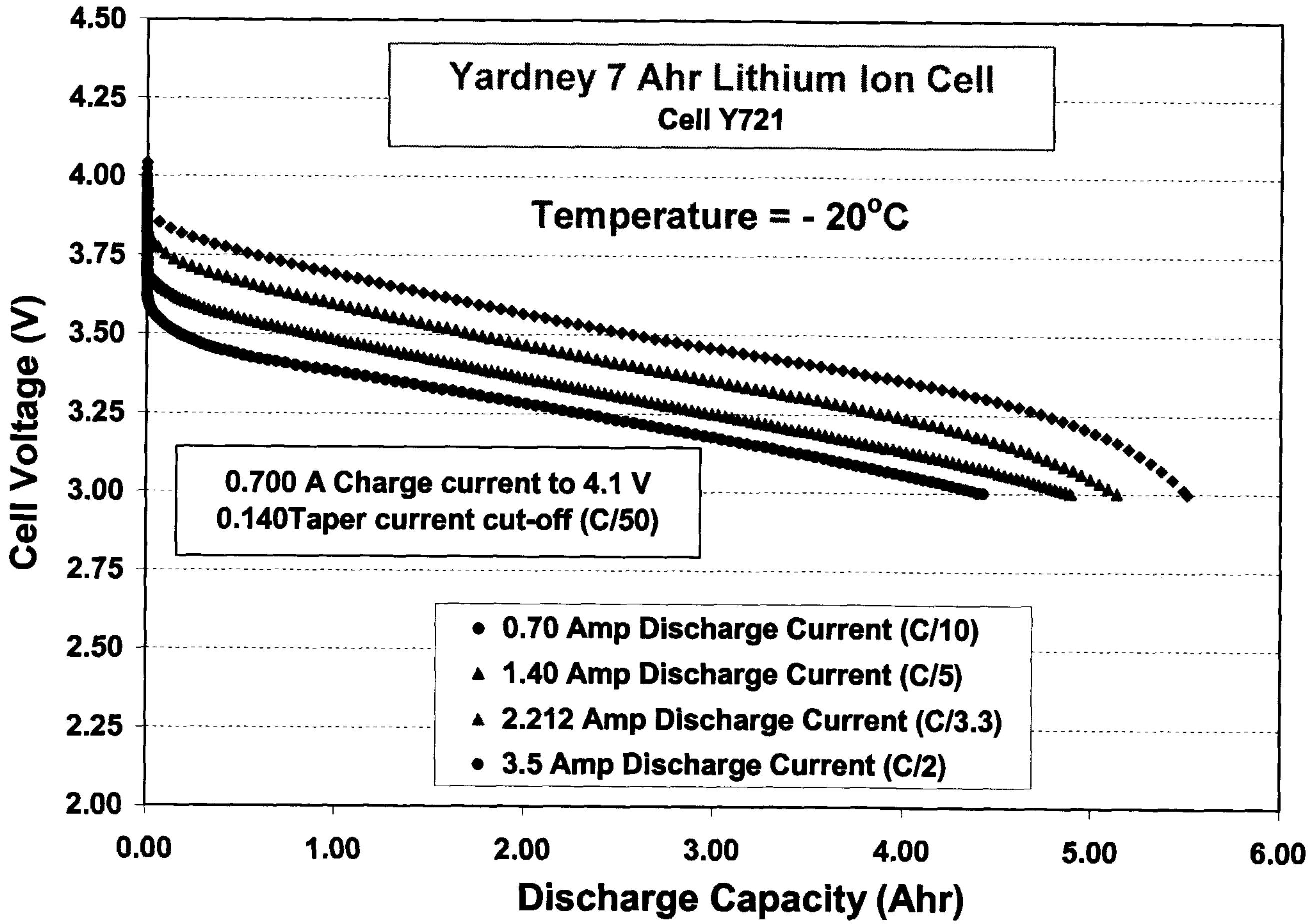
- **Characteristics of Lithium Ion System**
  - **High specific energy and excellent energy density**
  - **Good low temperature performance and high rate capability**
  - **High coulombic and energy efficiencies**
  - **Low self discharge, good cycle life and storage life**
- **Lithium Ion system selected for MER Rover battery**
- **Proposed Battery**
  - **Voltage : 32.8 -24 V (after diode)**
  - **Capacity**
    - **16 Ah (BOL) at RT and 14 Ah at 0°C (EOL) or 8.6 Ah at -20°C (EOL)**
  - **Discharge -Charge Rates**
    - **C rate discharge (max) during at RT and < C/2 at -20°C-30°C.**
    - **Charge < C/2 at 0 to 30°C to 4.1 V/cell minimum of 11 Ah (BOL)**
  - **16 Li ion cells of 8 Ah in two parallel strings of 8 cells each.**

Yardney Li Ion Cells



Yardney Li Ion Cells

Low temperature Performance



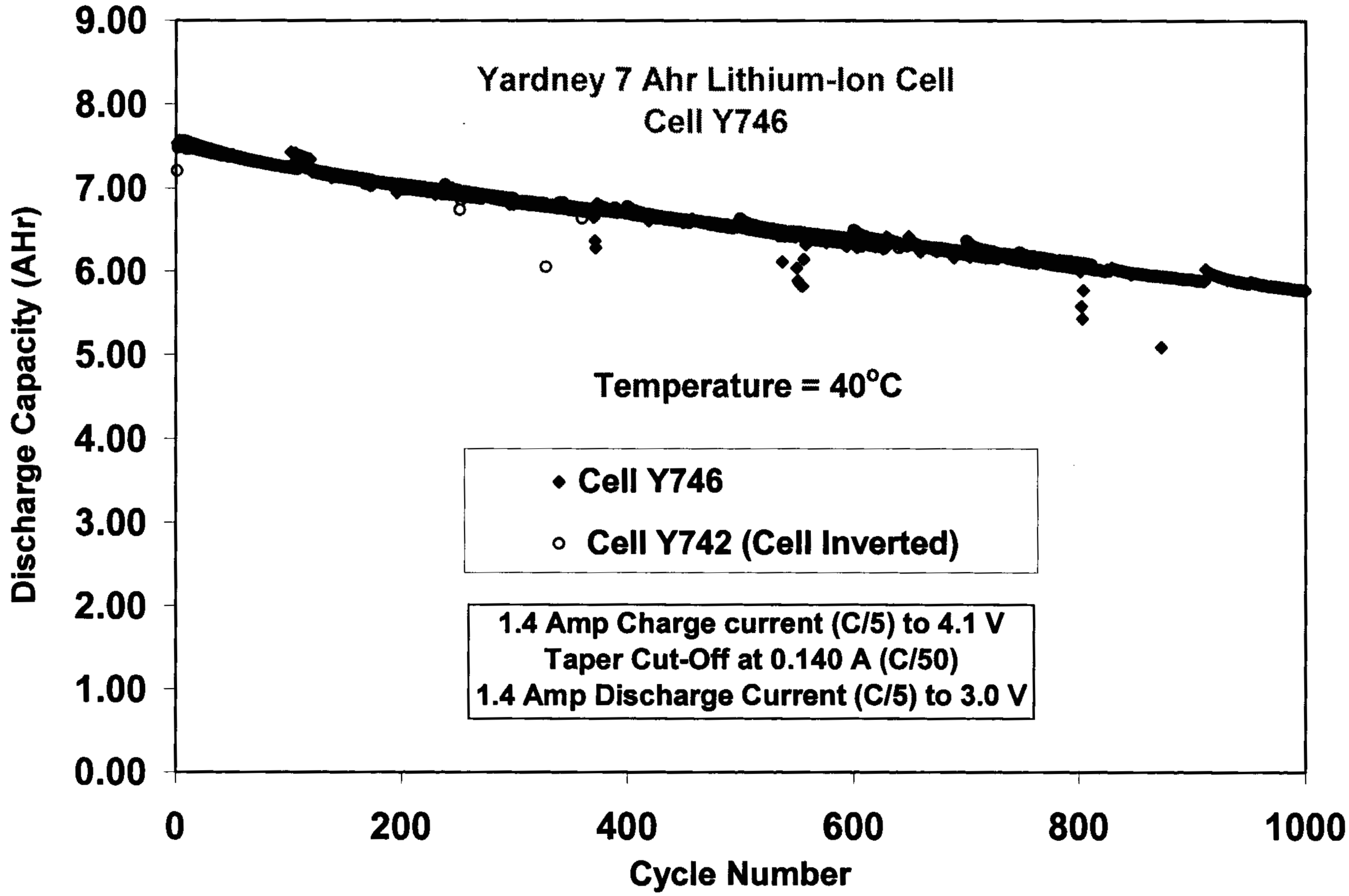
Yardney Li Ion Cells

Storage Characteristics

Cell Number	SOC on Bus	Initial Capacity 23°C (2nd Cycle)	Capacity Prior To Buss Storage at -20°C (2nd Cycle)	Capacity After 2 Years Buss Storage 23°C (6th Cycle)	% of Initial Capacity After 2 Years Buss Storage 23°C	Capacity After 2 Years Buss Storage -20°C (3rd Cycle)	% of Initial Capacity Prior to Buss Storage -20°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	

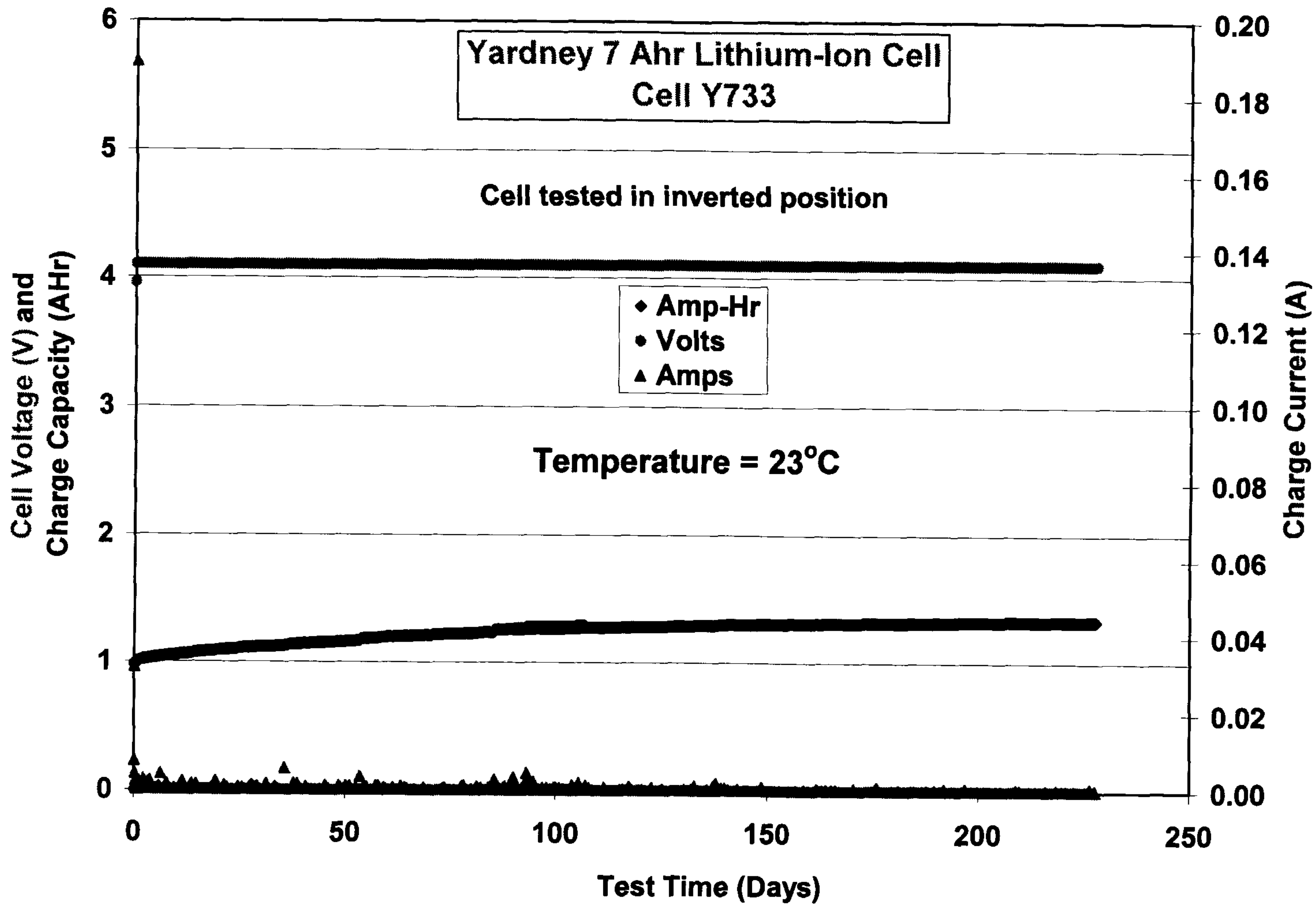
Yardney Li Ion Cells

Effect of Inverted Cell Orientation-100% DOD Cycling at 40°C



Yardney Li Ion Cells

Effect of Inverted Cell Orientation- On-buss storage at 4.1 V at 23°C

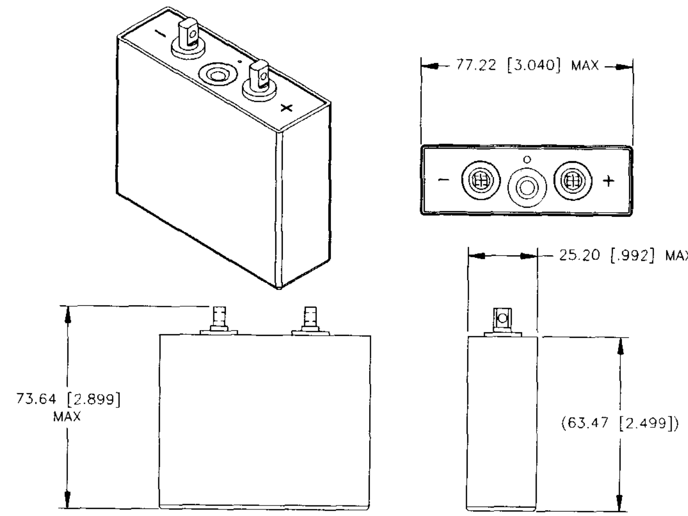


Cell and RBAU Electrical Specs

Test Article	Temperature	Preceding charge	Discharge condition	Capacity (Ah)	Remarks
Cell Capacity (BOL)	20°C	C/5 to 4.1 (taper)	C/5 to 2.9 V	10 Ah (min)	
		„	C/2 to 2.9 V	9.5 Ah	Nominal launch
		„	C to 2.9 V	9 Ah	
	30°C	C/5 to 4.1 (taper)	C/5 to 2.9 V	10 Ah (min)	
	0°C	C/5 to 4.1 (taper)	C/5 to 2.9 V	8.5 Ah (min)	
	-20°C	C/10 to 4.1 (taper)	C/5 to 2.9 V	6 Ah (min)	
	-10°C	C/10 to 4.1 (taper)	C/2 to 3.0 V	18 Wh (min)	Nominal Cruise
Cycle Life Validation	EOL defined as 2 years storage and 300 cycles; shown by analyses.				
Cell Capacity (EOL)	20°C	C/5 to 4.1 (taper)	C/5 to 2.9 V	8.5 Ah (min)	Loss of 10% on storage and 12% in 300 cycles
	-20°C	C/10 to 4.1 (taper)	C/5 to 2.9 V	5 Ah (min)	For Surface Ops (280 Wh)
	0°C	C/5 to 4.1 (taper)	C/5 to 2.9 V	7.0 Ah (min)	
RBAU Capacity (BOL)	20°C	C/10 to 32.4 (taper) or 4.15 V/cell	C/5 to 24 V	9 Ah (min) on each battery	
	-20°C	C/10 to 32.4 (taper) or 4.15 V/cell	C/5 to 24 V	5 Ah (min) on each battery	
	0°C	C/10 to 32.4 (taper) or 4.15 V/cell	C/5 to 24 V	7 Ah (min) on each battery	
	30°C	C/10 to 32.4 (taper) or 4.15 V/cell	C/5 to 24 V	9 Ah (min) on each battery	
	-10°C	C/10 to 31 (taper) or 3.875V/cell	C/2 to 27 V	160 W h (min) on the RBAU	Cruise –little margin

The Cell Design

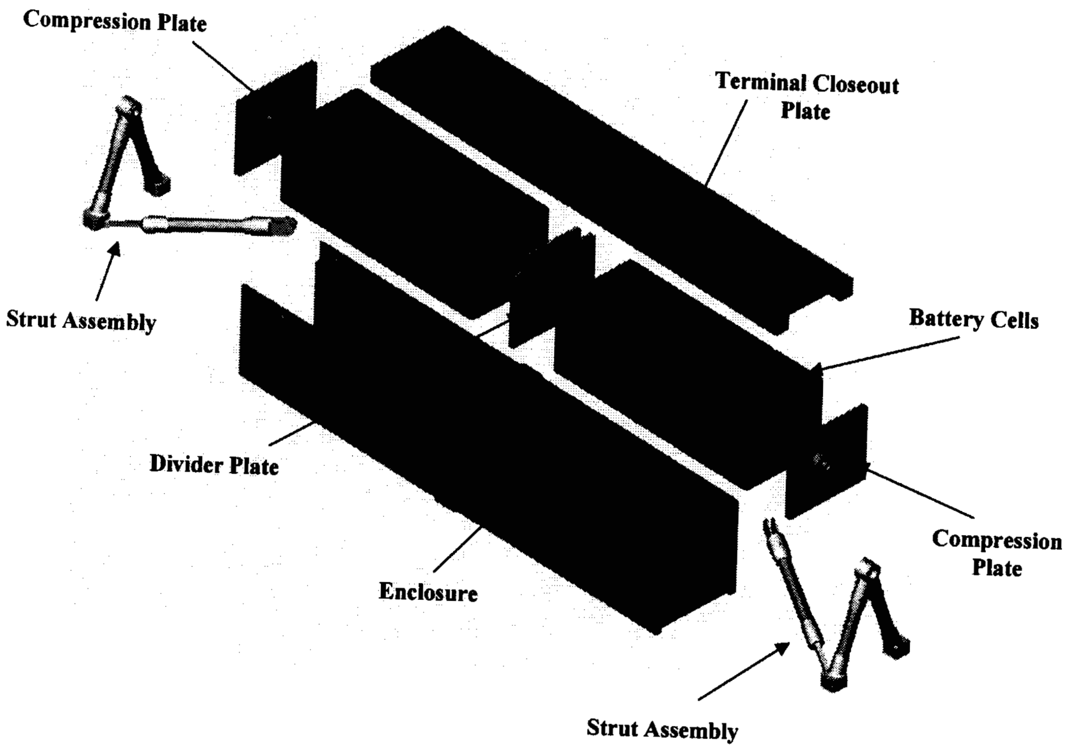
- **The cell is a true prismatic Lithium Ion cell.**
  - **Prismatic design offered improved fit into the envelope combined with superior thermal pathways.**
- **The cell used the same chemistry as was optimized for the MSP01 Lander.**
  - **This chemistry was originally developed at Yardney under the NASA/DoD Consortium.**
    - **Chemistry amenable to wide range of operating temperatures (-30 to +40oC).**
    - **Ternary electrolyte EC:DMC:DEC**
    - **Provides good storageability**
  - **Cells also utilized much of the physical cell design proven in under the MSP01 program**
    - **Time frame necessitated a low risk approach.**

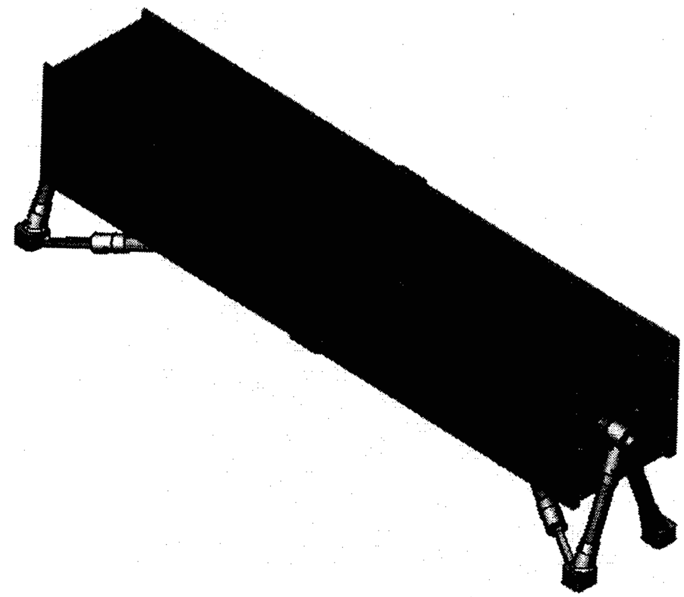


Mass: 295 grams

Volume: 123 cm^3

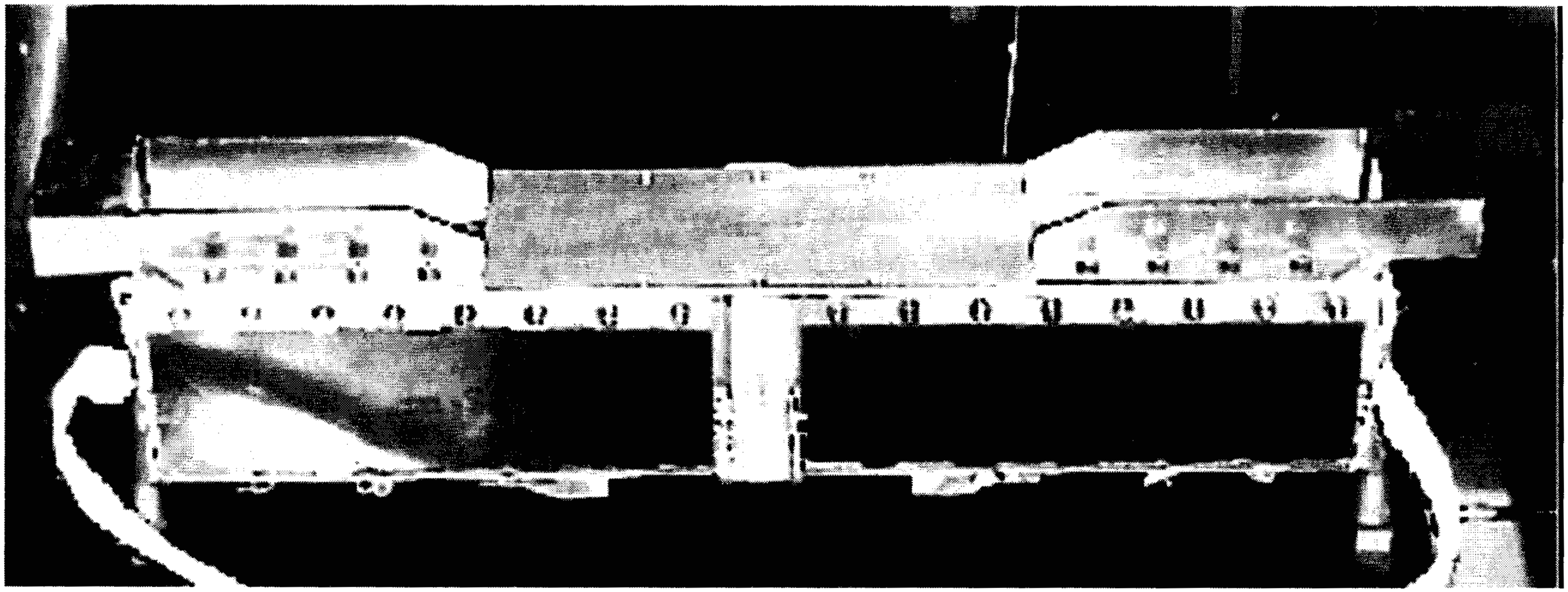
The RBAU Design





- **Two parallel batteries each with eight Li ion cells in series - 30 V, 16 Ah (480 Wh)**

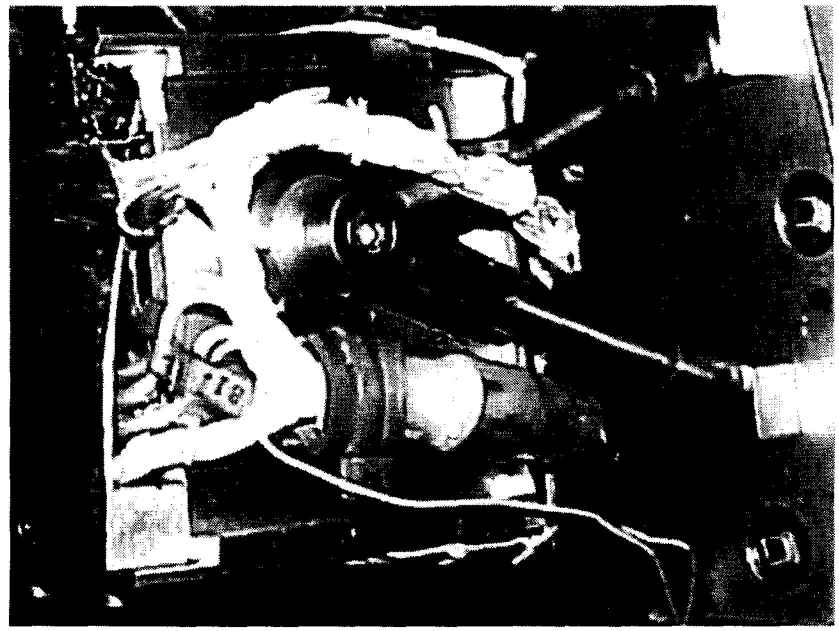
The RBAU Qualification



- **MER environments.**
  - **Random Vibration : 7.8 grms**
  - **Pyro Shock : 2000g**
  - **Landing load : 48 g (200 mS)**
  - **Thermal Vacuum : Eight cycles at 10-5 Torr at –30 to +40°C**

The RBAU Qualification

- **Environmental tests**
  - **RBAU had completed all temperature and electrical testing, vibration, pyro shock and 2 axis of centrifuge acceleration**
  - **An L-bracket was then added to the centrifuge to perform the Z axis acceleration and then…**
  - **At ~150 rpms, the centrifuge failed ; A 100 pound counter weight broke free and slammed into RBAU**
  - **Cover crushed; RHU sheared off (Eight 4mm bolts);Legs buckled (did not break)**



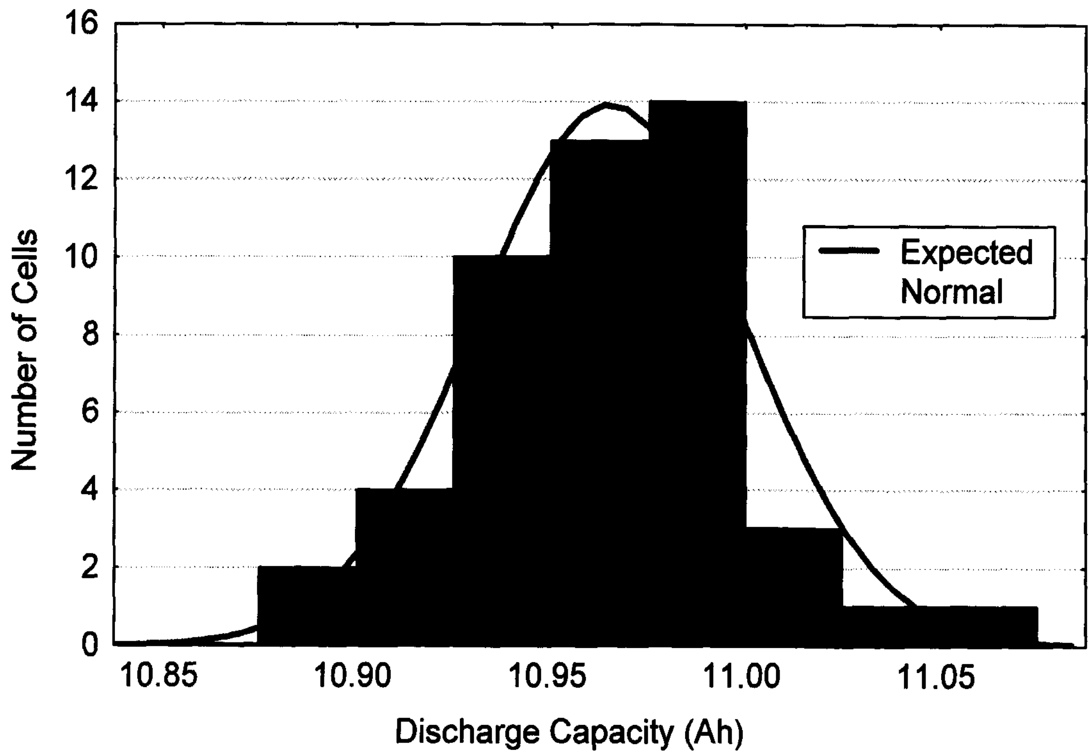
  - **Both batteries continued to function throughout the event. After *extensive* testing, no performance differences were observed with either battery in the RBAU.**
  - **Downgraded to an engineering unit. Another Qual RBAU was to be built.**

The RBAU Qualification

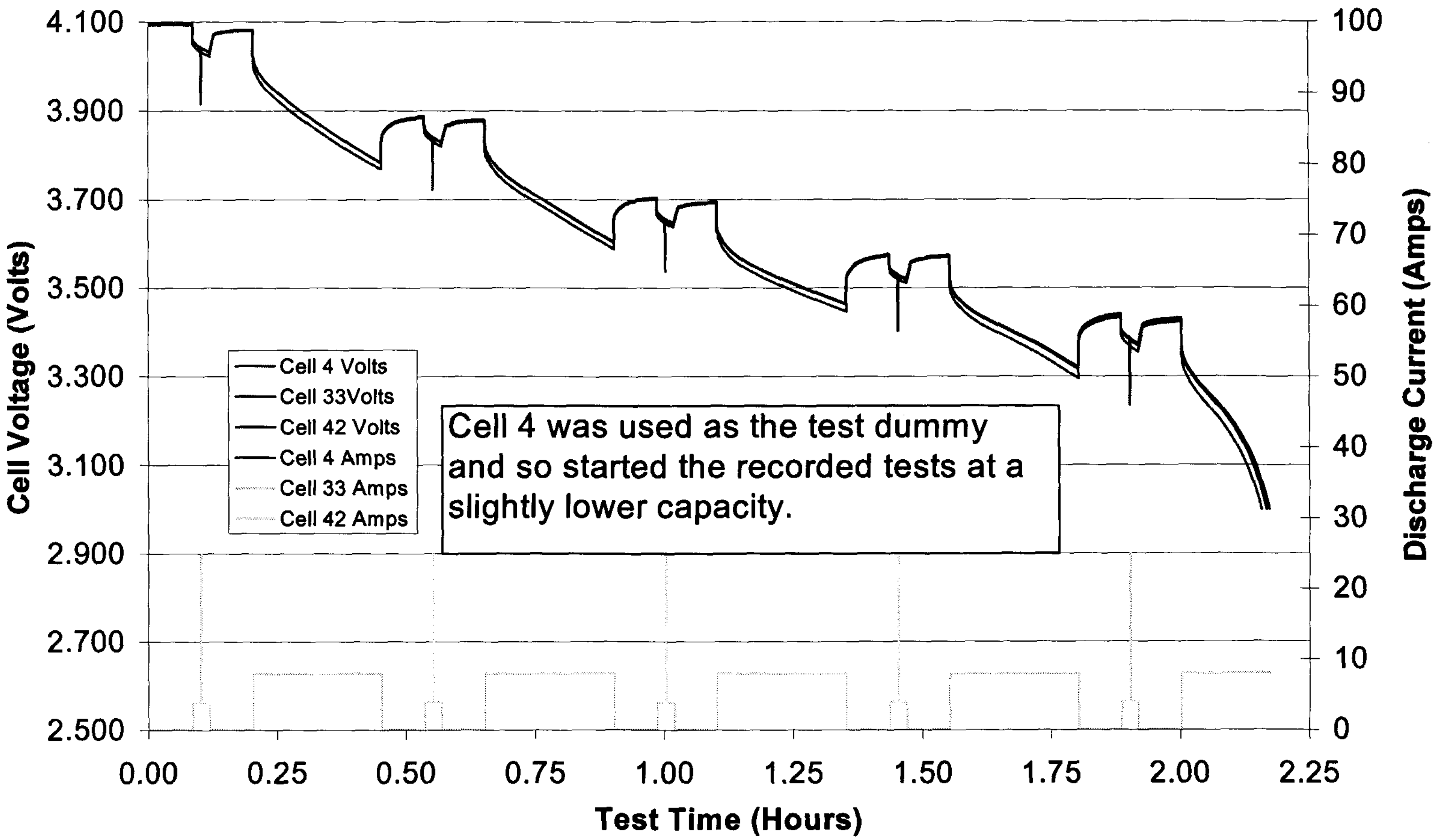
- **Corrective actions**
  - Another RBAU fabricated and subject to qual testing.
  - The acceleration test was modified.
    - Loads reduced to 34 g for 30-40 mS.
    - Could be performed on a shaker table
  - Environmental testing completed successfully.
  - Thermal vacuum tests completed over –30 to +40oC.
  - Mission profile tests were also completed to verify the capability of the battery to support the missions loads after environmental tests.
  - The before and after electrical tests were successful with both Qual Batteries with only minimal change in performance.

Cell Electrical Testing-Typical Results

- **Cells fabricated with additional QC steps (e.g., anode and cathode weights).**
- **The electrical testing of the cells showed a very tight cell to cell distribution**
  - **Entire Oualification build was less than ±1%**

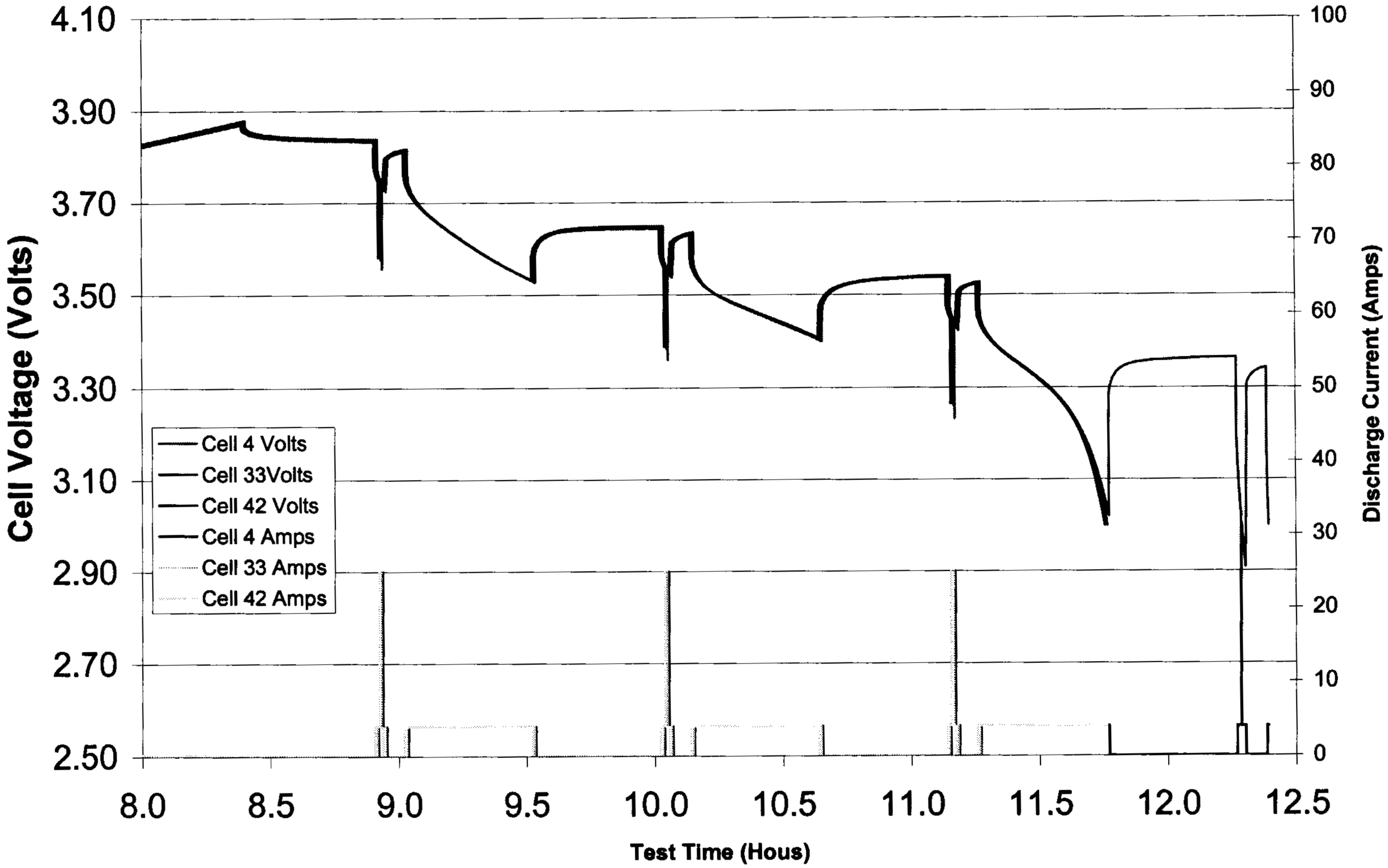


Pulse Capability of the Cells



- **20°C Requirement met at 100% of Charge and with 8Ah of capacity removed.**

Pulse Capability of the Cells



- **Cells were charged, at 0°C, at C/5, to 3.875 without a taper. Cells meet the requirement with 4 Ah removed.**
  - **This translates into a Cell OCV of 3.54 which corresponds to 35% SOC**

Electrical Testing-Cell Selection

- Cell selection consisted of two phases
  - Phase 1 was the removal of any cell that was not within ± 2.5σ on any process data or test.
  - The cells were then evaluated under an 8 criteria cell selection process.

    1.) C/5 @ 20 °C (Ah)
    2.) C/5 @ –20 °C (Ah)
    3.) C/2 @ –10 °C (Ah)
    4.) C/10 @ –20 °C (Time)
    5.) C/5 @ 20 °C (Time)
    6.) –20°C Rate Capability
    7.) 20°C Rate Capability
    8.) Self Discharge Rate
- Each of the 8 parameters underwent a weighting procedure based upon the amount that each cell varied from the mean.
  - A cell at nominal received a perfect score.
  - Variation from nominal decreased the score at the square of the amount of deviation.
- Each score was then multiplied by the weighting factor.
  - Weighting emphasis toward self discharge and charge times as ability to balance cells during mission was (is) uncertain.

Electrical Testing-Cell Selection

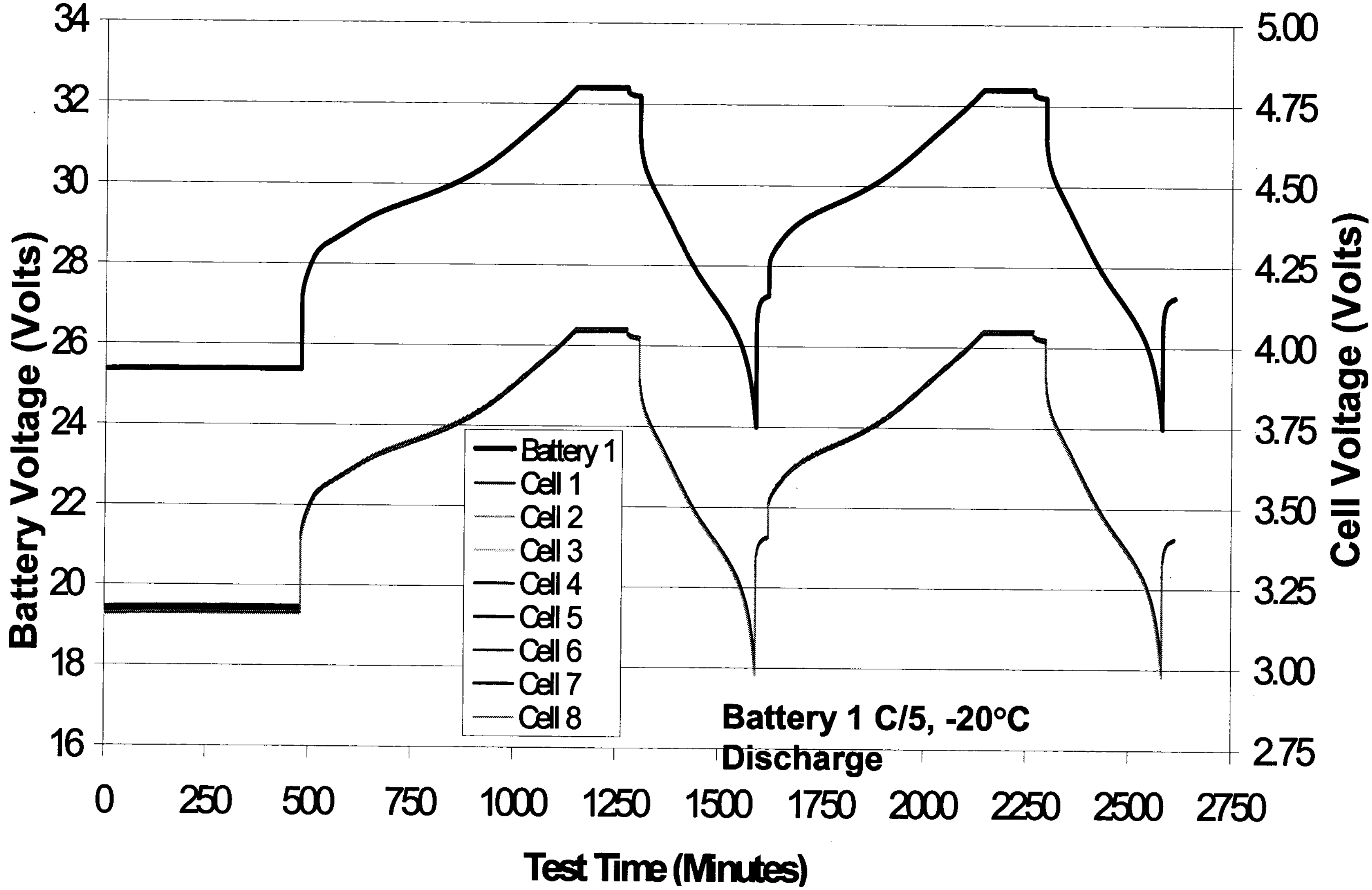
- **Results: FM5 Battery 1**

CELL ID	STAND	time_20	time_n20	C5_20A	N20_Rate	P20_rate	C2_N10A	C5_N20A
Cell 1	6.104	6.994	11.790	10.634	0.775	0.965	8.890	8.526
Cell 2	6.409	7.035	11.817	10.689	0.772	0.964	8.899	8.510
Cell 3	6.104	6.987	11.743	10.618	0.771	0.964	8.841	8.456
Cell 4	6.104	7.008	11.830	10.644	0.774	0.965	8.879	8.496
Cell 5	5.951	6.999	11.798	10.641	0.769	0.963	8.839	8.476
Cell 6	6.104	6.994	11.769	10.648	0.769	0.963	8.846	8.459
Cell 7	6.104	7.004	11.747	10.648	0.774	0.964	8.875	8.493
Cell 8	5.951	7.017	11.816	10.665	0.770	0.963	8.878	8.501
AVERAGE	**6.104**	**7.005**	**11.789**	**10.649**	**0.772**	**0.964**	**8.868**	**8.490**
STDEV	**0.141**	**0.015**	**0.033**	**0.021**	**0.003**	**0.001**	**0.023**	**0.024**
RANGE (±)	**3.85%**	**0.35%**	**0.37%**	**0.33%**	**0.45%**	**0.15%**	**0.34%**	**0.41%**

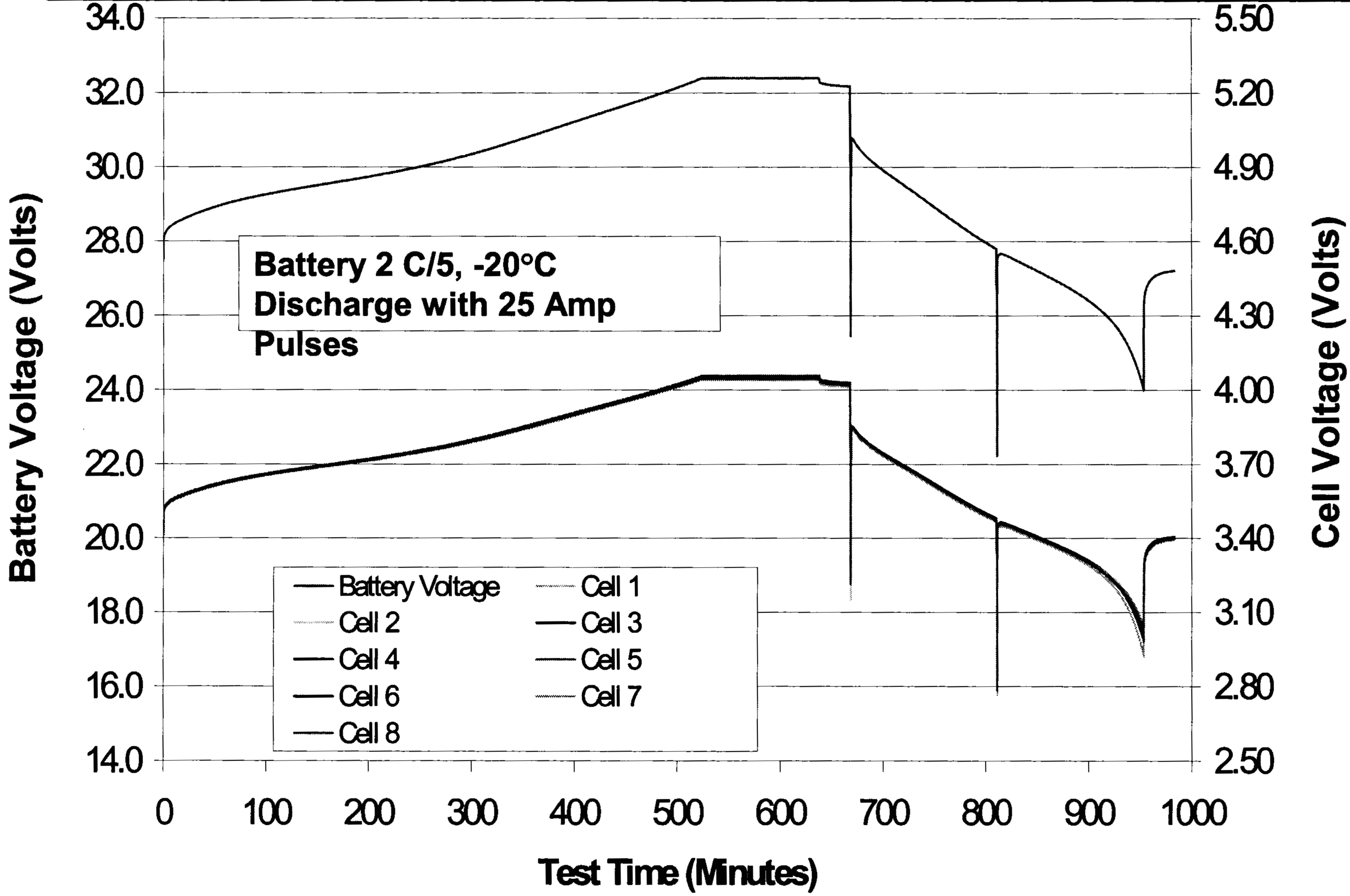
- **The 3.85% variation on the stand is multiplied by a factor of 1000 to be comparable. (Actual difference is <0.0005 V)**

Electrical Testing-RBAU Results

JPL



Electrical Testing-RBAU Results



RBAU Testing (2003 MER Program)

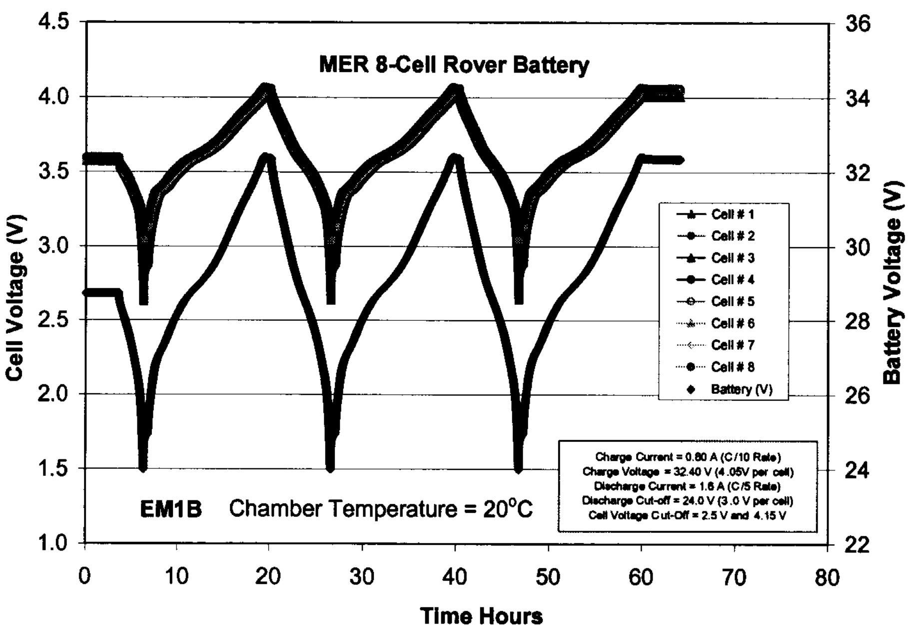
- **EM1 RBAU**
  - Acceptance Testing
  - Cruise Operation
  - EDL Operation (No pulsing)
  - Mission Surface Operation Simulation (~ 2 months of testing)
- **EM2 RBAU**
  - Acceptance Testing
- **FM1 RBAU**
  - Acceptance Testing
- **FM2 and FM 3 RBAU (ATLO)**
  - Acceptance Testing
- **Mission Simulation Battery**
  - Acceptance Testing
  - **Mission simulation**
- **Flight and flight spare RBAUs.**
  - Acceptance Testing

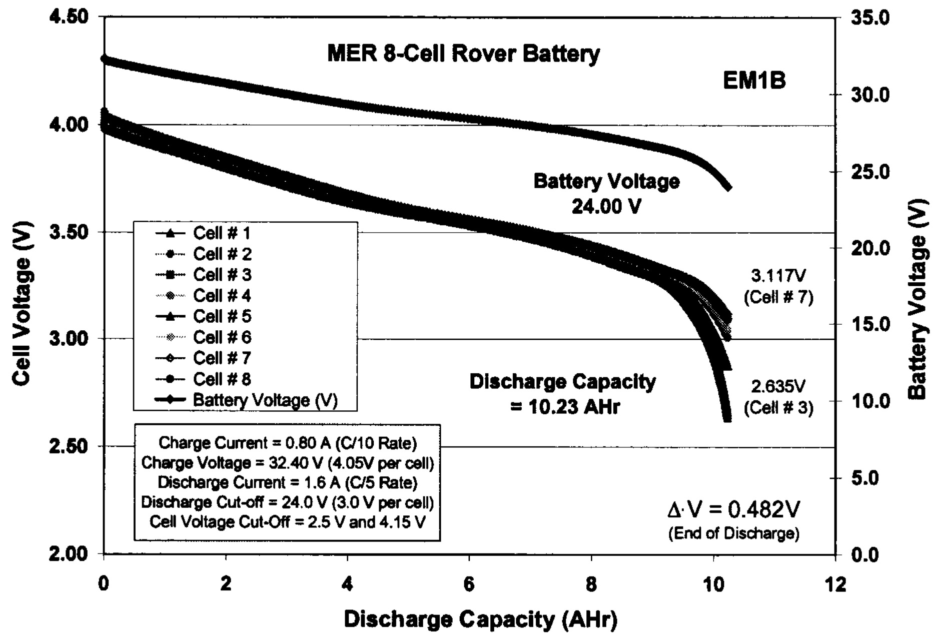
Acceptance Testing

- 3 Cycles at 20°C (C/5 Rate, charged to 32.4V)
- 72 Hour OCV Stand (Battery Fully Charged to 32.4V)
- 3 Cycles at - 20°C (C/5 Rate, charged to 32.4V)

MER RBAU Engineering Module

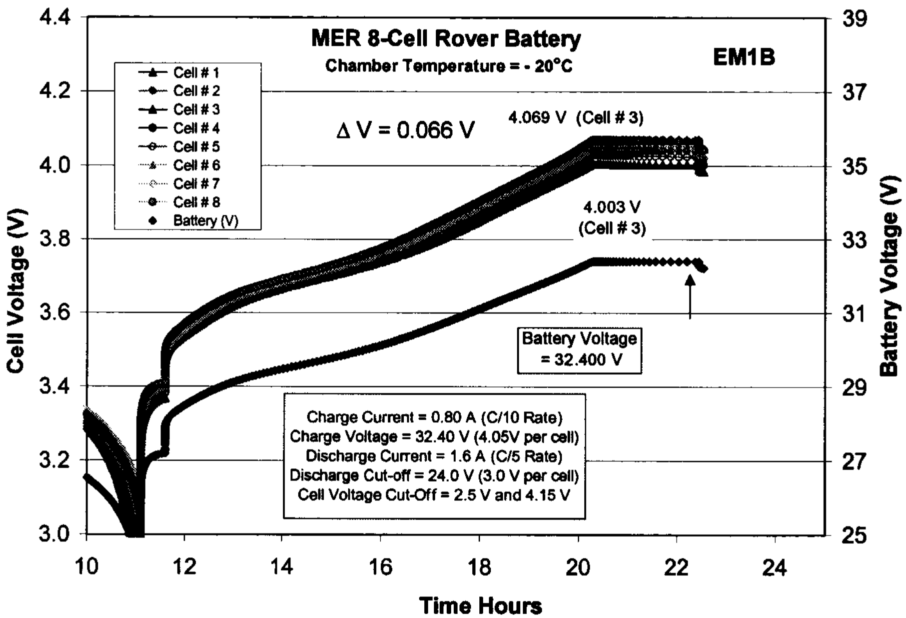
Initial Characterization/Conditioning at 20°C

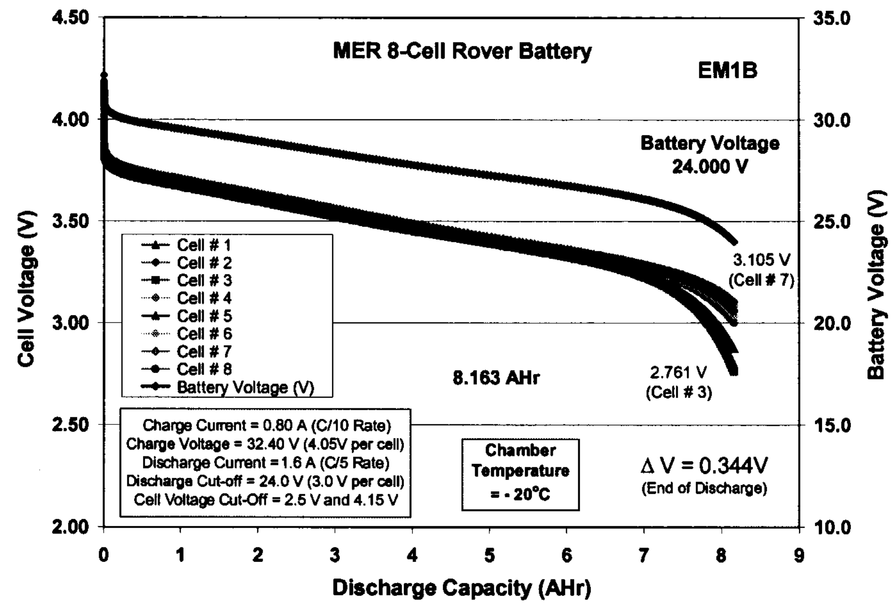




MER RBAU Engineering Module

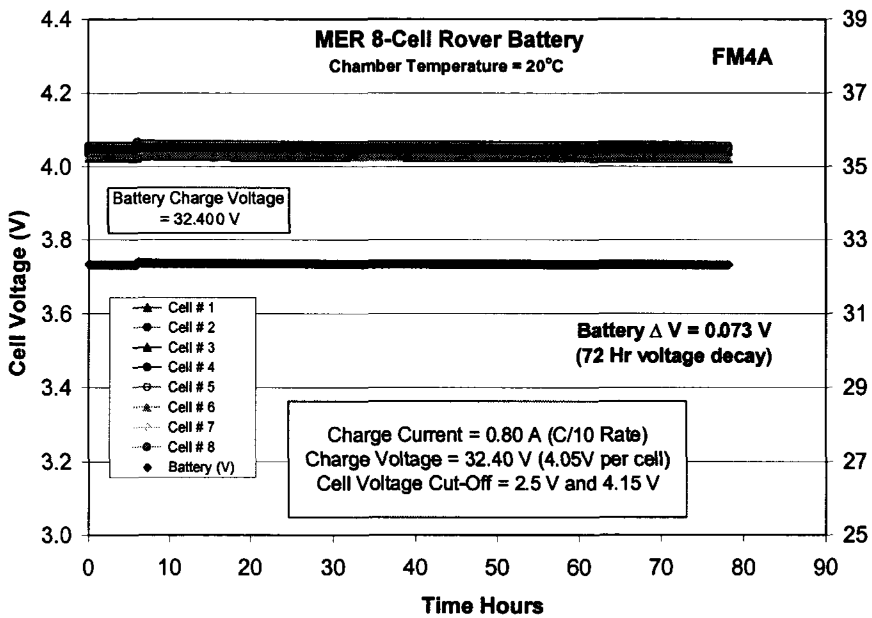
Initial Characterization/Conditioning at -20°C

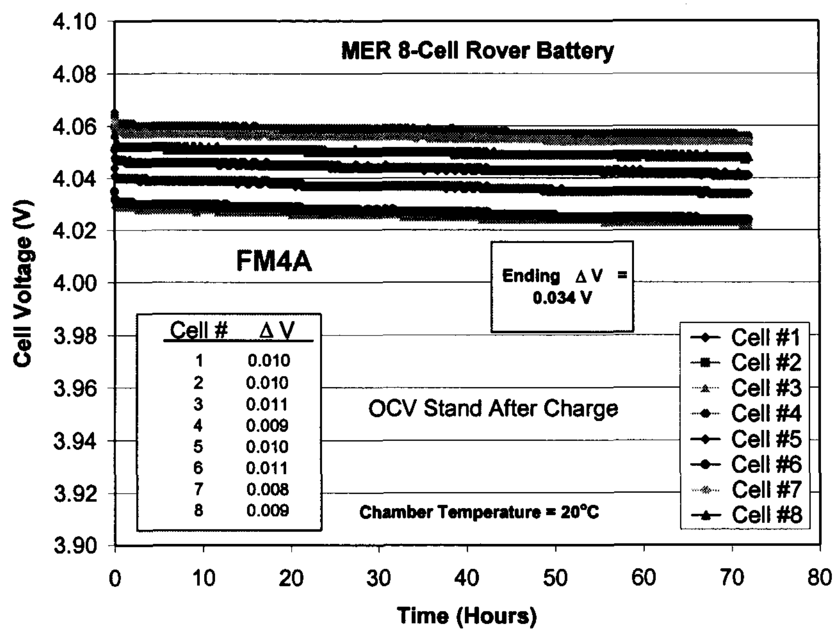




MER 8 Ah Rover Lithium-Ion Battery (FM4A)

Charge at 20°C + 72 Hr OCV Stand

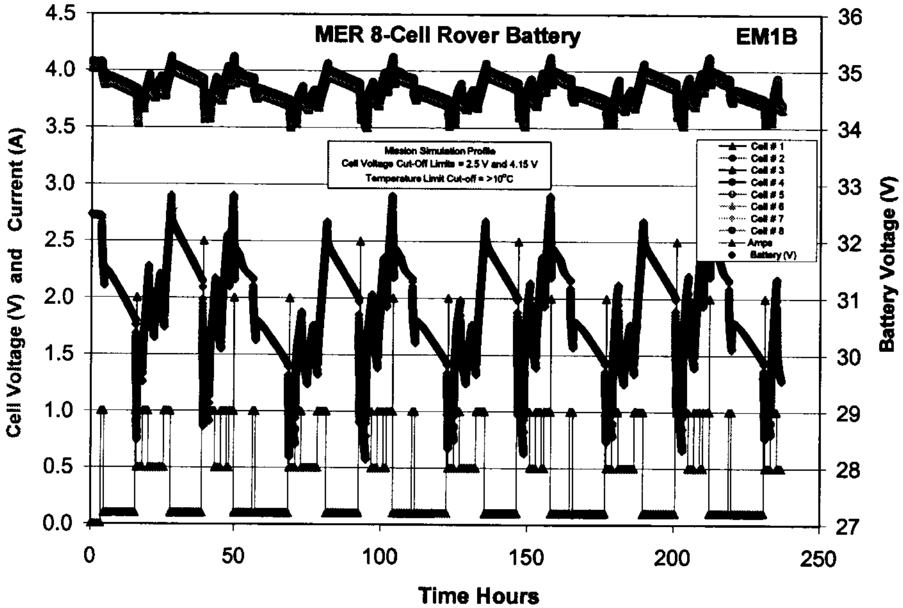


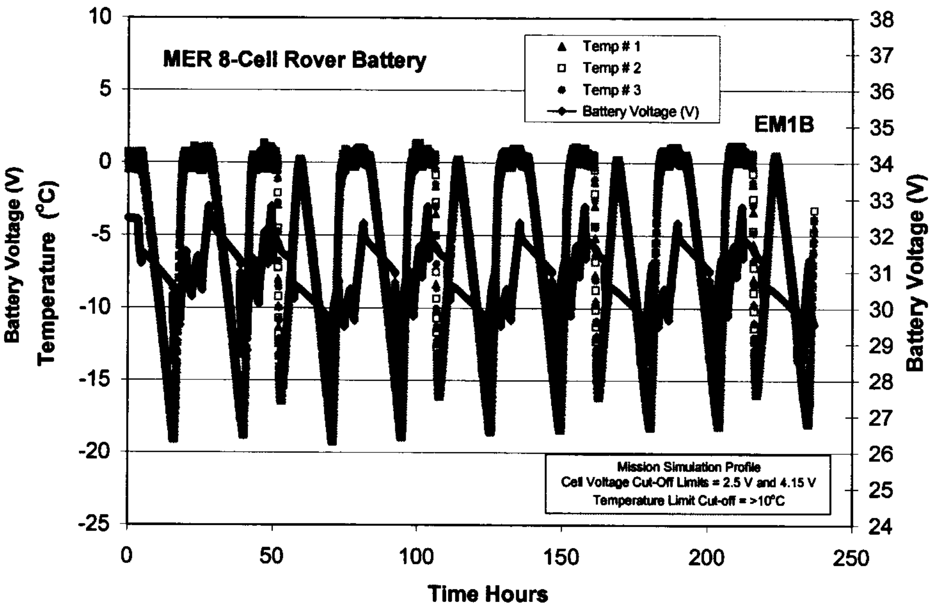


Cell #	Δ V
1	0.010
2	0.010
3	0.011
4	0.009
5	0.010
6	0.011
7	0.008
8	0.009

MER RBAU Engineering Module

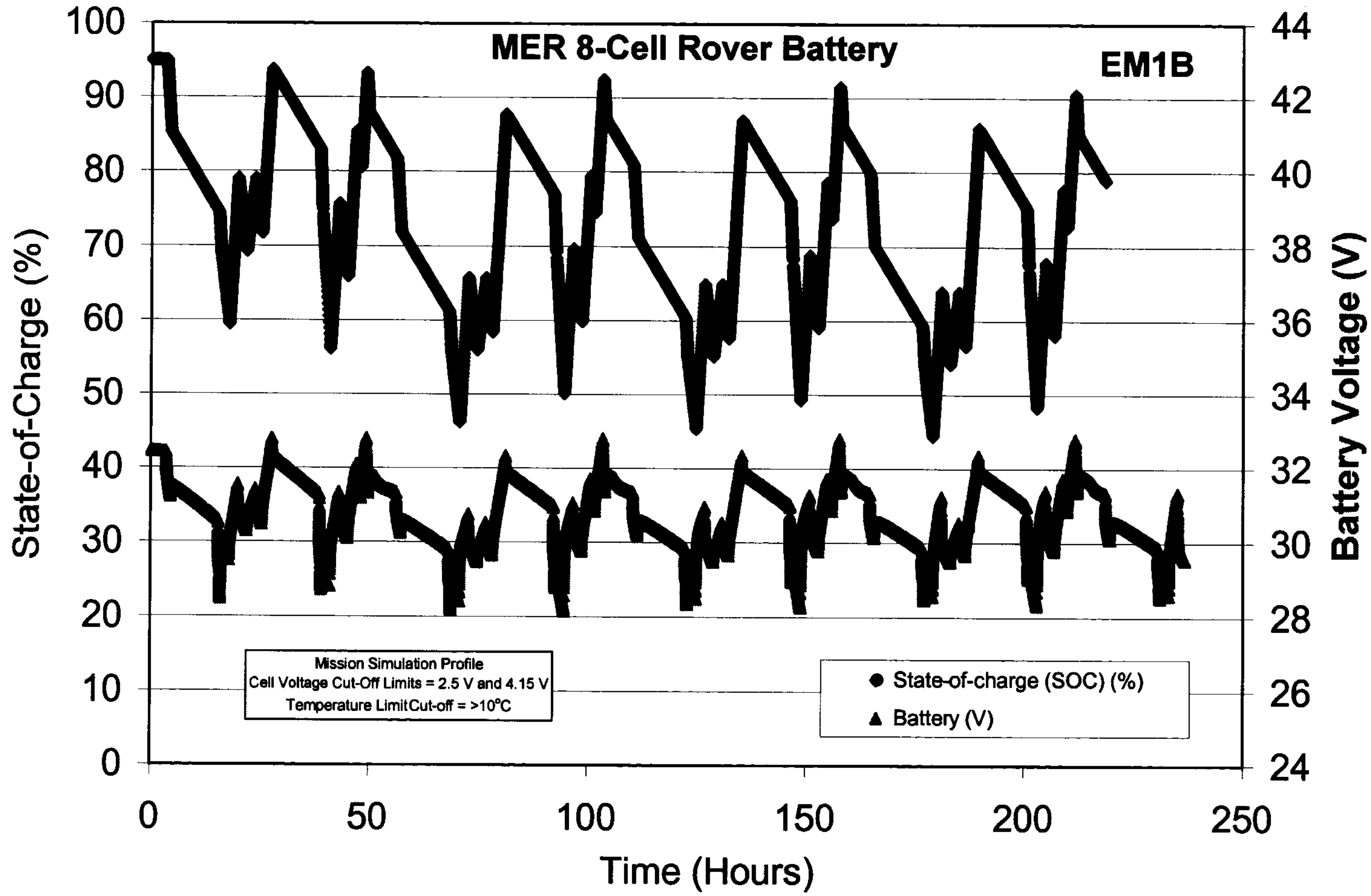
Mission Simulation Testing SOLS 1-8





MER RBAU Engineering Module

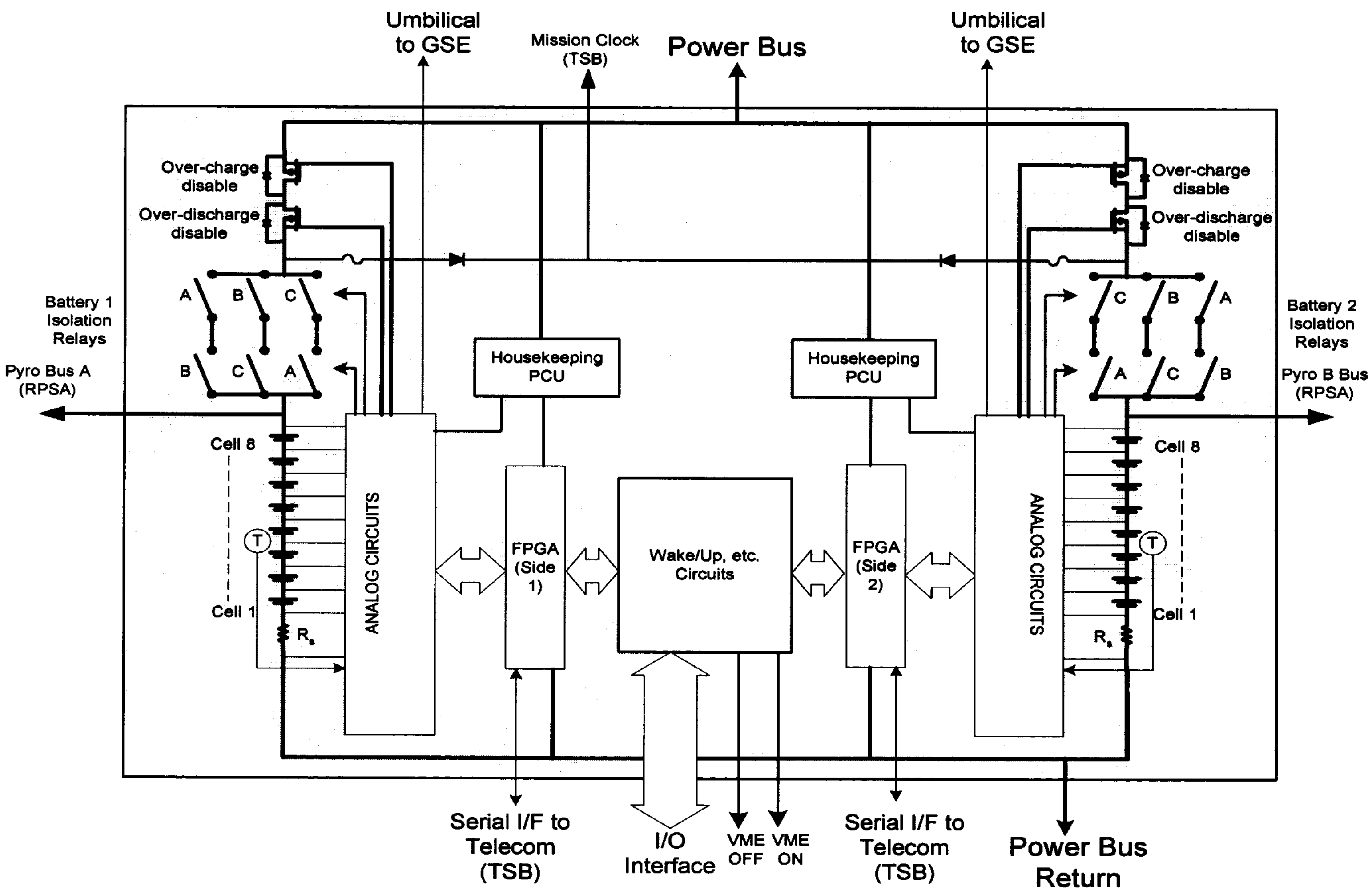
Mission Simulation Testing SOLS 1-8



Battery Control Board
Main Functional Requirements

- **Monitors all of the critical power analog telemetry signals in the Rover**
  - Rover solar array Voc
  - Rover solar array Isc
  - Bus voltage
  - Rover solar array current
  - Rover shunt current
  - Lander bus current (bi-directional)
  - Cruise bus current (bi-directional)
  - RPDU current
  - Rover battery voltage
  - Rover battery cell voltages (8 per battery)
  - Rover battery current (1 per battery)
  - Rover battery temperatures (5)
    - 3 internal, 1 battery case temperature, and routes 1 through umbilical
  - Measures and stores critical night time measurements
    - REM temp., SSPA LHP radiator inlet temp., Pan Cam CCD PRT

BCB: High Level Block Diagram



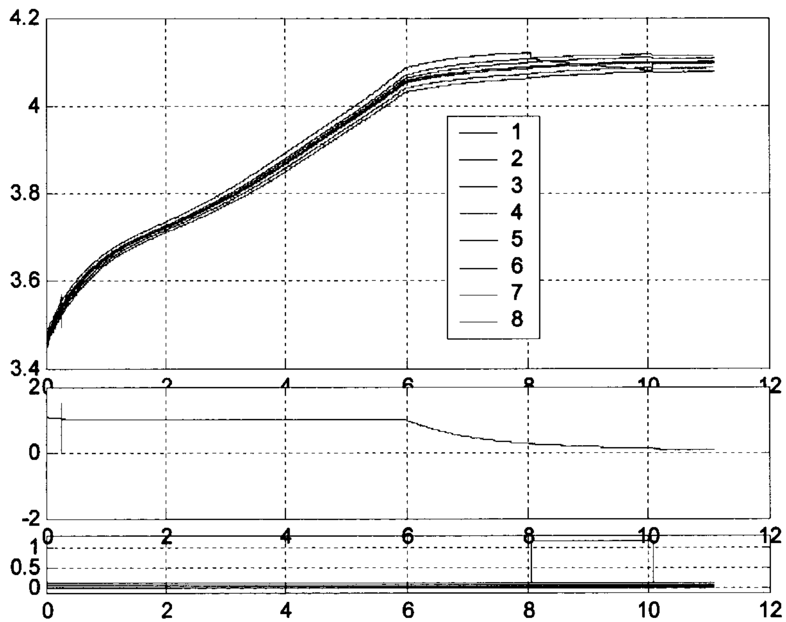
Battery Management

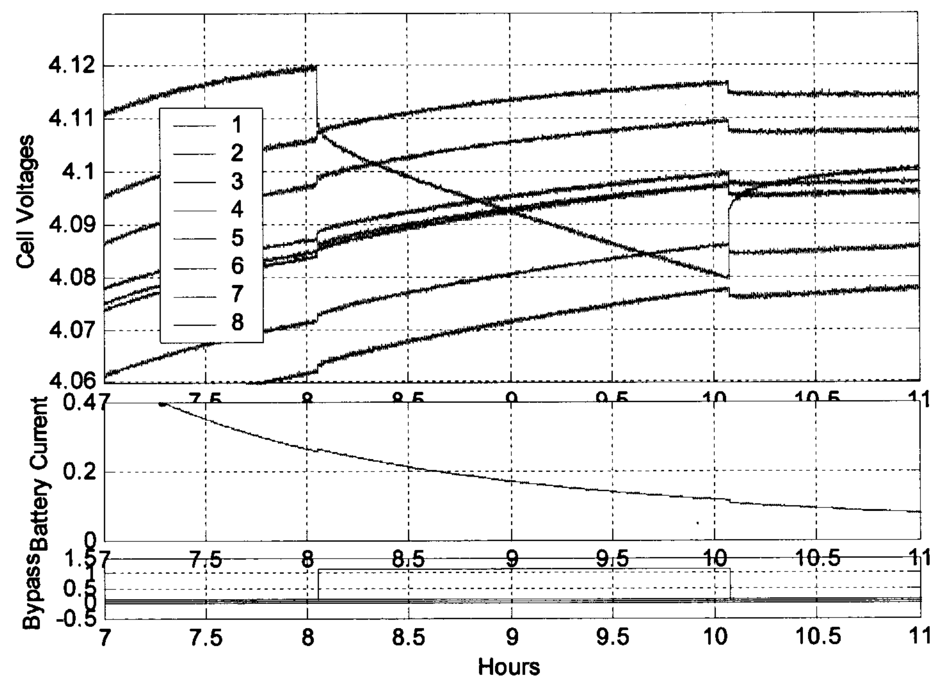
- Terminology Definitions
  - Vcmd (Vcommand)= Vsc (Vstop charge) = one of four prog levels (3.85, 3.95, 4.15, 4.20V)
  - Vbp (Vbypass) = Vcmd - 30mV
  - Vebp (Vend bypass) = Vcmd -70mV
  - Vch (Vcharge) = Vcmd - 150mV
  - Vd (Vdischarge) = 3.4V
  - Vsd (Vstop discharge) = 2.9V

Battery Management (cont.)

- Charge control
  - Stop Charge (open charge FET) if:
    - Any cell is greater than or equal to Vcmd
    - All cells are above Vbp
    - Charge rate is greater than 1C
    - Any cell is <1V and the battery is >20V.
  - Start Charge (close charge FET) if:
    - All cells are below Vch
    - After POR
  - Stop Discharge (open discharge FET) if:
    - Any cell is less than or equal to Vsd
    - Discharge rate exceeds 2C (latchoff, ground only)
  - Start Discharge (close discharge FET) if:
    - All cells are above Vd.
- Charge Balancing
  - Start cell bypassing at or above Vbp
  - Stop cell bypassing at or below Vebp

BCB/Battery Lab Results





Summary

- The 2003 Mars Exploration Rovers (MER) have Li-SO_2 primary batteries on the Lander to support the EDL operations, Li-FeS_2 thermal batteries on the back shell for firing pyros during cruise stage separation and Li ion rechargeable batteries on the Rover to assist in the launch, TCM and surface operations.
- The Rover is about ten times bigger in size, pay load and traversing capability than the previous Sojourner rover and will have a longer mission life with the rechargeable batteries.
- Lithium ion batteries fabricated by Yardney Technical Products for the MER mission show adequate performance in the operating range, in the MER environments, under steady state and pulse currents and, also in conjunction with a battery charger designed and built in-house.

Acknowledgements

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