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The 2001 NASA Aerospace Battery Workshop

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Proceedings of a workshop sponsored by the
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Preface

This CD contains proceedings of the 34th annual NASA Aerospace Battery Workshop, hosted by the Marshall Space Flight Center, November 27–29, 2001. The workshop was attended by scientists and engineers from various agencies of the U.S. Government, aerospace contractors, and battery manufacturers, as well as international participation in like kind.

The subjects covered included lithium-ion, nickel-hydrogen, and various advanced technologies and testing techniques.

Introduction

The NASA Aerospace Battery Workshop is an annual event hosted by the Marshall Space Flight Center. The workshop is sponsored by the NASA Aerospace Flight Battery Systems Program, which is managed out of NASA Glenn Research Center and receives support in the form of overall objectives, guidelines, and funding from Code R, NASA Headquarters.

The 2001 Workshop was held on three consecutive days and was divided into five sessions, some of which carried over from one day to the next. The first session was a General Session. The second session was a Nickel-Hydrogen Session. The third and fifth sessions covered the Lithium-Ion technology. The fourth session was a focused session on Lithium-Ion Charge Control.

On a personal note, I would like to take this opportunity to thank all of the many people that contributed to the organization and production of this workshop:

> **The NASA Aerospace Flight Battery Systems Program**, for their financial support as well as their input during the initial planning stages of the workshop;
>
> **Huntsville Hilton**, for doing an outstanding job in providing an ideal setting for this workshop and for the hospitality that was shown to all who attended;
>
> **Kumar Bugga, Jet Propulsion Laboratory,** for organizing and conducting this year's focused session**; Joe Stockel, National Reconnaissance Office, and George Methlie, U.S. Government**, for 11th-hour solicitation of presentations for a couple of sessions.
>
> **Marshall Space Flight Center employees**, for their help in registering attendees, handling the audience microphones, and flipping transparencies during the workshop.

Finally, I want to thank all of you that attended and/or prepared and delivered presentations for this workshop. You were the key to the success of this workshop.

Jeff Brewer
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Table of Contents

This Table of Contents does not reflect the order in which the presentations were made at the workshop. There were several last-minute additions and changes to the agenda that created, in some sessions, a mixture of subjects being presented. This CD, however, will take all inputs and group them together according to subject matter.

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SAFT Li-Ion Module Design
Dr. Y. Borthomieu and JP Semerie, SAFT Defense and Space Division Specialty Battery Group

Calendar and Cycle Life Prediction of 100Ah Lithium-Ion Cells for Space Applications
Takefumi Inoue, Takeshi Sasaki, Nobutaka Imamura, Hiroaki Yoshida, and Minoru Mizutani, Japan Storage Battery Co., Ltd.; and Masayoshi Goto, Mitsubishi Electric Corporation

Thermal Modeling of Prismatic Lithium-Ion Cells
Pinakin M. Shah, Mine Safety Appliances Company; and Michael T. Nispel, Consultant

SAFT Li-Ion Cells GEO and LEO Life Test Up-Date
H. Croft and R.J. Staniewicz, SAFT Advanced Battery System Division; Y. Borthomieu and J.P. Planchat, SAFT Defense and Space Division Specialty Battery Group

Evaluation of Cycle Life and Characterization of YTP 45 Ah Li-Ion Battery for EMU
Yi Deng, Judith Jeevarajan, and Raymond Rehm, Lockheed Martin Space Operations; Bobby Bragg, NASA Johnson Space Center; and Brad Strangways, Symmetry Resources, Inc.

Lithium Ion DD Cells Space Application Cycling Update
Haiyan Croft and Bob Staniewicz, SAFT America, Inc.

Simulated LEO Cycling of AEA-STRV Lithium-Ion Battery Modules 2001 Update
Philip Johnson and Chuck Lurie, TRW; and R. Spurrett, AEA Technology

PROBA, The First ESA Spacecraft Flying Lithium-Ion
M. Schautz, D. Olsson, and G. Dudley, ESTEC; and A. Holland, AEA Technology

Focused Session – Lithium-Ion Charge Control

Life Test Results With Adaptive Charge Control
Albert H. Zimmerman and Michael V. Quinzio, The Aerospace Corporation

A Dual Mode Lithium Ion Battery Charge Controller
Steve Girard and Greg Miller, Eagle-Picher Technologies, LLC

Impact of Charge Methodology Upon the Performance of Lithium Ion Cells
M.C. Smart, B.V. Ratnakumar, L. Whitcanack, K. Chin, and S. Surampudi, Jet Propulsion Laboratory

Performance of Li-Ion Cells Under Battery Voltage Charge Control
Hari Vaidyanathan, Consultant; and Gopalakrishna M. Rao, NASA Goddard Space Flight Center

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DPA of 1.6 Ah Li-Ion Pouch Cells Using Coin Cells
Enoch Wang, U.S. Government

Performance and Safety Tests on Samsung 18650 Li-Ion Cells: Two Cell Designs
Yi Deng, Judith Jeevarajan, and Raymond Rehm, Lockheed Martin Space Operations; Bobby Bragg; NASA Johnson Space Center; and Wenlin Zhang, Schlumberger Perforating and Testing

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Judith A. Jeevarajan, Yi Deng, and Ray Rehm, Lockheed Martin Space Operations; Walt Tracinski, Applied Power International; and Bobby J. Bragg, NASA Johnson Space Center

Pulse Performance of Small Lithium-Ion Cells
Eric C. Darcy, NASA Johnson Space Center; and Philip R. Cowles, COM DEV Battery Group

Low Temperature and High Rate Performance of Lithium-Ion Systems for Space Applications
R. Gitzendanner, F. Puglia, and C. Marsh, Lithion, Inc.

Study of the Effects of Overdischarge on SONY 18650HC Cells
G.J. Dudley, ESA-ESTEC; and R. Spurrett, AEA Technology

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13. ABSTRACT *(Maximum 200 words)*

This document contains the proceedings of the 34th annual NASA Aerospace Battery Workshop, hosted by the Marshall Space Flight Center, November 27–29, 2001. The workshop was attended by scientists and engineers from various agencies of the U.S. Government, aerospace contractors, and battery manufacturers, as well as international participation in like kind.

The subjects covered included nickel-hydrogen, nickel-cadmium, lithium-ion, and silver-zinc technologies.

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AEA Cell-Bypass-Switch Activation: An Update

2001 NASA Aerospace Battery Workshop

Denney Keys
Gopalakrishna M. Rao
David Sullivan
Harry Wannemacher*

NASA GODDARD SPACE FLIGHT CENTER
*QSS GROUP, INC

Objectives

- Verify the Performance of AEA Cell Bypass Protection Device (CBPD) under simulated EOS-Aqua/Aura flight hardware configuration
- Assess the Safety of the hardware under an inadvertent firing of CBPD switch, as well as the closing of CBPD switch under simulated high cell impedance
- Confirm that the mode of operation of CBPD switch is the formation of a continuous low impedance path (a homogeneous low melting point alloy)

BACKGROUND

EOS-Aqua Flight Hardware

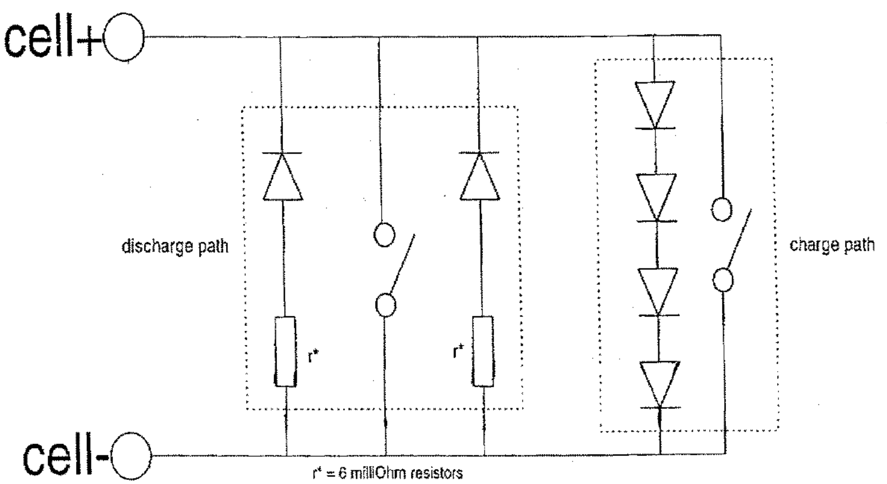
- Battery Cell:
  - Eagle-Picher 160 Ah NiH_2 (RNH 160-3)
  - Size: ~ 12cm Diameter
    ~ 32cm overall Height
  - Weight: ~ 4.3kg

- Cell-Bypass-Switch:
  - AEA Technology
    Cell Bypass Protection Device (CBPD)

AEA Bypass Switch Schematic

CBPD - LMPA Schematic

(Low Melting Point Alloy)



AEA

AEA Technology

Slide serial no 6

NOTE: Tested devices have 6 series diodes in charge path (not 4 as shown)

FLIGHT CBPD

AEA Cell-Bypass-Switch Spec

TRW spec for Aqua

90 grams

Icharge ~ 75A

R ~ 500 microOhms

CBPD - Specification

- 75grams
- Icharge < 35A
- I discharge < 235A
- Triggering - see operation summary
- R ~ 200 microOhms
- I operation < 400A - dependent on leads and mounting

AEA

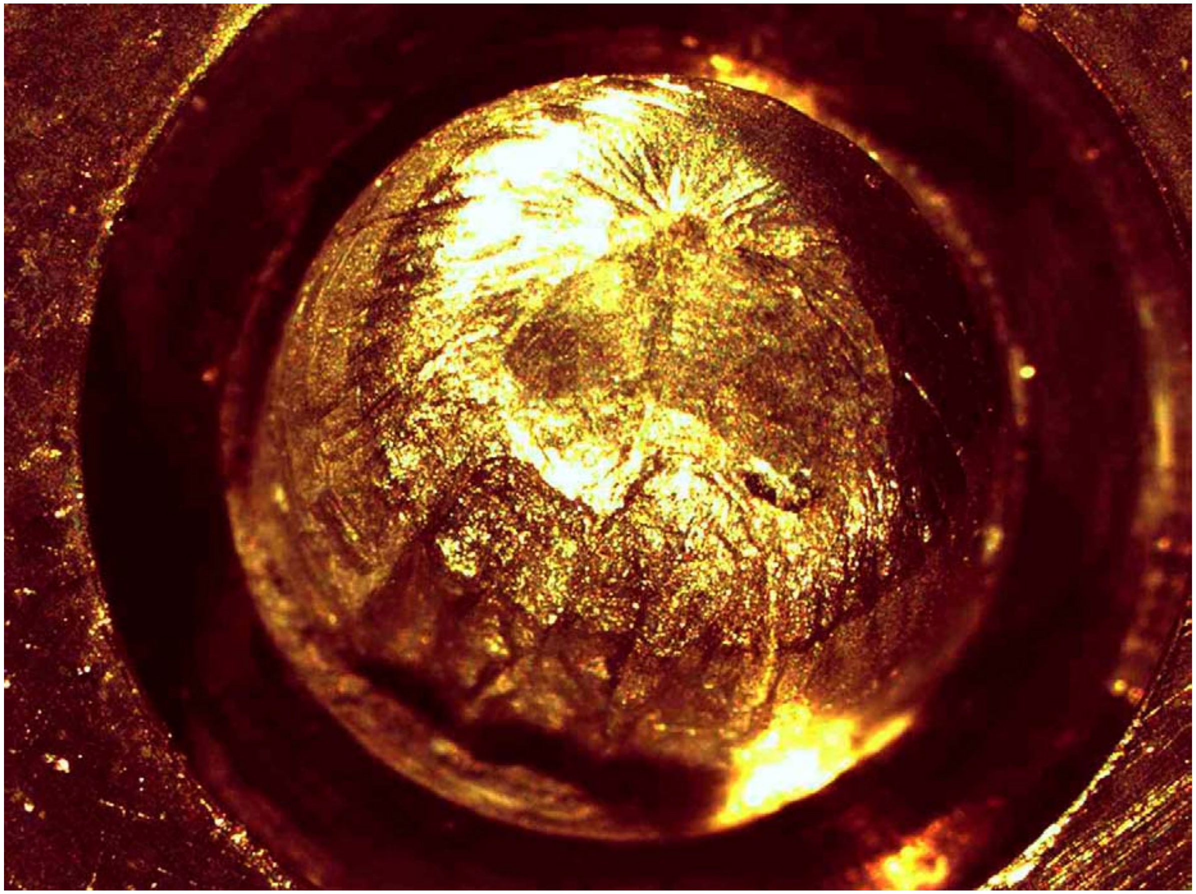
AEA Technology

Slide serial no 13

- Previously performed tests using AEA Engineering Model and Flight CBPDs, and demonstrated nominal performance under flight hardware configuration in laboratory atmosphere
- There was no evidence of cell rupture or excessive heat production during or after CBPD switch activation under simulated high cell impedance (open-circuit cell failure mode)
- When current was not limited (low-impedance short), none of four switches tested provided continuous electrical contact
- With simulated high cell impedance (open-circuit cell failure mode), continuous electrical contact was achieved.
  X-ray analysis confirmed the observation, but upon disassembly, there was no fusion between the two alloy halves

Switch Disassembled

(CBPD F029 - Charge side)



- Note contact area where switch halves separated easily

- Failure to provide fused contact between the two alloy halves may be due to an oxide layer on the surface(s) of the solid or molten alloy

- Because in-orbit switch closure would occur in vacuum, additional tests were performed under vacuum to confirm proper switch operation

STUDIES IN VACUUM

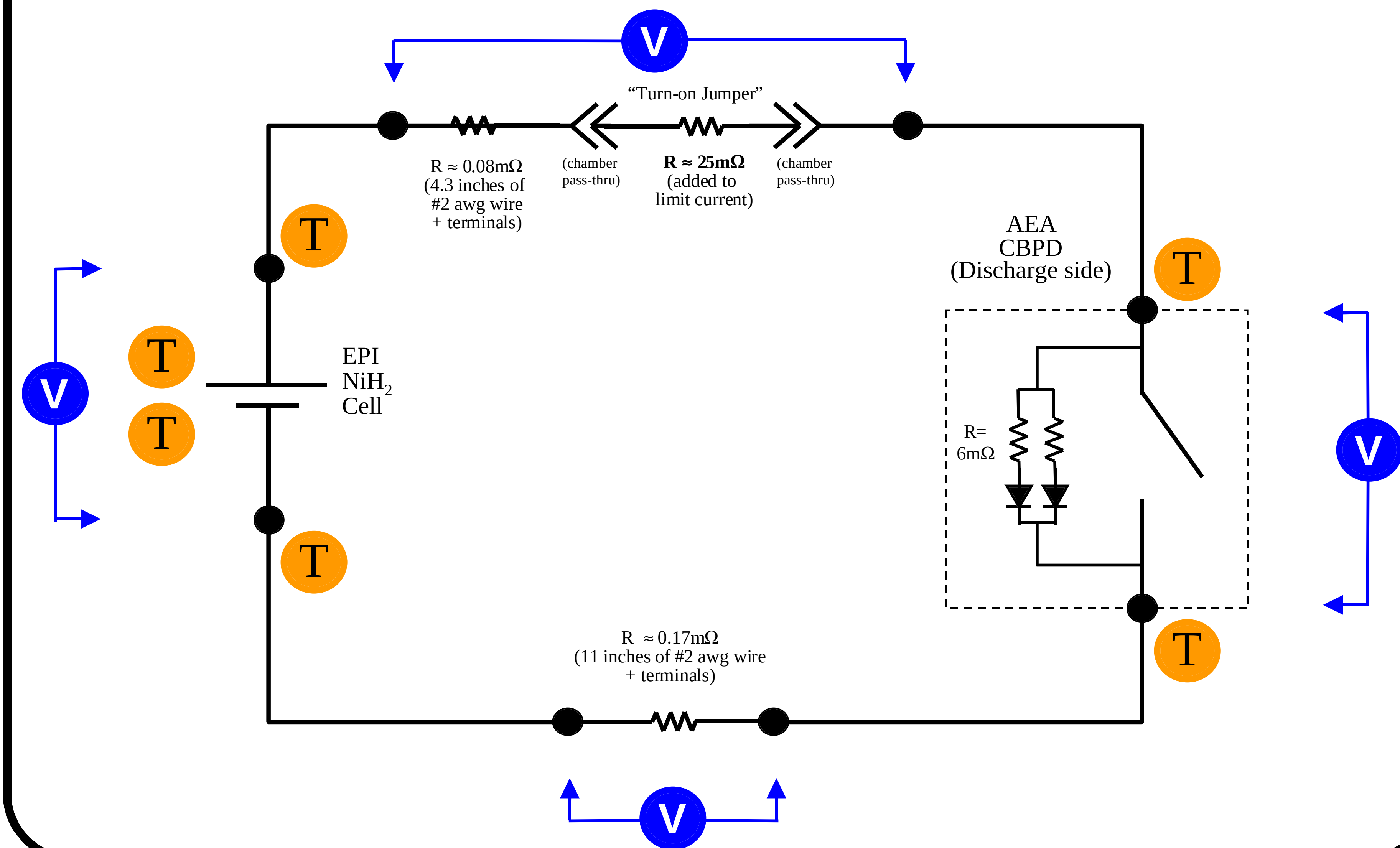
Tests Performed in Vacuum

- Test#1: Flight CBPD F029 (Unused discharge half)
  (charge side was cut off for DPA)
  Activated through discharge diodes
  Switch-axis Horizontal (launch orientation)

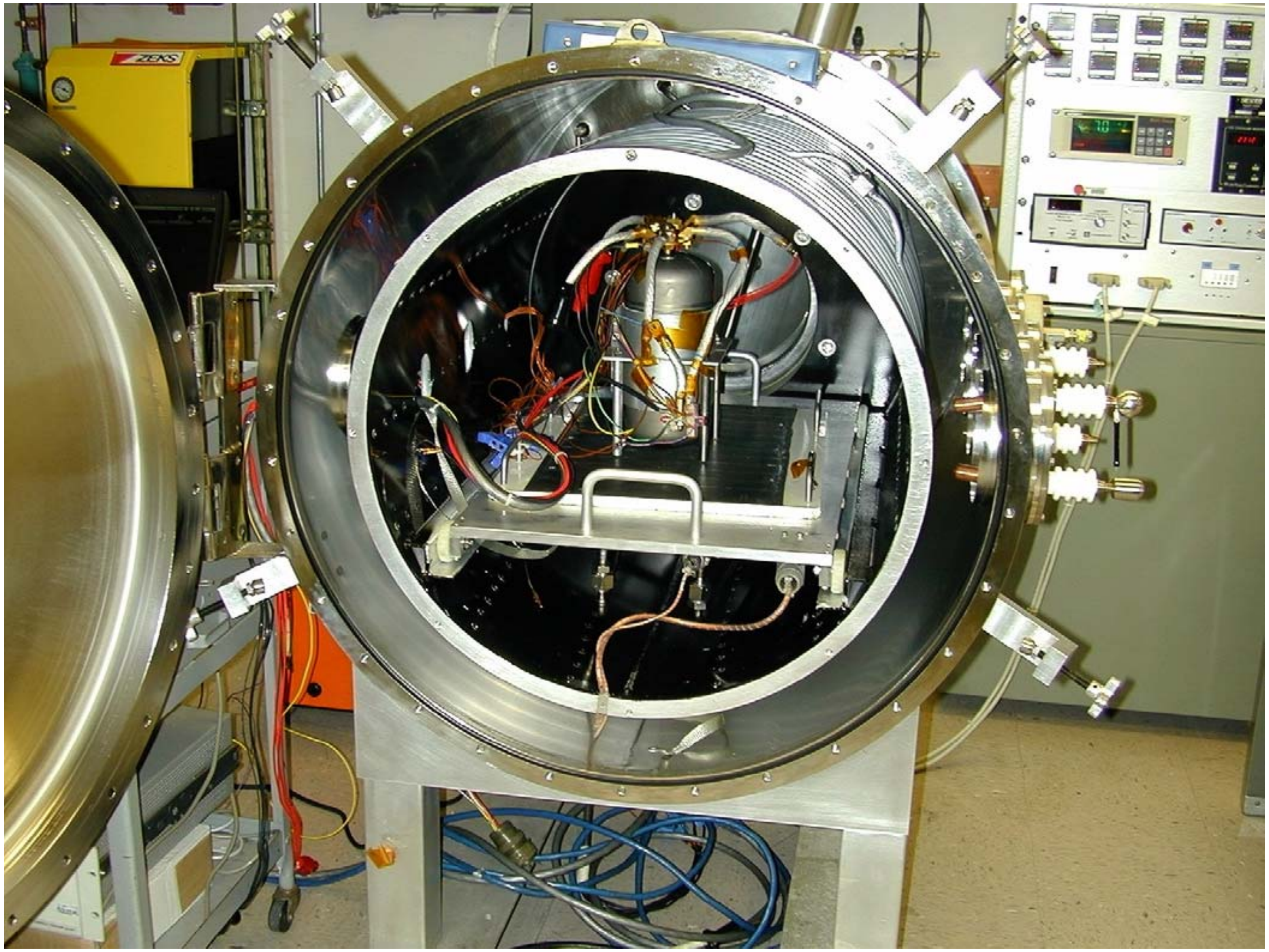
- Test #2: Flight CBPD F030
  (previously tested and failed to provide continuous contact)
  Activated through charge diodes
  Switch-axis Horizontal (launch orientation)

- Test#3: Engineering Model CBPD EM05
  (completely untested)
  Activated through charge diodes
  Switch-axis Horizontal (launch orientation)

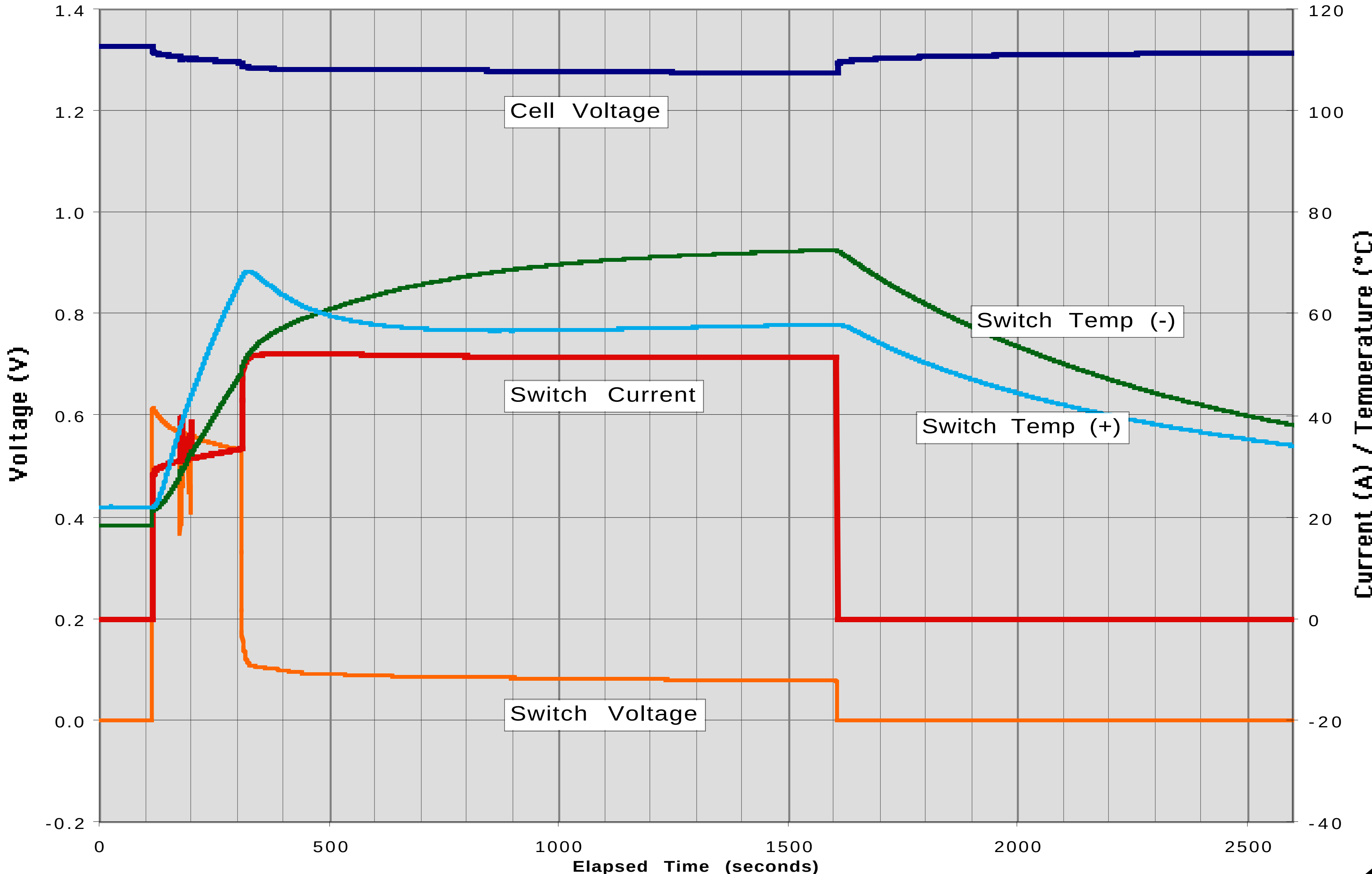
Test#1 Vacuum test setup (switch activated by installing turn-on jumper)



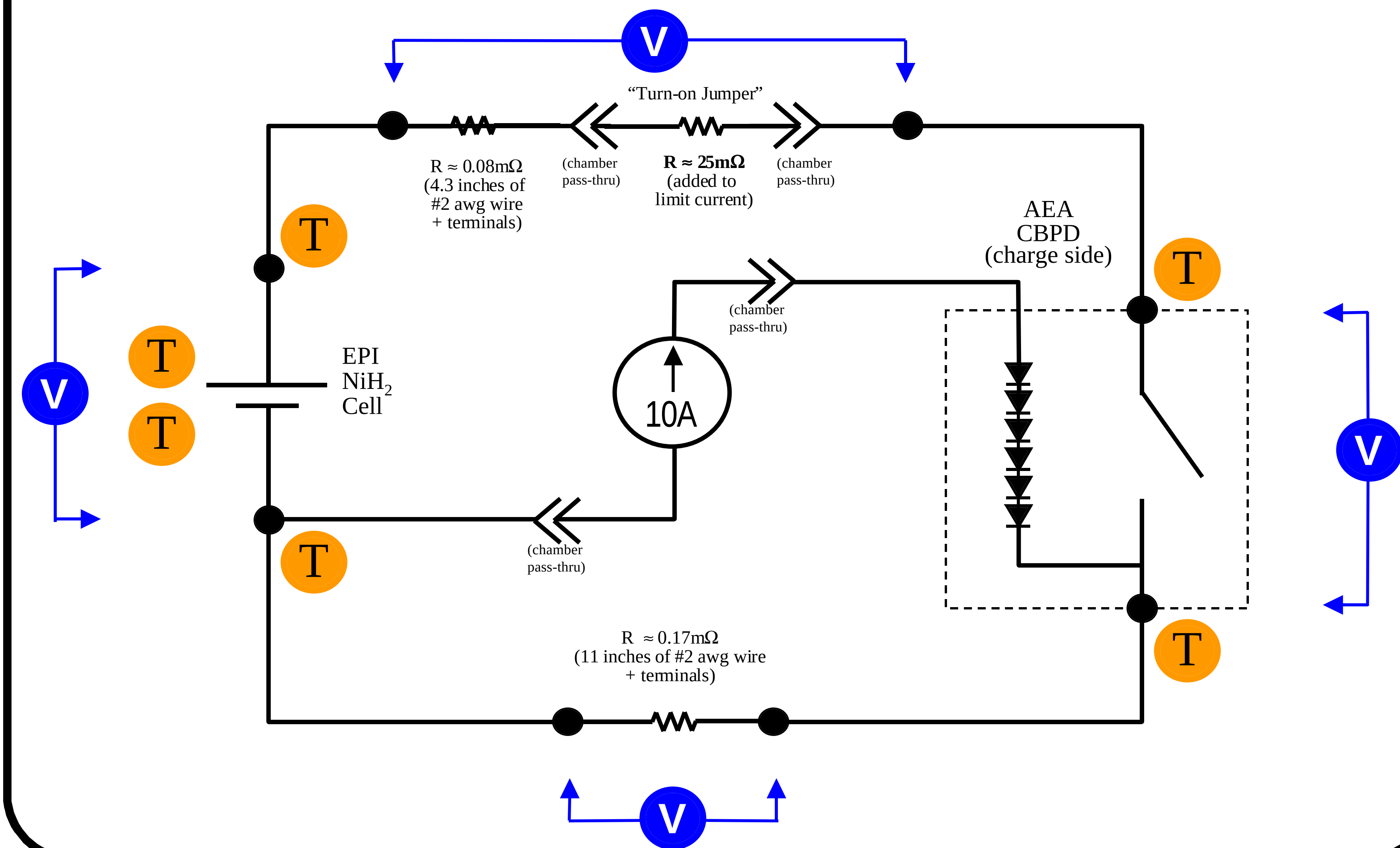
Test Setup



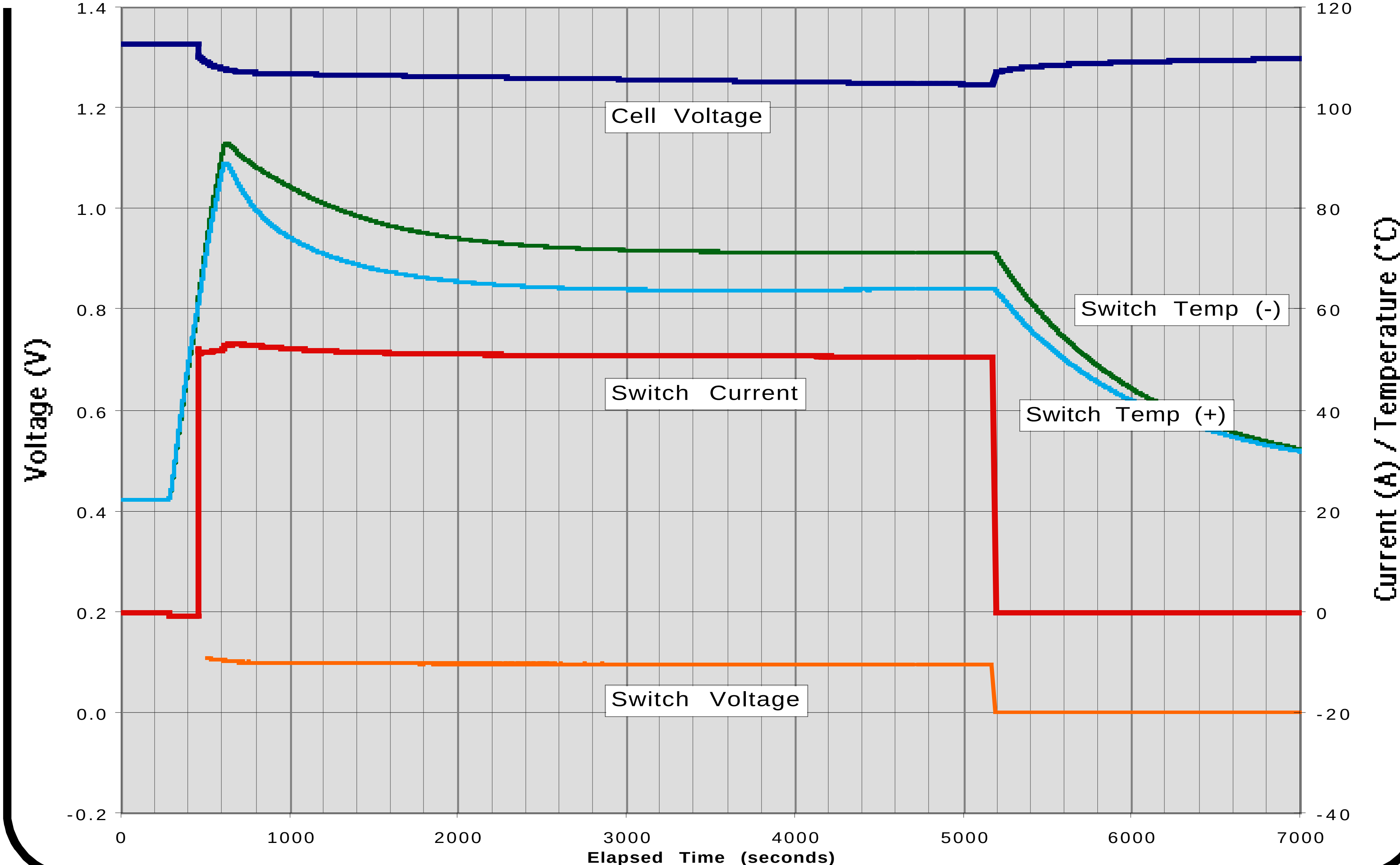
Test #1 Data (CBPD F029)



Test#2 & 3 Vacuum test setup (switch activated by 10 amps through charge diodes)

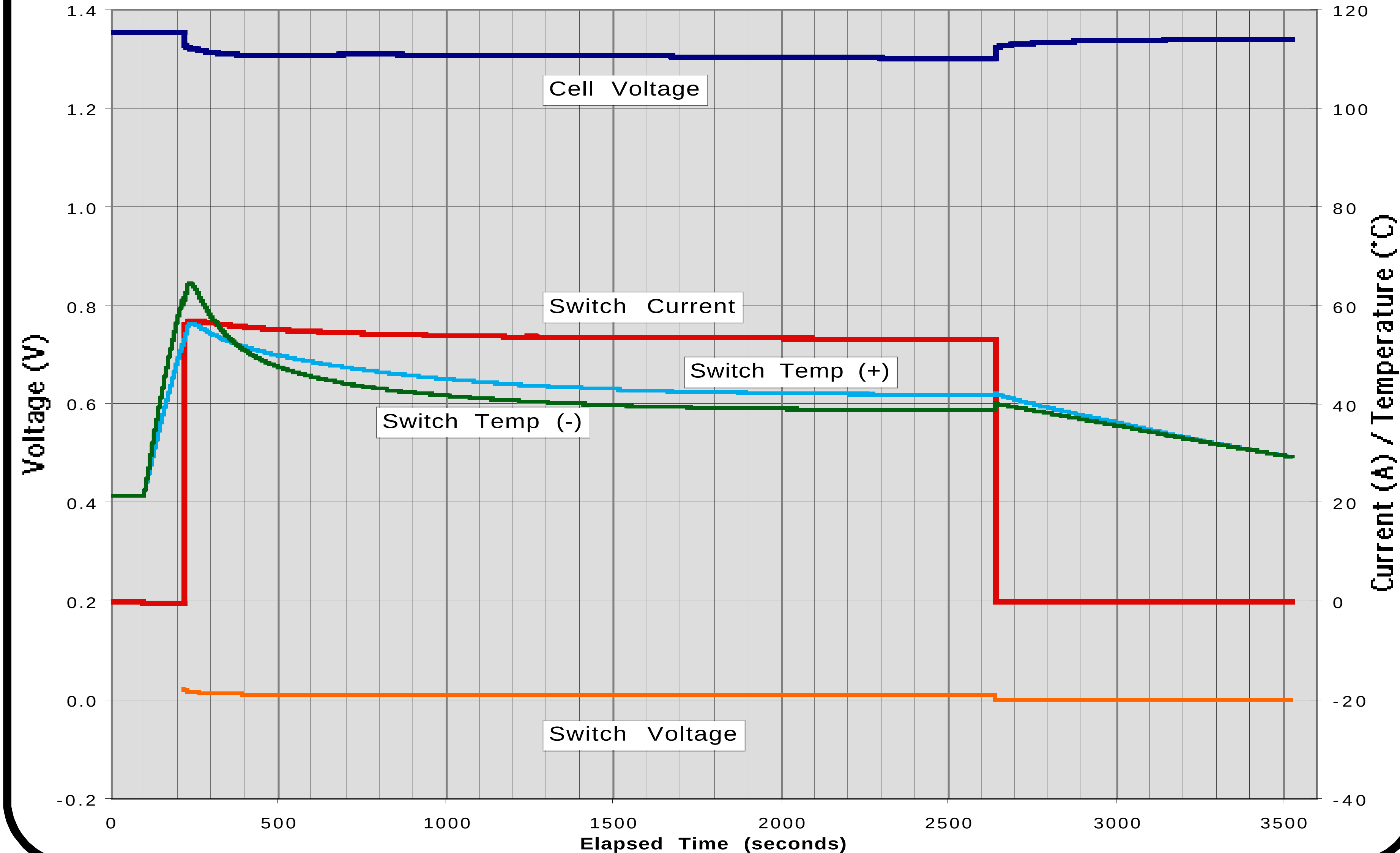


Test #2 Data (CBPD F030)

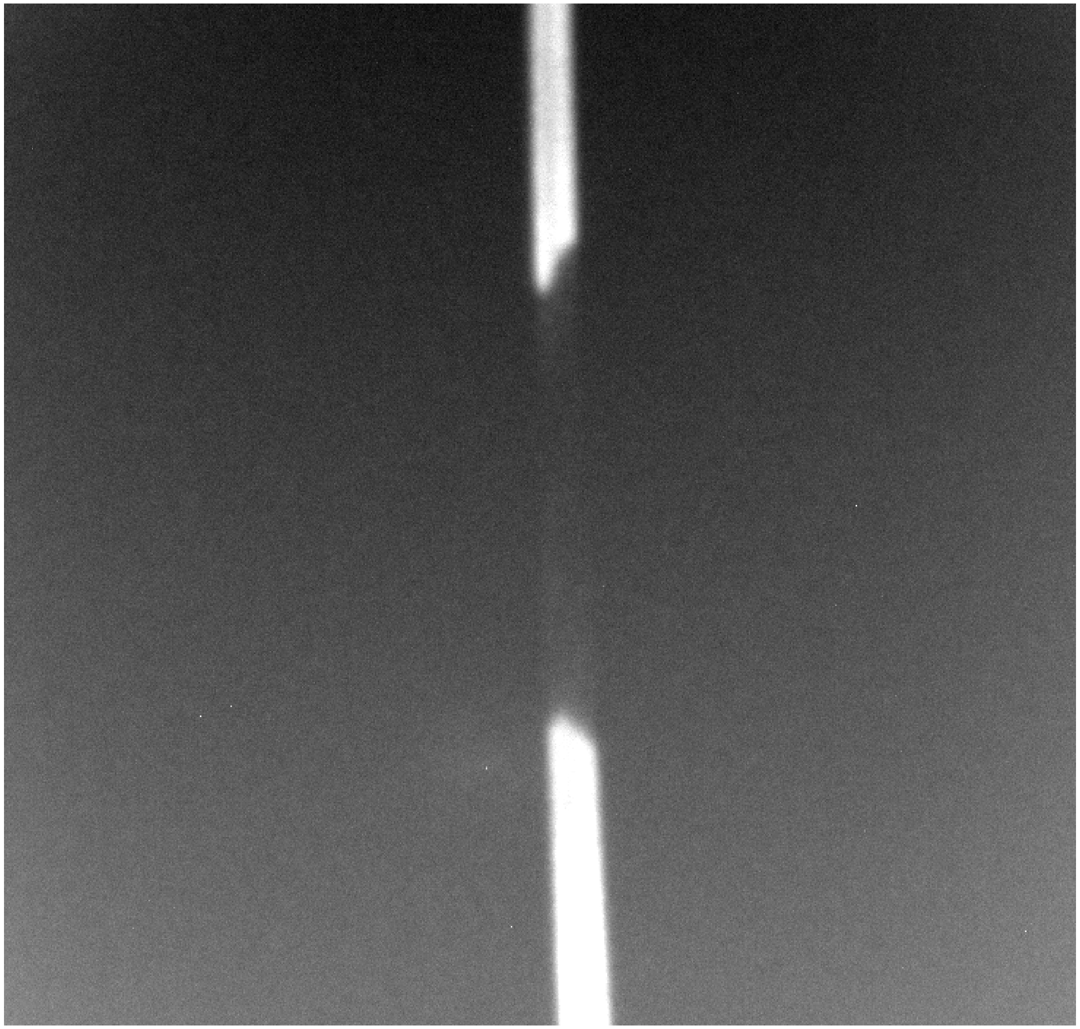


Testing Continues

Test #3 Data (CBPD EM05)



Fein Focus X-ray (CBPD EM05)



Fused alloy (CBPD EM05)

Microscopic X-Ray

Side view

Top view

Test Results

Test #	CBPD #	Result
1	F029 (discharge) Charge side of this switch was previously activated, and removed for DPA	- Switch fully closed after intermittent start - Retest after cool-down showed intermittent contact - Switch resistance during test and after cool-down = 1.5 milliohms
2	F030 Previously activated at atmosphere, and failed to provide continuous contact	- Switch fully closed for this test under vacuum - Retest after cool-down showed stable contact - Switch resistance during test and after cool-down = 1.8 milliohms
3	EM05 Untested engineering model	- Switch fully closed - Switch resistance during test and after cool-down = 0.16 milliohms - X-ray shows solid contact - Microscopic view shows fused alloy

Conclusions

- The nominal performance of AEA CBPD under flight operating conditions (vacuum except zero-G, and high-impedance cell) has been demonstrated
- There is no evidence of cell rupture or excessive heat production during or after CBPD switch activation under simulated high cell impedance (open-circuit cell failure mode)
- The formation of a continuous low impedance path (a homogeneous low melting point alloy) has been confirmed

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- Mr. Bill Moulford, AEA Technology
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- Mr. Dewey Dove, GSFC
- Ms. Diane Kolos, GSFC
- Mr. Bruno Munoz, GSFC
- Mr. Thomas Rozanski, GSFC

EOS-AQUA Nickel-Hydrogen Cell Life Test Update

R. F. Tobias

TRW Space And Electronics Group

Redondo Beach, California

The 2001 NASA Aerospace Battery Workshop

The Huntsville Hilton

Huntsville, Alabama

November 27-29, 2001

EOS PM-1

Presentation outline

TRW

- EOS-AQUA Overview
- Electrical Power System
- Cell Design
- Experimental Setup
- Test Results
- Summary

EOS PM-1

EOS-AQUA

TRW

- **Objective- To provide cloud, precipitation, sea surface temperature, terrestrial and oceanic productivity and atmospheric temperature data for Global Modeling**

- **Launch on a Delta II MELV in March 2002**

- **Polar, sun synchronous, 705 km orbit with the 1:30 PM nodal crossing**

- **Spacecraft weight is approximately , 2,933 Kg**

- **Six year mission**

EOS PM-1

AQUA Science Instruments

TRW

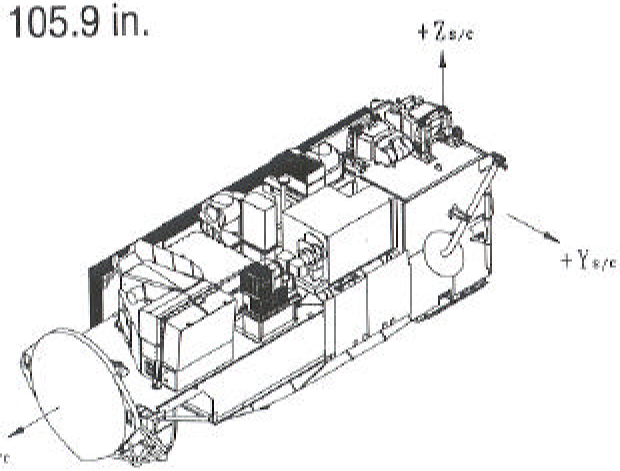
- AIRS (Atmospheric Infrared Sounder) - Measures visible and infrared bands simultaneously over 2,300 spectral channels
- AMSR-E (Advanced Microwave Scanning Radiometer) - Measures the earth's microwave radiation in 6 bands
- AMSU-A (Advanced Microwave Sounding Unit) - Measures earth's microwave radiation over 20 channels
- HSB (Humidity Sounder for Brazil) - Measures microwaves over 4 channels
- CERES (Cloud and Earth's Radiant Energy System) - Two units measure radiation at all wavelengths
- MODIS (Moderate-Resolution Imaging Spectroradiometer) - Measures visible and infrared radiation in 36 spectral bands

EOS PM-1

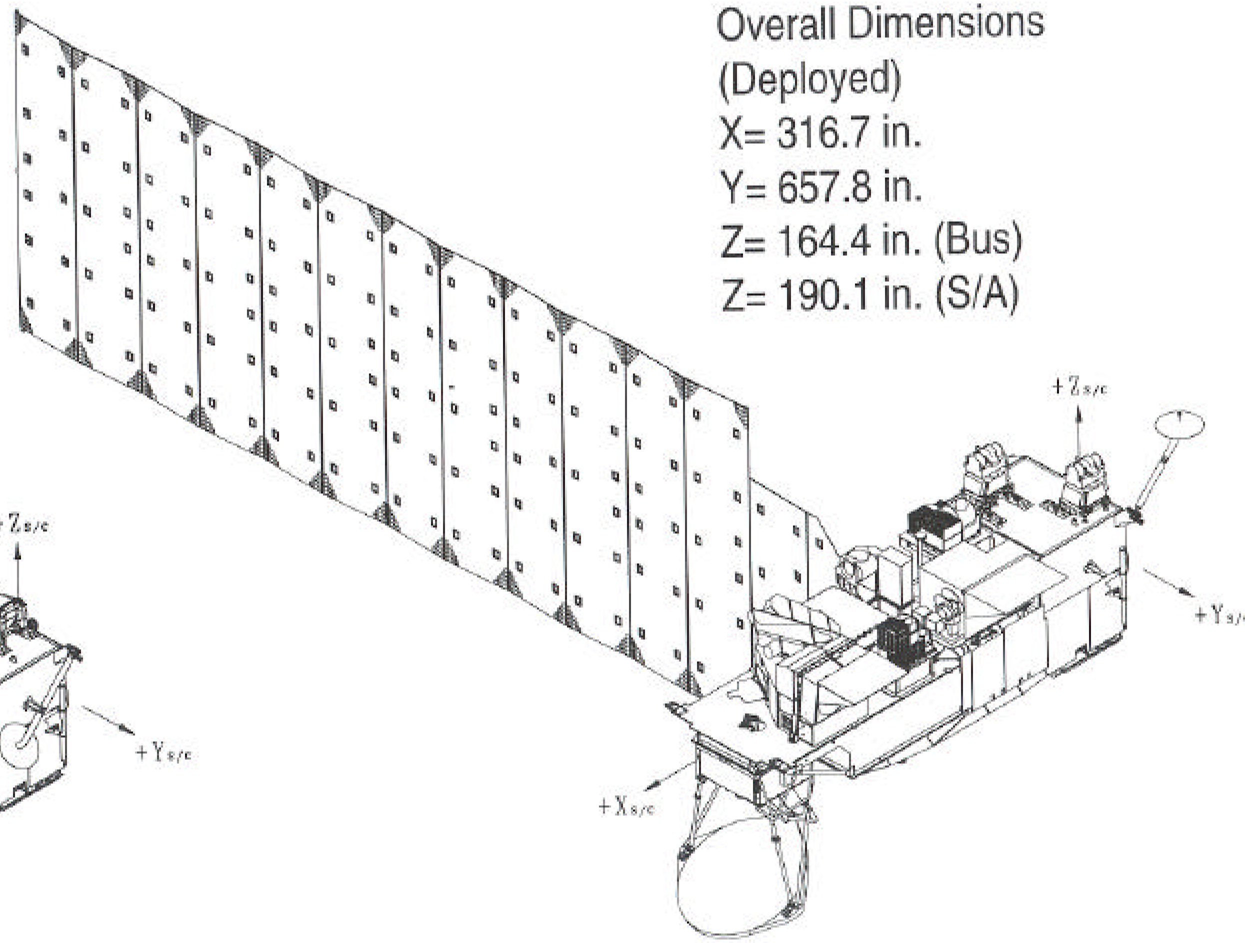
Spacecraft Configuration

TRW

Overall Dimensions
(Stowed)
X= 255.9 in.
Y= 98.1 in.
Z= 105.9 in.



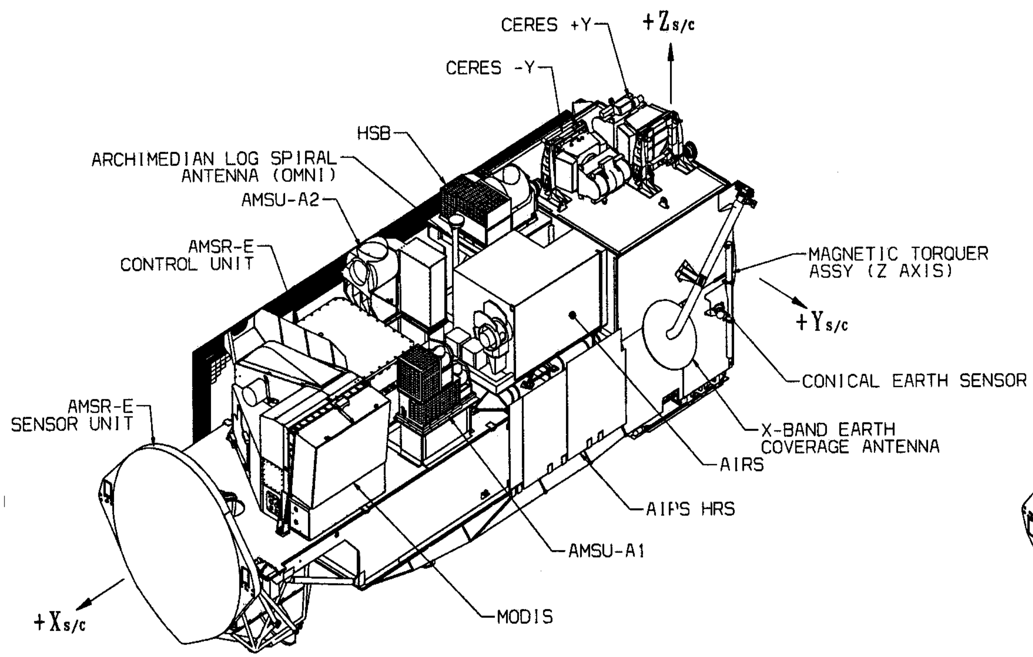
Overall Dimensions
(Deployed)
X= 316.7 in.
Y= 657.8 in.
Z= 164.4 in. (Bus)
Z= 190.1 in. (S/A)

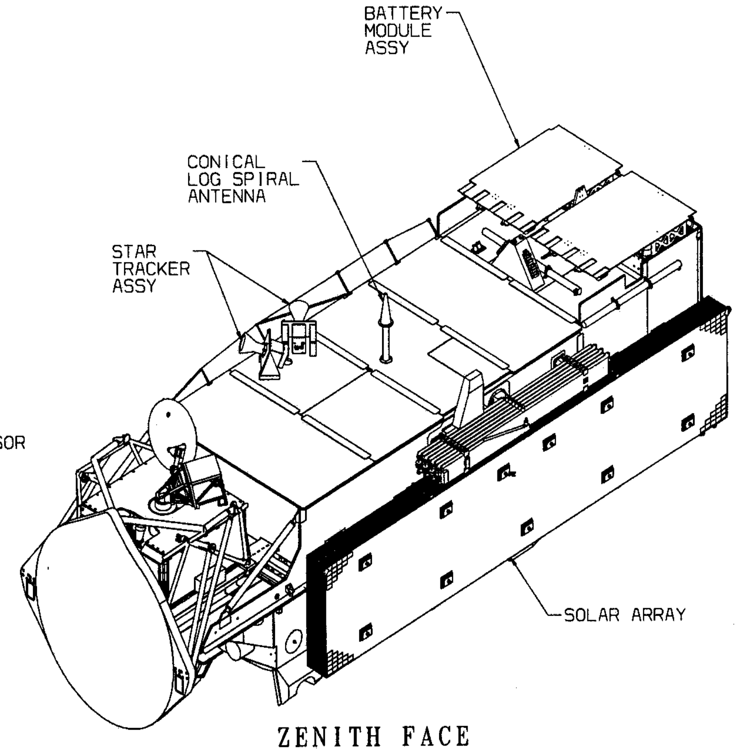


EOS PM-1

Payload External Features

TRW

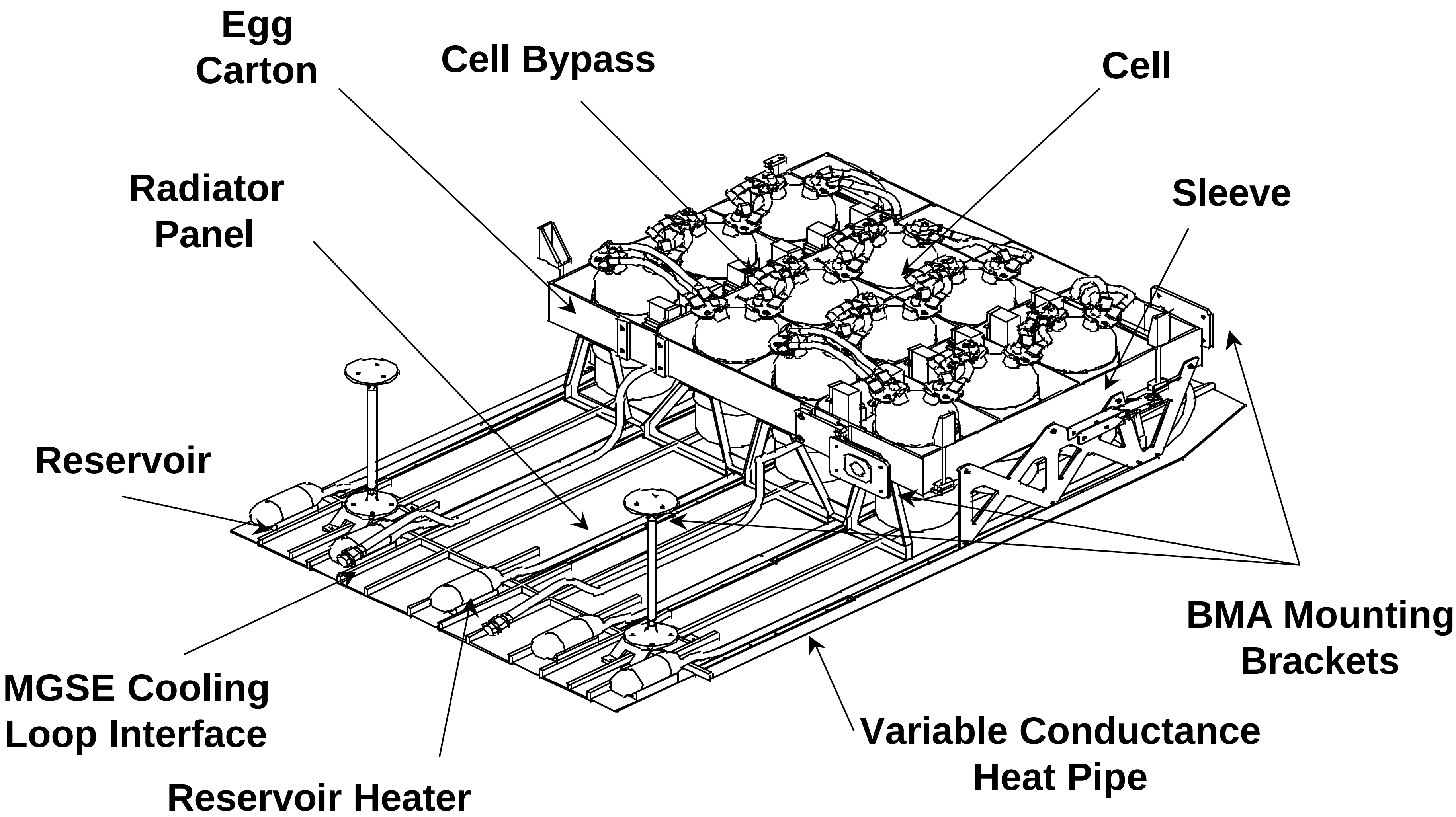




Electrical Power

- EPS via software provides power management, load shedding control, and battery management
- Electrical power is provided by the solar array and flight battery modules on orbit and a flight battery or ground power during prelaunch preparations
- Spacecraft power is nominallly 22.0 - 38.6 Vdc
- Circuit protection is provided by fusing, battery clamping overvoltage protection, bonding and grounding , and EMC controls
- Battery consists of 24 series-wired 160 Ah NiH2 cells contained in two-12 cell modules
  - Rate of charge is automatically controlled by charge determination and depth-of-discharge control software

Battery Assembly



NiH_2 160 AH Cell

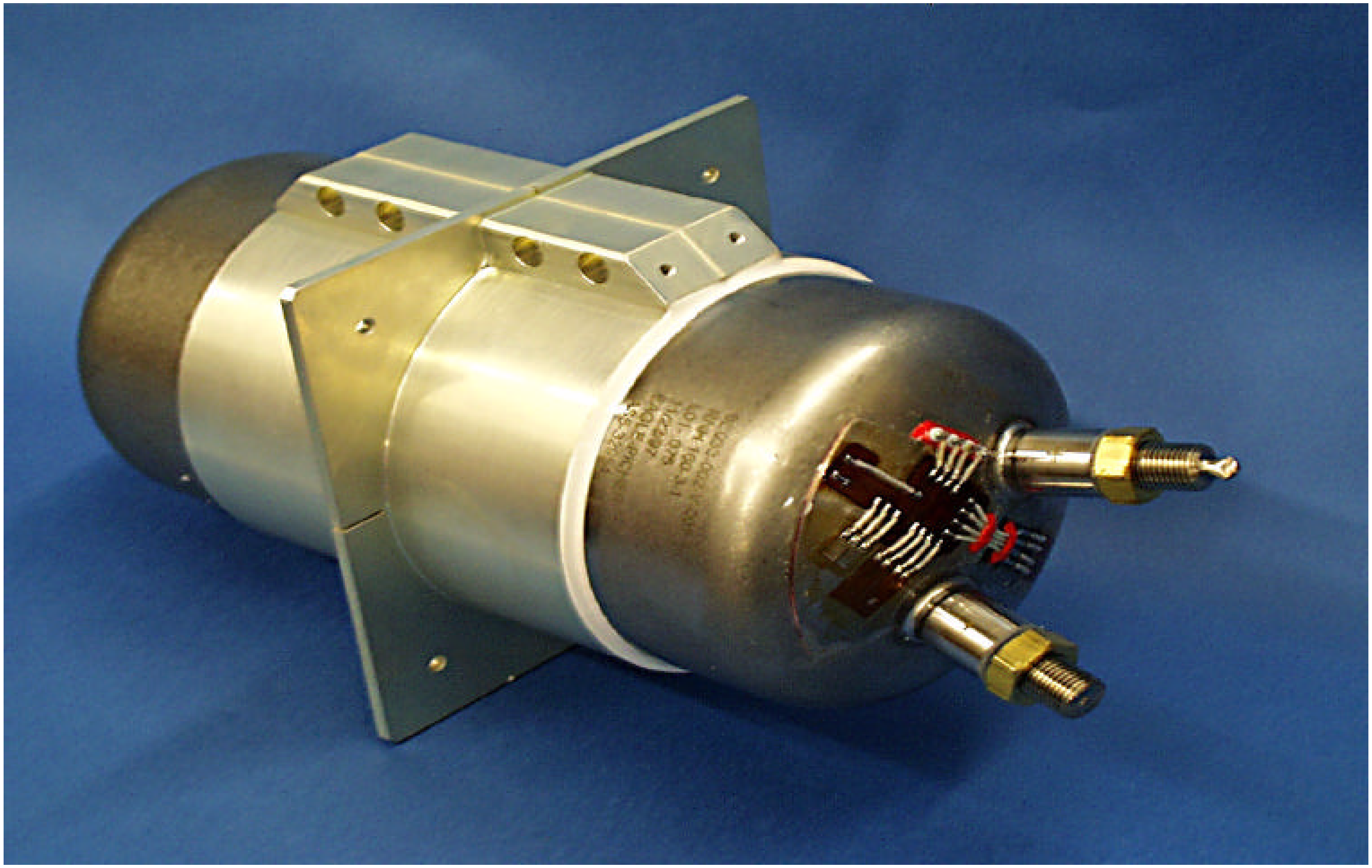
Cell Design

• Configuration	
– Stack	Single
– Electrode arrangement	Back-to-Back
– Bussing	“Pineapple shape”
• Internal coating	Zirconium oxide wall wick with catalyzed wall stripes
• Terminals	
– Seals	Ziegler nylon compression
– Placement	Rabbit ears
• Negative Electrodes	
– Number	64
– Substrate	Electro etched nickel foil
– Pt Loading	8 mg/cm^2

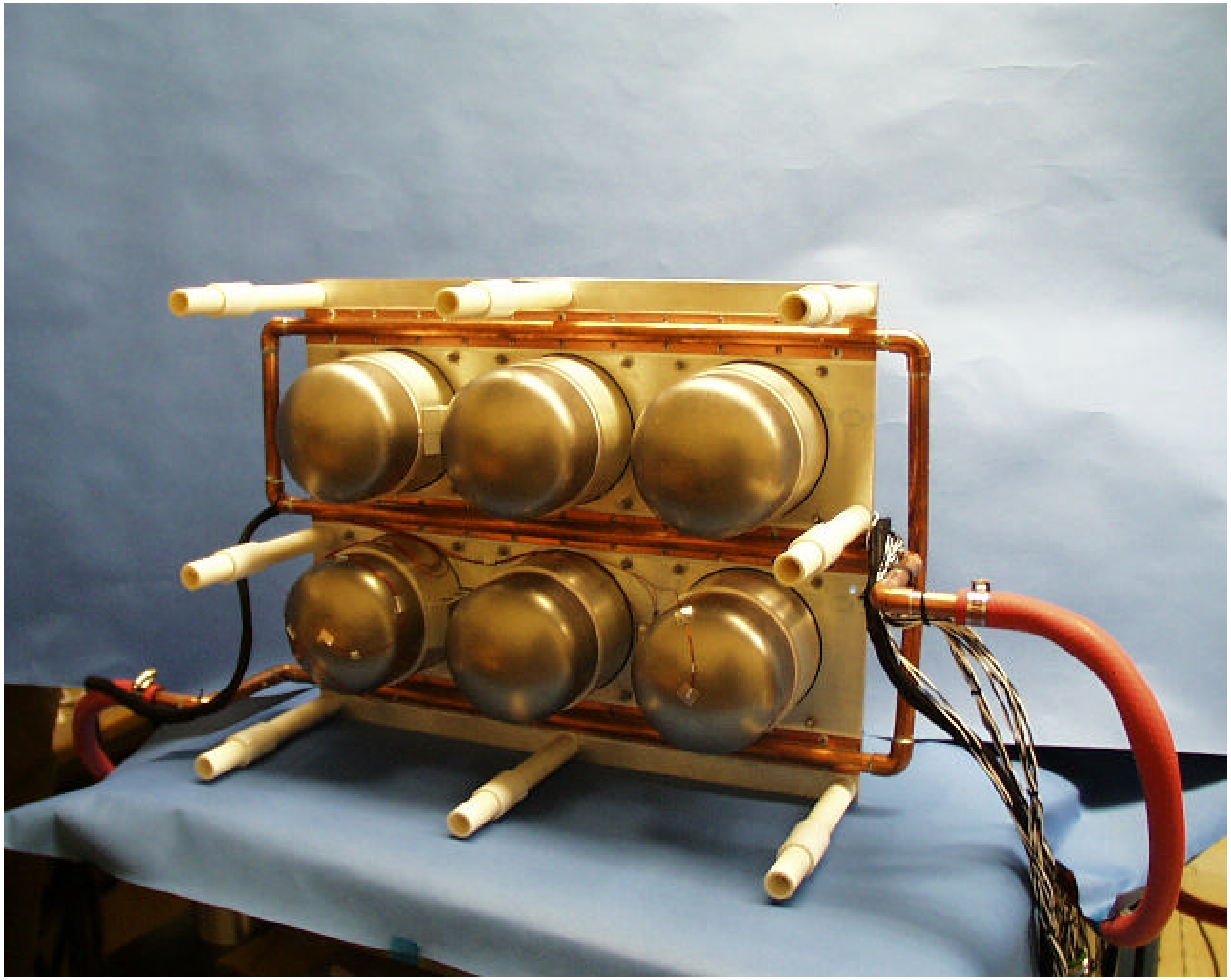
Cell Design (con't)

• Positive Electrodes	
– Number	64
– Plaque	Slurry
– Thickness	0.030 inch
– Porosity	80 %
– Impregnation	Aqueous electrochemical
– Active Material Loading	1.65 g/cc void
• Separator	
– Type	Zircar
– Layers	Two
• Electrolyte	
– Type	KOH
– Concentration	31 %
– Precharge	Nickel

Cell / Sleeve Arrangement



Bottom View of Cell Pack



Cell Packs

Experimental Setup

Experimental Design

- Test consists of two 6-cell packs
- Configuration designed to simulate conductive thermal design of the spacecraft battery
- Cells mounted in aluminum sleeves and placed on a mounting platform which contains cooling coils to control temperature
- Entire assembly is located in an insulated chamber

Experimental Conditions

- **Real Time LEO Condition**
- **Total orbit time:** **94.6 minutes**
- **Depth-of-discharge:** **25 % nominal**
- **Constant power discharge:** **550 watts for 34.8 minutes**
- **Charge to a given RR:**
  - **Initial current** **Approximately 45 amps**
  - **Taper current** **To 32 amps**
  - **Trickle current** **1.6 amps for 2 minutes minimum**

EOS PM-1

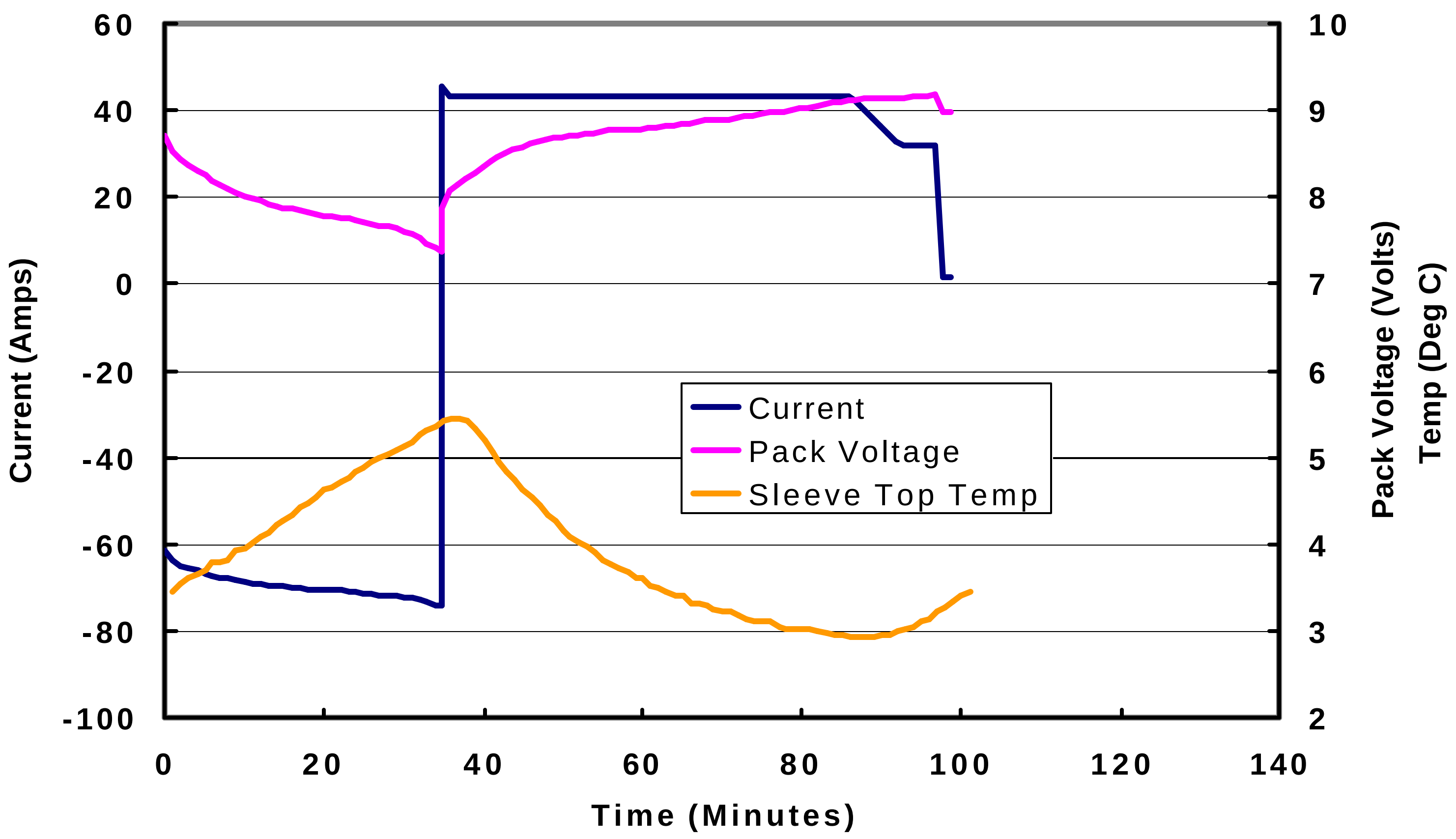
Cell Capacity Comparison
(Nameplate Capacity = 160 Ah)

TRW

Temp	TRW ATP	TRW Life Test	Eagle-Picher ATP
20 Deg C	162.6		146.9
10 Deg C	184.0	186.7	170.4
0 Deg C	202.8	200.1	186.9

EOS-Aqua Life Test
Current-Voltage-Temperature Profile

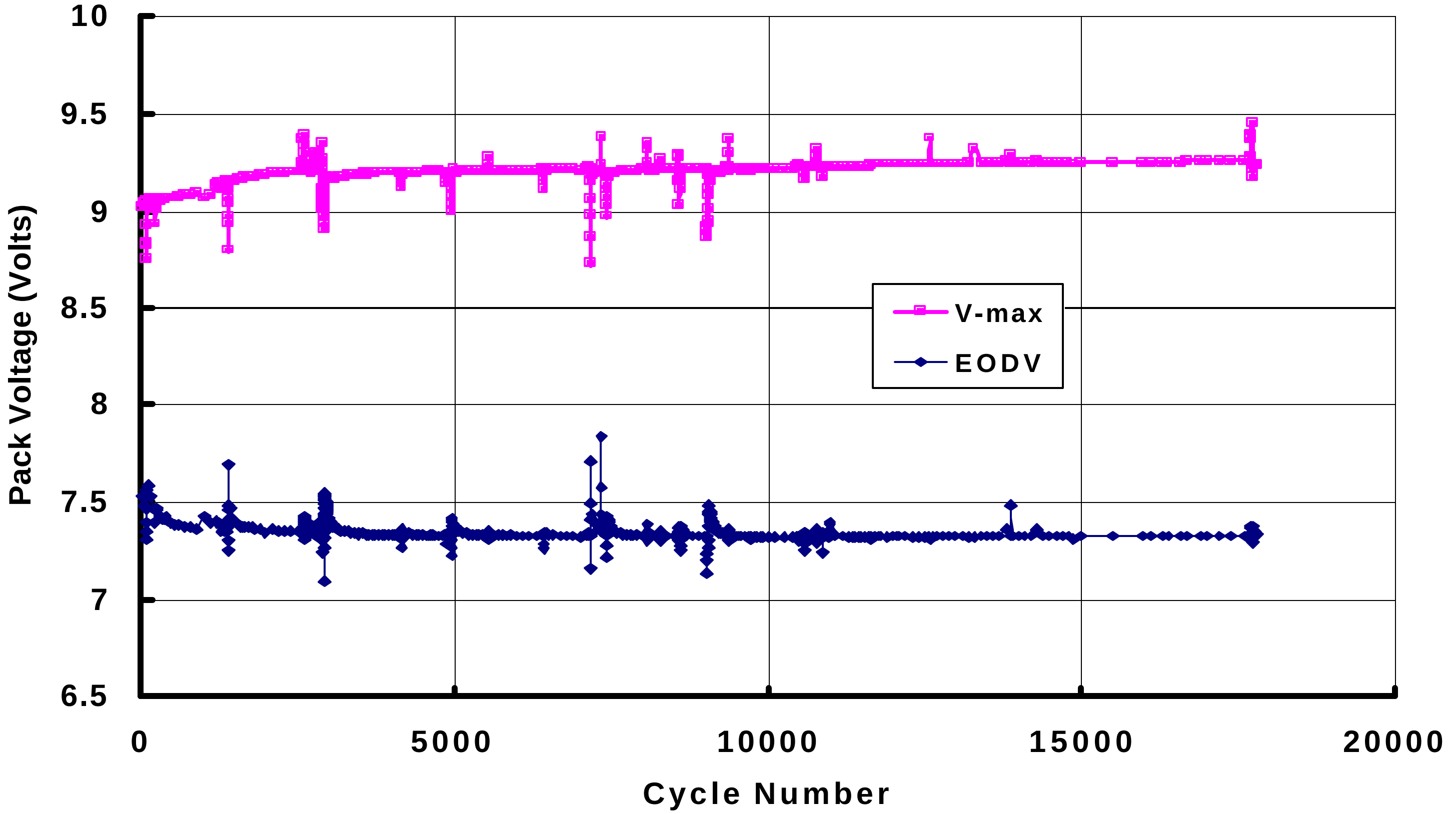
TRW



EOS PM-1

EOS-Aqua Life Test
Pack Voltage vs Cycle

TRW



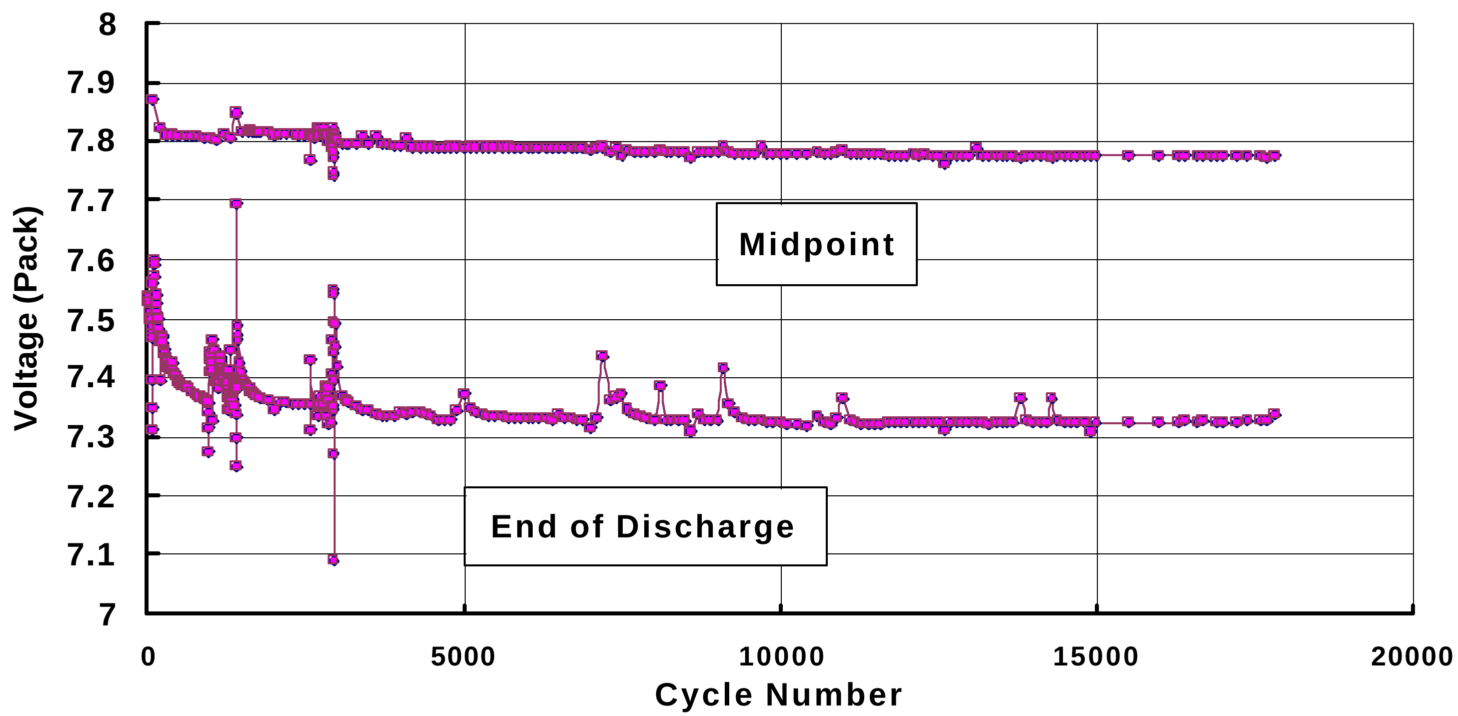
Test Anomalies

- Temperature control problems were the major cause of the test anomalies- old equipment which required constant vigilance
- Software and hardware problems during initial startup
- Electrical problems- Several times the power in the building was turned off for facilities repair

EOS-Aqua Life Test
Discharge Voltage vs. Cycle

TRW

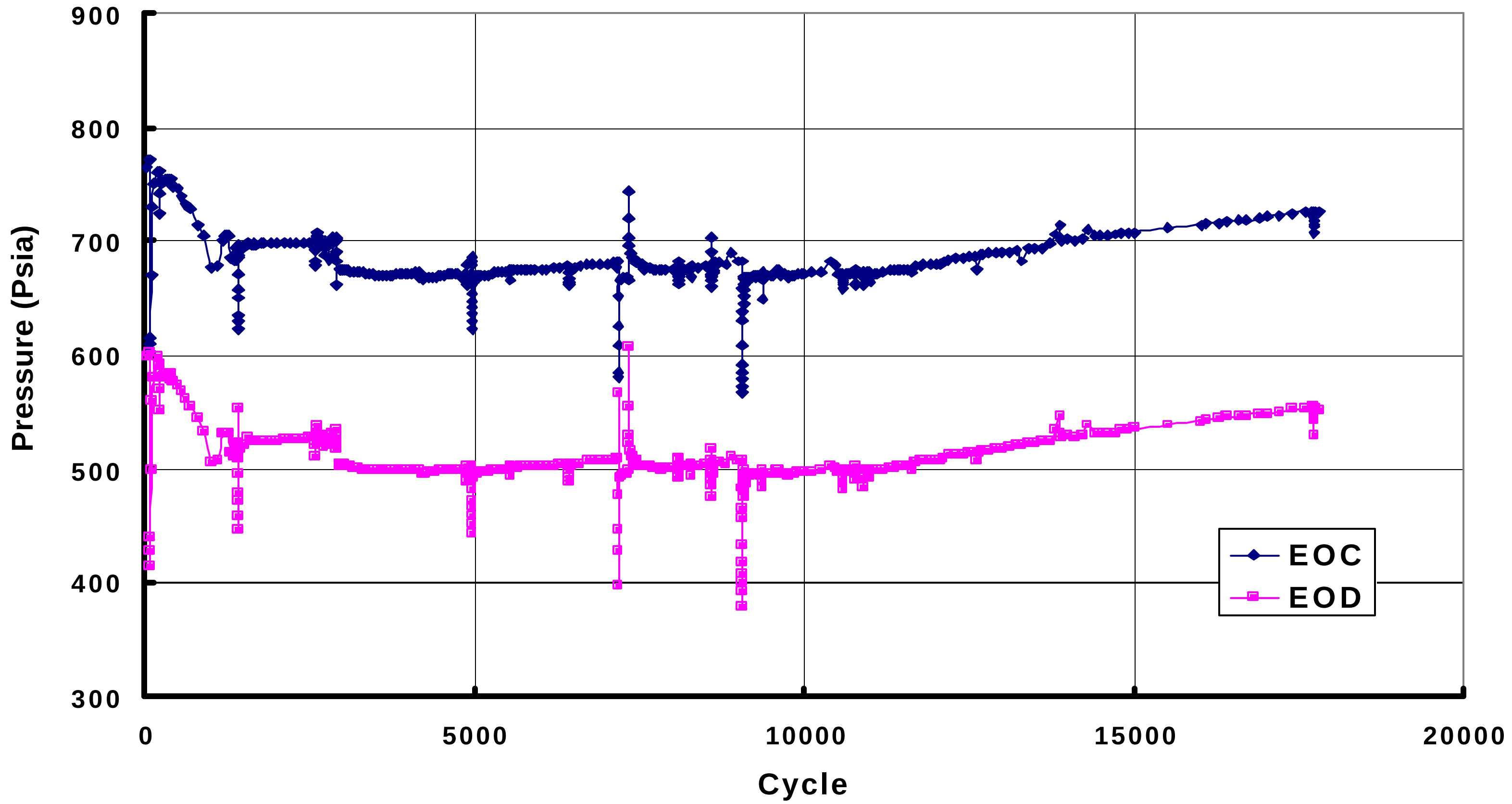
EOS PM-1



EOS-Aqua Life Test
Cell Pressure vs Cycle

TRW

EOS PM-1

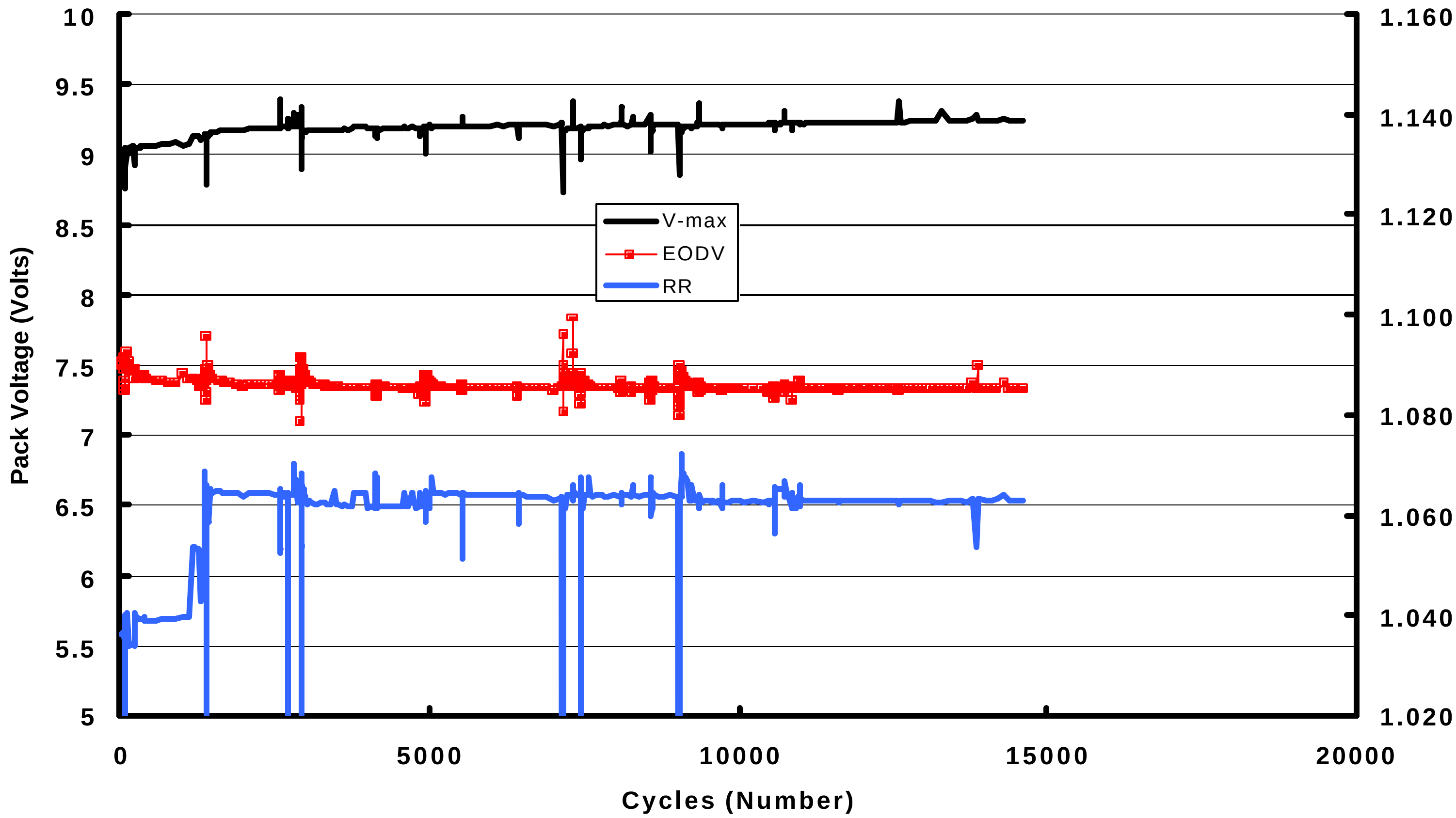


EOS PM-1

EOS-Aqua Life Test

Recharge Ratio & Pack Voltage vs. Cycle

TRW



Pack Voltage Dispersion

Cycle	EOC Dispersion	EOD Dispersion
250	3 mv	3 mv
3000	3	1
6000	4	1
9000	5	2
10250	5	2
11450	5	2
14500	6	2
17850	6	2

EOS PM-1

Summary

TRW

- As of 10/31/01 the cells have successfully completed over 17,900 LEO cycles at 25 % DOD
  - EODV is over 1.230 volts - well above the end of life requirement of 1.100 volts
- Pressure and end of discharge voltage decreased initially but stabilized after the RR was increased from 1.04 to 1.06.
- After approximately 10,000 cycles an increase in pressure with cycling has been observed
- End of charge voltage increasing slightly with cycles
- Voltage dispersion is minimal

Single Pressure Vessel Life Test Update

Jeff Dermott

Eagle-Picher Technologies, LLC

Joplin, Missouri

BACKGROUND

- NiH_2 Life Testing at EPT was originally started to support early flight programs.
- Test bed has been expanded over past 20 years to include new designs.
- Single Pressure Vessel (SPV) represents a significant change battery design.
- SPV life testing was required to prove reliability of the design.

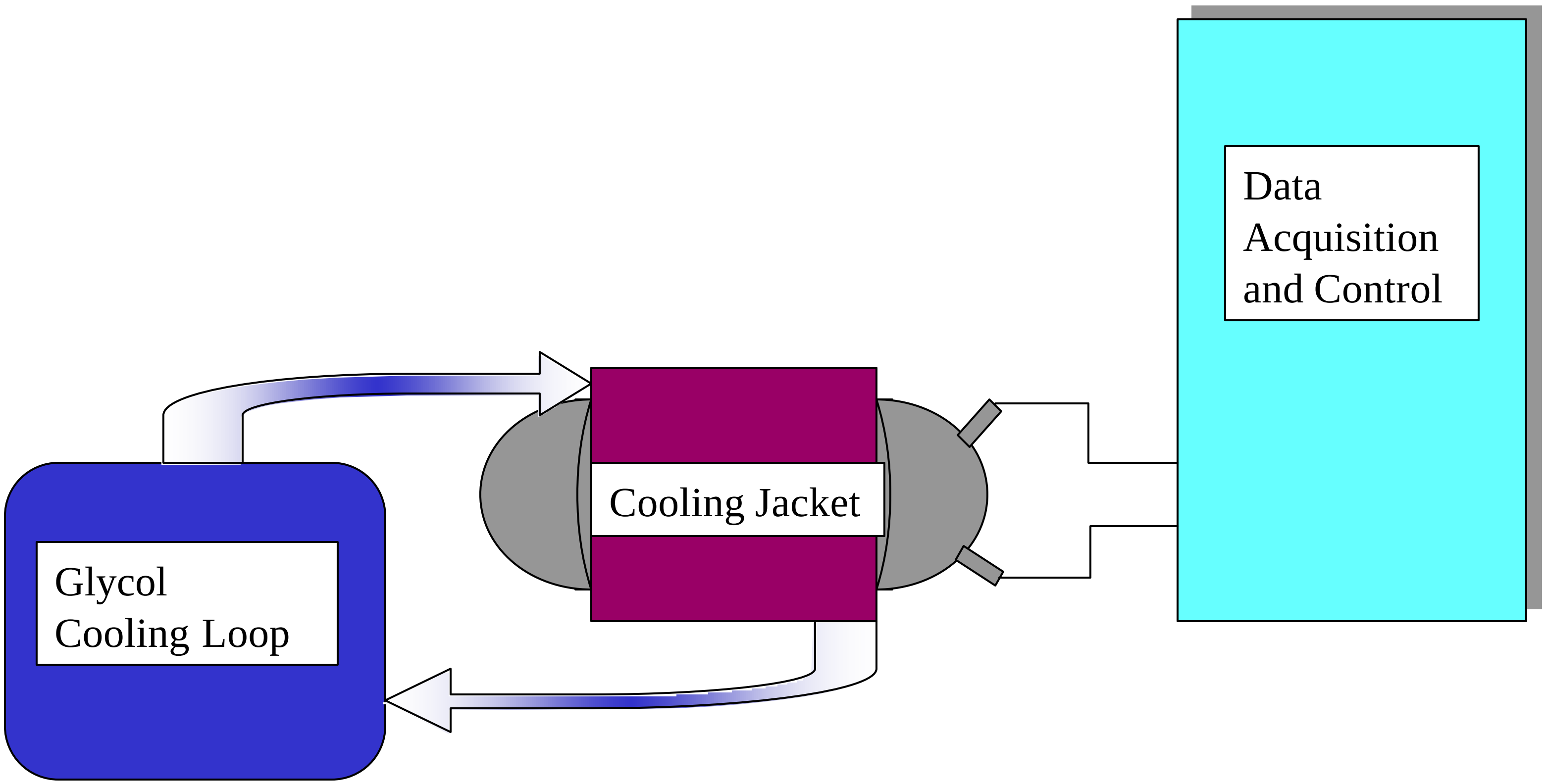
SPV DESIGN REVIEW

- SPV battery combines 22 cells into one vessel.
- Two transducers used for pressure monitoring.
- Typical 50AH SPV Characteristics
  - Length = 24.7 inches
  - Weight = 30.4 kg
  - Diameter = 10.1 inches
  - Specific Energy = 54.6 Wh/kg
  - Energy Density = 59.3 Wh/L

SPV DESIGN REVIEW

- SPV cells have stack design similar to IPV cells.
- Major difference is the Electrolyte Containment System (ECS).
- The ECS consist of 2 sealed plastic bags with gas vents.
- SPV cells share H_2 gas.

TEST SET-UP


Data
Acquisition
and Control
Cooling Jacket
Glycol
Cooling Loop

SPV LIFE TEST BATTERIES

- Three batteries have been subjected to Life Testing.
- Two of these are still on test at EPT. They are identified as RL-2(S162) and RL-3(S262).
- Both of these batteries were built by EPT at the Range Line Facility and they represent the current SPV technology.

SPV LIFE TEST SUMMARY

Battery	RL-2(S162)	RL-3(S262)
Nameplate Capacity	50 AH	60 AH
No. of Cells	22	22
Test Temperature	-5°C	+5°C
Test Start Date	6/3/96	1/28/97
No. of Cycles	27,723	24,705
DOD	30%	25%
EODV	26.861V	27.717V
EOCV	34.558V	33.949V

LIFE TEST CYCLE CONDITIONS

Battery	RL-2(S162)	RL-3(S262)
Cycle Duration	100 minutes	100 minutes
Nominal Charge Rate	20	20
Nom. Discharge Rate	21 amps	21 amps
Max. Discharge Rate	42 amps	42 amps
Recharge Ratio	1.02	1.02

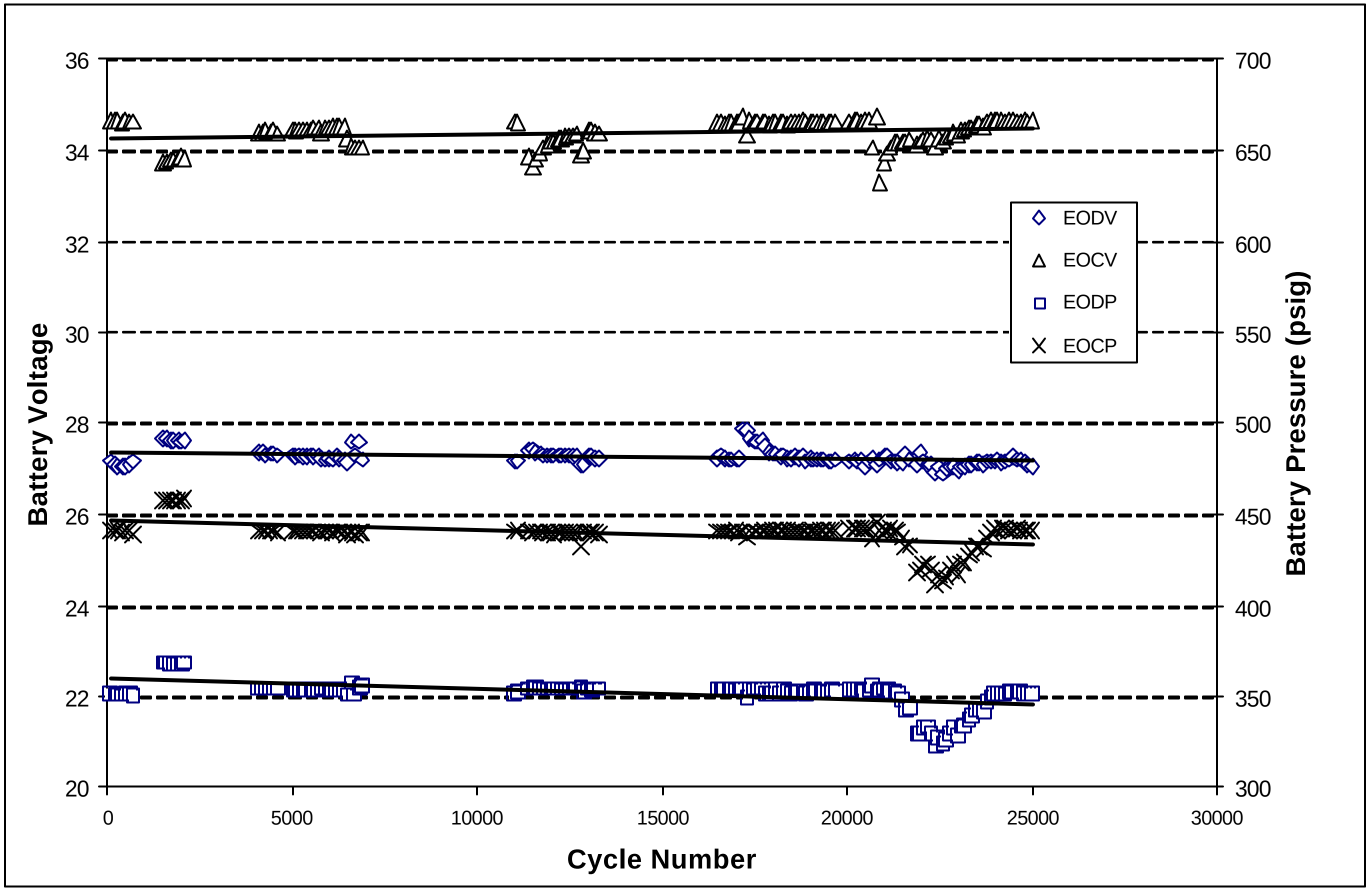
- **Exact cycle conditions are proprietary.**
- **Each cycle contains two discharges.**
- **Charge is controlled based on pressure.**

EAGLE PICHER

Eagle-Picher Technologies, LLC

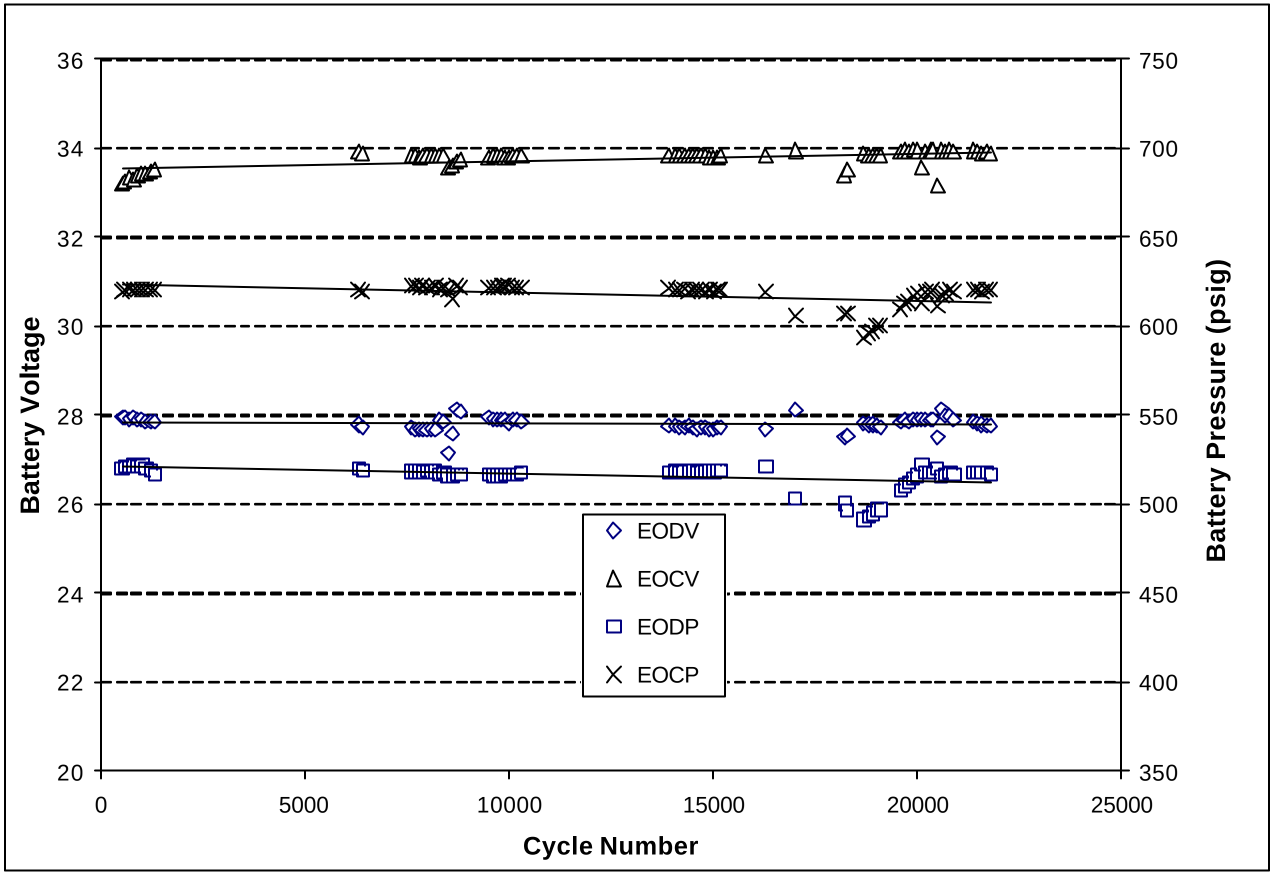
POWER Subsystems

RL-2 TREND DATA



Eagle-Picher Technologies, LLC

RL-3 TREND DATA



SPV LIFE TEST DATA TRENDS

- Based on current EPT IPV life test data cells cycling at 25-30% DOD should survive at least 75,000 cycles.
- Trend data indicates RL-2 EODV will be at 25.453V (1.157V/cell) when it reaches 75,000 cycles.
- Trend data indicates RL-3 EODV will be at 27.188V (1.235V/cell) when it reaches 75,000 cycles.
- Neither battery is showing any significant pressure trends at this time.

CONCLUSIONS

- Both batteries are showing stable performance under the current cycle regime.
- EODV trends indicate the batteries will meet performance levels of IPV's at similar DOD.

ACKNOWLEDGEMENTS

- *Chris Guilfoyle:* Eagle-Picher Technologies, LLC
- *Kevin Gray:* Eagle-Picher Technologies, LLC

Methods Used To Prevent Capacity Fade In Nickel Hydrogen Batteries

Jack N. Brill and Matt Mahan
Eagle-Picher Technologies LLC

Background

- **For some time it has been known that storage of cells with an internal hydrogen pressure can lead to capacity fade.**
- **Cells stored for periods of 8 years or more have shown normal performance when the nickel precharge is maintained.**
- **Other cells stored for less time have exhibited capacity loss.**
- **The loss in capacity is attributed to loss of precharge.**

Precharge Loss

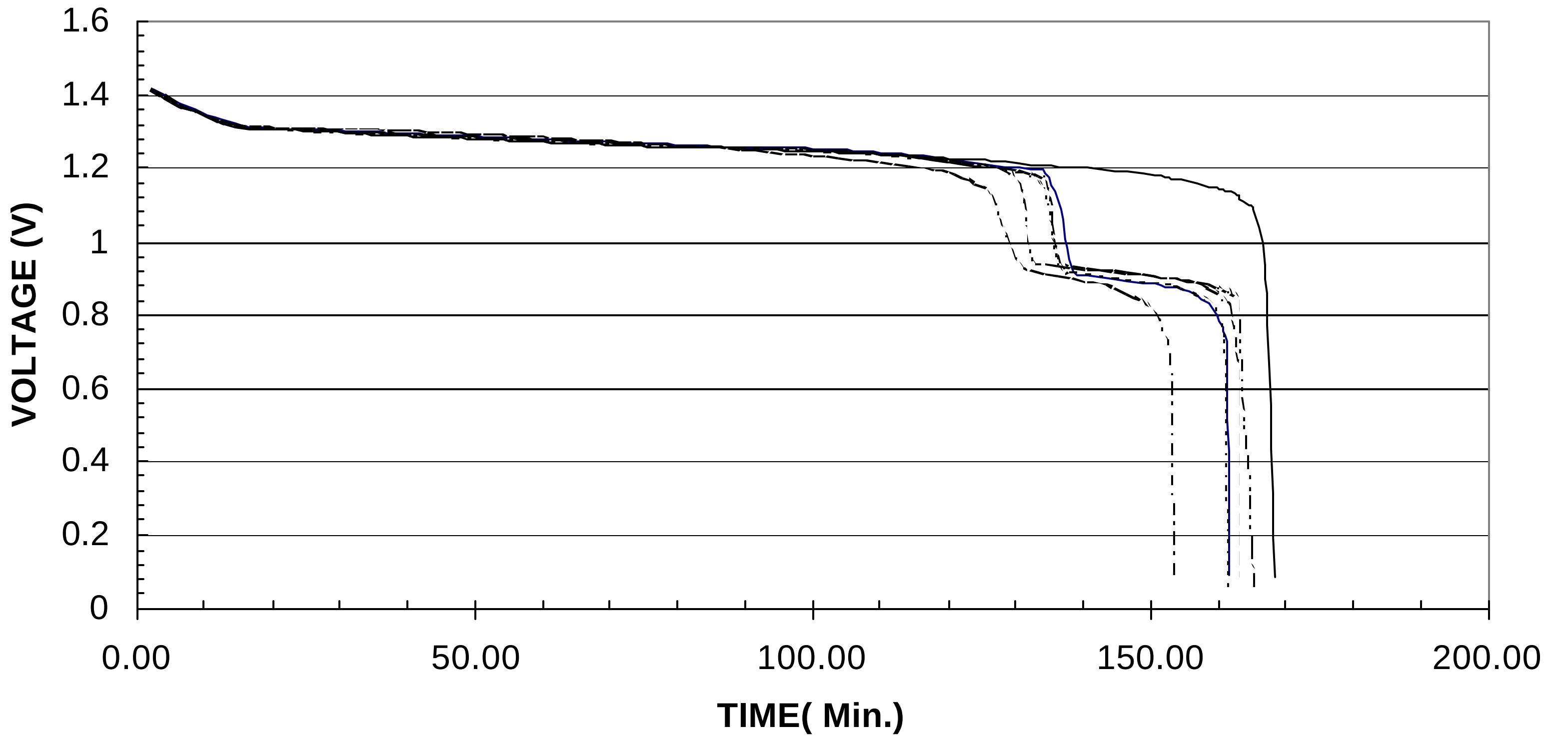
- **The loss of cell precharge can occur for various reasons.**
  - **Extended trickle charge.**
  - **Repeated overcharge of cells during integration and testing.**
  - **Allowing cells to stand in a partial charge condition for extended periods followed by overcharge.**

Capacity Loss

- **The capacity loss typically is a result of a second voltage plateau developing.**
- **A portion of the capacity is unusable since the cell terminal voltage is less than 1.00 volt.**
- **Normally the total capacity of the cell is the same.**

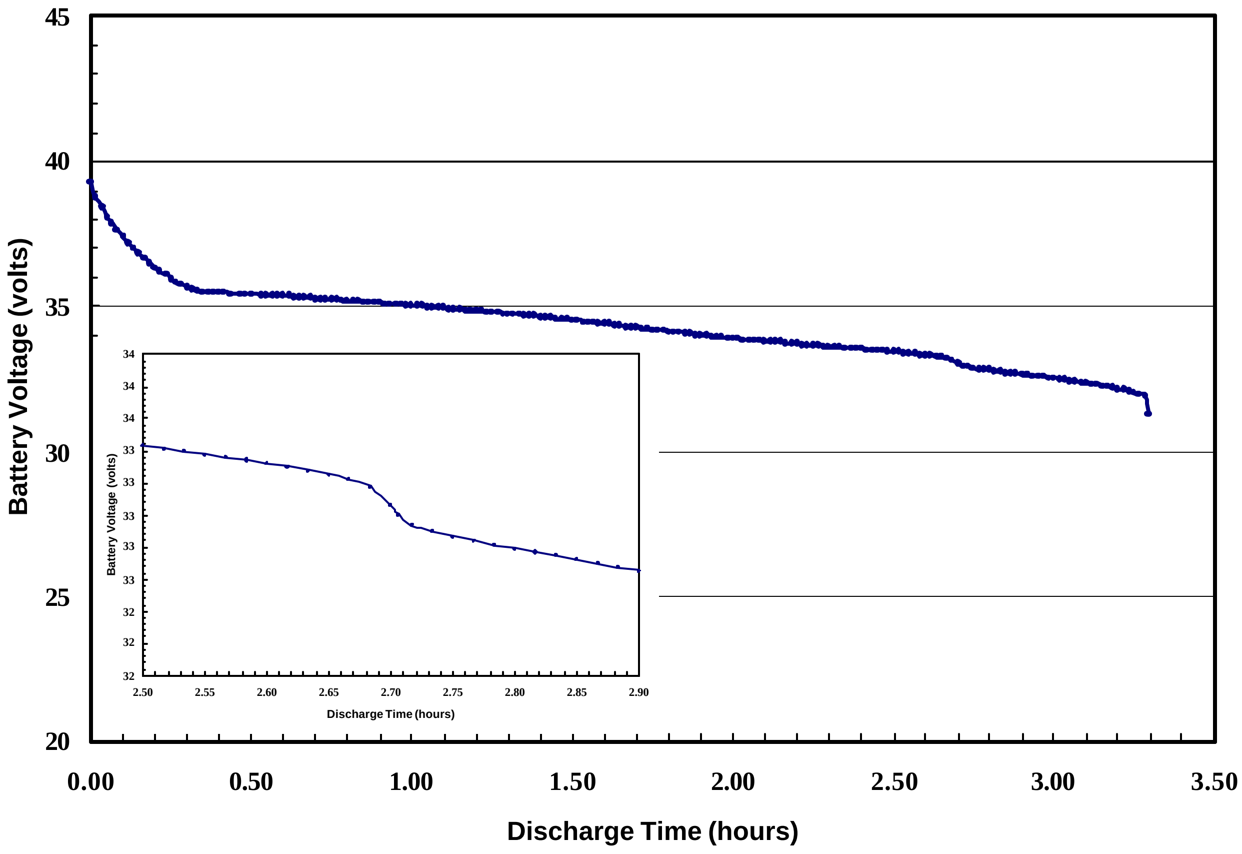
Capacity Loss (Cont'd)

- **Typical cell discharge with a second voltage plateau.**



Capacity Loss (Cont'd)

- **Typical battery discharge with a cell having a second voltage plateau.**



Capacity Loss (Cont'd)

- **Capacity losses may occur as a result of:**
  - ❖ **Discharge and storage after extended open circuit period in a charged condition.**
  - ❖ **Storage after discharge without a resistor drain.**
  - ❖ **Open circuit storage of cells after precharge is lost.**
  - ❖ **Warmer storage temperatures increase rate of capacity loss.**
- **If returned to inactive storage without the proper precautions or maintenance, loss of useable capacity can occur.**

Methods

- Two methods are used to assess the precharge in nickel hydrogen cells .

  - Cells can be evaluated and stored independently.

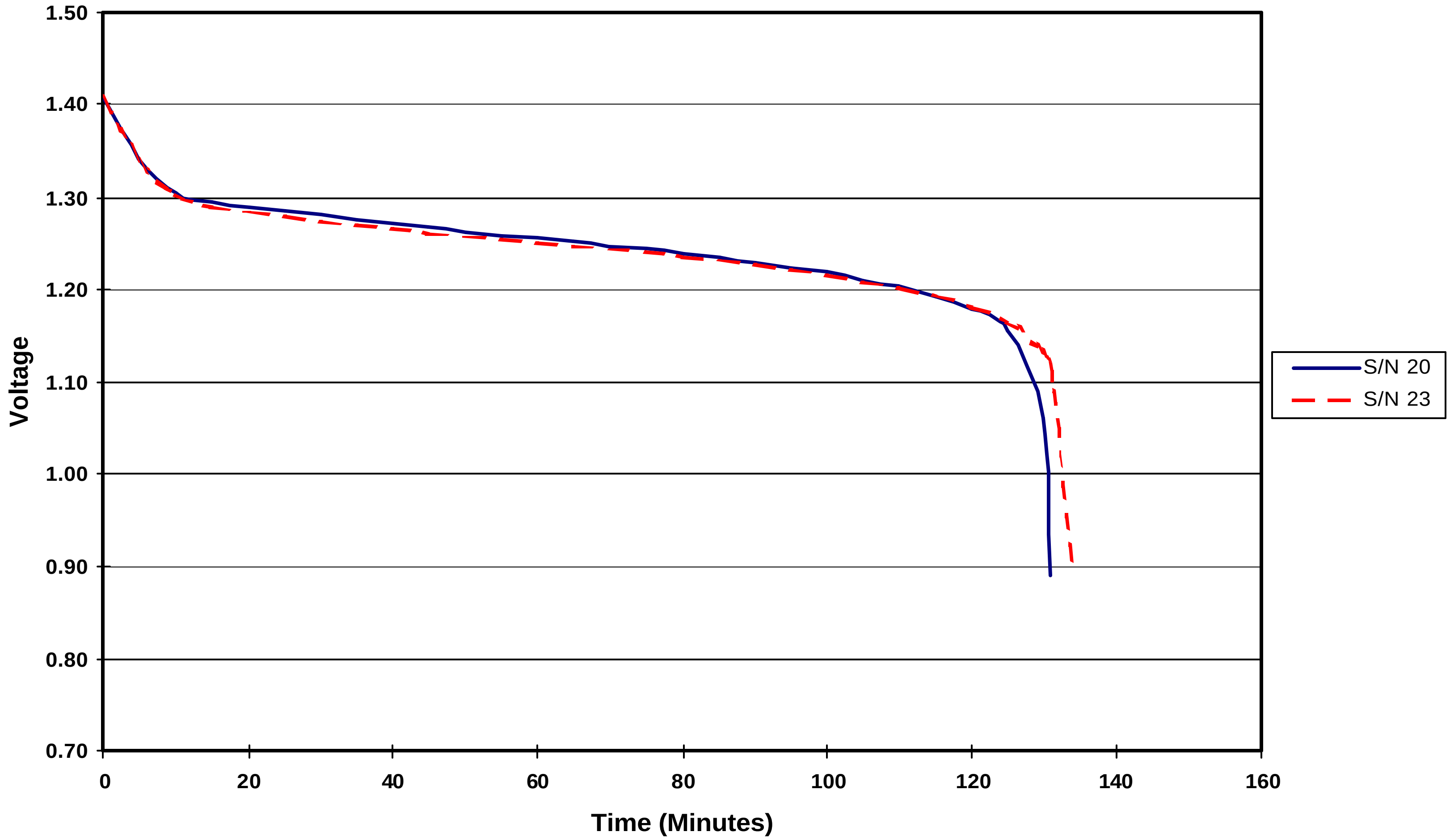
  - Cells grouped within a battery need to be evaluated and stored alike due to the configuration.

Method 1- Individual Cells

- **Allows individual verification of cell precharge.**
- **Decisions as to storage can be made collectively or as a single group.**
- **Method involves:**
  - **Discharging the cells from full charge to 0.9 volt at a C/2 rate.**
  - **Discharging the cells at a C/100 rate to a voltage of –1.20 volts.**
  - **Charging the cells at a C/100 rate to a voltage of 0.7 volt.**

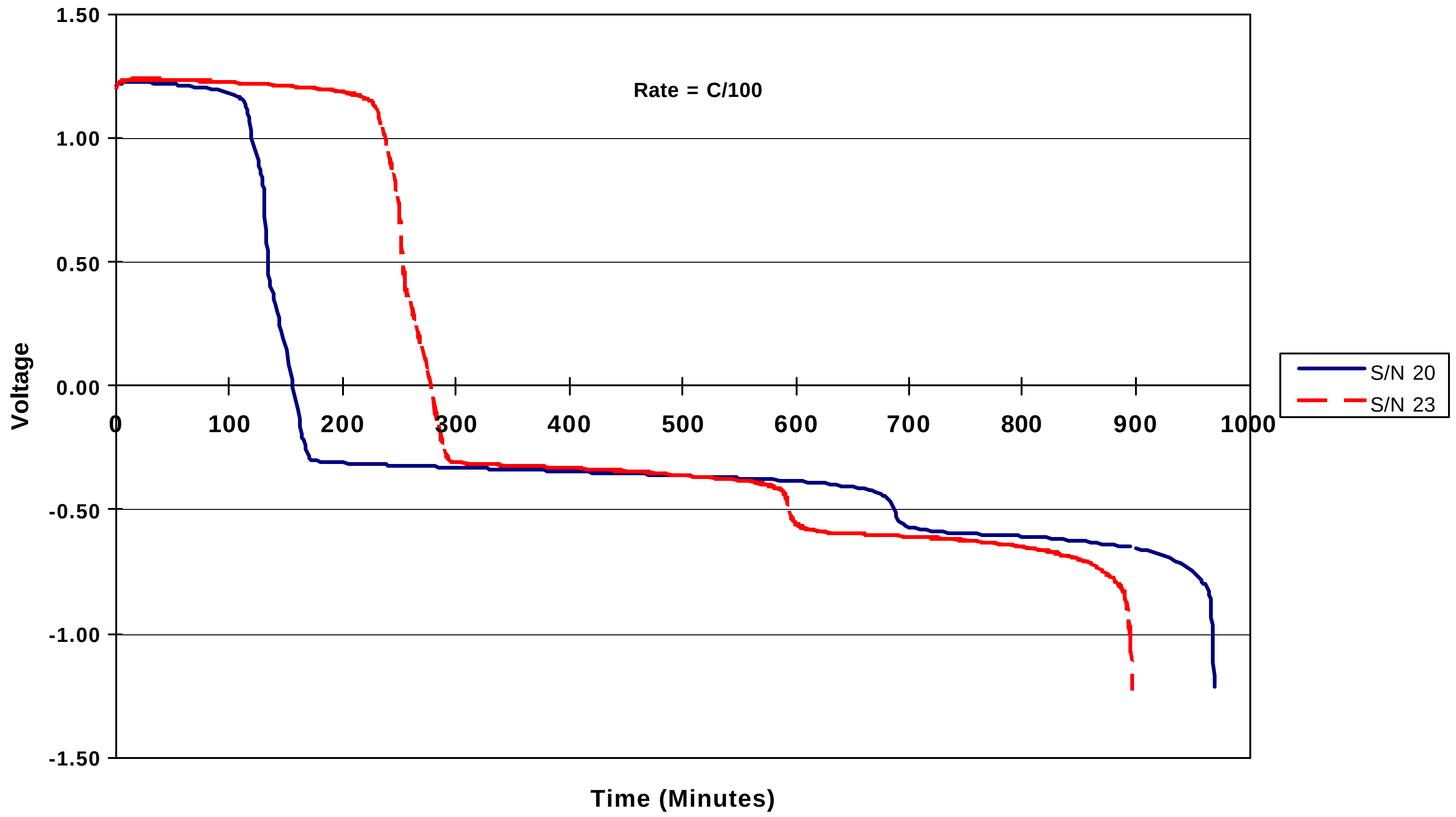
Individual Cells (Cont'd)

- **Typical C/2 capacity discharge**



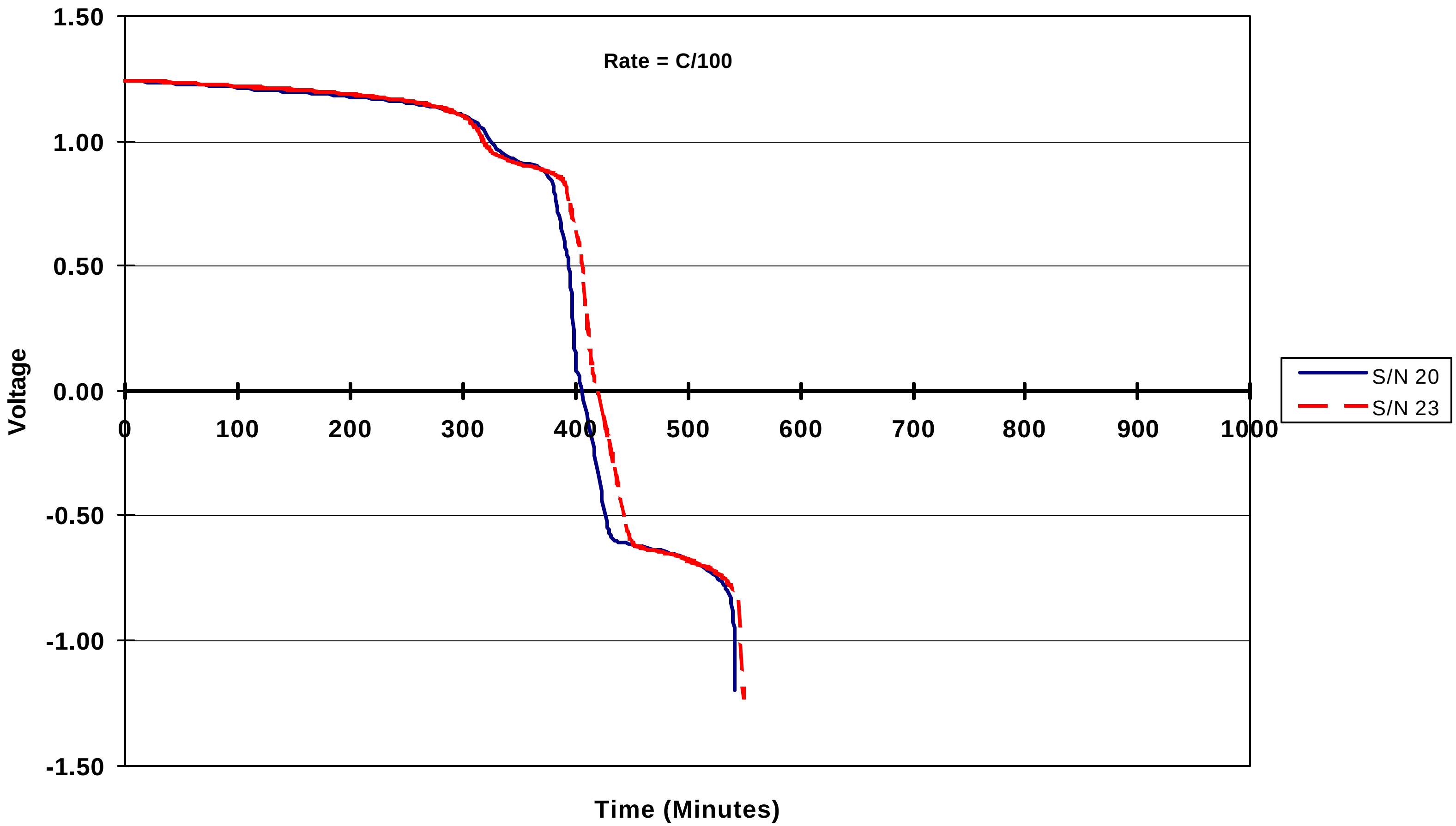
Individual Cells (Cont'd)

- **Typical nickel precharge**



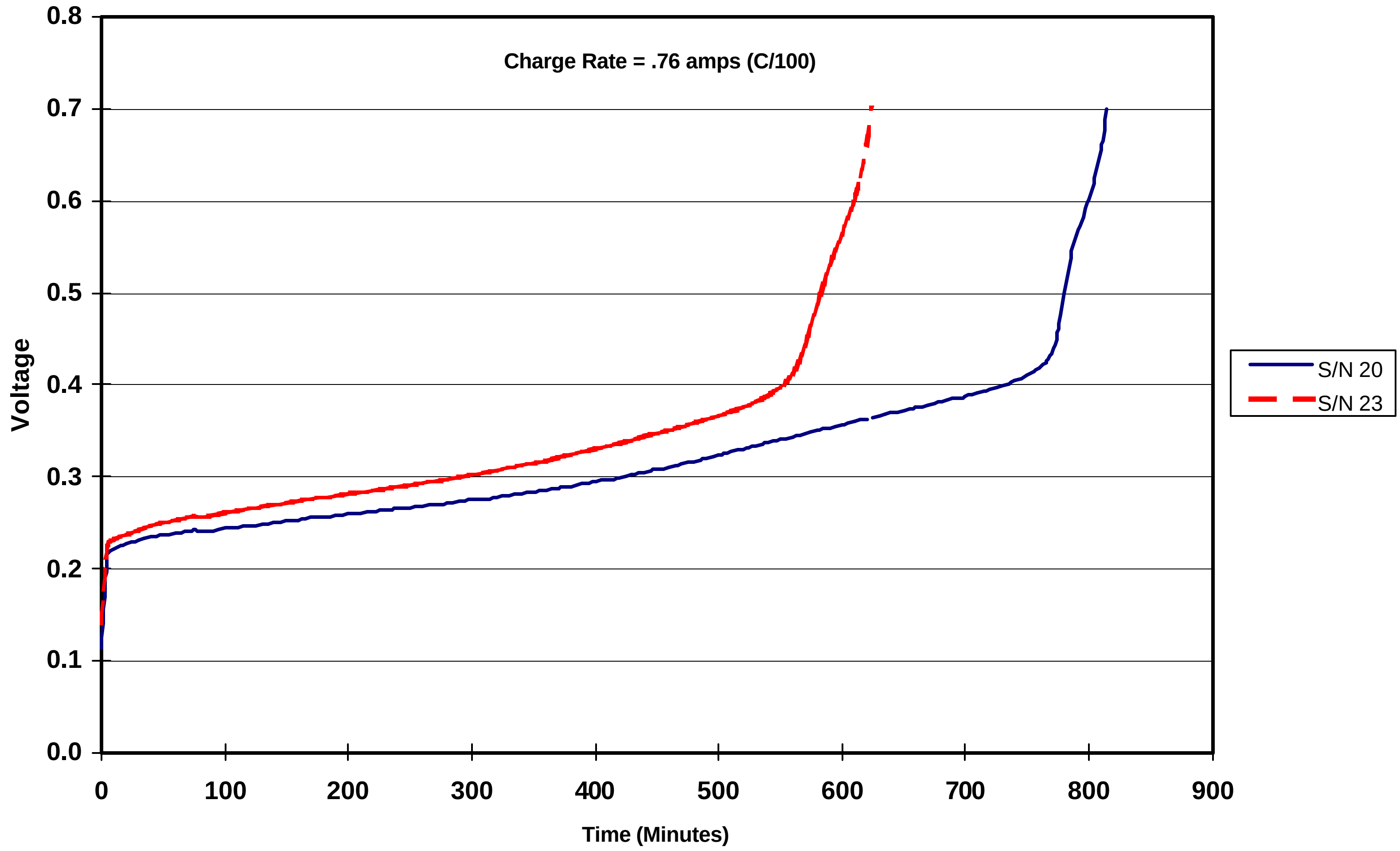
Individual Cells (Cont'd)

- **Typical hydrogen precharge**



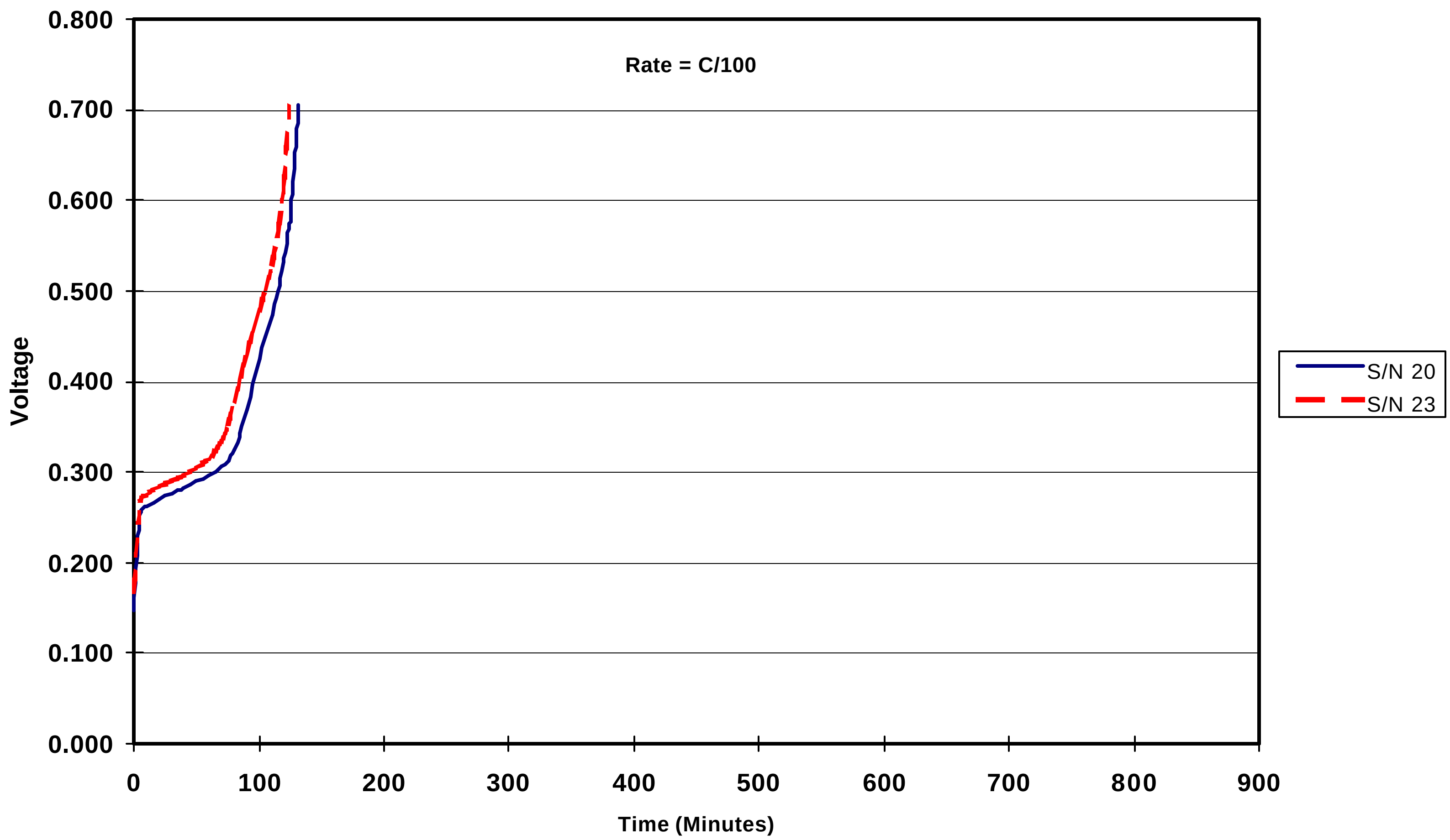
Individual Cells (Cont'd)

- **Typical nickel precharge at low rate charge**



Individual Cells (Cont'd)

- **Typical hydrogen precharge at low rate charge**



Cells Assembled in a Battery

- **Batteries, when let down, often terminate discharge with the first or second cell leaving hydrogen pressure in the remaining cells.**
- **Batteries during integration and testing are often allowed to remain for extended periods at open circuit conditions in a charged or partial charged state.**
- **Storage under these conditions is conducive to development of a second voltage plateau.**
- **Capacity loss (fade) occurs due to the second voltage plateau.**

Method 2 - Batteries

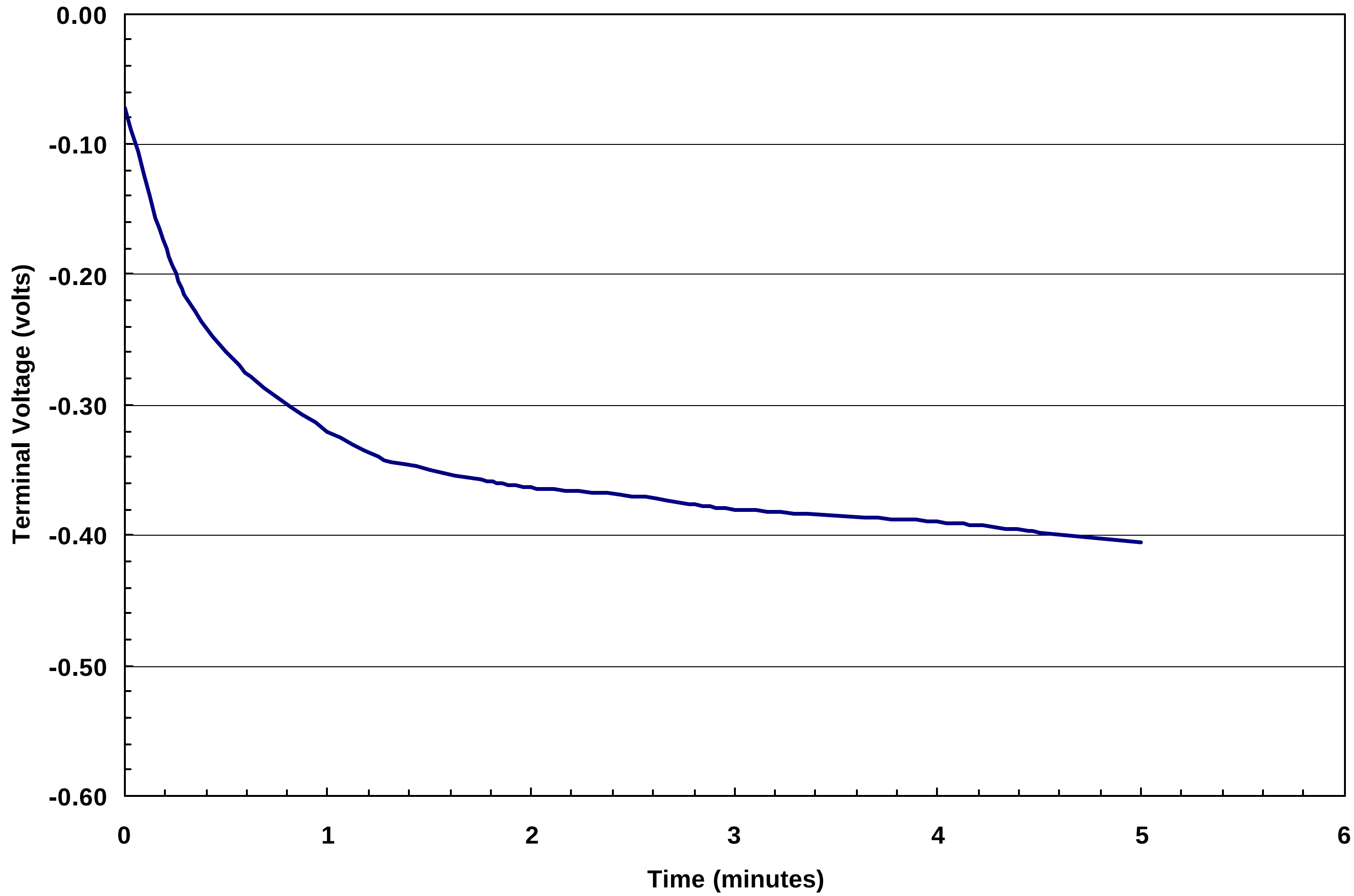
- Evaluates cells within a battery pack.

- A decision may be made that allows proper storage of batteries for the precharge found.

- Method involves:
  - Discharging the fully charged battery at a C/2 rate until the first cell reaches 0.500 volt.
  - Resistor draining each cell to 0.100 volt.
  - Discharging the battery at a C/20 rate for 5 minutes (reverses cells).
  - Placing the battery at open circuit and observing the voltage recovery.

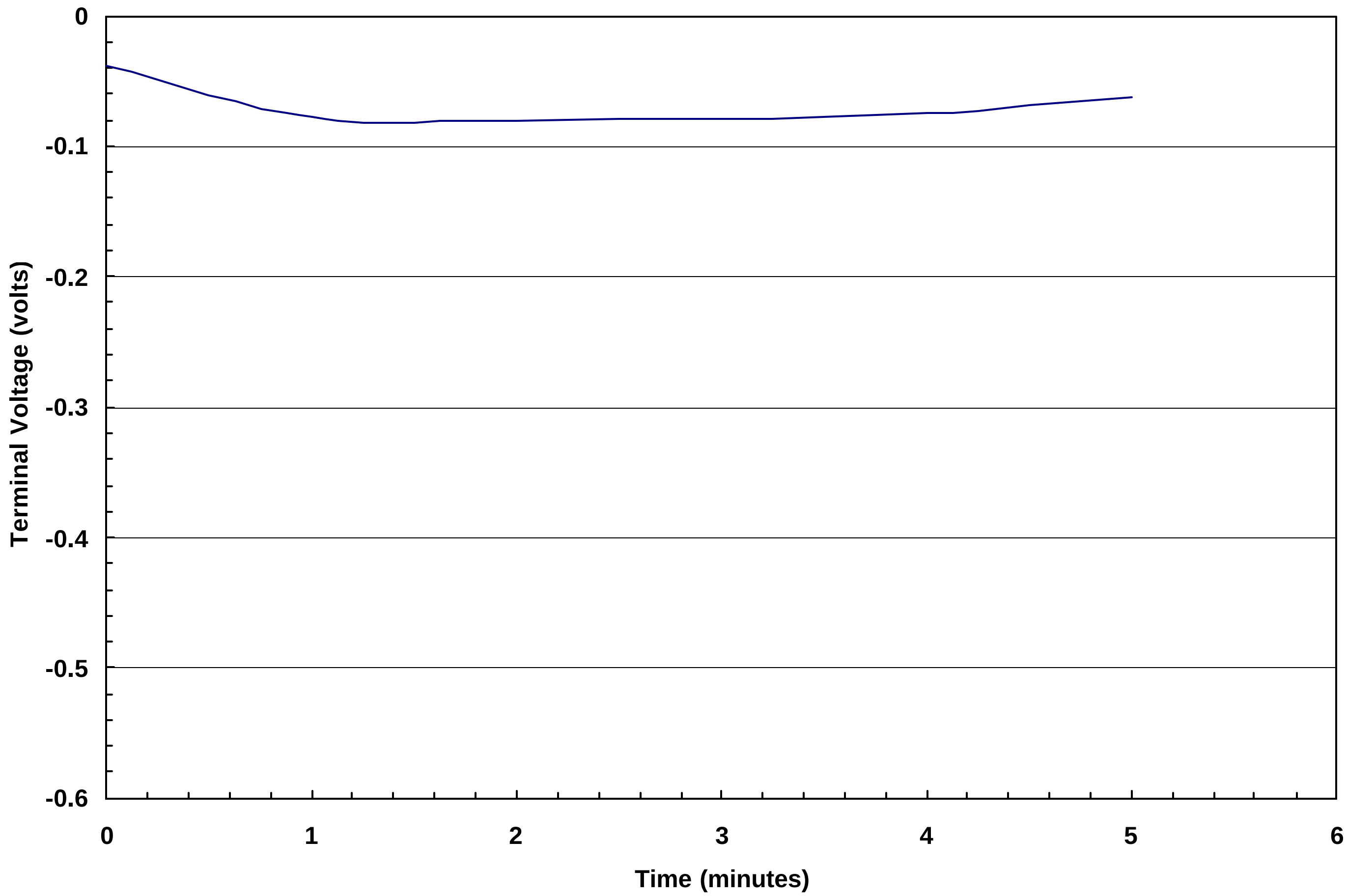
Batteries (Cont'd)

- **Typical nickel precharge voltage**



Batteries (Cont'd)

- **Typical hydrogen precharge**



Storage

- The precharge in the cell dictates the method of storage.

- Nickel (positive) precharge:
  - Storage is best at low temperature.
  - Cells should be fully discharged.
  - Either open circuit or active storage can be used.

- Hydrogen (negative) precharge:
  - An active storage plan must be implemented.
  - Storage is best at low temperature.
  - Cells must be at least partially charged.
  - A low rate at constant potential should be placed across the cell to prevent self discharge.

Summary

- When storing cells or batteries, the precharge should be determined prior to storage.
  - Positive precharge – fully discharged, open circuit, cold.
  - Hydrogen precharge – active mode, constant potential, cold.

- Positive precharge is preferred to prevent capacity fade during ground storage or integration.

Packaging Design Concepts for Use in Small Satellite Applications

William D. Cook

Eagle-Picher Technologies LLC

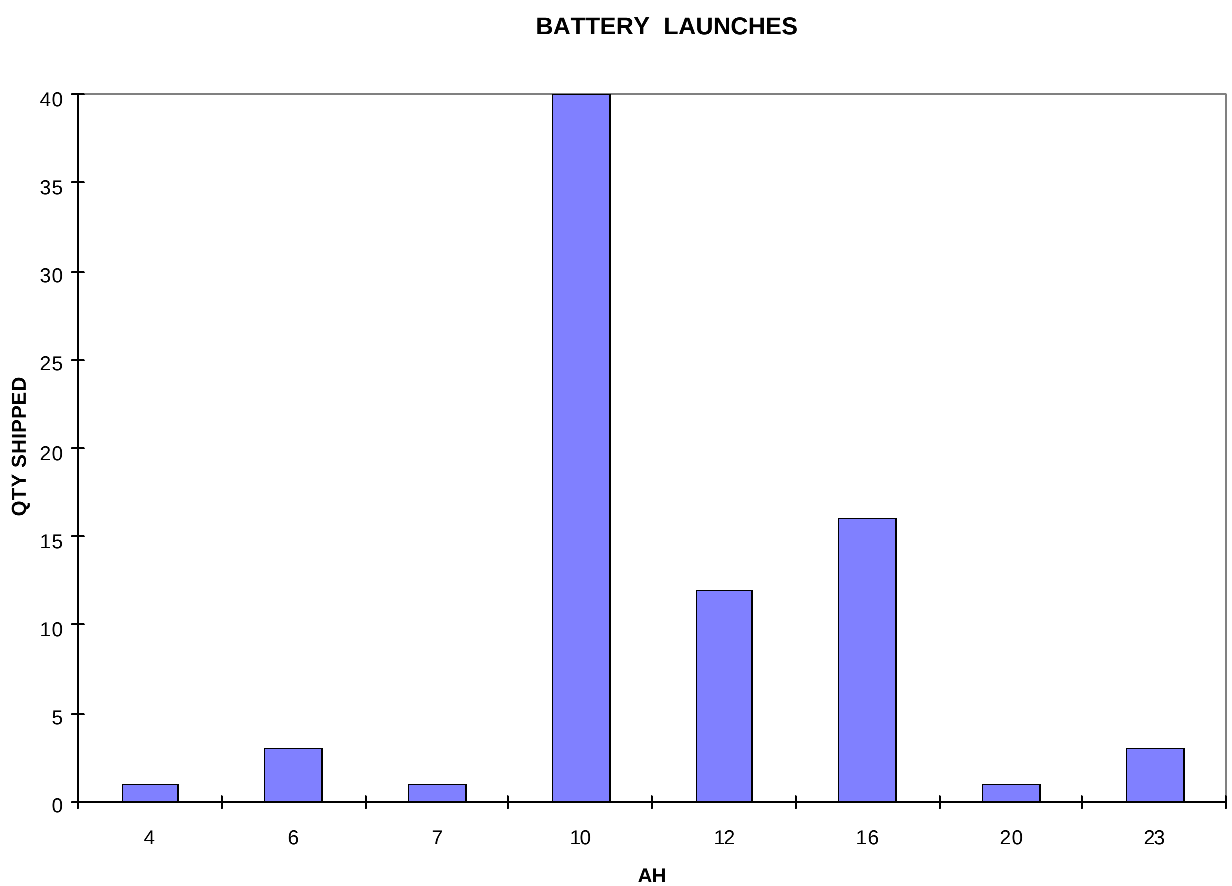
Background

- **Small Satellite Battery Usage Has Progressed From the Early 1990’S to Become a Dominant Factor in the Aerospace Industry**
- **To Date Sixty-Five Small Satellites Have Been Launched**
- **The Industry Has Demanded the Same Level of Reliable Performance from the Small Batteries As Needed with the Larger Battery Designs.**
- **Initial Design Concepts Were Small and Cheap.**

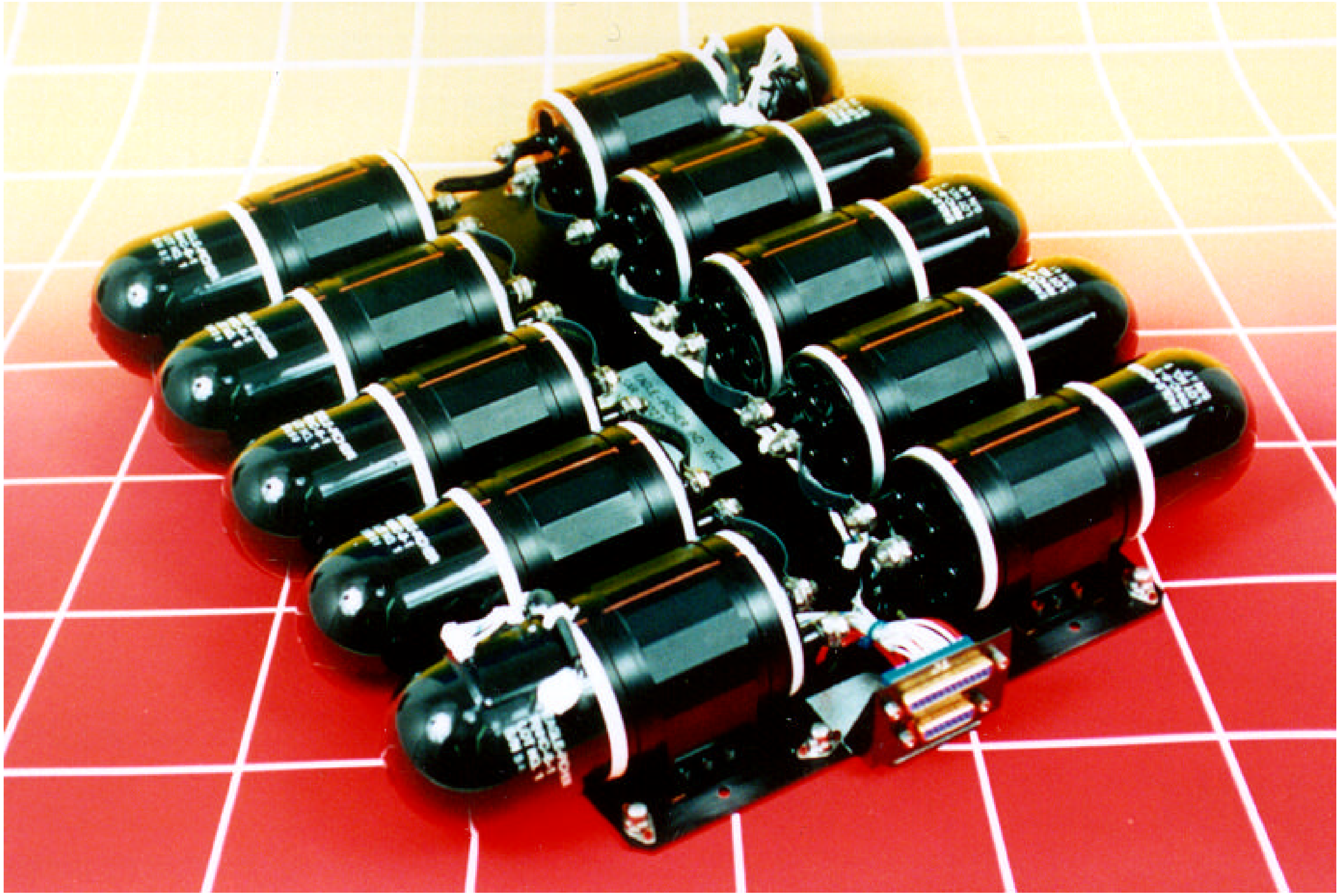
Wide Variety of Battery Designs

- 4AH to 23AH
- Layout
  - Horizontal Design
  - Coffee Can Design
  - Banded Design
  - Split Design
- Options
  - Cell Bypass
  - Heaters
  - Temperature Monitors
  - Cell Monitoring
  - Strain Gage / Amplification

Battery Launches



6 AH Battery Design



10 CPV's

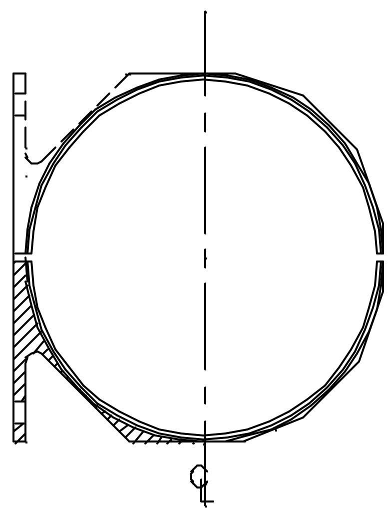
6AH

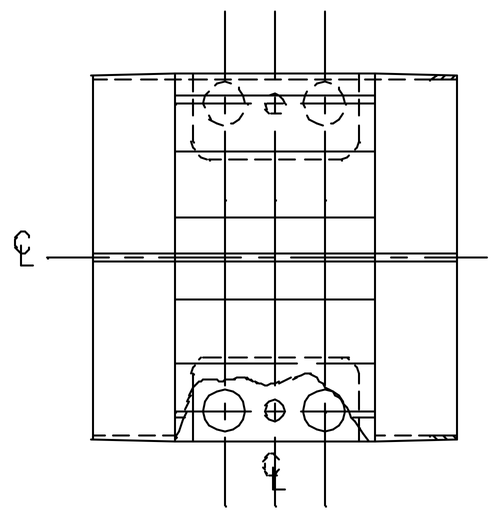
Two SG

One Heater

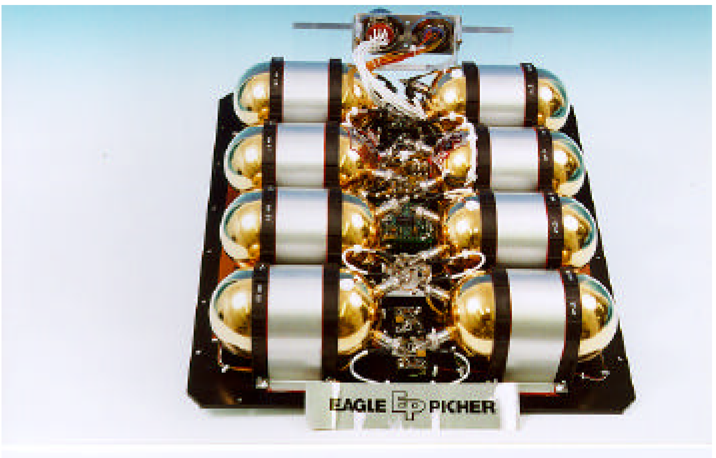
Horiz Mount

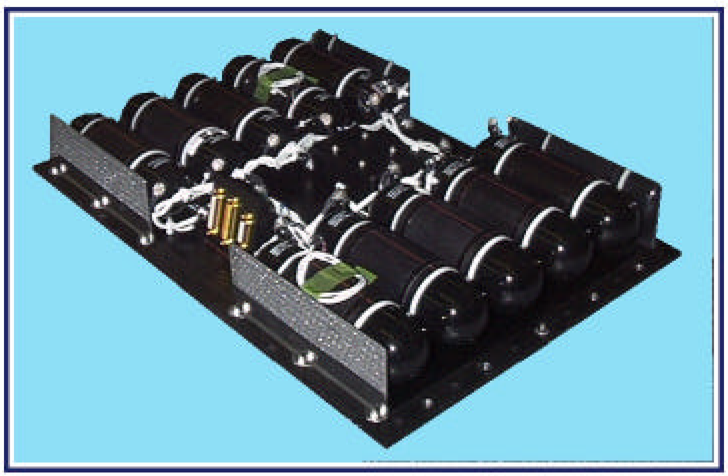
Horizontal Mount Sleeve Design





Horizontal Mount Battery Designs





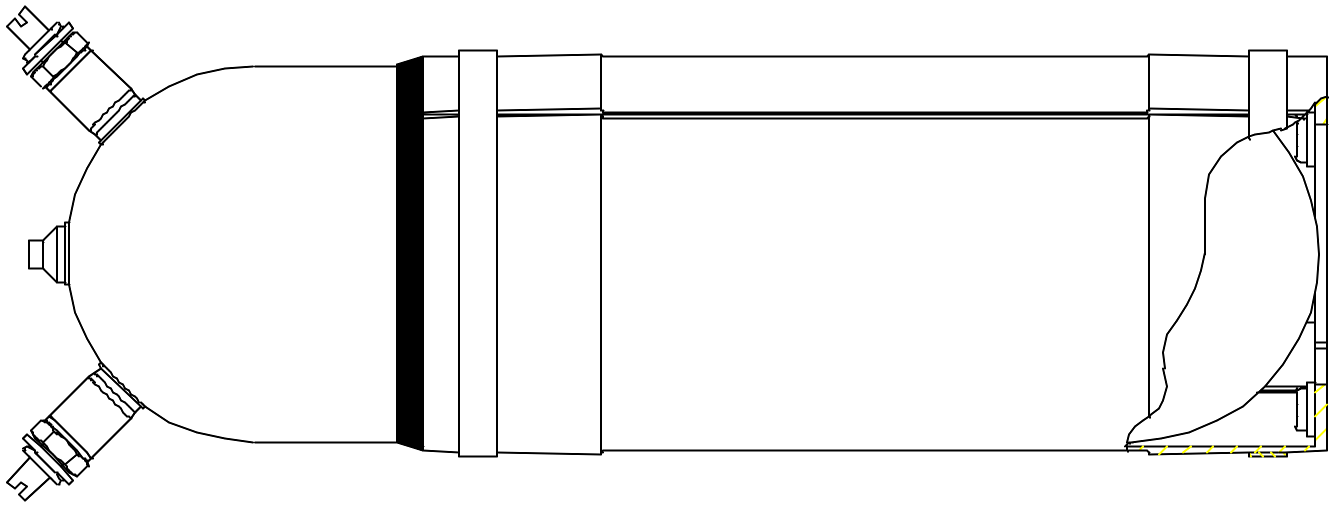
Vertical Mount(Coffee Can) Battery Design

11 CPV'S and 1 IPV

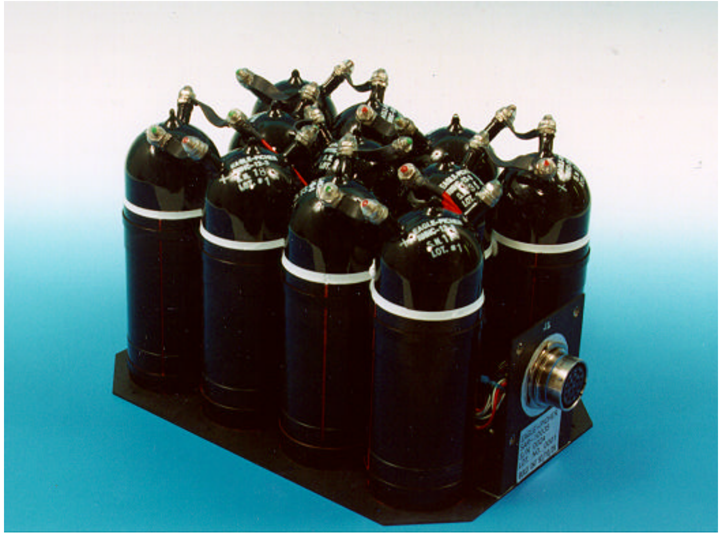
Two SG/Amp

Thermistor

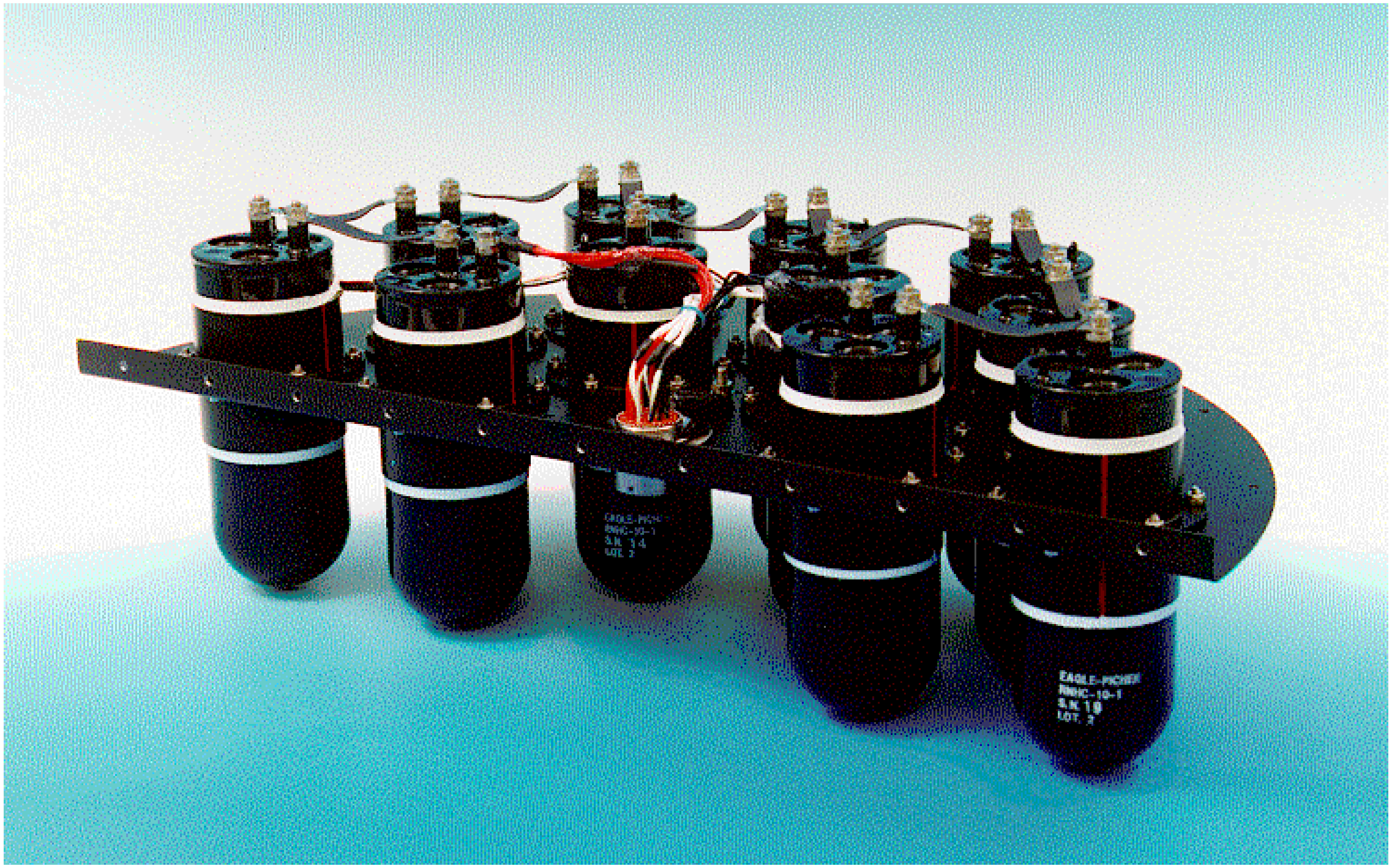
Vertical Cell Design



Vertical Mounted Battery Designs



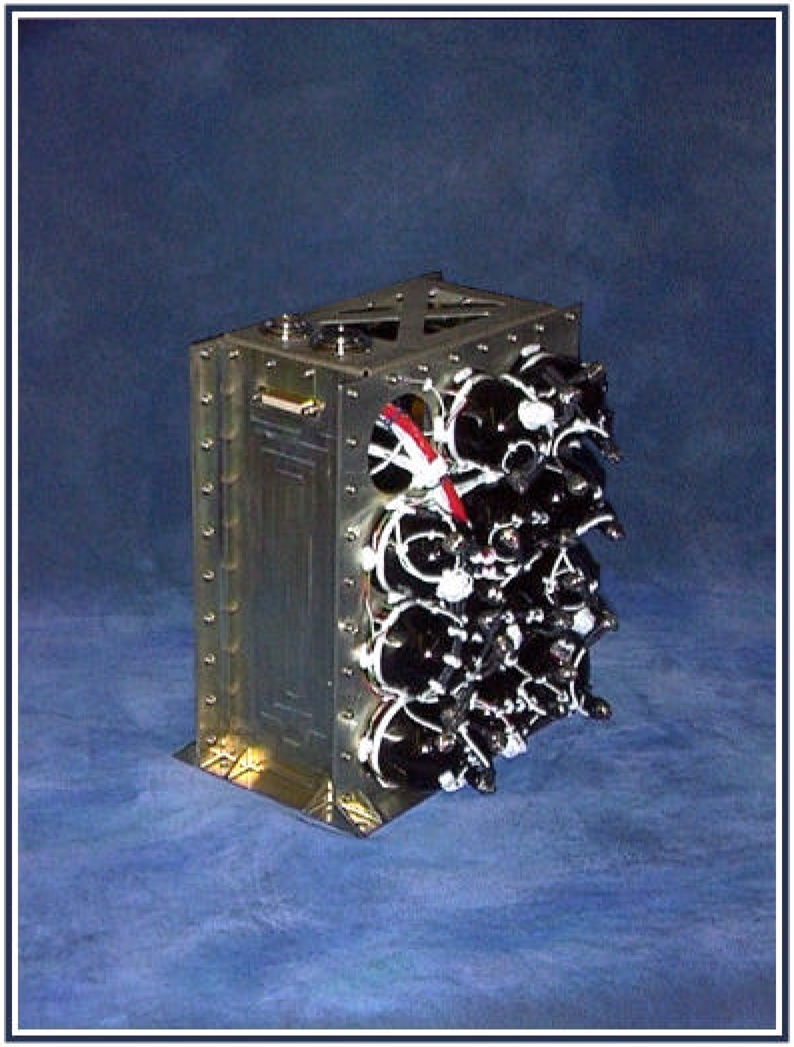
Unique Battery Mounting Designs



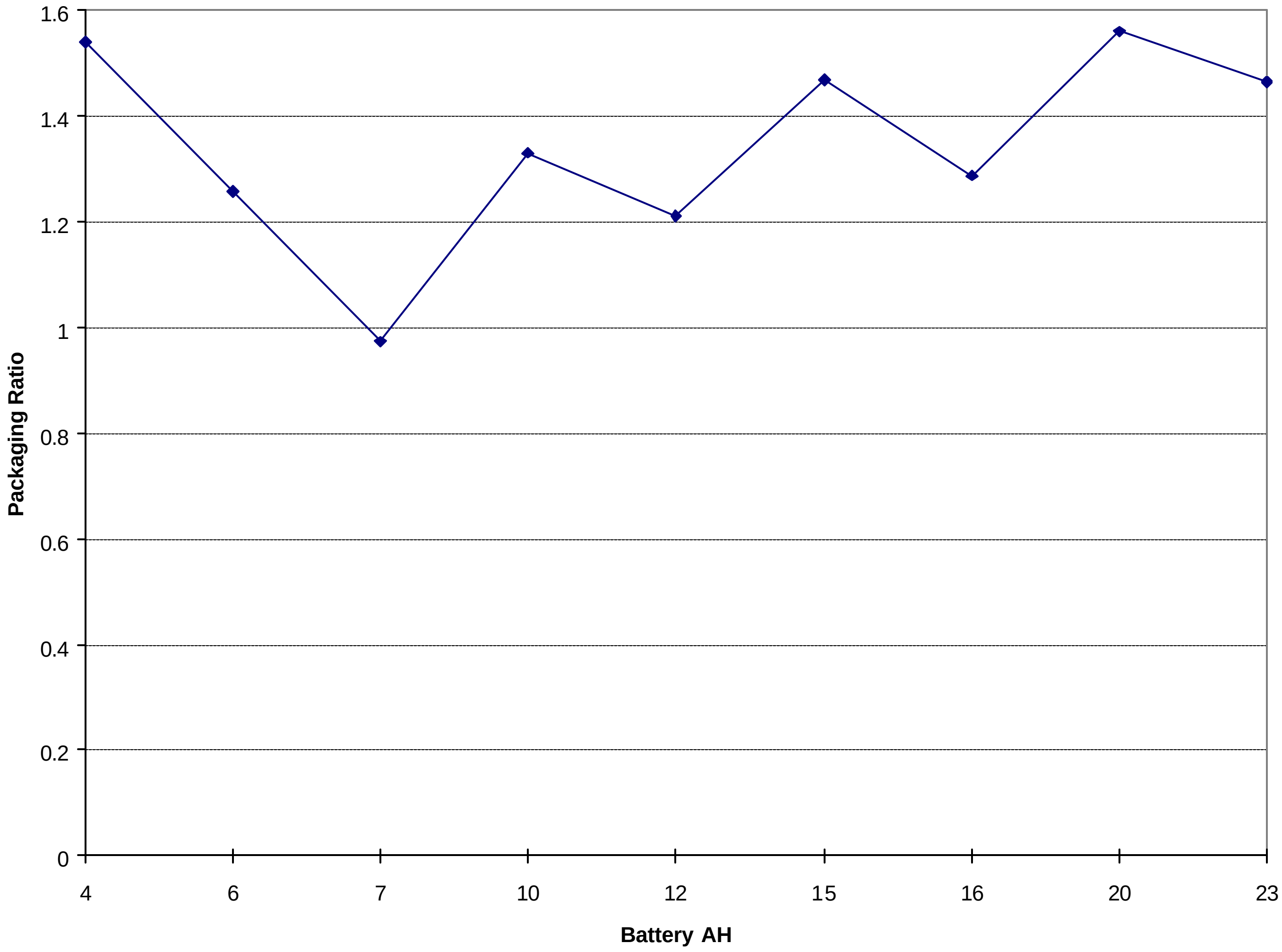
10 CPV'S

10 AH Design

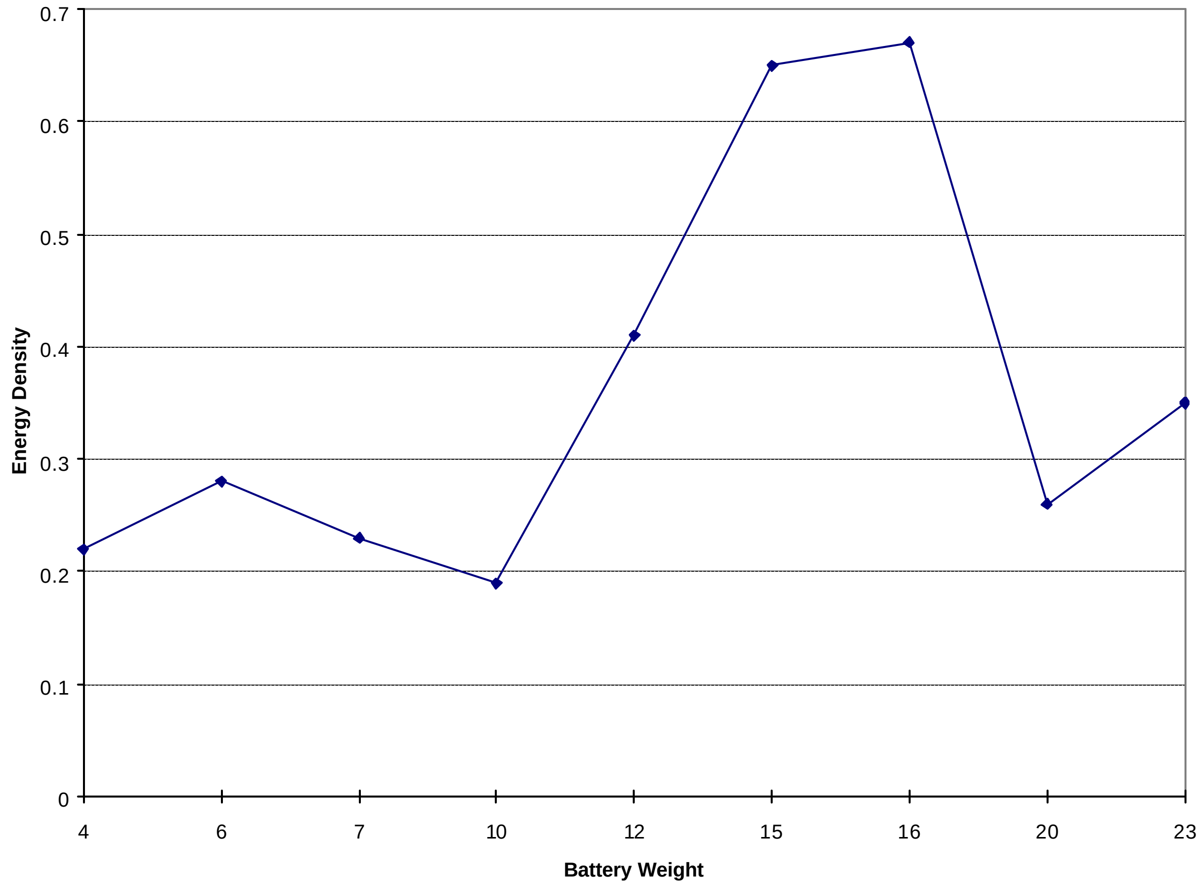
Unique Battery Designs



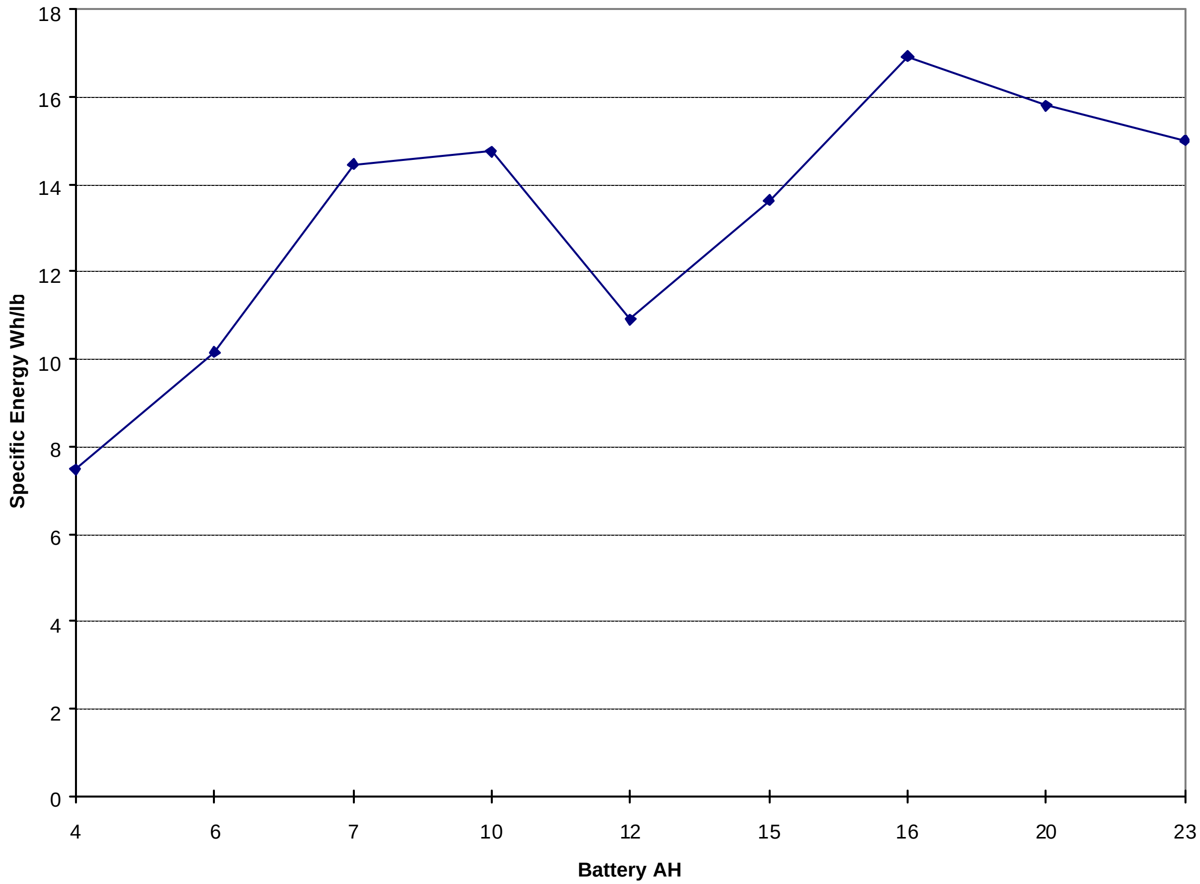
Packaging Ratio %



Energy Density Wh/In^3



Specific Energy Wh/lb



Battery Design / Selection

- Determine AH Capacity
- Establish an Envelope to Determine Basic Battery Layout
- Thermal Requirements to Determine Sleeve and Heater Design
- Strain Gage Requirements to Monitor Cell Capacity
- Thermistor Requirements to Monitor Temperature
- Heater Control (Internal or External Control)
- Max EOC and Min EOD to Determine Number of Cells

Summary

- **Small NiH_2 Batteries Have Established Themselves in Satellites for the Aerospace Market**
- **Packaging Ratio Averages 1.34% of Cell Mass**
- **Specific Energy Averages 13.23Wh/lb**
- **Energy Density Averages .36 Wh/in^3**
- **Battery Designs Using Horizontal Mounting Exhibit Better Thermal Heat Transfer Than Those Using Vertical Mounting**

International Space Station Nickel-Hydrogen Battery Start-Up and Initial Performance

2001 NASA Aerospace Battery Workshop

November 28, 2001

Presented by Gyan Hajela/The Boeing Company

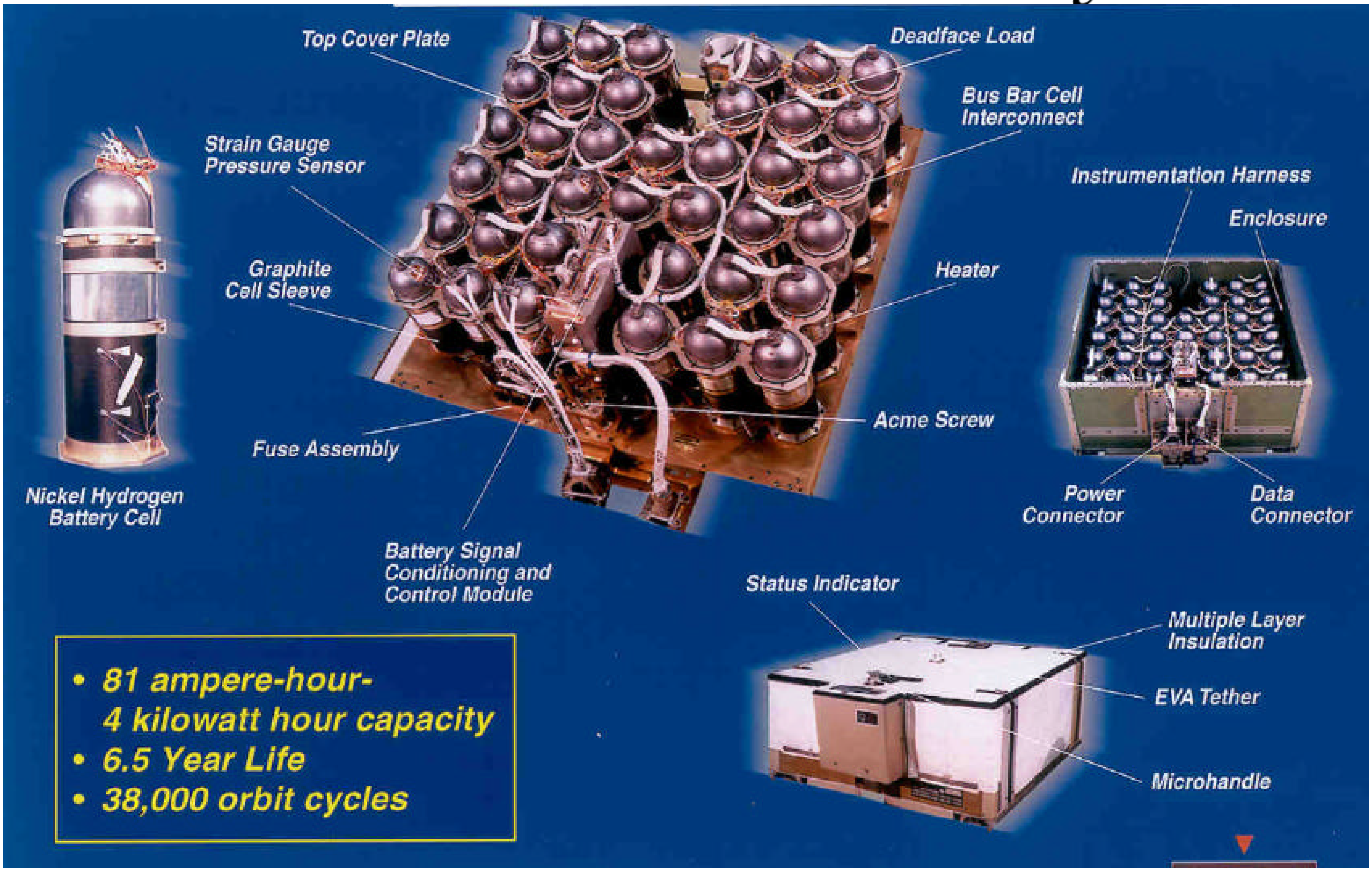
Penni Dalton / NASA GRC
Fred Cohen / The Boeing Company

Orbital Replacement Unit Design Considerations

- **Battery Orbital Replacement Unit (ORU) was designed to meet the following requirements:**
  - **6.5-year design life**
  - **38,000 charge/discharge Low Earth Orbit cycles**
  - **81-Amp-hr nameplate capacity**
    - Maximum reference Depth of discharge (DOD) less than 35%
  - **4 kWh Nominal storage capacity**
  - **Contingency orbit capability**
    - One additional orbit at reduced power after a 35% DOD without recharge
    - Maximum of two times per year
  - **Operating Temperature**
    - 5 +/-5 C Standard orbit
    - 5+5/-10 C Contingency orbit
  - **Non-operating Temperature**
    - -25 to +30 C
  - **5-year Mean Time Between Failure**
  - **On-orbit replacement using ISS robotic interface**
  - **One launch to orbit and one return to ground**

ISS Battery Subassembly Orbital Replacement Unit

BOEING



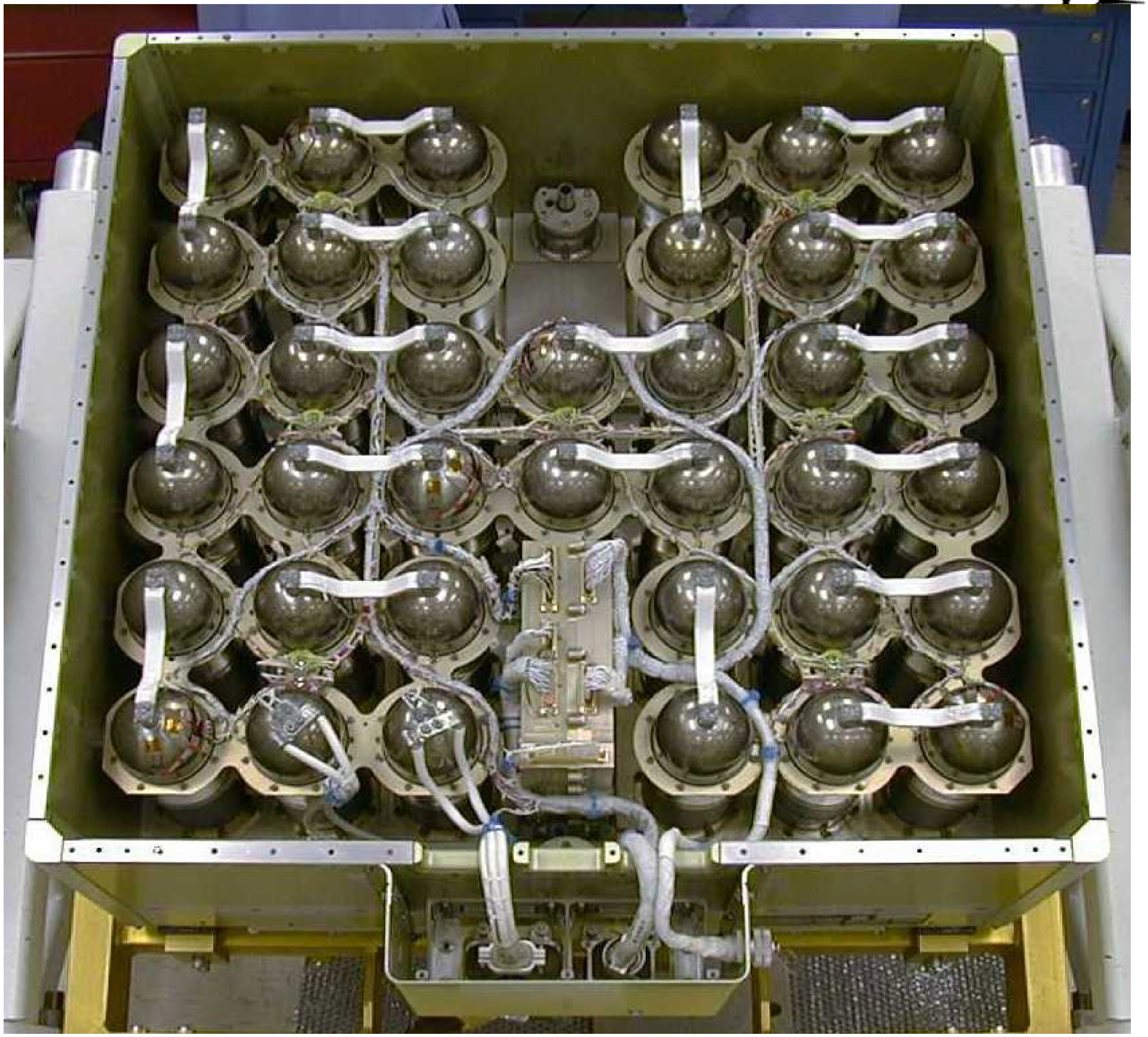
Reference Orbit Design Parameters For Battery ORU

Condition	Time (min) Start	End	Energy (Watt-hrs)	Power (Watts)
CONTINUOUS POWER REQUIREMENTS				
Constant Power Charge	0.0	43.9		1995*
Taper Charge	43.9	57.0		
Total Charge			1677*	
Constant Power Discharge	57.0	92.0	1342	2300
PEAKING POWER REQUIREMENTS				
Constant Power Charge	0.0	7.5		1554*
Constant Power Charge	7.5	43.9		2072*
Taper Charge	43.9	57.0		
Total Charge			1677*	
Constant Power Discharge	57.0	84.5	967	2110
Constant Power Discharge	84.5	92	375	3000
Total Discharge			1342	
CONTINGENCY POWER REQUIREMENTS				
Constant Power Discharge	0.0	92.0	997*	650
*Designates a maximum value				

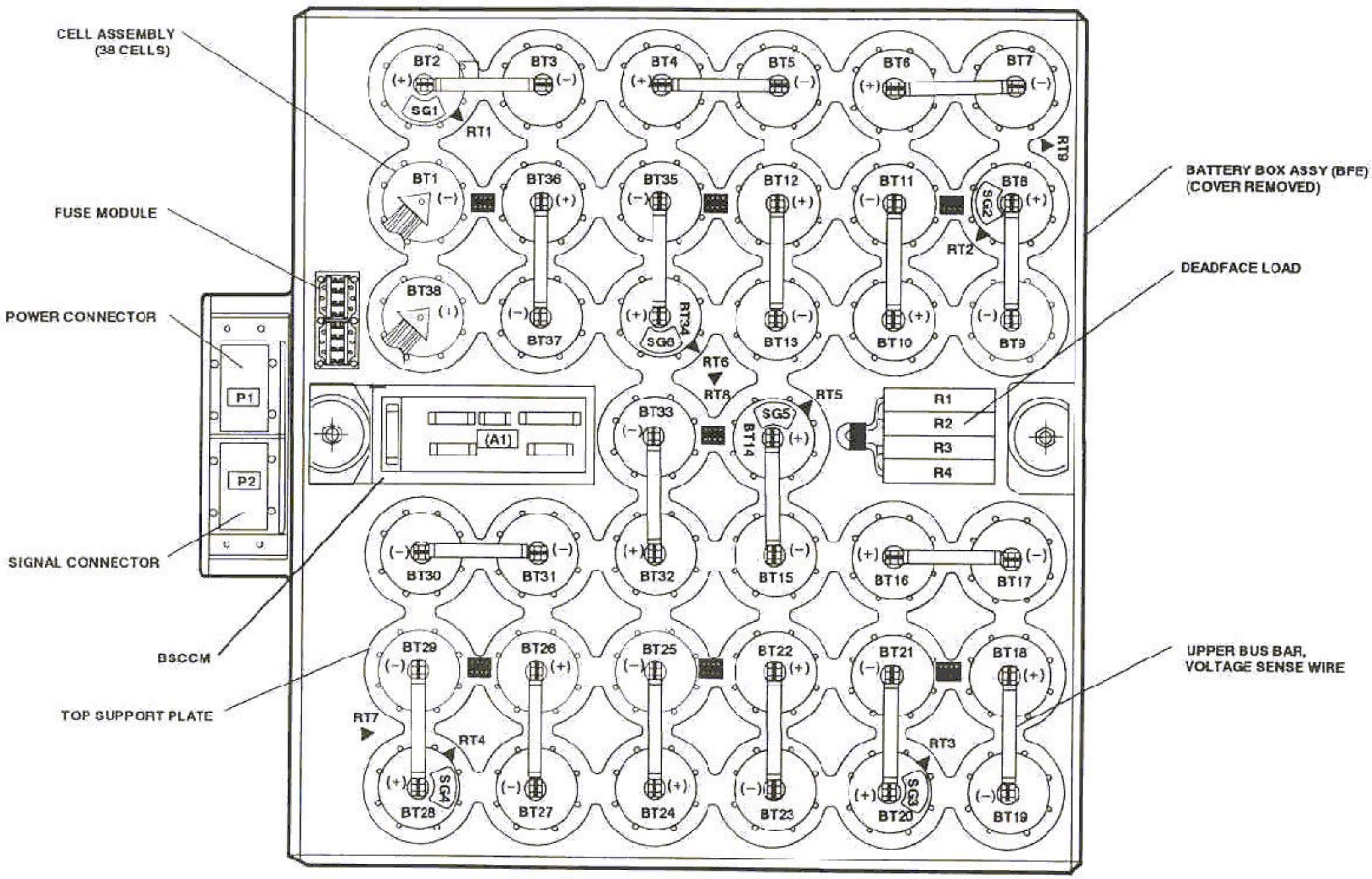
ORU As-Built Design

- **Assembled/acceptance tested by Space Systems Loral under contract to the Boeing Company**
- **Each ORU consists of:**
  - **38 series connected Nickel-hydrogen individual pressure vessel cells**
    - RNH-81-5 EPI
    - Back to back configuration
    - 31% potassium hydroxide electrolyte
  - **Individual cell Kapton film heaters – primary and secondary**
  - **Individual cell Graphite thermal sleeves**
  - **Radiant fin heat exchanger (RFHX) baseplate**
  - **120 Amp fuse**
    - 2 60 Amp modules
  - **Deadface load to "safe" ORU from 76 V to 1.9 V**
  - **Battery Signal Conditioning and Control Module**
- **Dimensions**
  - **37 x 41 x 19 in^3**
- **Weight**
  - **372 pounds**
- **Operating Voltage**
  - **38 to 61.3 V**

Flight ORU with Cover Removed



ORU Baseplate Layout

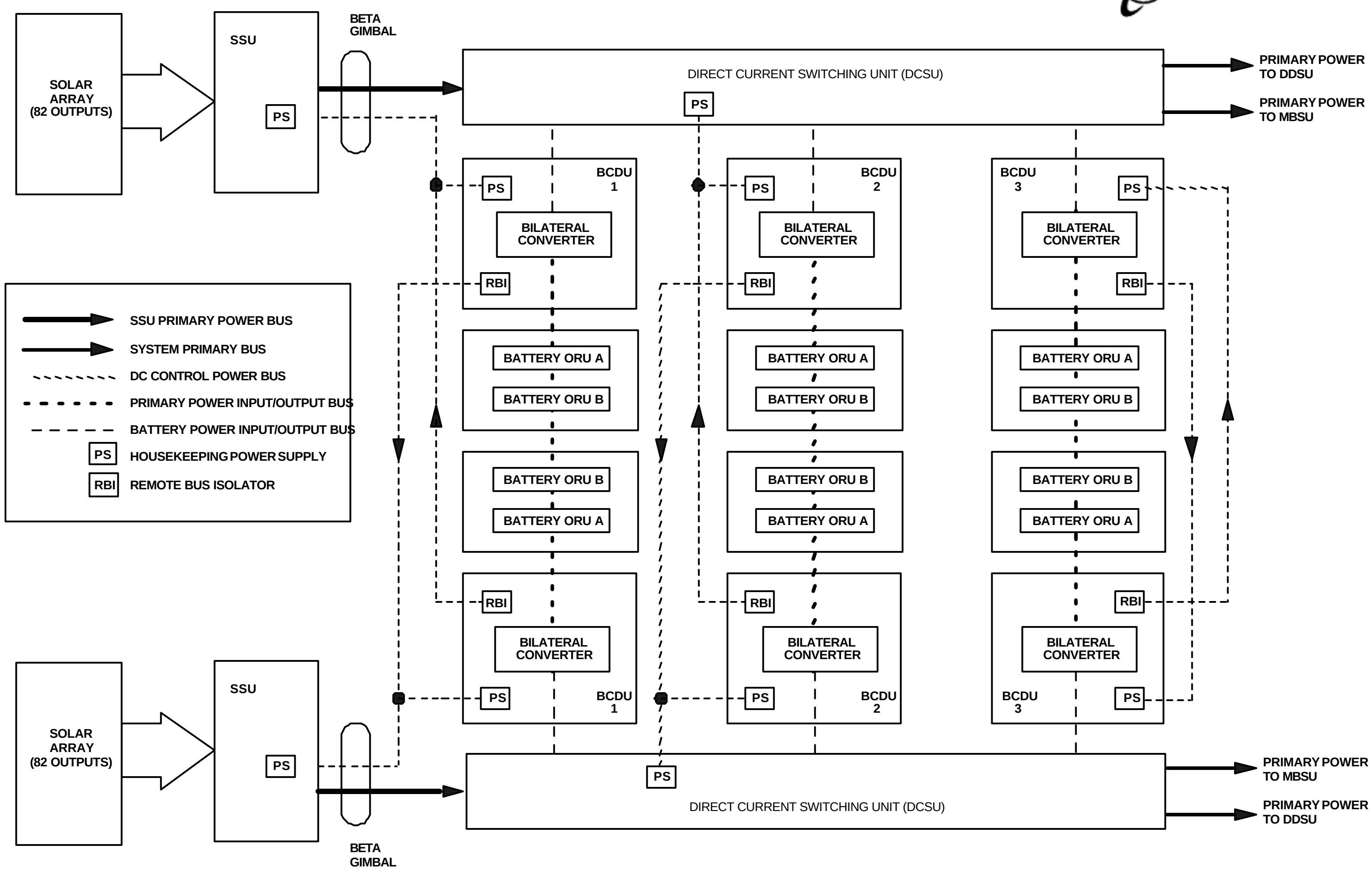


Flight ORU with MLI Blanket

Battery ORU Integration

- **Part of the Photovoltaic Module (PV) on the P6 (port) Integrated Equipment Assembly (IEA)**
  - **Launched ISS 4A, November 30, 2000**
- **ISS will have 4 PV modules at Assembly Complete**
- **Each PV module has**
  - **12 ORUs/6 Batteries**
    - 3.6 to 4.4 years from cell activation prior to flight
- **Current ISS configuration has 2 power channels**
  - **2B and 4B**

ISS Photovoltaic Electronics Block Diagram



Battery Control

- **Photovoltaic Control Unit**
  - **Integrates charge return**
  - **Calculates battery State of Charge (SOC)**
  - **Provides charge current rate to battery charge/discharge unit**
- **Battery Charge Discharge Unit (BCDU)**
  - **Two Battery ORUs connected in series to one BCDU**
  - **During insolation, the BCDU**
    - Conditions power from source bus to battery
    - Charges battery at calculated charge setpoints per charge algorithm
  - **During eclipse, the BCDU**
    - Extracts power from battery
    - Supplies conditioned power to source bus
- **Battery Signal Conditioning and Control Module (BSCCM)**
  - **Conditioned battery signals to/from the LDI in BCDU**
    - Cell heater function
    - Letdown function
  - **Analog multiplexed voltage**
    - Individual cell voltages
    - 4 strain gauge readings for pressure
    - 6 cell and 3 baseplate temperatures
- **Cooling provided through ISS Thermal Control System**
  - **Radiant fin heat exchanger baseplate**
  - **Mounted to ISS structure using ACME screws**
  - **Mated to TCS**

On-orbit Start-up

- All battery ORUs were launched in a discharged state
- Reduced power available during start-up
  - Use of Shuttle Auxiliary Power Control Unit
  - Charging and thermal conditioning only during insolation
- Thermal conditioning
  - Warm ORUs using internal heaters
  - Use average of 4 cell temperatures
  - 0 to 10 ^{0}C
- Charging
  - Low rate charge (~10 A) to 76 V per battery
  - 3 consecutive insolation charges at 30 A
  - Followed by taper charge in 4th isolation period
  - Total 103 Amp-hours charge to reach 100% SOC
  - Using this charge regime on ground, battery capacities ranged from 83.0 to 89.9 Amp-hours

Battery Charge Algorithm

- Battery Charge Algorithm is programmable
- Pre-set maximum charge rate to taper based on SOC
  - Reduce stress on batteries
  - Maximize available solar array power
  - Minimize heat generation
  - Taper charge start at 94% SOC – reduced charge efficiency
- Available charging current depends on:
  - ISS vehicle user loads
  - Extravehicular activity operations
  - ISS operational modes (sun-tracking versus locked arrays)
- BOL 100% SOC is set at 81 Ah
  - Algorithm calculates SOC using a pressure versus SOC relationship
    - Acceptance test data used to initialize
    - Strain gauge calibration
    - Moles H2
    - PSI per Amp-hour

On-orbit Operation

- **Current maximum charge rate table:**

SOC%	20	94	96	98	100	101	>105
Chg rate (Amps)	50	50	40	27	10	5	1

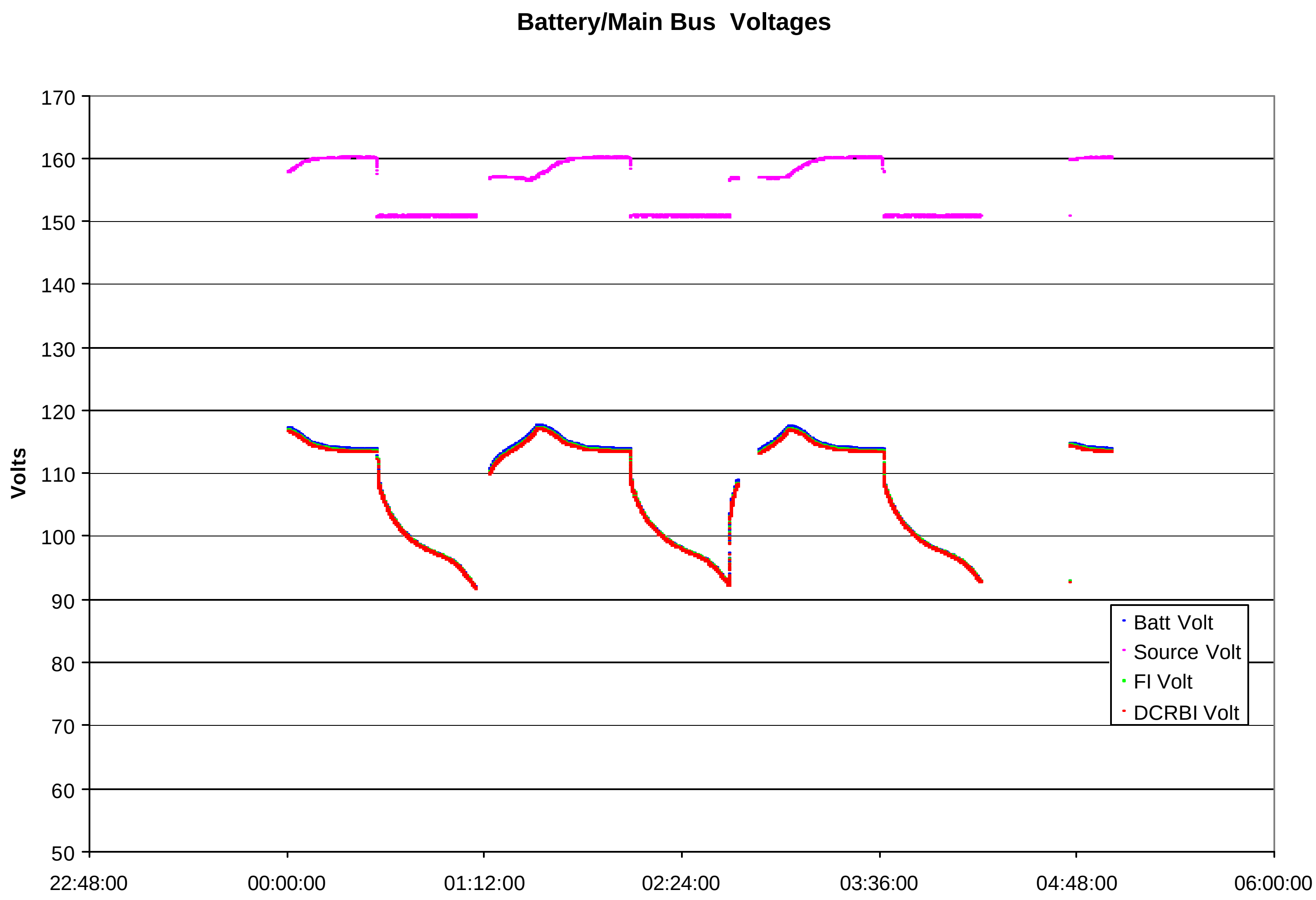
- **Settable parameters can be changed by upload from ground station**
  - **Charge algorithm**
    - SOC versus Recharge Ratio
      - Algorithm is using SOC 100% now
  - **Charge rate**
  - **Strain gauge calibration curves**
  - **Pressure offsets**

On-orbit Data

- Data is telemetered to ground
  - Available real time through console screens in Engineering Support Rooms and Mission Control Center
  - Available through archived Orbiter Data Reduction Complex
- Representative data - from Flight Day 320, (Nov. 2001)
- Approximately one year in orbit
- Channel 2B-2 battery (2 series connected ORUs)
- Spaces in data are due to data drop-outs/loss of signal
- Battery voltage (76 cells) 92 to 118 Vdc
- Maximum charge rate 50 Amps
  - Note that due to ISS EPS conventions, charging current is shown as negative
- SOC ~85 to ~103% (average DOD 15%)
- ORU temperature range ~-2 to +3.3 °C
  - Note heater cycling due to ISS operation at less than ORU power design loads
- Pressure ~500 to ~725 psi
- Cell voltages ~1.26 to ~1.5 Vdc

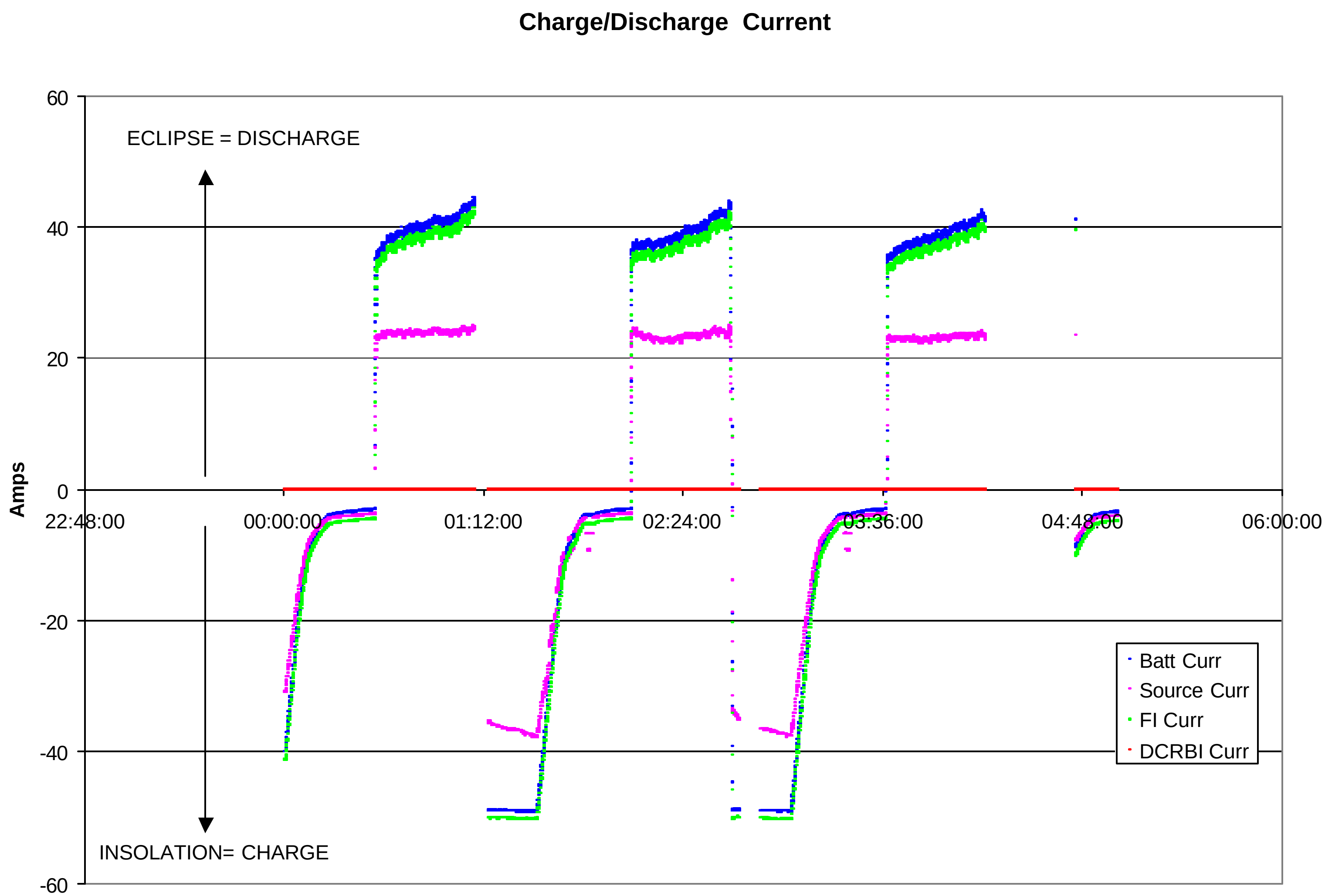
On-orbit Battery ORU Data

Battery 2B-2 Battery & Bus Voltages



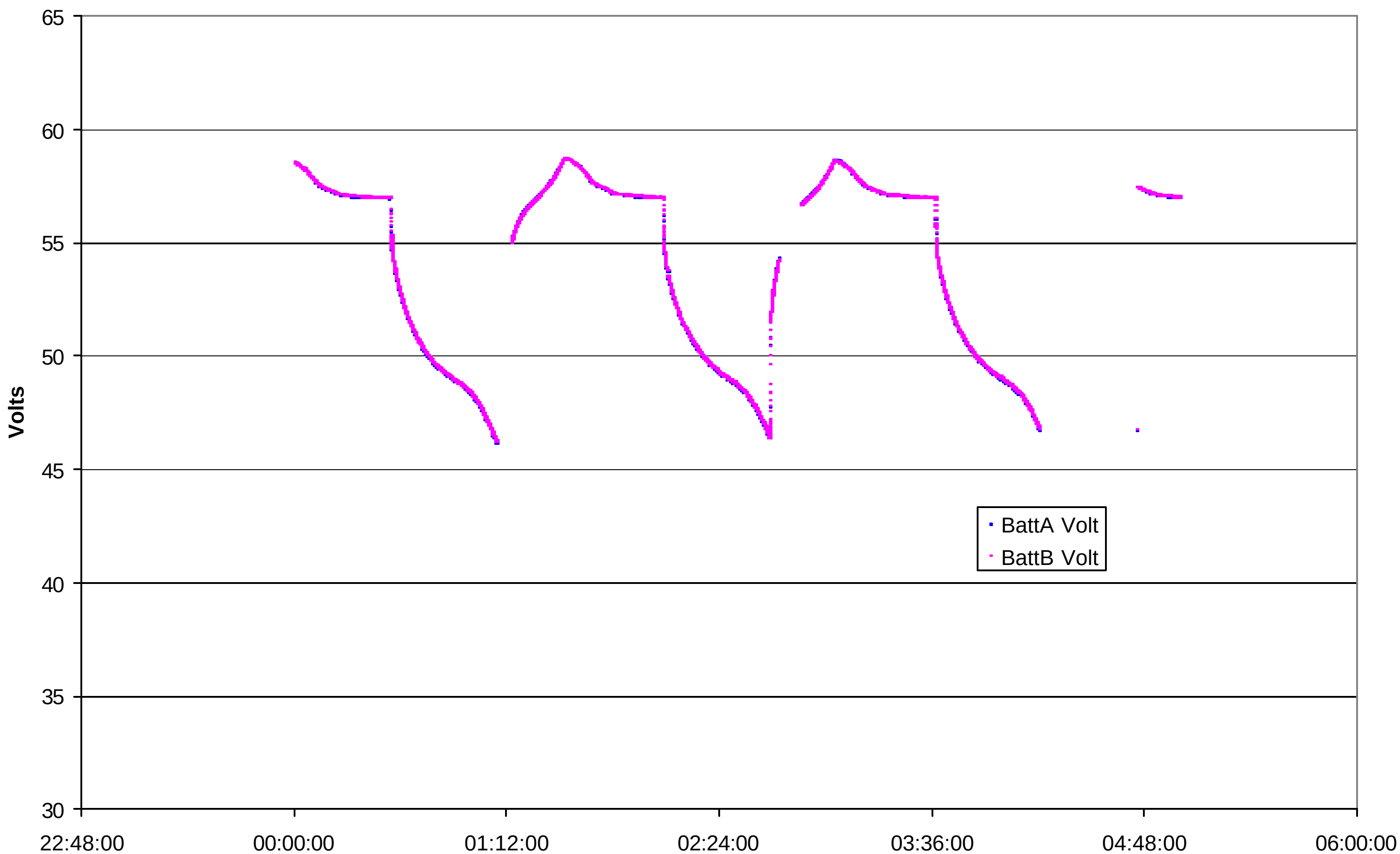
On-orbit Battery Data

Battery 2B-2 Charge/Discharge Current



On-orbit Battery ORU Data
Battery 2B-2 ORU Voltages

Battery ORU Voltages

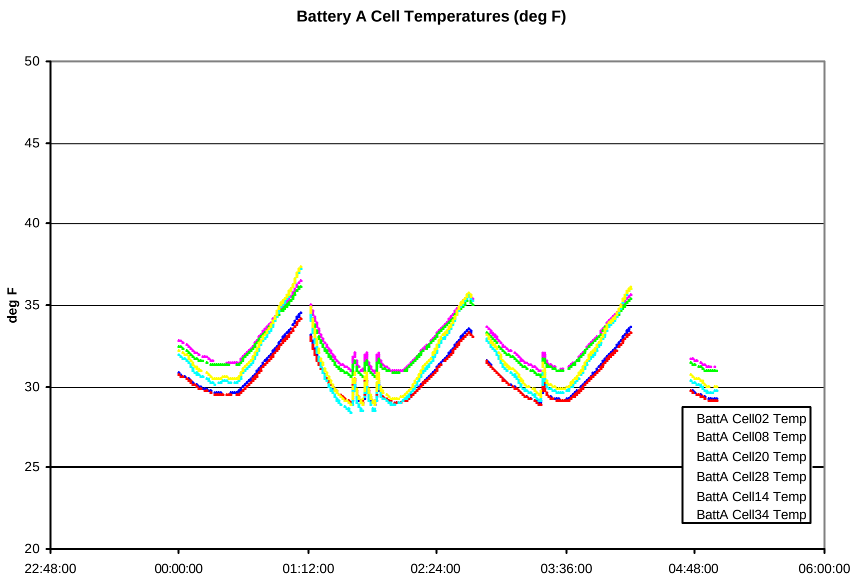


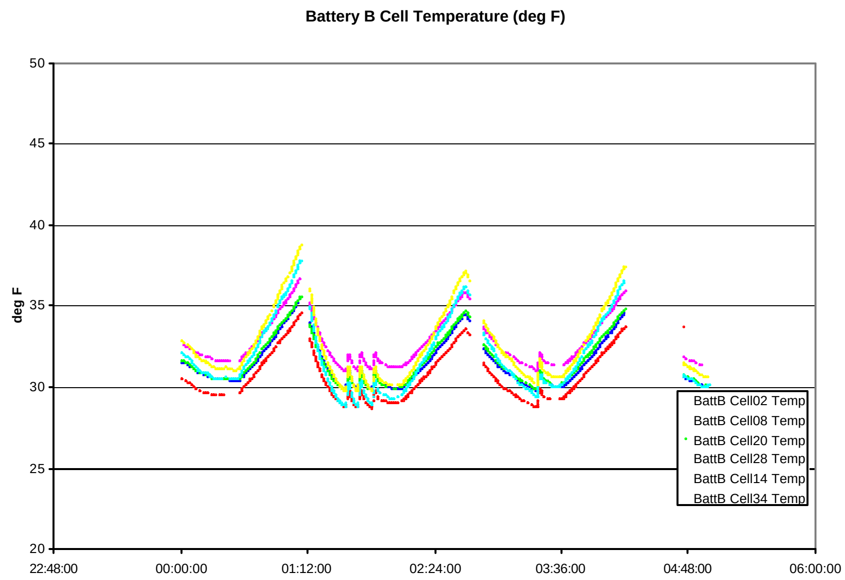
On-orbit Battery ORU Data

Battery 2B-2 Cell Voltages

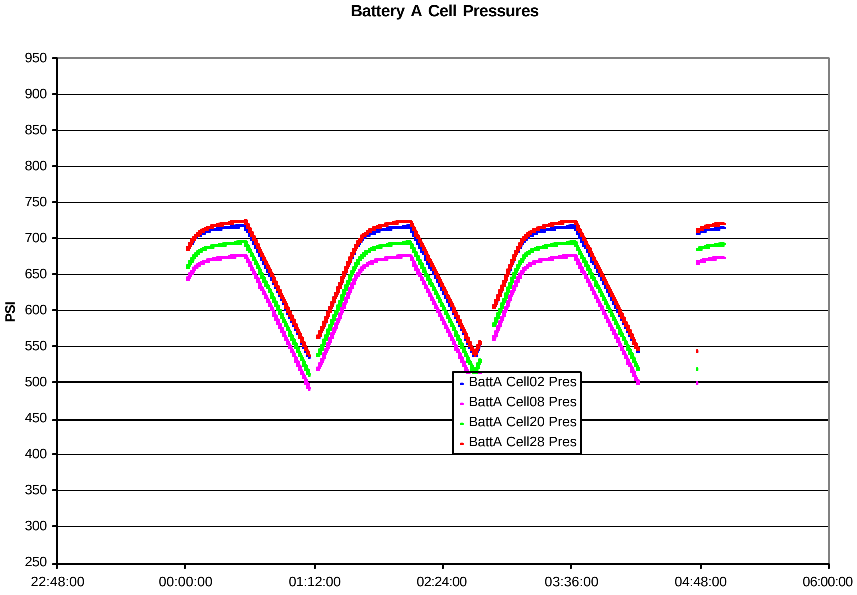
On-orbit Battery ORU Data

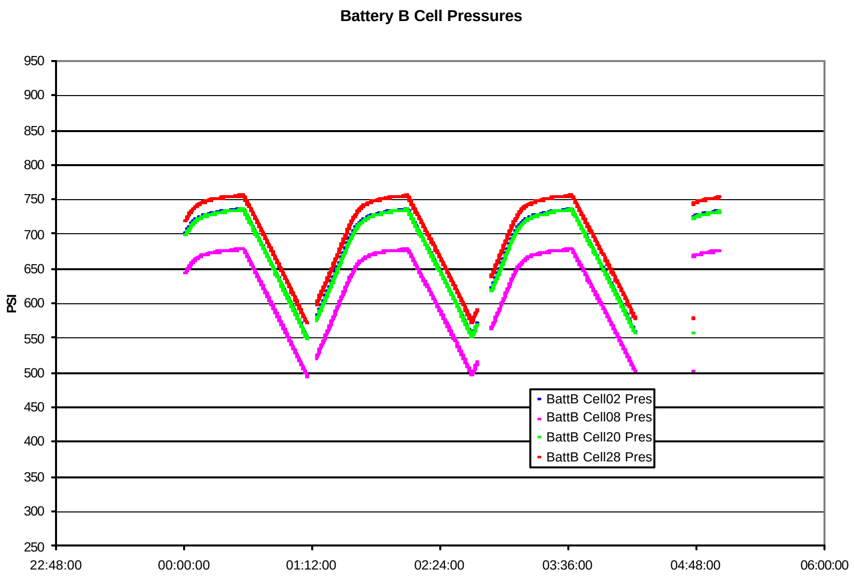
Battery 2B-2 Monitored Cell Temperatures (deg F)

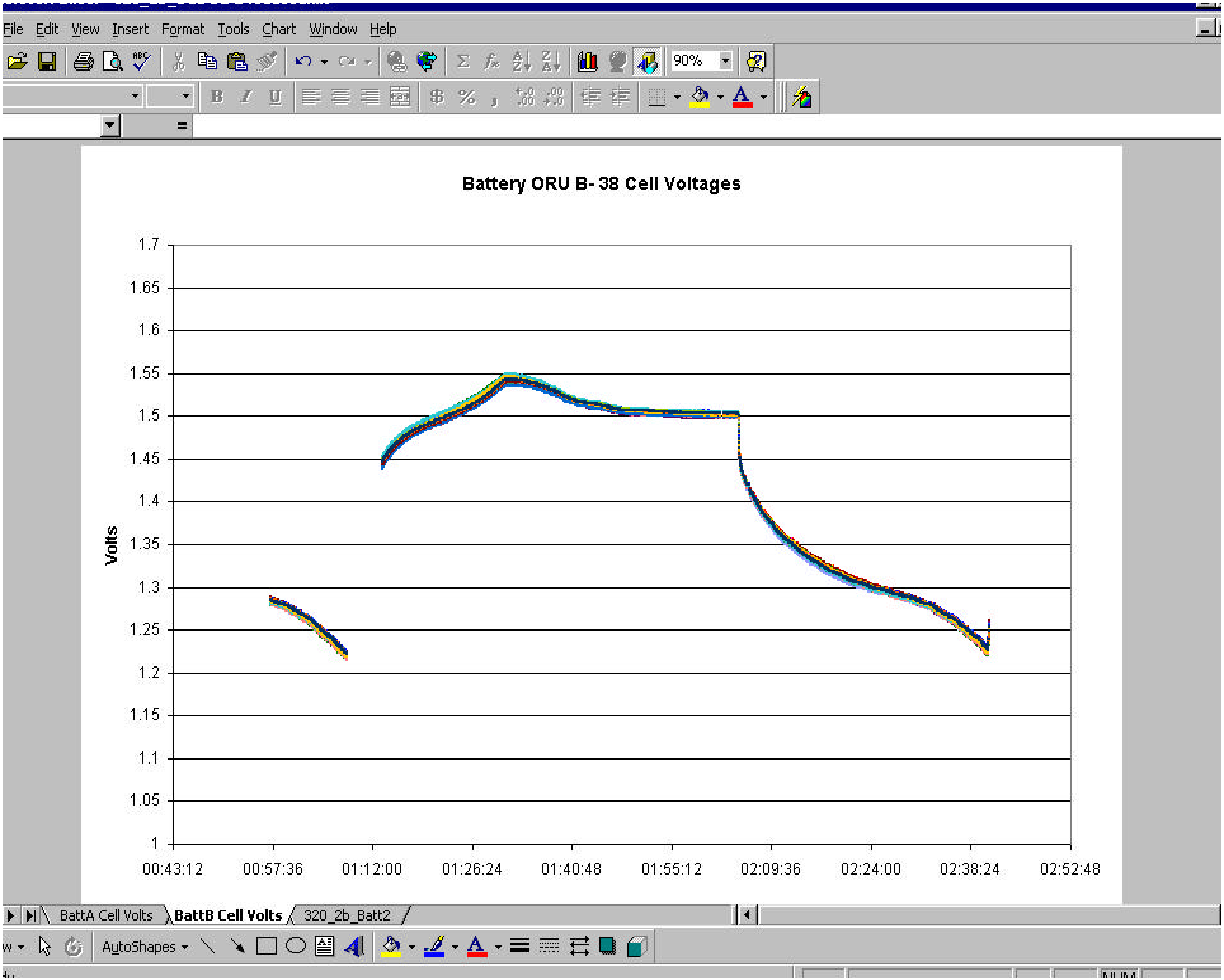




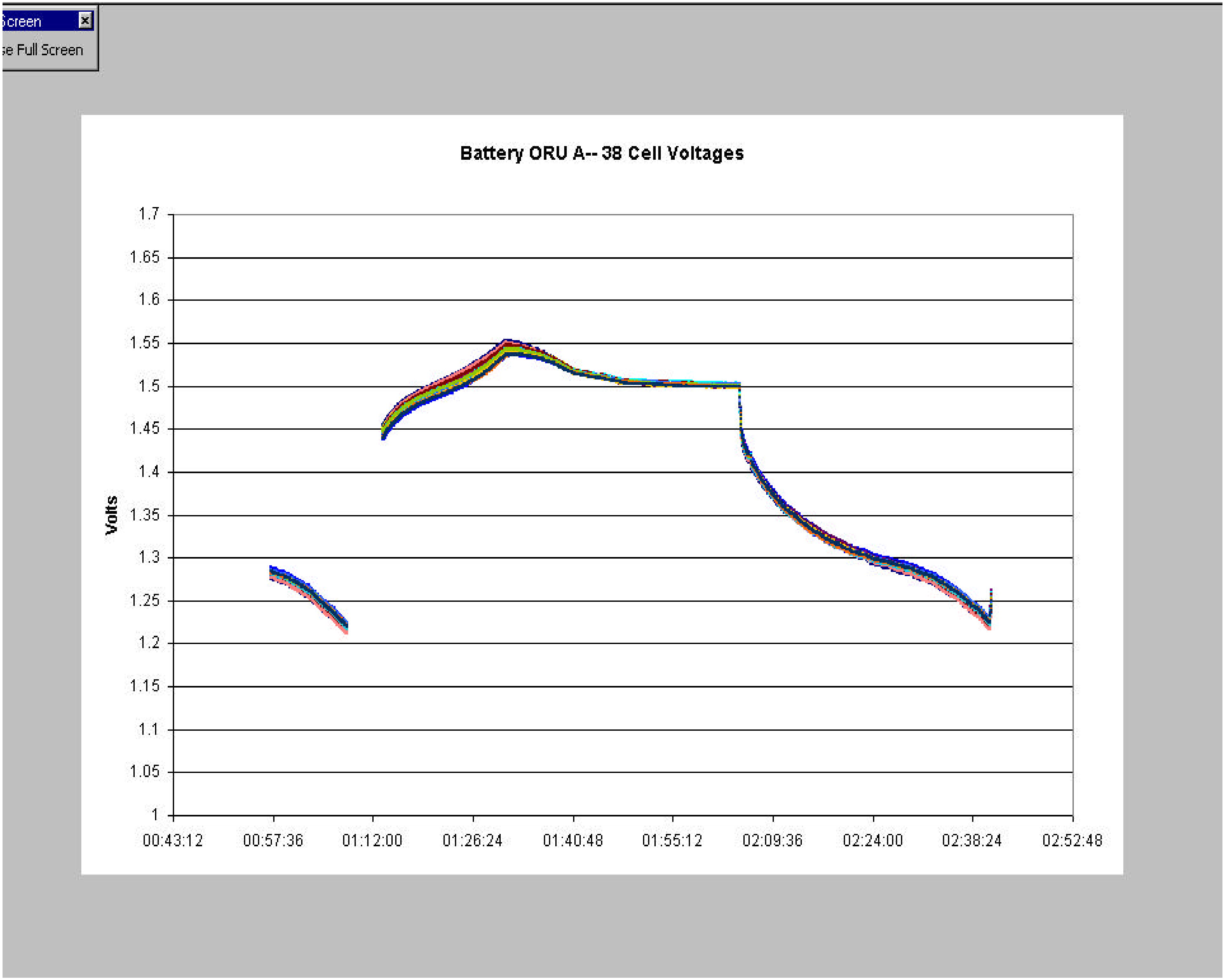
On-orbit Battery ORU Data
Battery 2B-2 Monitored Cell Pressure







File Edit View Insert Format Tools Chart Window Help
90%
Battery ORU B- 38 Cell Voltages
Volts
1.7
1.65
1.6
1.55
1.5
1.45
1.4
1.35
1.3
1.25
1.2
1.15
1.1
1.05
1
00:43:12
00:57:36
01:12:00
01:26:24
01:40:48
01:55:12
02:09:36
02:24:00
02:38:24
02:52:48
BattA Cell Volts
BattB Cell Volts
320_2b_Batt2
AutoShapes


Screen
se Full Screen
Battery ORU A-- 38 Cell Voltages
Volts
1.7
1.65
1.6
1.55
1.5
1.45
1.4
1.35
1.3
1.25
1.2
1.15
1.1
1.05
1
00:43:12
00:57:36
01:12:00
01:26:24
01:40:48
01:55:12
02:09:36
02:24:00
02:38:24
02:52:48

Conclusions

- ISS electrical power system is successfully maintaining power for all on-board loads
- ISS Eclipse power currently supplied by six Ni-H2 batteries (12 ORUs)
  - Designed for 35% DOD
  - Operating at approximately 15-25% DOD
- Operating nominally
- Meet/exceed all ISS requirements

SAFT Li-Ion MODULE DESIGN

Dr Y. Borthomieu, JP.Semerie

Specialty Battery Group

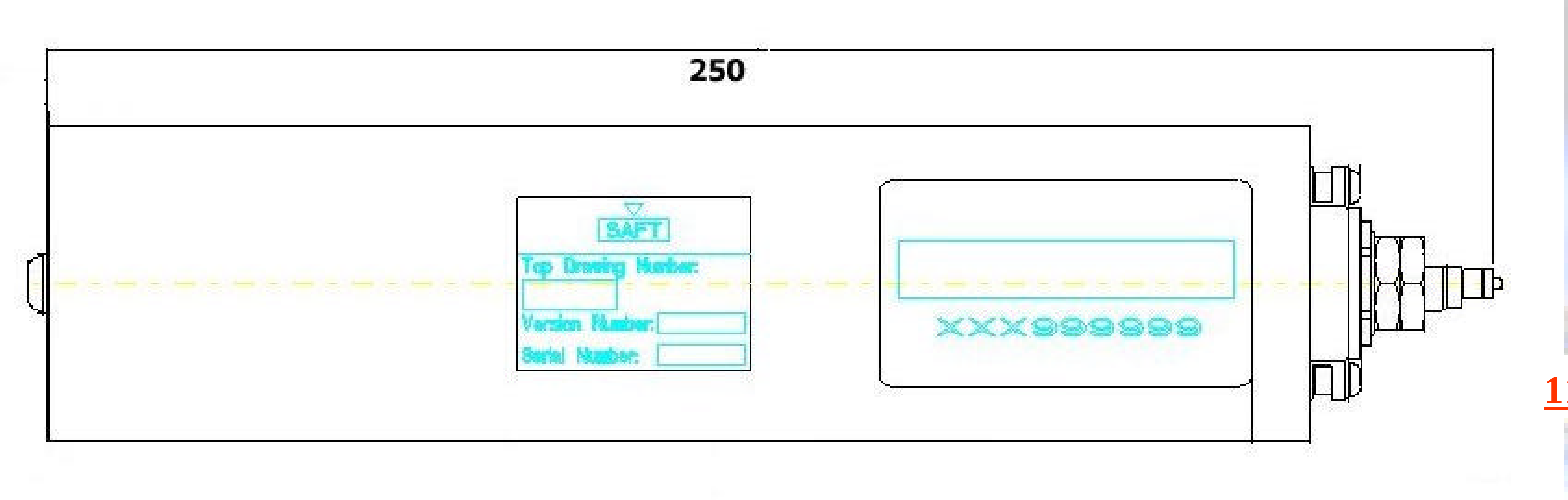
Defense and Space Division

SAFT POITIERS

♦ AGENDA

- VES140 Cell Design
- Module design
- Conclusion

VES 140 S Cell design



1116 +/- 25 g

VES 140 S

Cell Performances

- **VES 140 S cell :**
  - Max Weight = 1142g
  - Dimensions : Diameter 54, length 250 mm
  - Min Guaranteed BOL Energy > 139 Wh @ 4.10 V

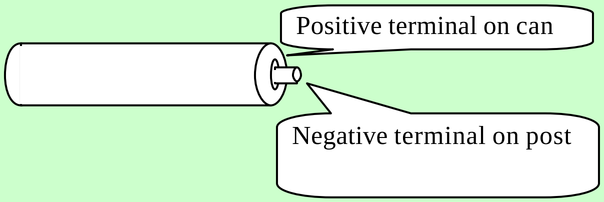
  - Space Qualified by various customers

  - VES140 C will be qualified mid of next year

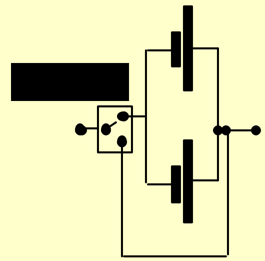
Cell Performances

- **VES 140 S cell :**
  - 3 years of storage at ambiant T : prediction at 15 years < 5 %
  - Cycling law $N=1.5*10^{6}*e^{-0.0846*DOD}$
    - 27 equivalent GEO years at 80 % DOD (< 3 % fading)
    - 20.000 LEO cycles at 20 % DOD (<12 % Fading)
- Will fly onboard Stentor

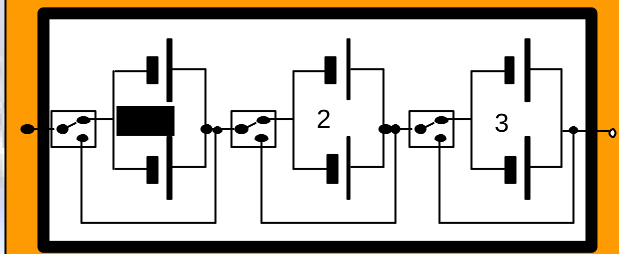
Cell Module Principles



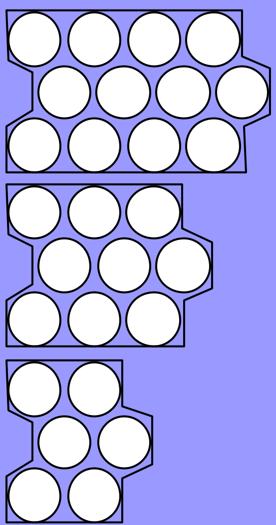
Cell



3 to 12 // Cells = Cell Module



x modules = 1 Battery



Structure of 12 cells

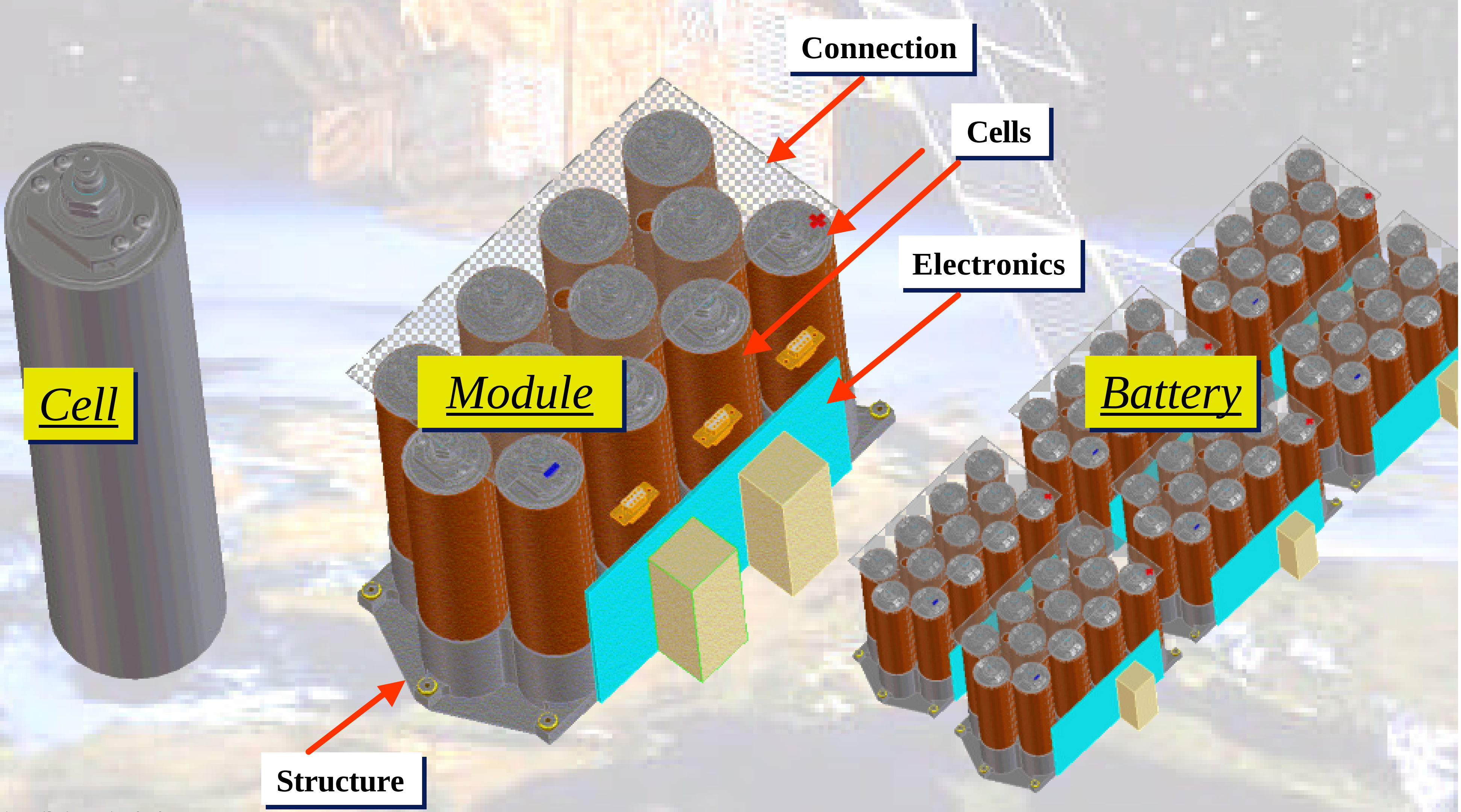
Structure of 9 cells

Structure of 6 cells

Cell Module structures

Cell Modules are installed in a supporting structure.

Li-Ion VES : Battery Modularity



The VES 140 battery (STENTOR)

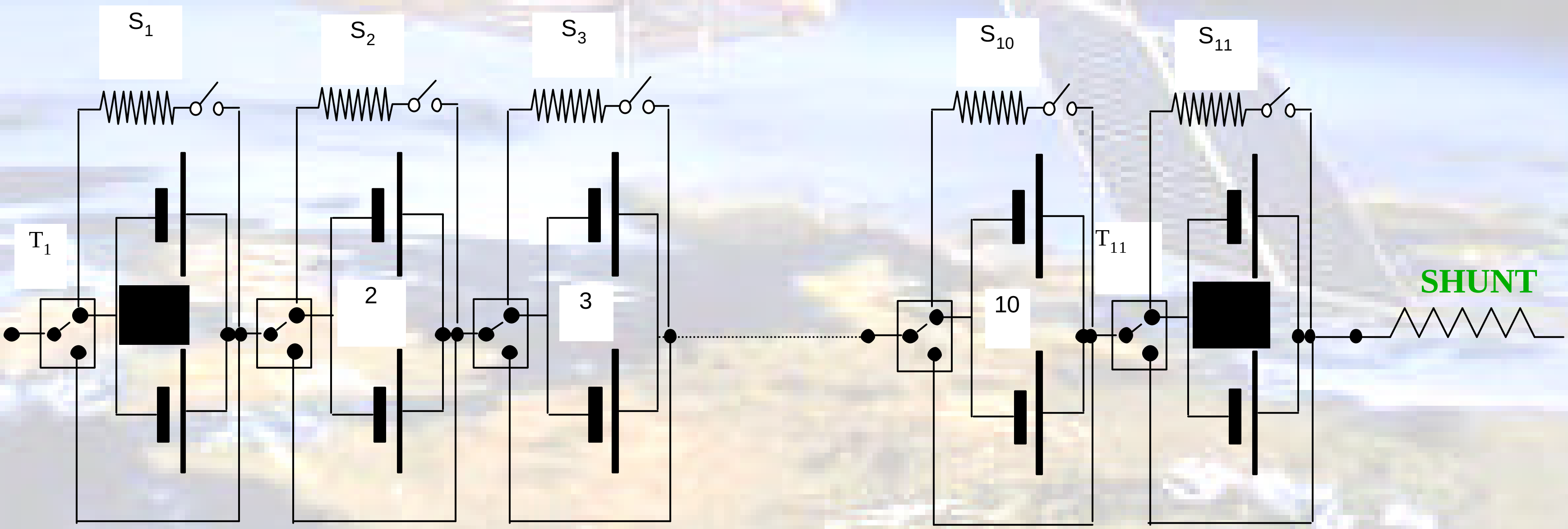
EQM battery for the French technological satellite STENTOR
(French space agency program)

- 2 batteries of 80 Ah (11 cell packages in series per battery)
- Each cell module consists in 2 ur cells in parallel
- The battery includes a balancing system which is managed by the board central computer using accurate cell voltage measureme
- The charge and tapering at end o charge are ensured by the PSR ar the EPS software
- Each cell module includes a by-p system
- FM1 and FM2 onboard satellite
- Launch date : March 2002

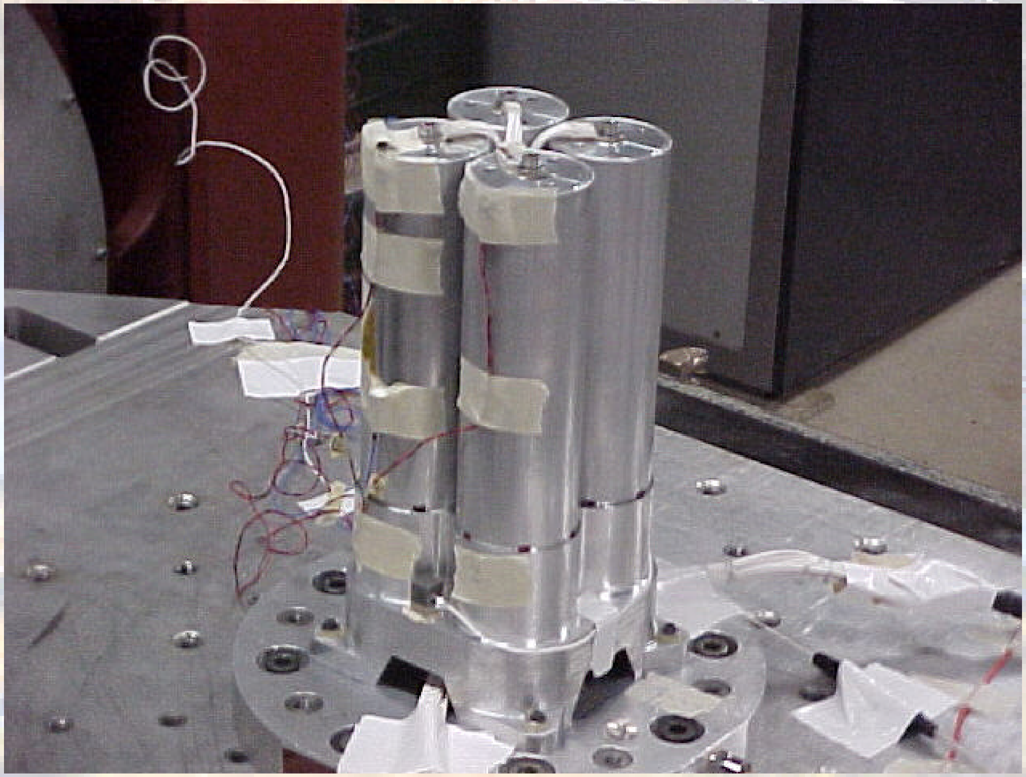
Battery Schematic

Cell Modules series connected + balancing relays and resistors

(to by-pass C/400 current on the highest charged cells)



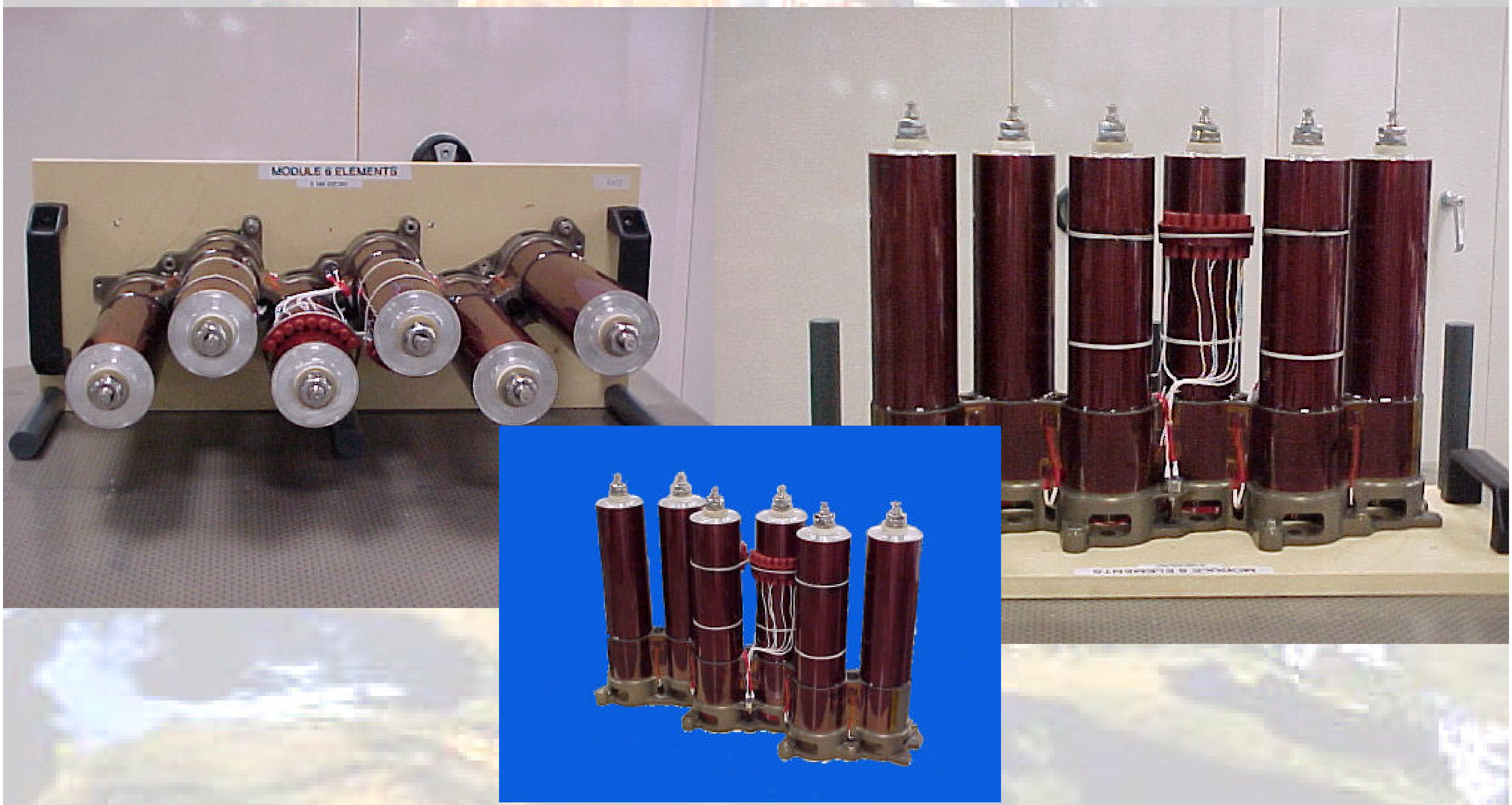
Application: 4 Cells Module



This specific module design has been used for thermal and mechanical studies

SAFT

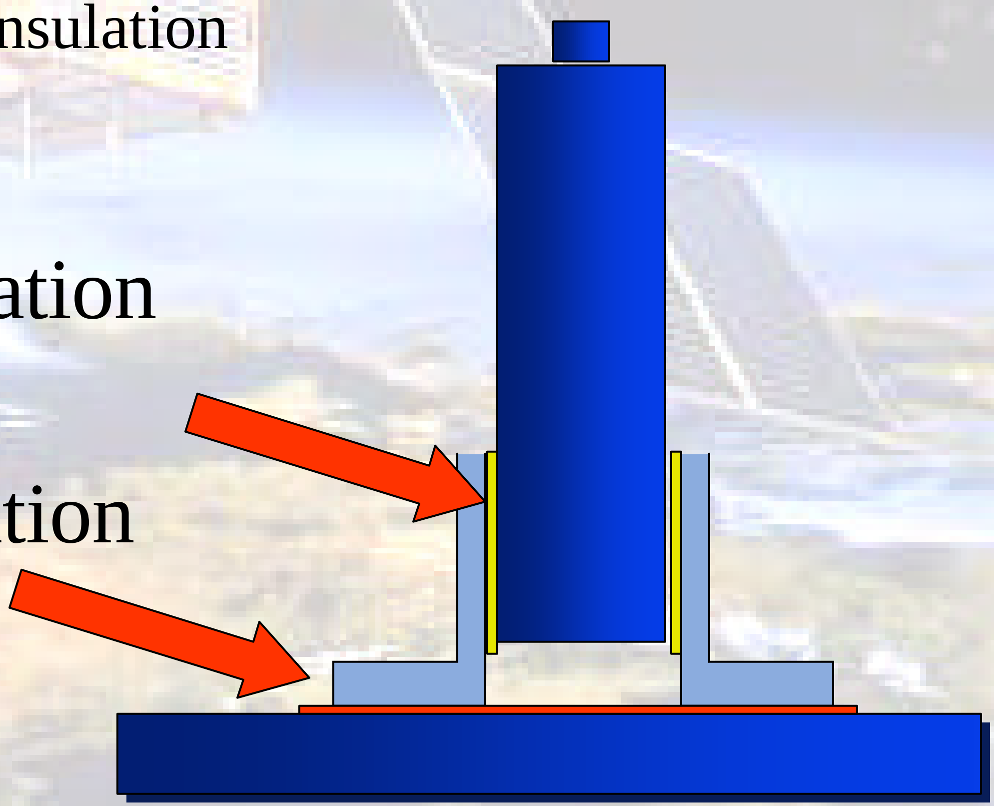
Application: 6 Cells Stentor module



Cell Module Design

- Module aluminum housing
- Cell to housing thermal junction
- Cell to housing electrical insulation

- First electrical insulation
- Second electrical insulation



Module Mechanical Performances

SINE

Sweep rate 2 octaves/minute

Frequency	Level
5 to 19 Hz	$\pm$ 10 mm
19 to 70 Hz	13.5 g
70 to 100 Hz	8 g

Sine vibrations level OX and OY

Sweep rate 2 octaves/minute

Frequency	Level
5 to 22 Hz	$\pm$ 10 mm
22 to 60 Hz	15 g
60 to 100 Hz	30g

Sine vibrations level OZ

RANDOM

Frequency	Level
20 to 100 Hz	+6dB/Oct
100 to 2000 Hz	0.05 g^2/Hz

Global 9.8 gRms

Random vibration level OX and OY.

Duration 3 minutes per axis

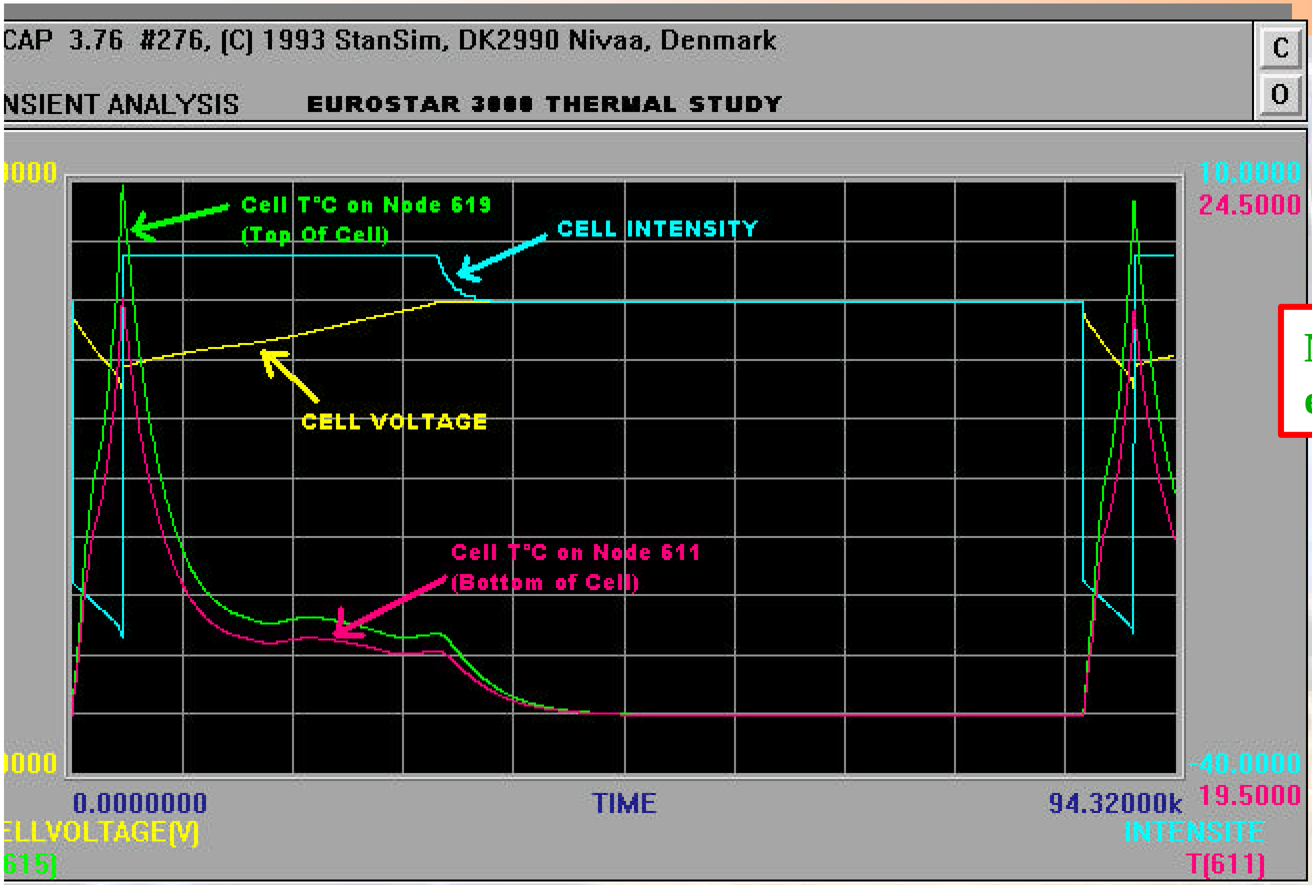
Frequency	Level
20 to 100 Hz	+6dB/Oct
100 to 350 Hz	0.2 g^2/Hz
350 to 2000 Hz	0.05 g^2/Hz

Global 11.8 gRms

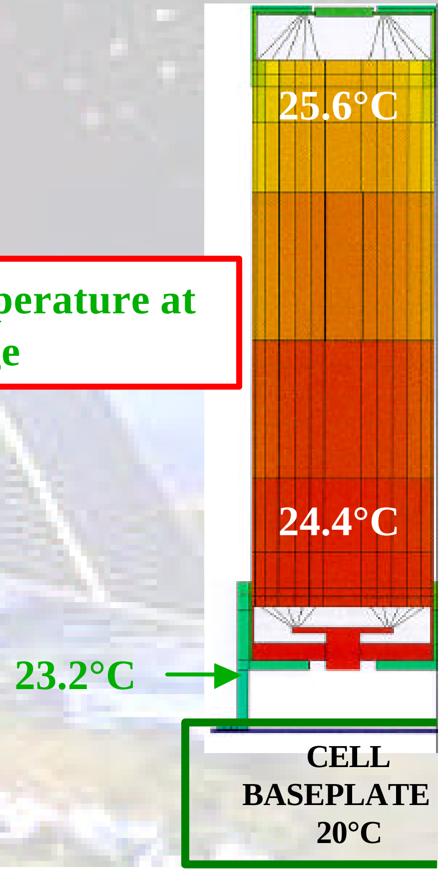
Random vibration level OZ..

Duration 3 minutes per axis

Intra-Cell gradient is very low (about 1°C worst Case)



Maximum temperature at end of discharge



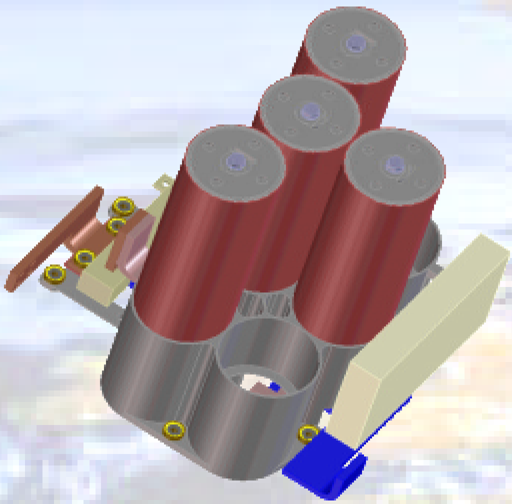
l Voltage between : 3.25 Volts and 4.0 Volts

l Dissipation during discharge : 5 Watts and 1.19 Watts (Average =2.06 Watts)

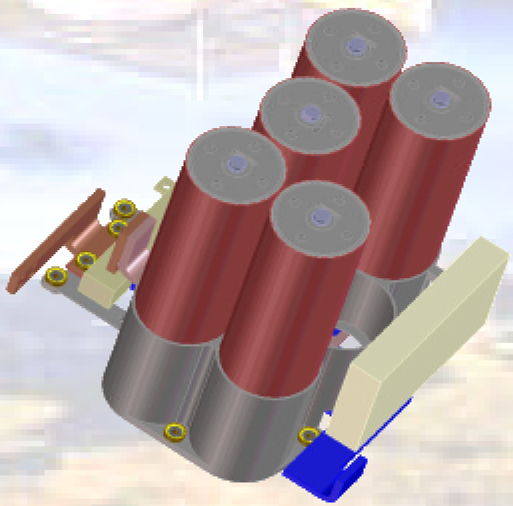
110 Wh are Discharged

Modularity of the concept issued from Stentor

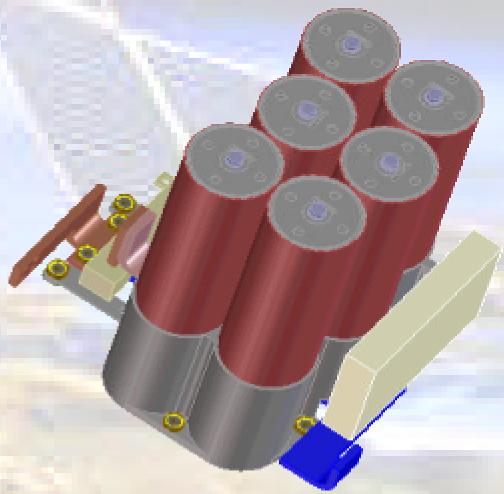
4 Cells Module



5 Cells Module

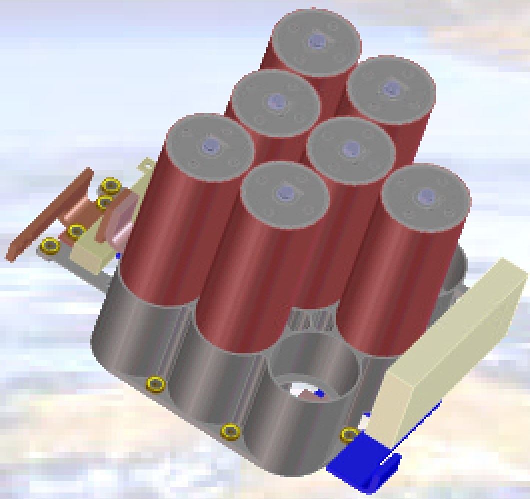


6 Cells Module

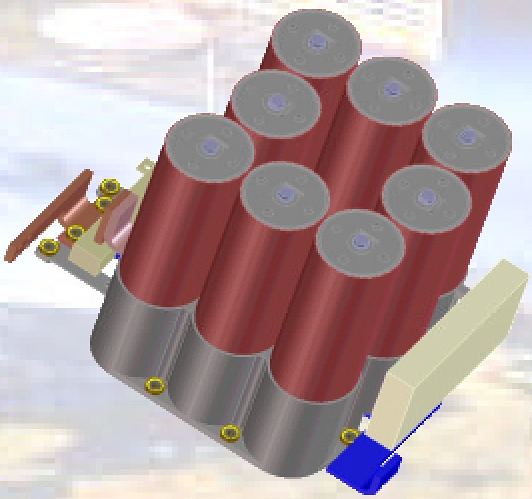


MODULE DESIGN FOR NEW PLATFORMS

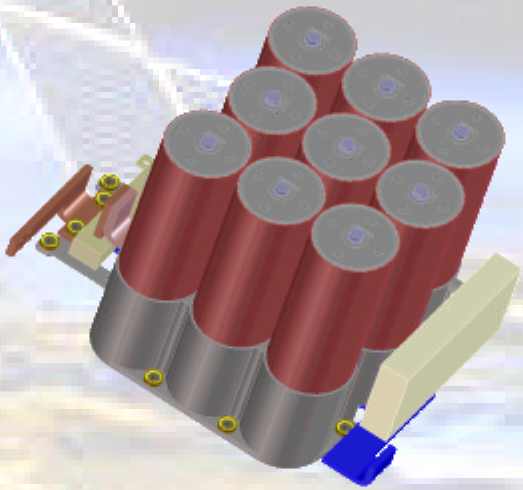
Modularity of this concept



7 Cells Module



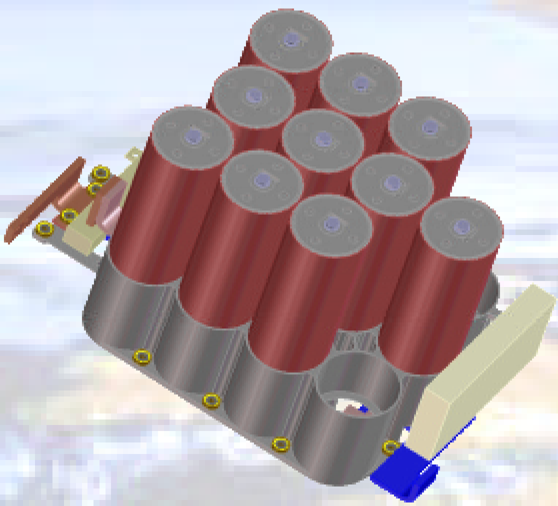
8 Cells Module



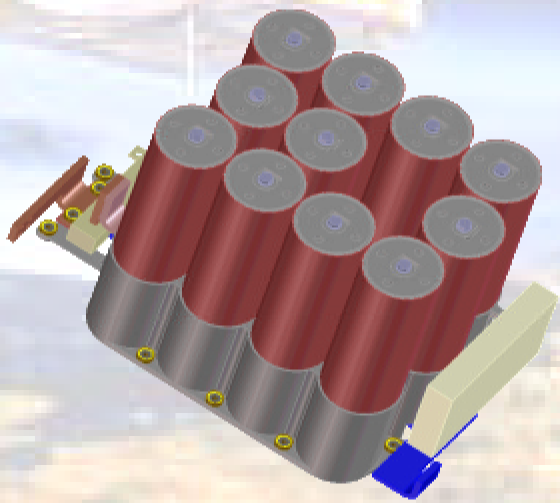
9 Cells Module

Modularity of this concept

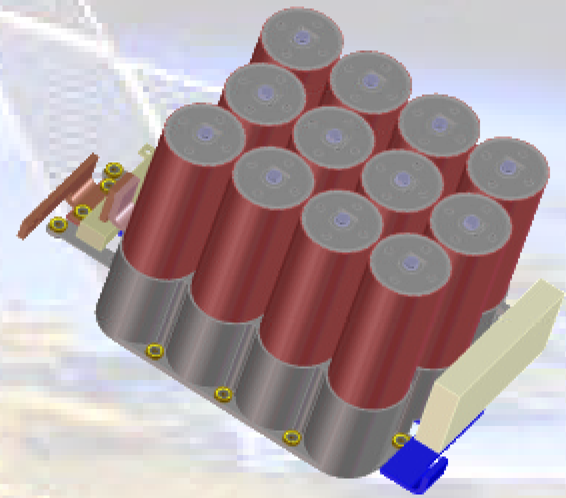
10 Cells Module



11 Cells Module

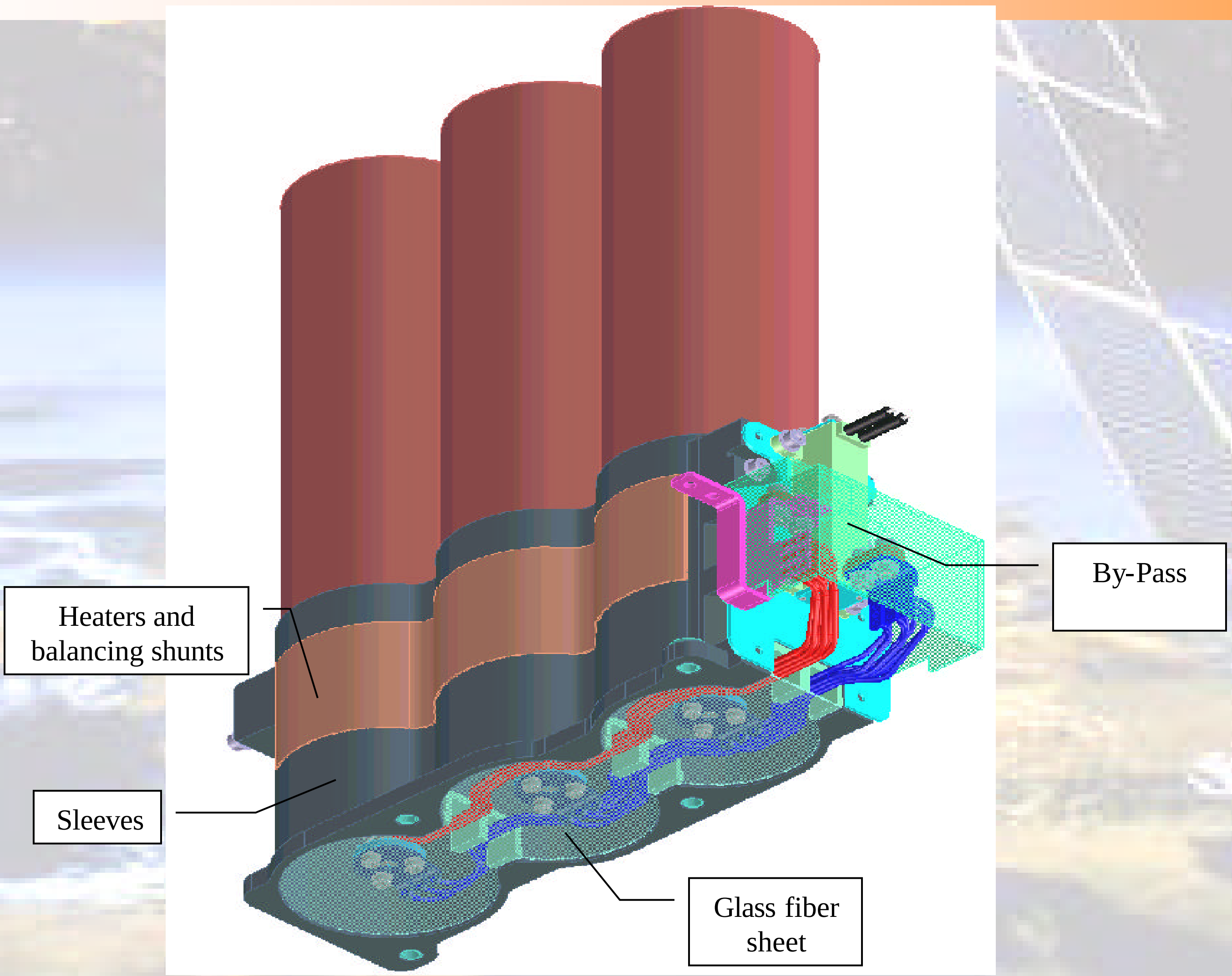


12 Cells Module

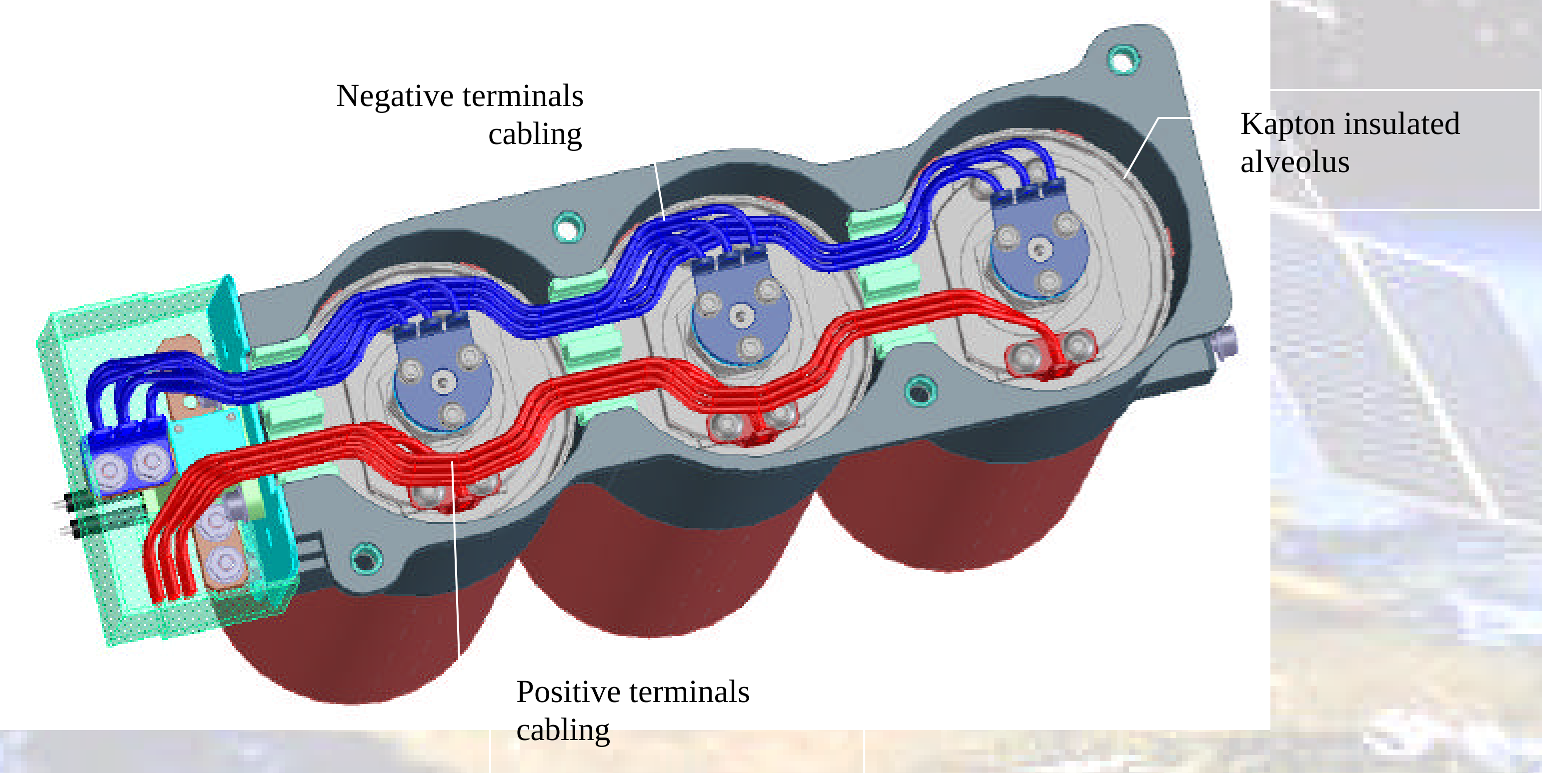


Cell Wiring

3P Module

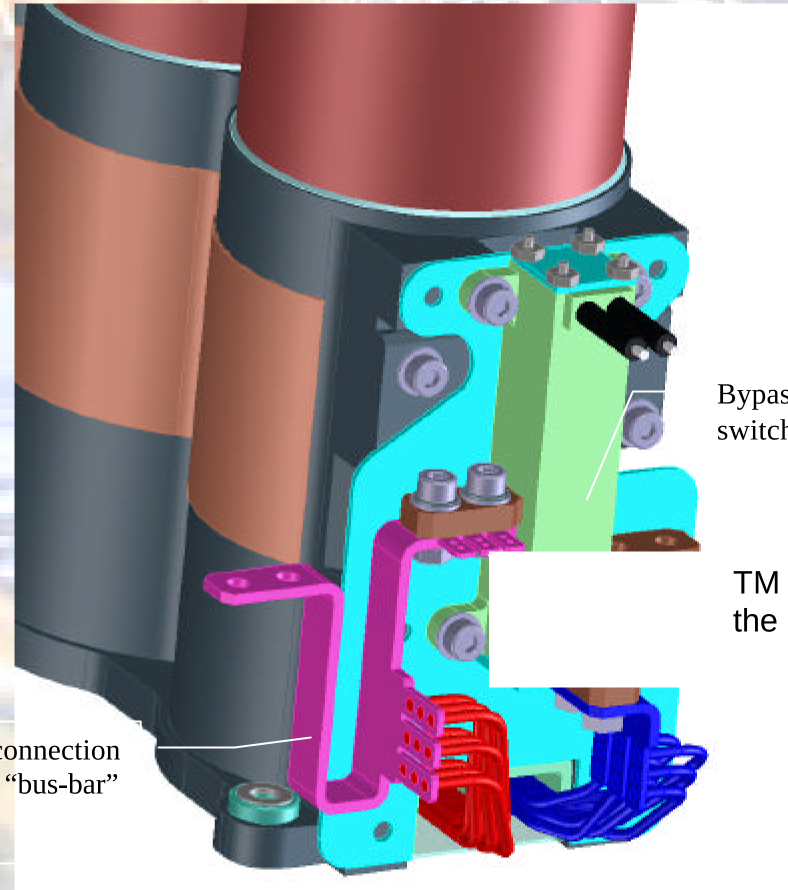

By-Pass
Heaters and balancing shunts
Sleeves
Glass fiber sheet

3P Module



Negative terminals cabling
Kapton insulated alveolus
Positive terminals cabling

3P Module

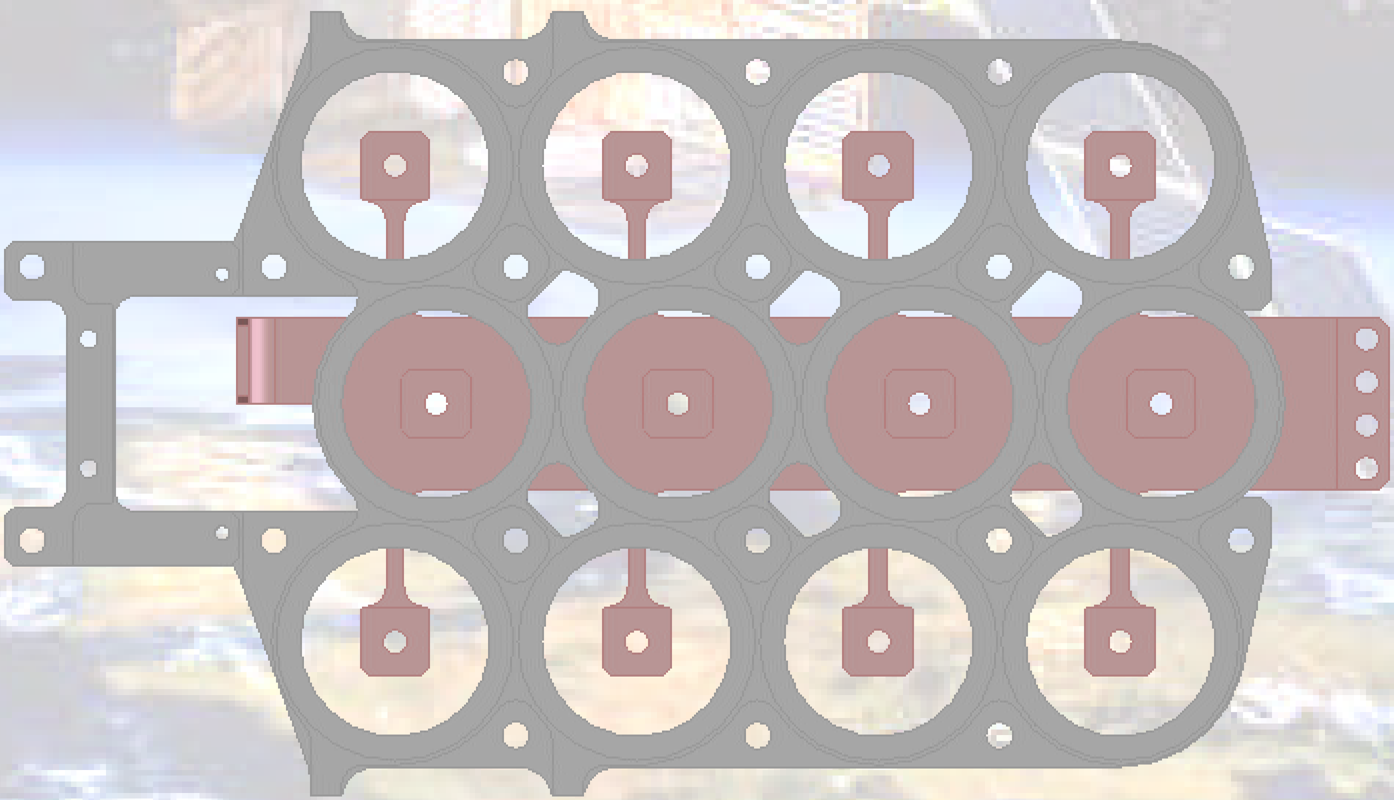


Bypass
switch
TM / TC connections with
the Lion electronics
Serial power connection
“bus-bar”

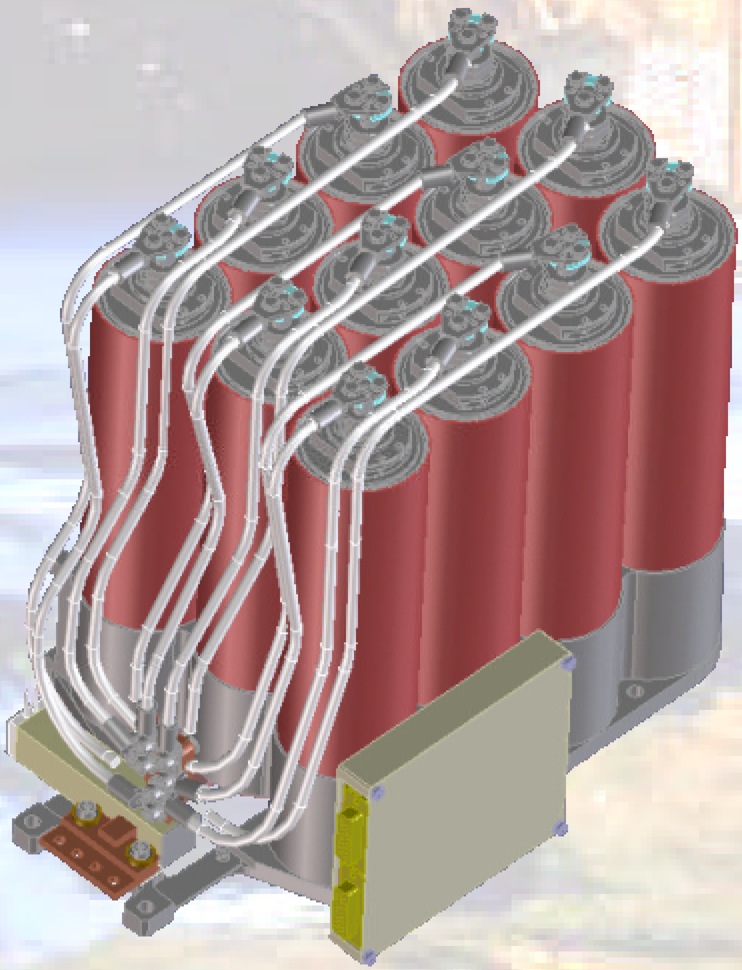
12P Module Base-Plate

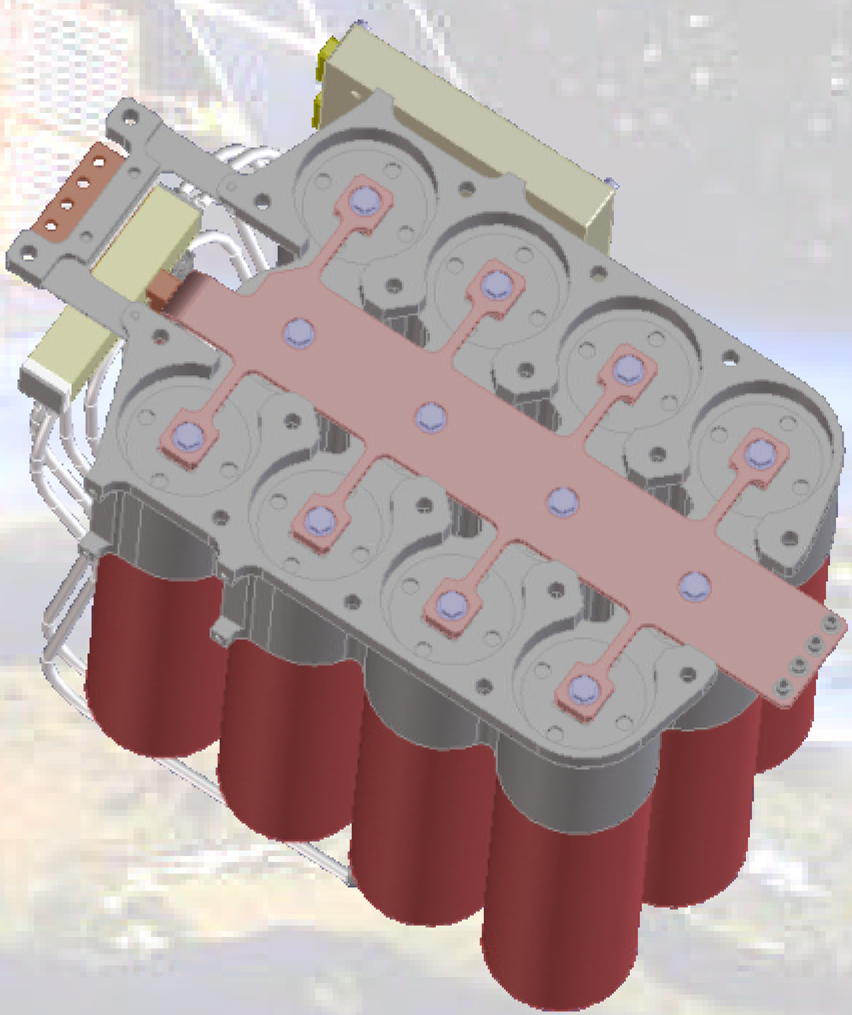
SAFT

12P Module Base-plate

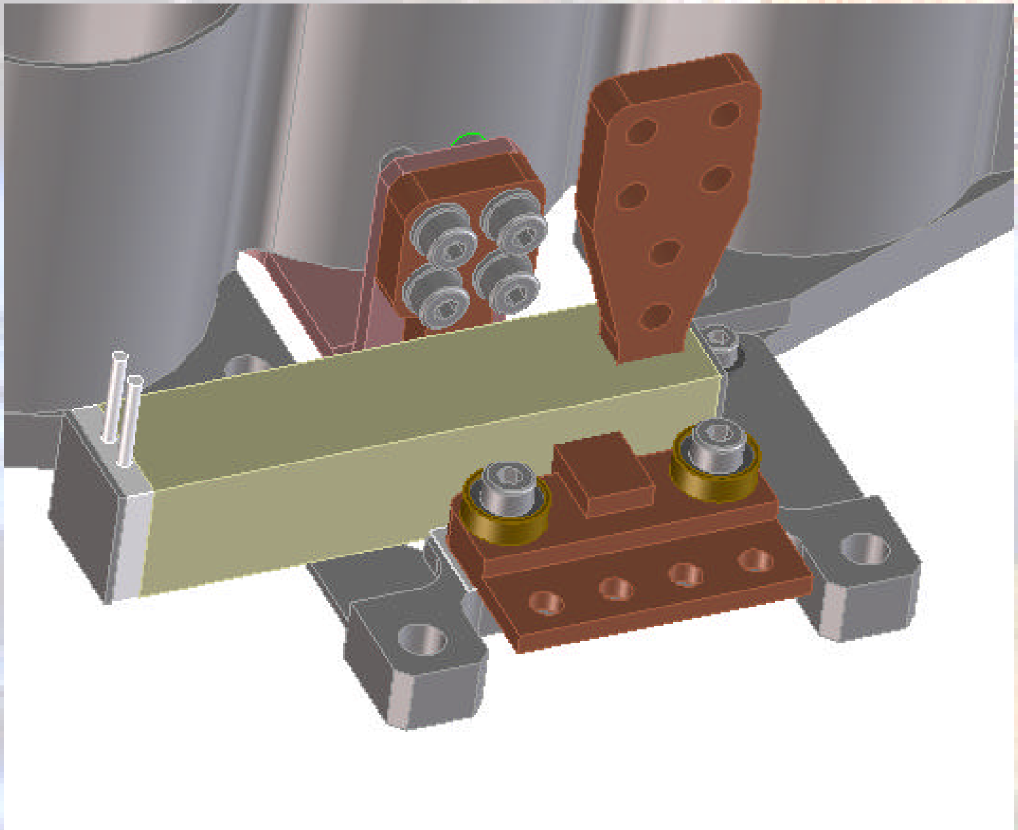


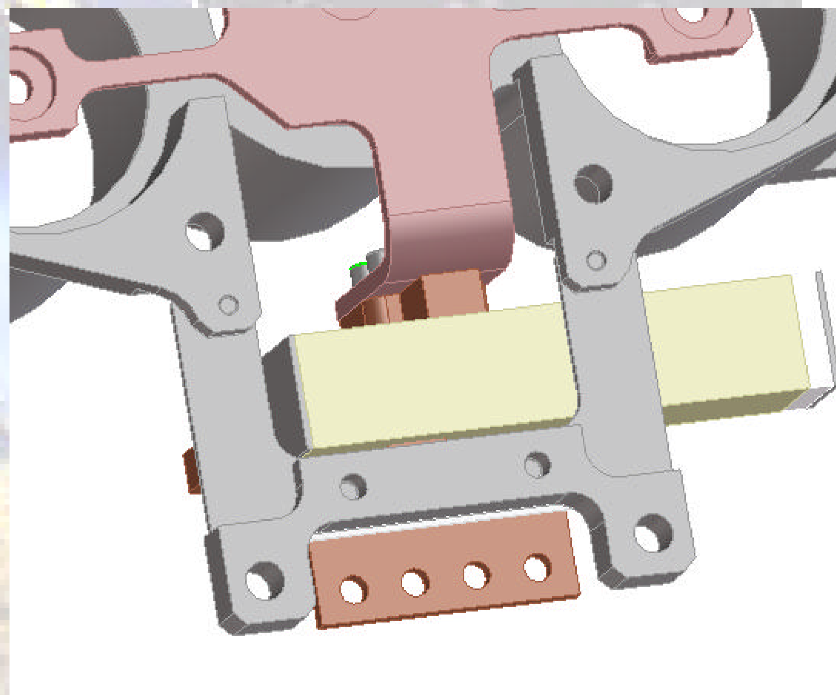
12P Module





Cell By-Pass





Cell Module By-Pass

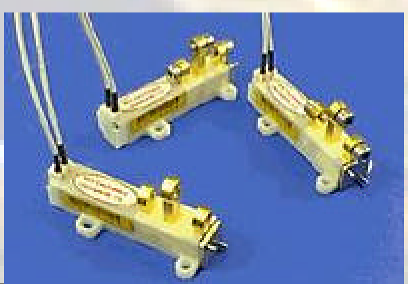
- Cell Modules are protected by non dissipative by-pass: Single pole double throw actuator :

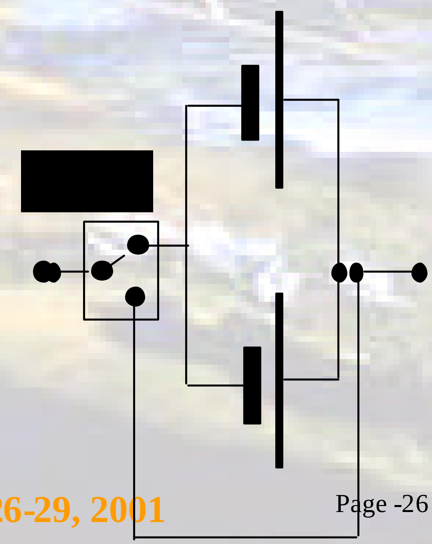
NEA 8020 100A — STENTOR bypass : Qualified

NEA 8030 200A — Prototype level

NEA 8043 430A — Development on going for 12 cells in parallel

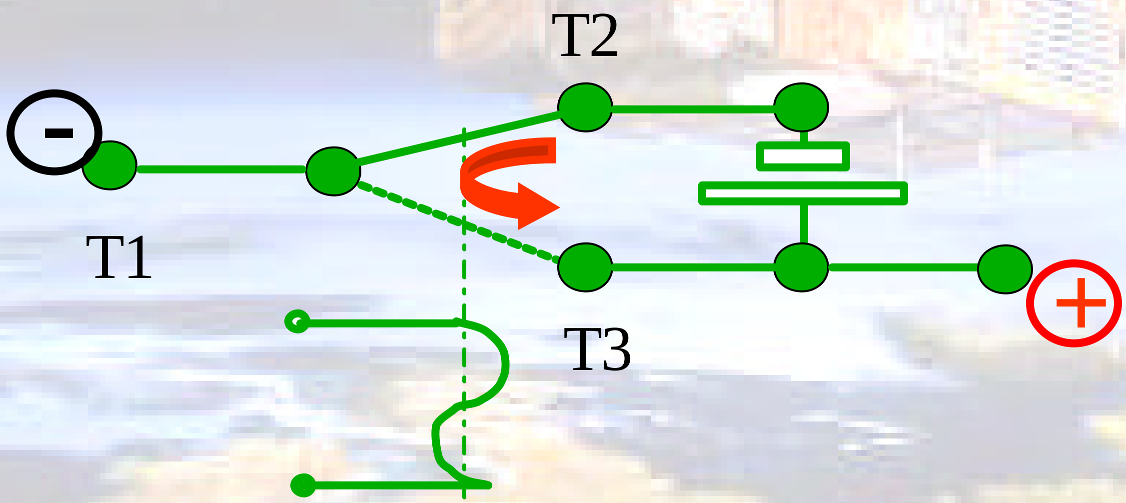
In case of cell module overcharge → By pass cell module →





NEA 430 A - Bypass characteristics

- Single pole double throw:



T1-T3 path is established by fus
blowing

Fuse characteristics :

1.2 $\pm$ 0.2 Ohms

0.35 A No fire

1 A Fire

Steady state carrying current is 430A.

NEA module bypass

- NEA Bypass (100A) already qualified on STENTOR
- Change on current carrying capability from 100A to 430A for 12 parallel cells
- Heritage from Stentor:
  - Same Actuation system
  - Same Materials (except Delrin casing changed to higher temperature resistant material)
  - Same processes
  - Same Test Procedures

SAFT

Module Range Weight

Modules Weight (equiped with By-pass, connectors, thermistors and electronic interface)

Configuration	3	4	5	6	7	8	9	10	11	12
Maximum Weight (Kg)	4,35	5,7	6,9	8,1	9,3	10,5	11,8	13	14,2	15
Cell/Battery Structure Coef	*1,281*	*1,259*	*1,219*	*1,193*	*1,174*	*1,159*	*1,158*	*1,148*	*1,140*	*1,1*
Module Energy Density (Wh/kg)	95,9	97,5	100,7	103,0	104,6	105,9	106,0	106,9	107,7	108

Specific energy at battery level > 100 Wk/kg

Failure Modes

- Cell Short :
  - Soft Short only considered :
    - if short current lower than the balancing current :
      - continuous activation of the balancing
      - compensation of the short by the balancing
    - if short current higher than balancing current :
      - decrease of the energy of the cell package
      - reversal during discharge : soft shorting of cells
      - battery operating with one cell package less

Failure Modes (cont ’d)

- Cell open :
  - Loss of 1 cell per cell package :
    - increase of the max DOD
    - increase of the max current
    - higher current discharge in the package
    - reversal at max DOD
    - Soft short of cell package
    - battery designed to adapt the loss of one cell package

Failure Rates

- Soft Short Circuit : 0.8 FIT
- Open Circuit : 0.8 FIT
- Drift : calculation to be done in function of battery design margin (DOD)

CONCLUSION

- SAFT is qualifying a module range :
  - From 3 to 12 P
  - Up to 30 kW (with 100 V battery : 24 S)
  - Specific energy >105 Wh/kg

Base-lined on 3 programs, including 2 GEO Satcoms

First FM Delivery Date: June 02

Calendar and Cycle Life Prediction of 100Ah Lithium-Ion Cells for Space Applications

Takefumi Inoue, Takeshi Sasaki, Nobutaka Imamura, Hiroaki Yoshida, and Minoru Mizutani
Large-scale Lithium-ion Battery Plant, Battery Manufacturing Center
Japan Storage Battery Co., Ltd.
and
Masayoshi Goto
Commercial Satellite Department, Kamakura Works
Mitsubishi Electric Corporation

Abstract

Calendar and cycle life characteristics of 100Ah lithium-ion cells were evaluated under the test conditions with wide range of temperature, depth of discharge, and state of charge. From this test results, based on the plausible deterioration models, our prediction shows that our lithium-ion cell has capability sufficient to achieve the GEO and LEO mission life requirements. We also present the relations between the cell internal resistance and the capacity loss to estimate the end of discharge voltage during the missions.

1. Introduction

Small-sized lithium-ion batteries have been already widely commercialized for cellular phones, handy VCR and other portable electronics equipments. Space applications such as the next generation satellites and other space usage also requires high energy density lithium-ion battery. However, its requirements are far larger in capacity, higher in reliability, and longer in life in vacuum condition comparing to the conventional small-sized commercial batteries.

Japan Storage Battery Co., Ltd. (JSB) has developed large capacity lithium-ion cells through cooperation with Mitsubishi Electric Corporation (MELCO). The cell with rated capacity of 100Ah has completely gastight structure achieved with ceramic hermetic seal [1] and has been qualified for space applications by MELCO [2].

In 1999 [1], we have already presented long life capability of our lithium-ion cells for space applications achieving 3,000 cycles on 25 %DOD cycle test and 12 months storage without no deterioration, and we had predicted over 30,000 cycle life at 25 %DOD at 15 ^{o}C based on the evaluation test data.

In this paper, we report further test results of calendar life and cycle life of our lithium-ion cells and refined life prediction for practical GEO and LEO satellite mission including estimation of capacity retention and internal resistance value under various conditions.

2. Cell structure and specifications

Fig.1 shows the 100Ah elliptic cylindrical cell appearance developed by JSB. The electrode assembly is constructed by spirally winding the positive and negative electrodes together with micro porous separators, which is contained in the elliptic cylindrically-shaped casing. The cell features are shown in Table1.

Fig.1 Elliptic cylindrical 100Ah cell for space applications
(“GS” is the trade mark of JSB.)

Table1 Specifications of 100Ah lithium-ion cell

Shape:	Elliptic cylindrical
Dimensions (mm):	208 H, 130 W, 50 T
Mass:	2.79kg
Casing material:	Aluminum alloy
Positive material:	Lithium cobaltate ($LiCoO_2$)
Negative material:	Carbon materials
Separator:	Microporous plastic film
Electrolyte:	Lithium salt dissolved in mixture of alkyl carbonate solvents
Rated capacity:	100Ah
Nominal voltage:	3.6V
Specific energy :	130Wh/kg (Rated value at BOL)

The nominal voltage of 3.6V is equivalent to that of three serial-connected cells of conventional nickel-cadmium (NiCd) and nickel-hydrogen (NiH_2) cells. The specific energy value of 130Wh/kg is twice of that of conventional NiH_2 cells.

The elliptic cylindrical cell design has the following advantages for space applications;

1) Good heat dissipation,

2) Efficient packing configuration,

and

3) Efficient production (low cost).

The good heat dissipation is obtained through close contact to wide flat surface on both sides of the cell. The empty space is remarkably reduced from battery assembly compared with cylindrical cells. Moreover, the cell construction of its electrode assembly is appropriate for mass production because of winding of only single positive and negative electrodes with separators comparing to the multi-electrode stacking construction.

3. Test conditions

3-1 Calendar life test

Calendar life tests were performed at various conditions to evaluate the effect of temperature and state of charge(SOC) during storage. A matrix of four temperatures (60, 35, 15, and 0 ^{o}C) and seven SOCs (100, 80, 60, 30, 5, 1, and 0 %) was used. Number of cells for each test condition is shown in Table 2.

Table 2 Calendar life test matrix (36 cells overall)

Temperature °C	SOC / float charging voltage						
	100% / 3.98V	80% / 3.90V	60% / 3.83V	30% / 3.78V	5% / 3.60V	1% / 3.30V	0% / 3.00V
60	1 cell	2 cells	2 cells	2 cells	1 cell	1 cells	1 cell
35	1 cell	2 cells	2 cells	2 cells	1 cell	1 cells	1 cell
15	1 cell	2 cells	5 cells*	2 cells	1 cell	-	-
0	1 cell	1 cell	1 cell	1 cell	1 cell	-	-

*For confirmation of dispersion.

Capacity check condition:

Charge: Constant current of 20 A followed by constant voltage of 3.98 V for 8 hours overall at 15 ^{o}C.

Discharge: Constant current of 20A to cut-off voltage of 2.75 V at 15 ^{o}C.

3-2 Cycle life test

Cycle life tests were performed at various conditions to evaluate the effect of temperature and depth of discharge (DOD) during cycling. A matrix of four temperatures (60, 35, 15, and 0 ^{o}C) and five DODs (80, 50, 25, 10, and 3 %) were used. Number of cells for each test and detailed test condition are shown in Table 3 and Table 4, respectively.

Table 3 Charge and discharge cycle life test matrix (33 cells overall)

Temperature / °C	DOD				
	80 %	50 %	25 %	10 %	3 %
60	1 cell	1 cell	1 cell	1 cell	1 cell
35	2 cells	2 cells	2 cells	2 cells	2 cells
15	2 cells	5cells*	2 cells	2 cells	2 cells
0	1 cell	1 cell	1 cell	1 cell	1 cell

*For confirmation of dispersion.

Table 4 Conditions for cycle life tests

DOD / %	Charge condition Constant current value / Constant voltage value / Over all duration	Discharge condition Constant current value / Duration / Cut-off voltage if reached
80	50A / 3.98V / 3.6h	50A / 1.6h / 2.75V
50	50A / 3.98V / 3.0h	50A / 1.0h / 2.75V
25	50A / 3.98V / 0.55h	50A / 0.5h / 2.75V
10	50A / 3.98V / 0.22h	50A / 0.2h / 2.75V
3	50A / 3.98V / 0.066h	50A / 0.06h / 2.75V

Capacity check condition:

Charge: Constant current of 20 A followed by constant voltage of 3.98 V for 8 hours overall at 15 ^{o}C.

Discharge: Constant current of 20A to cut-off voltage of 2.75 V at 15 ^{o}C.

4. Results and discussion

4-1 Calendar life test

Fig.2 shows changes in capacity retention of the 100Ah cells on the calendar life test at 100 % SOC (float charging voltage of 3.98V). Capacity loss at 60 ^{o}C and 35 ^{o}C is large, especially at the beginning of the test comparing to the quite small loss at 15 ^{o}C and 0 ^{o}C. The capacity loss values during last 6 months remain approximately at only 1 % and 0.5 % at 15 ^oC and 0 ^oC, respectively.

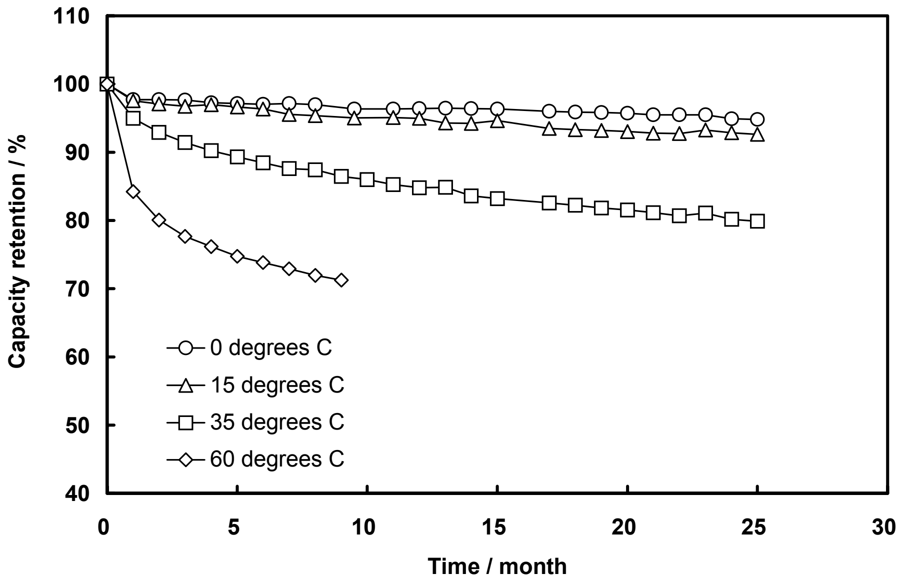


Fig.2 Change in capacity retention on calendar life test. (Floating charge at 3.98V corresponding to 100% SOC storage)

From this test results, estimation was carried out for calendar capacity loss during stand-by period such as solstice season at GEO application. We also recommend low temperature stand-by and storage.

4-2 Cycle life test

Fig.3 shows changes in capacity retention of the 100Ah cells on 50 %DOD cycle life test. The graph shows that the capacity loss is the smallest at 15 ^oC.

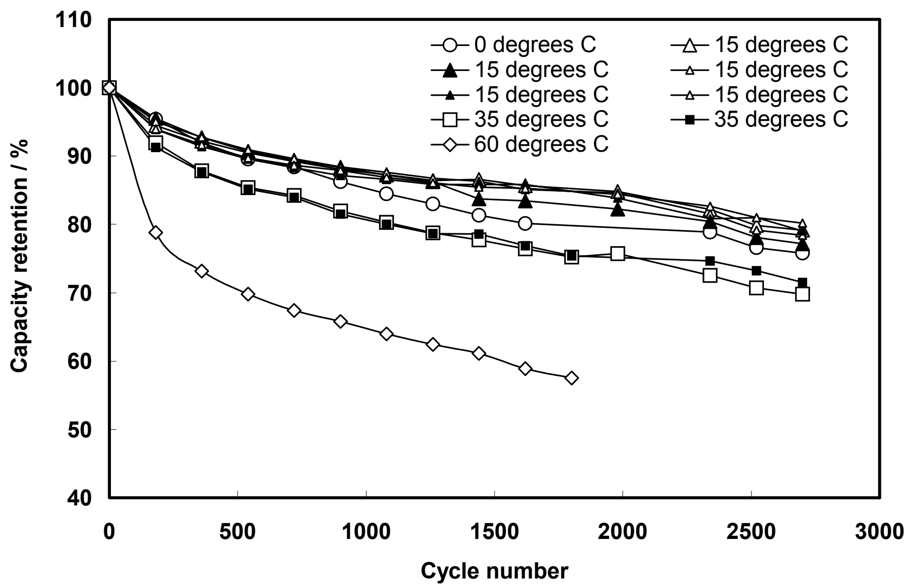


Fig. 3 Observed capacity loss on 50% DOD cycle life test

The measured capacity loss in this cycle life tests includes calendar capacity loss also, because the cells have been kept at charged conditions during each cycle life test period. Therefore, true cycle capacity loss to be used for life prediction must be calculated from subtracting the calendar capacity loss from the observed capacity loss.

[True cycle capacity loss] = [Observed capacity loss on cycle test] – [Calendar capacity loss]

True cycle capacity loss is shown in Fig.4 calculated from calendar capacity loss, cycle test duration, average SOC, and the temperature. As shown in this graph, the true cycle capacity loss has almost no dependence on the temperature except at 0 °C likely to be caused by some other mechanism.

From this investigation, we clarified the relation between the amount of true cycle capacity loss and number of cycles.

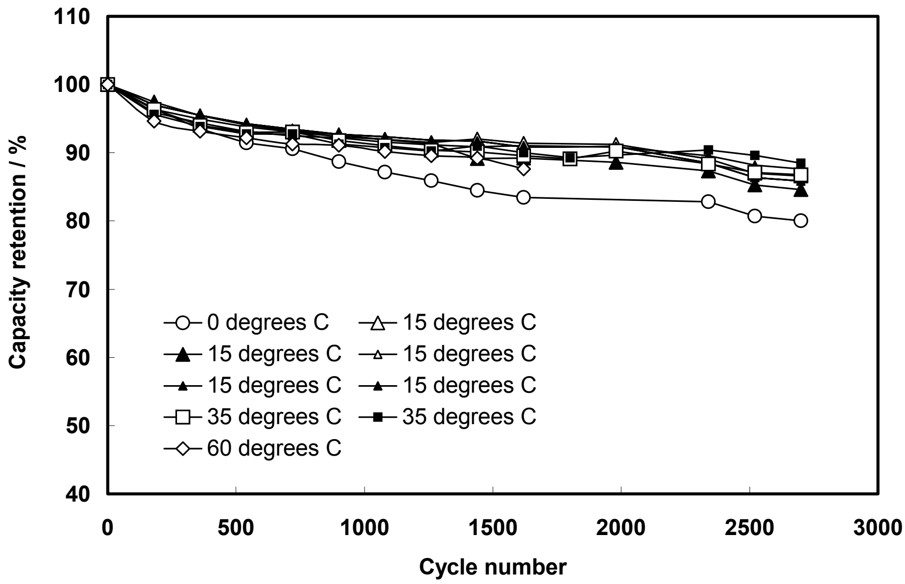


Fig. 4 Compensated cycle capacity loss on the cycle life test (50%DOD).

4-3 Internal resistance analysis

Cell Impedance and internal resistance at 15 °C were measured for all cells after calendar and cycle life tests and it was found that the cell internal resistance lineally increases with capacity loss percentage. The proportional coefficient was almost constant throughout all ranges of the test temperature, SOC and DOD for both calendar and cycle life tests. Fig.5 shows various time range internal resistance for degraded cells in various extent after the life tests.

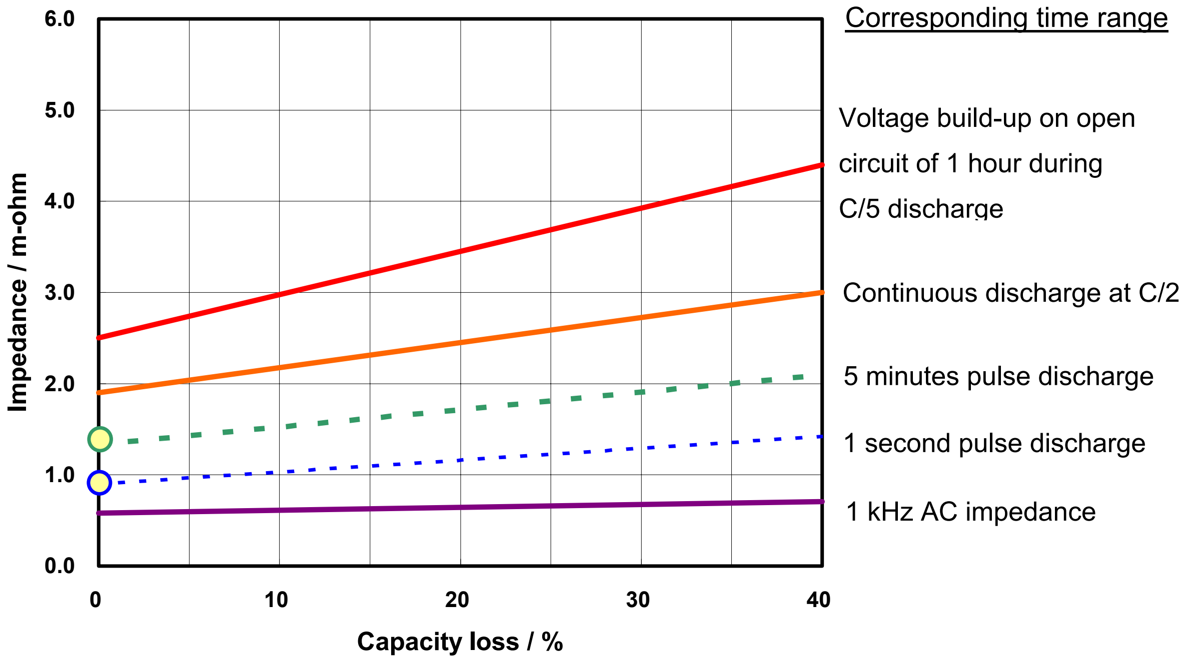


Fig. 5 Relations between cell impedance and internal resistance at 15 °C vs. capacity loss

The solid lines and two circles are actually measured data. The broken lines are predicted ones from those measured values. All the internal resistance and impedance measurements were carried out after cell temperature was stabilized at 15 °C for every life test temperatures. Impedance values of aged cell are predictable using of Fig.5 and estimated capacity loss value.

4-4 Practical prediction for actual satellite usage condition

From our investigation described above, cell capacity loss is predictable for actual satellite mission under various conditions in terms of cycling DOD, cycling duration, storage SOC, and the temperature calculating the amount of calendar capacity loss and cycle capacity loss independently.

4-4-1 GEO satellite mission

4-4-1-1 Conditions

The condition is shown below.

<Eclipse season>

Average cycle DOD: 56% (70% Max.)

Cycle number: 45 cycles/season x 2season/year x 15years = 1,350 cycles

Duration: 45 days/season x 2season/year x 15years= 1,350 days

Average temperature : 10 °C

<Solstice season>

Average storage SOC: 50%

Average storage temperature: 0 °C

Duration : 275 days/year x 15years = 4,125 days

<Ground storage>

Average storage SOC: 10%

Average storage temperature: 0 ^oC

Duration : 3 years = 1,095 days

4-4-1-2 Estimation results

Fig.6 shows the estimated capacity retention during typical GEO satellite mission. The capacity is estimated to be retained at 77 % at the end of the 18 years mission even charging voltage being maintained at 3.98 V. If the cell is charged at 4.1V after the mission, the capacity retention will be further improved to 93 %. From Fig.5, cell internal resistance for continuous discharge at C/2 rate is estimated to be 2.6 m-ohm at the end of this mission.

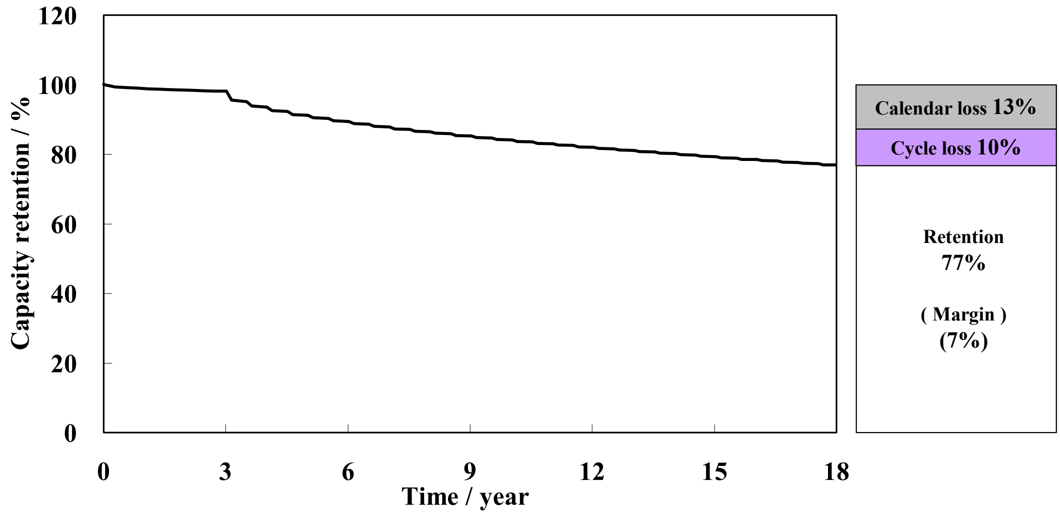


Fig.6. Predicted capacity retention during typical GEO satellite mission.

4-4-2 LEO satellite mission

4-4-2-1 Conditions

The condition is shown below.

<On orbit>

Average cycle DOD : 20 % (30% Max.)

Cycle number: 40,000 cycles

Duration: 8 years = 2,920 days

Average temperature: 15 ^oC

<Ground storage>

Average storage SOC: 10 %

Average storage temperature: 0 ^oC

Duration: 3 years = 1,095 days

4-4-2-2 Estimation results

Fig.7 shows the estimated capacity retention during typical LEO satellite mission. The capacity is estimated to be retained at 61 % at the end of the 11 years mission even charging voltage being maintained at 3.98 V. If the cell is charged at 4.1V after the mission, the capacity retention will be further improved to 77 %. From Fig.5, cell internal resistance for continuous discharge at C/2 rate is estimated to be 2.9 m-ohm at the end of this mission.

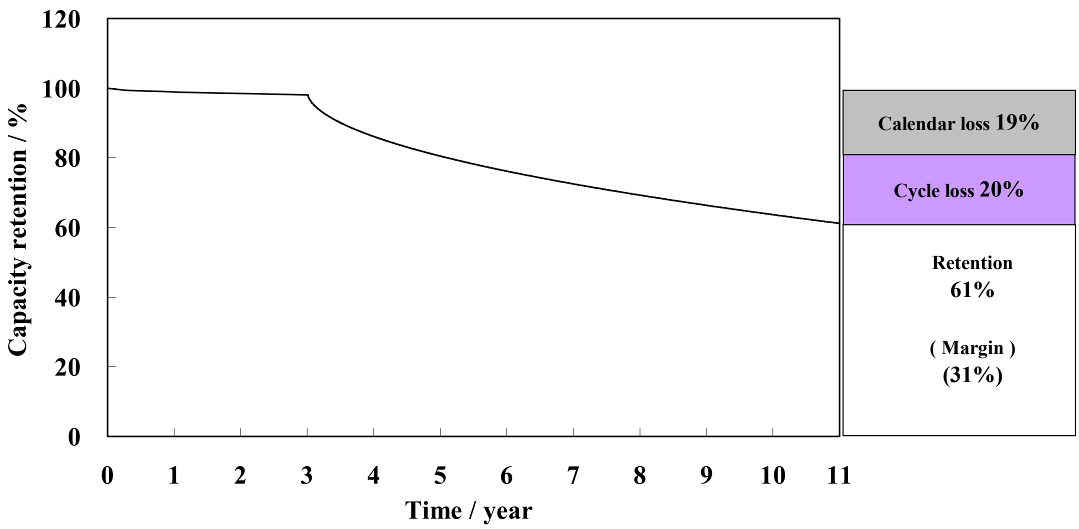


Fig.7 Predicted capacity retention during typical LEO satellite mission.

5. Conclusions

Our 100Ah lithium-ion cells with elliptic cylindrical shape have been tested, focusing on the calendar and cycle life performance and internal resistance required for their use in LEO and GEO satellite missions. It was confirmed that the cell life is predictable under any conditions for these applications using obtained test data and it has capability sufficient to achieve the required life of both satellite missions.

References

[1] H. Yoshida, S. Kitano, T. Inoue, M. Terasaki, K. Komada, M. Mizutani and M. Goto, "Development of Large-Scale Lithium-Ion Cells for Space Applications", 50th International Astronautical Congress, IAF-99-R.2.10, Amsterdam, Oct. 4-8, 1999.

[2] T. Inoue, H. Yoshida, M. Mizutani and M. Goto, "Qualification Test Results of 100AH Lithium Ion Cells for Space Applications ", 18th AIAA International Communications Satellite Systems Conference, Oakland, CA, Apr. 10-14, 2000.

Thermal Modeling
of
Prismatic Lithium-Ion Cells

Pinakin M. Shah

Mine Safety Appliances Company, Sparks, MD

Michael T. Nispel

12 Pine Road, Malvern, PA

Objectives and Cell Details

- **To Estimate the Transient Thermal Profiles of an Aerospace, Prismatic, 50 Ah, Lithium-Ion Cell During Repeated Low Earth Orbit (LEO) Charge / Discharge Duty Cycles.**
- **Perform Parametric Studies to Determine the Effects of Various Changes in Design; e.g., Materials, Dimensions, Boundary Conditions, Cell Age, etc.**
- **Low Earth Orbit (LEO) Satellite Battery, 90 Minute Duty Cycle @ 40% DOD -- 54 Minute Charge; 36 Minute Discharge**
- **Nameplate Capacity -- 50 Ah**
- **Dimensions -- 7" H x 3.2" W x 2.1" D**

Methods of Solution

- Finite Element Methods (FEM) Selected
- Heat Generation Rate
  - Entropic and Ohmic Contributions
- Modeling
  - Commercial Program
    - StarTopaz Module of Stardyne
  - Transient Inputs / Outputs
  - Parametric Studies

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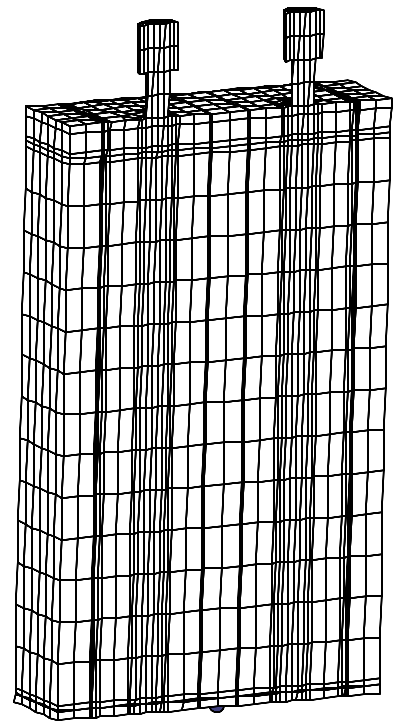
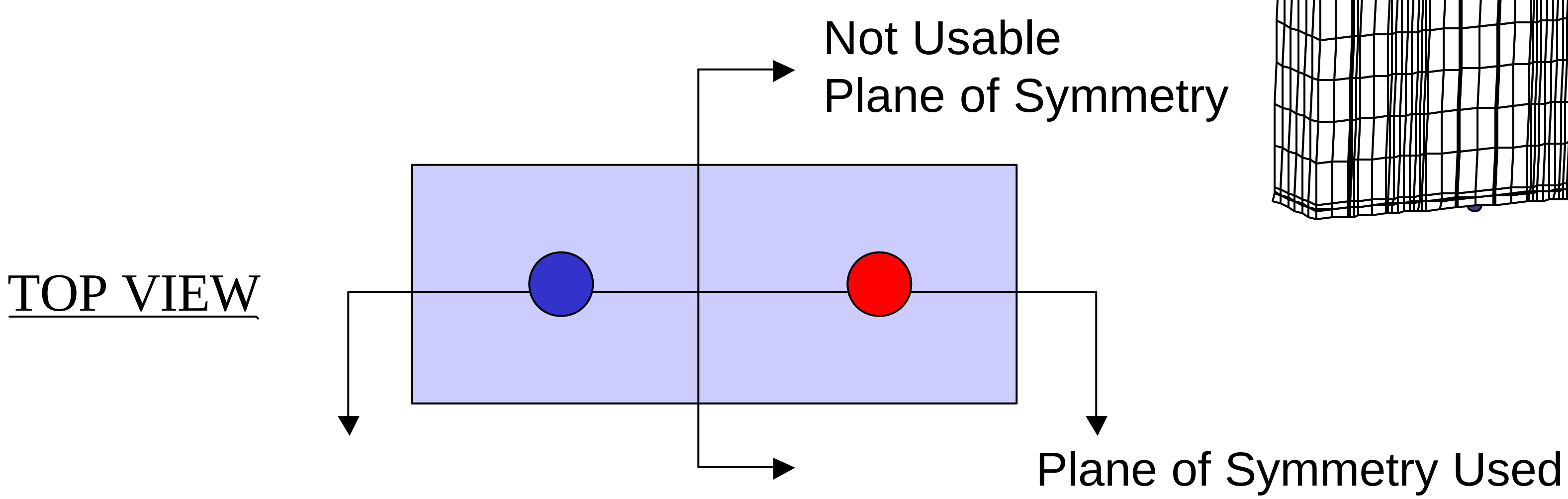
Model Basics

- 3-Dimensional Model
- 1/2 Cell Modeled Along Axis of Symmetry
- 1/4 Cell Model With Second Plane of Symmetry Precluded Because of Differences in Material Properties of Current Collectors and Terminal Posts
- ~6500 Total Nodes

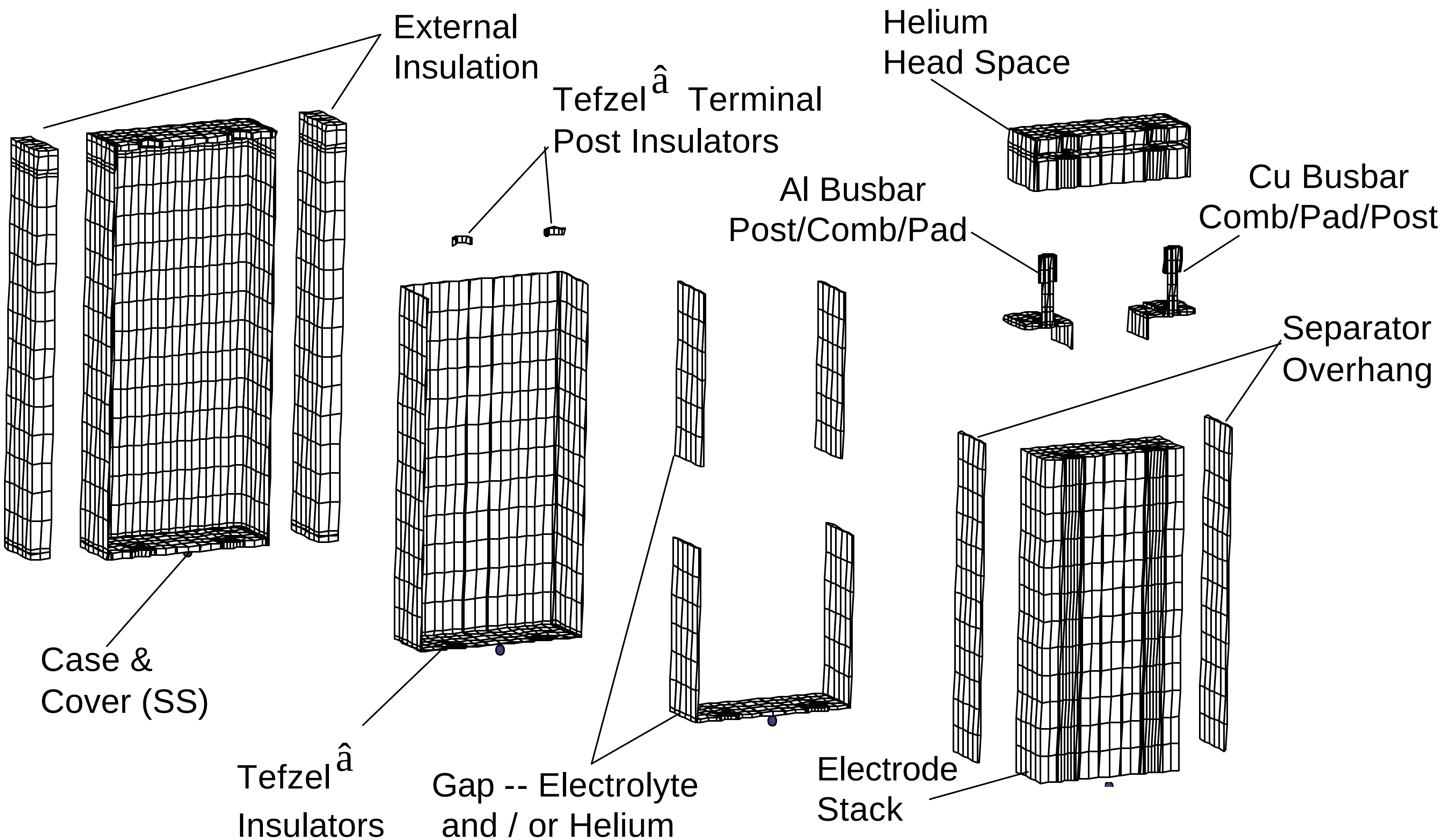




Physical Model Components and Materials

- **TOTAL NUMBER OF NODES ~6500**
  - **Hardware Parts -- Case, Cover, Bottom (316L SS and Al)**
  - **Terminal Seal Posts – Aluminum and Copper**
  - **Terminal Seal Insulators – Tefzel®**
  - **Positive Collectors, Comb, Pad – Aluminum**
  - **Negative Collectors, Comb, Pad – Copper**
  - **Insulators (Cell Inside Liners and Spacers) -- Tefzel®**
  - **Electrolyte/Separator – Part of The Gap Between Stack & Case**
  - **Electrolyte – Part of the Gap Between Stack & Case**
  - **Electrode Stack – Lumped Mass With Average Properties**
  - **Outside Insulation – Glass Fiber Filled Phenolic; 1 cm Thick**

Model Components



MSA

Thermophysical Properties

COMPONENT	MATERIAL	Specific Heat, C_p (cal/g-°K)	Thermal Conductivity, k (W/m-°K)	Density (g/mL)	References
Case, Cover	**316L SS**	**0.120**	**16.20**	**8.0**	**1**
Positive Busbar	**Aluminum**	**0.215**	**237.00**	**2.7**	**1,2**
Negative Busbar	**Copper**	**0.092**	**398.00**	**8.9**	**1,2**
Positive Electrode (including Electrolyte)	**Li_xCoO_2, C, PVDF, and Electrolyte**	**0.218**	**2.18**	**2.9**	**2,5**
Negative Electrode (including Electrolyte)	**C, PVDF, and Electrolyte**	**0.218**	**1.40**	**1.4**	**2,5**
Separator	**PP/PE**	**0.494**	**0.83**	**1.1**	**2**
Electrolyte	**1M LiPF6 in PC+EC+EMC+DEC**			**1.2**	**4**
Insulators (Internal)	**Tefzel®**	**0.250**	**0.24**	**1.7**	**3**
External Insulation	**Phenolic with Glass**	**0.230**	**0.26**	**1.8**	**3**

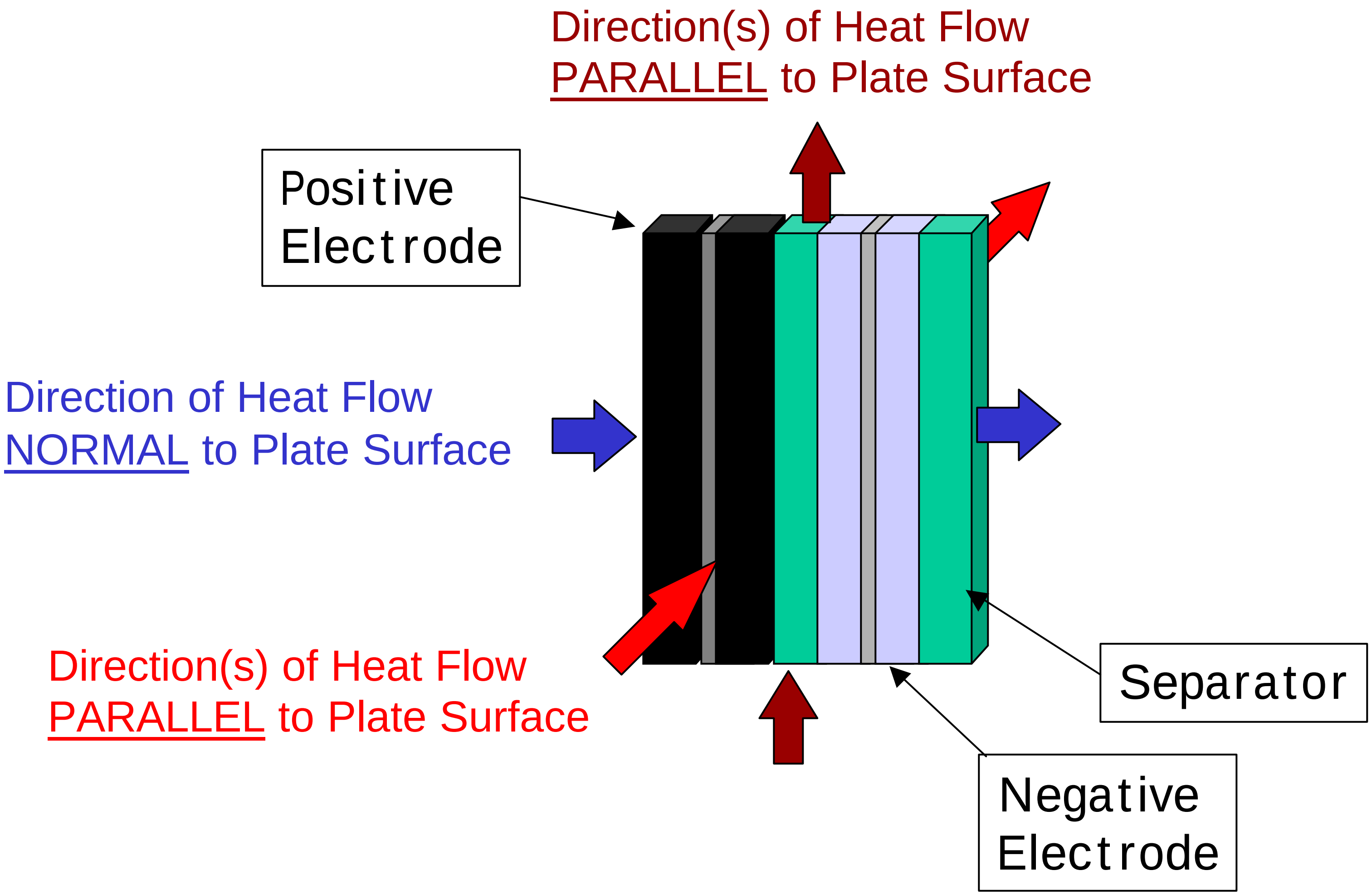
REFERENCES:

1. Chemical Engineer's Handbook, 5th Edition, Perry and Chilton, McGraw -Hill, NY, 1973
2. "Thermal Analyis of Lithium-Ion Batteries," Y. Chen and J. Evans, J. Electrochem. Soc., Vol. 143, No. 9, 1996
3. DuPont Fluoropolymer Resin Technical Bulletin, 1997
4. Mine Safety Appliances Data
5. "Temperature Rise in a Battery Module with Constant Heat Generation," J. Newman and W. Tiedemann, J. Electrochem. Soc., Vol. 142, No. 4, 1995

Thermophysical Properties of Electrode Stack

- **The Stack Consists of ~140 Pairs of Positive and Negative Electrodes and Is Modeled As a Single Mass**
- **The High Thermal Conductivity, Metallic Current Collectors Are All Oriented in the Same Plane**
- **This Plane of Orientation Is Accounted for by Modeling the Stack With Orthotropic Properties**
- **Thermal Conductivity Has Different Values in the Directions Normal and Parallel to the Electrodes**
  - **The Stack Is Separated Into 3 Major Components:**
    - **Current Collectors -- Aluminum(+) and Copper (–)**
    - **Active Materials -- Positive and Negative (with Electrolyte)**
    - **Separator (with Electrolyte)**

Orthotropic Resistances to Heat Flow



Orthotropic Properties

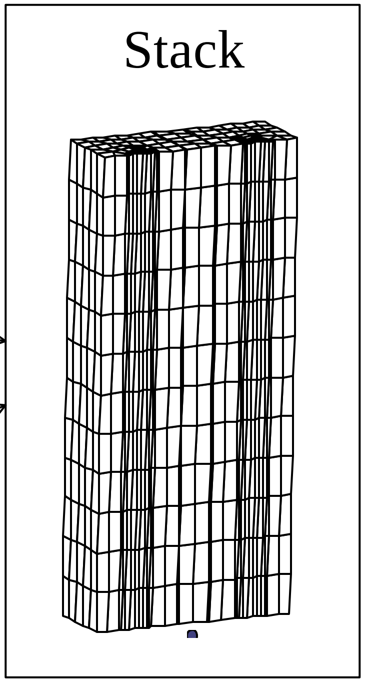
- **Composite Thermal Conductivity Calculations**
  - **Normal Direction -- Fourier's Law of Conduction Through a Layered Wall**
  - **Parallel Direction -- Parallel Resistances**

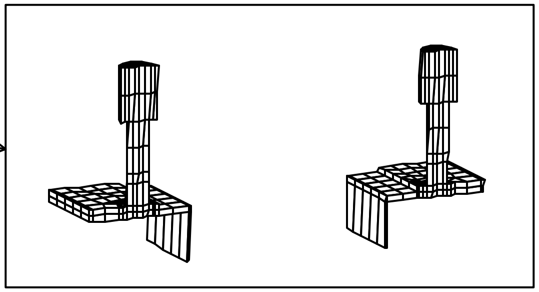
	Lumped parameter model (cal/s-cm-°C)	Orthotropic model (cal/s-cm-°C)
normal to plate surface	0.00425	0.00348
parallel to plate surface		0.0752

- ***k* = 18% Lower in Normal Direction**
- ***k* = 1770% Higher in Parallel Direction**

Heat Generation Rate

- **Heat Generation Consists of Three Major Components:**
  - **Entropic Contribution Within the Stack by Electrochemical Reactions,**
  - **Ohmic Contribution Due to Resistance to Current Flow Within the Stack, and**
  - **Ohmic Contribution Due to Resistance to Current Flow Through the Metallic Busbar Components and Welded Joints.**





Heat Generation Calculations

- **Rate Equation for Total Heat Generation**

$$Q_T = q_T t = -0.239 \cdot I \cdot t\,[(E° - E_L) - T(dE°/dT)_p]$$

- **Open Circuit Voltage, E°, Determined As a Function of DOD by Testing Sony 17670 Cells**

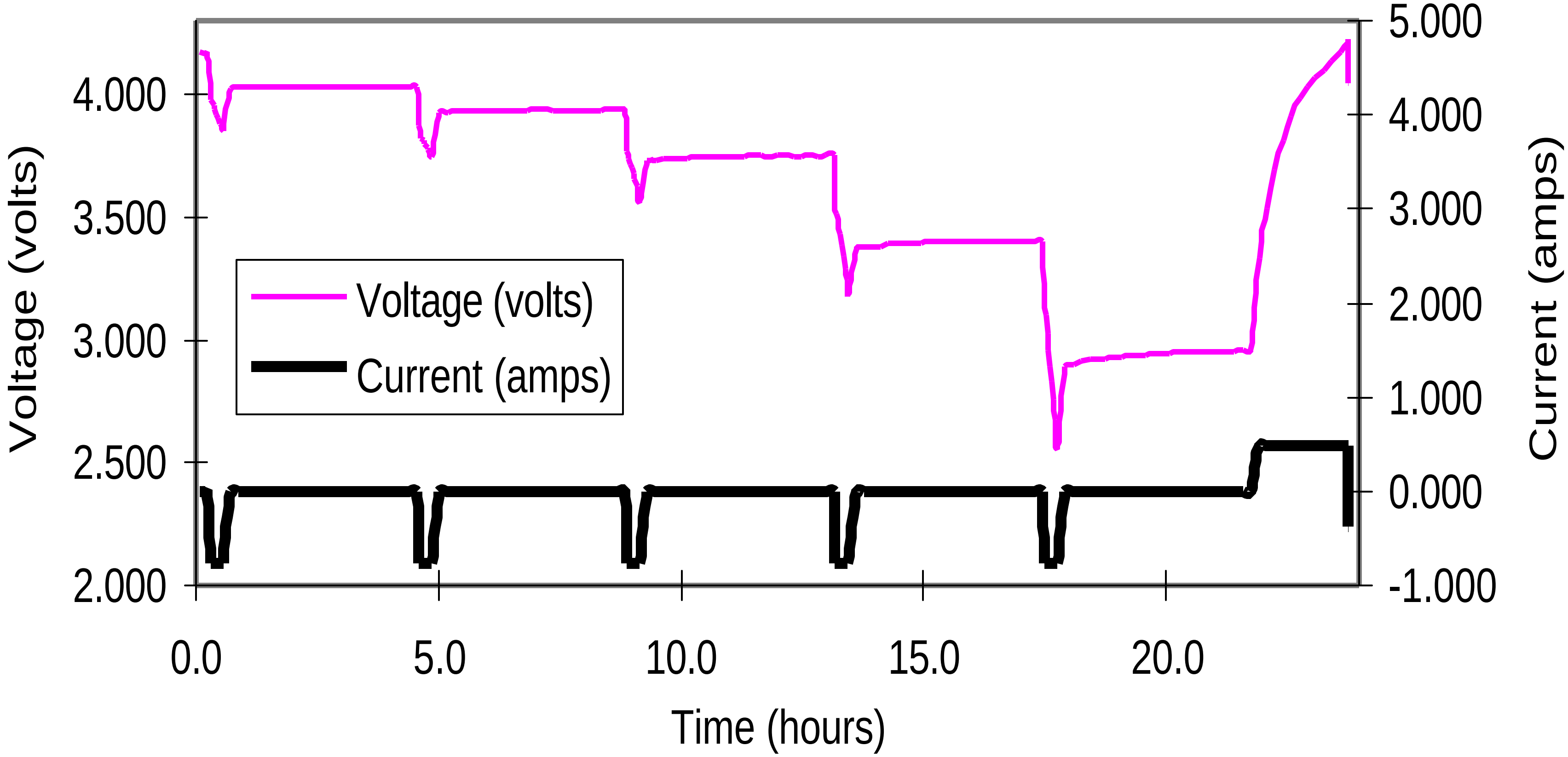
- **Load Voltage, E_L, Projected From Pouch Cell Performance Data for Beginning, Middle, and End of Life Conditions**

- **$(dE°/dT)_p = -4.14 \times 10^{-4}$ V/°K From Published Literature***

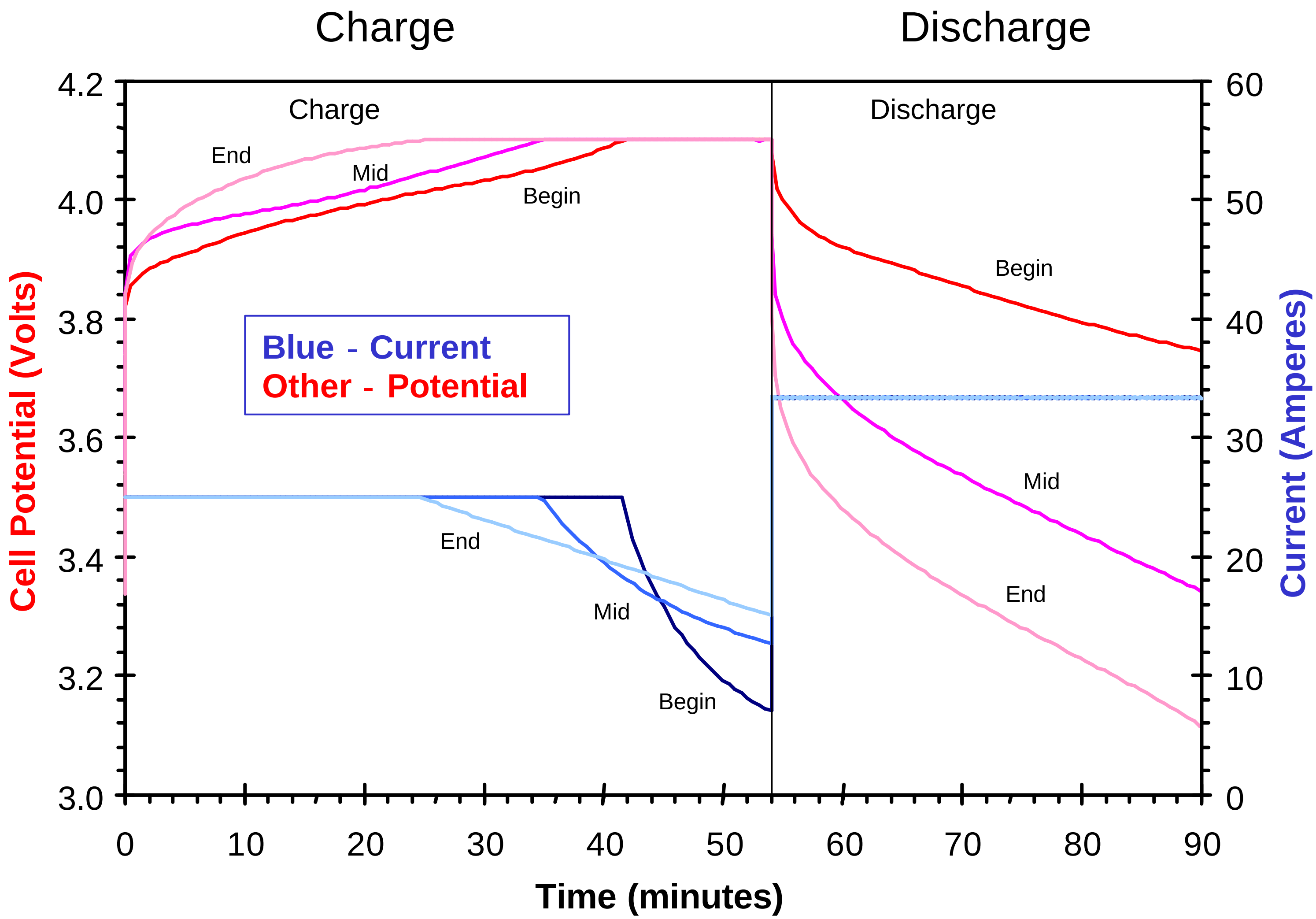
** Y. Saito, K. Takano, K. Kanari, and T. Masuda, in Proceedings of International Workshop on Advanced Batteries (Lithium Batteries), AIST. MITI Osaka, (1995).*

OCV vs. State of Discharge

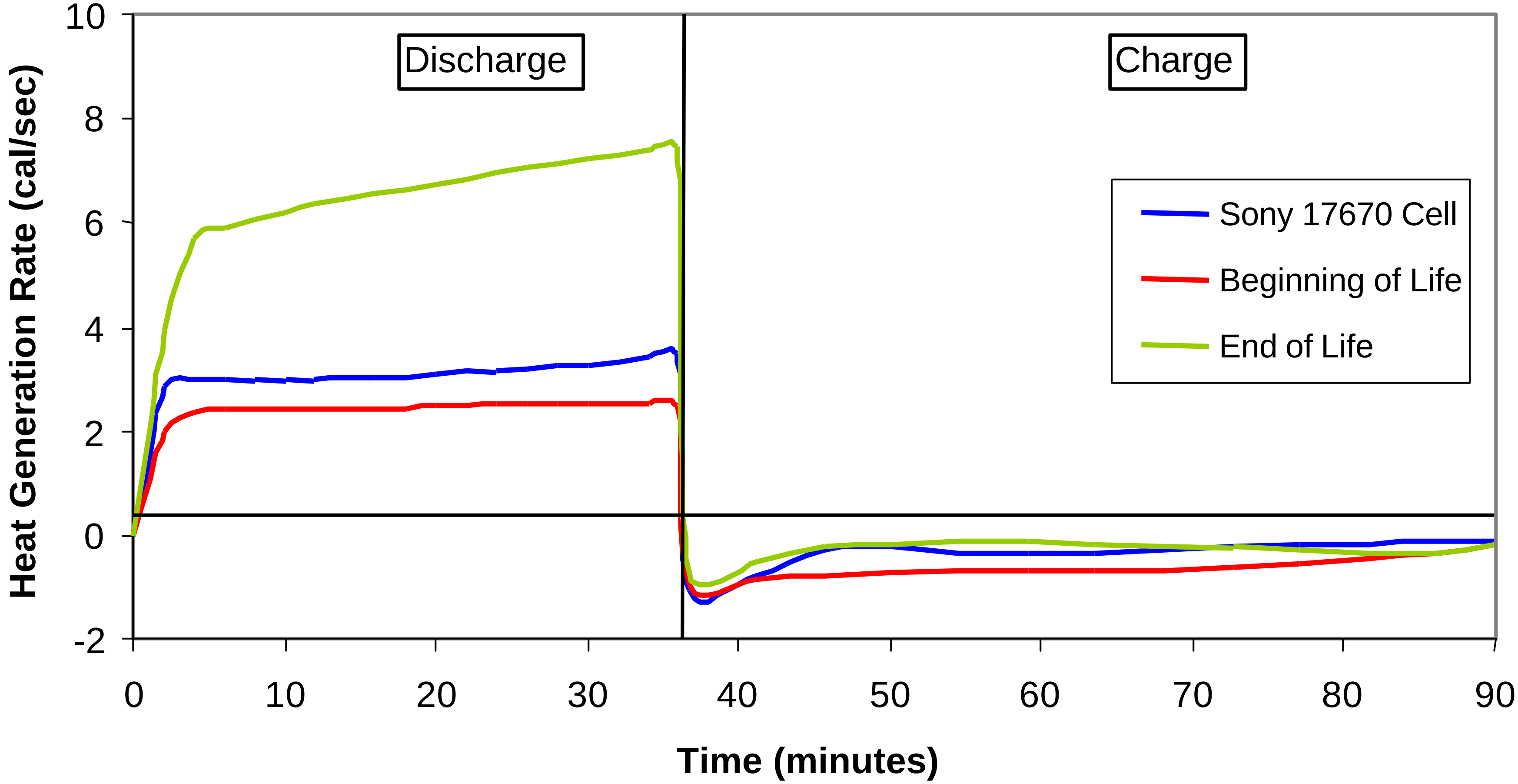
Sony 17670 Cells: Successive 18 Minute Discharges @ C/1.5 Rate (20% DOD) With 4 Hours Rest in Between



Projected Voltage Profiles (Beginning, Middle, and End of Life Conditions)

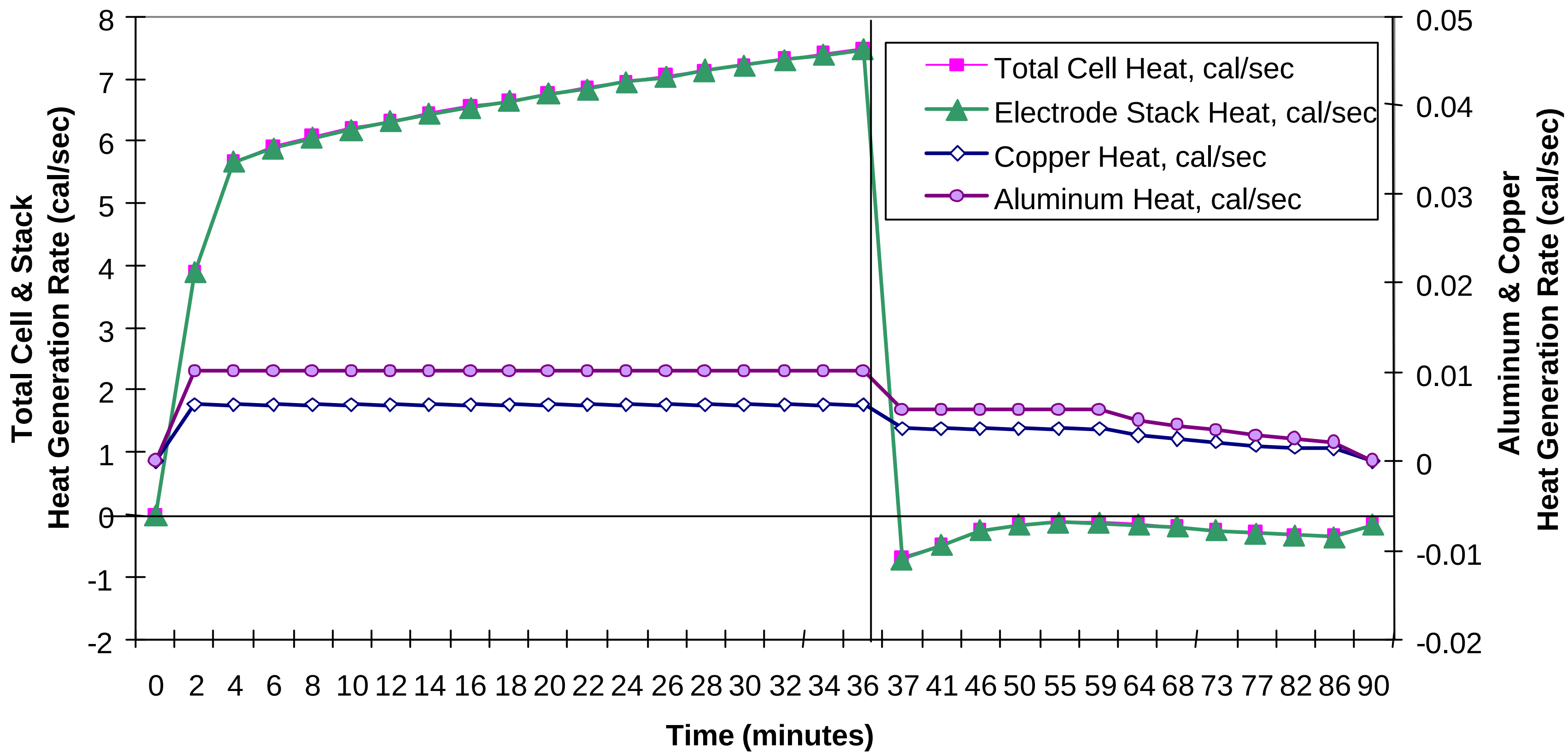


Total Heat Generation Rates



HEAT EVOLVED — Positive HEAT ABSORBED — Negative

Ohmic And Entropic Contributions



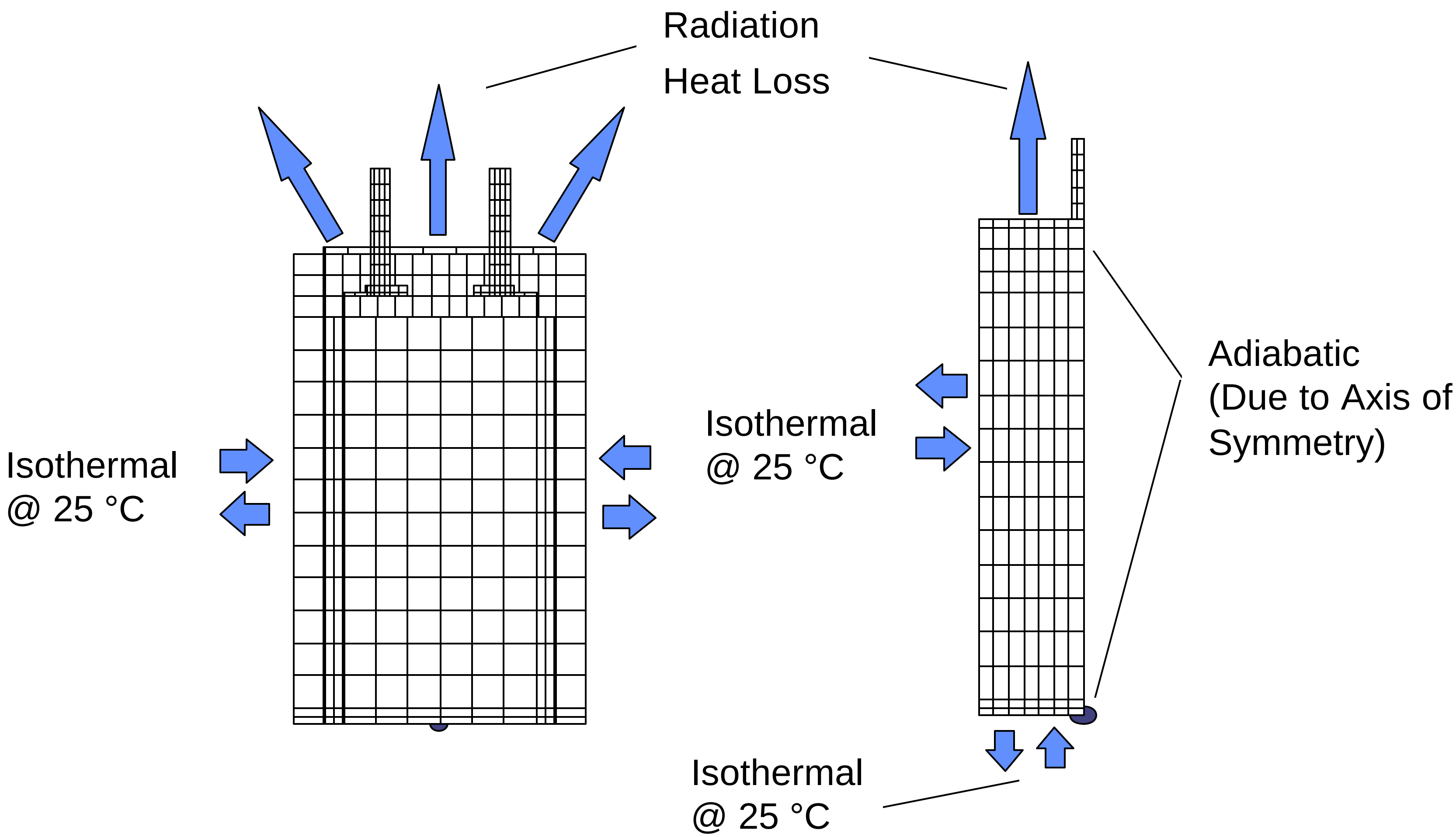
Model Input Conditions

- **Heat Generation in Tabs, Combs, Pads, and Posts**

	Discharge	Charge
Total Heat, kcal	-6.735	0.942
Copper Busbar, kcal	-0.015	-0.014
Aluminum Busbar, kcal	-0.024	-0.023

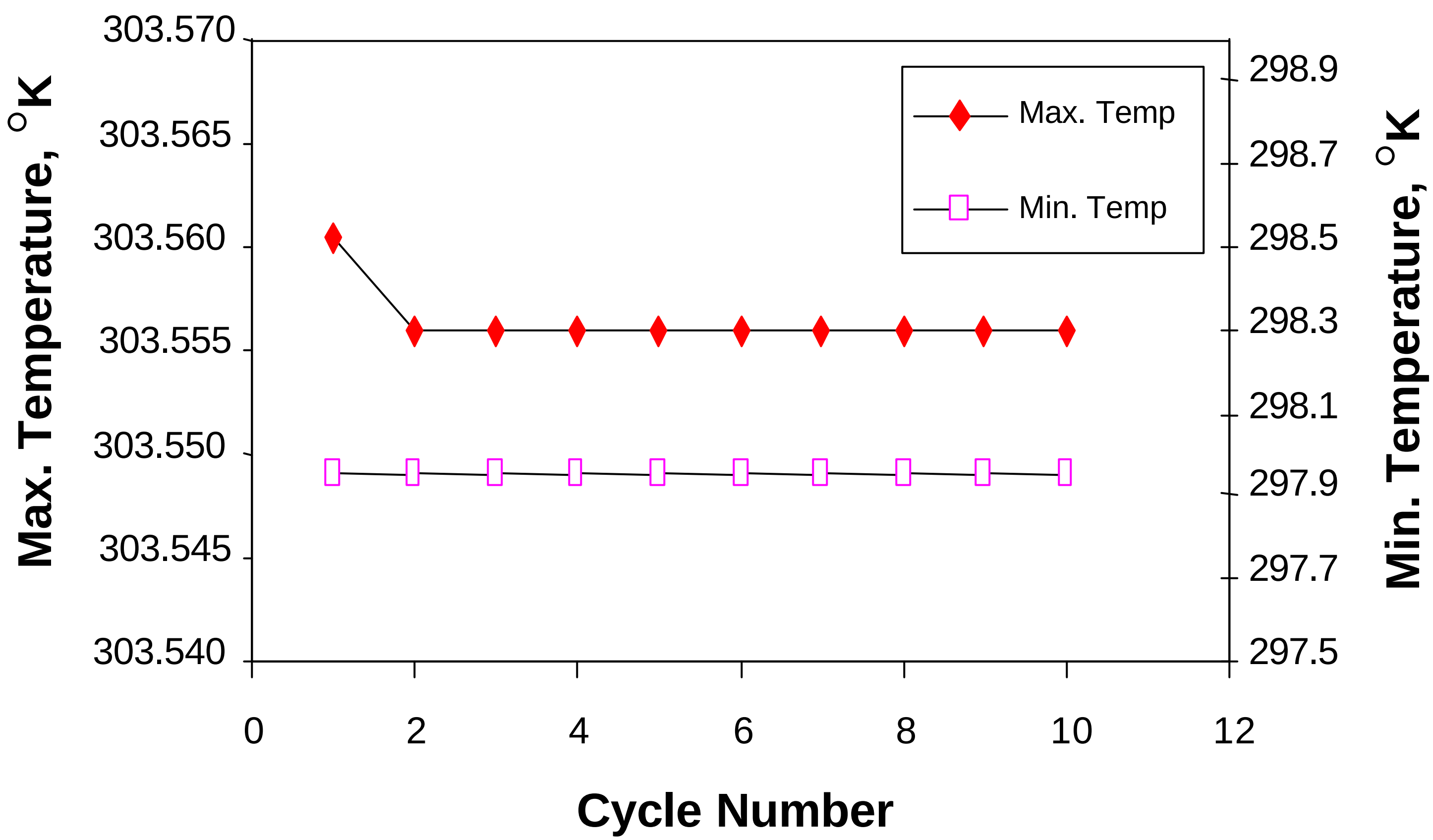
- **Driving Force: Time-Dependent Heat Generation Rate Input for the Electrode Stack and the Top Metallic Busbar Connections.**
- **Other Input Conditions:**
  - **Zero Contact Resistance Between All Components**
  - **Multiple, Consecutive Duty Cycles With No Rest in Between**

Boundary Conditions



INITIAL CONDITIONS: ALL NODES @ 298 °K

End of Discharge Temperatures



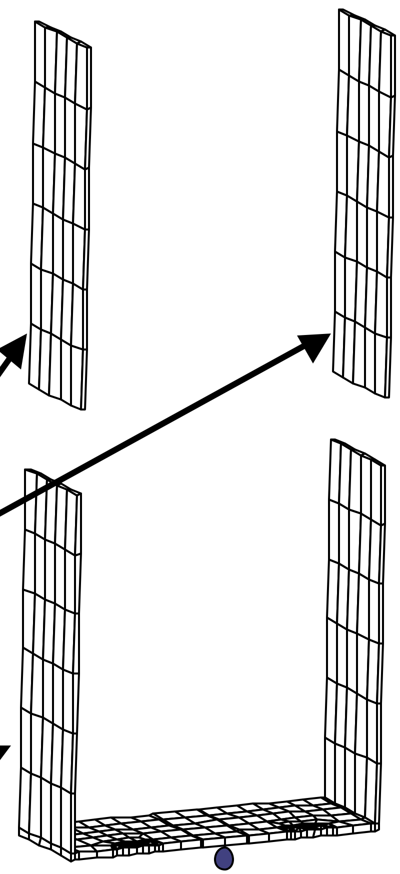
General Results

- **Maximum Temperature Rise of ~6°C, Depending on Particular Conditions of a Run**
- **Significant Parameters**
  - **Rise in Cell Impedance Due to Cycling**
  - **Hardware Material: 316L SS vs. Aluminum**
  - **Boundary Condition at the Ends of Terminal Posts**
  - **Location of Tabs / Connection of Terminals to Stack**
- **Less Significant Parameters**
  - **Electrolyte Level**
  - **Headspace Gas**

Electrolyte Level Variations

- ❖ **Electrode Stack Always Fully Saturated**
- ❖ **Side Gaps in Cell**
  - **Fully Filled With Electrolyte, or**
  - **Half Filled With Electrolyte**
    - **Other Half With Nothing or Helium**

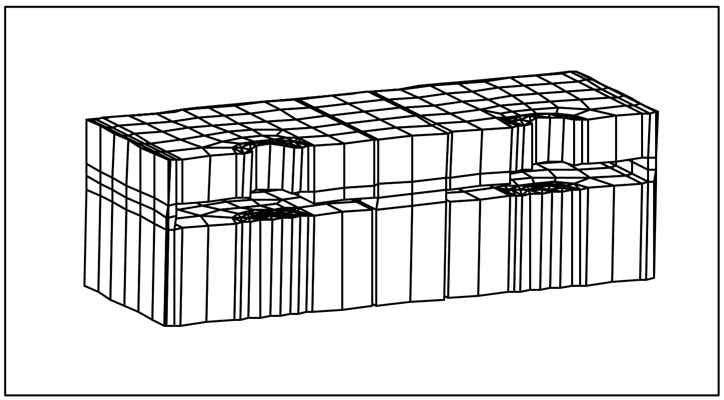
Top gap: 100% Saturation = Liquid Electrolyte
50% Saturation = Nothing or Helium Gas



Bottom Gap: Free Liquid Electrolyte

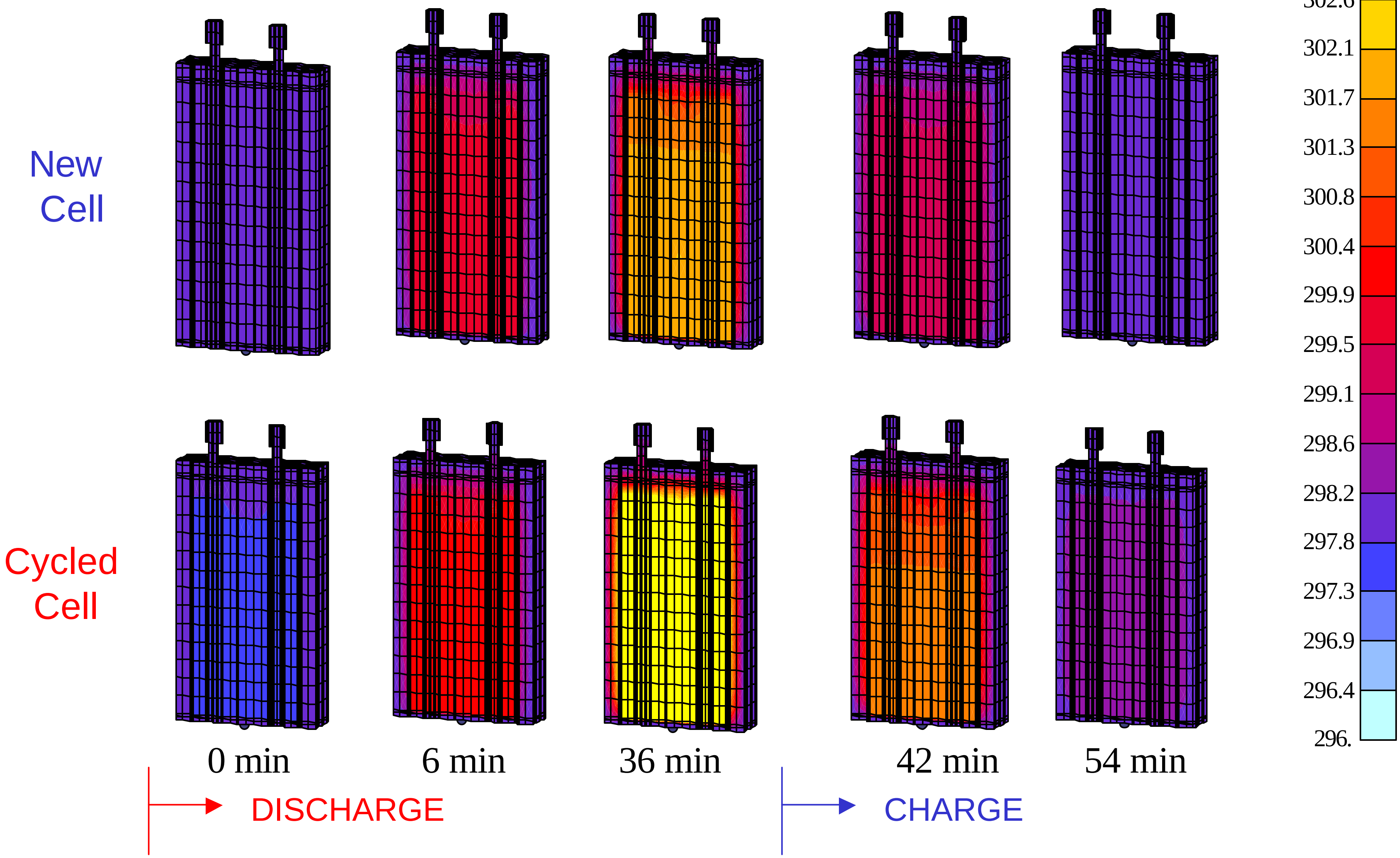
Boundary Conditions -- Headspace

- **Empty Space**
  - **Adiabatic -- No Heat Transfer From All Surfaces in Contact With the Headspace**
- **Helium Gas**
  - **Conductive Heat Transfer Through Gas Medium**



Headspace Isolated View

Thermal Profile Comparisons -- ‘New’ vs. ‘Cycled’ Cell



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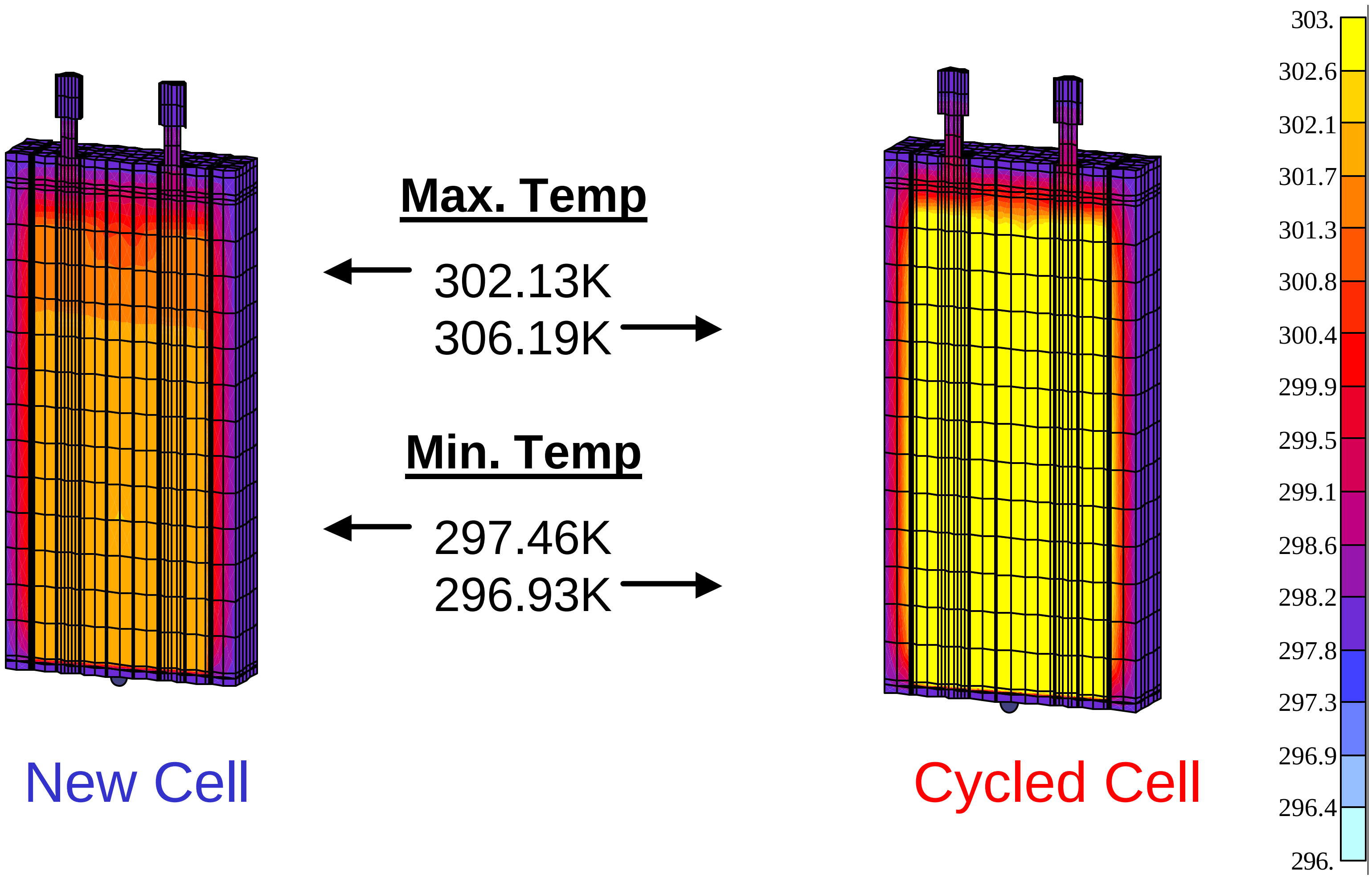
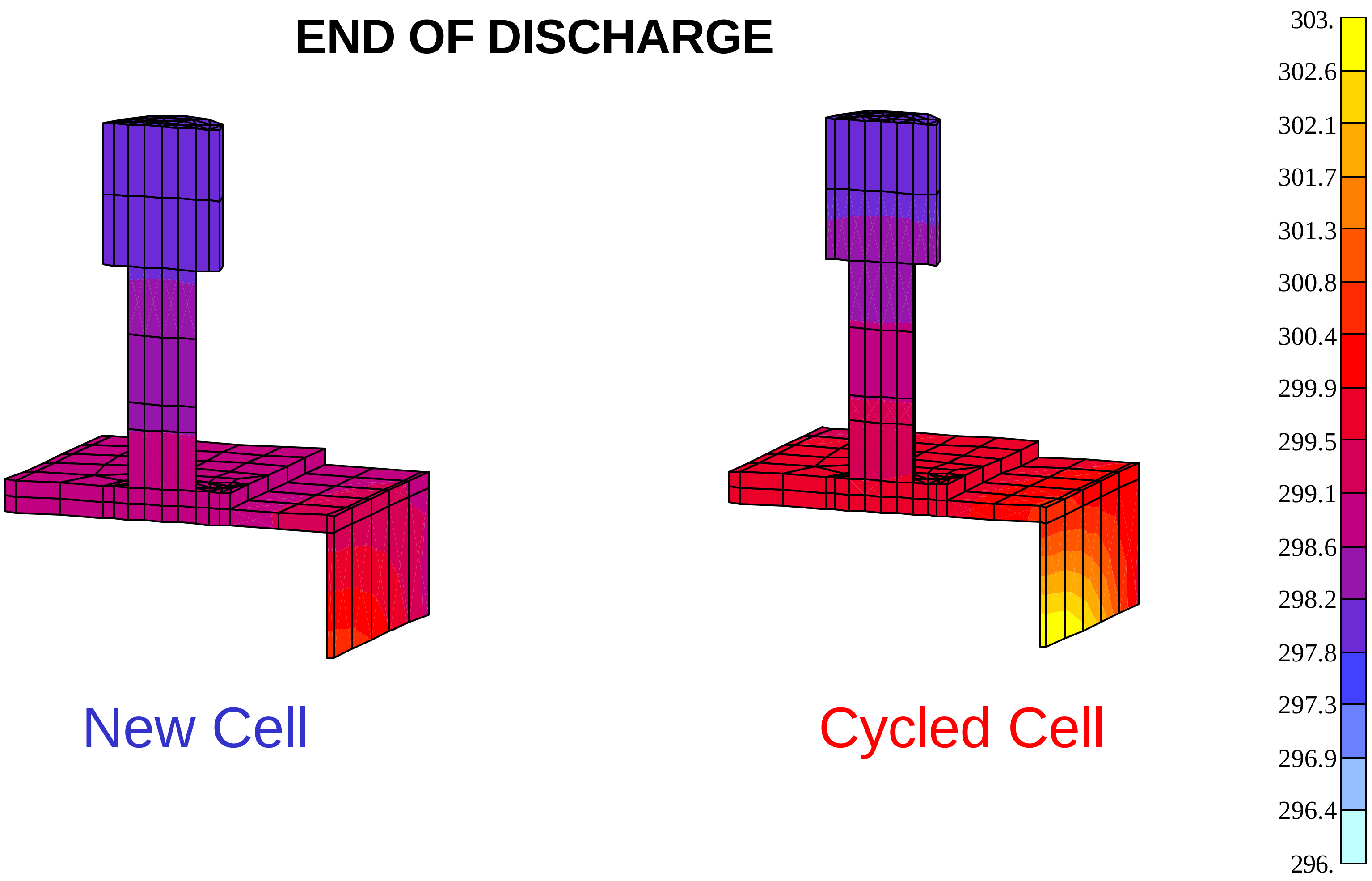
End of Discharge Results



Temperature Profile Comparisons in Busbars



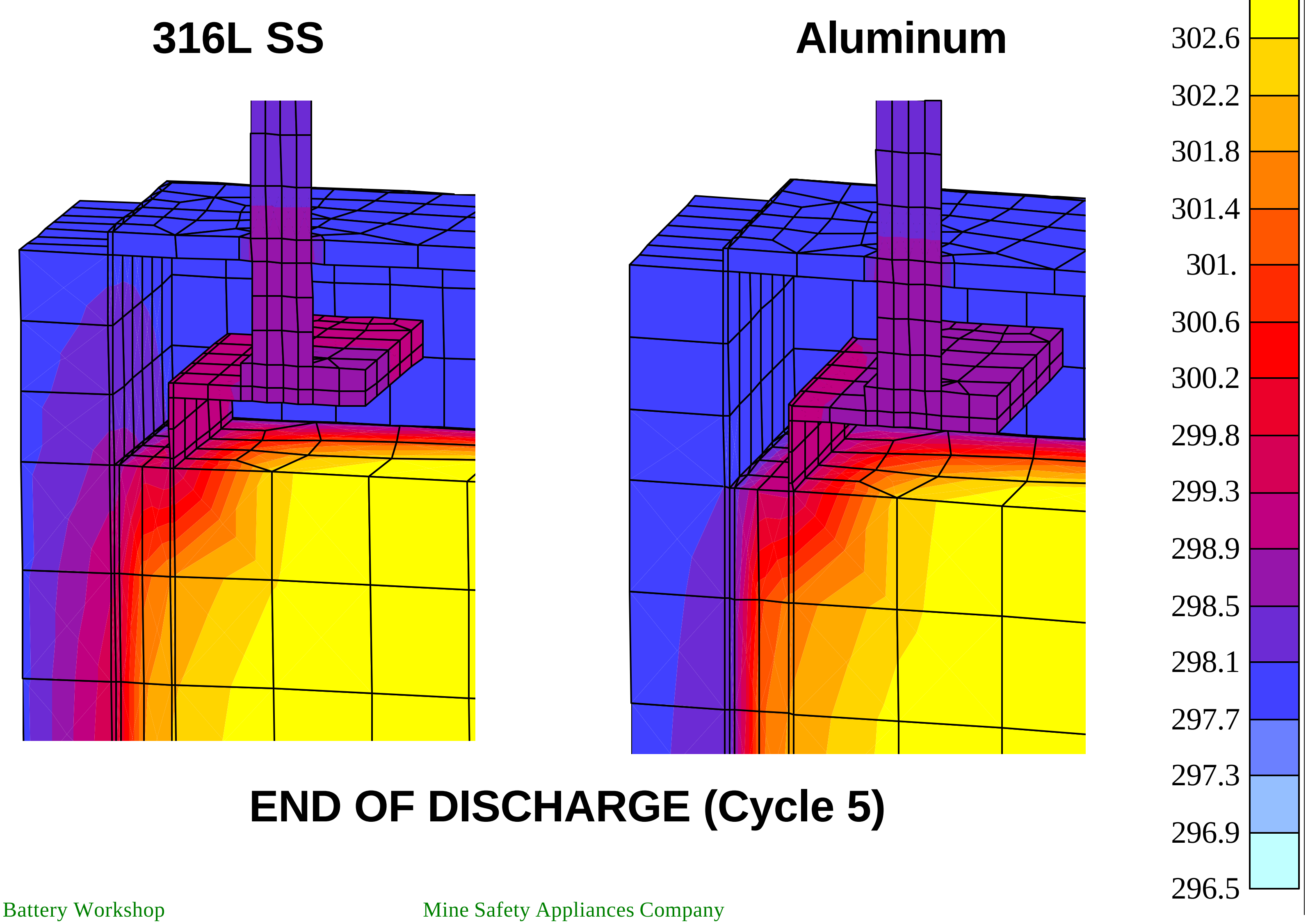
Stainless Steel Versus Aluminum Hardware

- **Material for Case and Cover Changed From 316L SS to Al**

	Stainless Steel	**Aluminum**
Density, g/mL :	**8.03**	**2.70**
C_p, cal/g-°K :	**0.12**	**0.215**
***k*, W/m-°K:**	**16.2**	**236.8**
***Emmisivity* :**	**0.54***	**0.05***

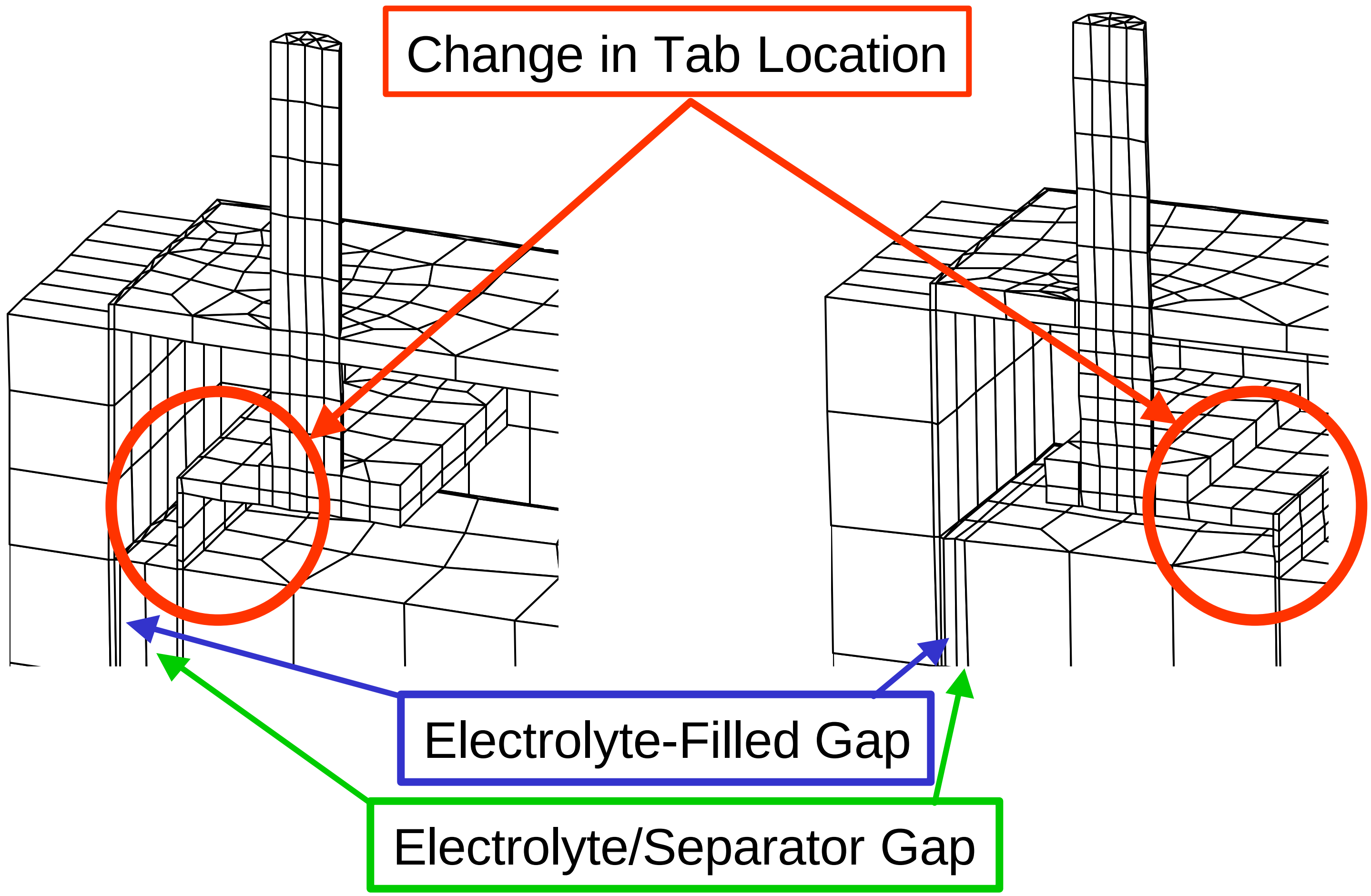
*** *Chemical Engineers' Handbook*, Perry & Chilton, Fifth Edition, 1973.**

Effects of Hardware Material Change



END OF DISCHARGE (Cycle 5)

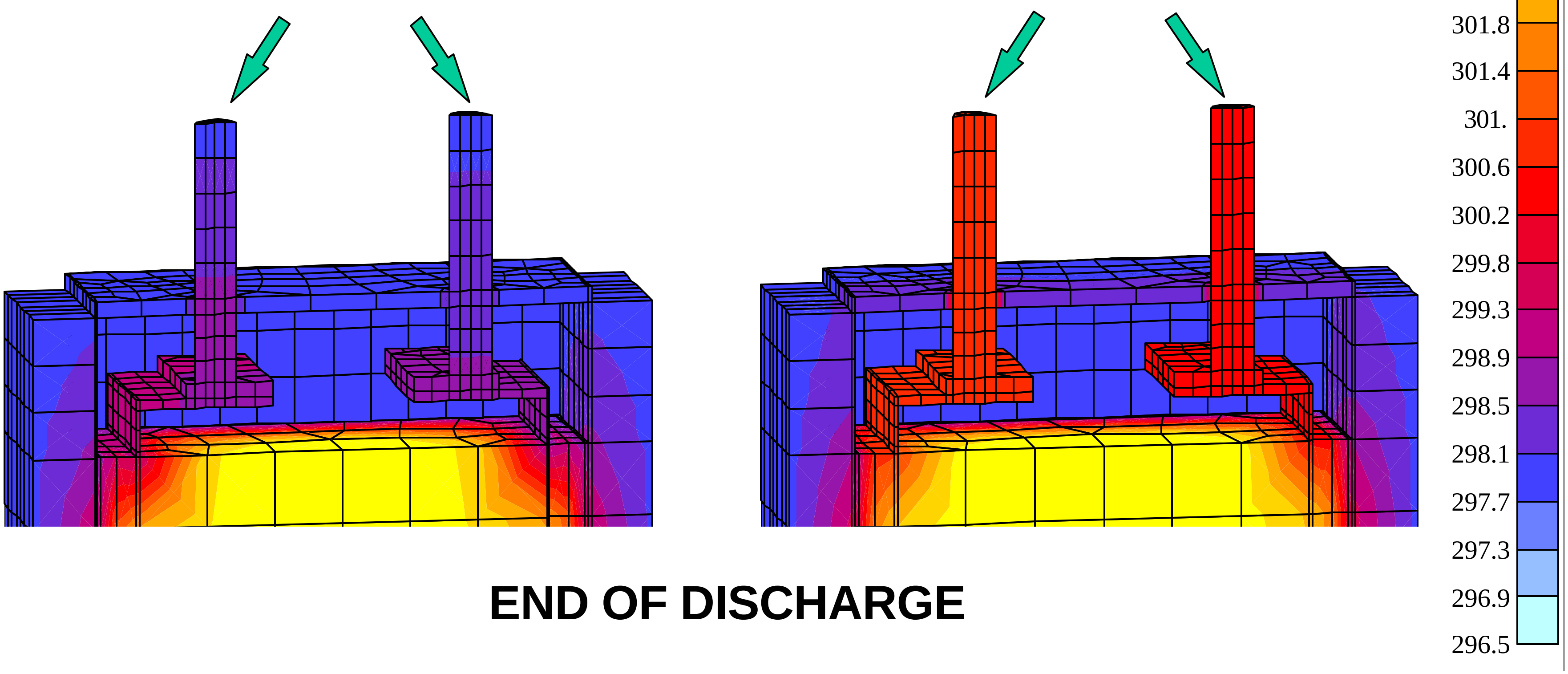
Modification of Current Collector Tab Location



Terminal Post Boundary Condition -- Adiabatic vs. Isothermal

ISOTHERMAL at 25°C - This Condition Simulates a High Rate of Heat Loss Through the Attached Cable

ADIABATIC - This Simulates a Condition of No Heat Transfer Through the Cable Because of the Adjacent Cells



END OF DISCHARGE

Thermal Modeling of Prismatic Lithium-Ion Cells

CONCLUSIONS:

- This Study Has Been Successful in Providing a Time and Cost Effective Tool for Estimating Thermal Profile of a Lithium-Ion Cell.
- A Number of Parametric Studies Are Possible to Optimize Component Designs and to Determine the Effects of Material Properties, Cell Aging, and Boundary Conditions on the Thermal Performance of a Cell.
- FEM Analyses Can Enhance Safety Studies by Projecting Operating Limitations Without Costly Experimentation.

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SAFT

SAFT Li-Ion Cells GEO and LEO Life Test Up-Date

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*** Advanced Battery System Division**

Cockeysville, MD

**** Specialty Battery Group**

Defense and Space Division

Poitiers, France

AGENDA

- Cell Designs and Qualification Status
- Life Test and Calendar Results
- Conclusions

Cell electrochemistry

- Positive : Metallic oxide containing Lithium ions
  Ni based mixed oxide (cost and performance versus Cobalt oxide

- Negative : Mix of Graphite.
  (Flat curve, no metallic lithium, no dendrite formation)

- Electrolyte : LiPF6 salt + organic solvent mixture
  (alkyl carbonates: PC, EC, DMC) + proprietary additive: VC

- Separator : PP/PE/PP

VES 140 and HE44 Cell

VES 140

HE44

VES 140 and HE44 Cell

	VES140	HE44
Status	Qualified	In test
Production Method	Industrial Line	Automated Line
Number of cells manufactured	800	100
Electrochemistry	Generation 4	Generation 4
Loading	A	A+ 6% on positive
Porosity	B	B- 5 % on negative
Case Material	Aluminum	Aluminum
Terminals	Same side (axial)	Same side (non axial)
Length (mm)	250	244.3
Diameter (mm)	54	54
Max Weight (g)	1.142	1.132
Capacity (Ah)	38.6	44
Energy (Wh)	139	154

Test in progress

223 CELLS IN TEST

64 CELLS IN CALENDAR TEST

169 CELLS IN CYCLING TEST

84 CELLS IN LEO TEST

85 CELLS IN GEO TEST

SUMMARY OF LEO LIFE TEST RESULTS

Cell Reference	Cell Version	Test	DOD	Nb Cells Tested	Nb cycle Performed
LEO1	**VES 140 O**	Accelerated	10%	3 Cells	13 100
LEO2	**VES 140 O**	Accelerated	20%	3 Cells	12 270
LEO3	**VES 140 O**	Real Time	30%	6 S Module	6 100
LEO4	**VES 140 O**	Accelerated : Variable DOD	10 to 30 %	3 S Module	20 280
LEO5	**VES 140 O**	Real Time	30%	3 S Module	9 040
LEO6	**VES 140 O**	Real Time	40%	3 S Module	4 500

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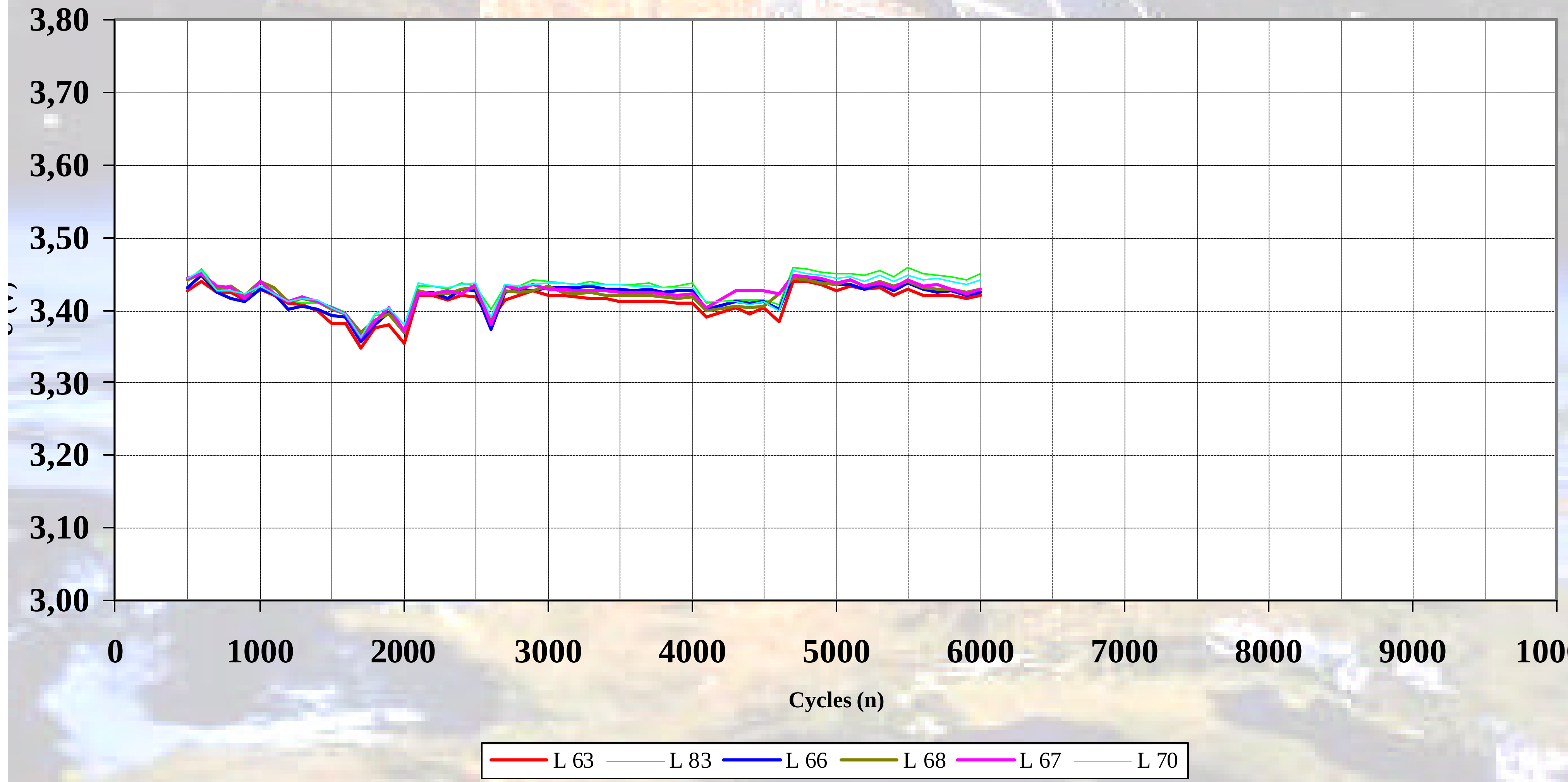
LEO Cycling 30 % (LEO3 test)

- Test on 6 cells Module
- Real time LEO cycling 30% DOD : 3.80V
- Energy checks +Peak Power evaluation : every 100 cycles
- Test started in August 1999
- Temperature 20 °C
- 7.000 cycles performed

LEO Cycling 30 % DOD (LEO3 test)



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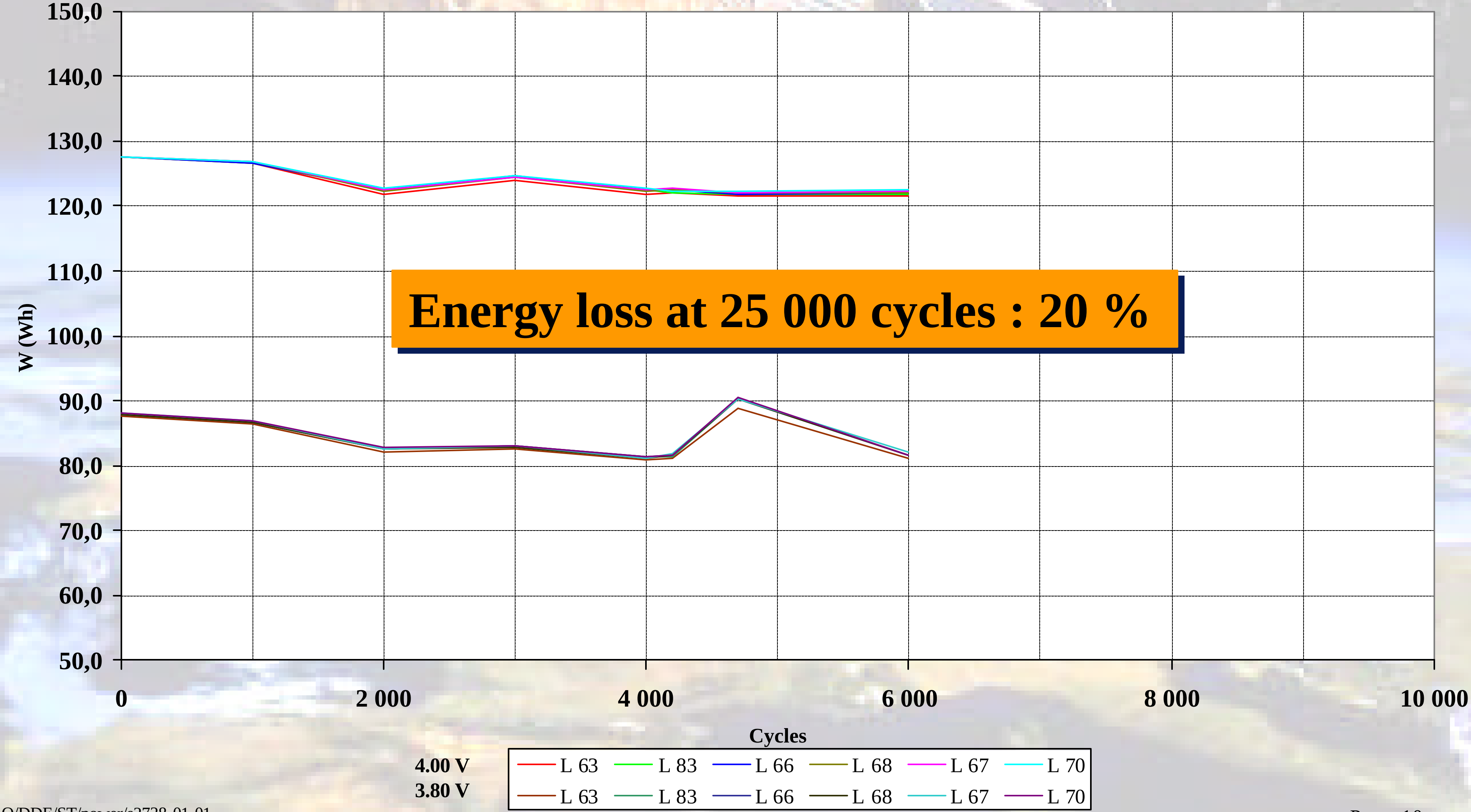
LEO Cycling 30 % DOD (LEO3 test)



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SUMMARY OF GEO LIFE TEST RESULTS

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Comparison Accelerated/Real Time

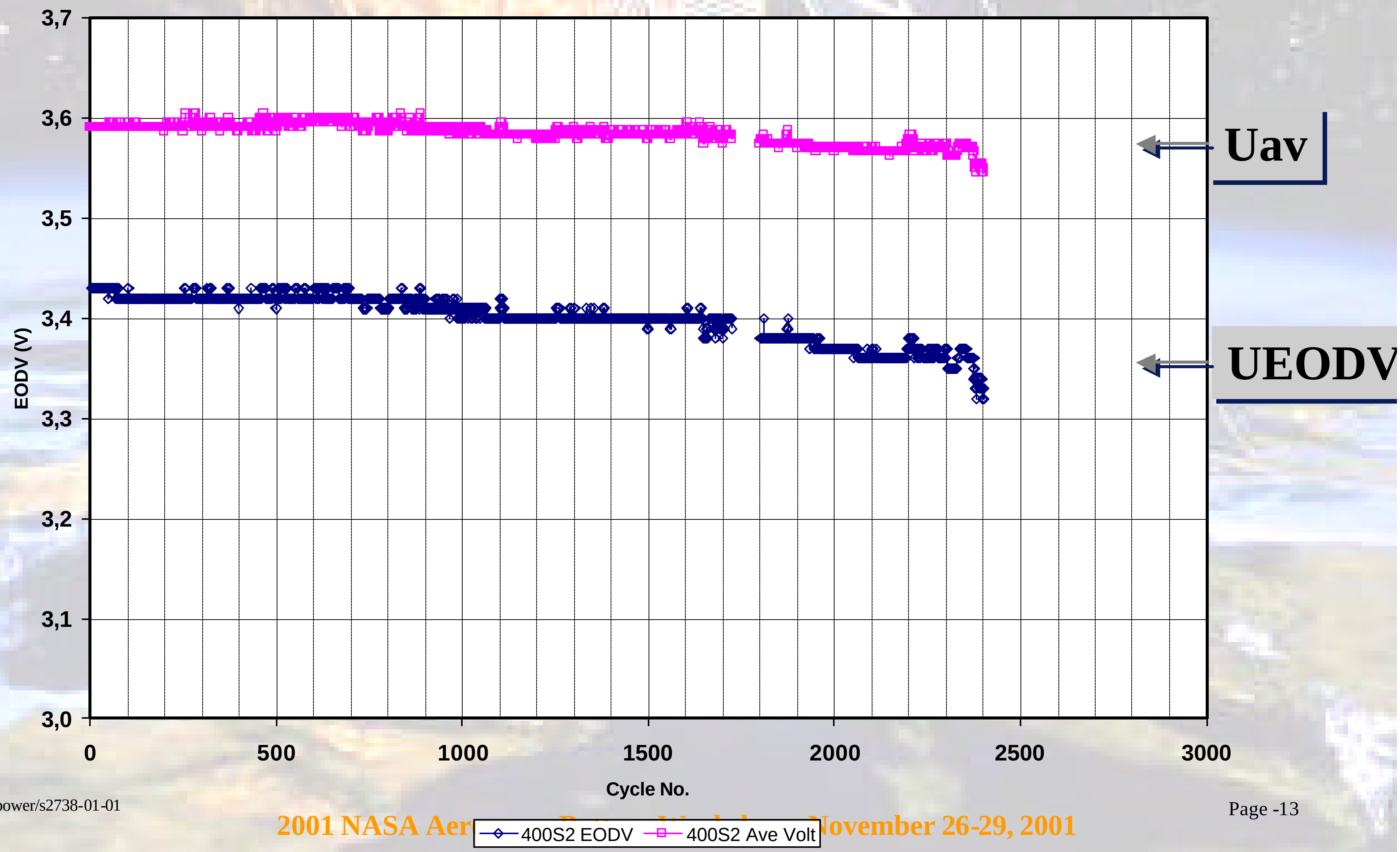
Test Reference	Cell Version	Test	DOD	Nb Cells Tested	Nb Seasons Performed	Fading	
						Measured	@15 years
GEO1	**Prototype 2**	Semi accelerated 2c/day +PPS	40%	6 S Module	34	8,0%	**7,1%**
GEO2	**Prototype 2**	Accelerated : Ic=12 amps	80%	2S2P Module	30	10,9%	**10,9%**
GEO3	**Prototype 2**	Semi Accelerated +PPS : Ic = 4 Amps	60%	6 S Module	20	6,1%	**9%**
GEO4	**Prototype 2**	Real Time+PPS : Ic = 4 amps	60%	6 S Module	5	2,0%	**12%**
GEO5	**HE44**	Accelerated : Constant DOD, Ic=15Amps	60%	10 cells	66 (2259 cycl)	14,8%	**3,6%**
GEO6	**VES140 0**	Accelerated : Ic from 12 to 6 amps	80%	3S2P Module	56	4%	**2,1%**
GEO7	**VES140 0**	Semi accelerated : Ic = 6 amps	85%	3S2P Module	30	3,5%	**3,5%**
GEO8	**VES140 0**	Accelerated : Constant DOD, Ic=15Amps	70% 60% 60%	2 cells 2 cells at 4V 2 cells at 3.9 V	62 (2259 cycl) 61 (2206 cycl) 61 (2210 cycl)	16,0% 11,8% 10,0%	**2,9%** **2,0%**
GEO9	**VES140 0**	Semi Accelerated : Ic=4 Amps	90%	3S Module	16	0,8%	**1,5%**
GEO10	**VES140 0**	Real Time + PPS : Ic =4 amps	70%	3S Module	8	0,5%	**1,9%**

Less than 3 % fading for 15 years GEO mission @ 80 % DOD

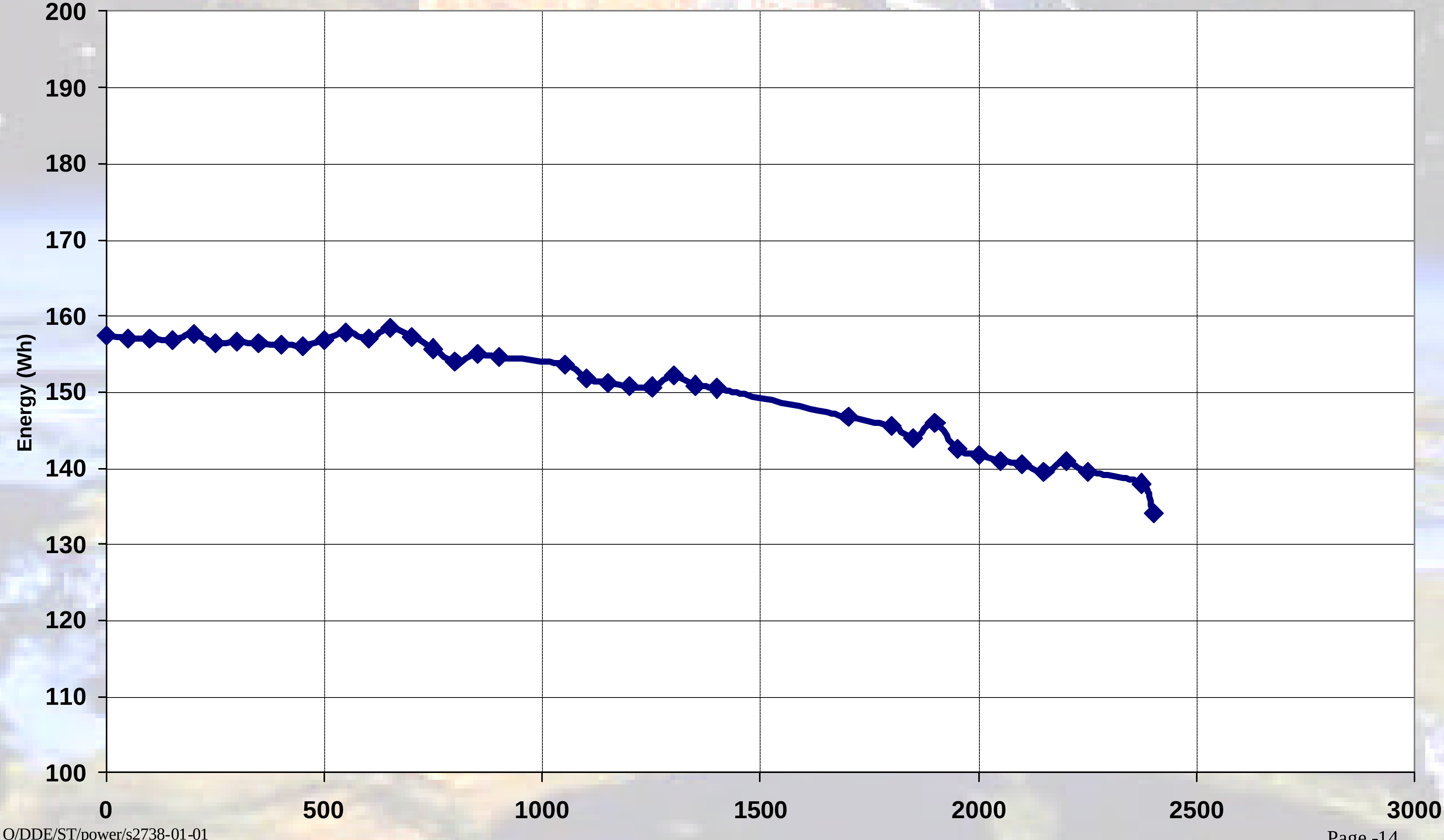
GEO 5 : Life tests performed on HE44 cel

- 10 HE44 :
- 60 %DOD Accelerated GEO cycling : Constant DOD
- Ambiant Temperature
- Charge current : 15 Amps
- 2.400 constant 60 % DOD cycles = (66 seasons)
- Energy variation @15 years : **3.5 %**

GEO 5 : 60 % DOD Life tests on HE44 c



GEO 5 : 60 % DOD Life tests on HE44 cell



GEO 6 : Life tests performed on VES 140 cel achieved 28 years lifetime @ 80% DoD

- 1 battery of 6 cells (3s2p)
- EOCV : 4.05 V during the first 10 seasons, 4.07V during the next twenty then 4.1 V form 31st to 56th
- 80 to 82 % DOD (ratio of Energy @4.1 V) and 20 °C
- Charge current : C/3 during the first 15 seasons, C/4 afterwards from seaso 15 to 40 and C/6 afterwards
- Accelerated conditions : 1 week= 1 season at BOL up to 14 days = 1 seaso
- Electric propulsion cycles neglected
- Cell balancing every six simulated months
- 56 seasons already performed (28 years)
- Capacity check after each season :

2.2 % Energy loss at season 30th (15 years)

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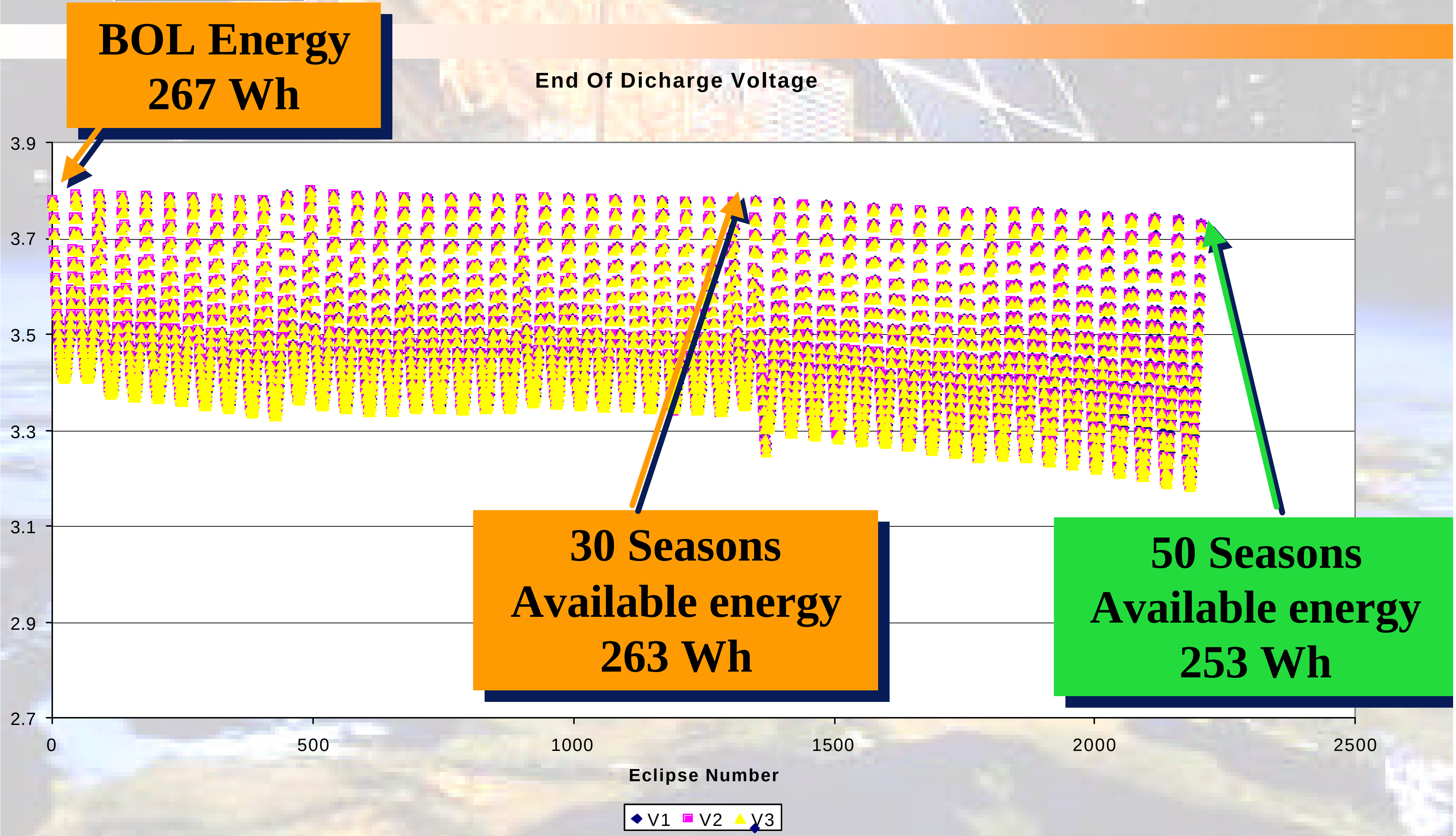
GEO6 : 56 seasons (80% DoD Lifetest)



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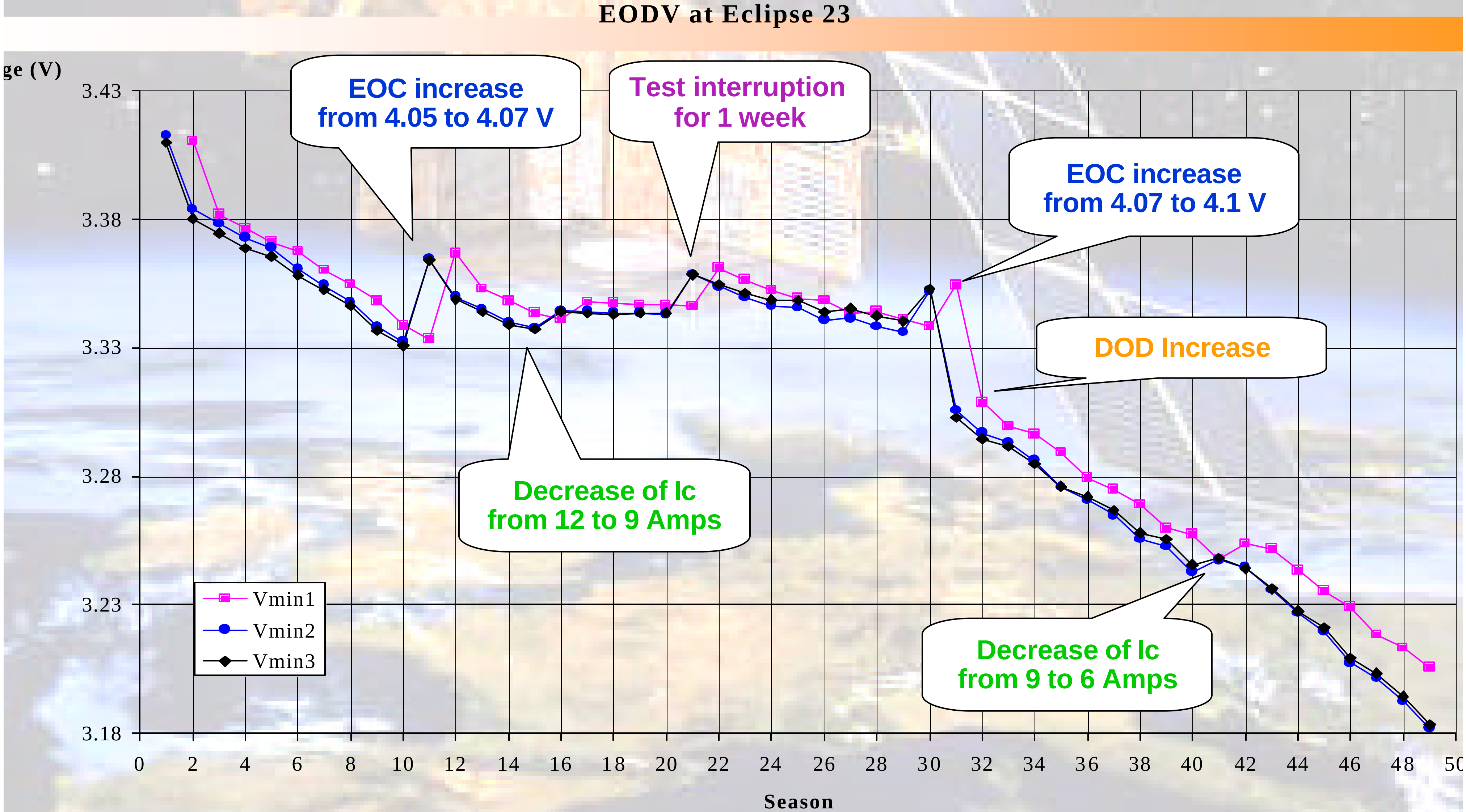
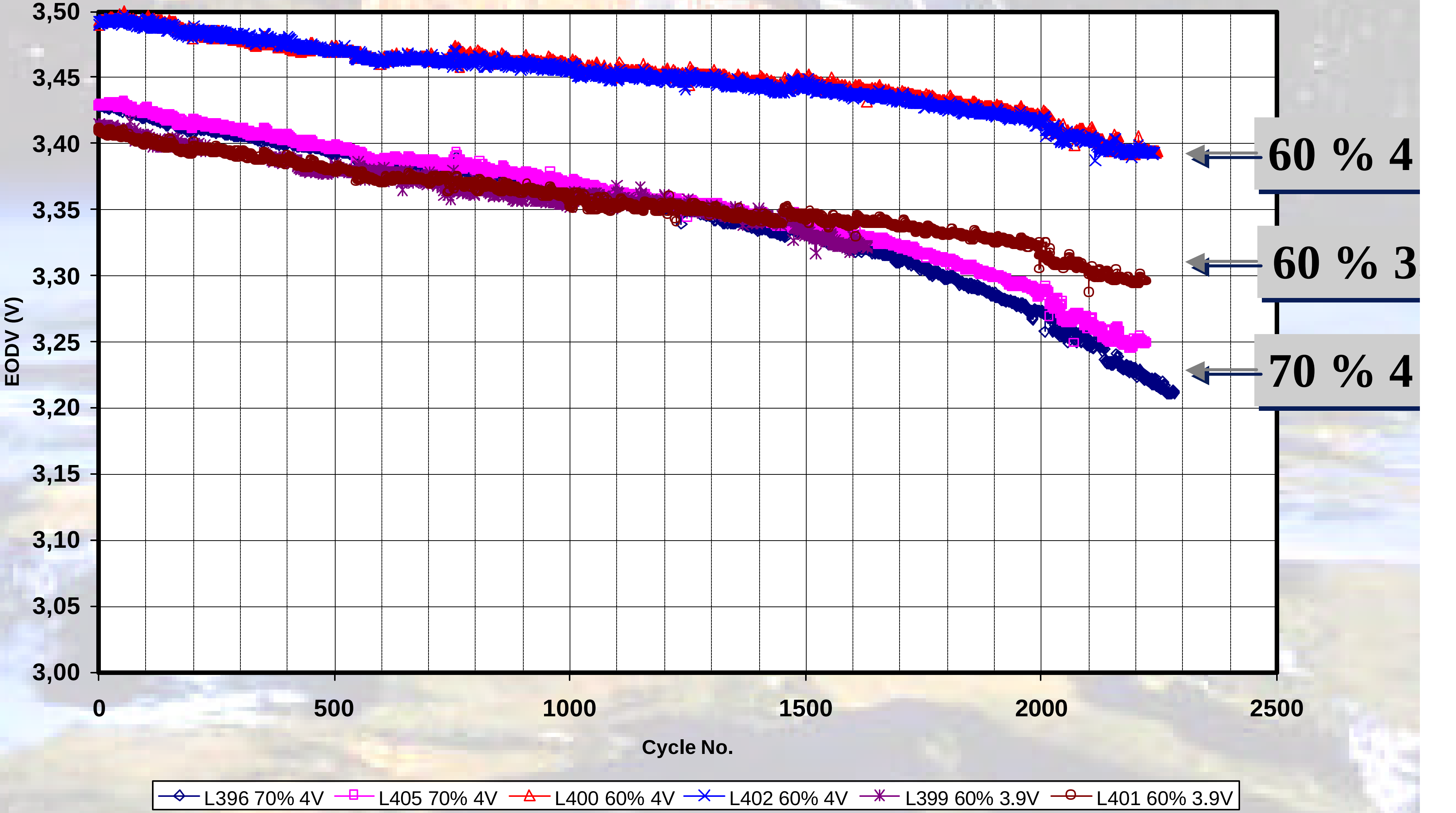
GEO6: EODV (80% DoD Lifetes



GEO8 : 60 and 70% Constant DOD GEO VES 140 Accelerated Cycling

- Test configuration :
  - 2 VES140 @70 % DOD 4 V
  - 2 VES140 @60 % DOD 4 V and 2 VES140 @60 % DOD 3.9 V
- Accelerated GEO cycling : Constant DOD, 20 °C
- Charge current : 15 Amps
- 2200 constant DOD cycles = 60 seasons performed
- Energy variation @15 years :
  - 2.9 % @70 % DOD 4V
  - 2 %   @60 % DOD 4 V
  - 2.3 % @60 % DOD 3.9 V

GEO8 : 60 and 70% Constant DOD GEO VES 140 Accelerated Cycling - EODV



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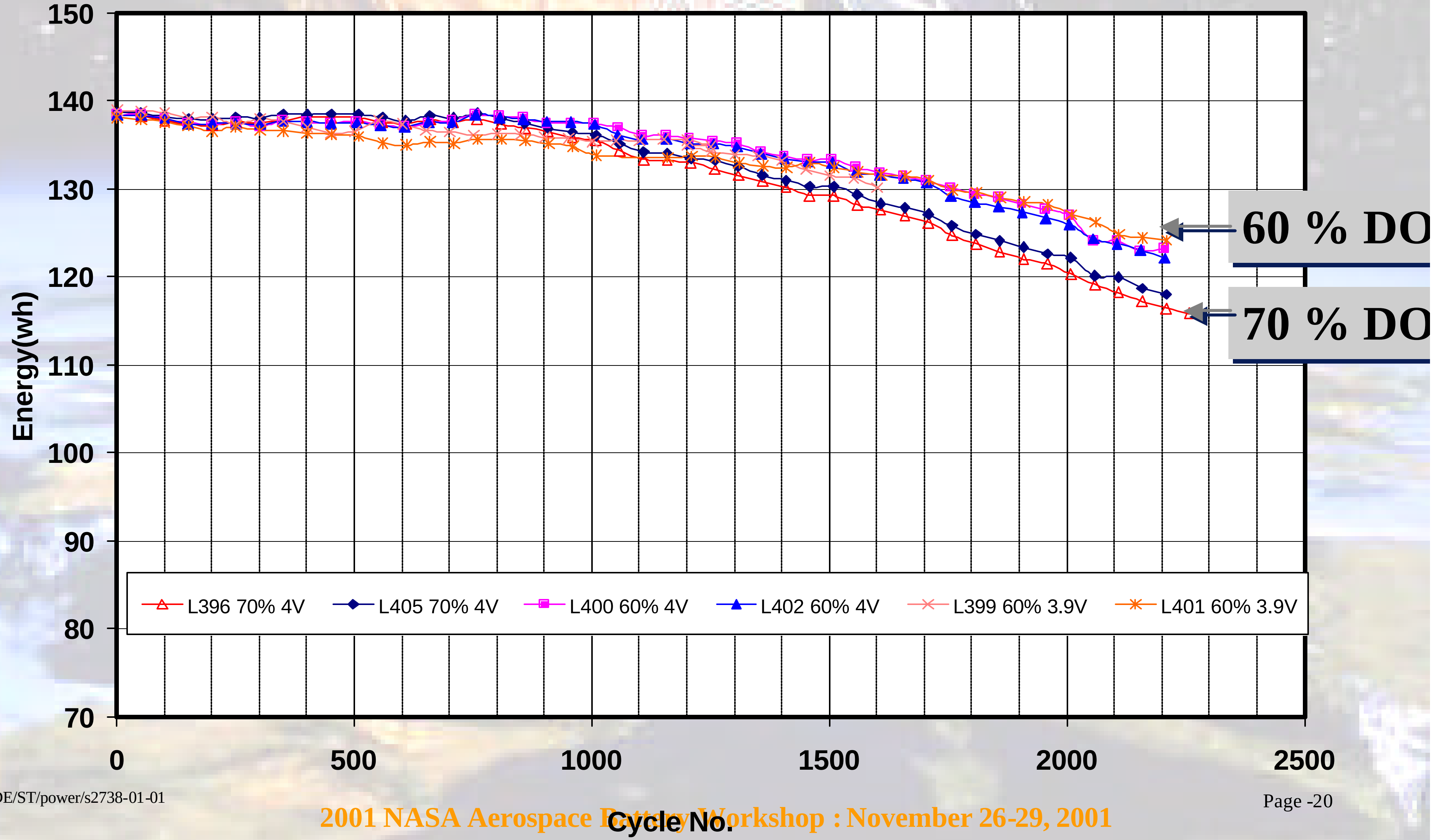
GEO8 : 60 and 70% Constant DOD GEO VES 140 Accelerated Cycling - Energy



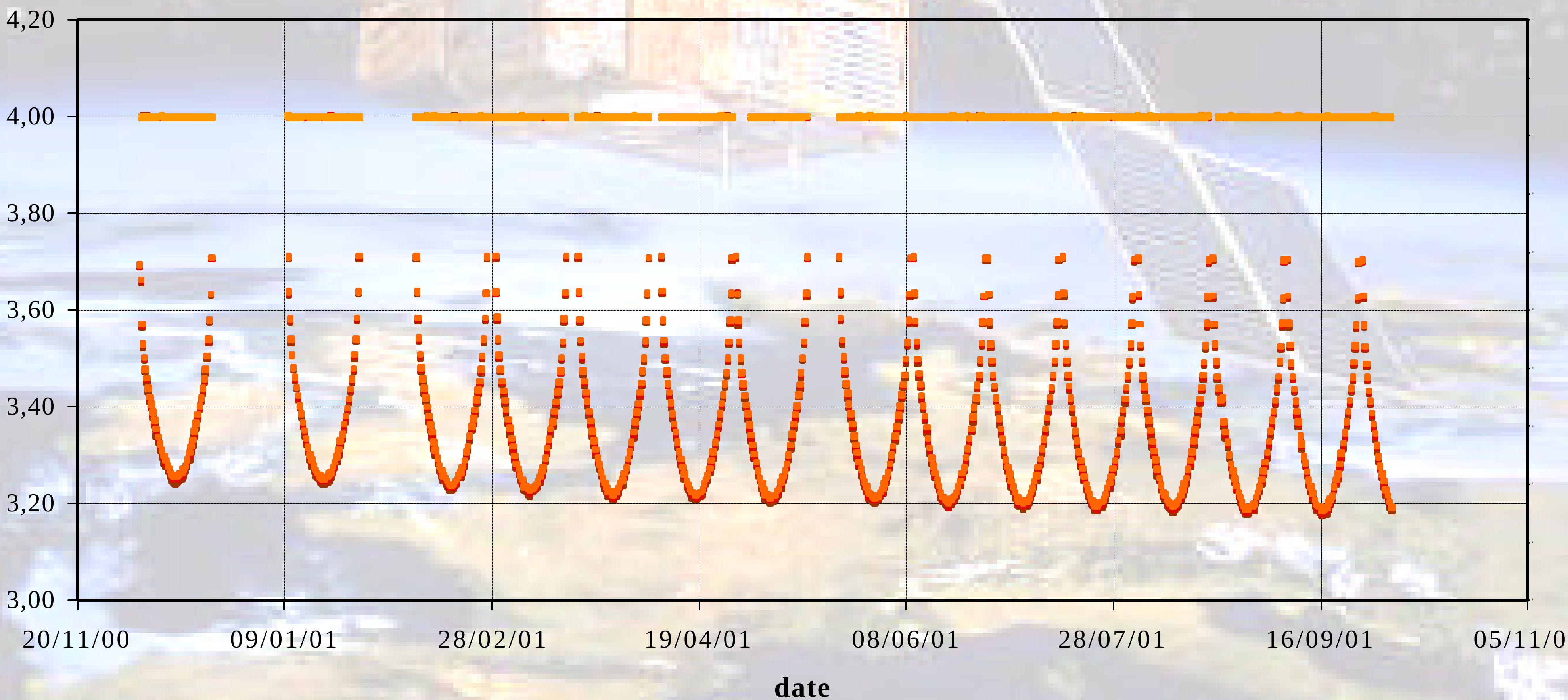
GEO9 : 90% DOD GEO VES 140

- Module configuration (3S VES140)
- Accelerated GEO cycling 90 % DOD, 20 °C
- Charge current : 4 Amps
- EOCV = 4.0 V
- Season profile
- Test started in December 2000
- 15 seasons performed
- Energy variation : 0.8 %

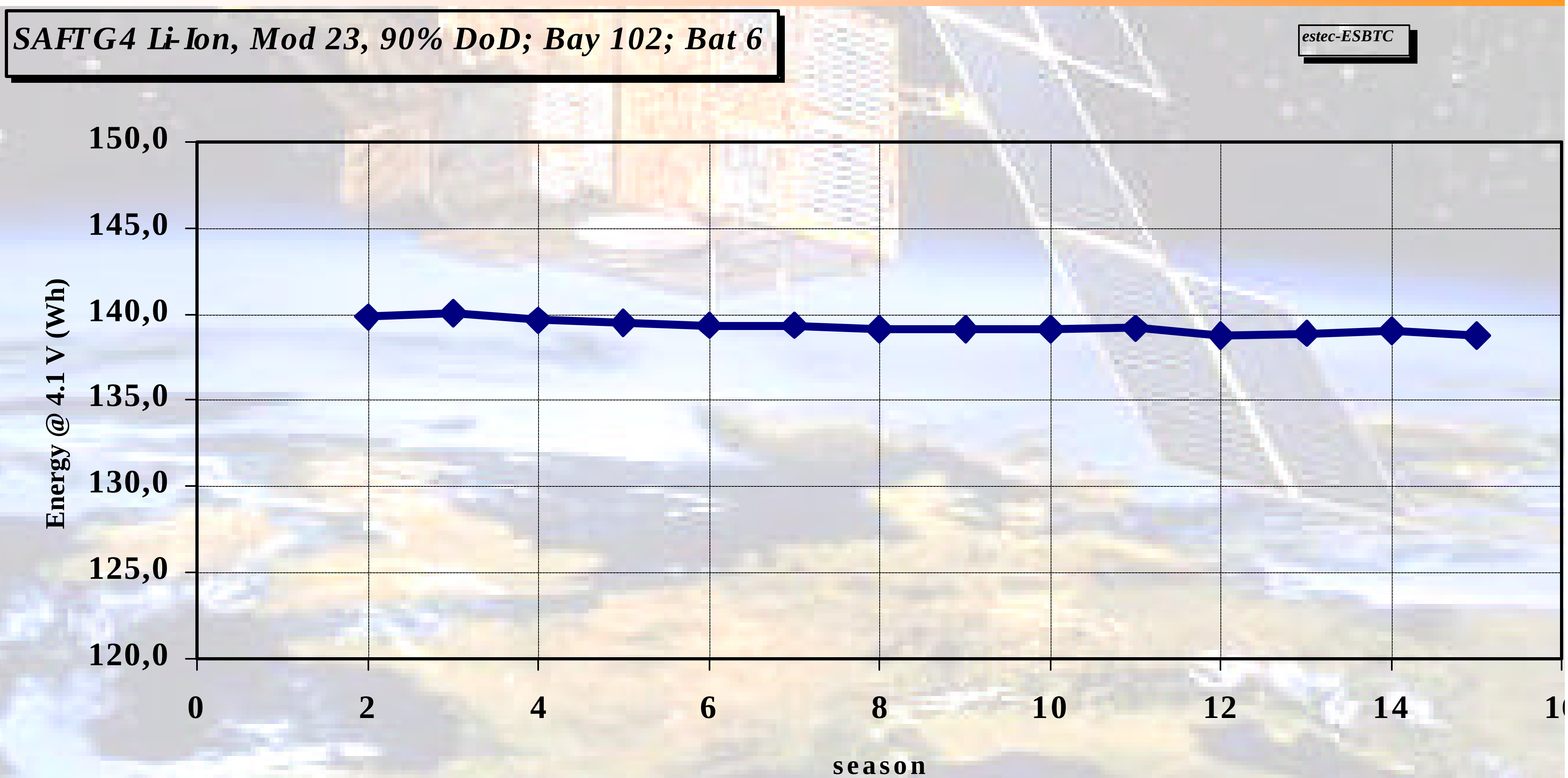
GEO9 : 90% DOD GEO Accelerated Cycling

FT G4 Li-Ion, Mod 23, 90% DoD; Bay 102; Bat 6

estec-ESBTC



GEO9 : 90% DOD GEO Accelerated Cycling



0.8 % Fading after 15 seasons @ 90 % DOD

Cycling laws

- Mathematical law based on experimental values :

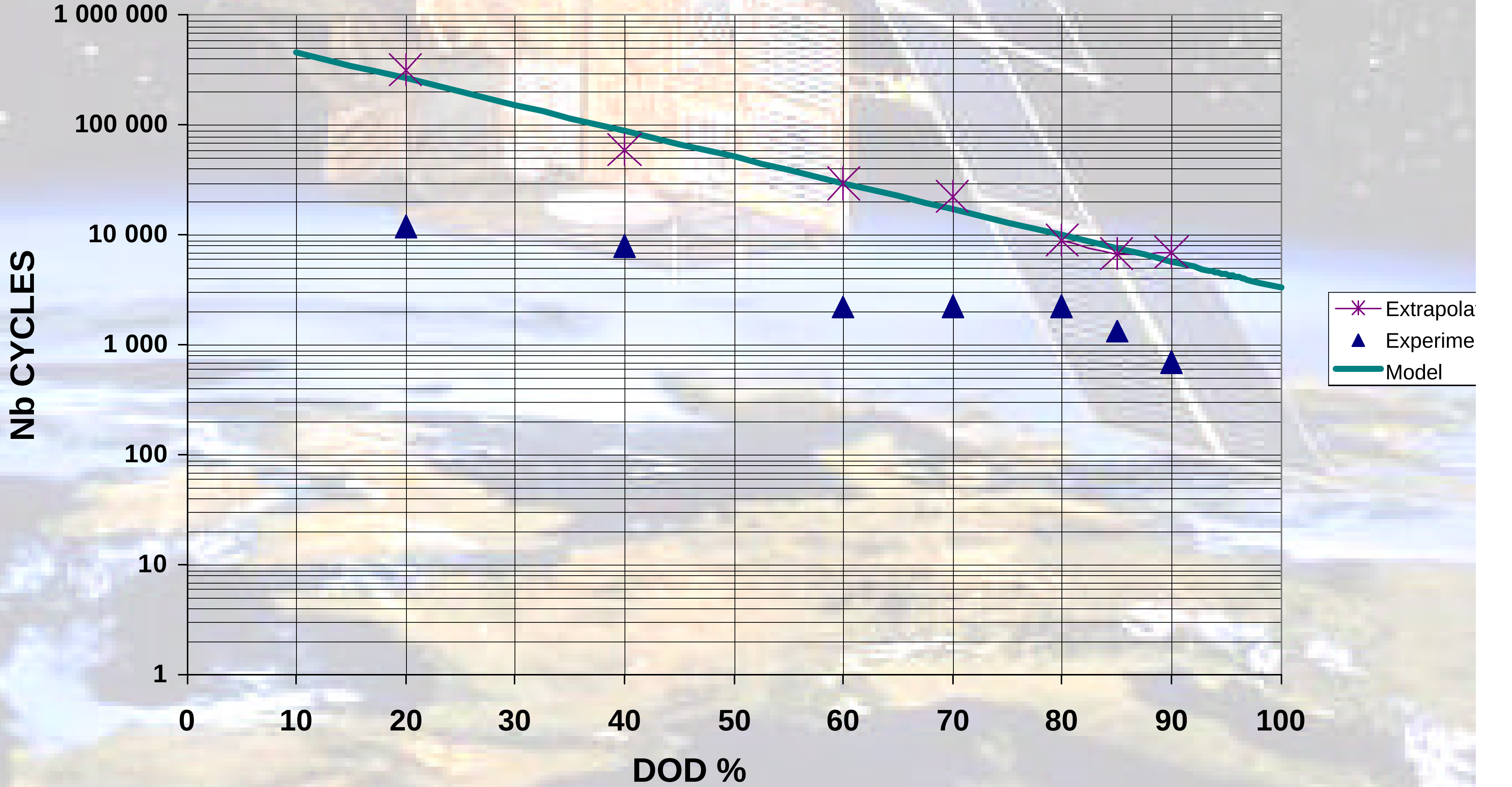
$$N=8.9*10^5\ Exp^{(-0.0547*DOD)}$$

- For 80 % DOD :
  - 2 250 cycles performed with 4 % loss

Margin factor = 8

11 250 cycles to failure

LIFE TIME PREDICTION FOR VES 140



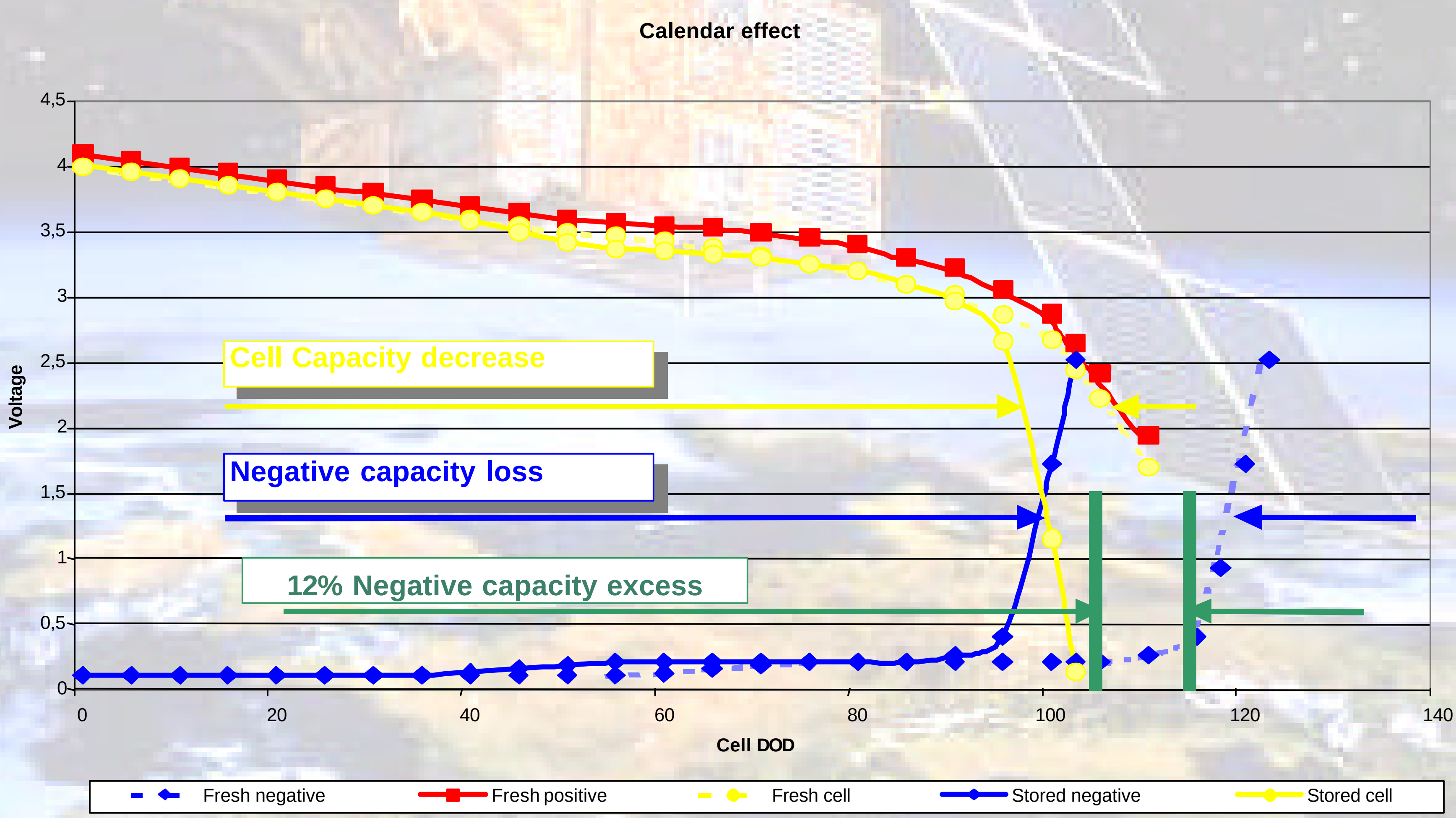
File : O/DDE/ST/power/s2738-01-01

Calendar effects

- **Cell capacity decrease due to lithium loss :**
  - Corrosion of lithium is due to a parasitic reaction occurring between the lithium inserted in the carbon and the electrolyte.

- **Main driving Parameters :**
  - The conductance of the passivation interface layer (Solid Electrolyte Interface)
  - The initial construction of the SEI
  - The temperature

Calendar effect

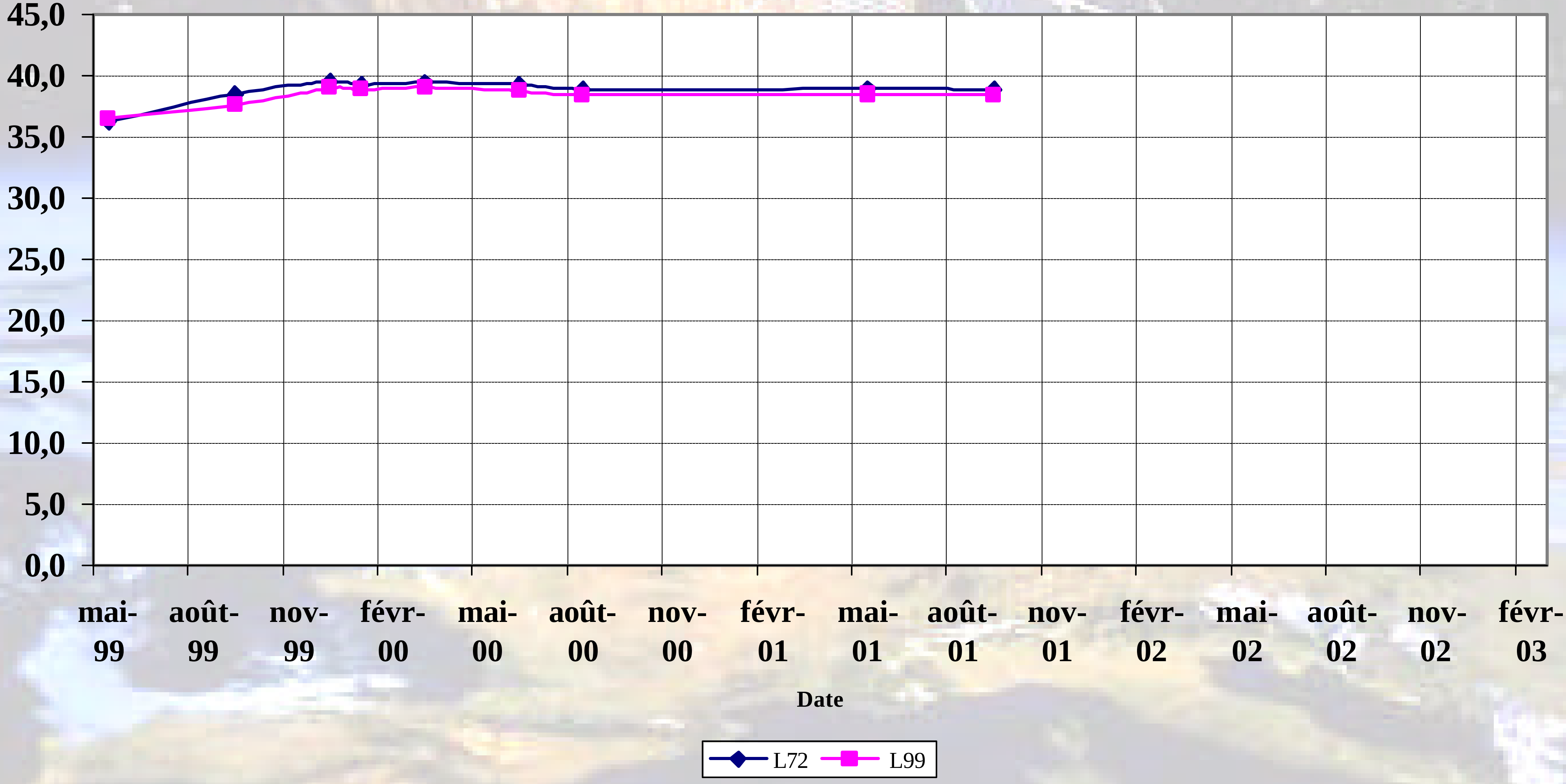


Thanks to Li excess, calendar effect is limited over the life

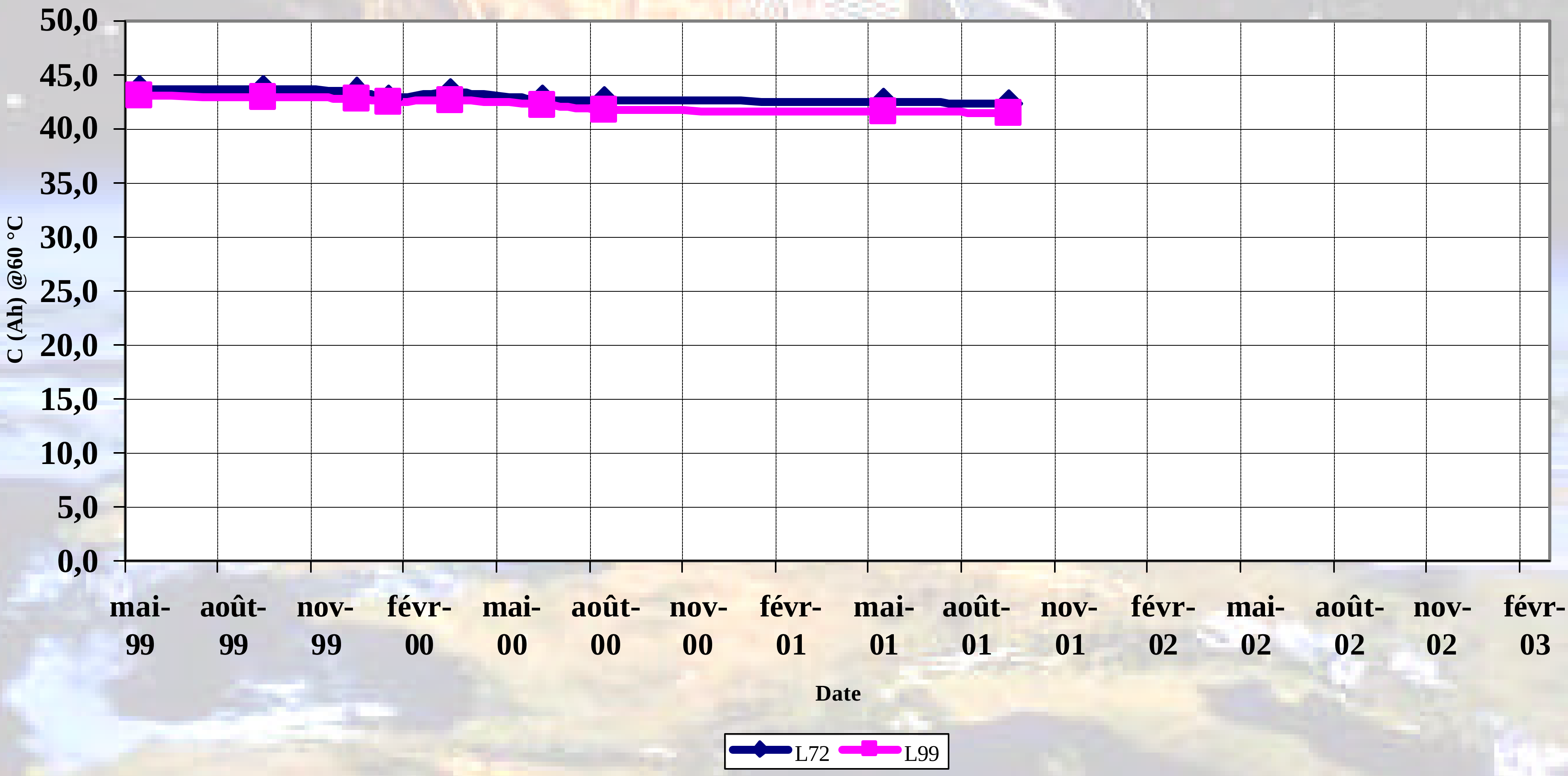
Calendar test plan

- Storage Temperature
  - **From 0°C to 60°C**
- EOCV
  - **From 3.70 V to 4.10 V**
- Conditions
  - **OCV and floating**

Cell stored @30 °C EOCV=4V float conditions
Capacity @25 °C 14 Amps

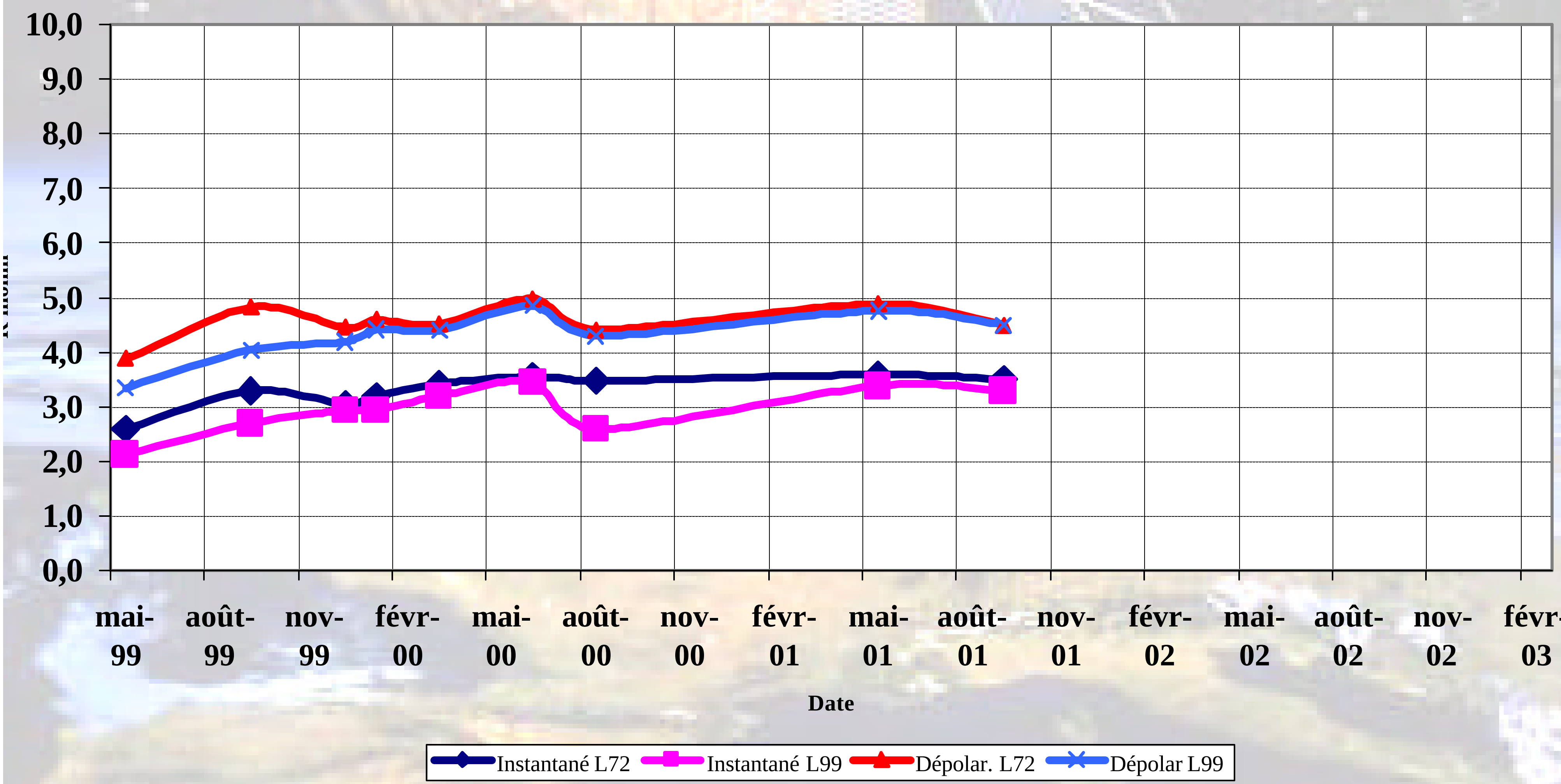


Cells stored @30 °C EOCV=4V float conditions
Capacity @60 °C 14 Amps



Cell stored @30 °C EOCV=4V float conditio

Internal resistance after 1 s and 5 m



Calendar effect laws

- Lithium loss Chemical reactions :

$$t = A(T)\, x^2 + B(T)\, x$$

$$x = 0.2\, t^{0.59} \text{ at } 20\ °C$$

x=%Li loss, t = duration in day, T= temperature °K

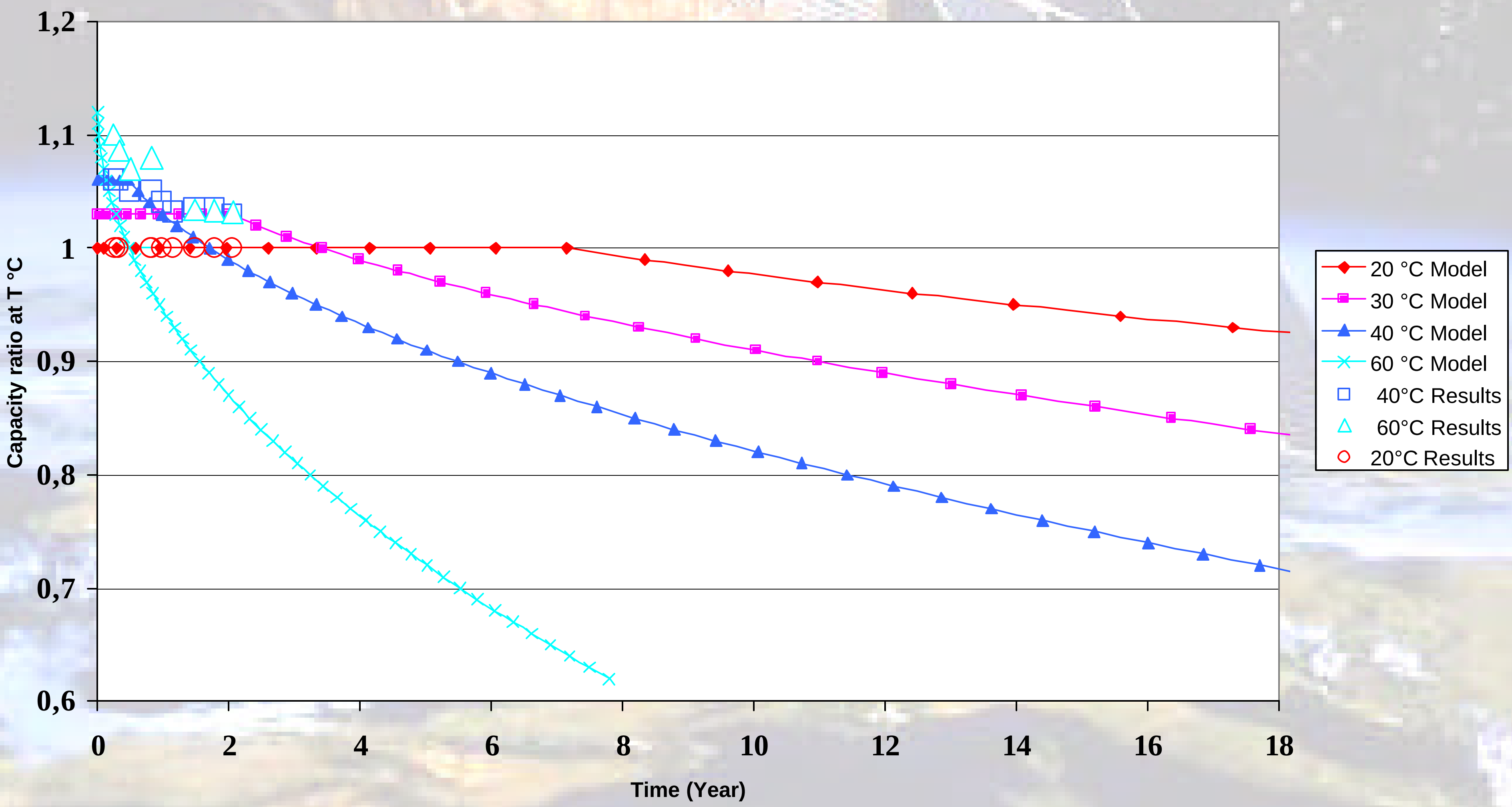
- If $x<12\%$ no capacity loss

  If $x>12\%$ Capacity loss=x - 12 %

- A and B coefficients determined with experiments

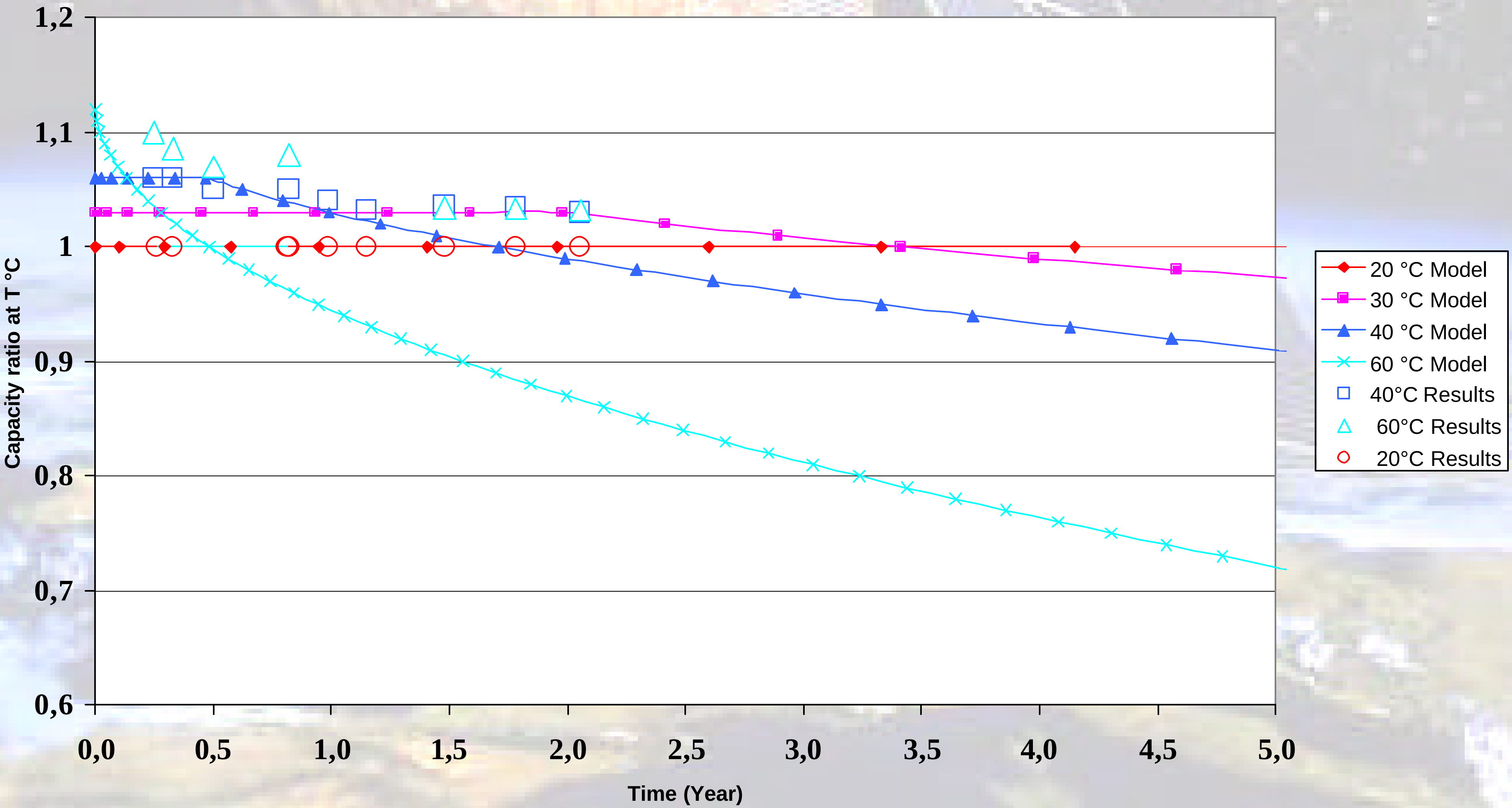
Capacity decrease due to calendar effec and versus temperatur

Capacity Loss due to Calendar Effect vs Temperature



Model correlation

Capacity Loss due to Calendar Effect vs Temperature



File : O/DDE/ST/power/s2738-01-01

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Conclusion (1)

- **Life and calendar tests have shown :**
  - Limited effect of the EOCV
  - Impacts of high charge (>12 Amps) current on fadin effects :
    - Reversible energy loss due to current density
    - Partial localized Li plating (at end of charge)
  - Advantages of the Li excess (Ni based) for calendar

Conclusion (2)

- LEO life tests demonstrate 8 years missions @ 20-25 % DOD
- 56 GEO seasons @80 % DOD have been performed :
  less than 3 % fading for 15 years
- Expected calendar effect is less than 7 % for 18 years at 20 °C

Total energy decrease for 15 years in GEO : 10 %

Evaluation of Cycle Life and Characterization of YTP 45 Ah Li-Ion Battery for EMU

Yi Deng, Judith Jeevarajan, Raymond Rehm
Lockheed Martin Space Operations
Bobby Bragg
NASA Johnson Space Center
Brad Strangways
Symmetry Resources, Inc.

Outline

- Introduction
- Configuration of cell and battery of Yardney Technical Products (YTP)
- Principle of work in Li-ion cell/battery
- Cycle life test
- Characterization tests at various temperatures
- Thermal testing on battery before and after 500 cycles
- Conclusion

Introduction

Li-ion batteries, with longer cycle life and higher energy density features, are now more and more attractive and applied in multiple fields. YTP 45 Ah Li-ion battery has been evaluated here and may be employed in EMU in the future. Evaluations were on:

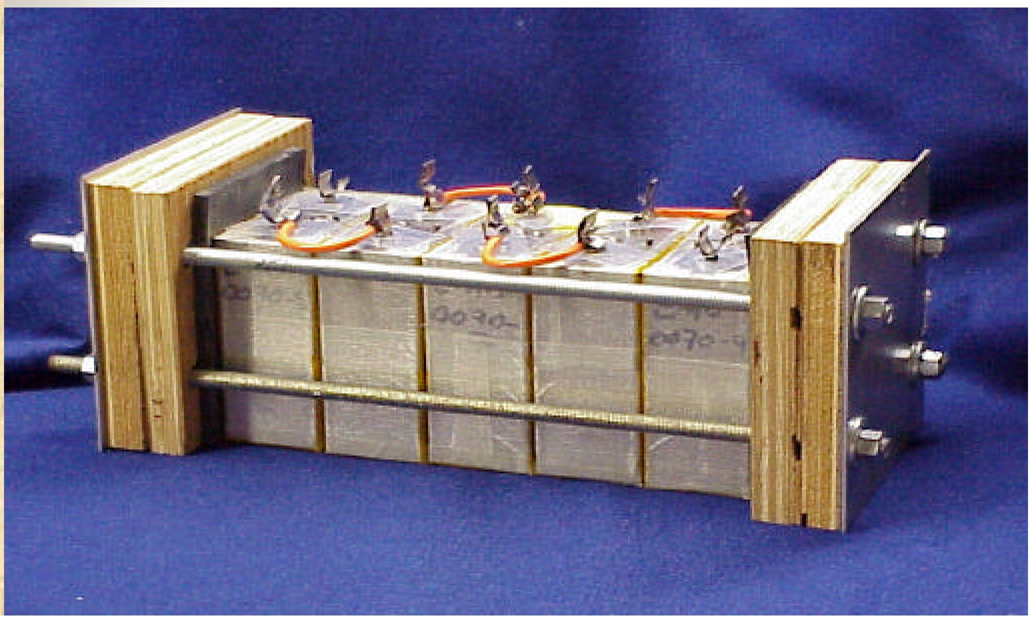
- Cycle life test – 500 cycles total
  - Completed 40 cycles in simulated shuttle use mode
  - Completed 460 cycles in an accelerated use mode
  - Recorded differential voltage of individual cell in battery
- Characterization test

  Discharge capacity measurement in environment temperature of –10, 25, 50 degree C before and after 500 cycles
- Thermal testing

  Charge and discharge at 50 degree C and –10 degree C before and after 500 cycles

Configuration of Battery

Cell capacity: 45 Ah
Cell nominal voltage: 3.6 V
Cell dimensions: 3.45” x 4.47” x 1.77”
Cell weight: 1.108 Kg
Energy density: 366.3 Wh/L
Specific energy: 147.5 Wh/Kg



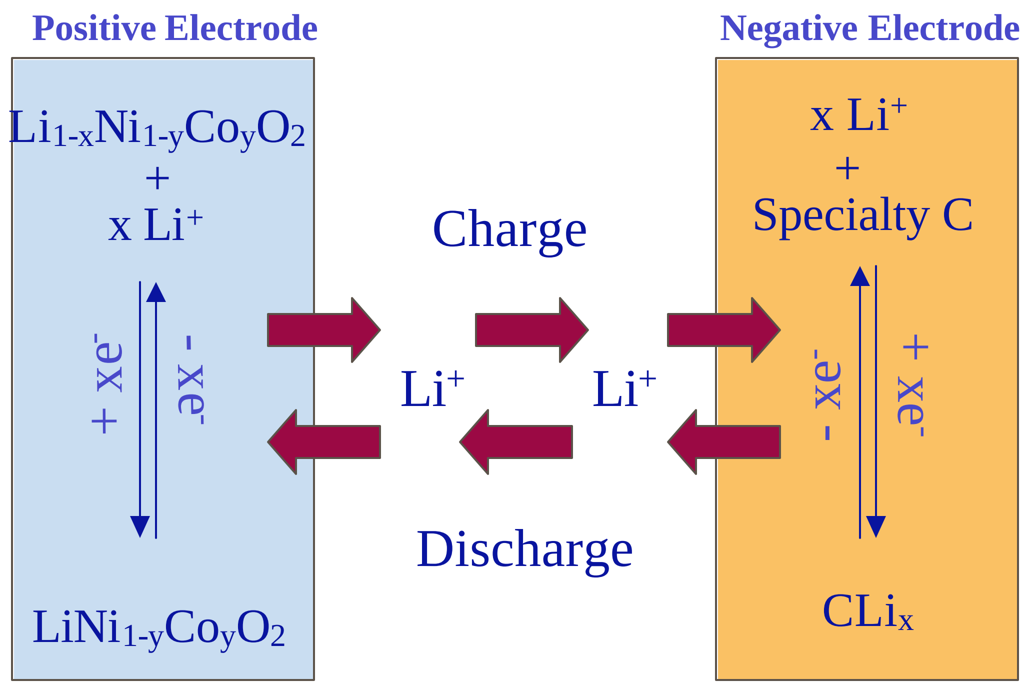
The battery module with 5 cells in series

Battery capacity: 45 Ah

EMU requirement voltage:
16.0 – 21.8V

Battery voltage: 16.0 – 20.5V

Principle of Reaction in YTP Li-ion Cell/Battery



$$LiNi_{1-y}Co_yO_2 + C \underset{\text{Charge}}{\overset{\text{Discharge}}{\rightleftarrows}} Li_{1-x}Ni_{1-y}Co_yO_2 + CLi_x$$

Electrolyte: 0.92M $LiPF_6$ in EC:EMC

Experimental:

- Maccor Series 2000 was employed to perform cycling test on EMU Li-ion battery
- Tenney environmental chamber was used for thermal testing on battery

Cycle Life Test

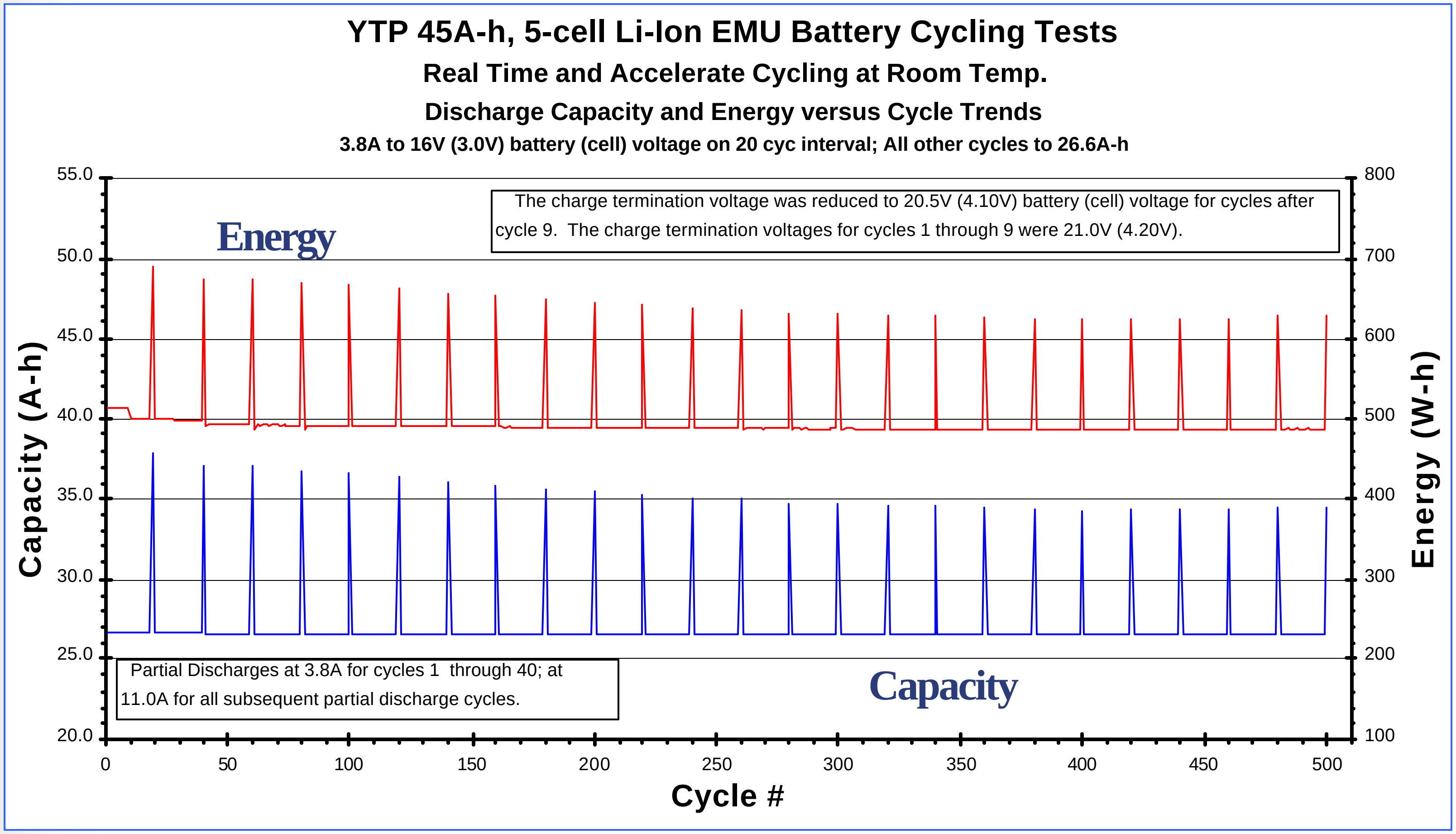
Comprehensive cycling:

- **CC charge protocol was employed in all 500 cycle life tests with no taper charge.**
- **Shuttle Airlock charger real time charge at initial 40 cycles with 1.55A charge and 3.8A partial discharge (26.6Ah, 59% DOD) and full discharge at every 20th cycle to 16.0V.**

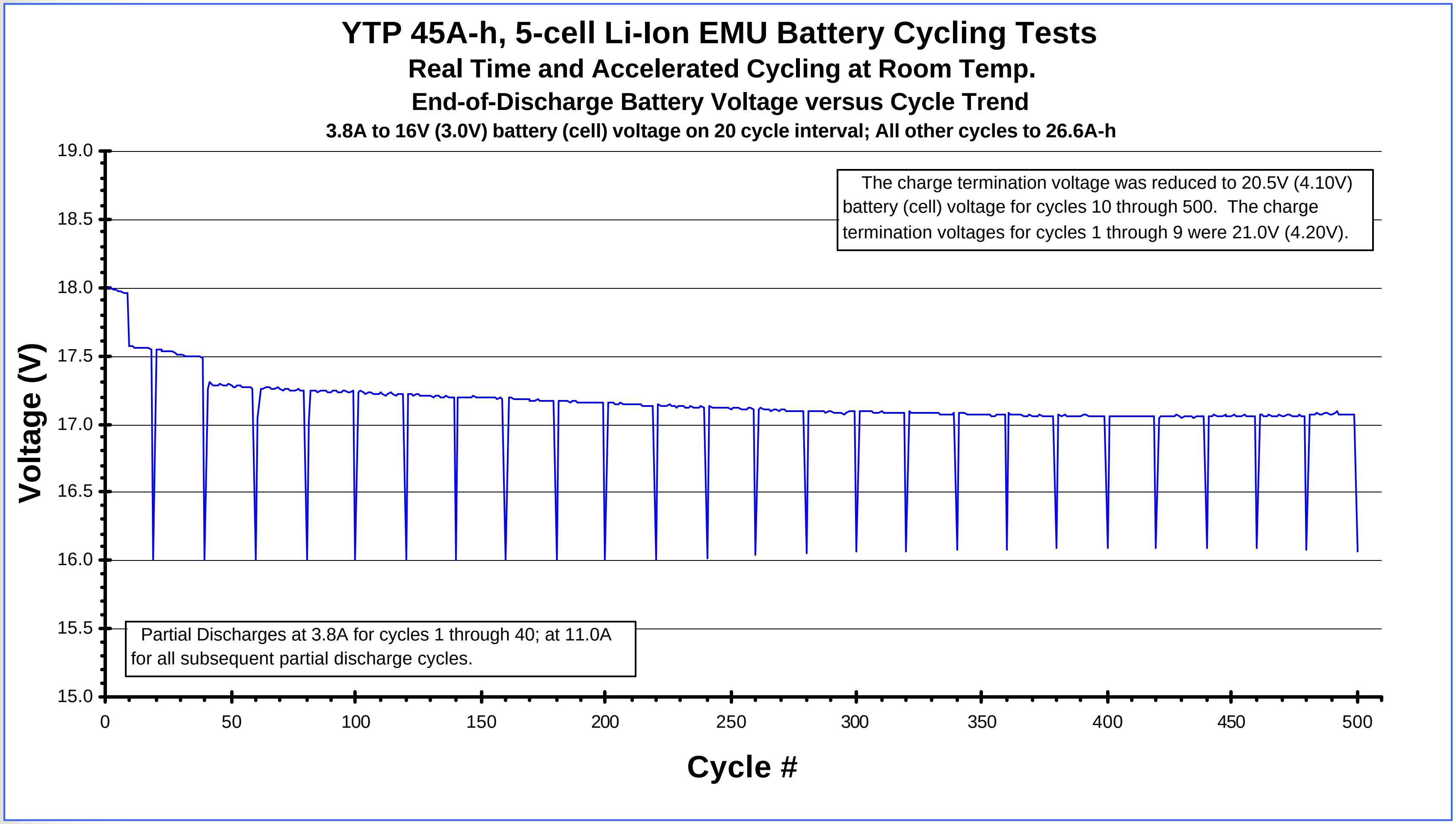
  First 9 cycles – 1.55A charge to 21.0V or 4.2V/cell max.

  From 10 through 40 cycles– 1.55A charge to 20.5V or 4.1V/cell max.
- **Accelerated charge/discharge for subsequent 460 cycles with successive constant current of 11.0A, 5.0A, 2.0A, and 1.0 A charge to 20.5V for battery (4.1V/cell) and 11.0A partial discharge (26.6 Ah, 59% DOD) and full discharges at 3.8A to 16.0V at every 20th cycle.**

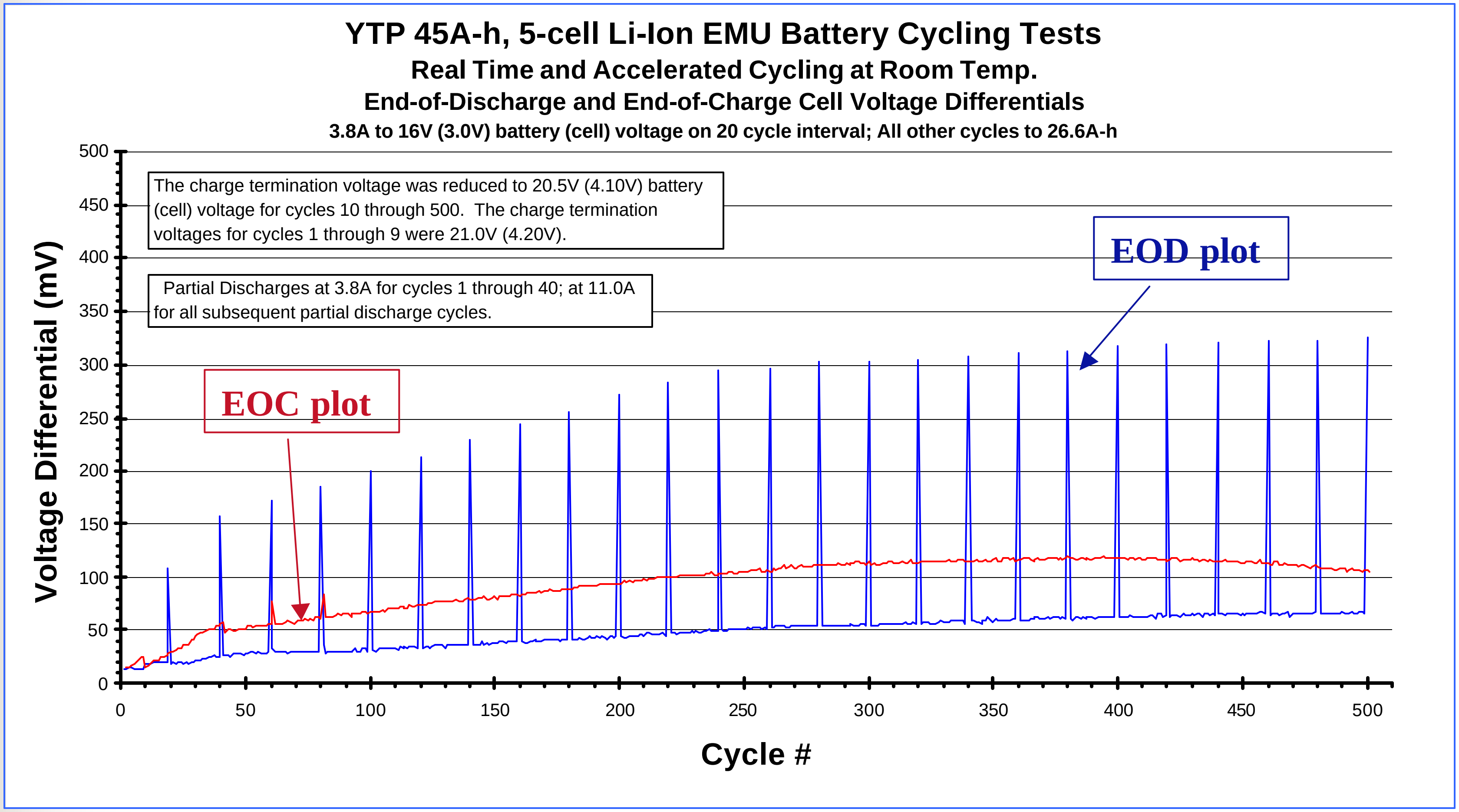
Trends of Discharge Capacity and Energy in the Initial 500 Cycle Life Testing



Trend of Voltage at End of Discharge in the Initial 500 Cycle life Testing



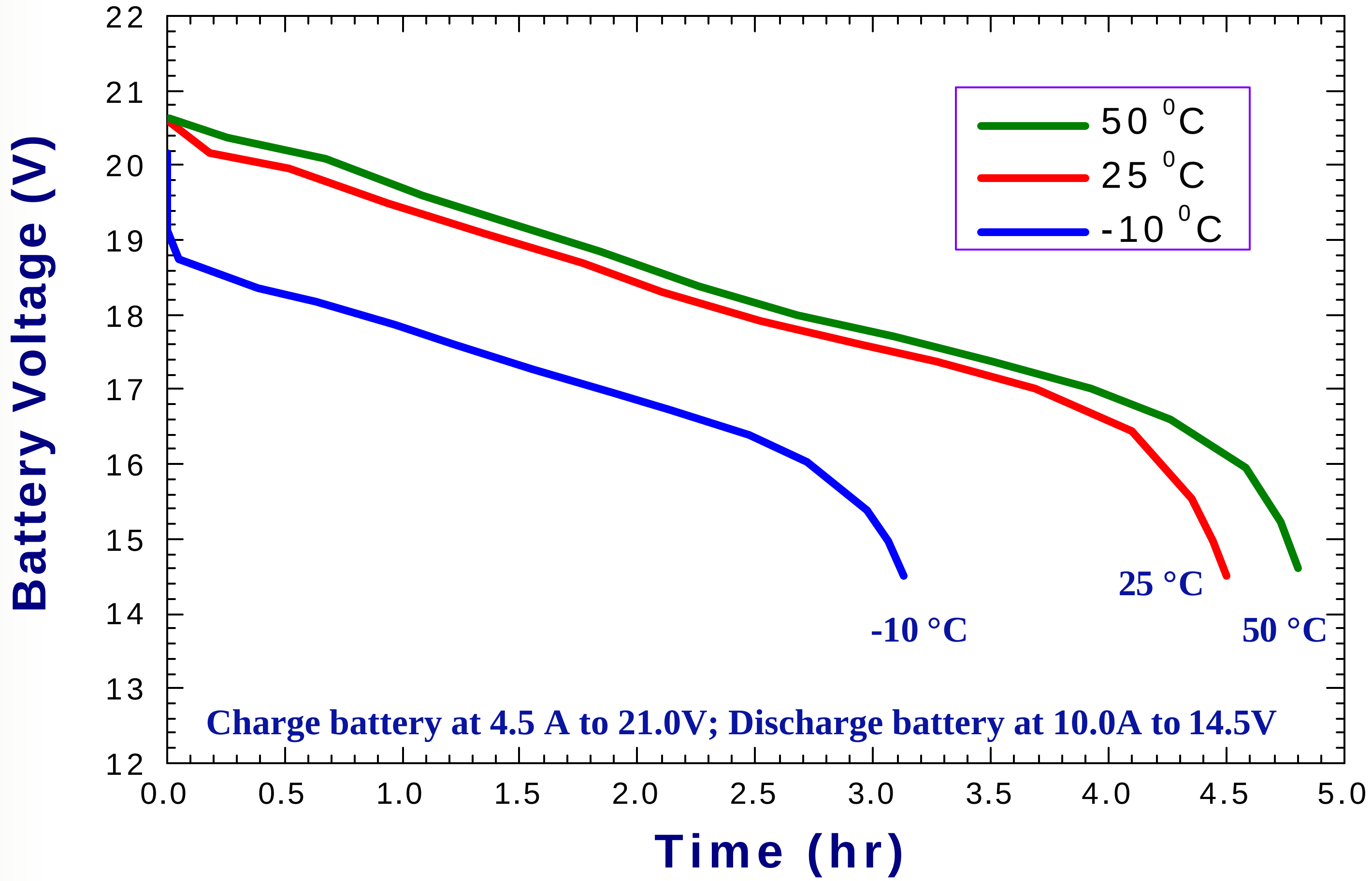
The Differential of Voltage of Individual Cells in Battery at End-of-Charge (EOC) and End-of-Discharge (EOD) in the Initial 500 Cycles



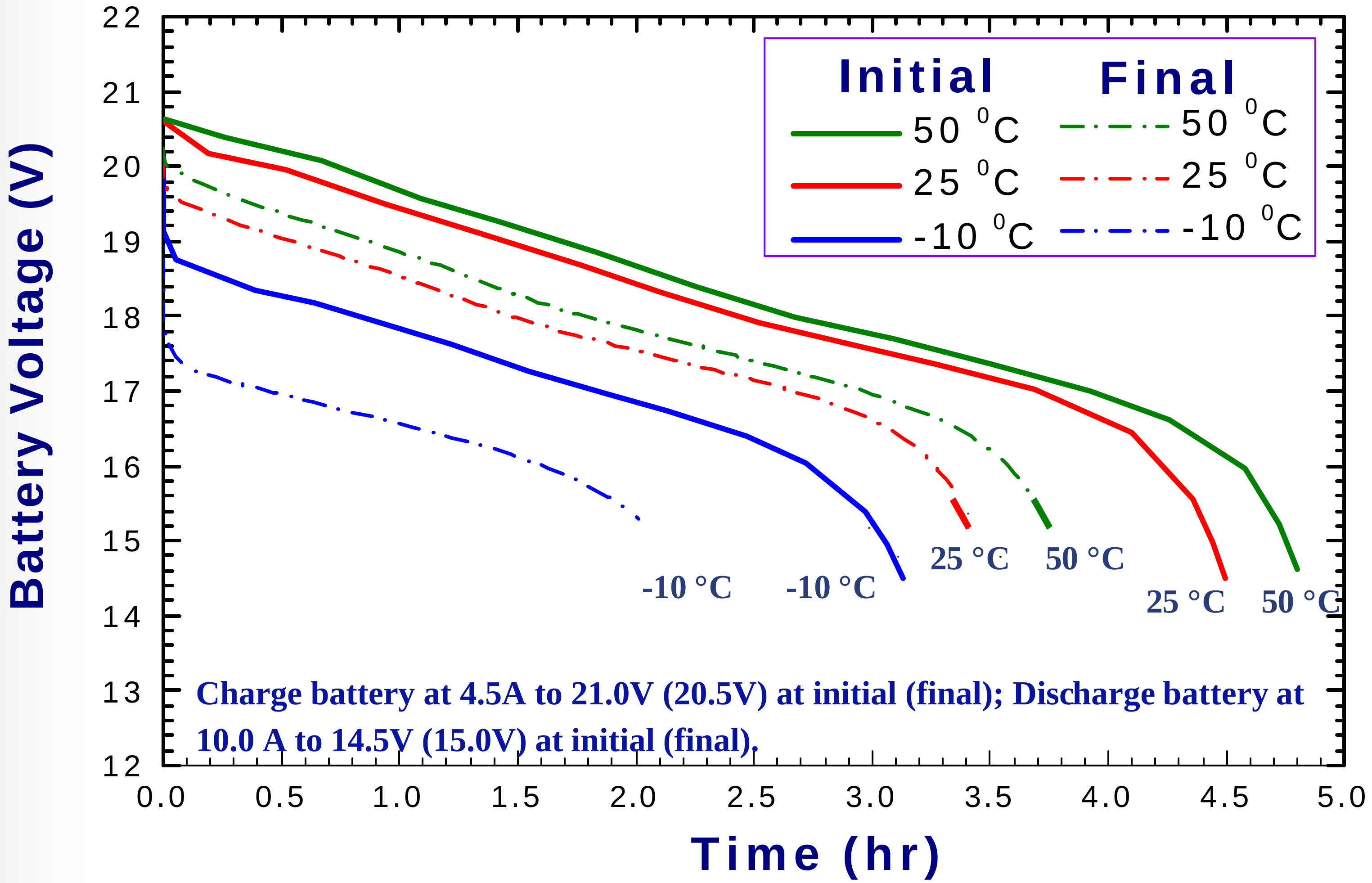
OCV Performance

The battery was fully charged and kept at open circuit for six months after completed previous 500 cycle tests. The OCVs of individual cells in battery were measured before balancing condition supplied. The OCV of all individual cells in battery is almost same with voltage at 4.1V.

Characterization Tests of Battery at Various Temperatures Before 500 Cycles



Discharge Characteristics for the EMU Li-ion Battery Before and After 500 Cycles



Test Data of Battery Discharge Capacities and Energies at Various Temperatures Before 500 Cycles

(cut off voltage at 21.0V during battery charge and cut off voltage at 14.5V during battery discharge)

Temperature (℃)	*Capacity of discharge (Ah)*		*Energy of discharge (Wh)*	
50	48.09	107%	880.7	108%
25	44.96	100%	818.7	100%
-10	31.31	70%	538.4	66%

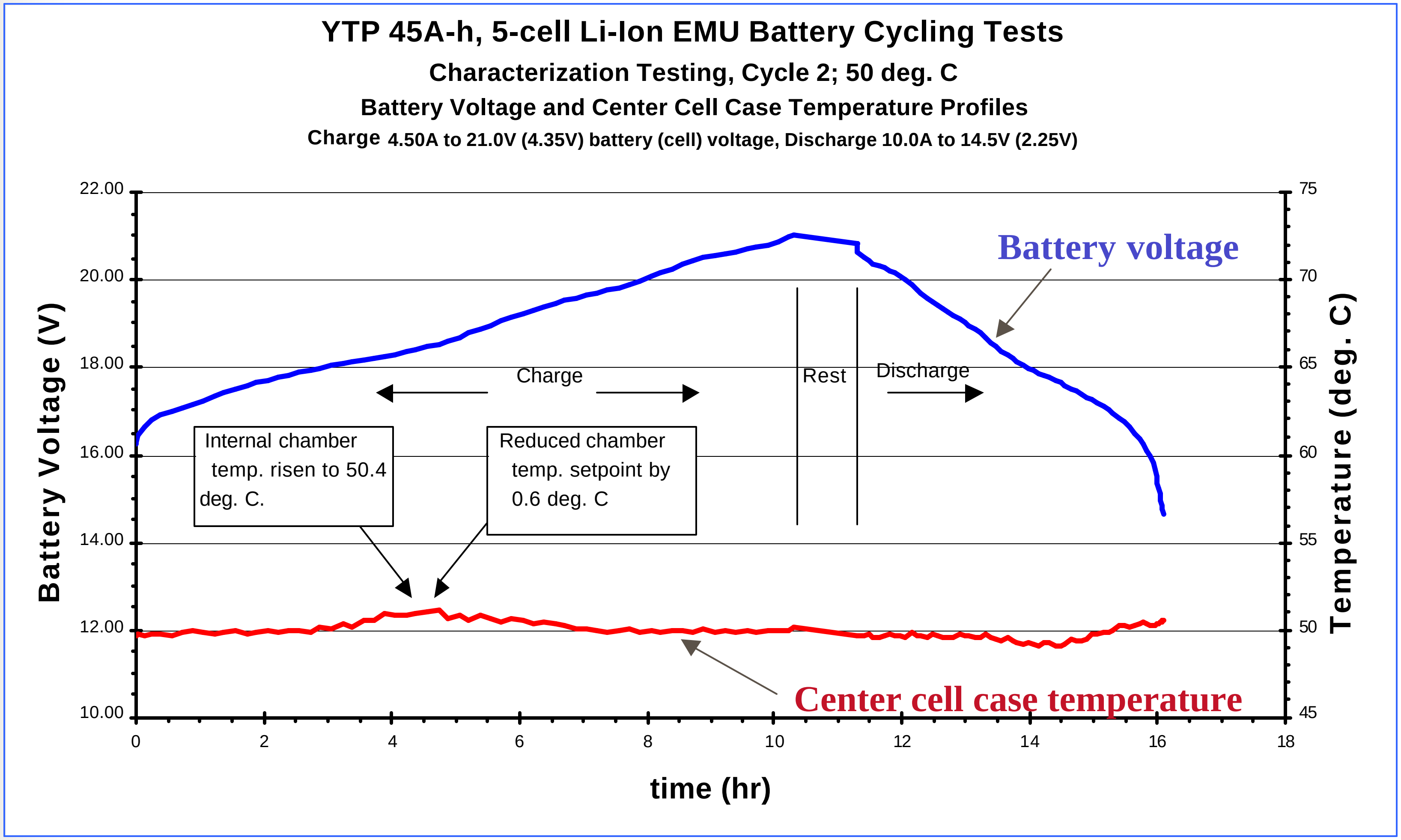
Test Data of Battery Discharge Capacities and Energies at Various Temperatures After 500 Cycles

(cut off voltage at 20.5V during battery charge and cut off voltage at 15.0V during battery discharge)

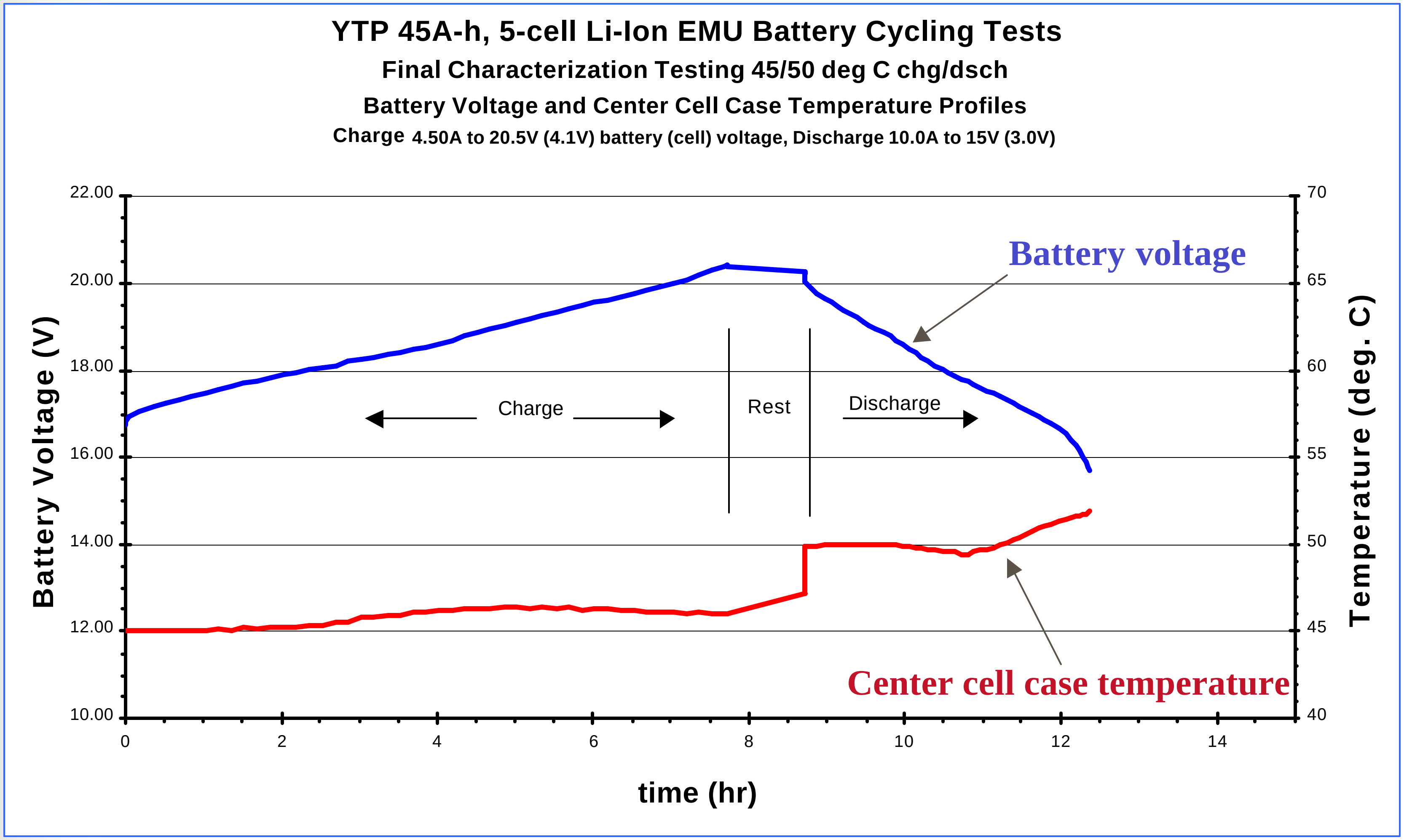
Temperature (℃)	*Capacity of discharge (Ah)*		*Energy of discharge (Wh)*	
50	36.56	109%	659.2	110%
25	33.50	100%	598.7	100%
-10	20.12	60%	332.2	55.5%

Thermal Property of Center Cell Case in Battery When Charge/Discharge at Cell Extreme Temperature

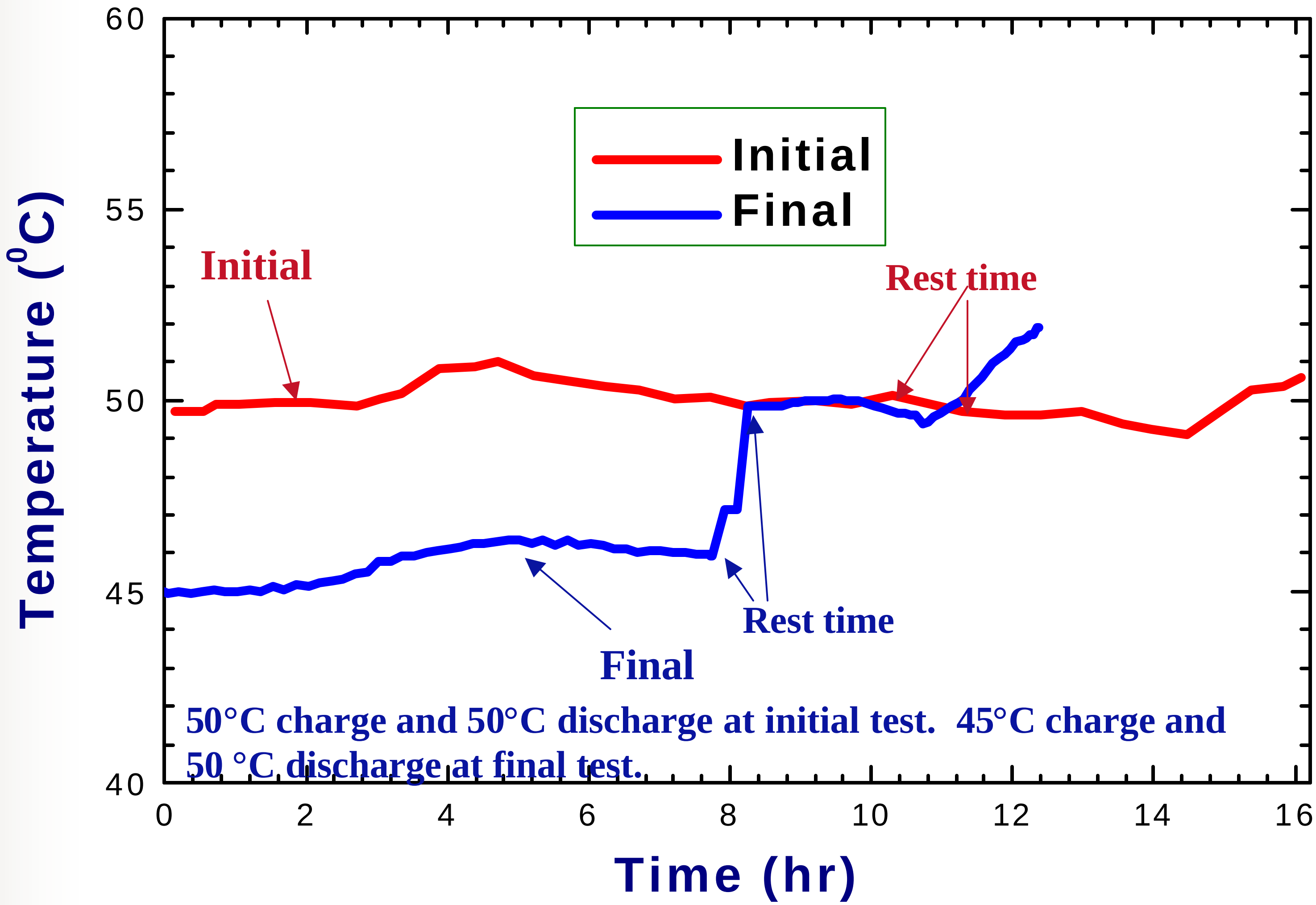
Testing at 50 °C Environmental Temp. Before 500 Cycles



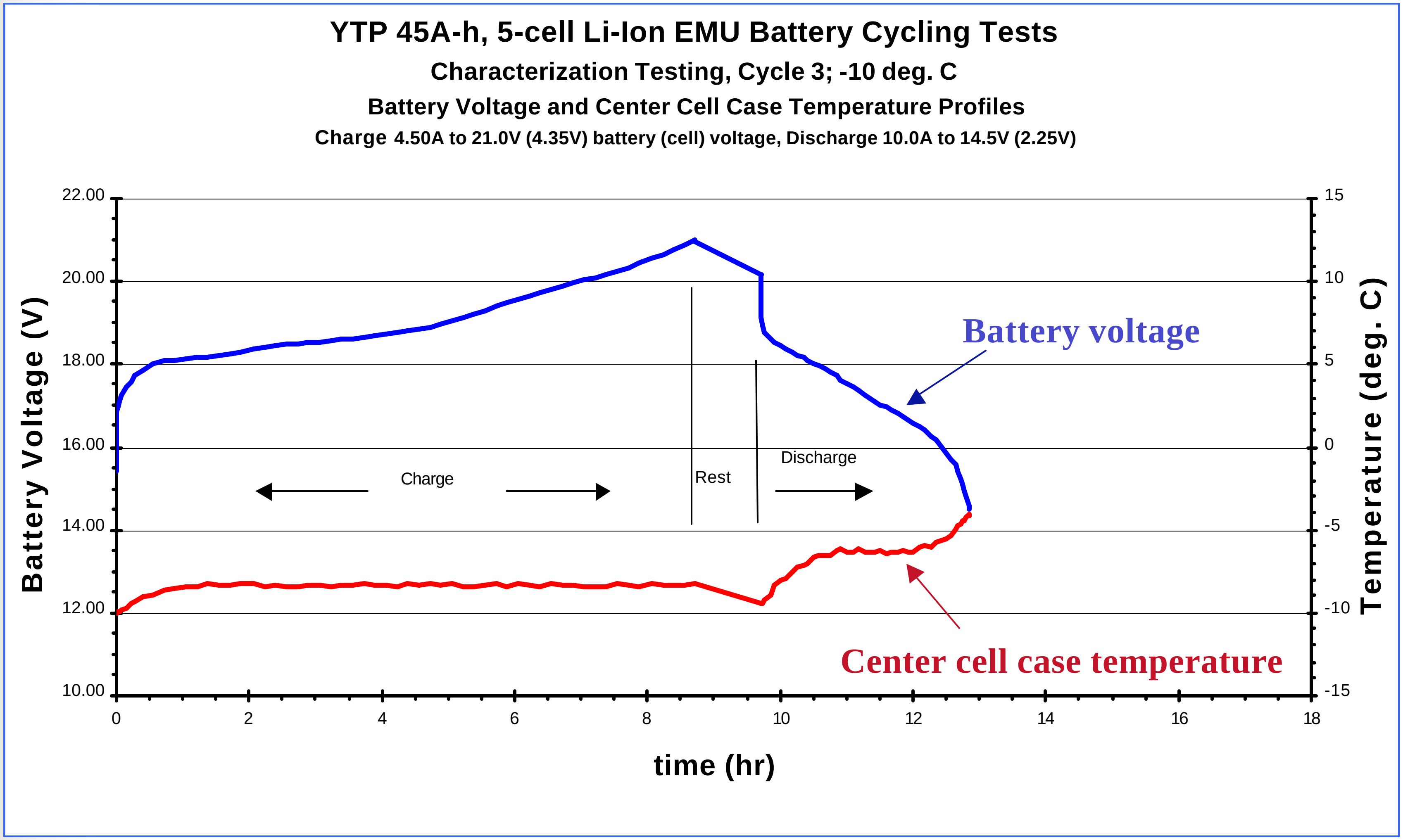
Thermal Property of Center Cell Case in Battery When Charge/Discharge at 45/50 °C Environmental Temp. After 500 Cycles



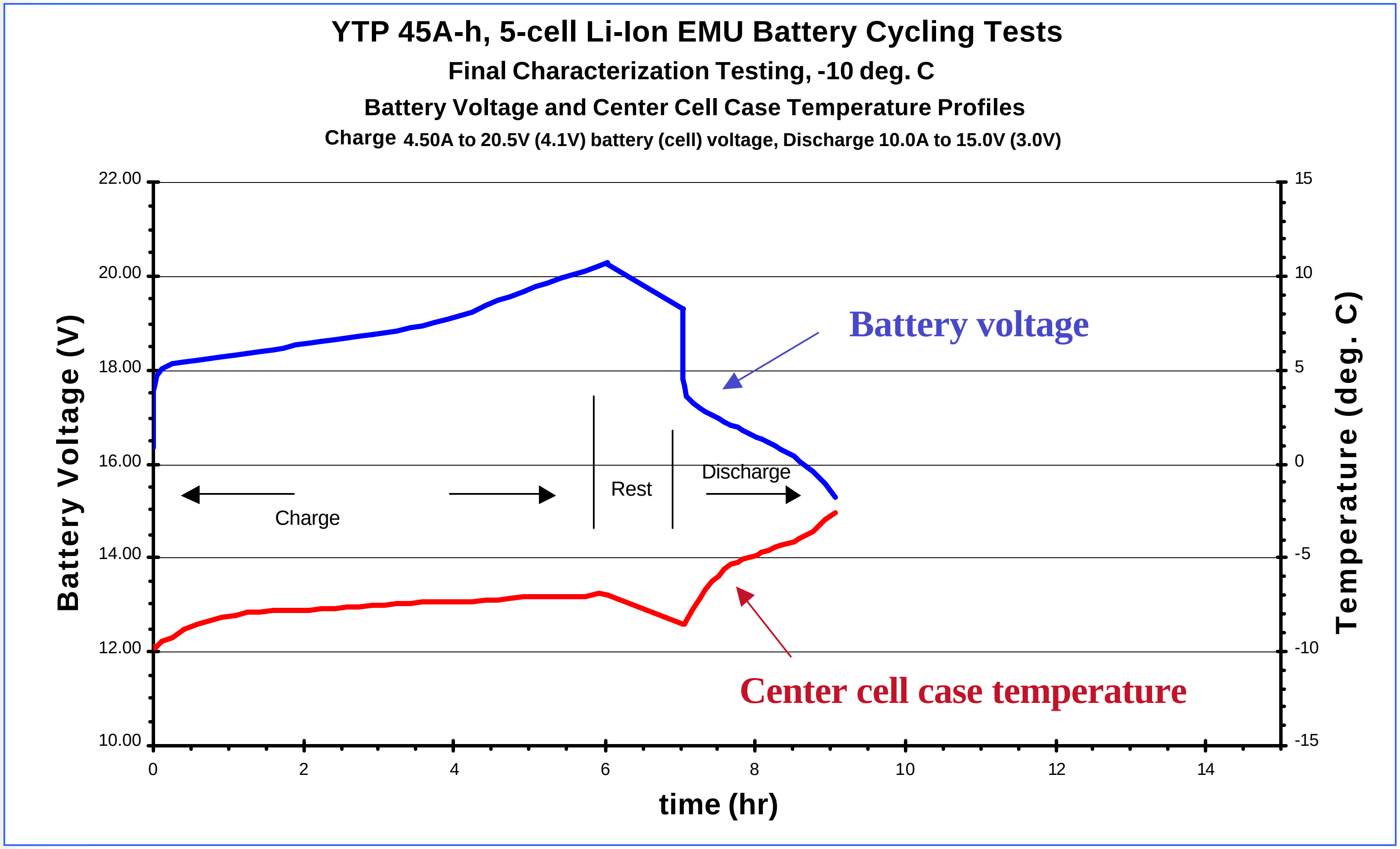
Comparison of Center Cell Temperature at 50/45 °C Before and After 500 Cycles



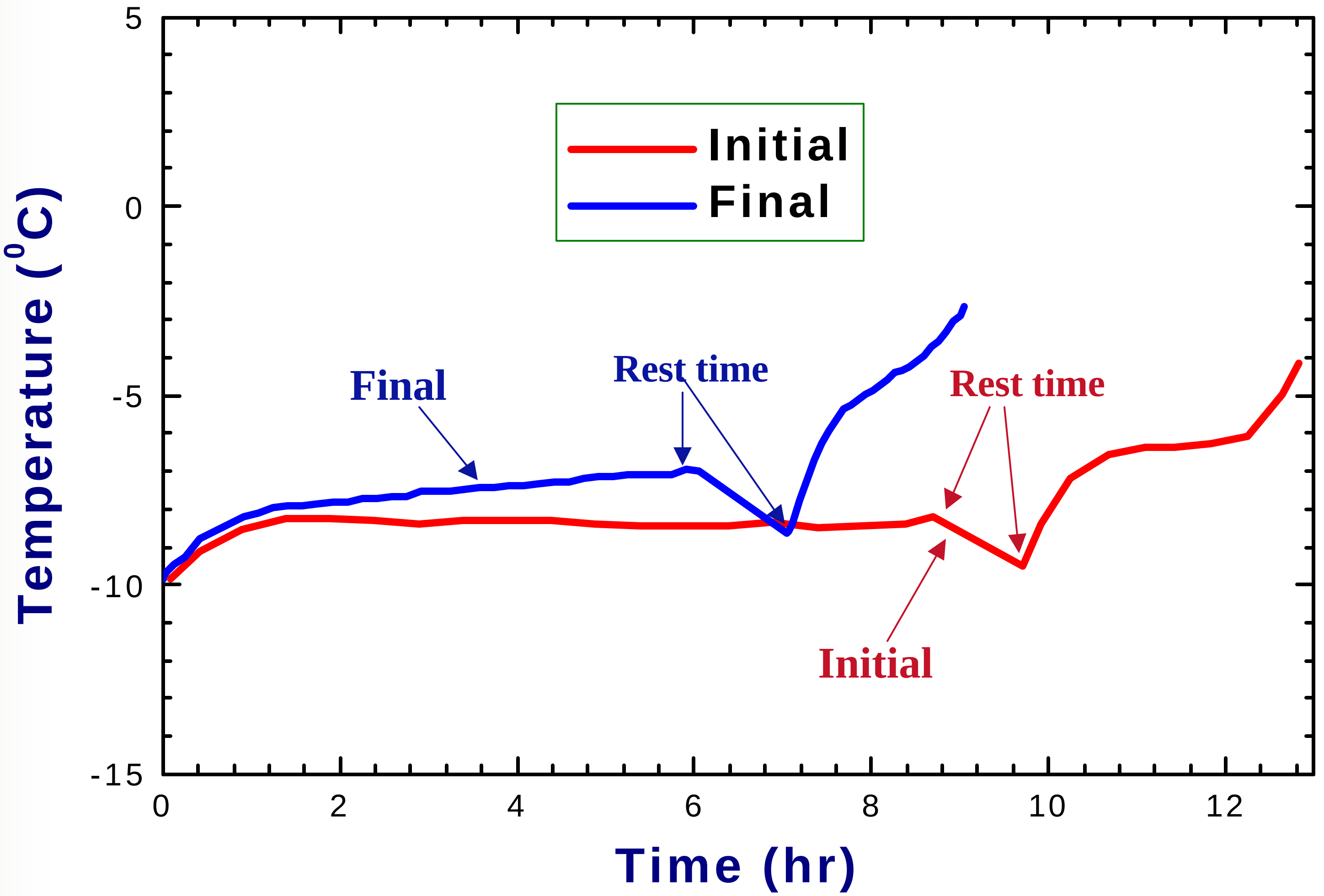
Thermal Property of Center Cell Case in Battery When Charge/Discharge at -10 °C Environmental Temp. Before 500 Cycles



Thermal Property of Center Cell Case in Battery When Charge/Discharge at -10 °C Environmental Temp. After 500 Cycles



Comparison of Center Cell Case Temperature at -10 °C Before and After 500 Cycles



Conclusion

- Battery showed less than 9% drop of initial discharge capacity and energy within 500 cycles with 475 cycles 59% DOD plus 25 cycles 100% DOD.
- The EOD voltage ranged for 16.0-18.0V which fits the requirement for operation of the EMU.
- In 500 non-stop cycles, the results of maximum differential voltage of individual cells in the battery displayed:

  less than 0.13V at EOC and showed decrease trend after 350th cycle;

  less than 0.33 V at EOD and showed increase trend.
- Capacity variation resulting from temperature extremes is only minimally affected by the 500 cycles.
- External temperature of battery case displayed increase tendency after 500 cycle tests, due to increased internal impedance.

Acknowledgment

We acknowledge Yardney Technical Products, Inc. for supplying the EMU Li-ion cells as a Phase II deliverable.

LITHIUM ION DD CELLS

SPACE APPLICATION CYCLING UPDATE

HAIYAN CROFT

BOB STANIEWICZ

SAFT America Inc.

Advanced Battery Systems Division

Cockeysville, MD

The 2001 NASA Aerospace Battery Workshop

Huntsville, Alabama

November 27- 29, 2001

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DD Cell

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OVERVIEW

- DD CELLS
  - CHEMISTRY
  - HOW ACCELERATED TESTING IS PERFORMED
  - LEO TESTING
  - GEO TESTING
  - 100% DOD at RT
  - 100% DOD at -20^{0}C
  - CONCLUSION

CHEMISTRY

- CHEMISTRY
  - POSITIVE MATERIAL: $LiNi_{1-x-y}Co_xM_yO_2$
  - NEGATIVE IS ADMIXTURE OF TWO GRAPHITES WITH NON-PVDF BINDER
- CAPACITY: 9.5 AH
- ENERGY DENSITY: 140 WH/KG

HARDWARE

- STAINLESS STEEL HARDWARE
- CELL DIMENSION: CYLINDRIAL
  - CELL OD 32 MM OR 1.32 IN
  - CELL HEIGHT 122MM OR 4.8 IN
- MULTIMPLE TABS ON ELECTRODES
- CELL WEIGHT: 250 GRAMS

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- **LEO AND GEO CYCLING DEMONSTRATING PERFORMANCES FOR PLANETARY AND INTERPLANETARY APPLICATIONS**

DEPTH OF DISCHARGE	CYCLES ACHIEVED TO DATE	EOL
30%	20,000	40K CYCLES
60%	2800	1350
100%@-20C	1000	

ACCELERATED TESTING METHODS

WE JUDGED WHAT MIGHT BE REASONABLE, ACCELERATED TRADE-OFFS OF TIME AND CURRENT TO ACCOMPLISH CYCLE DEMONSTRATION

GEO – ACCELERATION IS STRAIGHTFORWARD:

WE ADOPTED 1.2 HOURS FOR DISCHARGE

4.8 HOURS FOR CHARGE

THE DISCHARGE IS AT A CONSTANT DOD RATHER THAN A TRUE SEASON WITH THE WELL-KNOW PARABOLIC ECLIPSE DURATION

LEO – ACCELERATION REQUIRES A CAREFUL BALANCE OF SHORTEN TIME AND CURRENT INCREASE

	CYCLES/DAY	CURRENT (A)	TIME (M)
30% DOD	28.7	DIS 10	15.12
		CHG 5.25	35

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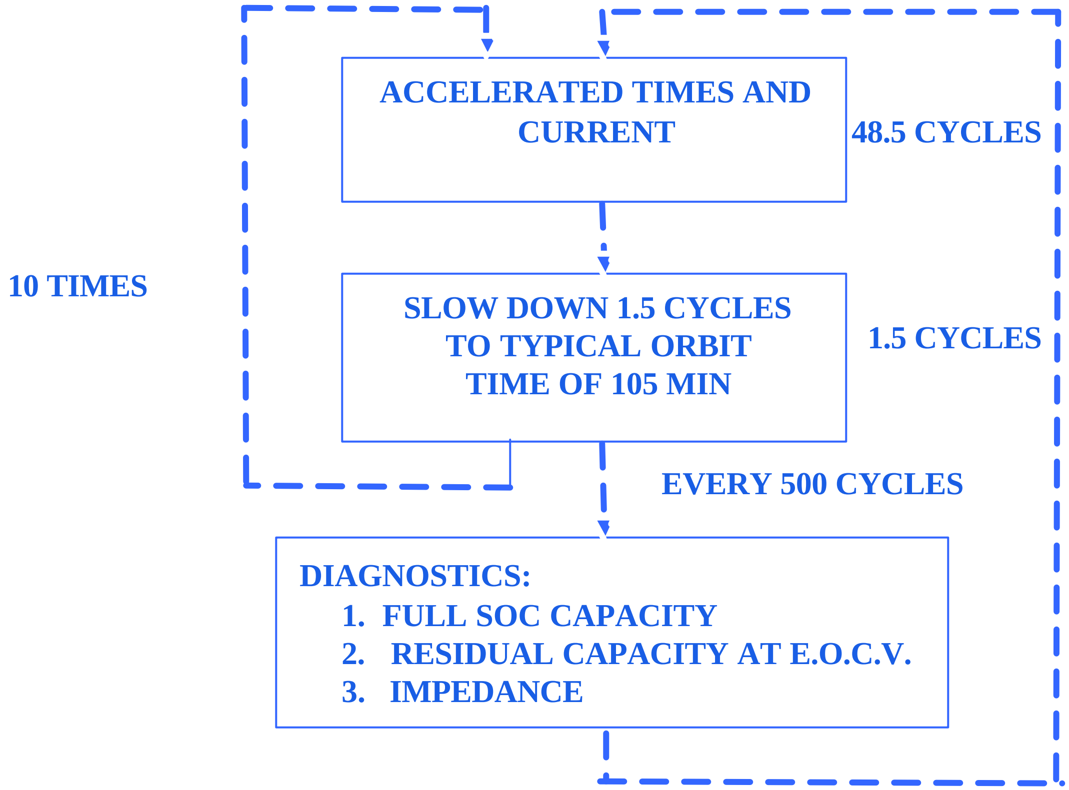
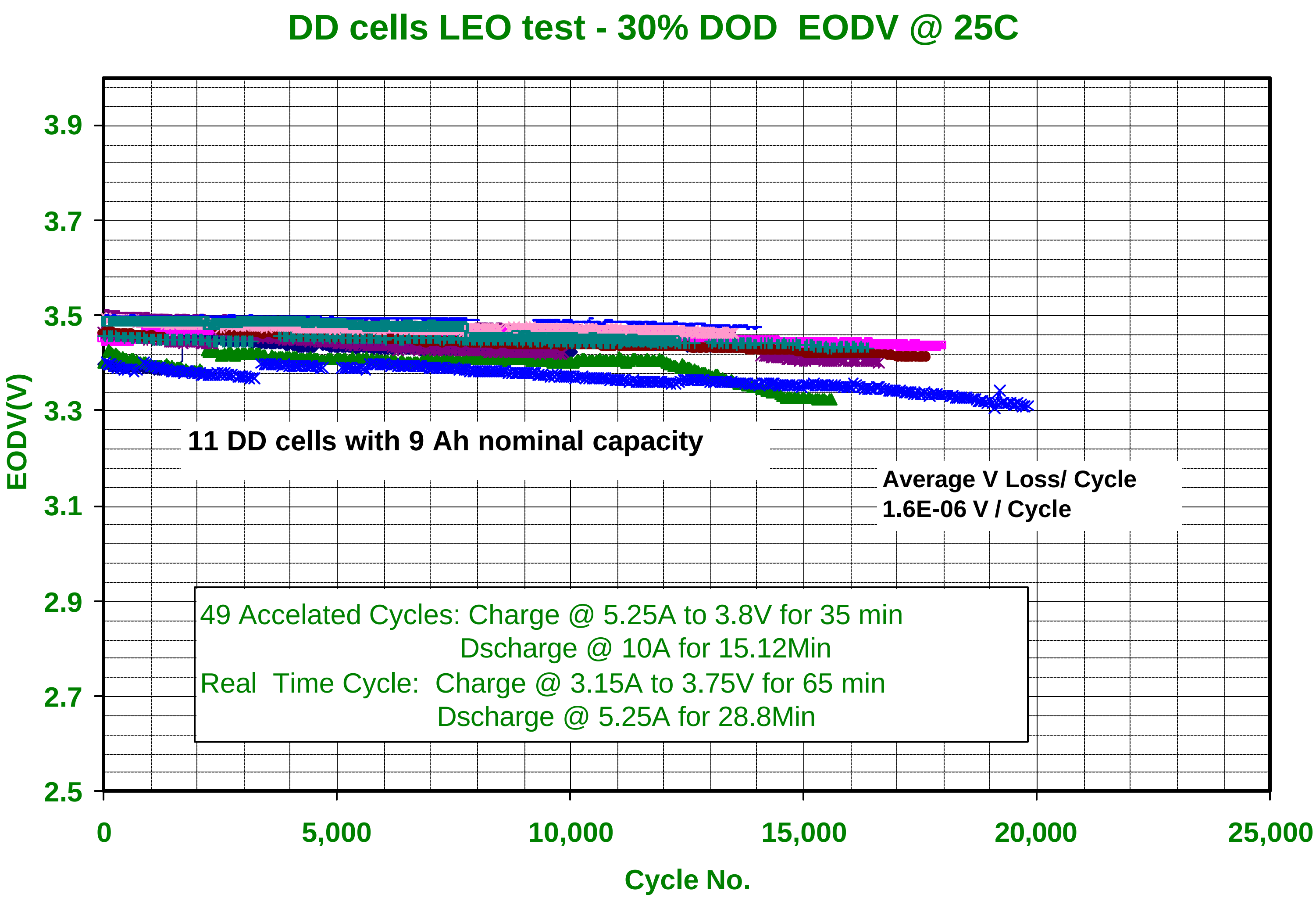
LEO TESTING

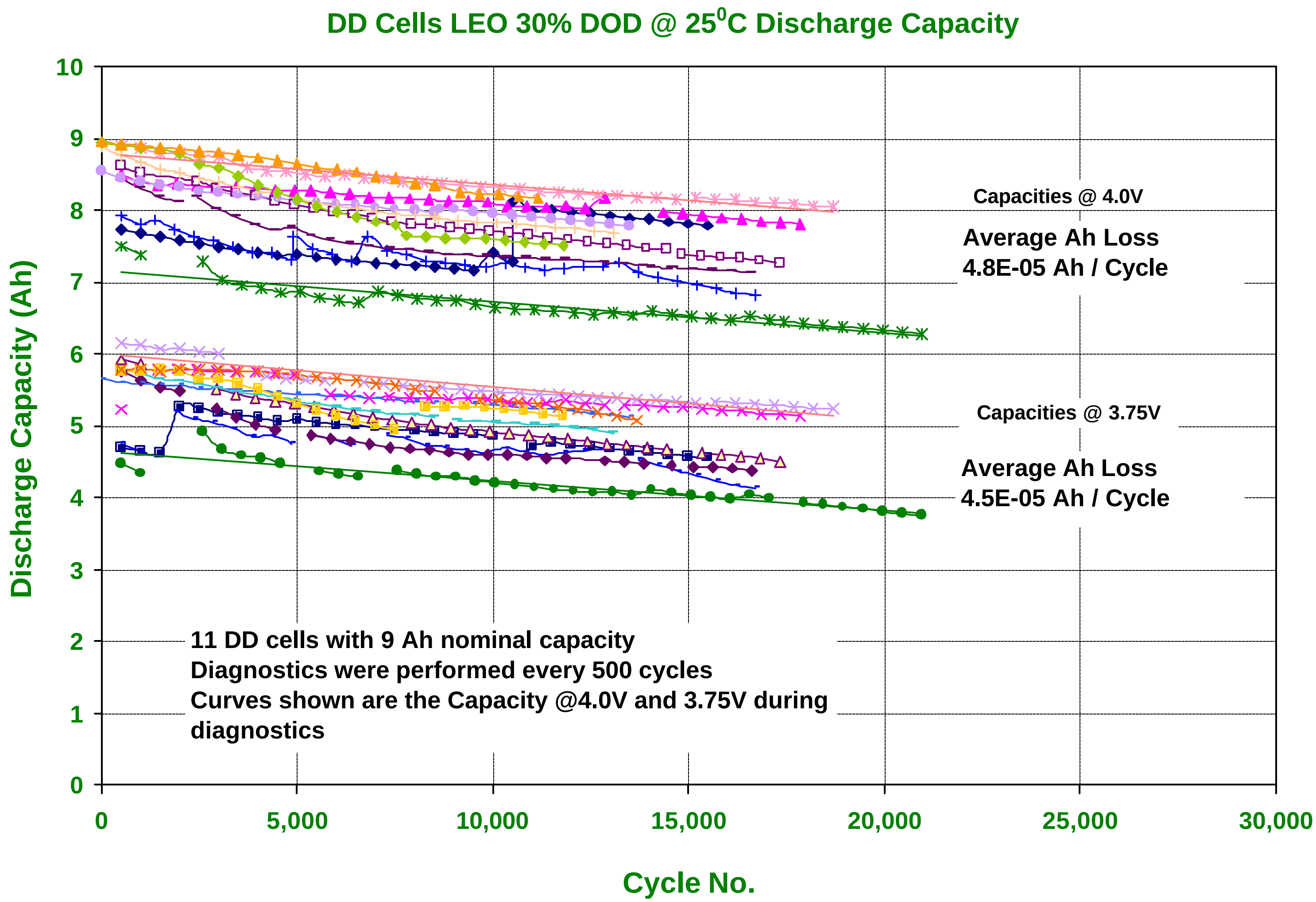


SLOWING DOWN TO REAL TIME ORBIT RATES OF 105 MIN. EVERY 50 CYCLES IS ESSENTIAL SO THAT E.O.D.V. REFLECTS TRUE ORBIT CONDITIONS

LEO TESTING


DD cells LEO test - 30% DOD EODV @ 25C
EODV(V)
3.9
3.7
3.5
3.3
3.1
2.9
2.7
2.5
0
5,000
10,000
15,000
20,000
25,000
Cycle No.
11 DD cells with 9 Ah nominal capacity
Average V Loss/ Cycle
1.6E-06 V / Cycle
49 Accelated Cycles: Charge @ 5.25A to 3.8V for 35 min
Dscharge @ 10A for 15.12Min
Real Time Cycle: Charge @ 3.15A to 3.75V for 65 min
Dscharge @ 5.25A for 28.8Min

LEO TESTING



DD Cells LEO 30% DOD @ 25^{0}C Discharge Capacity
Discharge Capacity (Ah)
Cycle No.
0
1
2
3
4
5
6
7
8
9
10
0
5,000
10,000
15,000
20,000
25,000
30,000
Capacities @ 4.0V
Average Ah Loss
4.8E-05 Ah / Cycle
Capacities @ 3.75V
Average Ah Loss
4.5E-05 Ah / Cycle
11 DD cells with 9 Ah nominal capacity
Diagnostics were performed every 500 cycles
Curves shown are the Capacity @4.0V and 3.75V during diagnostics

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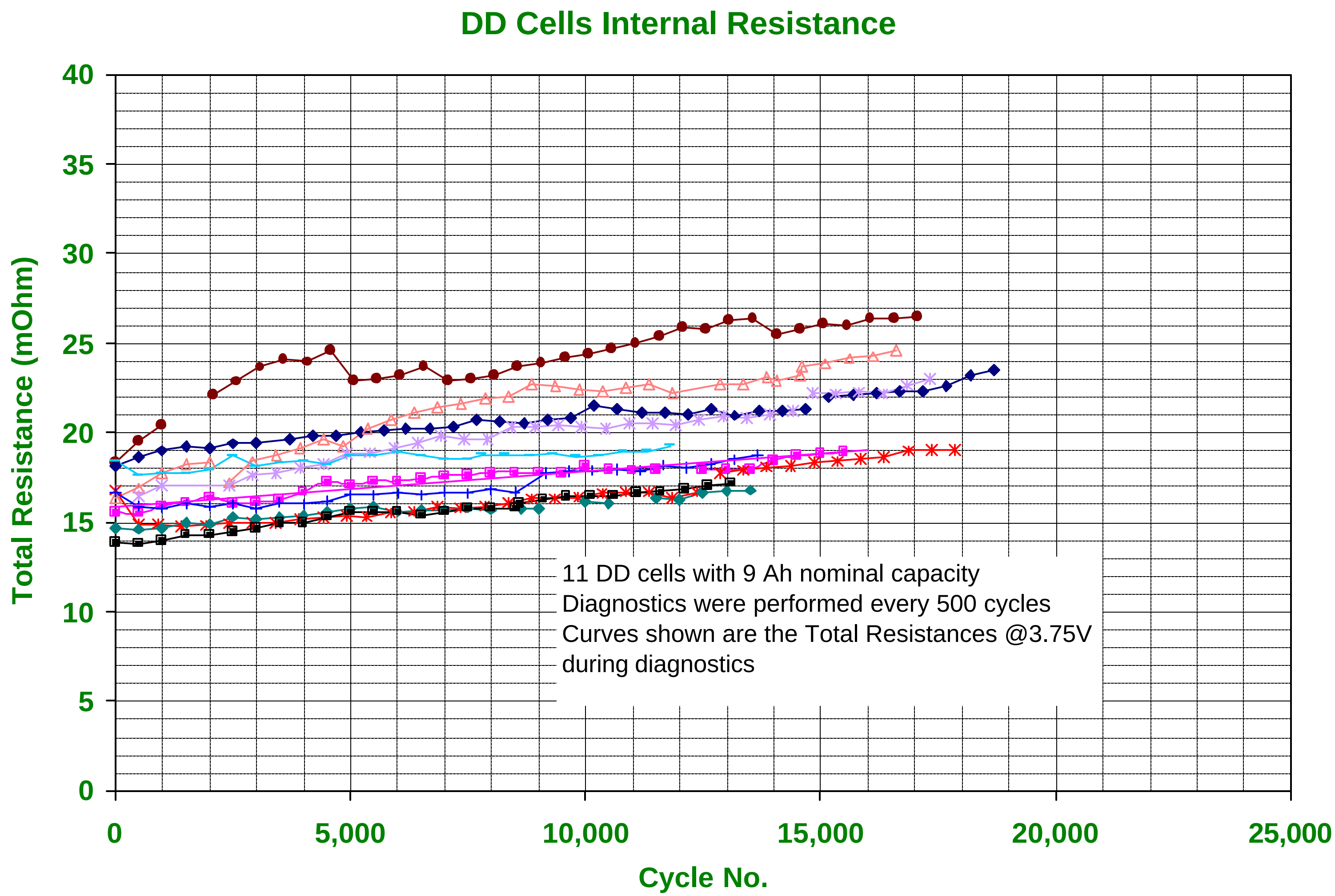
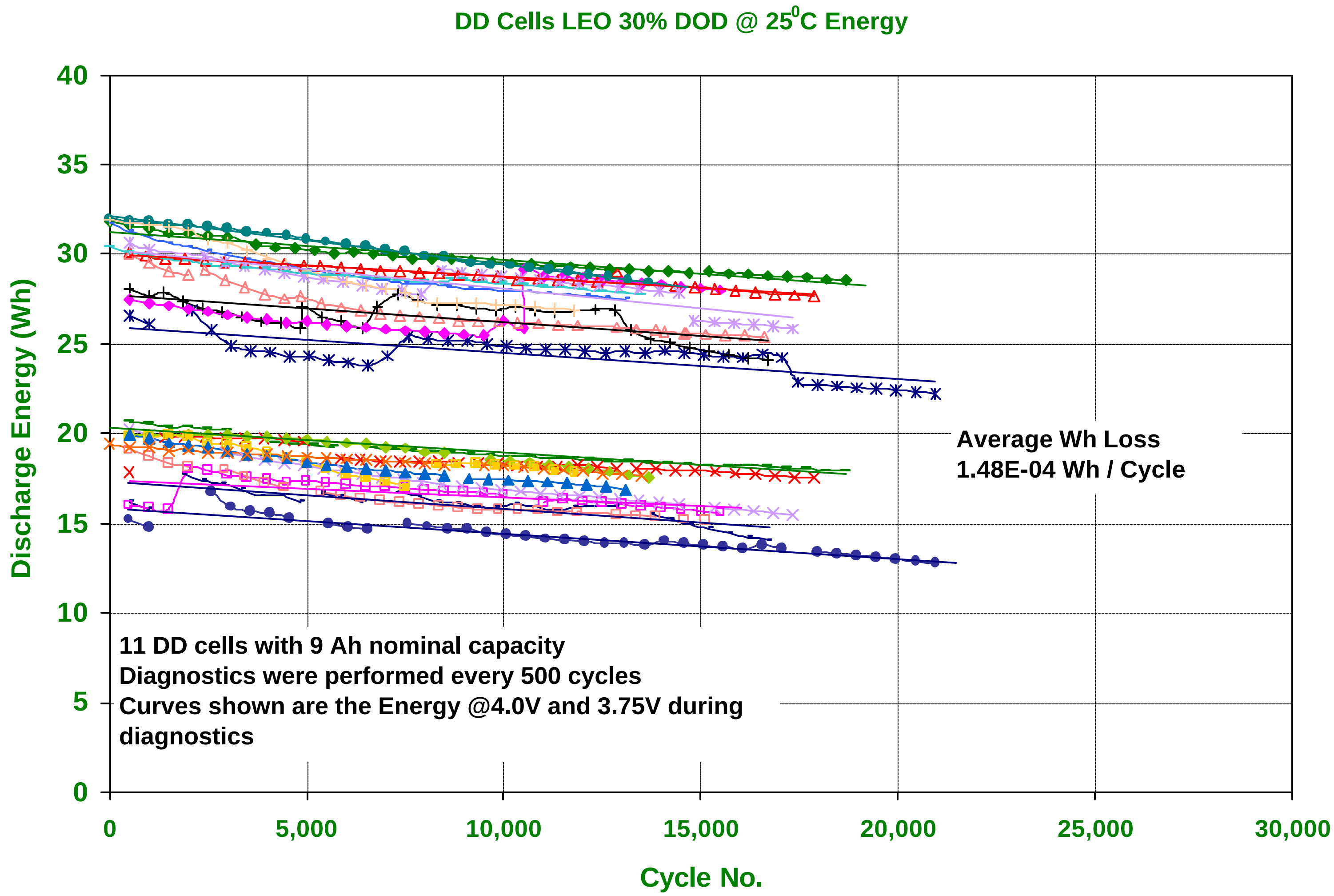
LEO TESTING



LEO TESTING



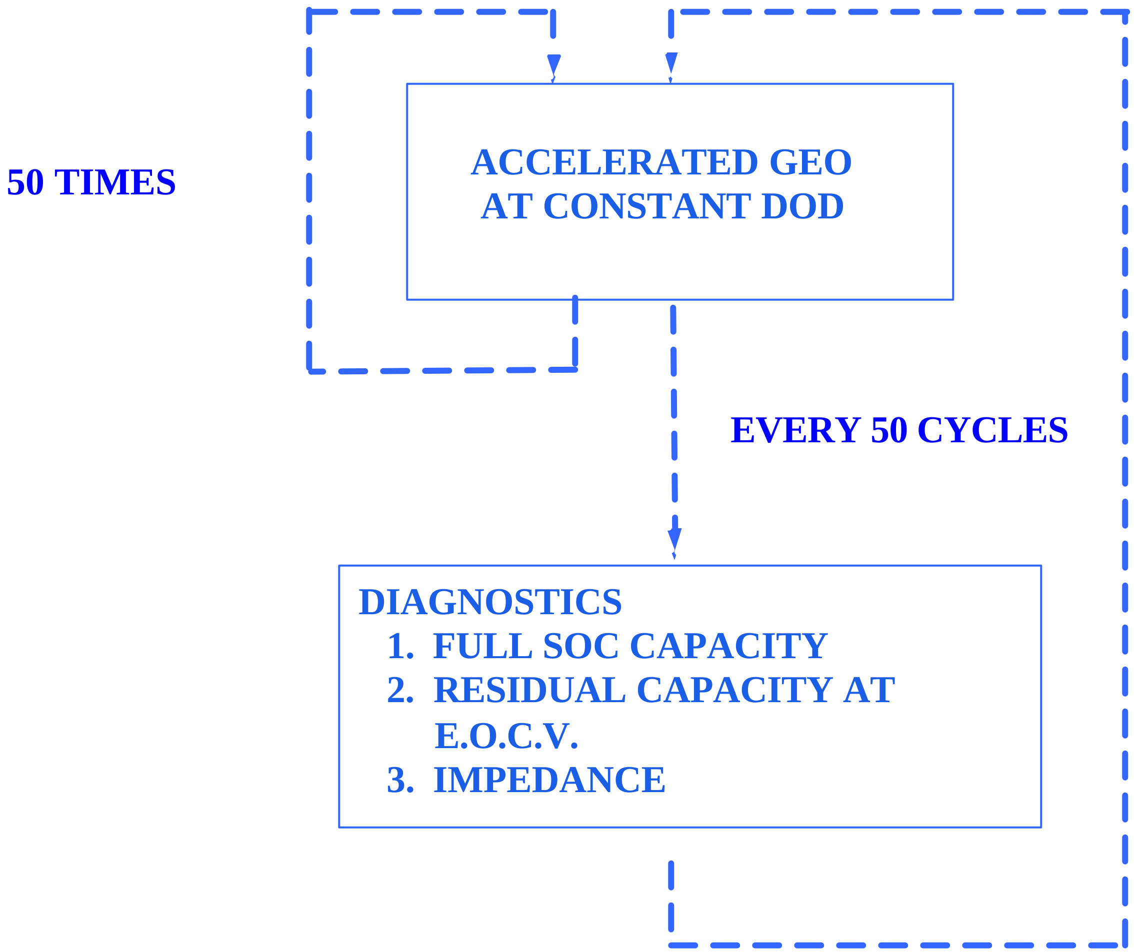
DD Cells LEO 30% DOD @ 25°C Energy
Discharge Energy (Wh)
40
35
30
25
20
15
10
5
0
0
5,000
10,000
15,000
20,000
25,000
30,000
Cycle No.
Average Wh Loss
1.48E-04 Wh / Cycle
11 DD cells with 9 Ah nominal capacity
Diagnostics were performed every 500 cycles
Curves shown are the Energy @4.0V and 3.75V during diagnostics

25^{0}C 30% DOD LEO Cycling, Prediction For 40,000 Cycles

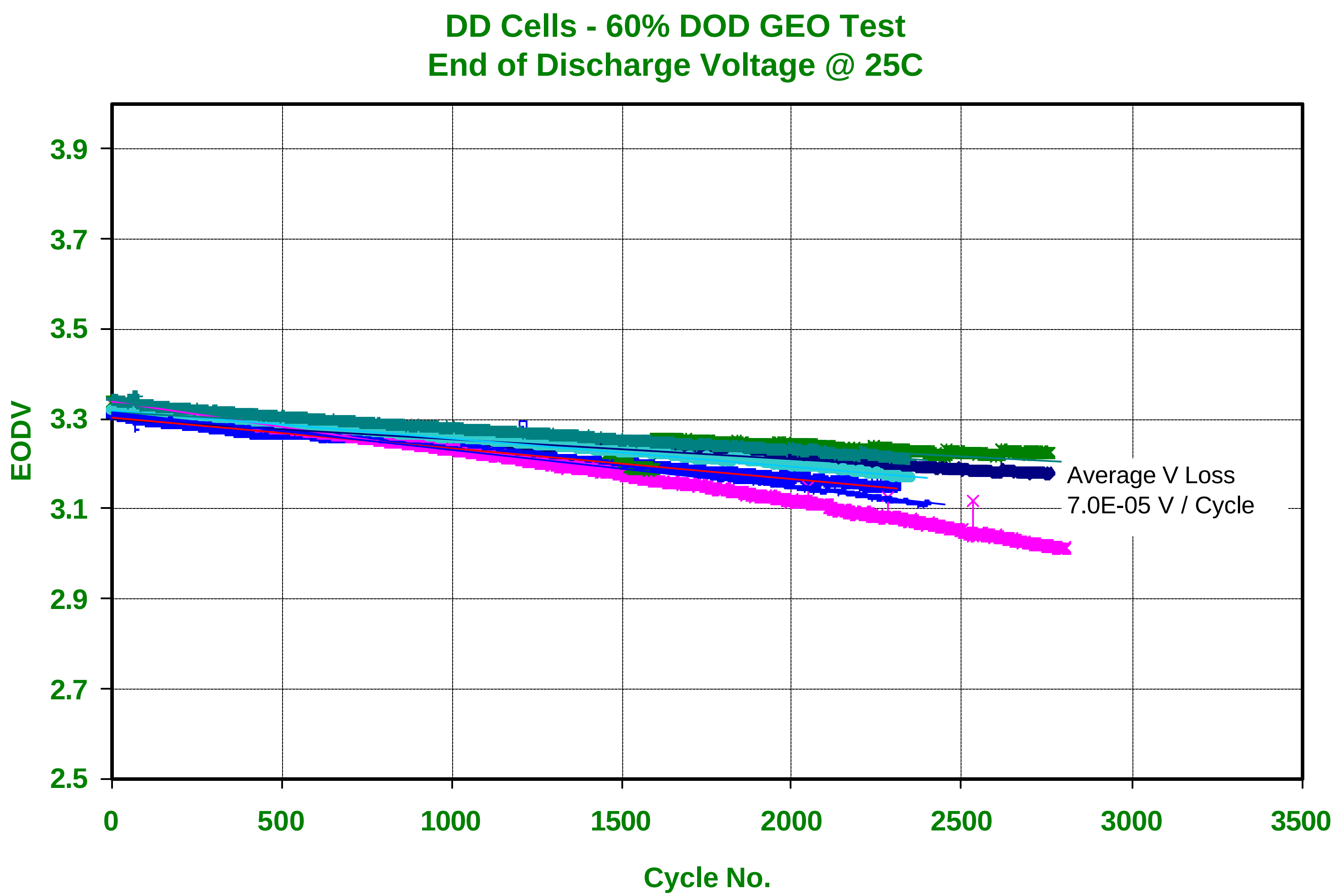
	Start	EOL	
➢ EODV	3.46V	DV=64 mV	EODV=3.396
➢ Capacity	8.5Ah @4.0V	DAh=1.92Ah	6.58Ah@4.0V
➢ Energy	30Wh	DWh=5.9Ah	24Wh

- EOL Conditions are 9Wh out, still a reserve of 5Wh charged or a reserve of 55% over demand

GEO TESTING


50 TIMES
ACCELERATED GEO
AT CONSTANT DOD
EVERY 50 CYCLES
DIAGNOSTICS
1. FULL SOC CAPACITY
2. RESIDUAL CAPACITY AT
E.O.C.V.
3. IMPEDANCE

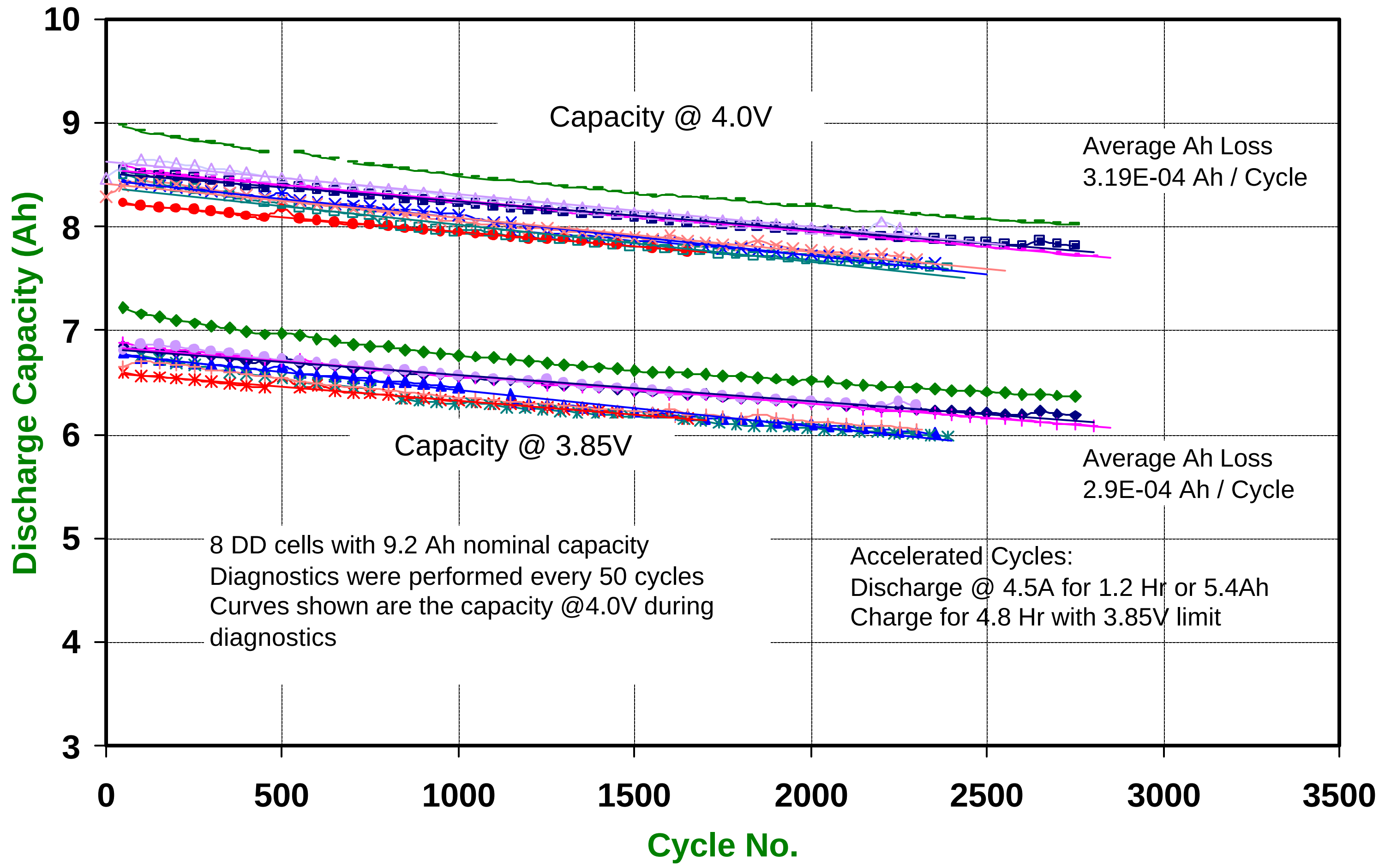
GEO TESTING



DD Cells - 60% DOD GEO Test
End of Discharge Voltage @ 25C
EODV
3.9
3.7
3.5
3.3
3.1
2.9
2.7
2.5
0
500
1000
1500
2000
2500
3000
3500
Cycle No.
Average V Loss
7.0E-05 V / Cycle

GEO TESTING

DD Cells GEO 60% DOD @ 25C   Discharge Capacity



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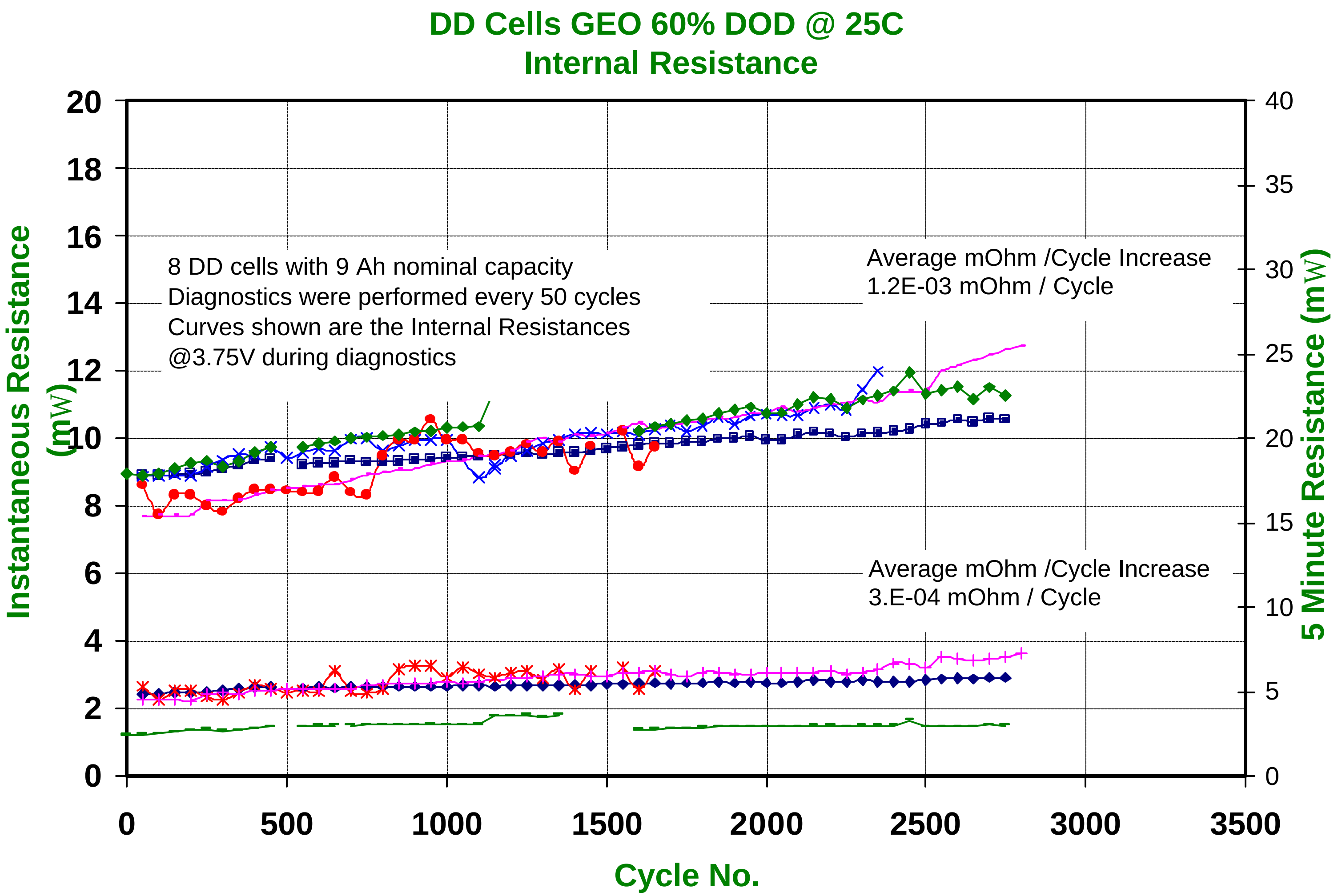
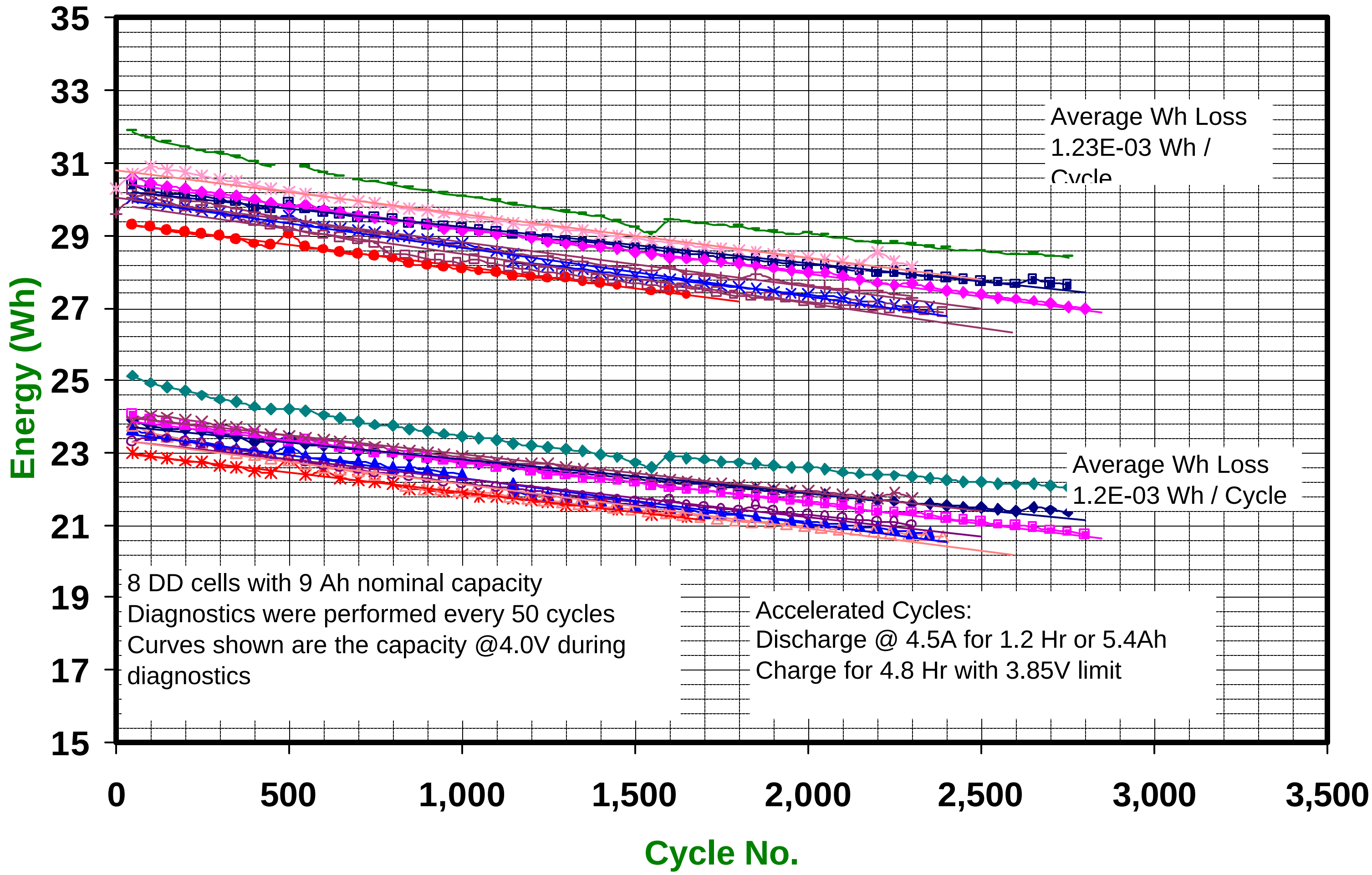
GEO TESTING



GEO TESTING

DD GEO 60% DOD @ 25C Energy



25^0C 60% DOD GEO Cycling

- By EOL 1350 cycles, 5.4% Energy Loss
- 2800 cycles, 11.5% Energy Loss

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CALENDAR LIFE

LIMITED NO. OF CELLS ON OCV TEST

- Cells stored on open circuit at 50% SOC at ambient temperature which is reasonable since a cycling cell is on average at 50% SOC

- Capacity measurement conducted at ambient temperature

- Diagnostic tests performed for impedance and capacity

- After 2.5 years storage data shows almost no capacity loss or impedance growth yet, thus we are unable to quantitatively state a loss factor on this group of cells, but it will be very low.

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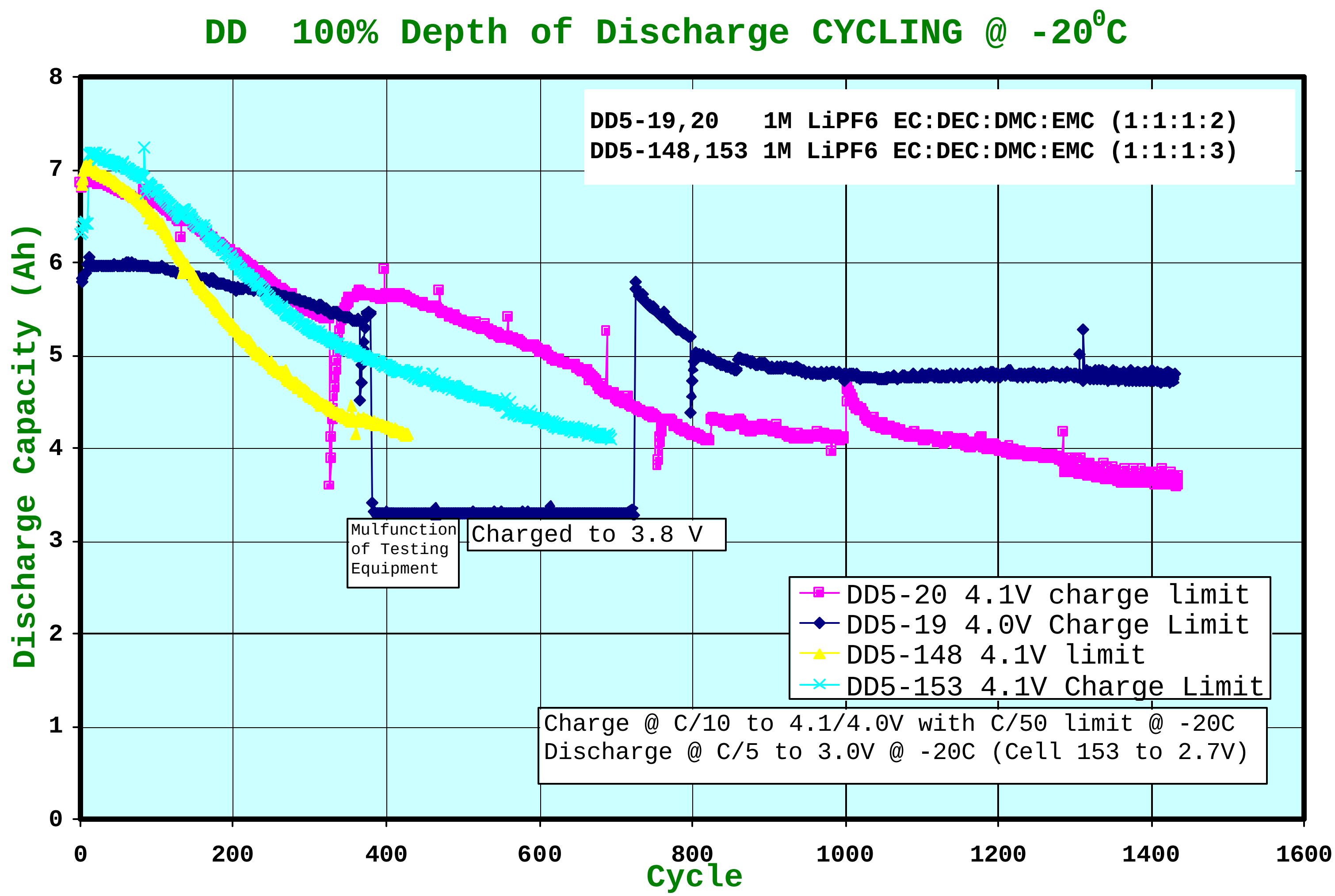
100% DOD @ -20^{0}C



100% DOD

-20^{0}C 100% DOD Cycling

- **@ 4.0V Charge Limit Capacity loss is less than 4.1V Charge Limit**
- **@4.0V Charge Limit**
  17% loss at 1430 cycles

CONCLUSION

- 30% DOD LEO Cycling,
  Predicted 19% Energy loss by 40,000 cycles
- By EOL 1350 cycles, 5.4% Energy Loss
  2800 cycles, 11.5% Energy Loss
- 100% DOD at -25^{0}C, 17% loss at 1430 cycles for 4.0V charge limit

Simulated LEO Cycling of AEA-STRV Lithium-Ion Battery Modules 2001 Update

Philip Johnson and Chuck Lurie
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R. Spurrett
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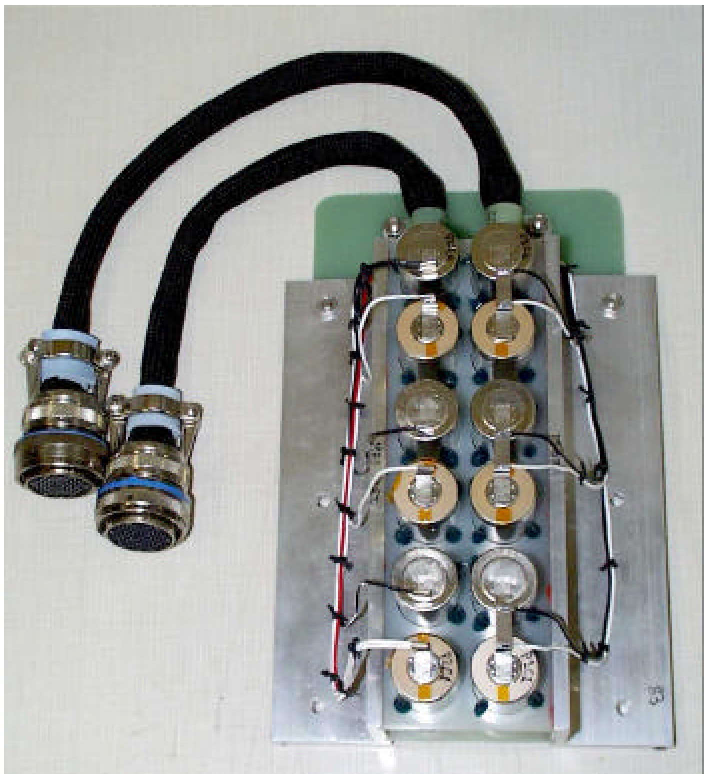
Abingdon, Oxon., England

The 2001 NASA Aerospace Battery Workshop
Huntsville Hilton
Huntsville, Alabama
November 27 - 29, 2001

Scope

- Lithium-ion battery modules, similar to the modules flown on the STRV spacecraft, have been on test for almost three years.
- The modules, designed and assembled by AEA Technology plc, each contain twelve Sony 26650 cells.
- Characterization testing and LEO cycling through 7700 25% DOD cycles were reported at this workshop last year.
- This presentation summarizes the results of the simulated LEO cycling to date.

Test Articles



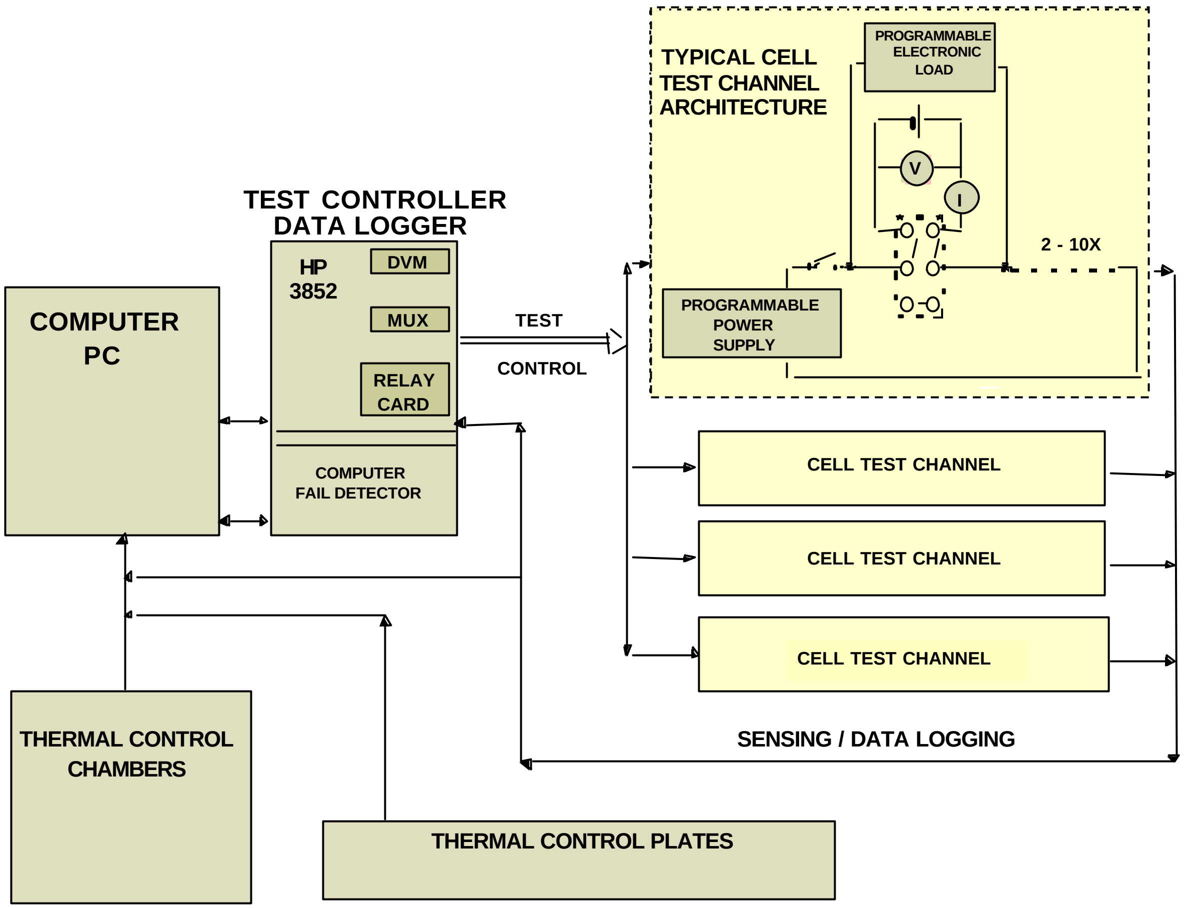
- STRV modules consist of two 6-cell strings of Sony 26650 cells.
- Test modules were reconfigured
  - one 6-cell string
  - two 2-cell strings
  - two individual cells
- Each cell is equipped with a thermocouple at its midpoint.

Test Plan

Simulated Leo Cycling

- Depth of Discharge: 25% (basis 2.7 Ah nameplate capacity)
- Orbit: 100 minutes with 36 minute eclipse periods
- Charge regime: 0.5C to CVL; taper until eclipse discharge
- Charge management: Pack level, e.g.,
  - 6-cell average voltage for the 6-cell packs
  - 2-cell average voltage for the 2-cell packs
  - individual cell control for the single cells
- Discharge: 0.42C (36 minutes)
- Two modules were tested; one at 25°C and one at 15°C

Test Setup



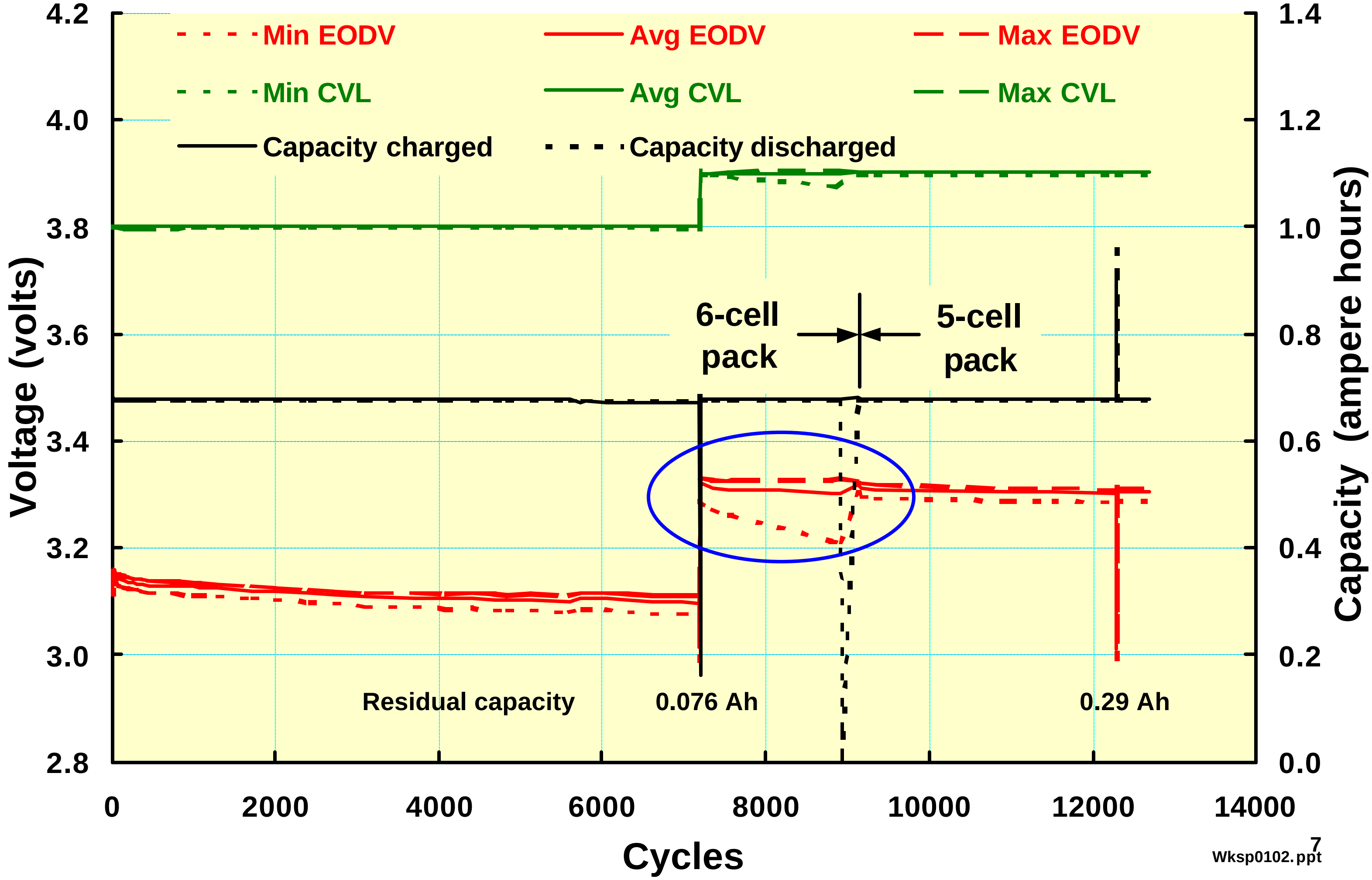
TYPICAL CELL
TEST CHANNEL
ARCHITECTURE
PROGRAMMABLE
ELECTRONIC
LOAD
V
I
2 - 10X
PROGRAMMABLE
POWER
SUPPLY
TEST CONTROLLER
DATA LOGGER
HP
3852
DVM
MUX
RELAY
CARD
COMPUTER
FAIL DETECTOR
COMPUTER
PC
TEST
CONTROL
CELL TEST CHANNEL
CELL TEST CHANNEL
CELL TEST CHANNEL
SENSING / DATA LOGGING
THERMAL CONTROL
CHAMBERS
THERMAL CONTROL PLATES

Simulated LEO Cycling Results

- 25°C End of Discharge Voltage trend charts
  - 6-cell pack
    - Became 5-cell pack at 9000 cycles
    - Discussion of unplanned event
  - 2-cell pack (typical of two)
  - single cells (both cells on one plot)
- 15°C End of Discharge Voltage trend charts
  - 6-cell pack
  - 2-cell pack (typical of two)
  - single cells (both cells on one plot)
- 6/5-cell pack dispersion analysis
  - EODV Trending
  - Rate of Change of EODV
  - EOCV Trending

25% DOD LEO Cycling at 25 Deg C

6/5-Cell Pack



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Cell No. 4 Anomaly

- Cell 4 was at the lowest SOC of the 6 cells in the 25ºC pack
  - 0.023 volts lower than the pack average at 25% DOD EOD
  - The test was started and run with about the same imbalance
- During test set configuration, following capacity discharge and CVL adjustment, the pack load went full-on driving cell 4 into reverse and terminating the test.
- The test was restarted manually, one time
  - e.g., the reversal event occurred twice.

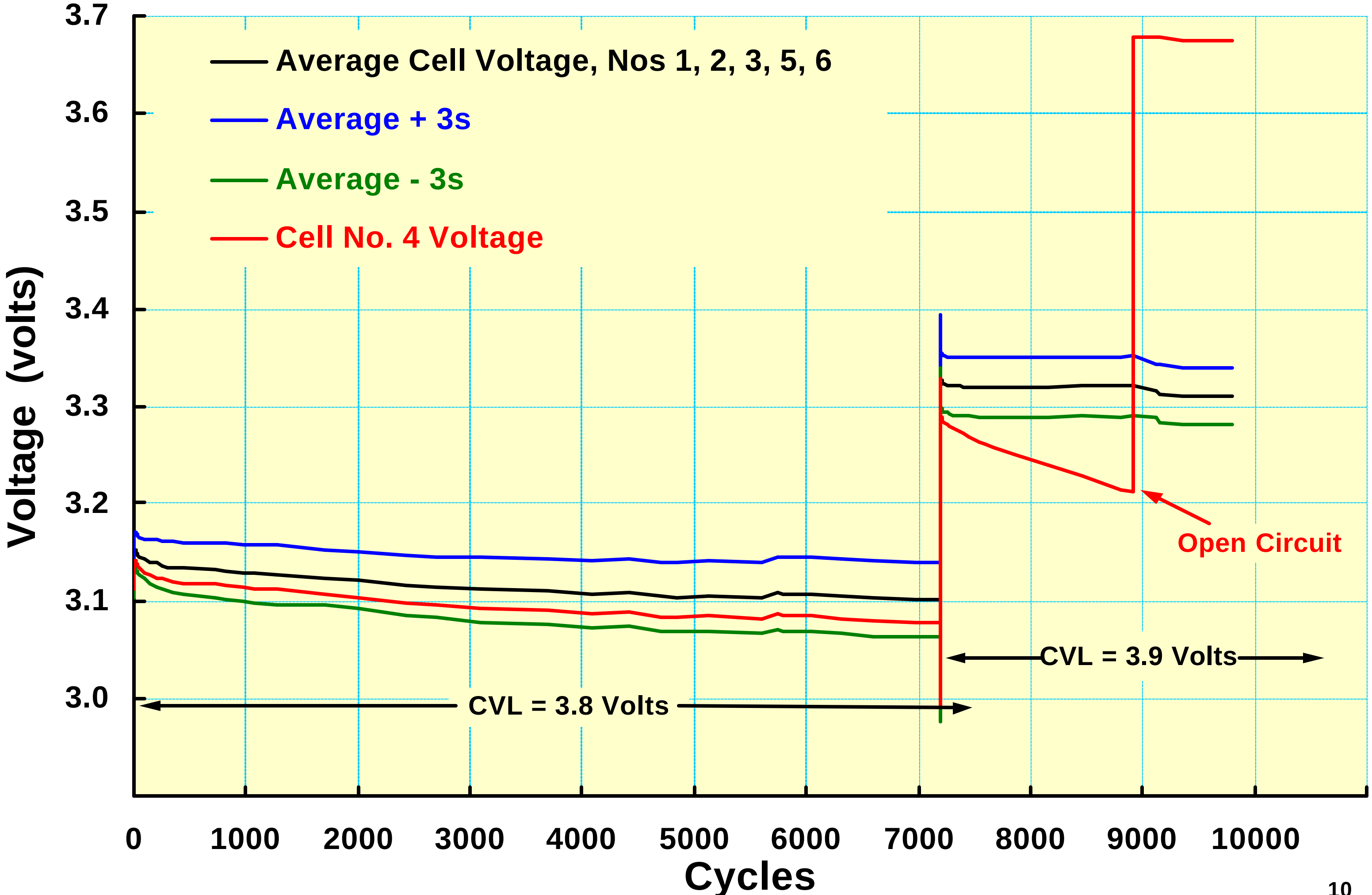
Cont'd

Cell No. 4 Anomaly Cont'd

- Anomaly Data
  - The events were short and only grab samples are available
  - Duration, each event: 5 - 15 seconds
  - Voltage, Current
    - First: V = -7.8 volts, I = > 10 amperes
    - Second: V = < -10 volts, I = 4.8 amperes
    - Temperature excursions were negligible
- The test was shut down
  - The problem diagnosed and corrected
  - No physical damage was observed and the test was resumed with Cell 4 in place
- Performance was degraded and Cell 4 was removed from the test after ~1700 additional cycles

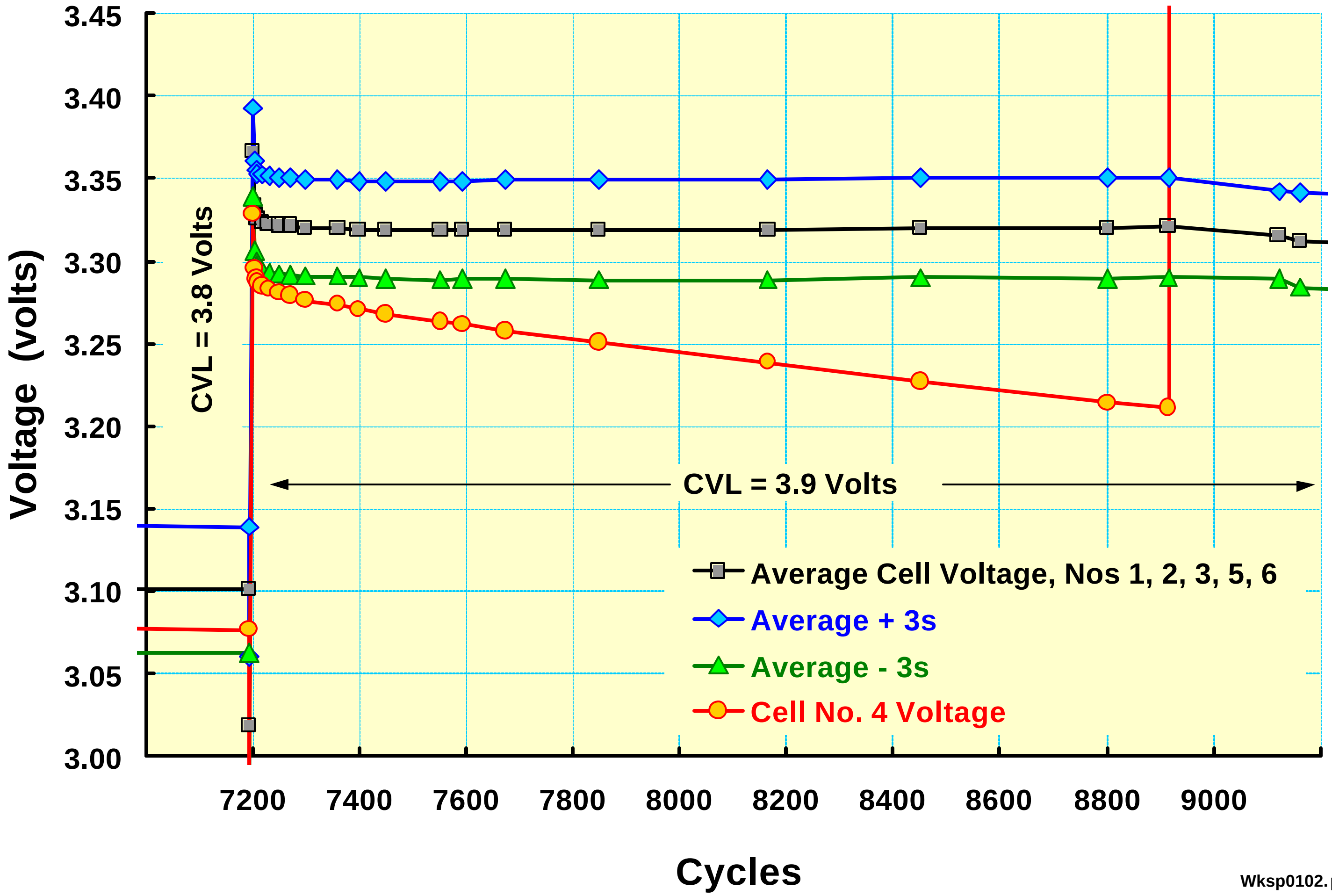
Cell No. 4 Performance Change

End of Discharge Voltage Following Anomaly

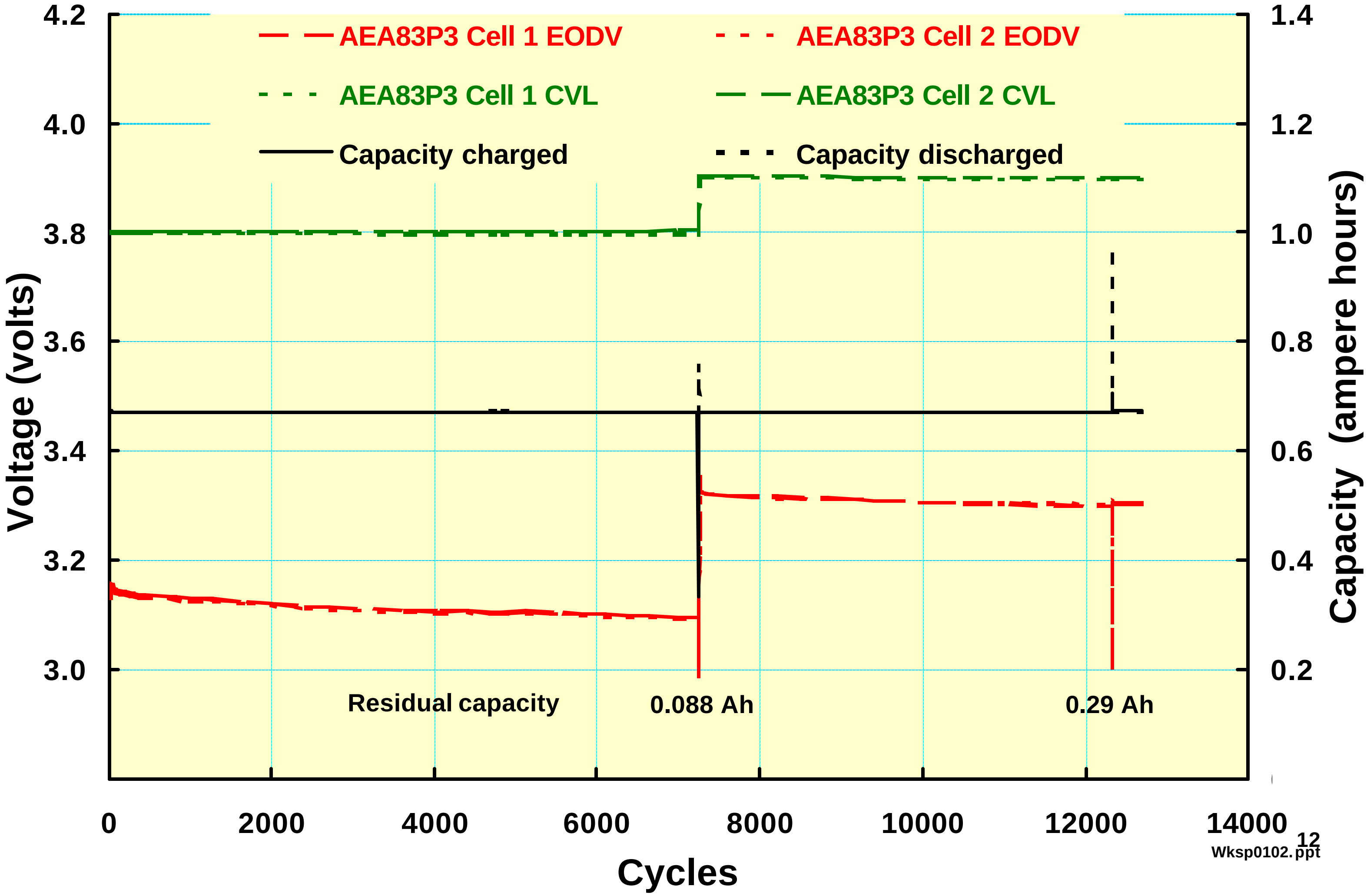


Cell No. 4 Performance Change

End of Discharge Voltage Following Anomaly -- Detail



25% DOD LEO Cycling at 25 Deg C
2-Cell Pack



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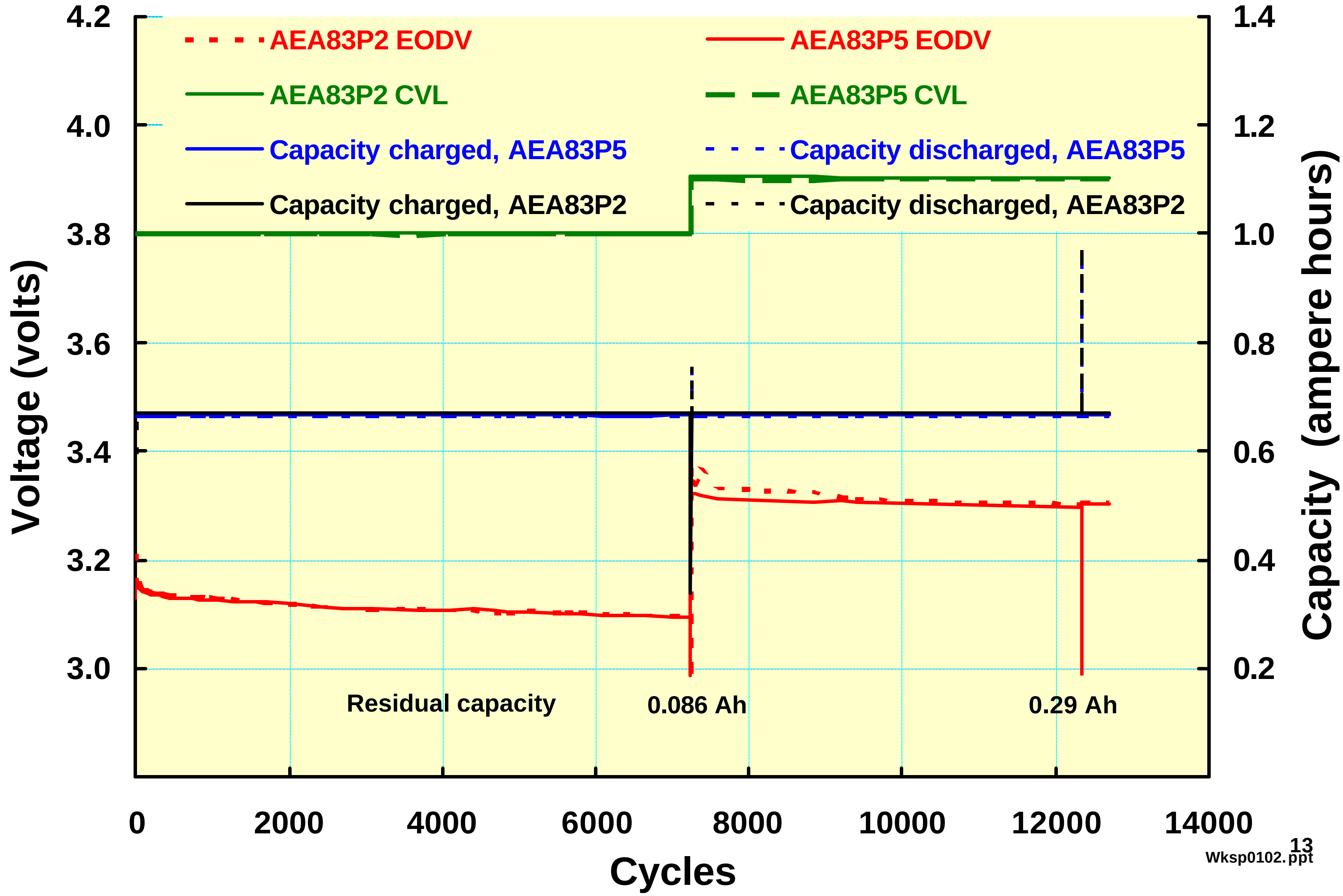
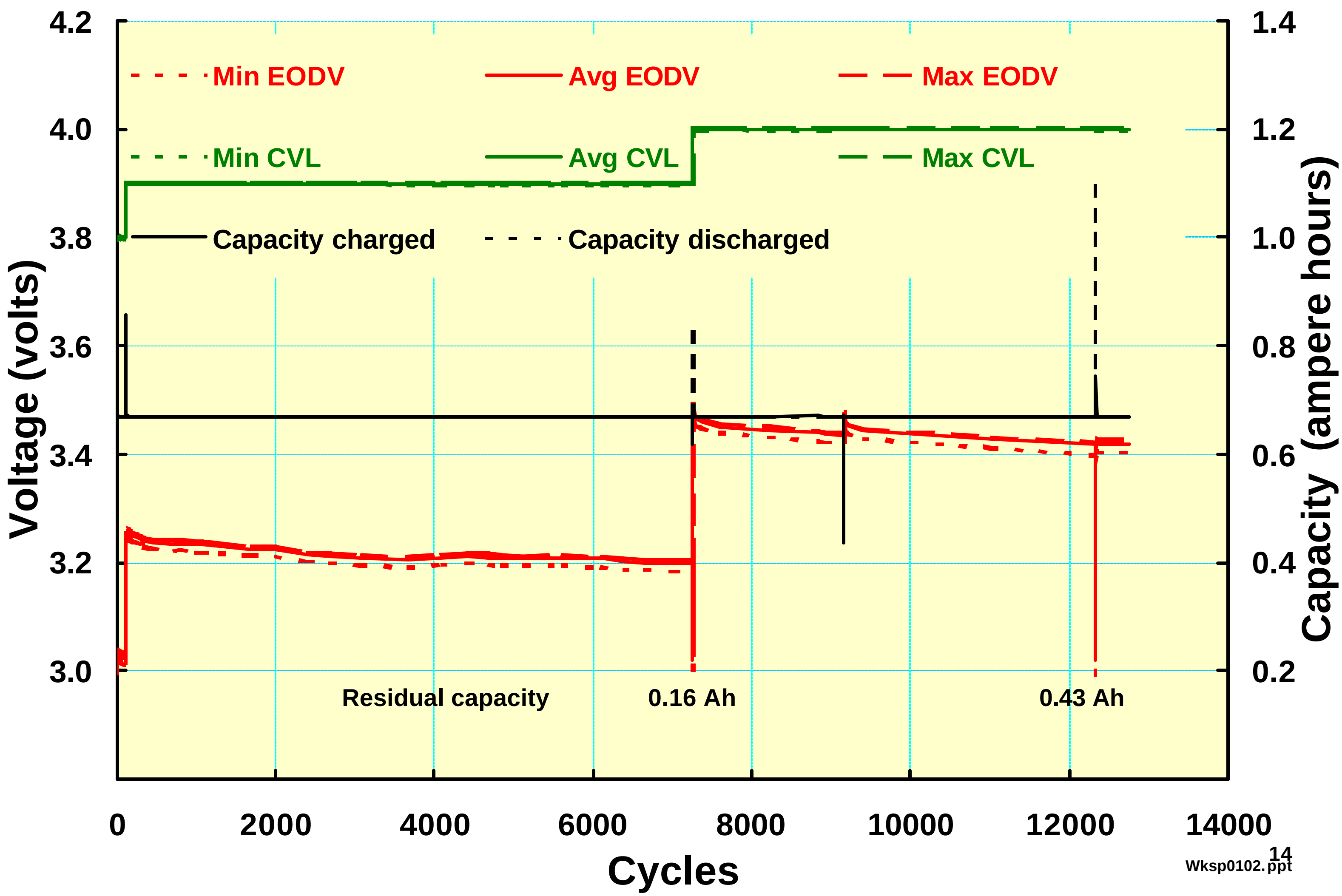
25% DOD LEO Cycling at 25 Deg C

Single Cells



25% DOD LEO Cycling at 15 Deg C

6-Cell Pack



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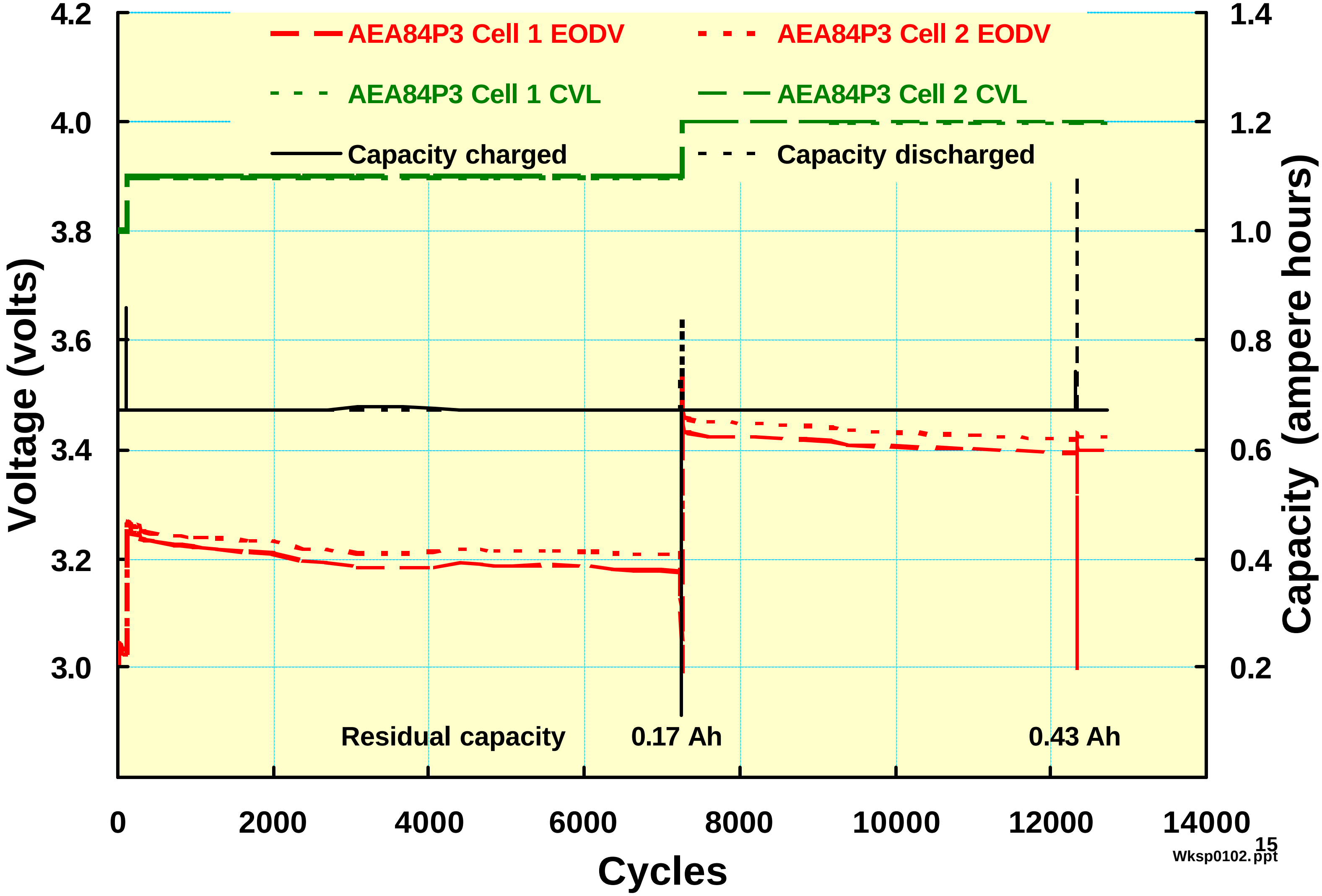
25% DOD LEO Cycling at 15 Deg C

2-Cell Pack



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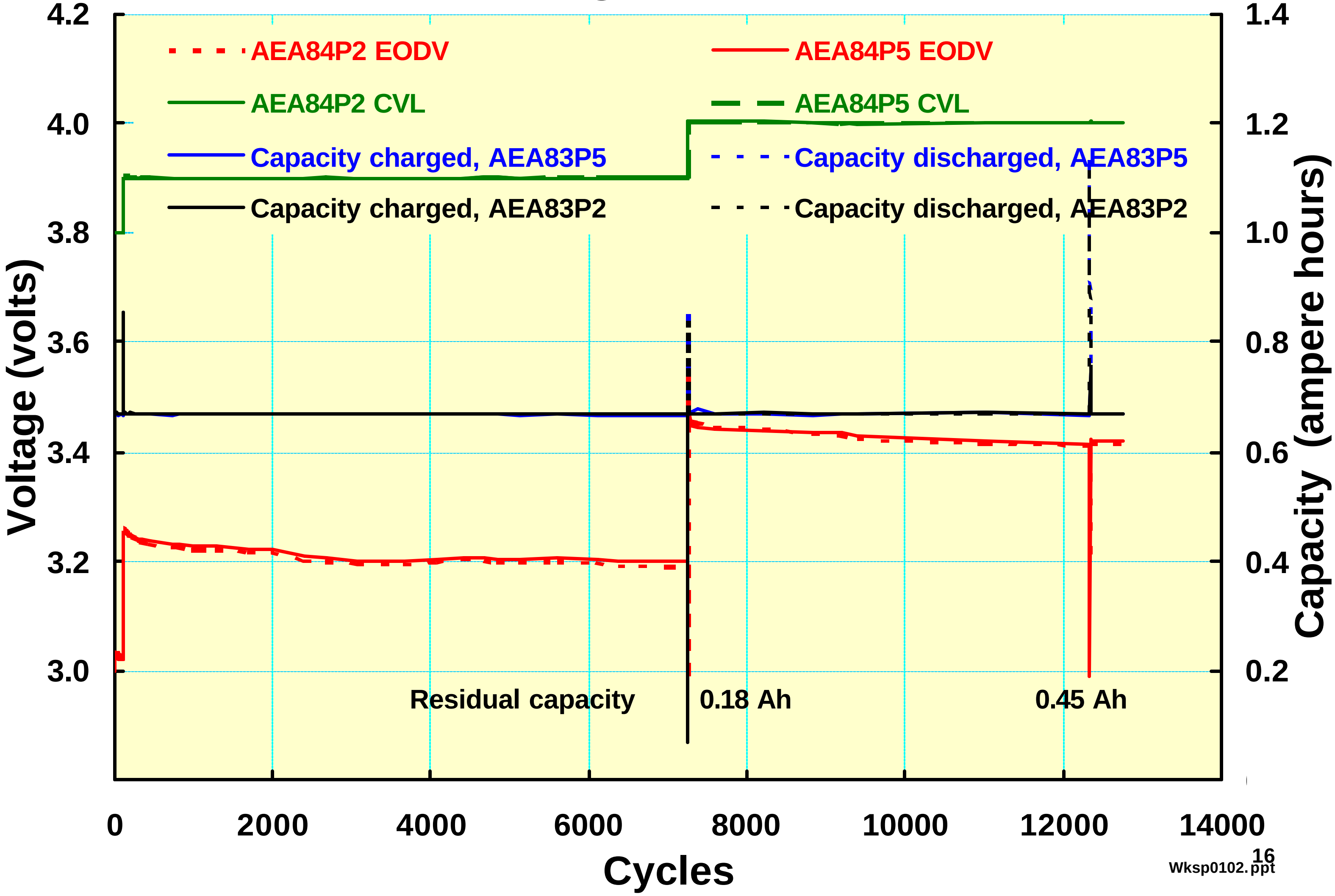
25% DOD LEO Cycling at 15 Deg C

Single Cells



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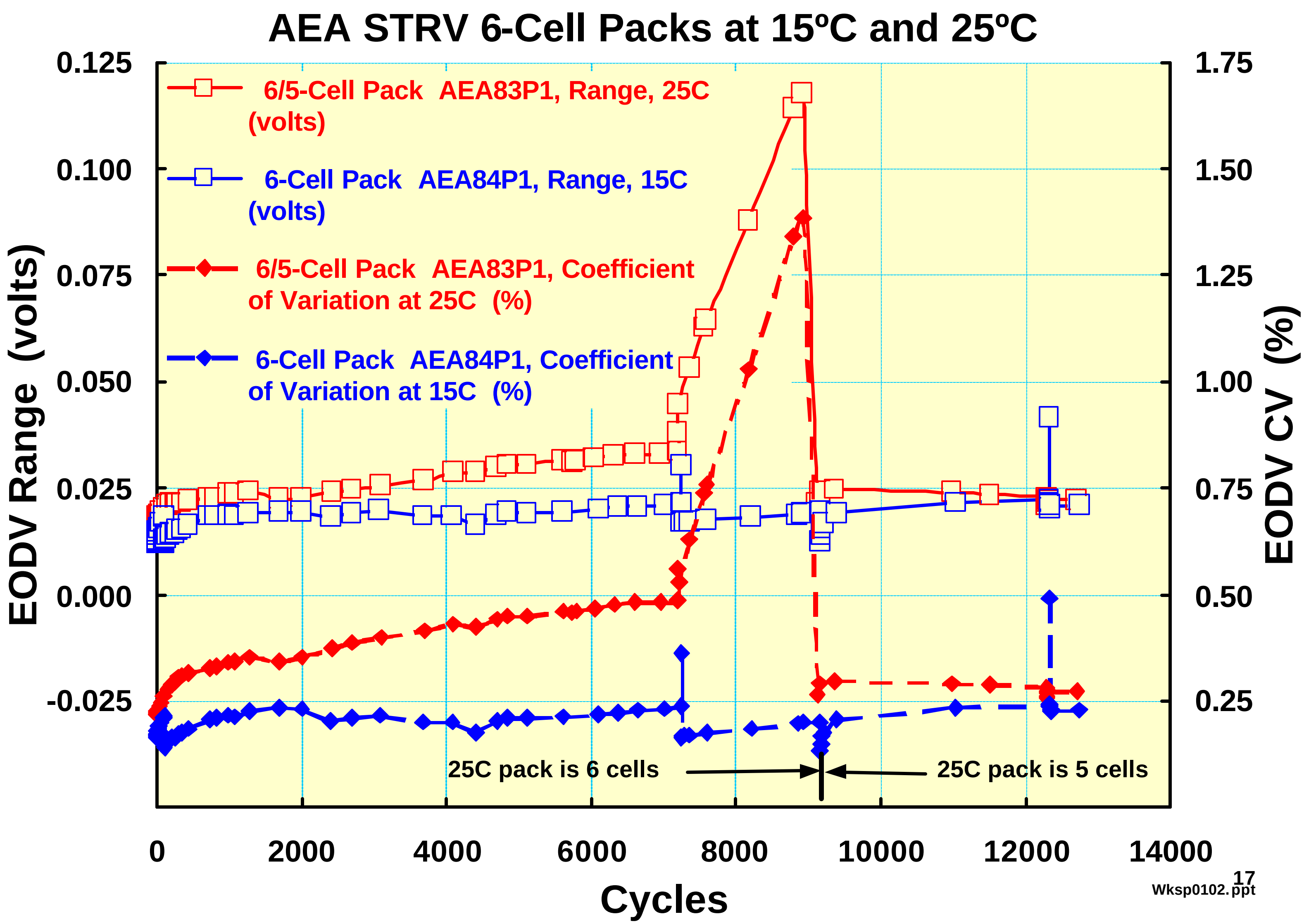
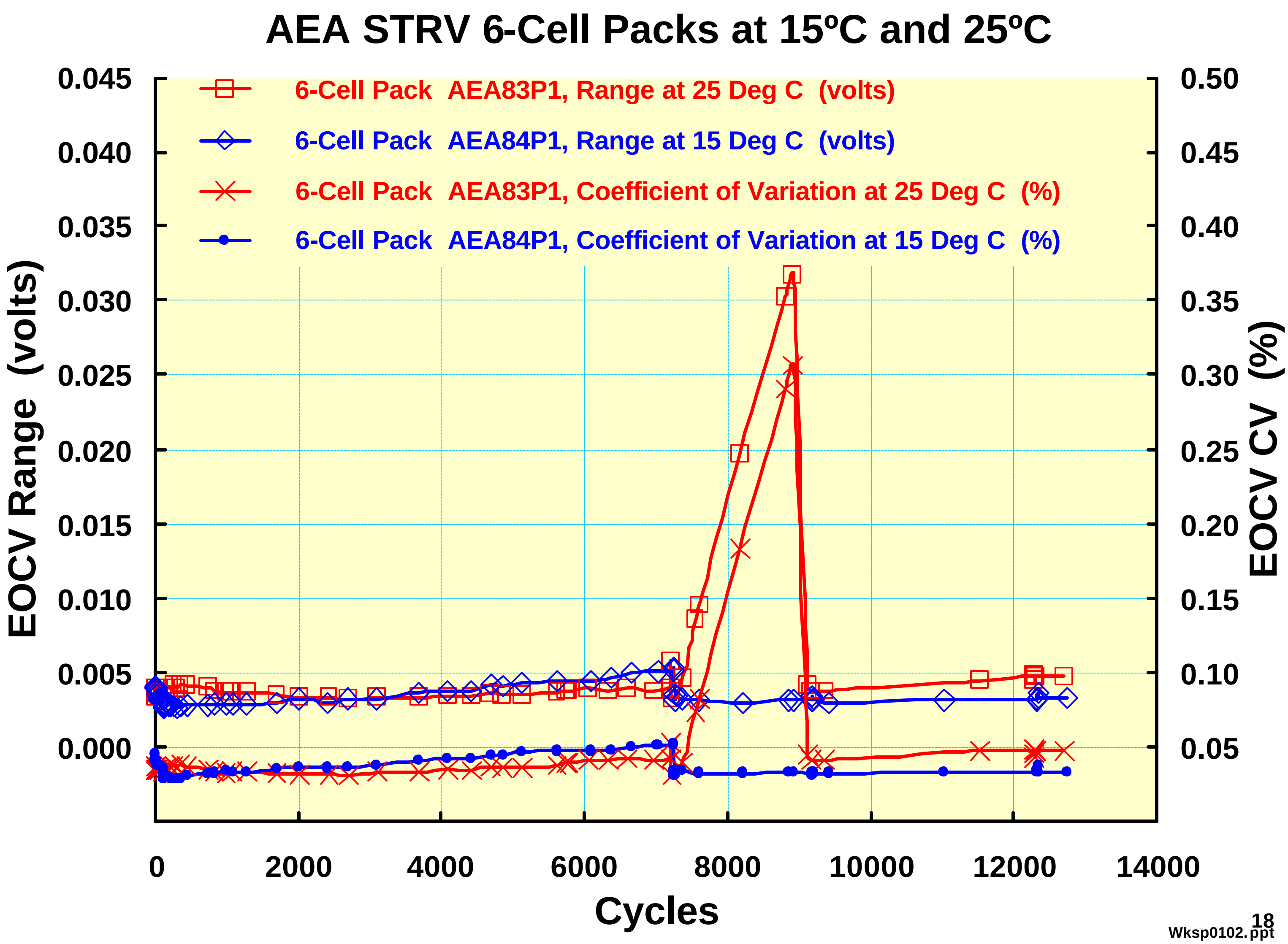
EODV Dispersion Trending



EOCV Dispersion Trending



Summary

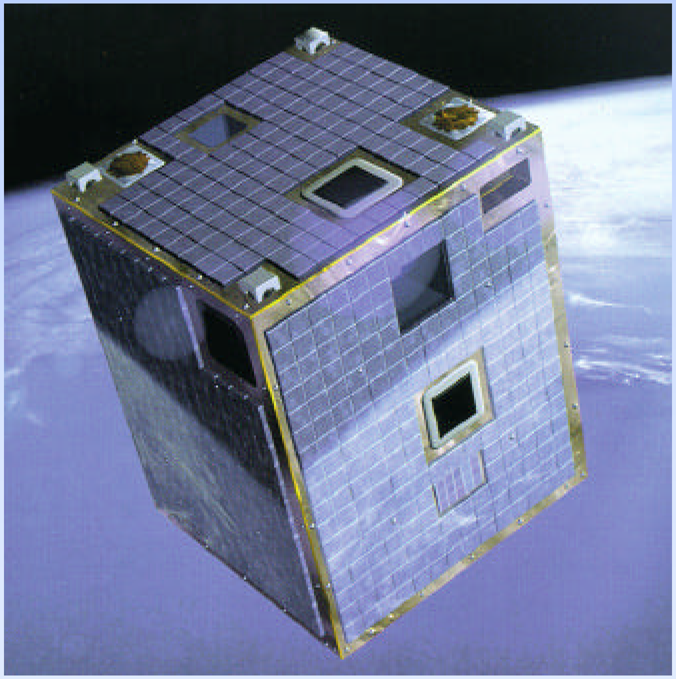
- Simulated 25% DOD LEO cycling of AEA STRV battery modules is continuing at 15ºC and 25ºC
  - The STRV "two 6-cell strings" configuration was modified to provide 6-cell strings, 2-cell strings and individual cells.
  - Charge control is at the pack level.
- > 13000 cycles have been completed.
- A significant cell reversal anomaly occurred and has been described.
- EOD and EOC voltage dispersion (in the absence of cell level balancing) is stable and similar for all packs.
- The test is continuing.

PROBA, The First ESA Spacecraft Flying Lithium-Ion

M. Schautz, D. Olsson & G. Dudley

European Space Technology Centre (ESTEC)

A. Holland (AEA Technology)



Contents:

Proba overview

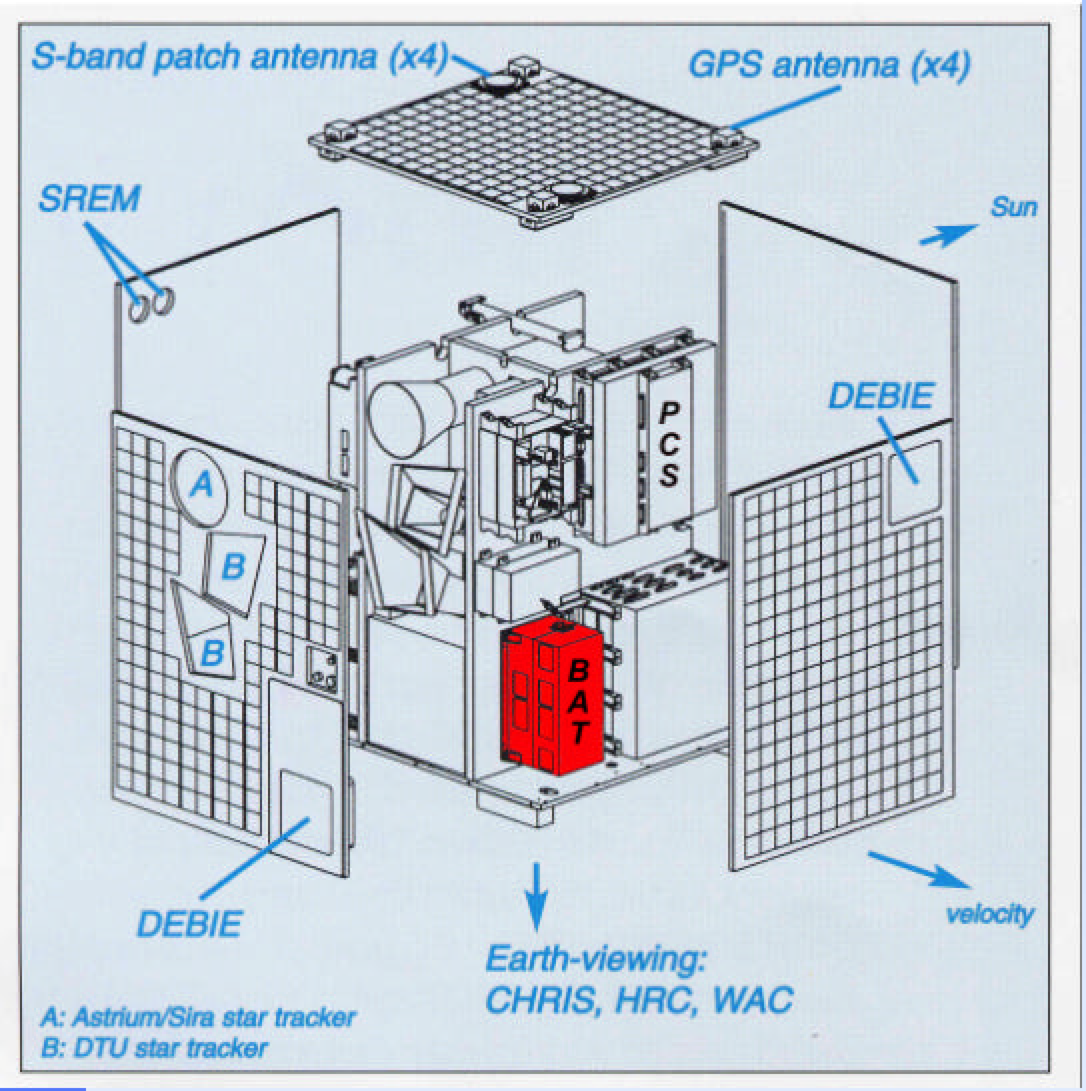
Battery design

In-orbit performance

PROBA Objectives

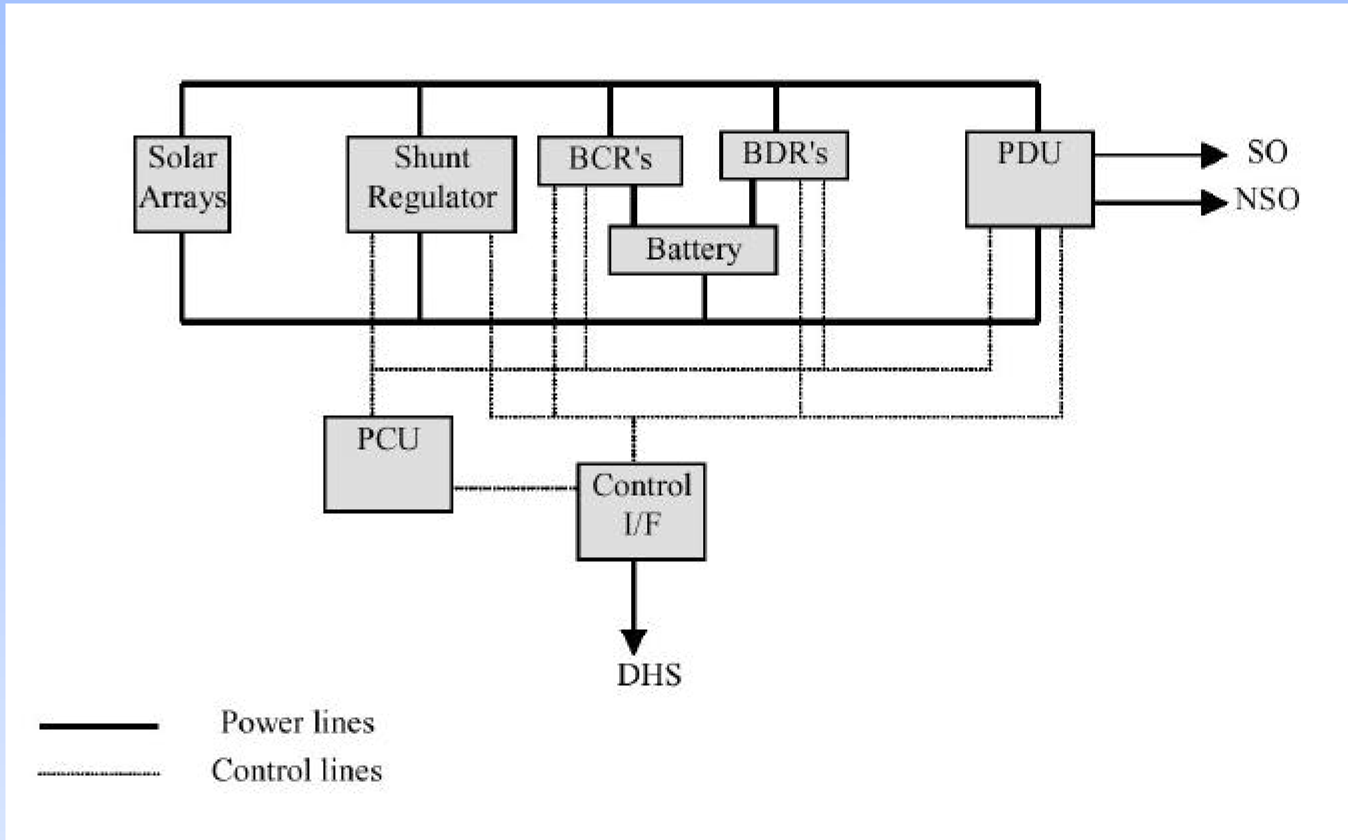
- *PRoject for On Board Autonomy:*
  - *Onboard resource management, housekeeping*
  - *Scheduling and execution of scientific observations*
  - *Scientific data collection, storage, processing & distribution*
  - *Data communication management*
  - *Performance evaluation, failure detection*
  - *Failure detection, reconfigurations, software exchanges*
- *Payload:*
  - *Compact High Resolution Imaging Spectrometer (CHRIS)*
  - *Space radiation Environment Monitoring (SREM)*
  - *Debris in orbit evaluator (DEBIE)*
- *Technology Demonstration:*
  - *GPS receiver for navigation and attitude determination*
  - *High resolution camera (HRC) and wide angle camera (WAC)*
  - *Autonomous star tracker*
  - *High performance computer*
  - *Lithium ion battery (BAT)*

Spacecraft Overview



- *Mass: 95 kg*
- *Dimensions: 600 x 600 x 800 mm*
- *2 yr mission*
- *Polar (97.8 deg), 600 km orbit*
- *3-axis stabilised*
    - *Attitude detection by star tracker + GPS-based attitude sensor + 3-axis magnetometer*
    - *Control by magneto-torquer + reaction wheels*
- *Radiation-hard version of SPARC V7 processor (10 MIPS)*
- *No propulsion (2 deg/yr drift from sun-synchronism acceptable)*
- *No heaters (passive T/C)*

PROBA Electrical Power Sub-system



- *Regulated 28V bus with S^3R control (heritage from STRV)*
- *Body-mounted GaAs SA (90W peak)*
- *Triple redundant majority-voting PCU*
- *Dual redundant BCRs and BDRs*
- *Single 9 Ah Lithium-Ion Battery*
- *Each PDU output has current-limiter. SO also have PCU-controlled switch*

Battery Choice for PROBA

- *Originally specified Ni-Cd battery, using spare ESTEC stock of 7 Ah cells to be packaged into battery similar to Meteosat-1.*
- *21y old freezer-stored Ni-Cd cells were found still to have nominal performance!*
- *But marginal capacity with respect to needs and high mass (6.4 kg compared to 1.9 kg for Li-Ion)*
- *Small Li-ion battery concept from AEA Technology already qualified.*
- *Less critical pre-launch and integration handling constraints.*
- *Opportunity to fly Li-ion quickly.*
- *Added as a technology demonstration but confidence sufficient to rely entirely on single lithium ion battery.*

esa

Lithium ion battery development

- *Use of commercial off-the-shelf (COTS) SONY hard-carbon cells for space introduced by AEA Technology for STRV 1d (launched Nov. 99) in the frame of a UK national programme sponsored by the BNSC.*
- *Battery concept developed qualified for small-medium applications by AEA Technology under UK-funded ESA GSTP contract in 1997-1998. This included comprehensive lot acceptance testing philosophy required to overcome reduced configuration control associated with COTS components*
- *Ground life-testing at ESTEC very promising (ongoing tests have now reached >16000 30% DoD LEO cycles)*
- *Confirmation obtained that cells remain balanced in state of charge without need for adjustment by electronics*
- *EM + PFM batteries for Proba provided under rider to above contract starting Jan. 2000*
- *Battery PFM qualification completed Nov 2000*

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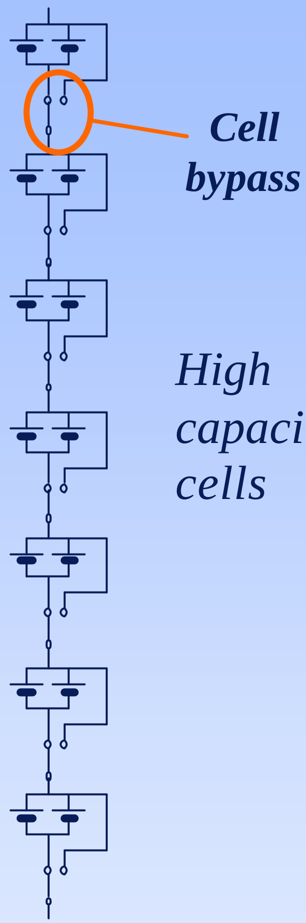
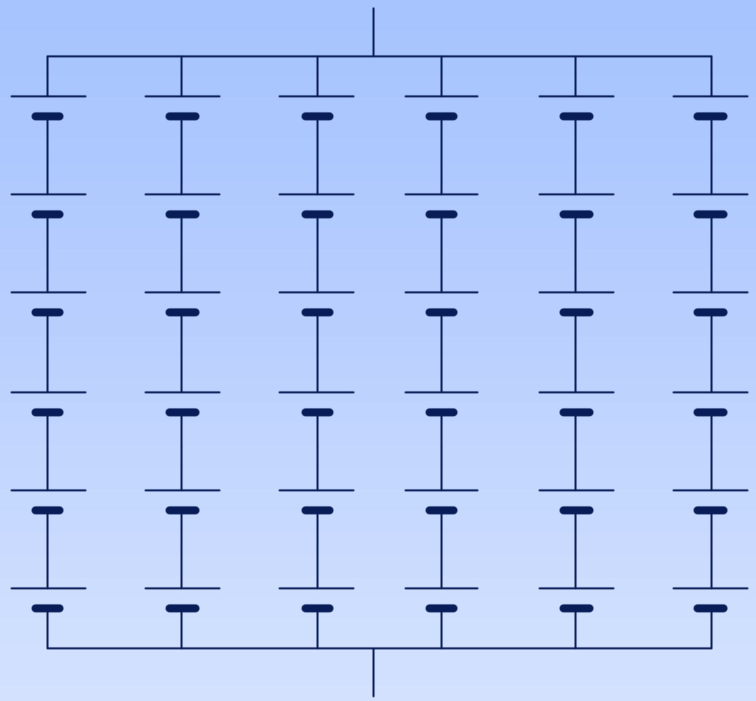
Cell Stringing Approach



High capacity cells

"Conventional" stringing

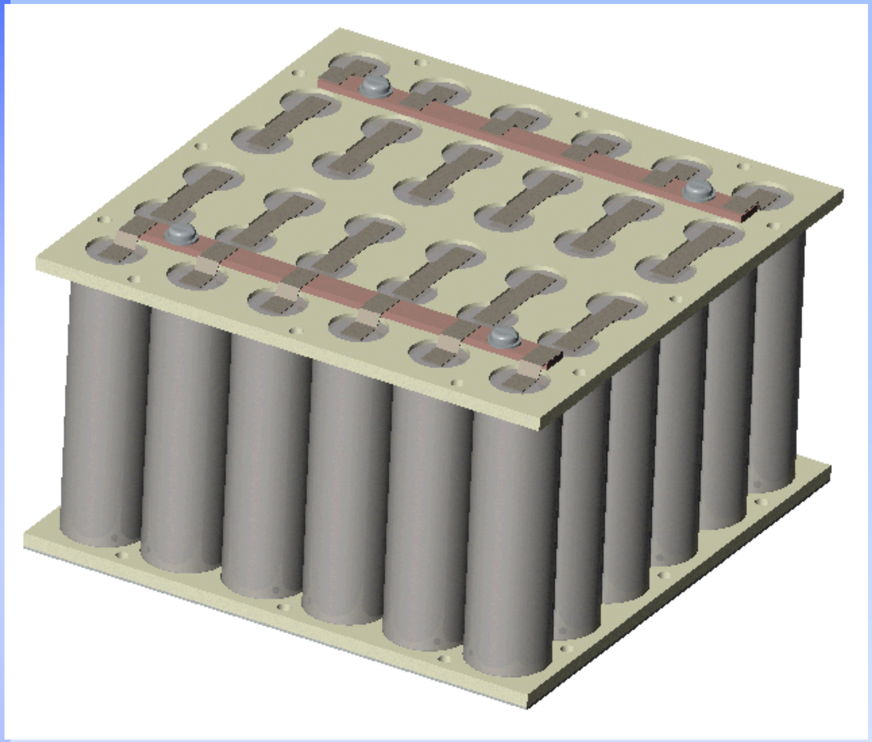
1.5 Ah cells



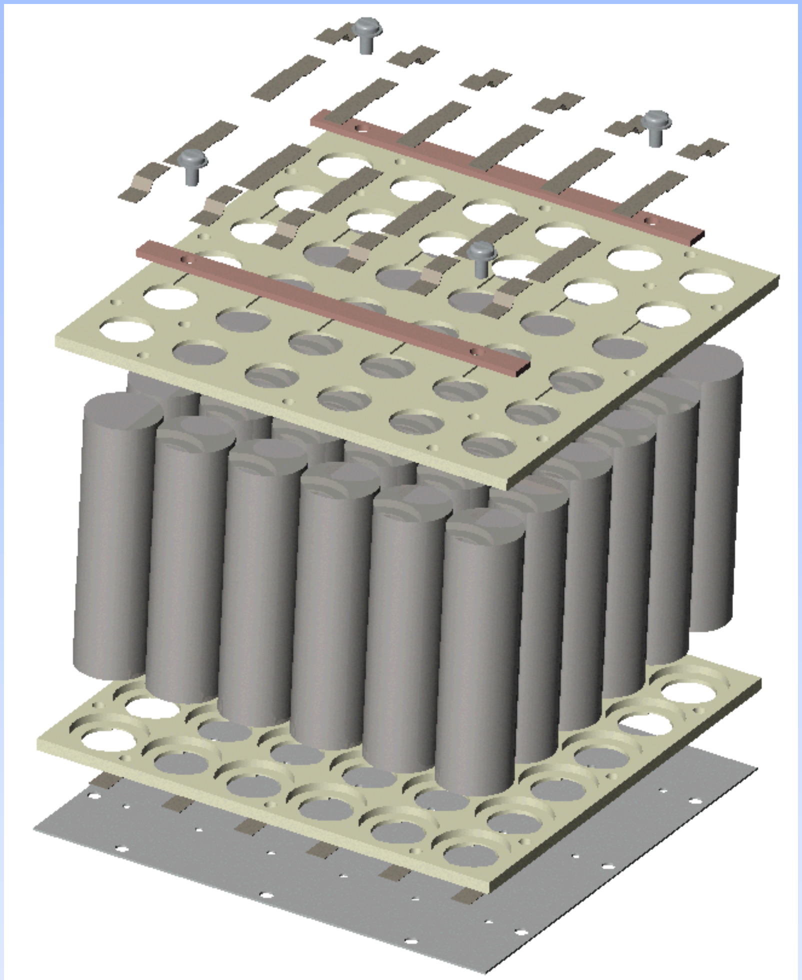
AEA/SONY PROBA 6s6p battery. Any cell failure leads (eventually) to loss of 1 (redundant) series string. No cell bypass necessary.

esa

Battery Construction



36 Sony 18650 HC cells glued into insulating GRP plates. Spot-welded nickel cell interconnects. Ni-plated copper bus bar



Exploded view

PROBA Battery

- *Mass: 1.87 kg*
- *Specific energy: 104 Wh/kg*
- *GRP cell-holding plates supported in aluminium structure.*
- *Cell interconnects protected by Kapton sheets.*
- *Single-point failure tolerant design.*
- *Shown mounted on interface plate (Verhaert) providing thermal decoupling from spacecraft*

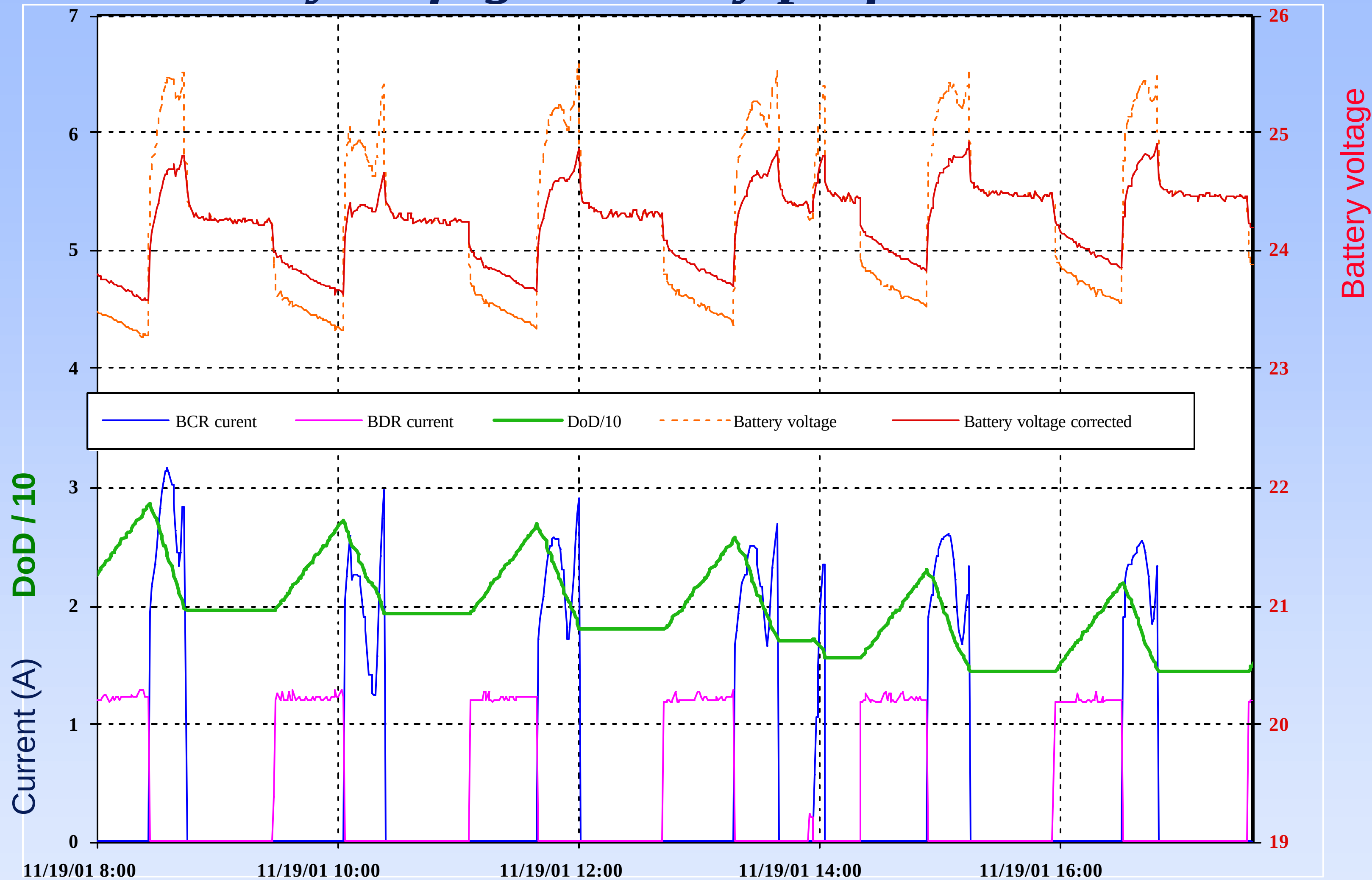
Proba Schedule

- *10 M€ program funded from ESA General Study Technology Program (GSTP)*
- *Kicked off February 1998*
- *Prime contractor: Verhaert Design and Development (Belgium)*
- *SDR June 1998*
- *FAR July 2001*
- *Launched from Shriharikota (India) on PSLV Oct 22 2001*
- *Currently in checkout / calibration phase*
- *One ground station (Redu Belgium)*

Proba Launch Configuration

Launched together with Bird (German minisatellite) as piggyback paylod to Indian experimental remote sensing satellite.

Early in-flight battery performance



Charge terminates when battery voltage including harness voltage drop reaches programmable limit (taper charge not operational). DoD expected to increase from 8% to 15% in operational phase

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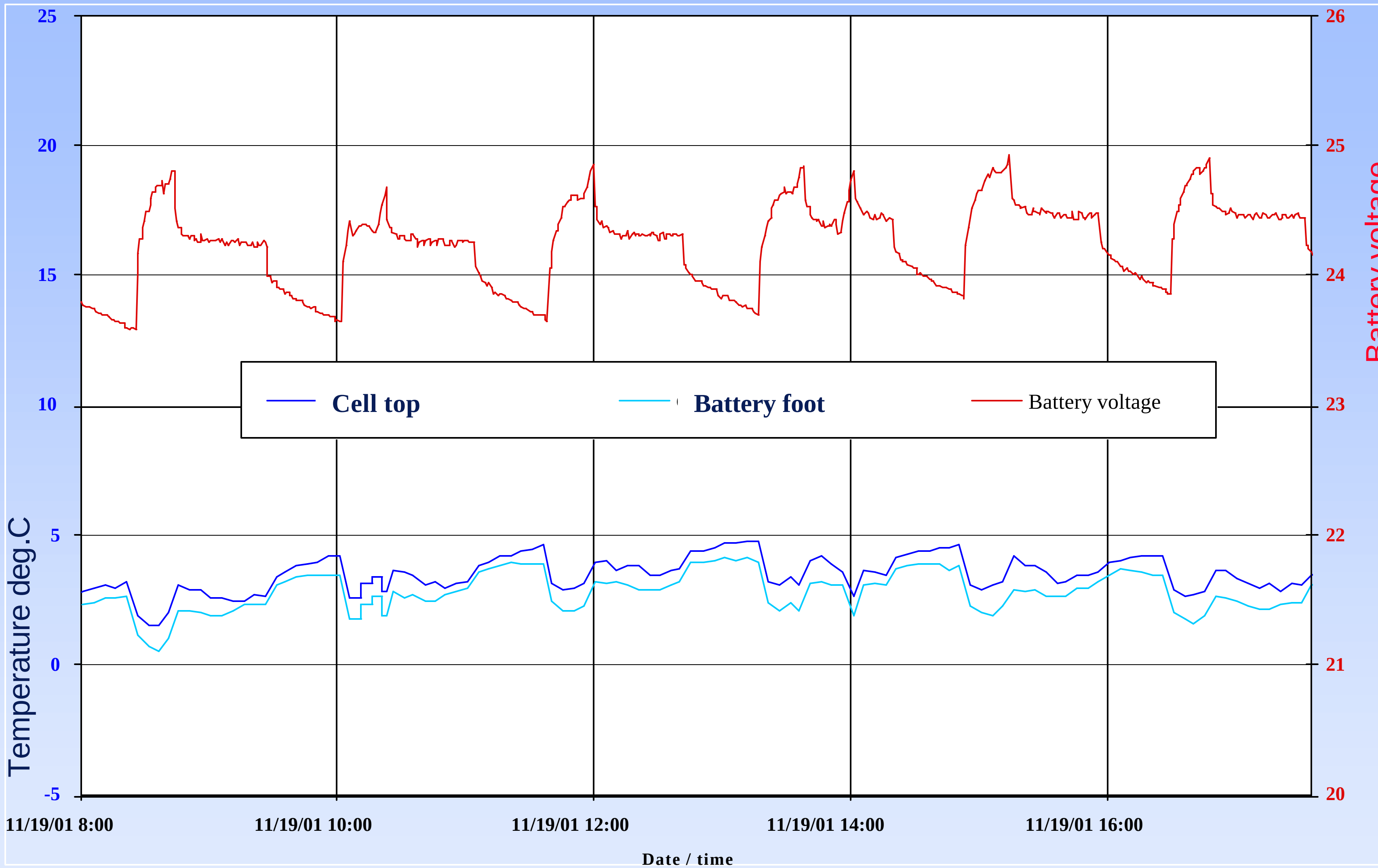
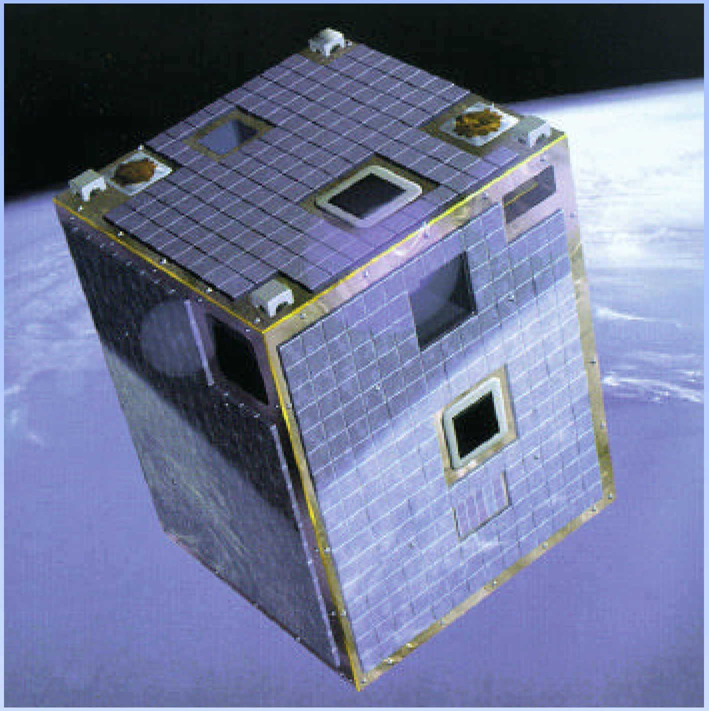
Early in-flight battery performance (2)



Battery currently cold because of limited payload use during check-out phase (no heaters)

Conclusions

First European Spacecraft to rely entirely on lithium ion battery is now in orbit.



- *Battery performance is nominal*
- *Lithium-ion batteries are baselined for most future European programmes including Stentor, Rosetta (+Roland lander), Mars Express (+Beagle lander), Smart-1, Cryosat, GOCE, Netlander …etc.*

Life Test Results with Adaptive Charge Control

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The Aerospace Corporation
El Segundo, California USA 90245

Abstract

Adaptive charge control has been developed to enable a power system to automatically sense the recharge needs of each cell in its complement of batteries, and to provide only the recharge that that cell requires. This enables the charge control system to handle any imbalances in performance behavior between the cells, to minimize the stress on each cell, and to automatically adjust recharge behavior according to the cell's changing needs over life. Results will be presented from thermal vacuum life tests on Li-ion cells, from a life-test running Li-ion cells in the same pack as nickel cadmium and nickel metal hydride cells, and from a nickel hydrogen life test. Adaptive charge control has demonstrated the capability to optimally operate cells having widely different behavior in the same battery pack.

Introduction

An Adaptive Charge Control (ACC) technique has been developed at The Aerospace Corporation[1] that is capable of determining and maintaining the correct amount of recharge needed by battery cells as they are charged and discharged over their lifetime. As a battery cell is operated in a power system, the ACC determines the amount of recharge required by each cell to keep that cell at a required operating voltage level. As each battery cell ages or otherwise changes its performance, the ACC automatically adjusts the recharge to both maintain performance while eliminating any unneeded overcharge. The basis for this charge control method is the following general conclusion that we have come to - that any unneeded overcharge on a battery cell produces a significant stress that contributes to wear out and that can be avoided.

The basis for the ACC system is the use of a recharge fraction specific to each individual cell in a battery. When the prescribed recharge fraction is reached for a cell, all recharge current is shunted around that cell but remains available to recharge other cells that may need more recharge. The needed recharge fraction for each cell is based on where the minimum discharge voltage and peak recharge voltage levels are relative to an operational voltage band consistent with cell performance and the minimum voltage level needed from each cell for the power system. The ACC allows this voltage band to expand if needed to accommodate changes in cell performance over life. Within the ACC paradigm, cell failure occurs when a cell cannot deliver the required capacity above the minimum system level voltage and when the cell cannot be recharged without exceeding maximum safe levels for recharge voltage and recharge fraction. Thus, not only will the ACC respond to changes in cell performance due to aging, but it will also automatically adjust for any variations in temperature, charge current, or current measurement accuracy that may affect battery performance.

Here we describe three different battery life tests that demonstrate the features and capabilities of the ACC system, as well as providing a useful database for the performance of a range of battery cells operating in a minimum stress cycling mode. The first of these tests demonstrates the use of the ACC system in a thermal vacuum test of a mockup nanosatellite power system. This system operates a 2-cell lithium-ion battery having a capacity of 0.8 Ah, and operating with a predicted diurnal nanosatellite temperature swing at 20% DOD. The second test is designed to demonstrate the ability of the ACC system to correctly adapt to the disparate charge needs of cells having widely different performance behavior, but still operating successfully in a single battery pack. This test puts two 7 Ah lithium-ion cells, two 7Ah NiCd cells, and two 7 Ah NiMH cells in a single battery pack and operates them in series at 5 deg C and 20% DOD. The ACC system is expected to adapt to the needs of each of these cells and operate it in an optimal way over its cycle life. This test also provides the first head-to-head comparison between lithium-ion, NiCd, and NiMH cells when operated under identical charge control and environmental conditions. The final test applies the ACC system to five 60 AH advanced nickel hydrogen cells operated at –5 deg C and 60% DOD. Here the ACC system is used to minimize the overcharge stresses that have contributed to early failure in numerous other 60% DOD life tests of nickel hydrogen cells.

Nanosatellite Power System Mockup Test

This test uses two commercial lithium-ion cells having a 0.8 Ah capacity. The cells are sealed with thermally conductive RTV into a layer within the middle of a spherical nanosatellite mass simulator made of pure silicon. The cells were instrumented for both voltage and temperature measurements. The mockup was placed in a thermal vacuum chamber and operated in a 90-minute orbit; 30 minutes in eclipse and 60 minutes in the sun. During the entire orbit the bottom of the spherical mockup was cooled using a cooling plate that was held at 13-14 deg C. During the sunlit part of each orbit the temperature was raised with a heater on the top of the spherical mockup. Typically, the battery cell temperature varied about 8 deg C, between about 16 and 24 deg C, during each orbit. Discharge during each eclipse period was at 320 ma, providing a 20% DOD. Figure 1 shows the battery cells in an aluminum holder before being sealed into the spherical silicon mockup.

Figure 2 shows the end of discharge and end of charge voltage performance of these cells during the course of this life test. Cell recharge is done at 320 ma until a 0.75 recharge fraction is reached, then recharge is continued at a rate chosen by the ACC system to allow all cells to reach their prescribed recharge fraction about 1-2 minutes before the end of the sunlit period. Since each cell goes to zero current when the prescribed recharge fraction is attained, the end of charge voltage shown in Figure 1 is for a charged cell at zero current. Peak cell recharge voltages are presently 4.01 to 4.03 volts at the 320-ma recharge rate. The life test is planned to go until cell failure is reached. Failure for a cell is defined as occurring when the peak charge voltage goes above 4.1 volts while in the same cycle the end of discharge voltage drops below 3.0 volts.

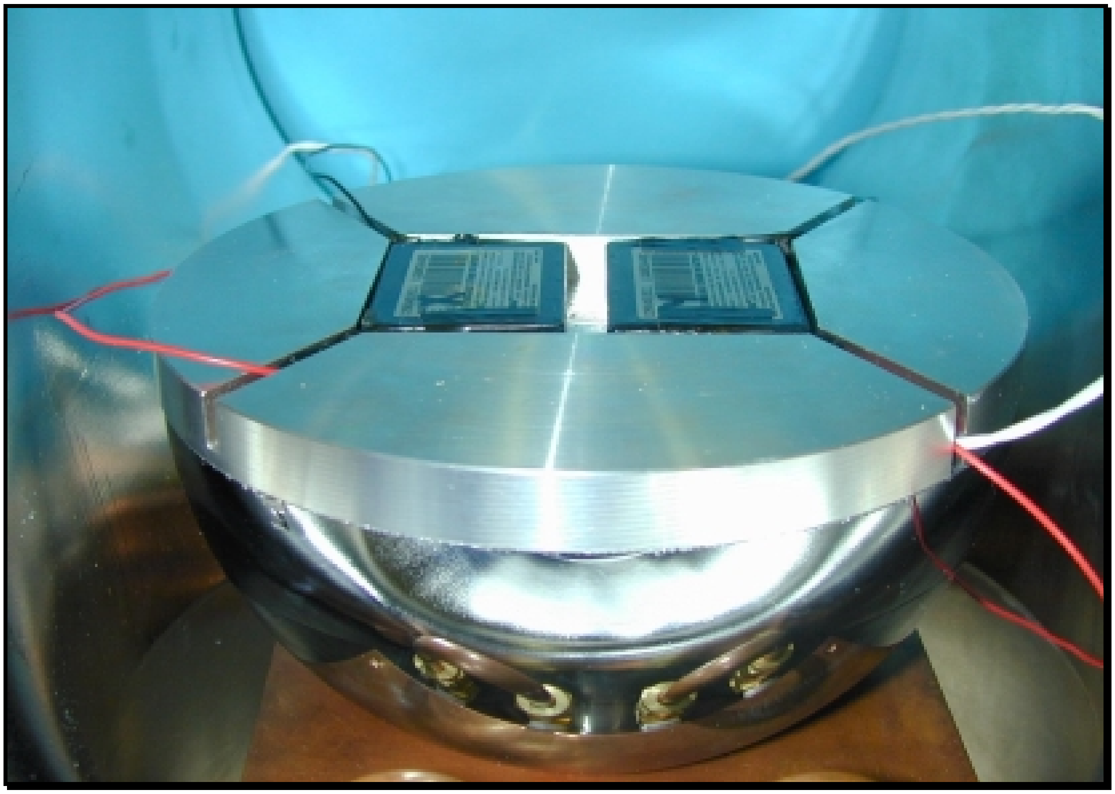

Figure 1. Bottom Hemisphere of Nanosatellite Mockup Showing lithium-ion Cells.

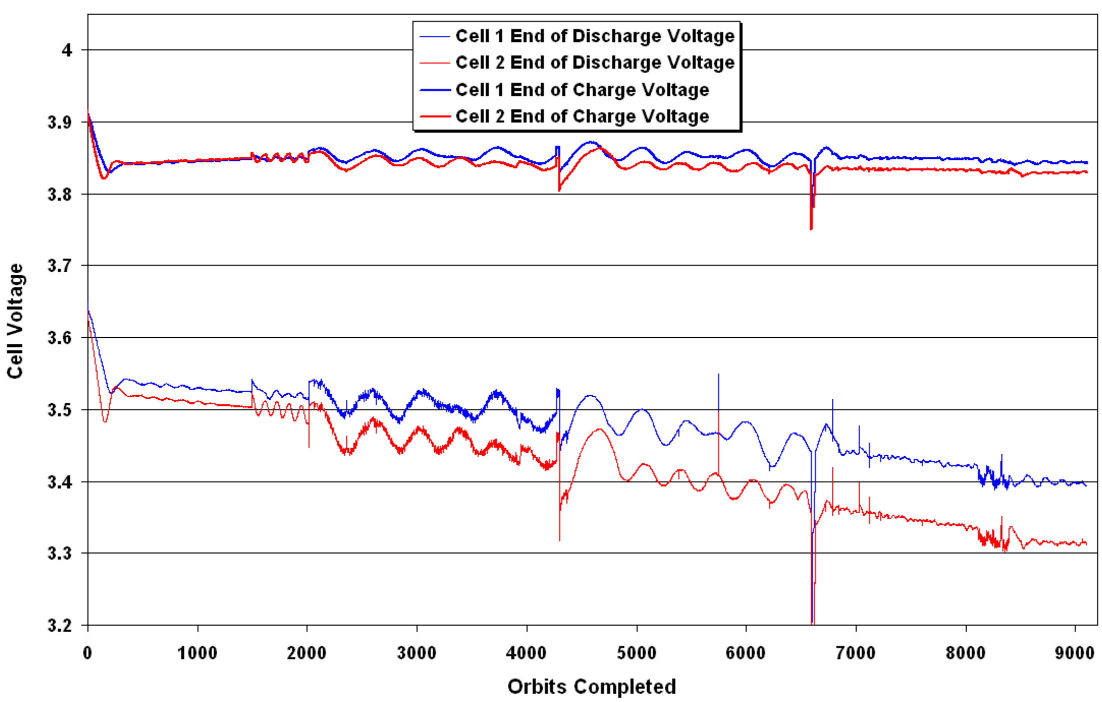

Figure 2. End-of-Charge and End-of-discharge voltages for lithium-ion cells in nanosatellite mockup life test.

An indicated earlier, the recharge fraction is the principal means of maintaining the state of charge of each cell, while avoiding unnecessary overcharge. For lithium-ion battery cells, which have very low self-discharge rates, a recharge fraction near 1.00 is anticipated as the desirable charge control point. As indicated in Figure 3, the ACC system does in fact establish an average recharge fraction level within measurement error of 1.0 for each cell. The oscillatory behavior of the recharge fraction for the first approximately 6500 cycles of the test was because the charge control algorithm did not have the recharge fraction damping-mode activated. This mode basically prevents any change in the prescribed recharge fraction of a cell if the cell peak recharge and minimum discharge voltages are already drifting in the desired direction. As demonstrated around cycle 7000, this feature stabilizes the recharge fraction so that it does not overshoot the needed level. Much of the noise seen in the recharge fraction arises from the thermal fluctuations seen by these cells, as well as cycle-to-cycle fluctuations in performance.

It should be noted that a fixed recharge fraction could not be used for controlling these cells. The actual recharge fraction needed is most likely closer to 1.00 than can be accurately measured. Thus, the choice of any fixed recharge fraction will eventually result in either undercharge or some small amount of long-term overcharge. Either of these situations is undesirable for lithium-ion battery cells.

The end of life for these cells occurs when the voltage during one cycle swings from 4.1 volts during recharge, to 3.0 volts during discharge, which is a 1.1-volt swing. Figure 4 shows the delta between the peak recharge voltage and the minimum discharge voltage. This delta is slowly increasing as the cells are cycled. Extrapolation to 1.1 volts gives an indication of the expected cycle life for these cells, about 25,000 to 30,000 cycles.

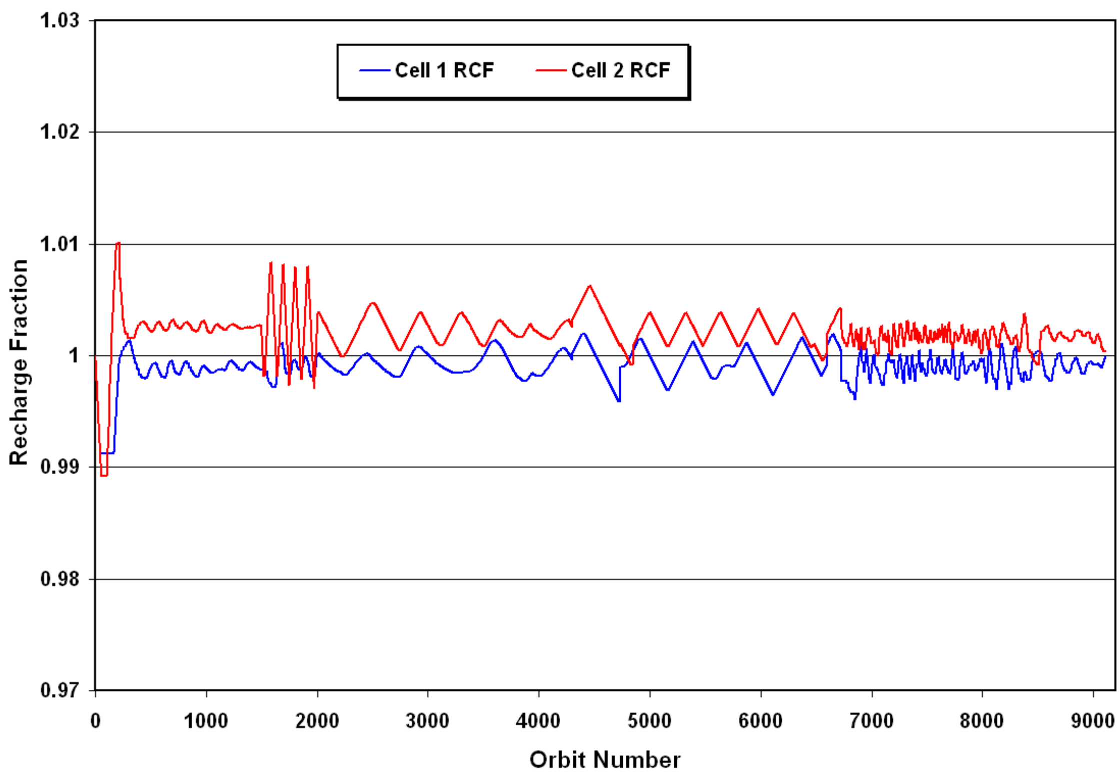

Figure 3. Recharge fractions for lithium-ion cells in nanosatellite mockup life test.

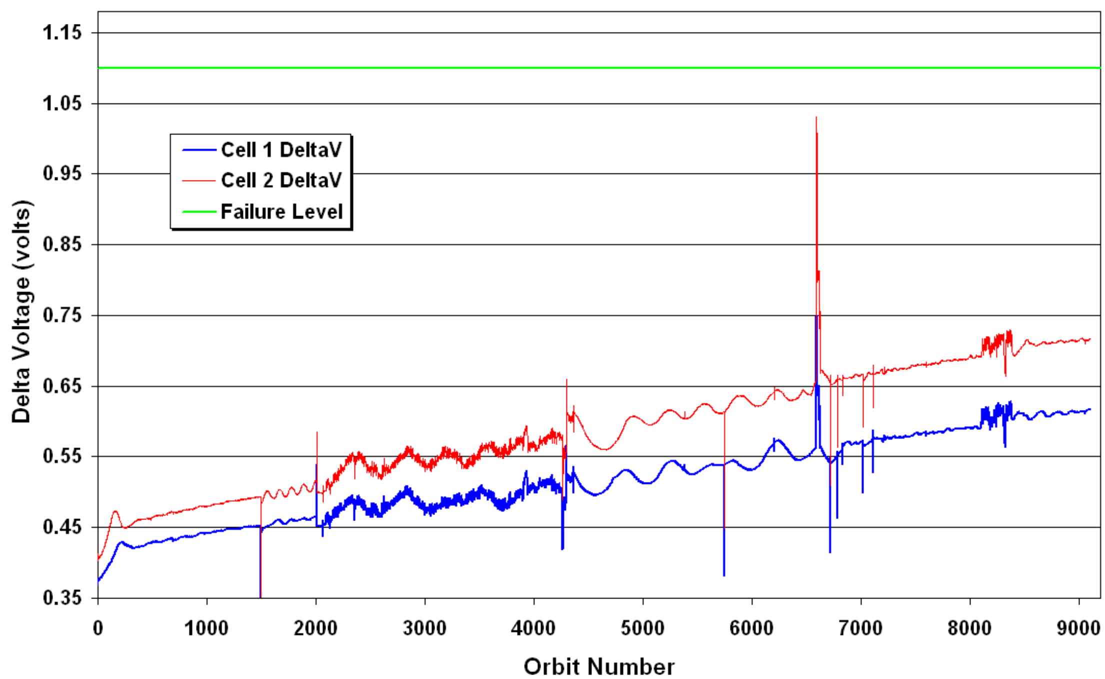

Figure 4. Difference between peak recharge and minimum discharge voltages for lithium-ion cells in nanosatellite mockup life test.

ACC Demonstration in Mixed Cell Pack

The ACC system is theoretically capable of responding to any cell type or chemistry to find the most appropriate recharge conditions for that cell. To evaluate this capability in a battery pack that contains mismatched cells, a pack was built that contained two 7 Ah lithium-ion cells, two 7 Ah NiCd cells, and two 7 Ah NiMH cells. Each of these cell types should require significantly differing charge management for optimum life. In addition, the cells were obtained from commercial sources, and no attempts were made to match cell performance characteristics. This test pack was put in a life test at 5 deg C using a 20% DOD cycle with 30 minutes for discharge and 60 minutes for recharge. The recharge current returned 75% of the recharge in 30 minutes, then dropped back to a lower recharge rate appropriate to attain the highest cell recharge fraction 1-2 minutes before the end of the recharge period. After each cell reached its prescribed recharge fraction, all current was shunted around that cell, effectively putting it at zero current.

Figures 5-7 indicate the end of discharge and peak recharge voltages for the NiCd, NiMH, and Li-ion cells respectively in this test pack for the 2400 cycles presently completed. It should be noted in Figs. 5 and 6 that the NiCd and NiMH cells are not closely matched to each other. All cells have stabilized at 1850 cycles

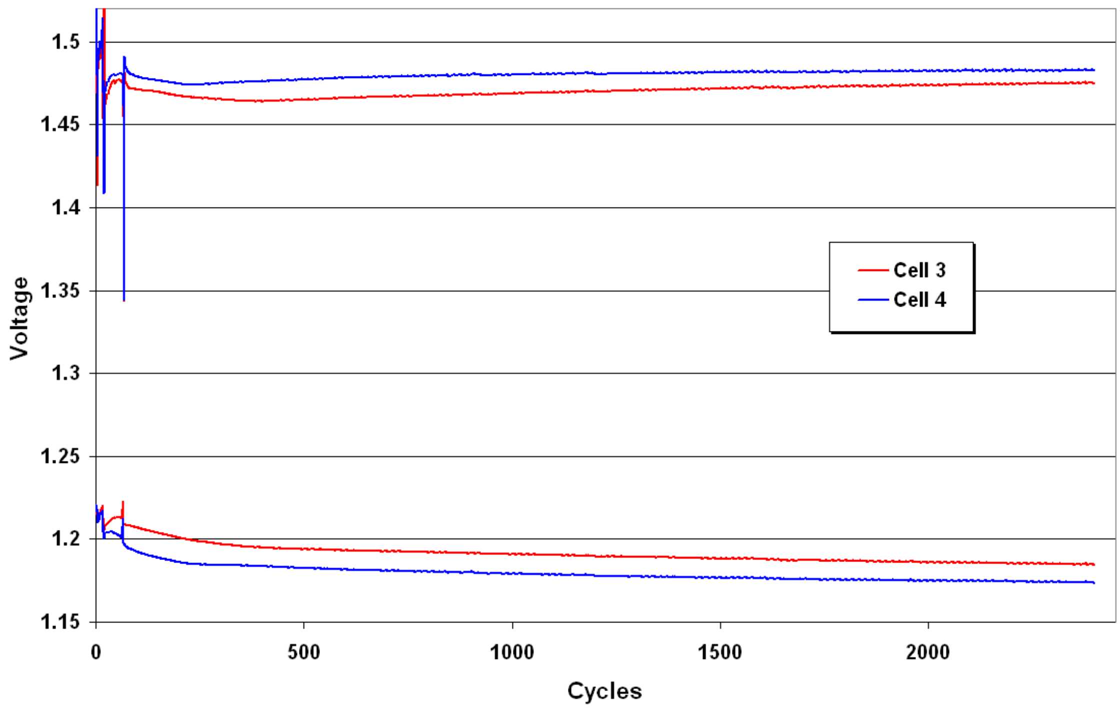

Figure 5. End-of-discharge and peak recharge voltages for the two NiCd cells in the mixed cell test.

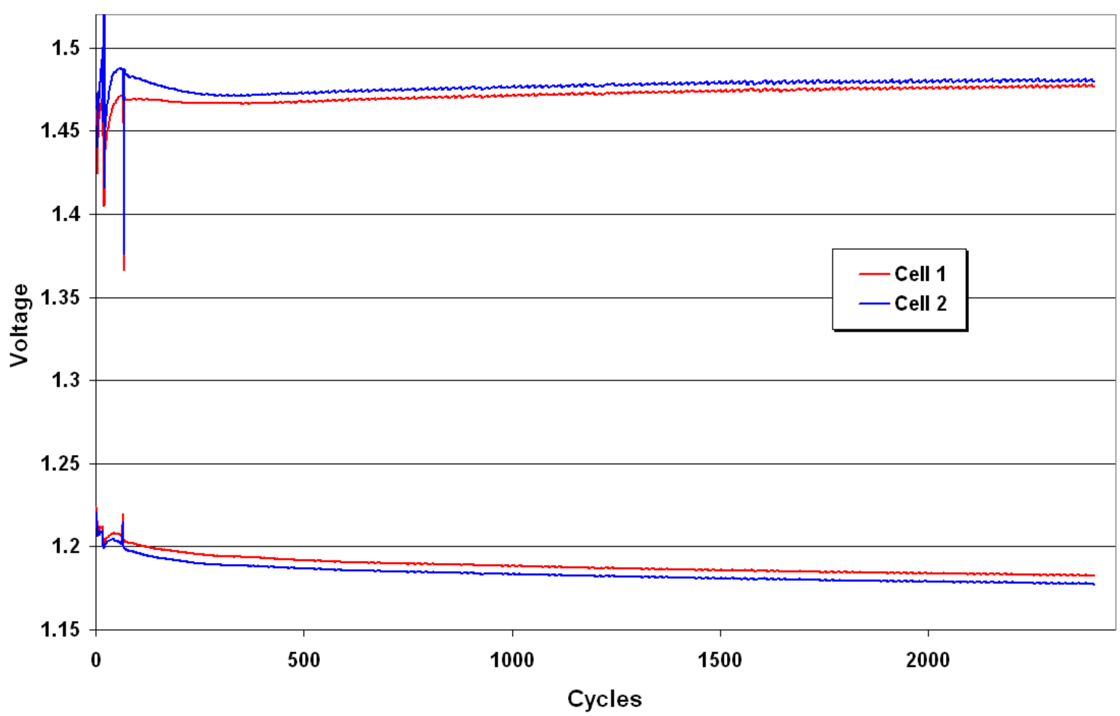

Figure 6. End-of-discharge and peak recharge voltages for the two NiMH cells in the mixed cell test.

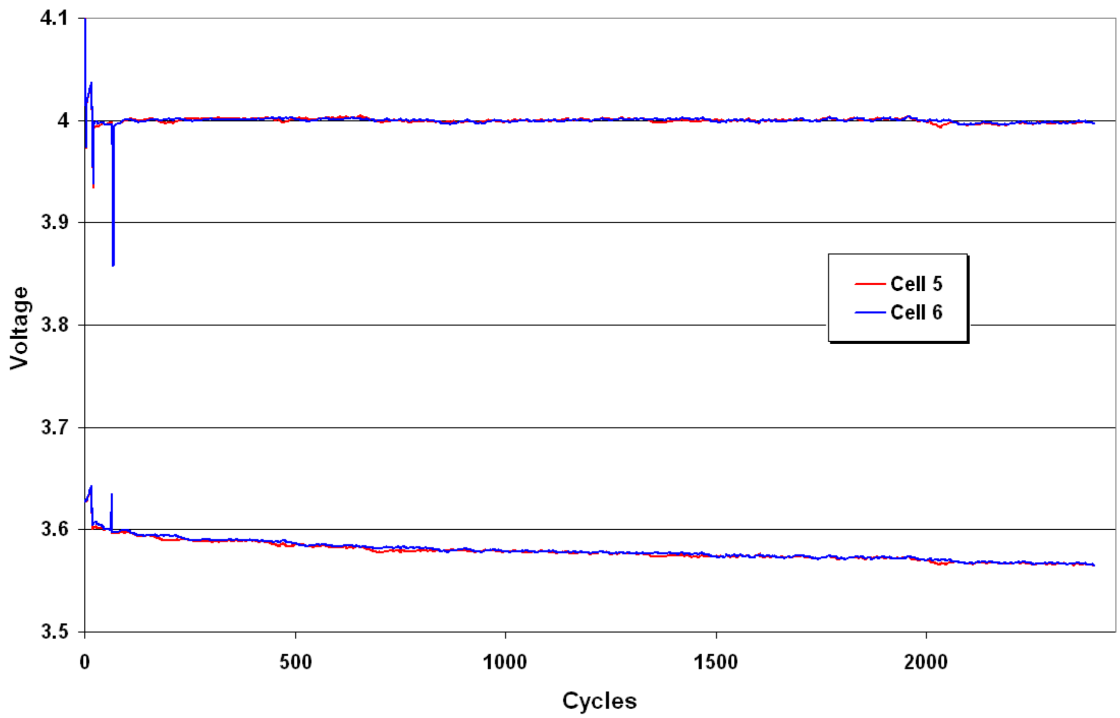

Figure 7. End-of-discharge and peak recharge voltages for the two lithium-ion cells in the mixed cell test.

The ACC system has in fact adapted to the recharge requirements of each of these three cell types quite well. Figure 8 shows for each cell type the recharge fractions that the ACC system found to be needed for optimized charge maintenance. As anticipated, for the lithium-ion cells the recharge fraction is within measurement accuracy of 1.000. It is interesting that the recharge fraction for the two lithium-ion cells has dropped slightly as they are cycled. Whether this is due to changes in the cells or to a drift in the charge control electronics cannot be established at present, however the ACC system has in fact found that this slight shift is required to maintain optimum charge control. The NiCd and NiMH cells have settled on a recharge fraction of about 100.5%, which is significantly lower than is traditionally used in life tests of these cell types. Clearly for these nickel electrode based cells, the ACC system has adopted a minimum stress recharge protocol that has eliminated all unneeded overcharge.

Trending of the data from this pack as the cells degrade is best done by following the difference between the minimum discharge voltage and the peak recharge voltage for each cell. This plot is shown in Fig. 9. Each cell has stabilized with a slight upwards slope in this plot. The cell failure levels in Fig. 9 are about 0.52 volts for the NiCd and NiMH cells, and 1.1 volts for the Li-ion cells. If the slopes seen in Fig. 9 are extrapolated to these failure conditions, the Li-ion cells should give about 65,000 cycles, the NiCd cells 34,000 cycles, and the NIMH cells 24,000 cycles.

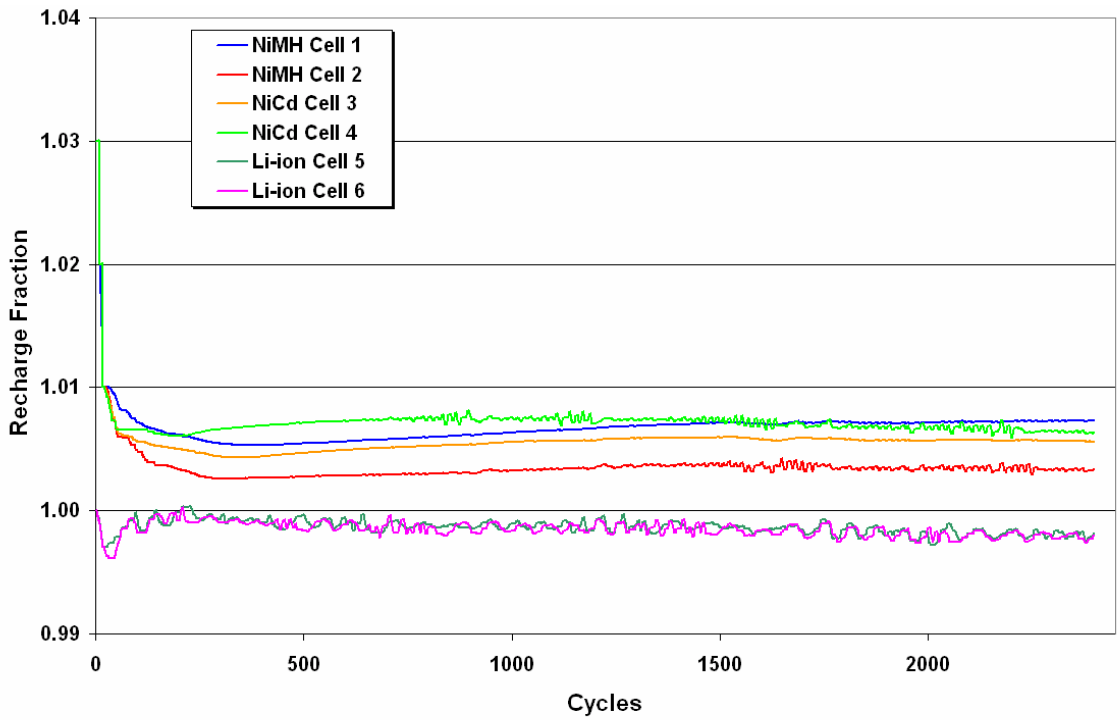

Figure 8. Recharge fractions for the six cells in the mixed cell test.

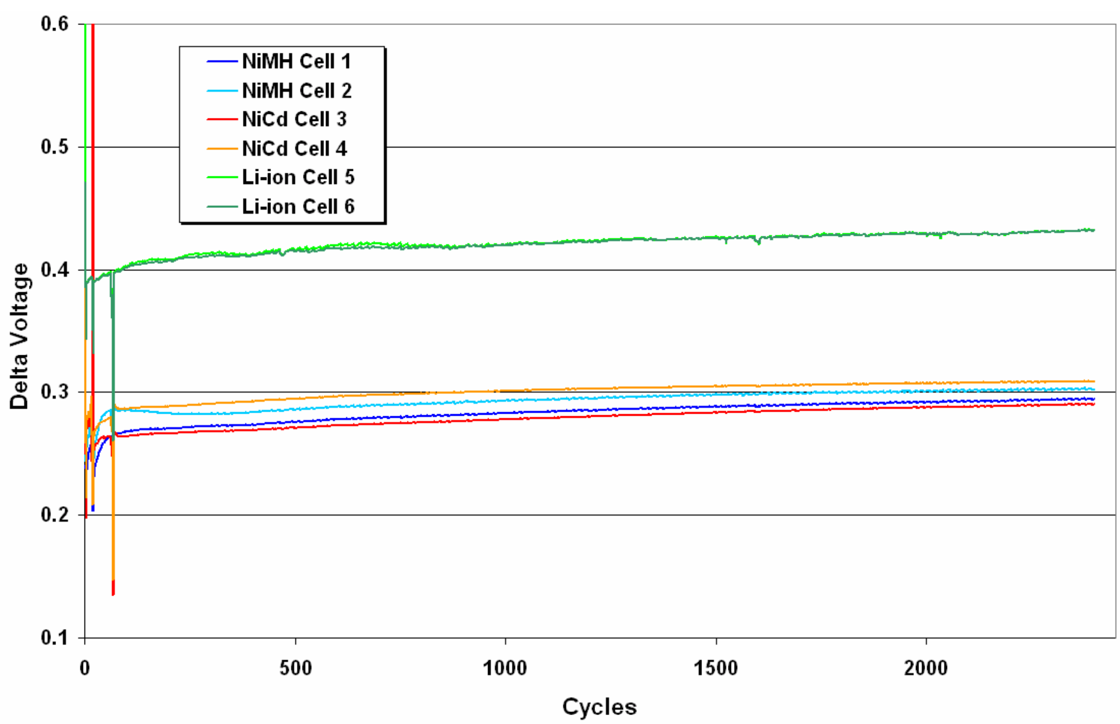

Figure 9. Difference between peak recharge and minimum discharge voltages for lithium-ion cells in the mixed cell test.

Advanced Nickel Hydrogen Cell Test

A recently completed project has provided a correlation between life test performance for nickel hydrogen battery cells and cell design variables, test environment, and charge control protocols[2]. These results indicated that maximum NIH_2 lifetime performance could be obtained by using 26% KOH, cold operation (-5 deg C), and minimizing overcharge. In addition, the use of a dual anode stack arrangement[3,4] decreases the superficial current density on the nickel electrodes and the ionic diffusion path lengths by a factor of two. A single layer of zircar separator in the dual anode stack provides just as much electrolyte volume in the stack as does the double layer zircar separator in a back-to-back stack design. However, the ionic conduction path through the single layer of zircar is 50% as long. The use of separate leads from each nickel electrode further reduces cell impedance. An axial terminal design provides matched resistances between the stack units over the entire length of the stack. The cells are mounted with a thermal conduction flange at their center, thus minimizing thermal gradients through the stack length.

Five 60 Ah cells of this design were put into a stressful life test involving 60% DOD and 16 cycles per day. The test temperature was set such that the average cell temperature (top of stack) was –5 deg average at the end of recharge. Each cycle involved discharge for 30 minutes, followed by recharge for 60 minutes using the ACC system in its auto taper mode. In this mode, which is most appropriate for high DOD cycling where charge must be returned quickly, recharge is started at a peak rate (C rate in this test). When the voltage of any cell rises to within 1 mv of a specified peak voltage target, the current is cut back (10% in this test). This process continues until any further reduction in current would prevent the required recharge fraction from being attained for any cell. When this occurs, the current is simply set at the level needed to return the needed recharge fraction, and the voltage is allowed to rise with no further changes in current. If the voltage goes above the target peak charge voltage level, the recharge fraction may be decreased if the cell also remains above the target minimum discharge voltage, or the peak recharge voltage target may be increased if the cell has gone below the target minimum discharge voltage. This mode essentially provides a software current taper based on the voltage behavior of the individual cells in the test pack.

The cells were started cycling after recharge to about 80% state-of-charge. The ACC system was set such that the target minimum discharge voltage was 1.10 volts for each cell and the peak recharge voltage target was 1.50 volts. This corresponds to cycling between about 5% and 65% state of charge. This cycling range was chosen to provide the Ah throughput while minimizing overcharge of the cells. For the first several hundred cycles, the ACC system allowed the cells to slowly run down to the desired state-of-charge range. This is indicated in Figures 10 and 11, which show the end-of-charge voltage and the recharge fraction over the first 1000 cycles. After about 260 cycles the cells had dropped down to the desired state-of-charge range, and have proceeded to stabilize. While we have insufficient stable data to extrapolate meaningfully to the end of life, the difference between the minimum discharge voltage and the peak recharge voltage may be plotted to trend cell changes over life. This plot is shown in Figure 12, where a voltage difference of about 0.58 corresponds to cell end of life. At these temperatures and cycling conditions, these cells need only about 100.3% recharge ratio for stable performance.

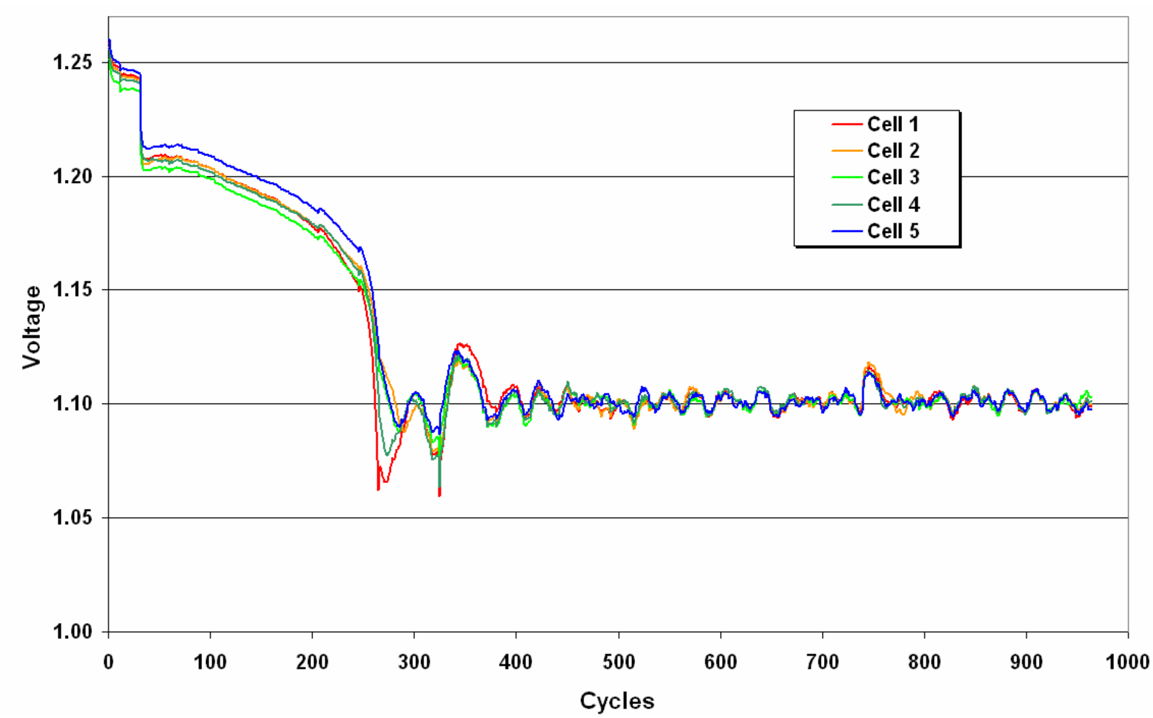

Figure 10. End of discharge voltages for NiH_2 cells test in advanced dual-anode test.

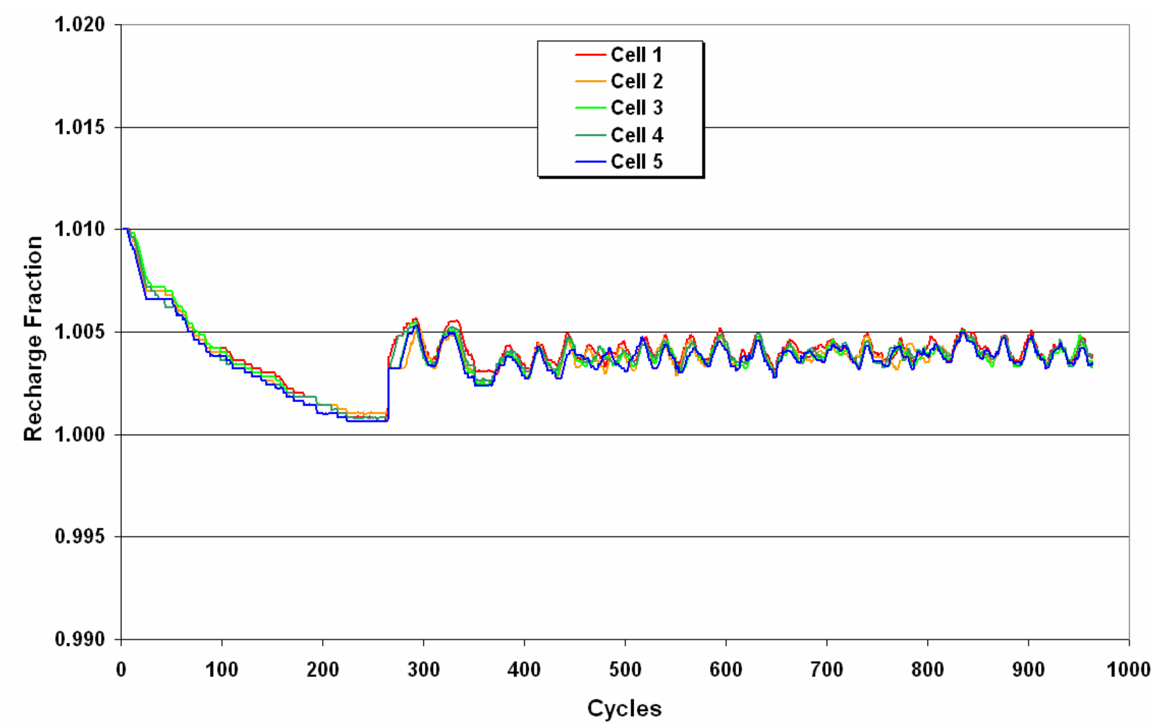

Figure 11. Recharge fractions for NiH_2 cells test in advanced dual-anode test.

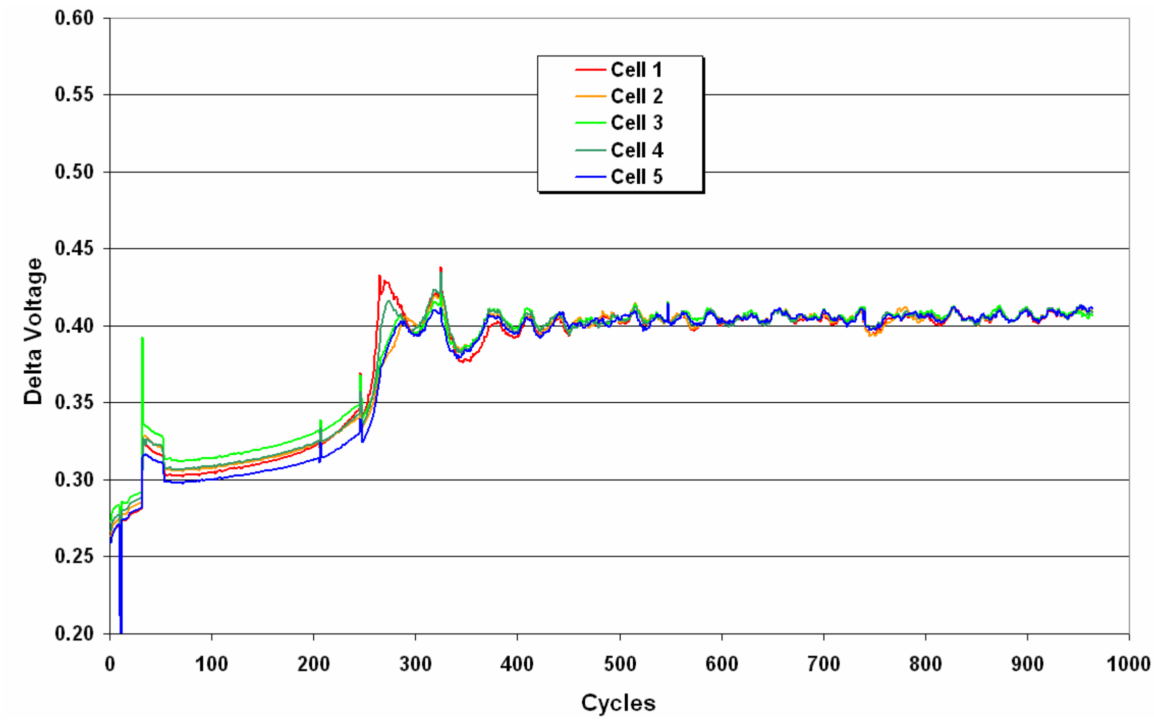

Figure 12. Difference between peak recharge and minimum discharge voltages for NiH_2 cells test in advanced dual-anode test.

Conclusions

The ACC system for automatically maintaining the optimum recharge protocol in a power system has been demonstrated to effectively manage a wide variety of battery cells, and to handle wide variability between cells in the system. The ability of the charge control system to maintain a truly minimum stress condition is illustrated by the exceptionally low recharge fractions that the ACC system has selected as appropriate for nickel hydrogen, nickel cadmium, and nickel metal-hydride cells. For lithium ion cells the ACC system has rapidly zeroed in on a recharge fraction within measurement error of 1.000, as desired for cells that have no tolerance for overcharge.

These tests will continue to the point where the cells fail, which if present trends continue should be well beyond 50,000 cycles for the lithium-ion cells. The lithium-ion cells are presently out-performing the NiCd cells, which are performing better than the NIMH cells. The nickel hydrogen cells cycling at 60% DOD have a target of 60,000 cycles in this test, but will continue to the point where all cells have failed.

Acknowledgements

The Aerospace Corporation is gratefully acknowledged for supporting this work as part of the Aerospace IR&D Program.

References

1. Zimmerman, A. H. and M. V. Quinzio, *Adaptive Charging Method for Lithium-Ion Battery Cells*, U.S. Patent 6,204,634, The Aerospace Corporation, 20 March 2001.
2. Thaller, L. H. and A. H. Zimmerman, *A Critical Review of Nickel Hydrogen Life Testing*, ATR-2001 (8466)-2, The Aerospace Corp., 15 May 2001.
3. Gahn, R. F., *Performance of a Dual Anode Nickel Hydrogen Cell*, Proc. of the 1991 Space Electrochemical Research and Technology Conf., NSAS Conf. Pub. 3125, 1991, pp. 195-208.
4. Zimmerman, A. H., J. Matsumoto, A. Prater, D. Smith and N. Weber, *Characterization and Initial Life-Test Data for Computer Designed Nickel Hydrogen Cells*, NASA/CP-1998-208536, Proc. of the 1997 NASA Aerospace Battery Workshop, July 1998, pp 471-484.

A DUAL MODE LITHIUM ION BATTERY CHARGE CONTROLLER

NASA Aerospace Battery Workshop

November 27-29, 2001

Authors

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Eagle-Picher Technologies, LLC

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Overview

- Design concept was initially developed to support launch and orbital activity for a reusable space vehicle
- Charging to be performed pre-launch and in orbit while docked
- Design consists of two elements: An on-board system and an external system

Two Common Approaches for Lithium Ion Chargers

- Battery Level Chargers
  - Advantages: Simpler and cheaper
  - Disadvantages: Lacks cell balancing
- Cell Level Chargers
  - Advantages: Cell balancing for improved life and performance
  - Disadvantages: More complex, higher cost and thermal issues

Dual Mode Lithium Ion Charger

Uses a combination of the two approaches:

- Bulk charge with control and termination based on the cell and/or battery level
- Cell balancing charge with control and termination based on cell level

Proposed Charge Steps

- Bulk charge at C/5 or greater until predetermined cell and/or battery voltage level
- Bulk charge at C/10 or greater until predetermined cell and/or battery voltage level
- Cell balancing charge at C/100 or greater with current control and termination at cell level

Charger System Description

- Two subsystems
- Battery Management System (BMS)
  - On-board the battery
  - Provides charge control at cell level
- External Current Source (ECS)
  - External Current Source/Sink
  - Provides bulk charge/discharge current to battery/BMS

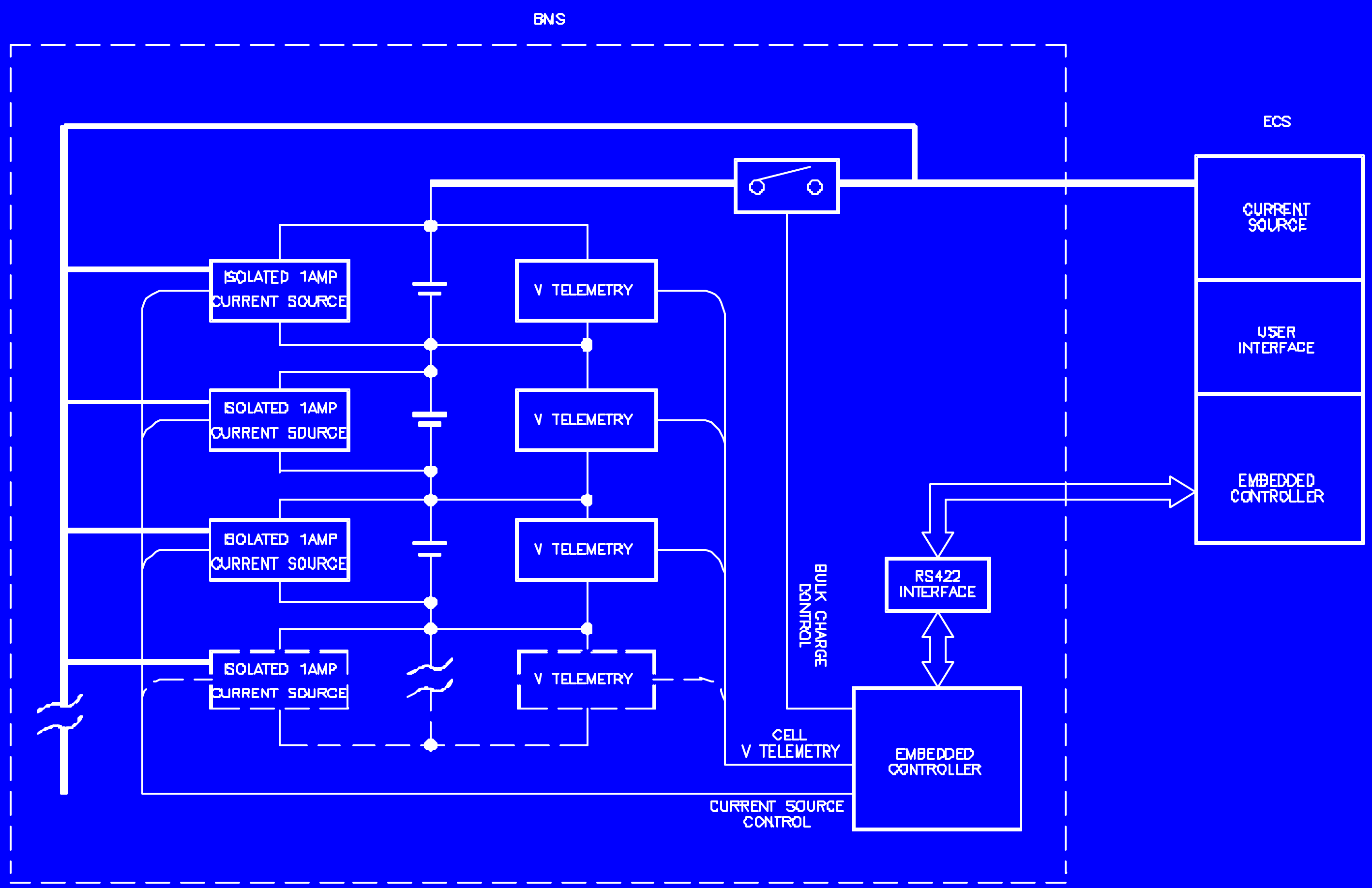
BMS Requirements

- Input Power: From ECS
- Environment:
  – Operating: Pre-flight
  – Non-operating: Flight
- Communication: Serial data link to ECS
- Protection: Battery and individual cell monitoring

ECS Requirements

- Input Power: 120VAC, 60Hz
- Operating Environment: Ground, sheltered
- Communication:
  - Serial data link to BMS
  - Operator interface
- Protection: Battery monitoring and BMS serial data link
- Added Function: User selected battery via hardware or software tag

Block Diagram



Projected BMS Hardware

- Embedded controller with A/D, digital I/O and SPI
- Mechanical relay for bulk current enable/disable
- Isolated constant current sources for each cell
- Voltage sense and conditioning
- Enclosure and filtering for environmental and EMC protection
- Connectors for charger to battery integration

Projected ECS Hardware

- Embedded controller with D/A, digital I/O, SPI and user interface
- Current source and Load bank
- System power supply
- Fan/heatsink cooling system
- System enclosure for environmental and EMC protection
- Connectors for charger to umbilical integration

Summary

- Concept attempts to achieve “best of both worlds”
- Cell balancing at lower current removes large heat source from the battery system
- External subsystem reduces on-board mass and provides convenient user interface
- Embedded controllers provide for greater flexibility

Impact of Charge Methodology Upon the Performance of Lithium Ion Cells

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NASA Battery Workshop
Huntsville, Alabama
Nov. 27, 2001

Outline

- Introduction
- Charge Characteristics of Lithium Ion Prototype Cells
  - Charge Rate Characteristics at Different Temperatures
  - Effect of Charge Methodology Upon Cycle Life Performance
  - Effect of Charge Voltage Upon Cell Performance
    - Impact upon Low Temperature Performance
    - Impact of Charge Voltage at High Temperature
- Charge Characteristics of Three-Electrode Cells
  - Charge Characteristics at Low Temperature
- Charge Characteristics of Lithium-Ion 8-Cell Battery
- Conclusions
- Acknowledgements

Lithium-Ion Cells for NASA and DoD Applications: Program Objectives

- Assess viability of using lithium-ion technology for future NASA and Air Force applications.

- Demonstrate applicability of using lithium-ion technology for future Mars Lander and Rover applications.

Lithium-Ion Cells for NASA and DoD Applications:

Summary of General Characterization Tests On-Going at JPL

- Cycle life performance at room temperature (25°C)
- Cycle life performance at low temperature (-20°C)
- Discharge rate characterization (at 40, 25, 0, and -20°C)
- Charge rate characterization (at 40, 25, 0, and -20°C)
- Capacity retention characterization tests
- Storage characterization tests (cruise conditions)
- Pulse capability tests (Entry Descent and Landing)
- VT charge characterization tests
- Electrical characterization by a.c. impedance
- LEO and GEO characterization tests
- Thermal characterization (microcalorimetry)

Charge Characteristics of Prototype Lithium Ion Cells

- **Charge acceptance at various rates and temperatures**
  - **Various chemistries, cell designs and sizes studied**
  - **Range of charge rates investigated (C/20 to C rate)**
  - **Range of temperatures investigated (-40^o to $+40^oC$)**

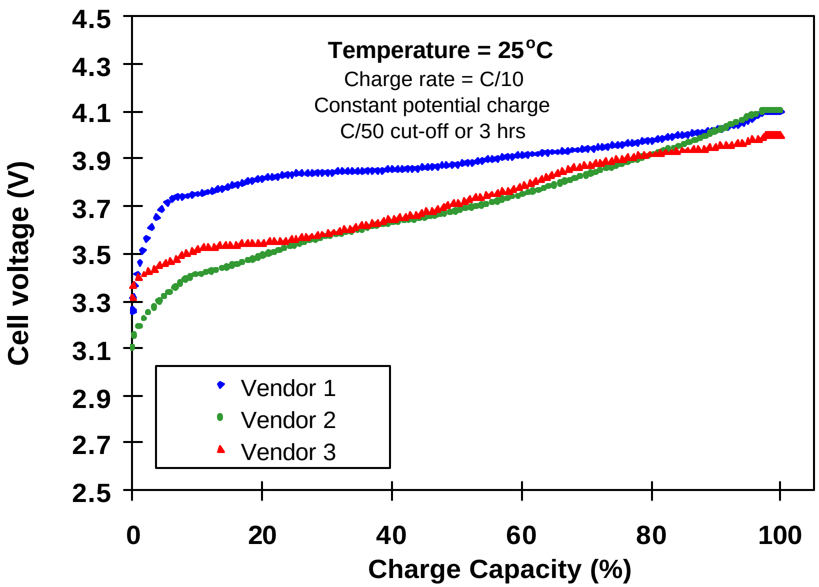
- **Effect of Charge Methodology Upon Cycle Life Performance**
  - **Effect of charge voltage**
  - **Effect of taper current cut-off**
  - **Effect of storage on the bus (float charging)**

- **Effect of charge voltage upon cell performance**
  - **V/T characterization**

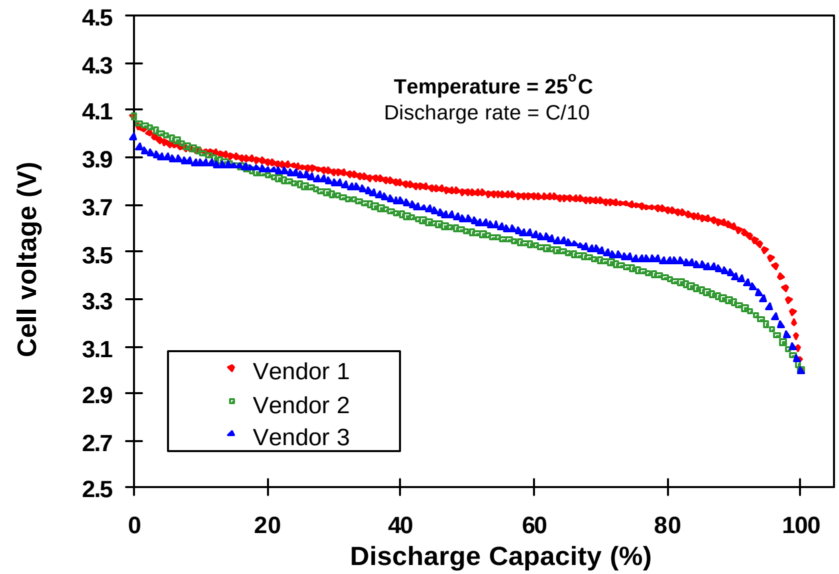
Large Capacity Lithium-Ion Cells for Future Mars Applications

Room Temperature Charge/Discharge Characteristics

Voltage Profile on Charge



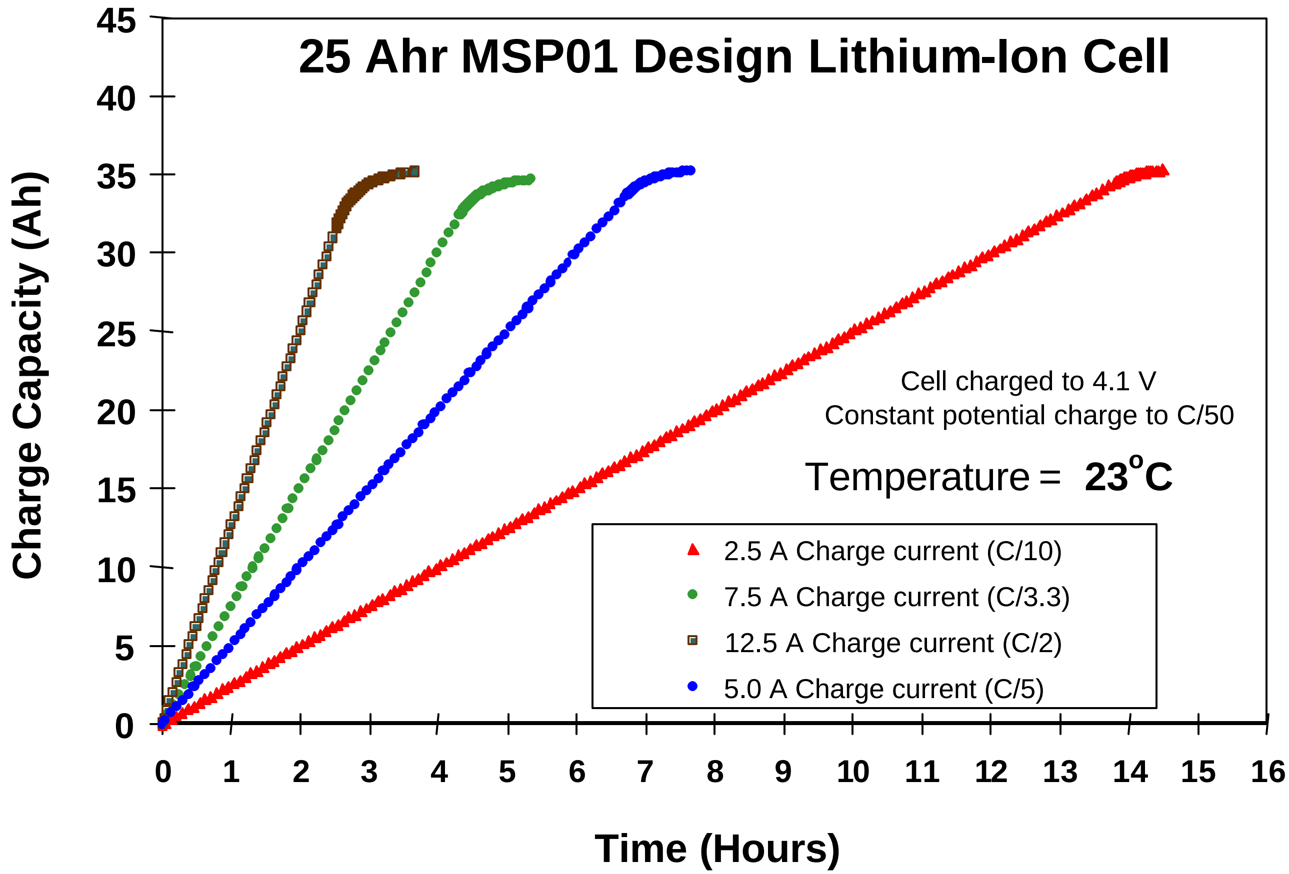
Voltage Profile on Discharge



- Depending upon the chemistry employed (i.e., cathode and anode type) the voltage profile on charge and discharge can be distinctively different.

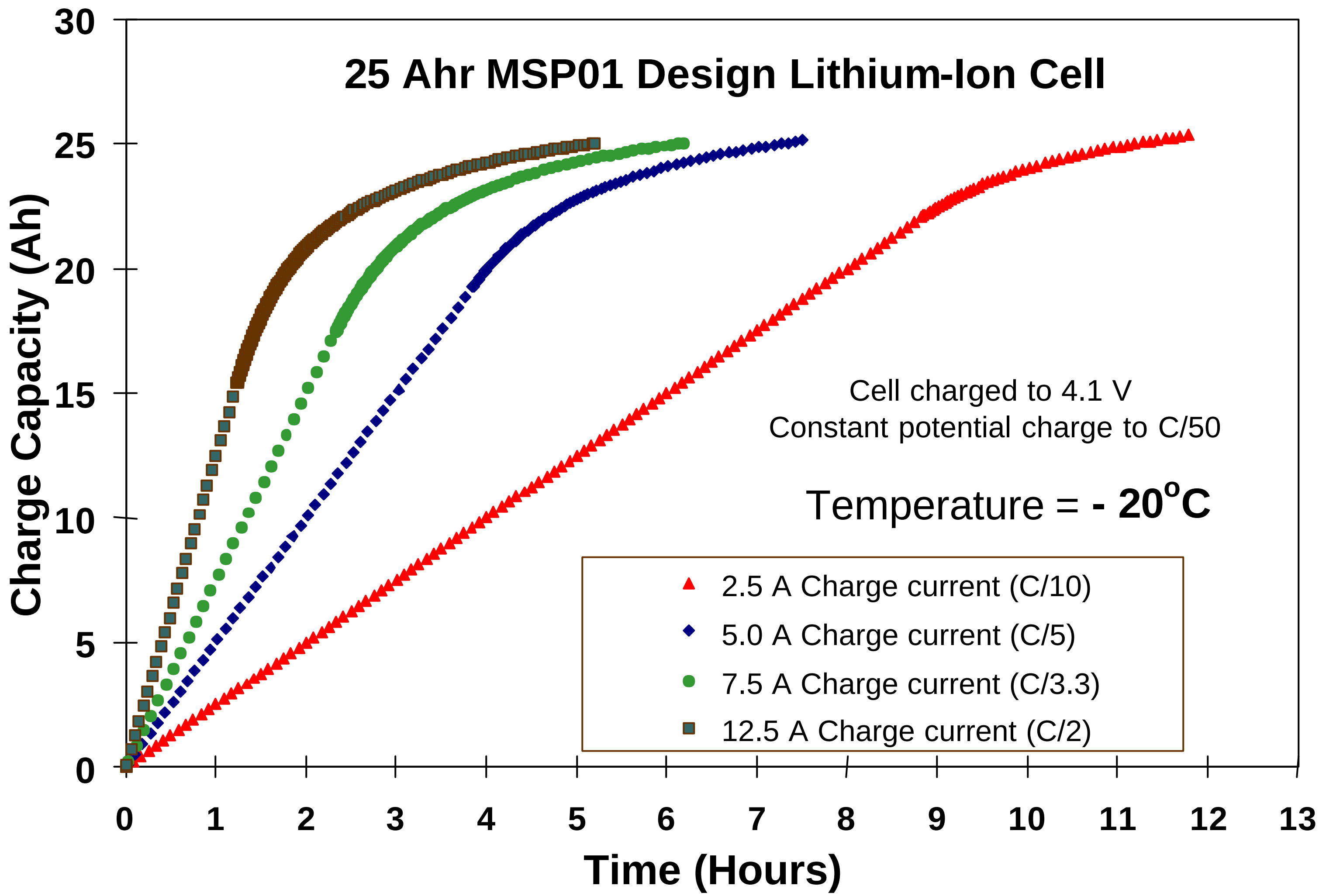
Lithium-Ion Cells for Mars Surveyor 2001 Lander

Room Temperature Charge Characteristics



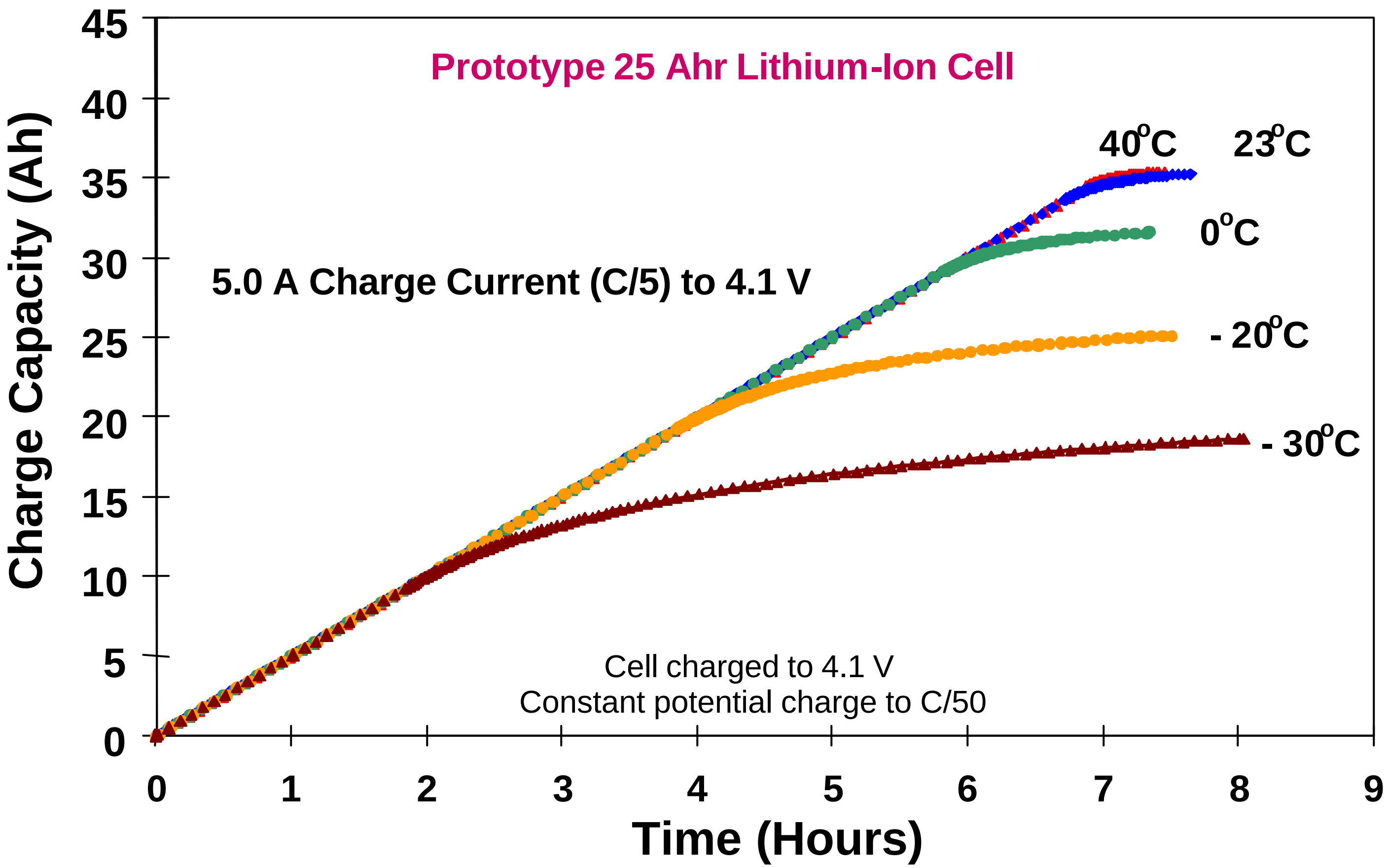
Lithium-Ion Cells for Mars Surveyor 2001 Lander

Low Temperature Charge Characteristics (-20^{o}C)



Lithium-Ion Cells for NASA and DoD Applications:

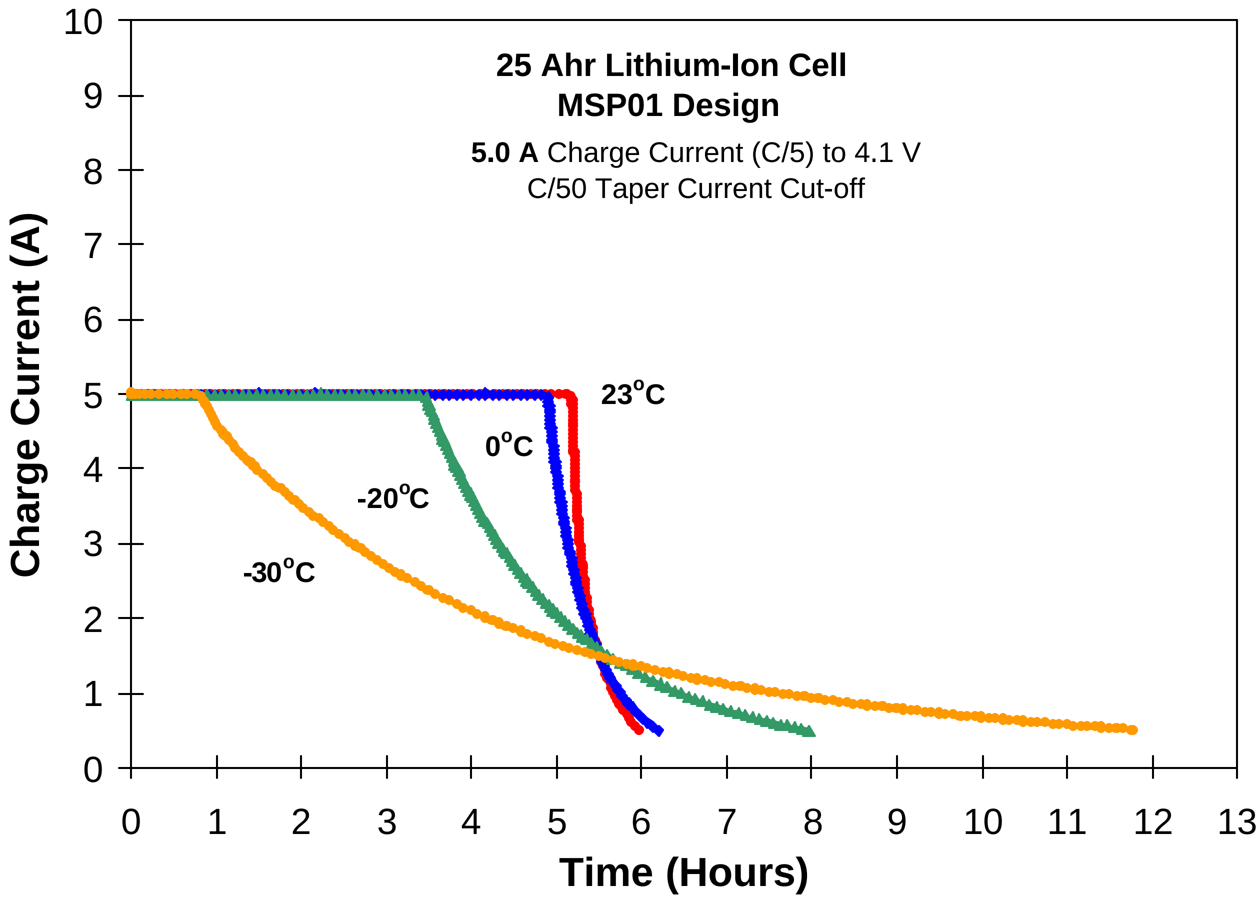
Charge Capacity as a Function of Temperature



*** C/5 Charge Current**

Large Capacity Lithium-Ion Cells for Mars Lander Applications

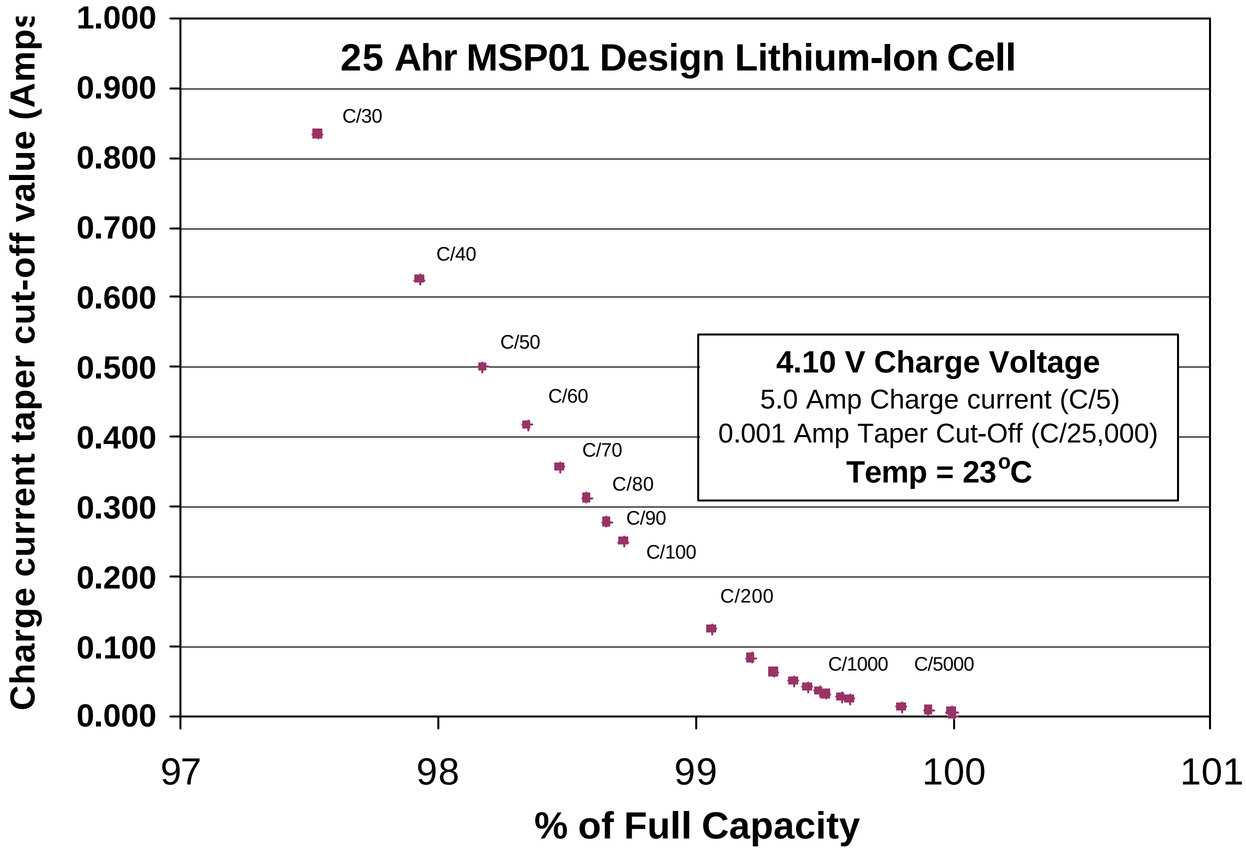
Charge Characteristics as a Function of Temperature



- **At lower temperatures, significantly more capacity is obtained while the cell is in the taper mode (constant potential charging).**

Large Capacity Lithium-Ion Cells for Future Mars Applications

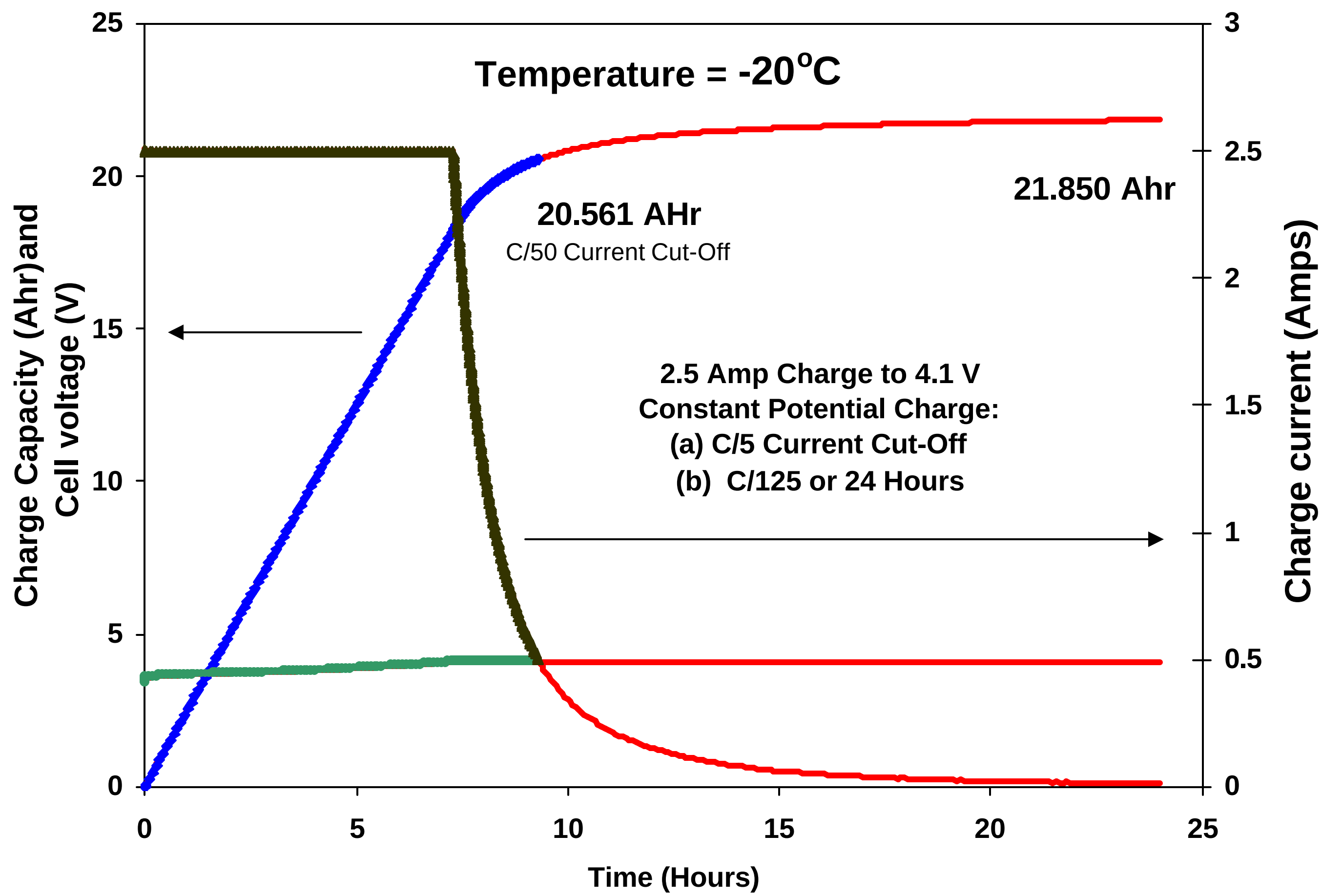
Effect of Taper Current on Charge Characteristics



- **With a fresh cell, the impact of the taper current cut-off value does not have a dramatic impact upon charge capacity (given that it is <C/30 and the constant current charge is of moderate rate (<C/5).**

Large Capacity Lithium-Ion Cells for Future Mars Applications

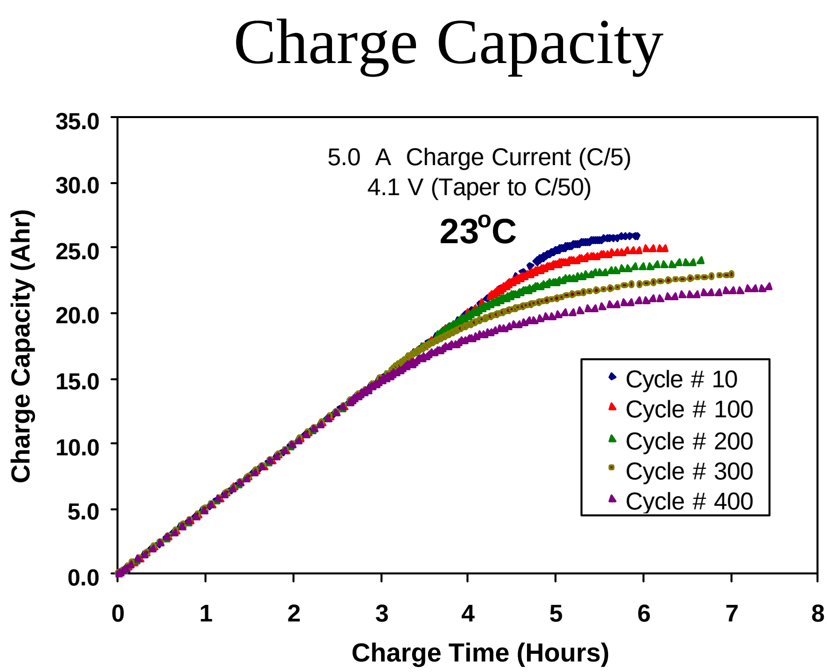
Effect of Taper Current on Charge Characteristics

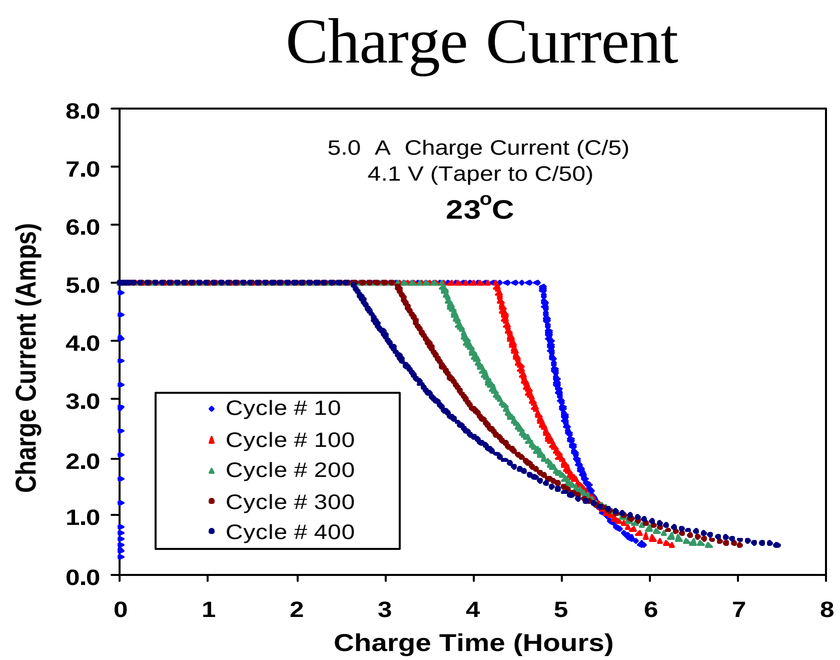


- At low temperatures (-20°C), approximately 6% more capacity is obtained with an extended "taper mode" vs. C/50 cut-off.

Large Capacity Lithium-Ion Cells for Mars Lander Applications

Effect of Cycle Life on Charge Characteristics

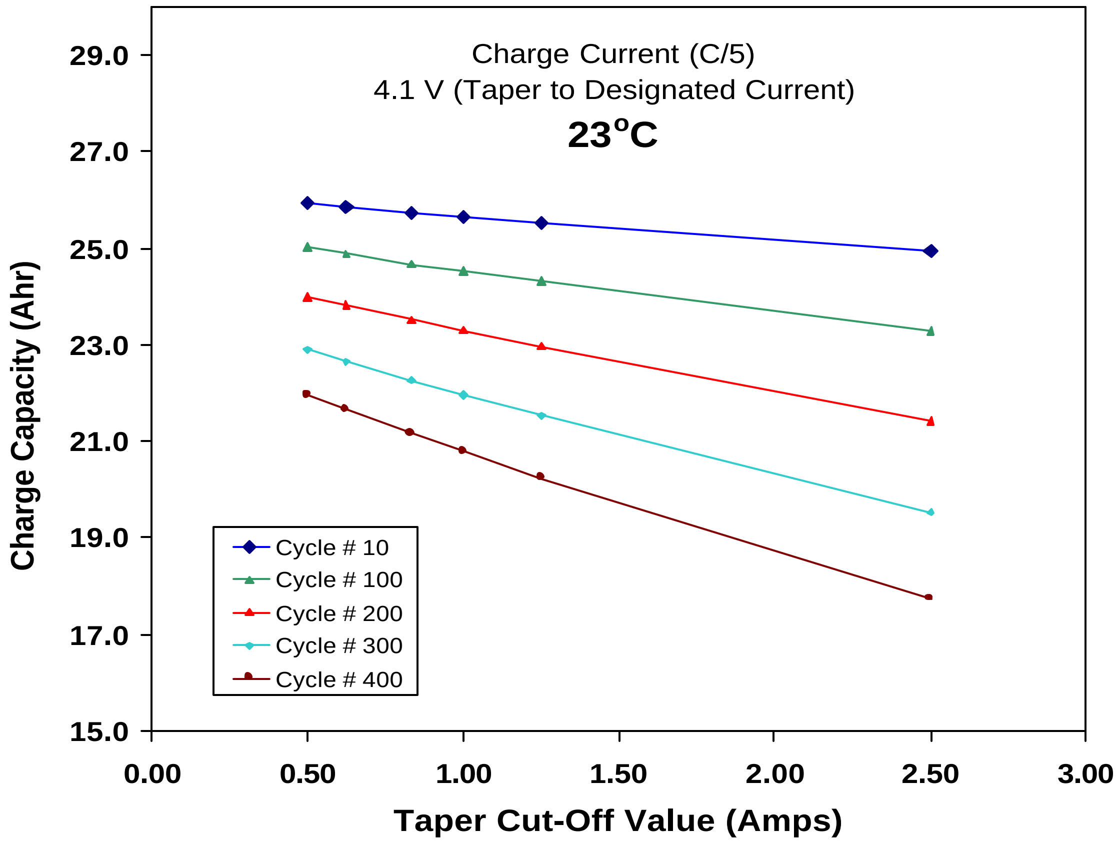




- **Later in cell life, significantly more time is spent in the taper mode (constant potential charging) while being charged.**
- **Due to increased impedance, the overall charge time can increase (even though capacity has declined with cycling).**

Large Capacity Lithium-Ion Cells for Future Mars Applications

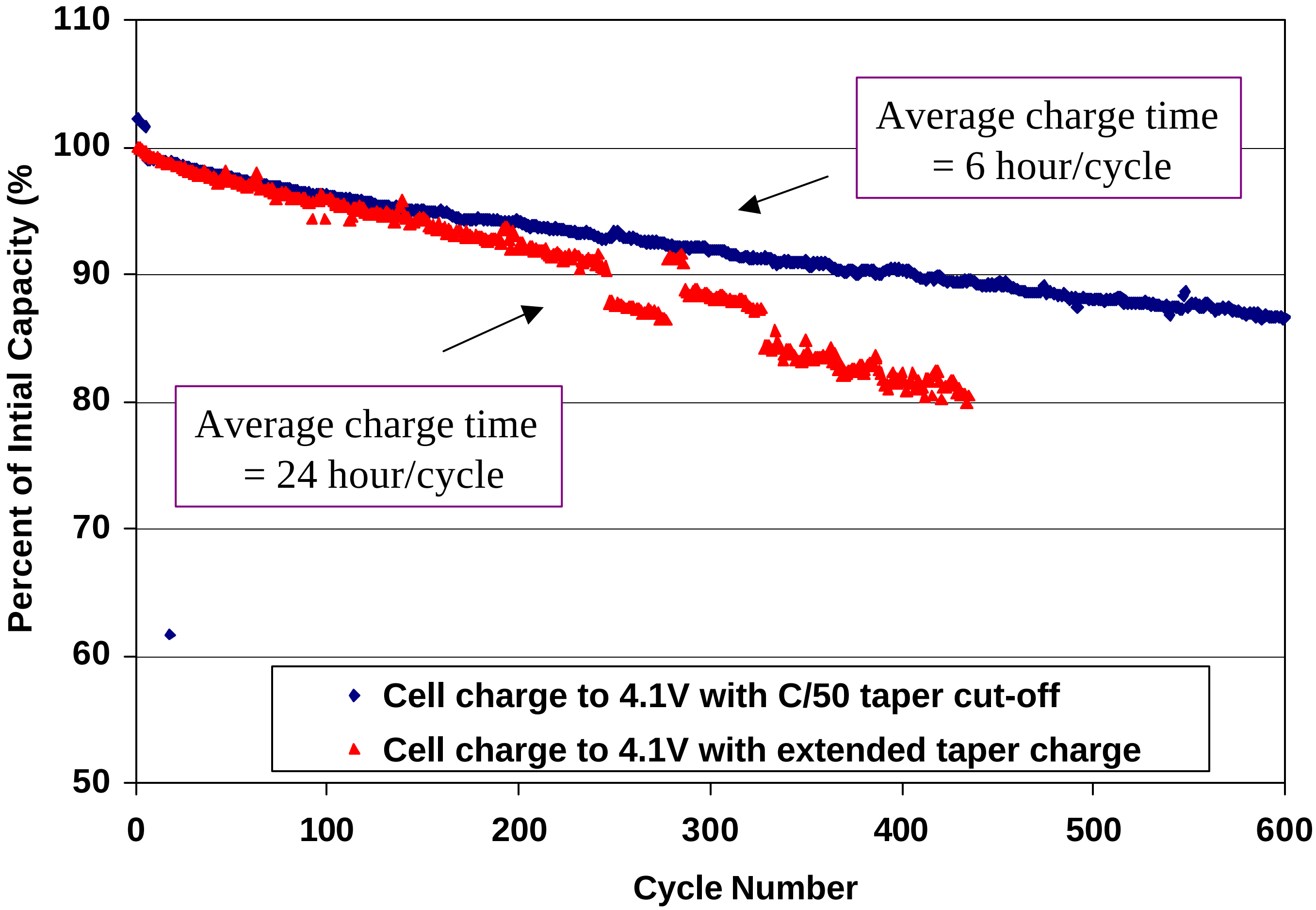
Effect of Cycle Life on Charge Characteristics



• **Later in cell life, the impact of the selected taper current cut-off value upon charge capacity is more dramatic (due to increased cell impedance and poorer lithium intercalation/de-intercalation kinetics)**

Large Capacity Lithium-Ion Cells for Future Mars Applications

Effect of Taper Current on Charge Characteristics

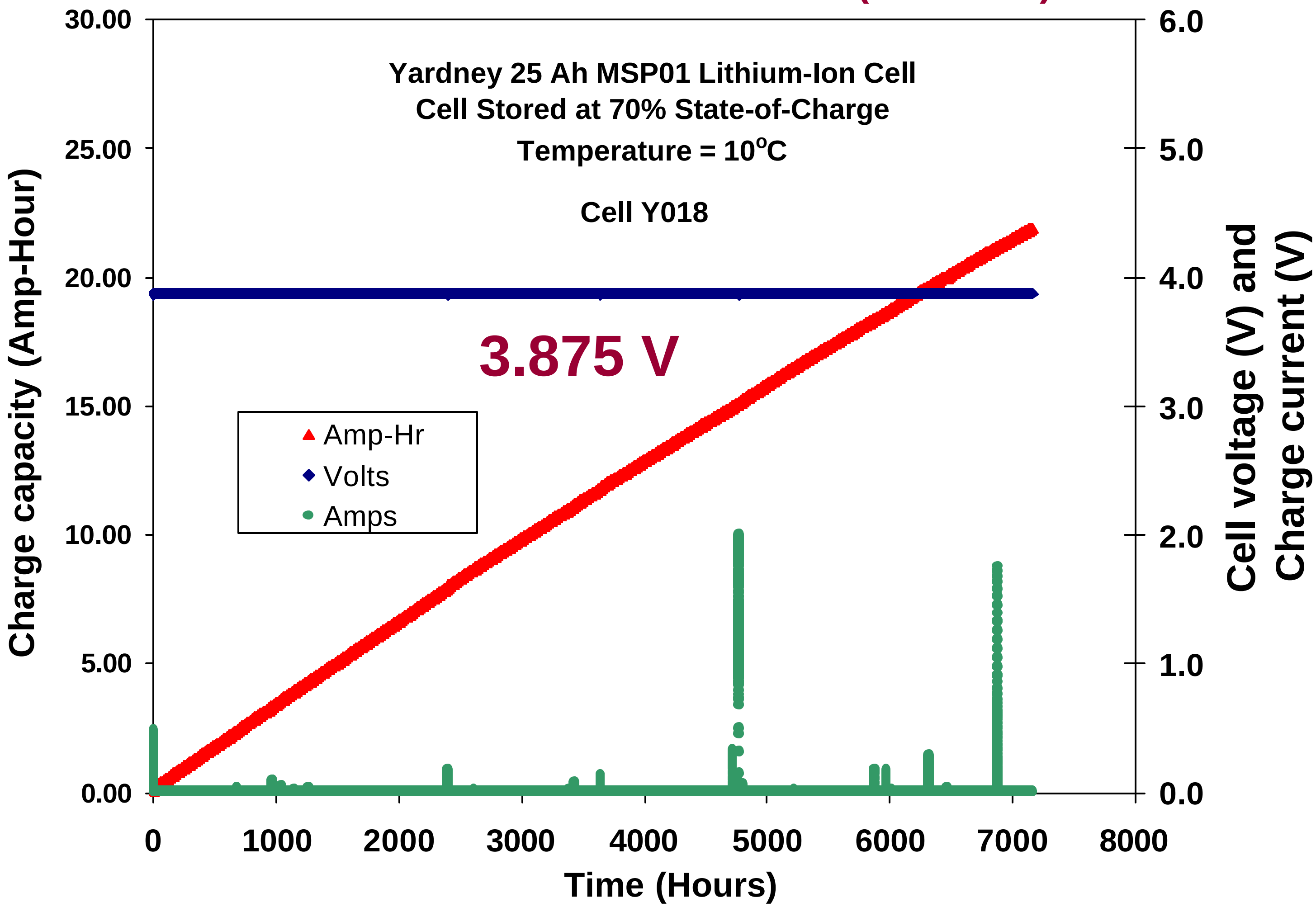


- Extended taper charging appears to limit cycle life characteristics (similar to floating at high V).
- Capacity decline most likely due to enhanced impedance build-up and increased electrolyte oxidation

Lithium-Ion Cells for NASA and DoD Applications:

Storage Characteristics of a 25 Ahr Cell- Results of 11 Month Storage Test

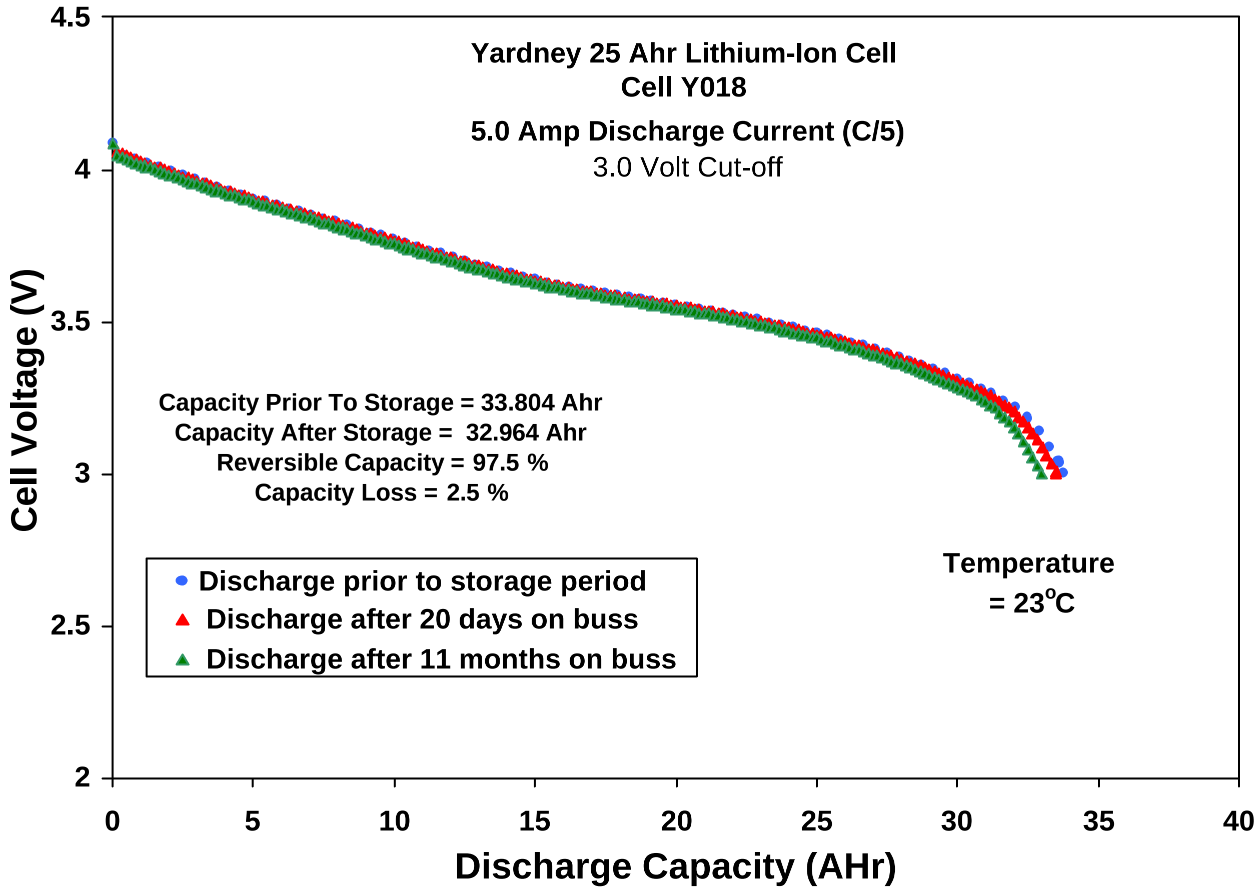
Cell Stored on the Buss at 10°C (70% SOC)



Lithium-Ion Cells for NASA and DoD Applications:

Storage Characteristics of a 25 Ahr Cell- Results of 11 Month Storage Test

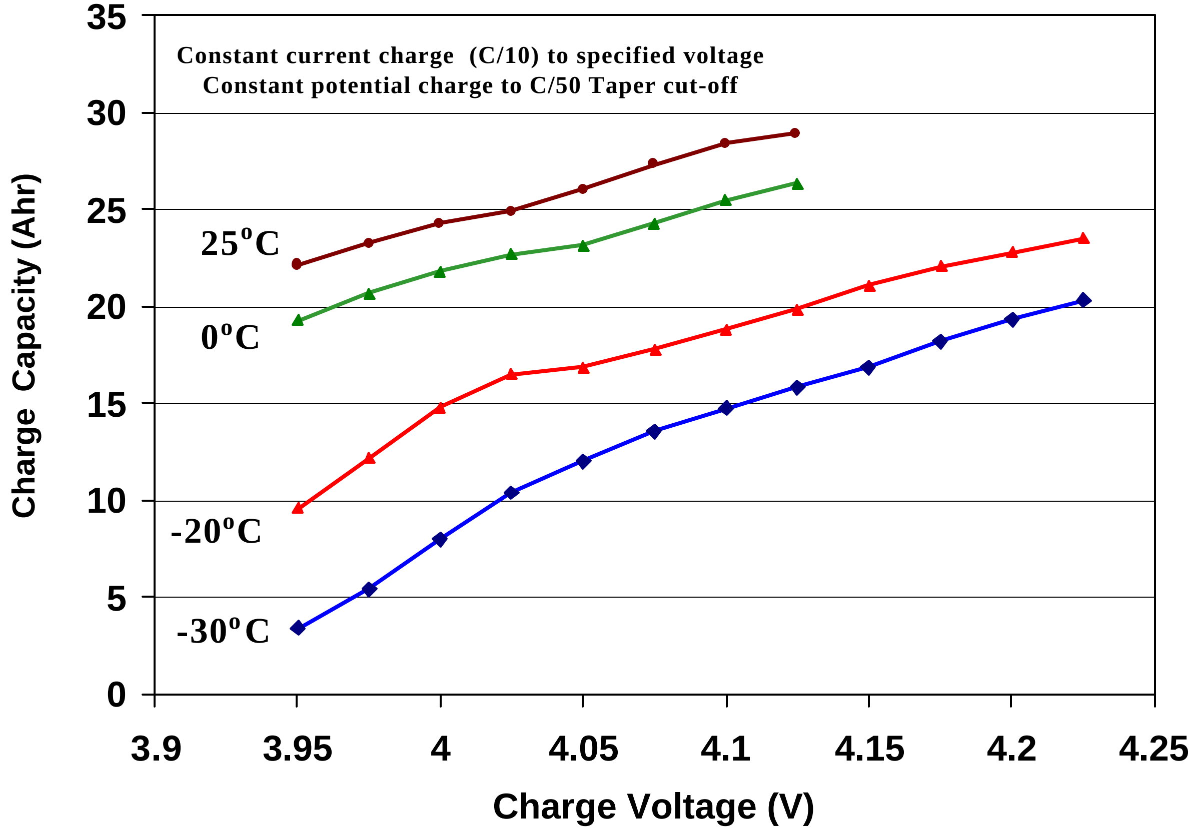
Cell Stored on the Buss at 10°C (70% SOC)



- Float charging (storage on the bus) results in minimal cell performance degradation if a moderately low voltage (low SOC) is selected.

Large Capacity Lithium-Ion Cells for Future Mars Applications

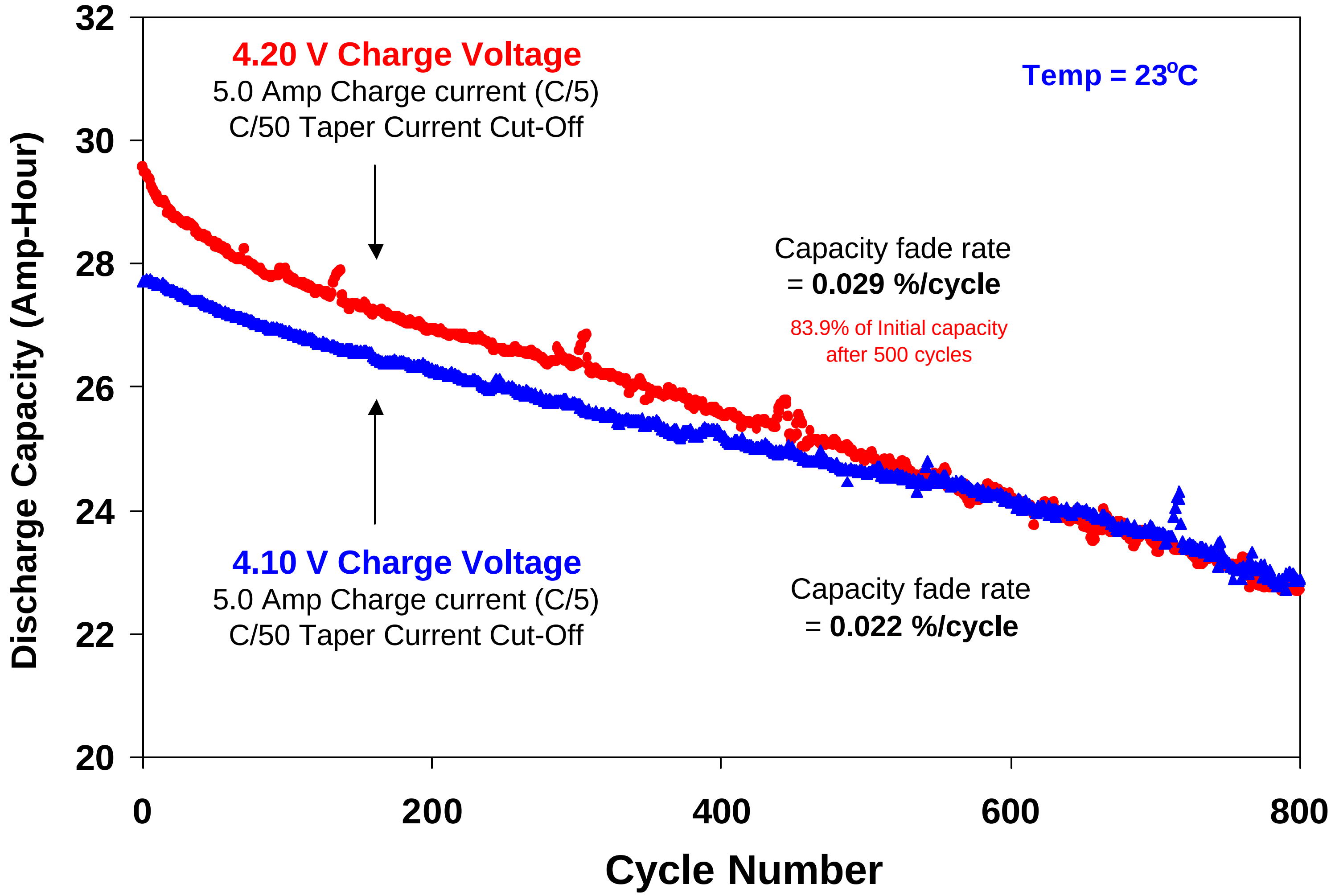
Effect of Charge Voltage on Charge Characteristics



- Selected charge voltage has a more dramatic impact upon charge capacity at lower temperatures.
- Although charging to higher voltages yields higher capacity, it may also be accompanied by undesirable effects (I.e., electrolyte oxidation and/or lithium plating)

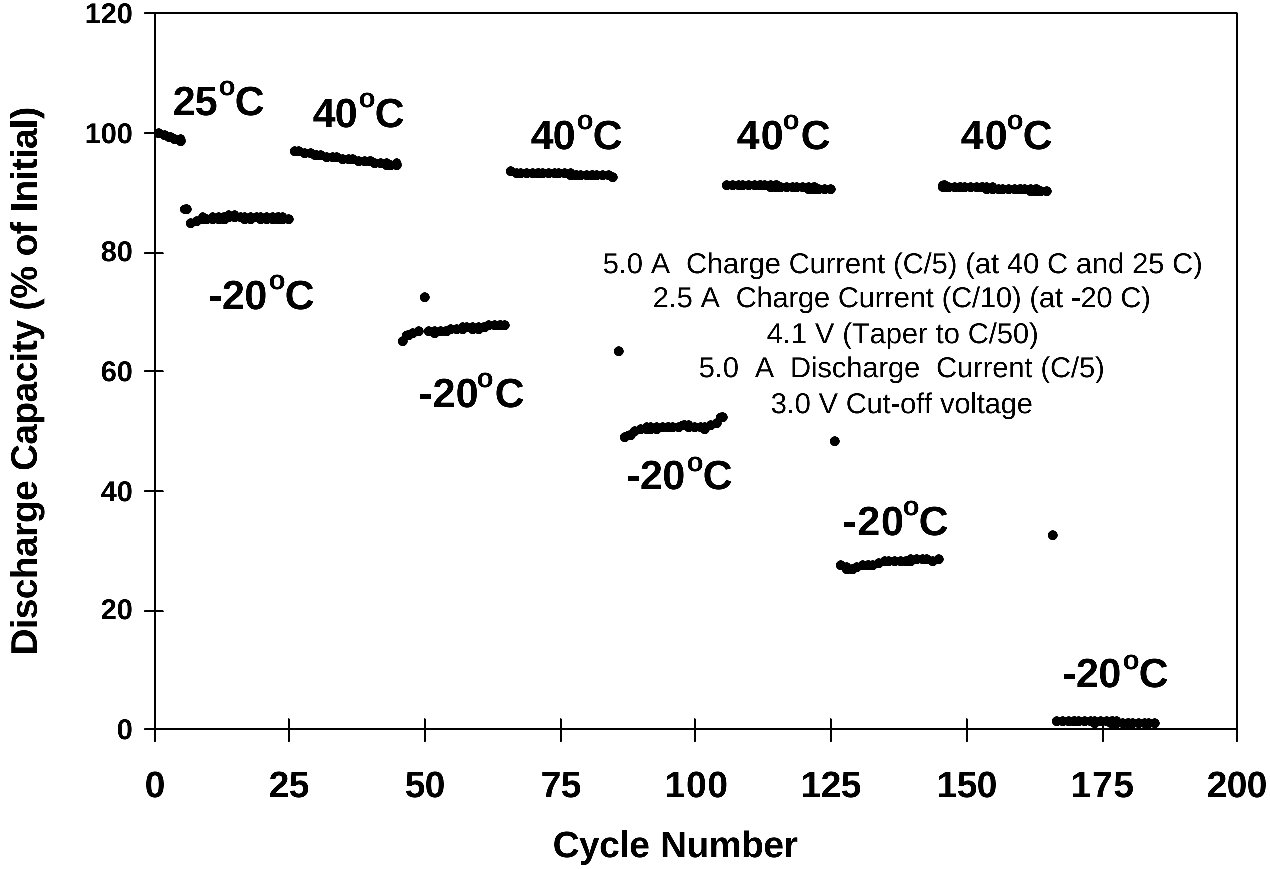
Large Capacity Lithium-Ion Cells for Future Mars Applications

Effect of Charge Voltage on Cycle Life Characteristics



Large Capacity Lithium-Ion Cells for Future Mars Applications

Cycle Life Performance at Varying Temperatures

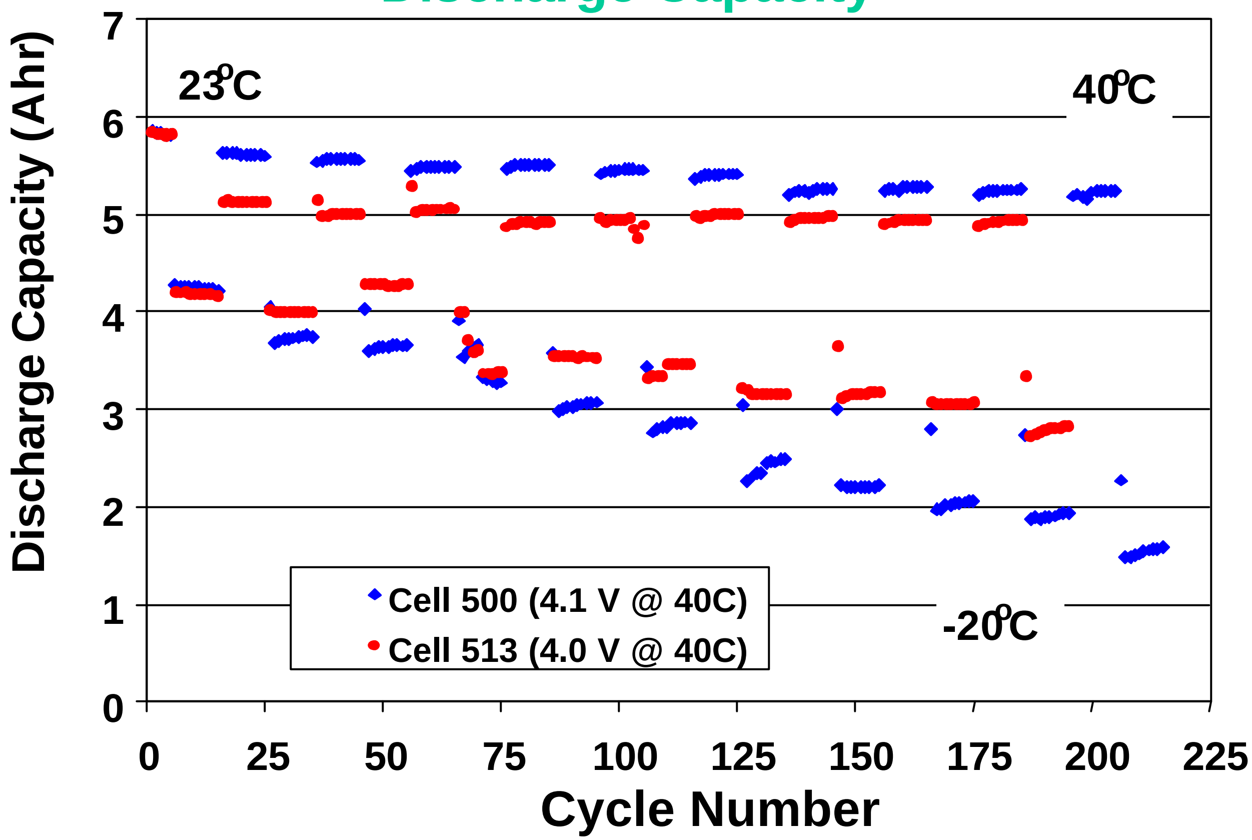


- **An increase in cell impedance and a decrease in low temperature performance capability was observed upon cycling between two temperature extremes.**
- **It was ascertained that the *charge voltage at high temperature* can influence trend.**

Lithium-Ion Cells for NASA and DoD Applications:

Rover Cell Design - Variable Temperature Cycling

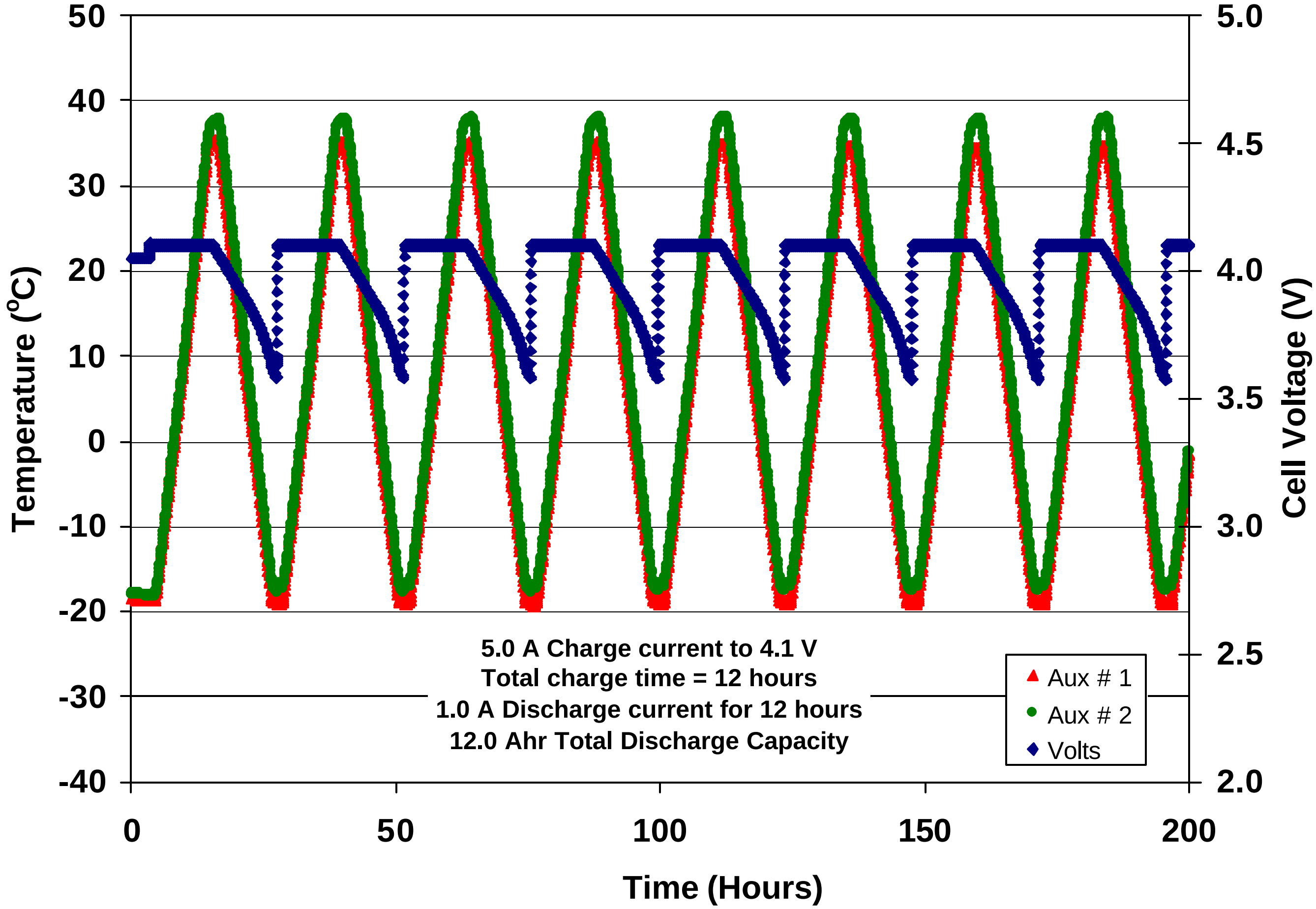
Discharge Capacity



• Using lower charge voltages at high temperatures was observed to preserve the low temperature performance capability and extend life characteristics.

Lithium-Ion Cells for Mars Lander Applications

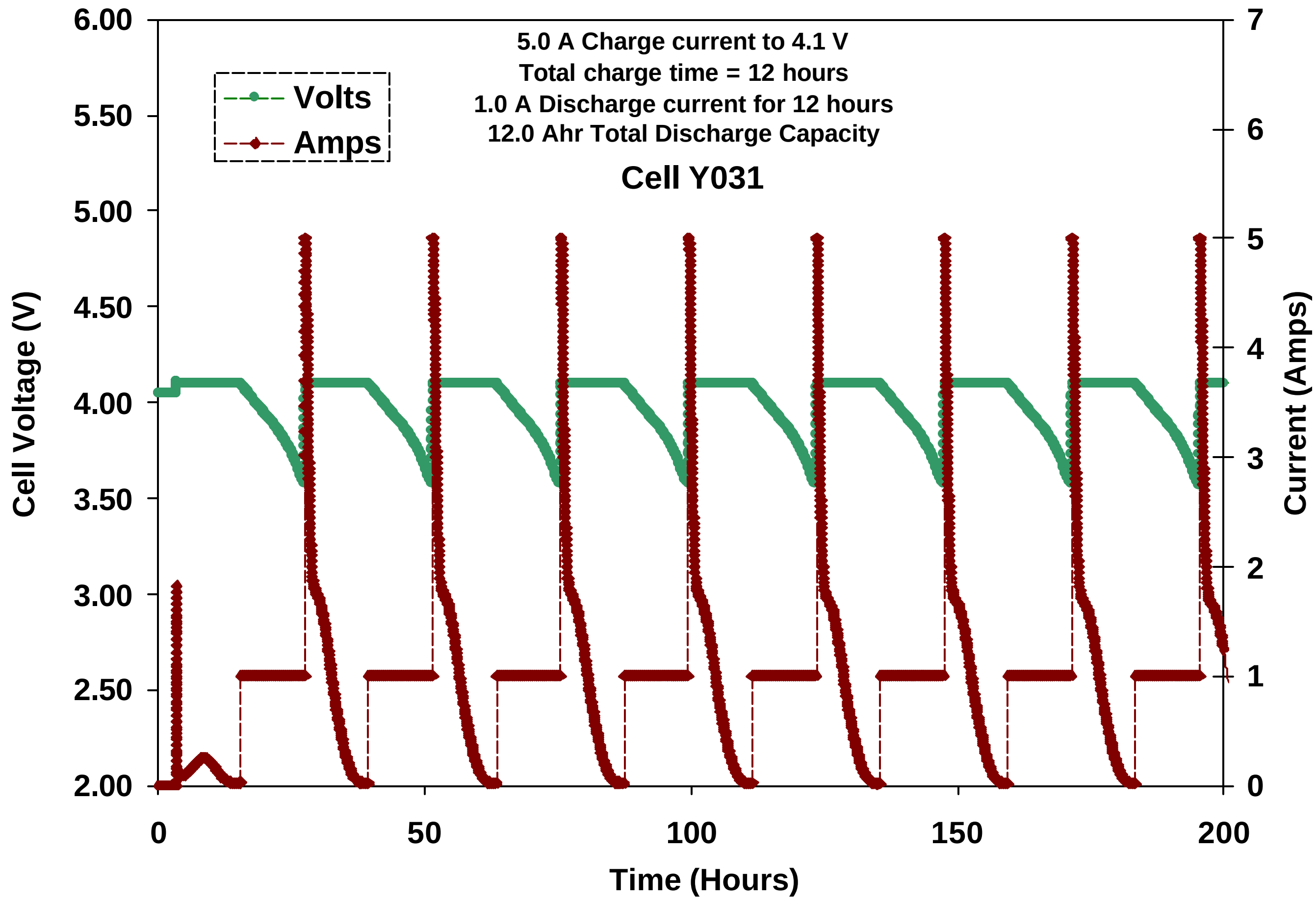
Mission Simulation Cycling (Temperature Range = - 20 to +40^{o}C)



- **Under typical Mars surface operation conditions, the cell (battery) charging process can occur over a range of temperatures.**

Lithium-Ion Cells for Mars Lander Applications

Mission Simulation Cycling



- If the cell/battery charging begins when the temperature is the coldest (-20ºC), representing a worst case scenario, high charging currents (> C/5) cannot be sustained.
- However, due to the constant potential current taper mode, full charge is accomplished.

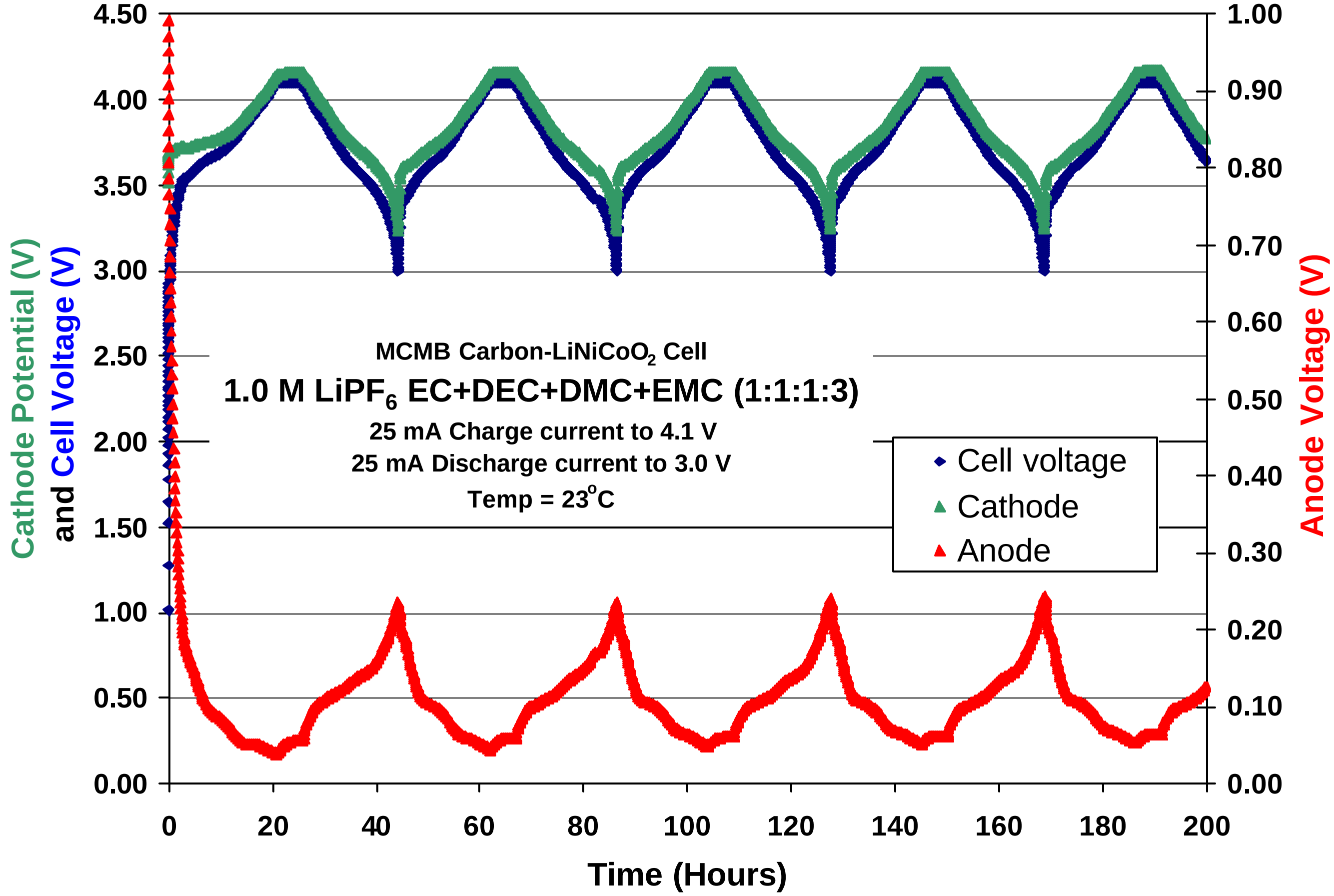
Charge Characteristics of Experimental Lithium Ion Cells (Three Electrode Cells)

- **Cell Design/Chemistry**
  - **MCMB anodes and $LiNiCoO_2$ cathodes**
  - **Cells equipped with Li metal reference electrodes**
  - **Number of different electrolyte studied (esp. low temp)**
  - **300-400 mAhr size cells**
  - **Jelly roll design (cylindrical)**

- **Charge acceptance at various rates and temperatures**
  - **Effect of charge voltage**
  - **Effect of charge current and taper current cut-off**
  - **Effect of electrolyte (and corresponding SEI layers formed) upon charge characteristics**
  - **Identification of conditions which lead to lithium plating**

Formation Characteristics of a MCMB-$LiNiCoO_2$ Cell

Fabricated with JPL Quaternary Carbonate Low Temperature Electrolyte

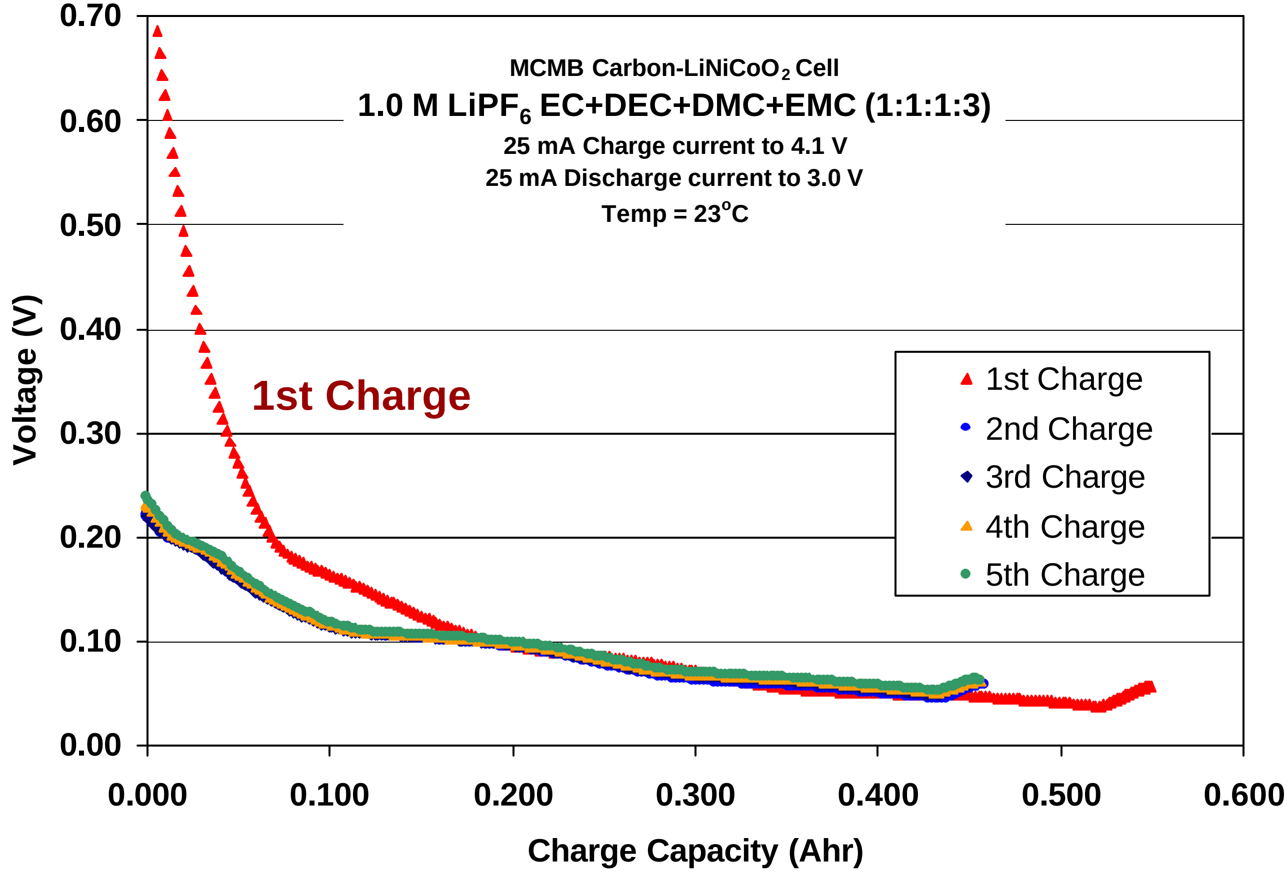


• Three-electrode cell design enables one to determine individual electrode potentials in addition to the cell voltage.

Formation Characteristics of MCMB-$LiNiCoO_2$ Cells

Fabricated with JPL Quaternary Carbonate Low Temperature Electrolyte

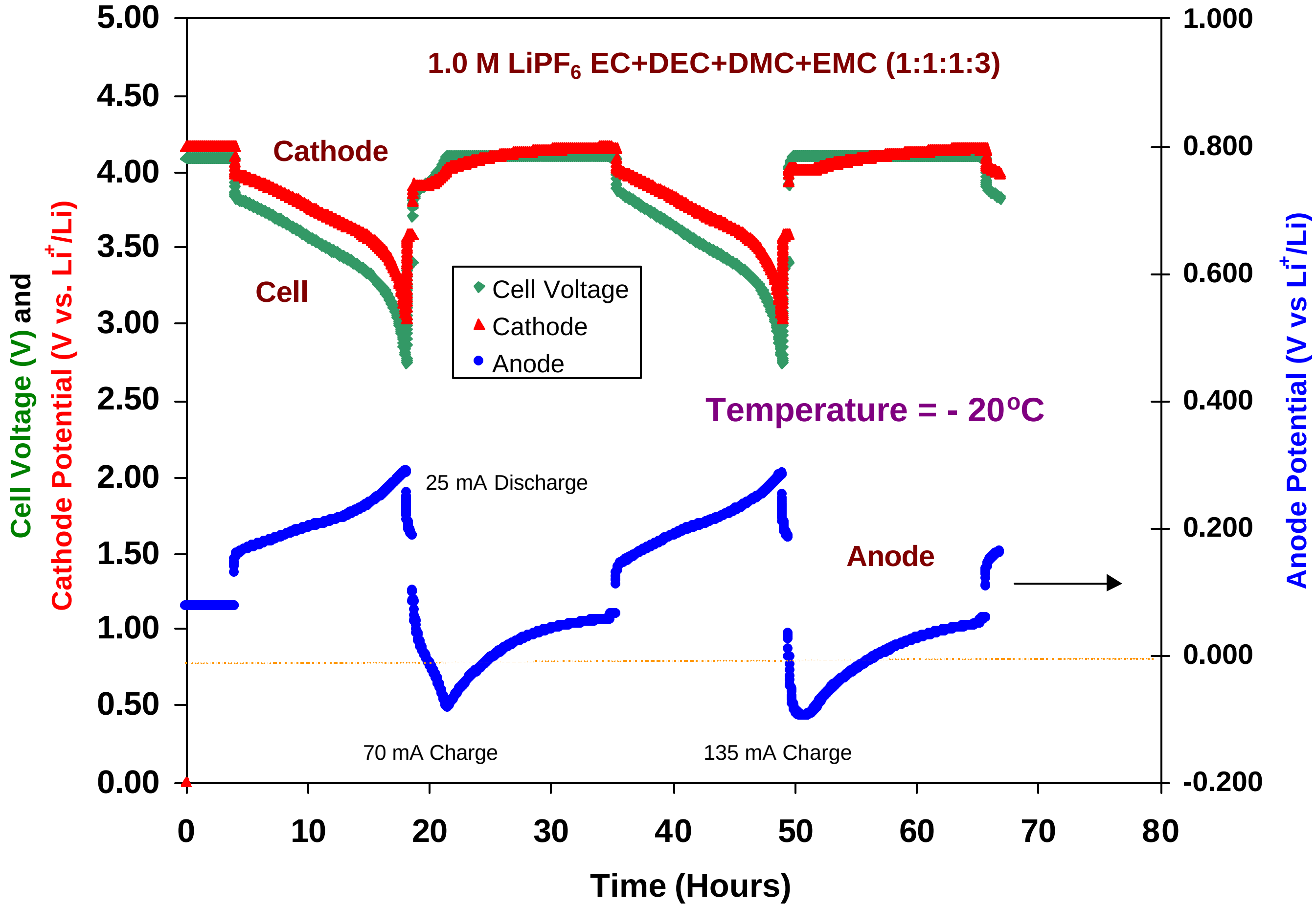
Anode Potential During Charge



- Upon charge, the anode electrode potential is typically between 0.025-0.250 V at 23ºC.
- During cell formation, initial charge goes to forming protective SEI layer.

Low Temperature Performance of MCMB-$LiNiCoO_2$ Experimental Cells

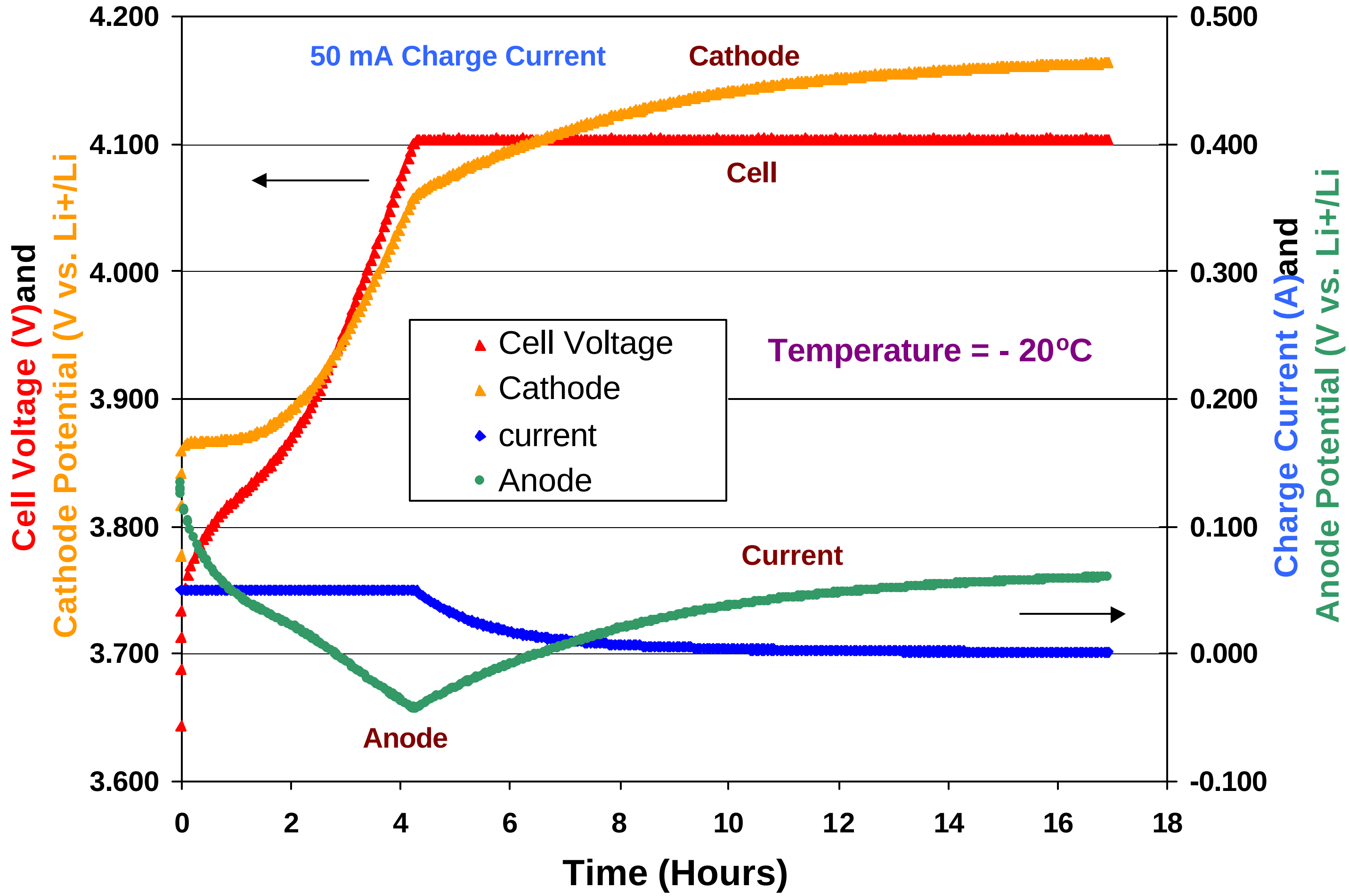
Effect of Electrolyte Upon Low Temperature Performance



• **At low temperatures, the anode potential can become negative with respect to Li^+/Li.**

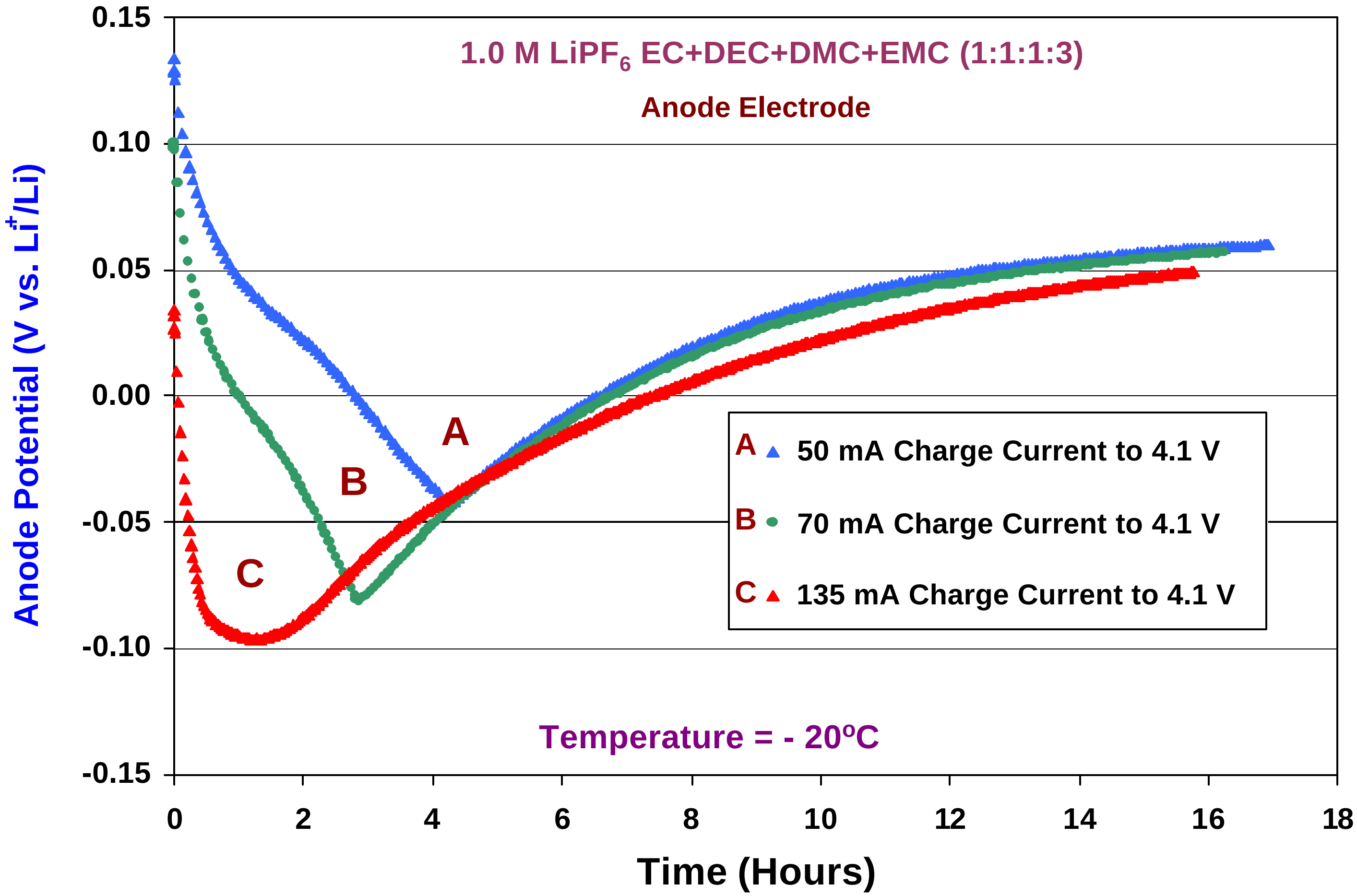
Charge Characteristics of Experimental Lithium Ion Cells

Effect of Charging at Low Temperature (- 20°C)



• As shown, the point at which the anode potential becomes the most negative (~ -70mV vs. Li^+/Li) is when the charge voltage and current are highest.

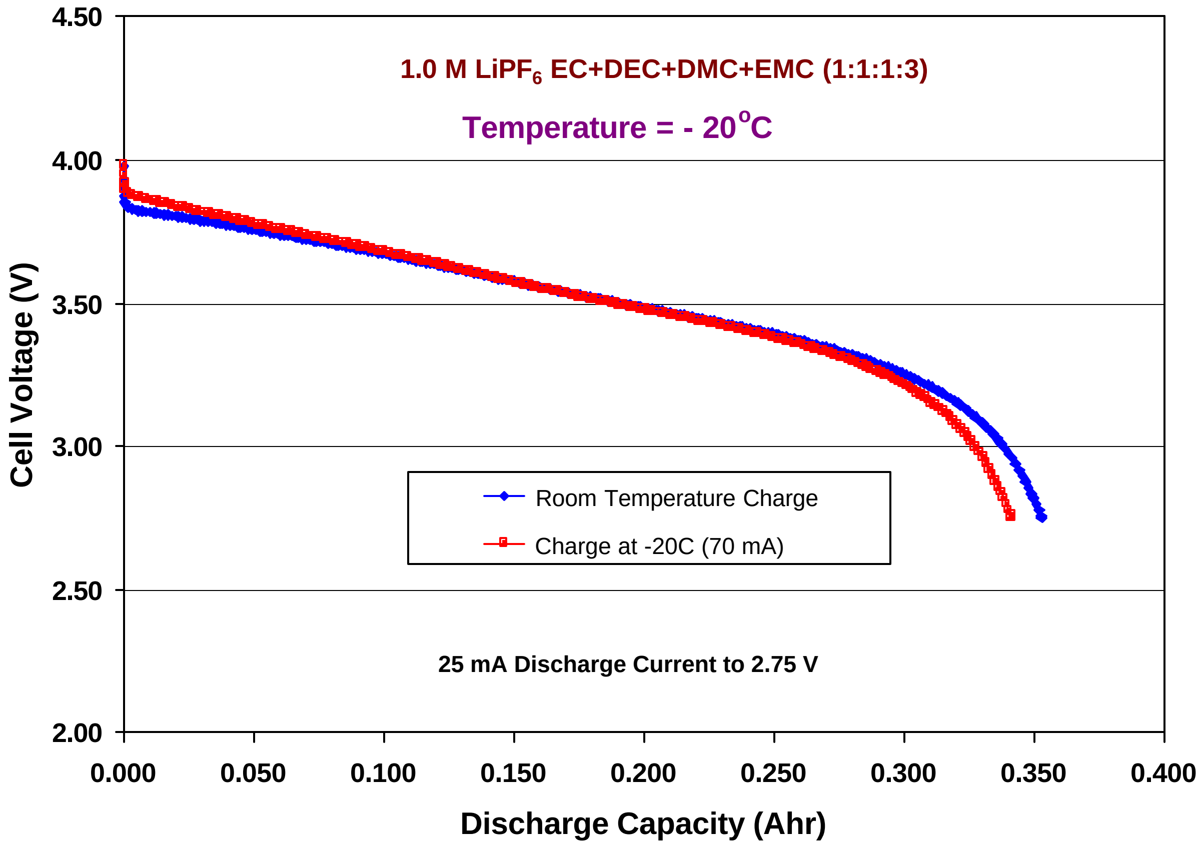
Effect of Charge Rate Upon Electrode Polarization Behavior of Li-Ion Cells:
Charge Characteristics at Low Temperature



• As shown, the anode potential becomes more negative when higher charge currents are used at low temperature

Charge Characteristics of Experimental Lithium Ion Cells

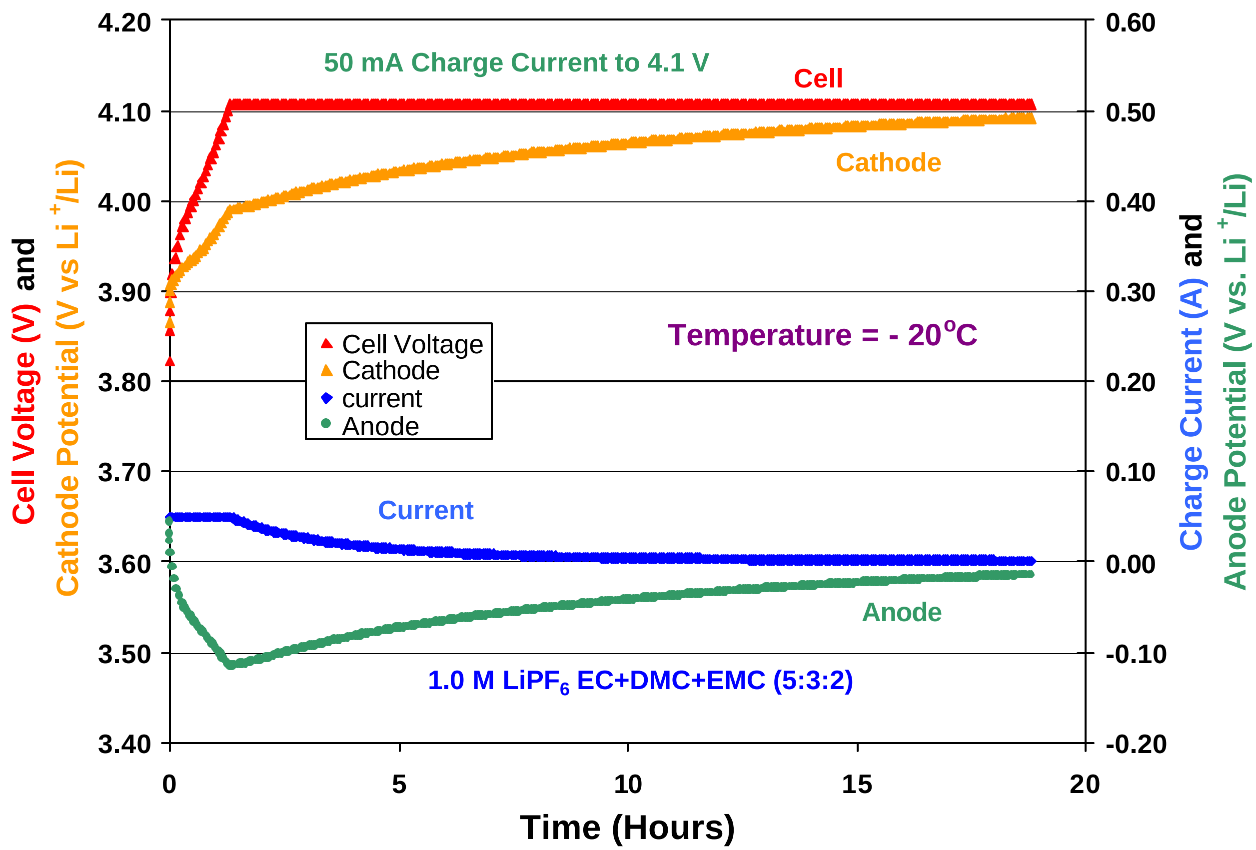
Effect of Charging at Low Temperature (- 40°C)



- **Although the anode potential became negative, no lithium plating was observed with this cell in the subsequent discharge profiles.**
- **This might be due to the fact that the potentials were not sufficiently negative and/or any lithium plated on the electrode surface had time to intercalate during the taper mode.**

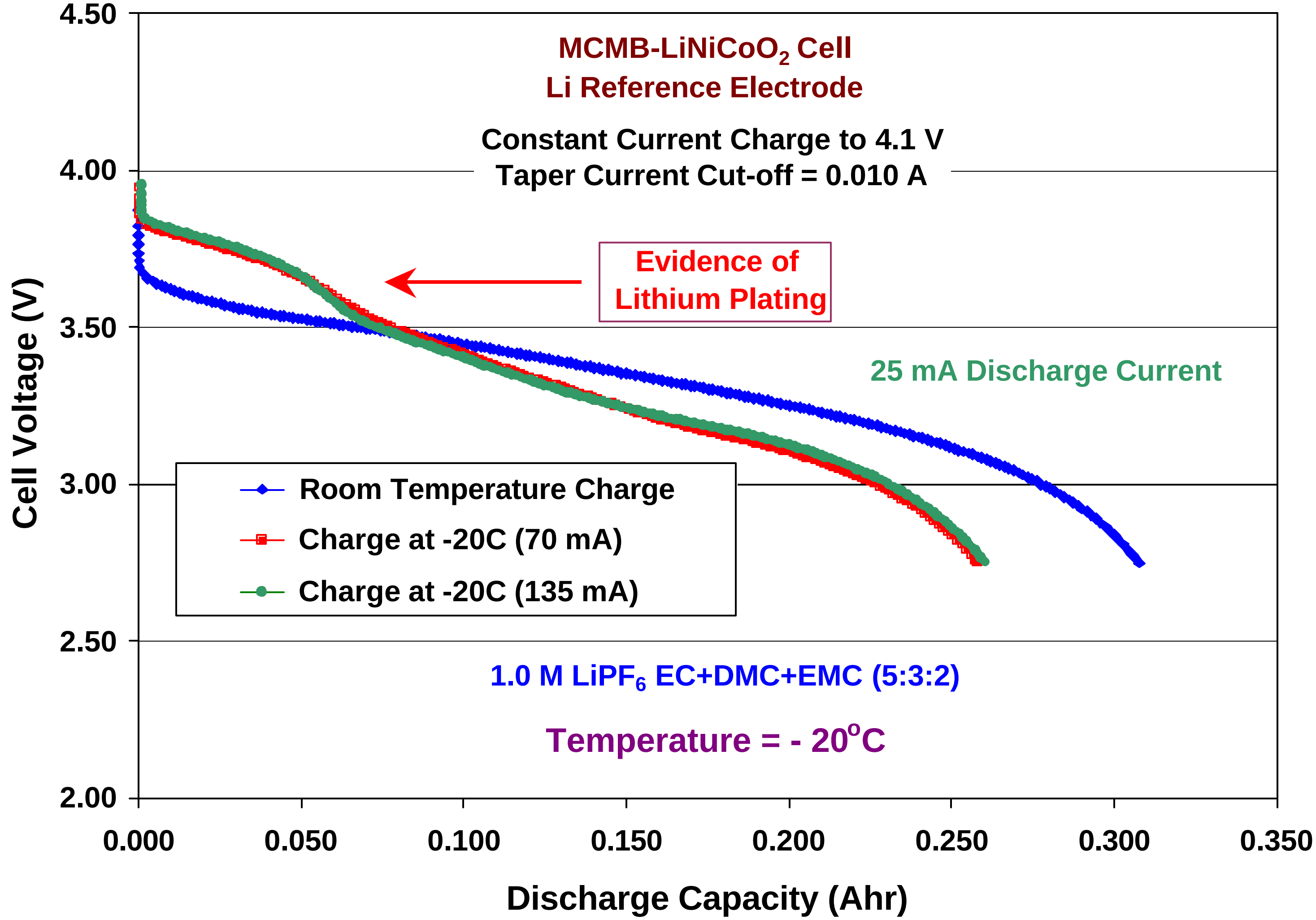
Charge Characteristics of Experimental Lithium Ion Cells

Effect of Charging at Low Temperature (- 20°C)



- In some cases, the anode can be excessively polarized in contrast to the cathode resulting in the possibility of lithium plating occurring.
- **In this example, the anode potential never becomes positive during entire charge.**

Effect of High Temperature Exposure on MCMB-$LiNiCoO_2$ Cells
Effect of Electrolyte Upon High Temperature Resilience



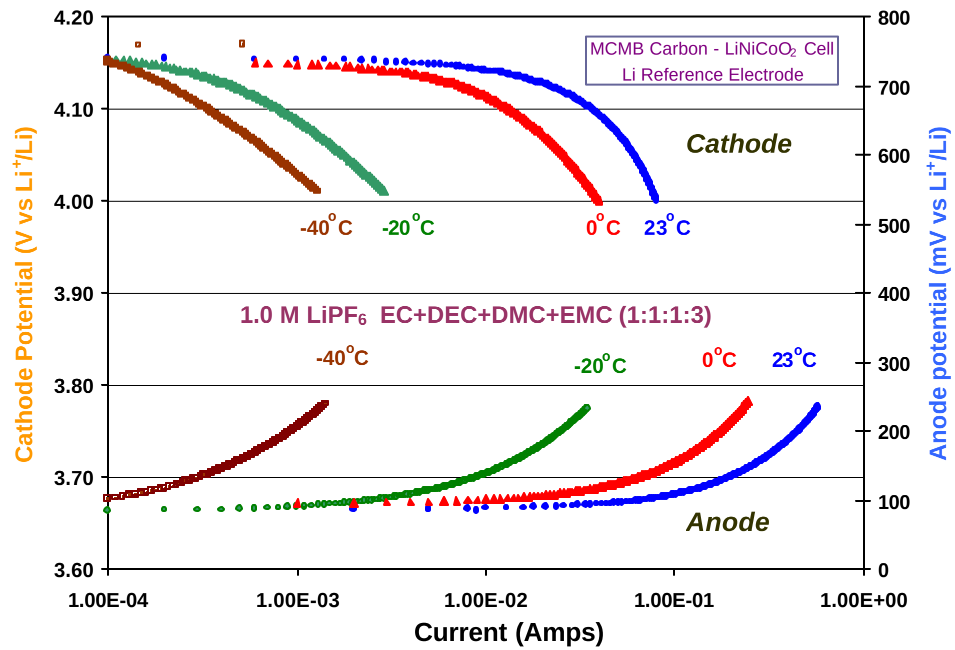
Tafel Polarization Measurements of MCMB and $LiNiCoO_2$ Electrodes
Effect of Electrolyte upon Polarization at Different Temperatures

- Tafel polarization measurements allow further insight into the kinetics of lithium intercalation/de-intercalation on MCMB anodes and $LiNiCoO_2$ cathodes in these electrolytes.

- These measurements were made at scan rates slow enough (0.5 mV/s) to provide near-steady state conditions and yet with minimal changes in the state of charge of the electrode or its surface conditions.

- The cells were tested in near full state of charge and biased over a 150 mV range.

- Both anode and cathode polarization characteristics were measured at various different temperatures (23, 0, - 20 and – 40ºC).



- In most cases, the cathode displays poorer kinetics and is performance limiting.

Linear Micropolarization Measurements

* At low overpotentials (<<RT/αnF) the electrochemical rate equation can be linearized resulting in a linear current-potential relation.

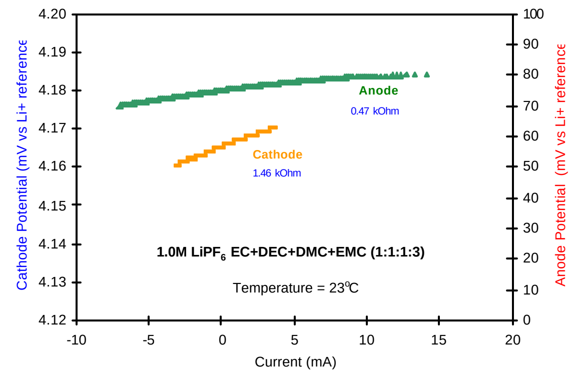
* The curves were obtained under potentiodynamic conditions conditions at scan rates of 0.02 mV/sec.

* The polarization resistance, or the exchange current density, can be calculated from the slopes of the linear plots.

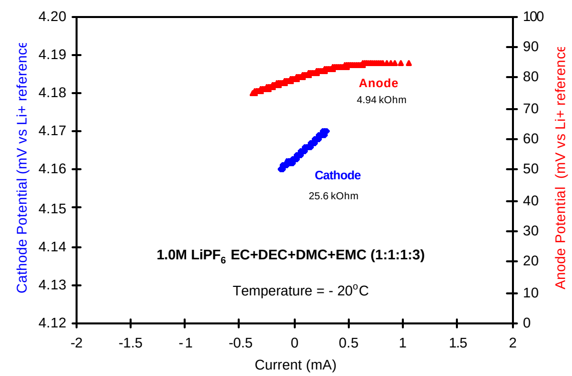
* The electrodes were tested in near full state of charge and biased over a 10 mV range.

* The resulting polarization resistance value is indicative of the facility of both the lithium inter-calation and de-intercalation processes in the material (encompassing Li+ diffusion through the SEI layer as well as bulk diffusion in the carbon electrode).

Measurements at 23ºC

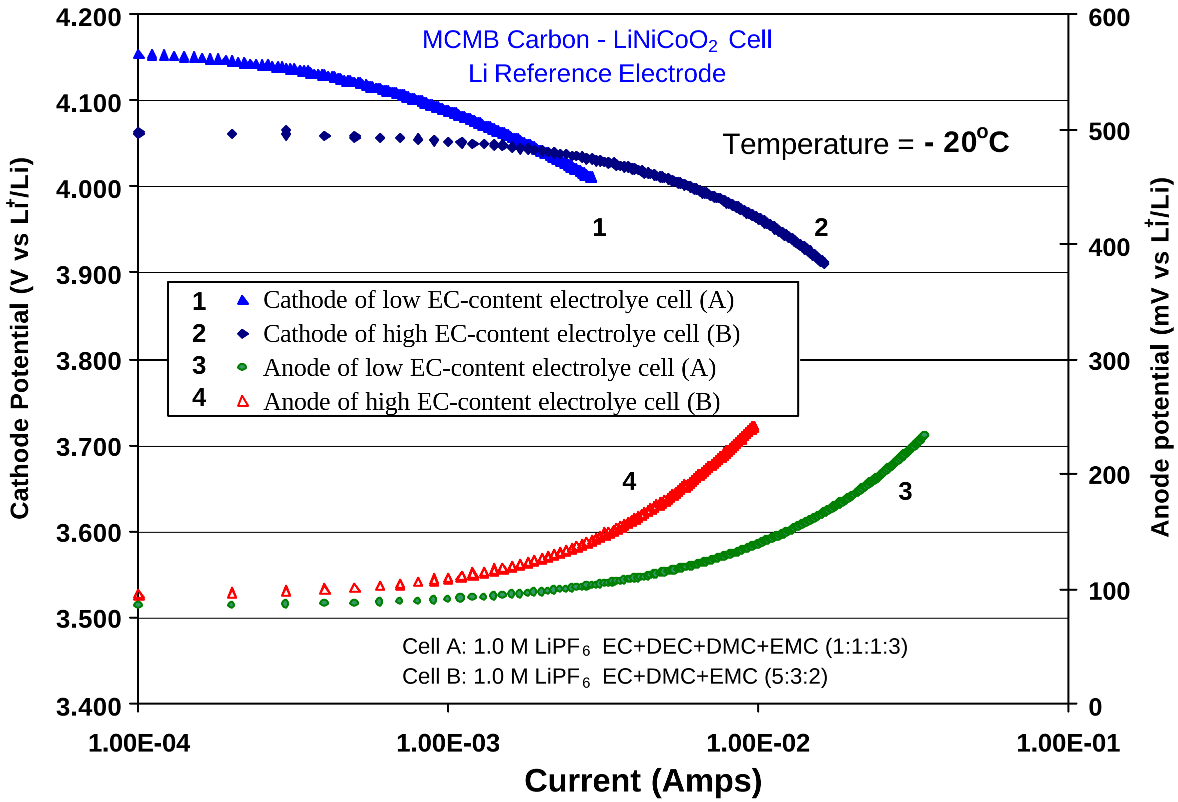


Measurements at - 20ºC



▷ Polarization resistance is observed to be higher for the cathode with most systems.
▷ Good tool to investigate kinetics at different temperatures as a function of electrolyte type

Tafel Polarization Measurements of MCMB and $LiNiCoO_2$ Electrodes
Effect of Electrolyte upon Polarization at Different Temperatures

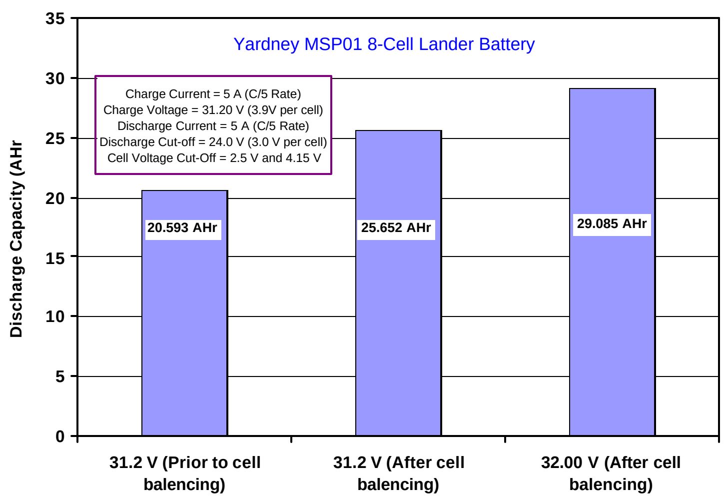


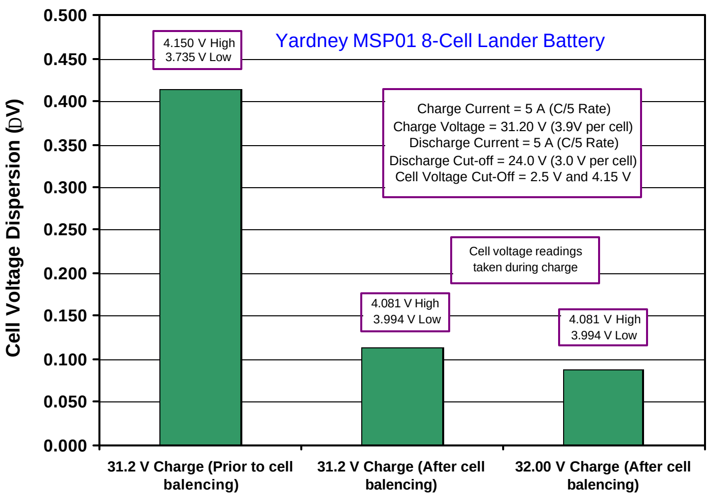
- In the case where no lithium plating was observed (good low temp electrolyte), the cathode was observed to have poorer kinetics at low temperature.
- **Whereas, in the case where lithium plating was observed (poor low temp electrolyte) the anode displayed poorer kinetics and increased polarization.**

Charge Characteristics of Prototype Lithium Ion Batteries

- **MSP01 Yardney 8-Cell Lander ATLO battery testing**
- Lander battery is being testing according to a Mars mission simulation profile
- Test plan reflects needs and requirements of ‘09 Smart Lander
- Test plan includes initial characterization, cruise period, EDL profile, and surface operation profile.
- **Charge Control**
  - 25 Ahr 8-cell battery (24-34.4 V)
  - Battery voltage controlled charging
  - Constant current and constant potential charging
  - Individual cell monitoring
  - Battery protection limits
    - Individual cell voltage exceeded (> 4.2 V)
    - Temperature limits exceeded (> 50^{o}C for any input)
    - Charge/discharge capacity limit (>35 Ahr)
    - Step time (> 10 hours)
  - Battery cell balancing methodology (TBD)
    (i.e., resistively discharging cells to specified voltage)

Lithium Ion Technology Demonstration for 07 Smart Lander Application
2001 MSP01 Lander Battery Testing





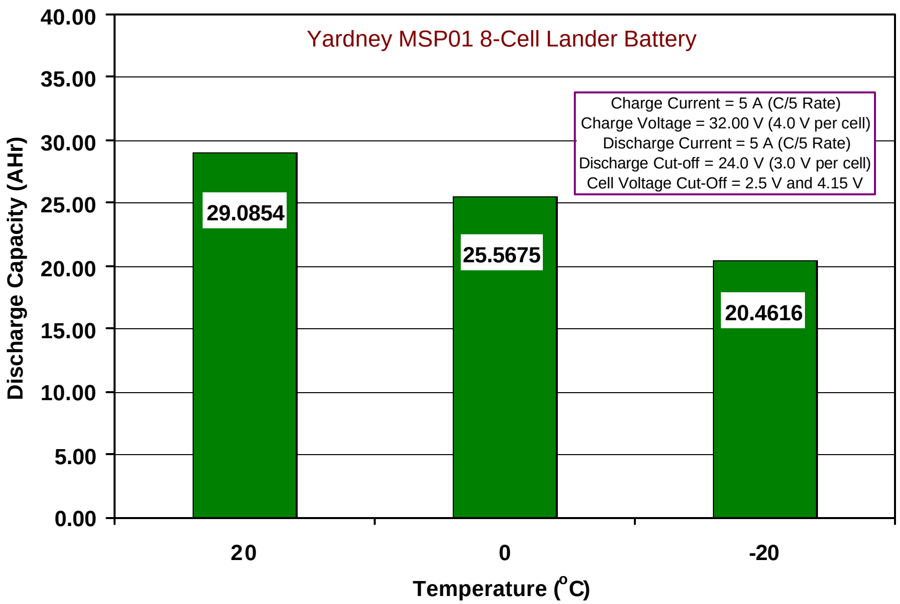
Discharge Capacity (AHr) *Cell Voltage Dispersion (DV)*

- Effect of cell balancing upon performance evaluated
- 25% more capacity delivered after cell balancing
- Much tighter grouping of cells observed (small cell voltage dispersion)

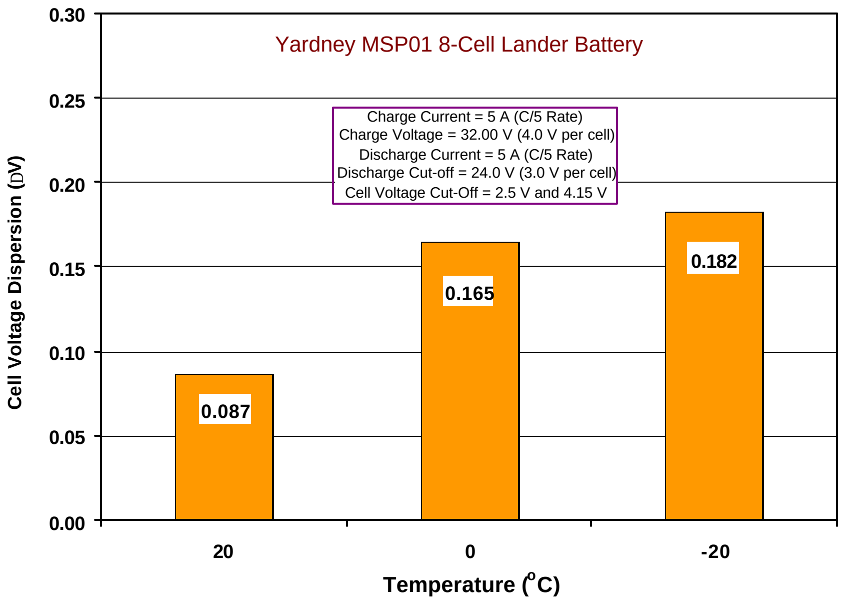
Yardney MSP01 25 Ah Lithium-Ion Battery for Mars Lander Applications

Initial Characterization/Conditioning at Different Temperatures

32 V Charge - Discharge Capacity (AHr) at Various Temperatures



Discharge Capacity (AHr)



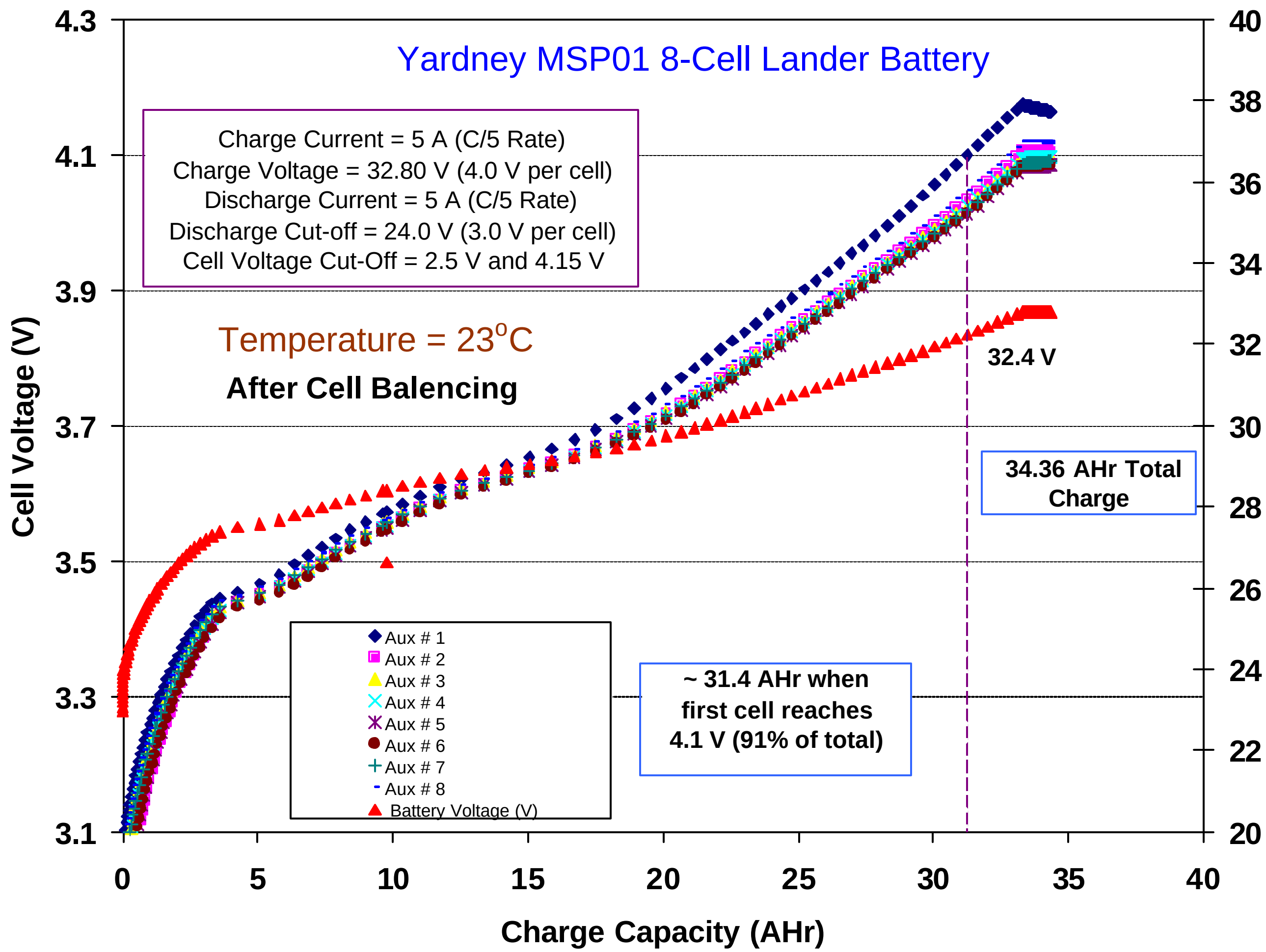
Cell Voltage Dispersion (DV)

- Battery capacity at different temperatures determined
- Capacity determined after cell balancing
- Greater cell voltage dispersion observed at lower temperature

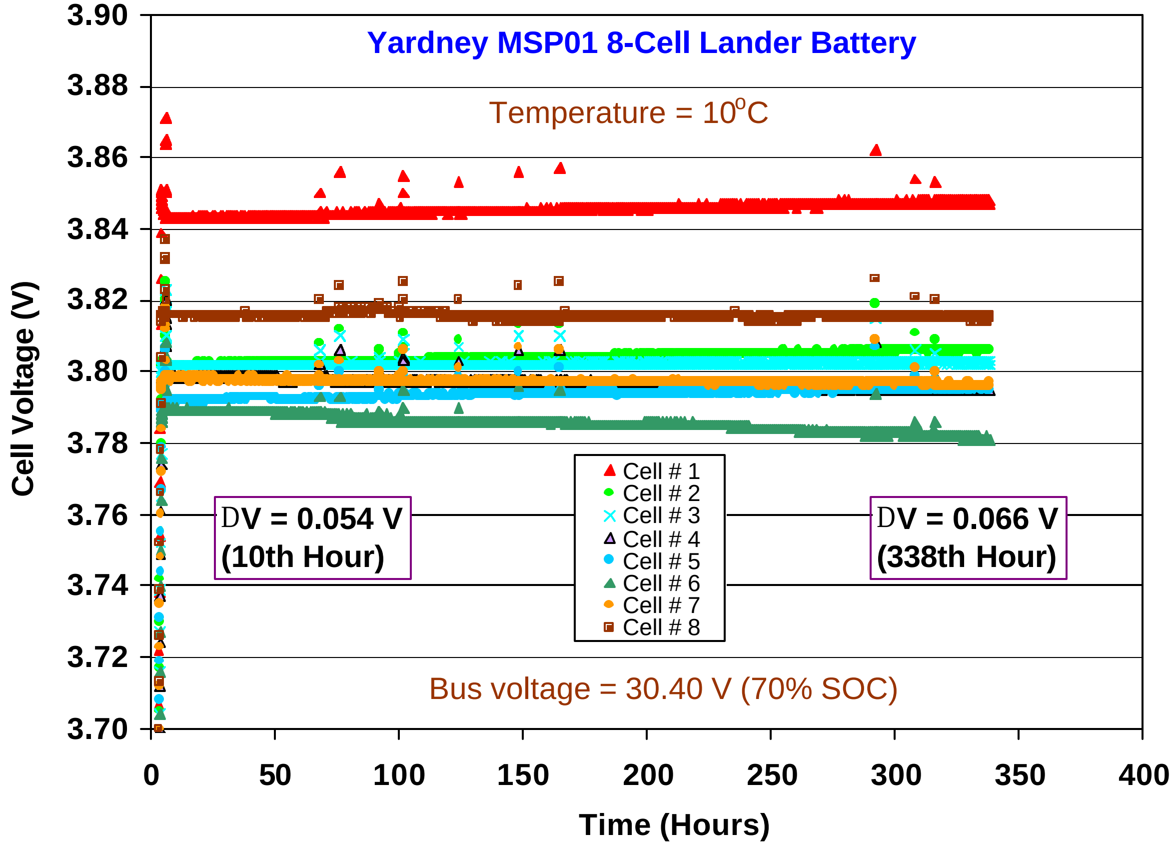
Yardney MSP01 25 Ah Lithium-Ion Battery for Mars Lander Applications

Initial Characterization/Conditioning at 20^{o}C

32.8 V Charge (After Cell Balancing-Second Time)



Lithium Ion Technology Demonstration for 07 Smart Lander Application
2001 MSP01 Lander Battery Testing-Cruise Period Test



- Cells balanced prior to storage test
- Cell dispersion potential issue depending upon charge methodology

Summary and Conclusions

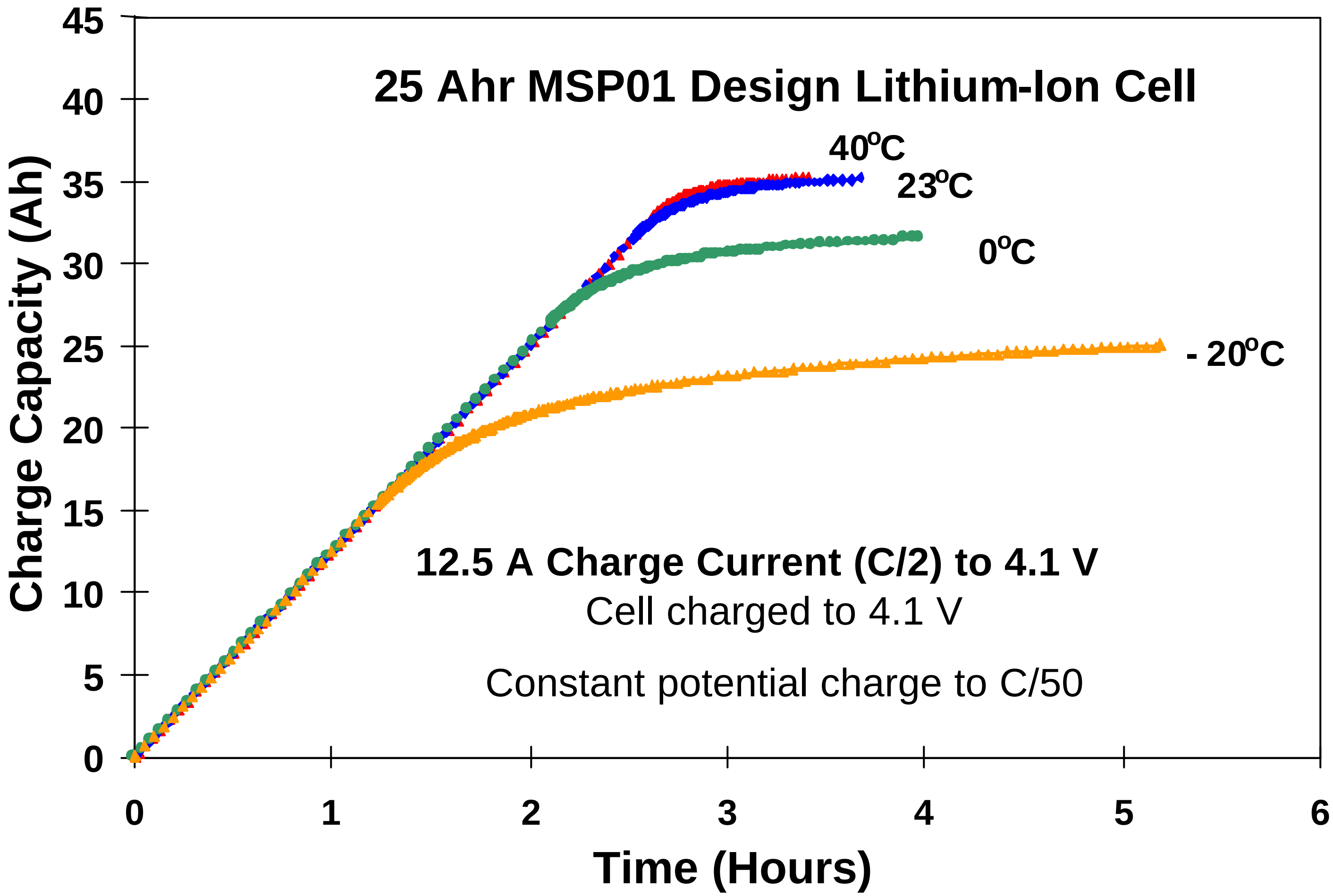
- The charge characteristics of a number of aerospace quality lithium-ion cells has been investigated.
- The effect of charge voltage upon performance has been determined, especially at lower temperatures, and has been observed to result in higher capacities.
- The effect of charge taper current cut-off methodology upon performance has been determined with the following observations being made: (1) lower taper current values at low temperature can result in significantly more capacity, (2) the impact of taper current value selection becomes more significant later in cell life, and (3) extended taper charging can limit life characteristics.
- The possibility of lithium plating occurring at low temperatures (and/or with high charge voltages) has been investigated in experimental three electrode cells. It was observed that high charge voltages, high charge currents and undesirable electrode kinetics can lead to conditions where lithium plating on the anode can occur.
- The charge characteristics of an 8-cell lithium ion battery has been investigated (without individual cell charging) with emphasis upon determining the extent of cell voltage dispersion.

Acknowledgments

The work described here was funded by the Code S Battery Program, Mars Exploration Program and the Mars 2003 MER Program and the and carried out at the Jet Propulsion Laboratory (JPL), California Institute of Technology, under contract with the National Aeronautics and Space Administration (NASA).

Lithium-Ion Cells for Mars Surveyor 2001 Lander

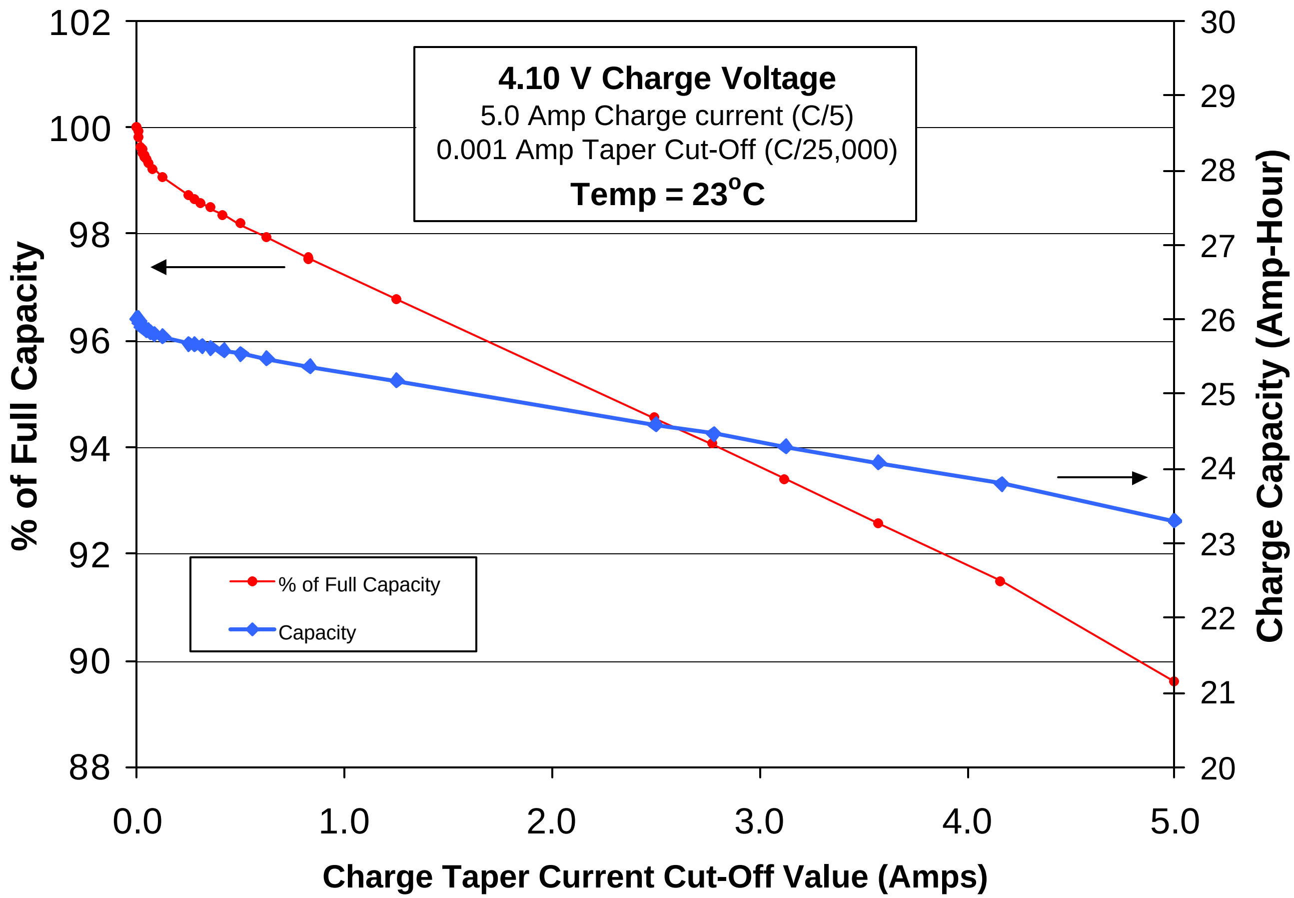
Charge Characteristics as a Function of Temperature



*** C/2 Charge Current**

Large Capacity Lithium-Ion Cells for Future Mars Applications

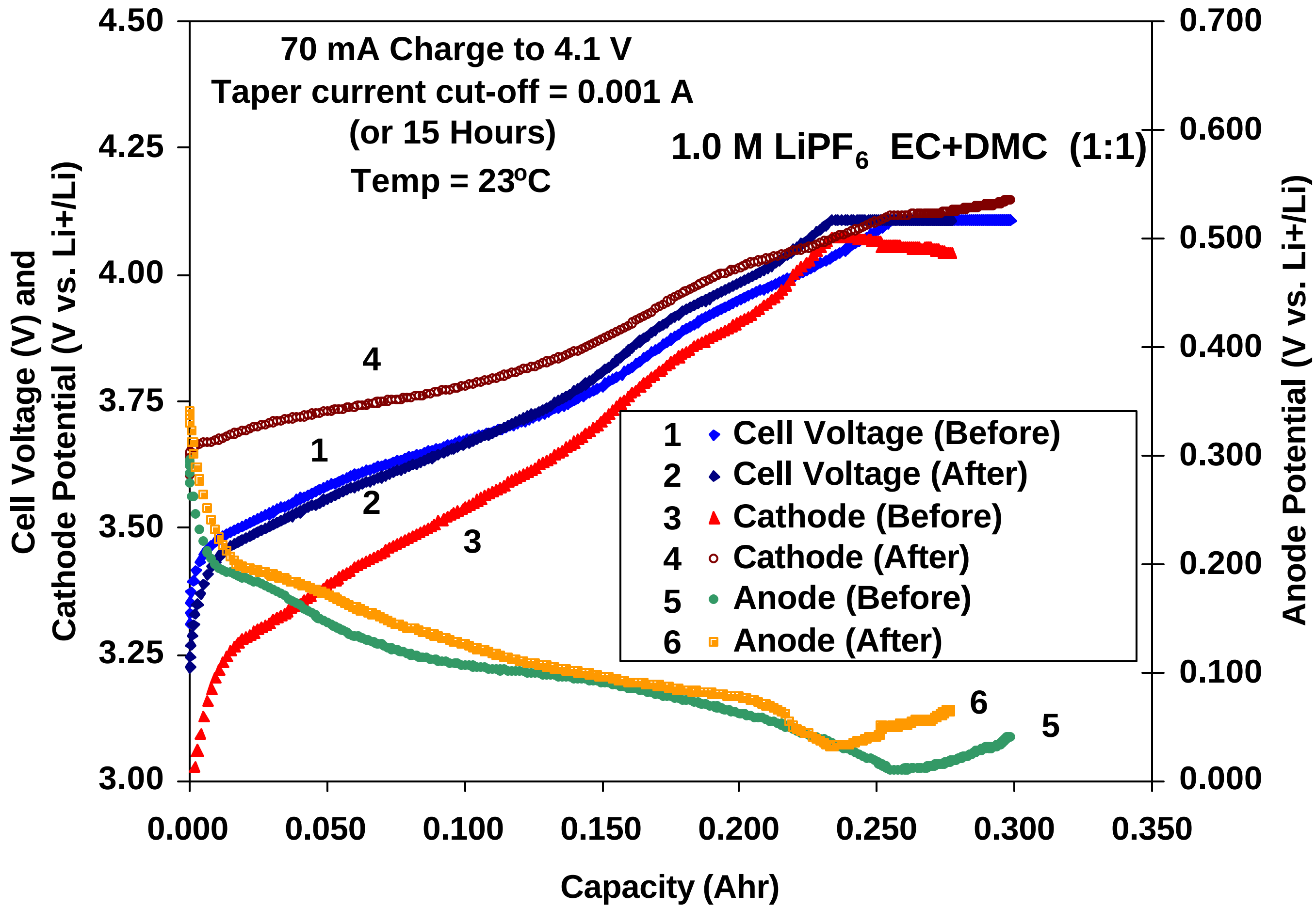
Effect of Taper Current on Charge Characteristics



• **With a fresh cell, approximately 10% of the total capacity is obtained in the "taper mode" of the charge**

Effect of High Temperature Storage Upon the Performance of Li-Ion Cells:

Cell Stored for 10 Days at 60ºC (Full SOC)



• The three-electrode cells are also helpful in trying to understand the impact of high temperature storage upon the polarization effects of the individual electrodes.

Performance of Li-Ion Cells Under Battery Voltage Charge Control

Hari Vaidyanathan, Consultant
Gaithersburg, Maryland
And
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Greenbelt, Maryland

2001 NASA Aerospace Battery Workshop
Huntsville, Alabama
November 27-29, 2001

Objective

Determination of Cycling Performance as a Battery Pack under LEO regime

- Number of cycles
- Charge voltage
- Temperature
- Reconditioning Effect

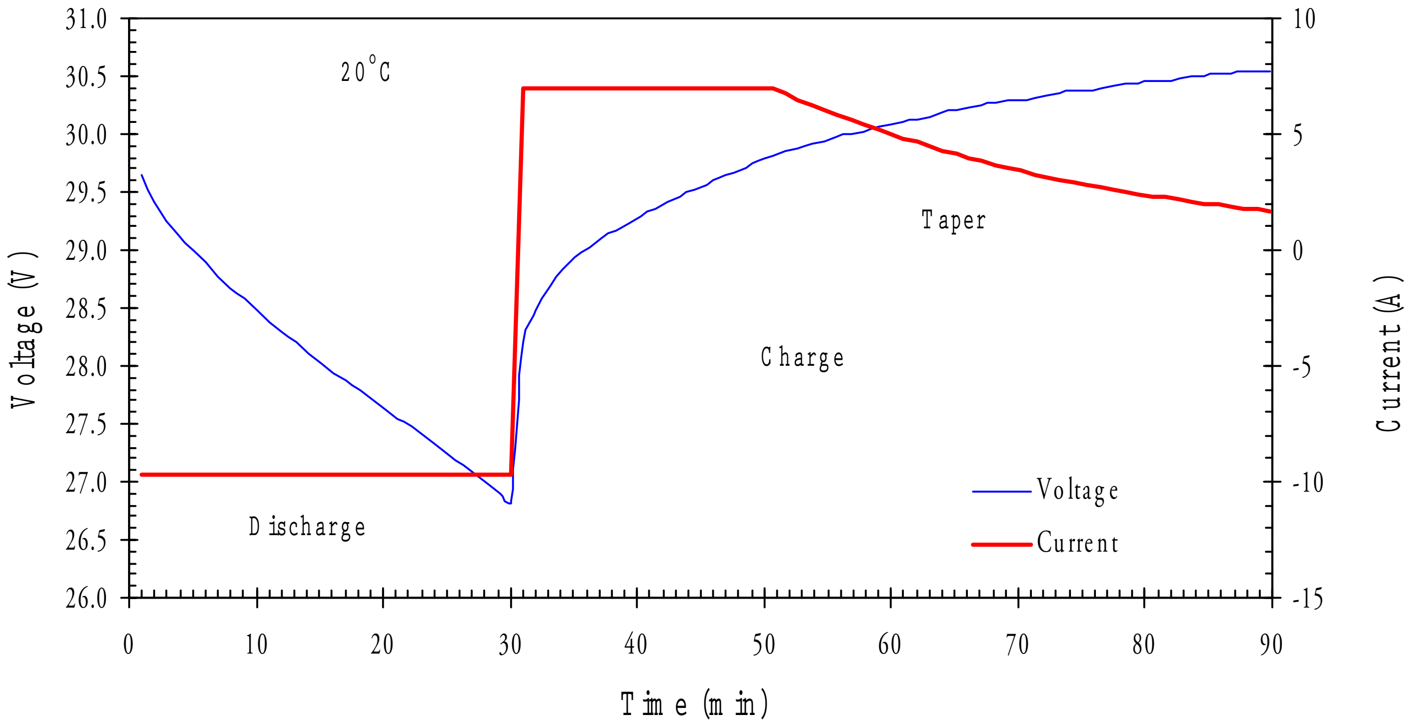
Cells Under Study

- Prismatic Cells
  - Yardney Technical Products, Inc. (YTP), 20 Ah, mixed-oxide (Co and Ni) positive, graphitic carbon negative, $LiPF_6$ salt mixed with organic Carbonate solvents
  - Mine Safety Appliances Company (MSA), 10 Ah, Co oxide positive, graphitic carbon negative, $LiPF_6$ salt mixed with organic Carbonate solvents
- Cylindrical Cells
  - SAFT, 12 Ah, mixed-oxide (Co and Ni) positive, graphitic carbon negative, $LiPF_6$ salt mixed with organic Carbonate solvents

LEO Cycling: Conditions

- Continuous cycling in a regime consisting of 30 min. discharge and 60 min. charge at the rate of 16 cycles/day
- Temperature = -20°C to 20°C
- Depth of discharge = 40%
- Voltage clamped at a Battery/Pack voltage at C/2 charge rate with current taper
- Recharge ratio = 1-1.01

TYPICAL BATTERY VOLTAGE CHARGE CONTROL PROFILE



TEMPERATURE VARIATION DURING CYCLING

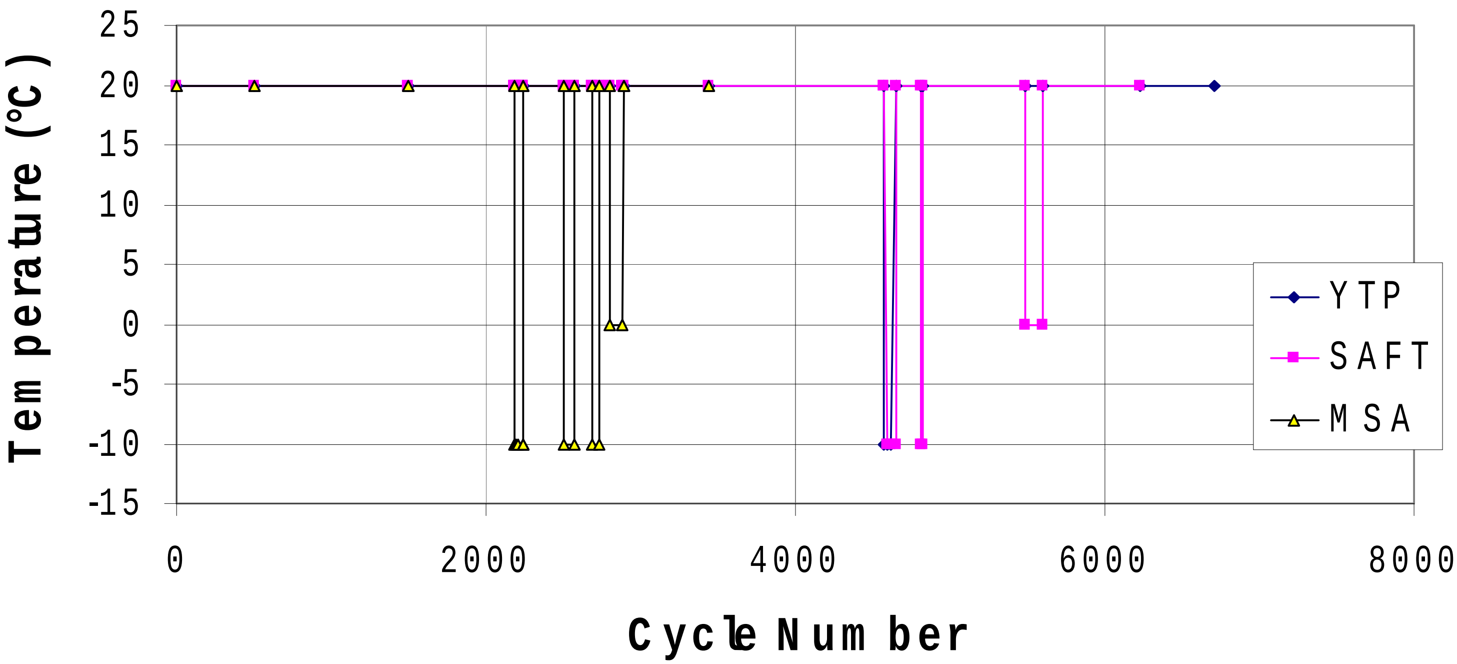


Table 1 – History YTP

Cycle Number		Temp °C	Avg. Discharge Pack Volt	Avg. Charge Pack Volt	V limit/cell
1	4575	20	25.9	31.9	4.00
4576	4613	-10	23.1	33.4	4.15
4613		-10	23.5	34.2	4.25
4614	6076	20	25.4	32.2	4.00
6076	6714	20	24.7	32.3	4.05

Note: Values for cycles 4576-4613 are average values. The specific value for cycle 4613 is included since the charge voltage changed.

Table 2 - History SAFT

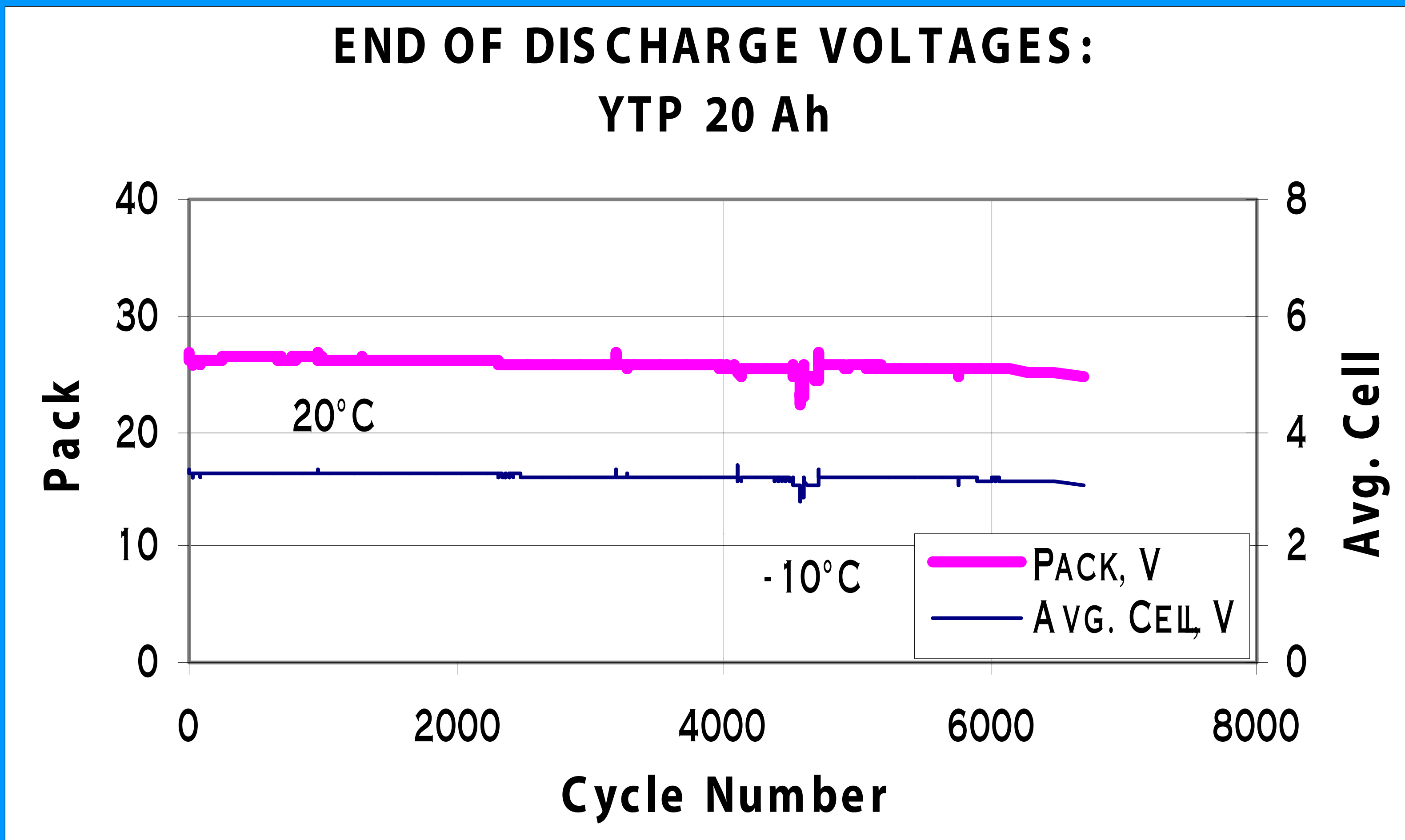
Cycle Number		Temp °C	Avg. Discharge Pack Volt	Avg. Charge Pack Volt	V limit/cell
1	4594	20	27.0	30.6	3.85
4595	4596	-10	25.5	31.1	3.85
4597	4598	-10	25.8	31.2	3.90
4599	4600	-10	26.4	31.6	3.95
4601	4611	-10	26.7	33.4	4.15
4612	4616	-10	26.9	33.8	4.20
4617	4649	-10	27.7	34.9	4.35
4650	4807	20	26.6	31.3	3.95
4808	4825	-10	26.7	34.3	4.30
4826	5488	20	28.3	33.0	4.10
5489*	5603*	0	24.6*	31.2	4.45
5604	5685	20	28.7	33.7	4.20
5685	5715	20	28.4	33.7	4.2
5715	6226	20	28.1	33.7	4.2

* 7 cells

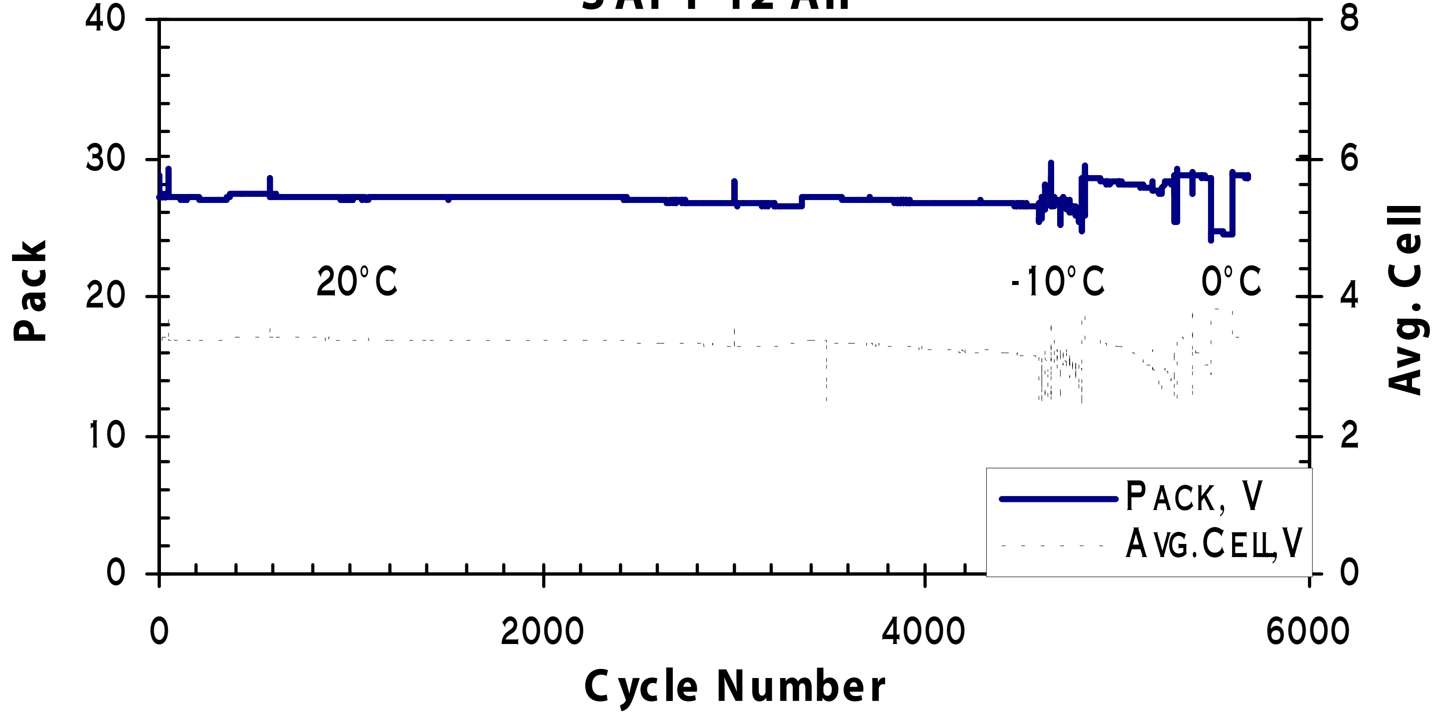
Table 3 - History MSA

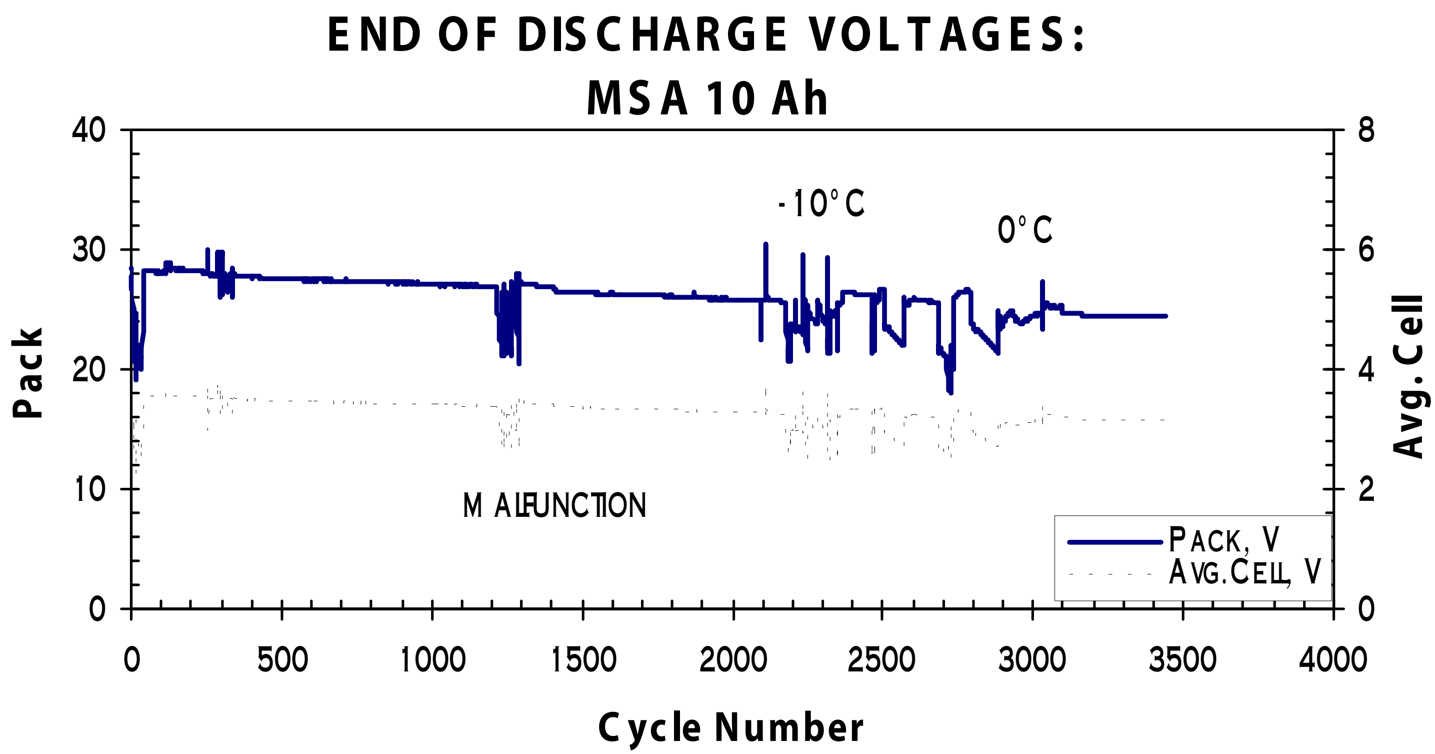
Cycle Number		Temp °C	Avg. Discharge Pack Volt	Avg. Charge Pack Volt	V limit/cell
1	2182	20	26.8	32.0	4.00
2183	2190	-10	21.0	32.6	4.05
2191	2196	-10	21.4	33.5	4.15
2197	2198	-10	23.5	33.9	4.20
2199	2202	-10	23.6	34.6	4.30
2203	2235	-10	23.5	34.9	4.35
2236	2507	20	25.3	32.6	4.05
2508	2572	-10	22.8	36.0	4.48
2573	2683	20	25.7	32.7	4.05
2684	2716	-10	21.4	36.0	4.48
2717*	2733*	-10	18.7	31.7	4.48
2734	2796	20	26.3	33.6	4.15
2797	2885	0	22.6	36.0	4.48
2886	3247	20	24.6	33.7	4.20
3248	3302	20	25.0	34.3	4.25
3303	3359	20	24.8	34.2	4.25
3359	3385	20	24.5	34.0	4.25
3386	3441	20	25.1	34.7	4.30

* 7 cells

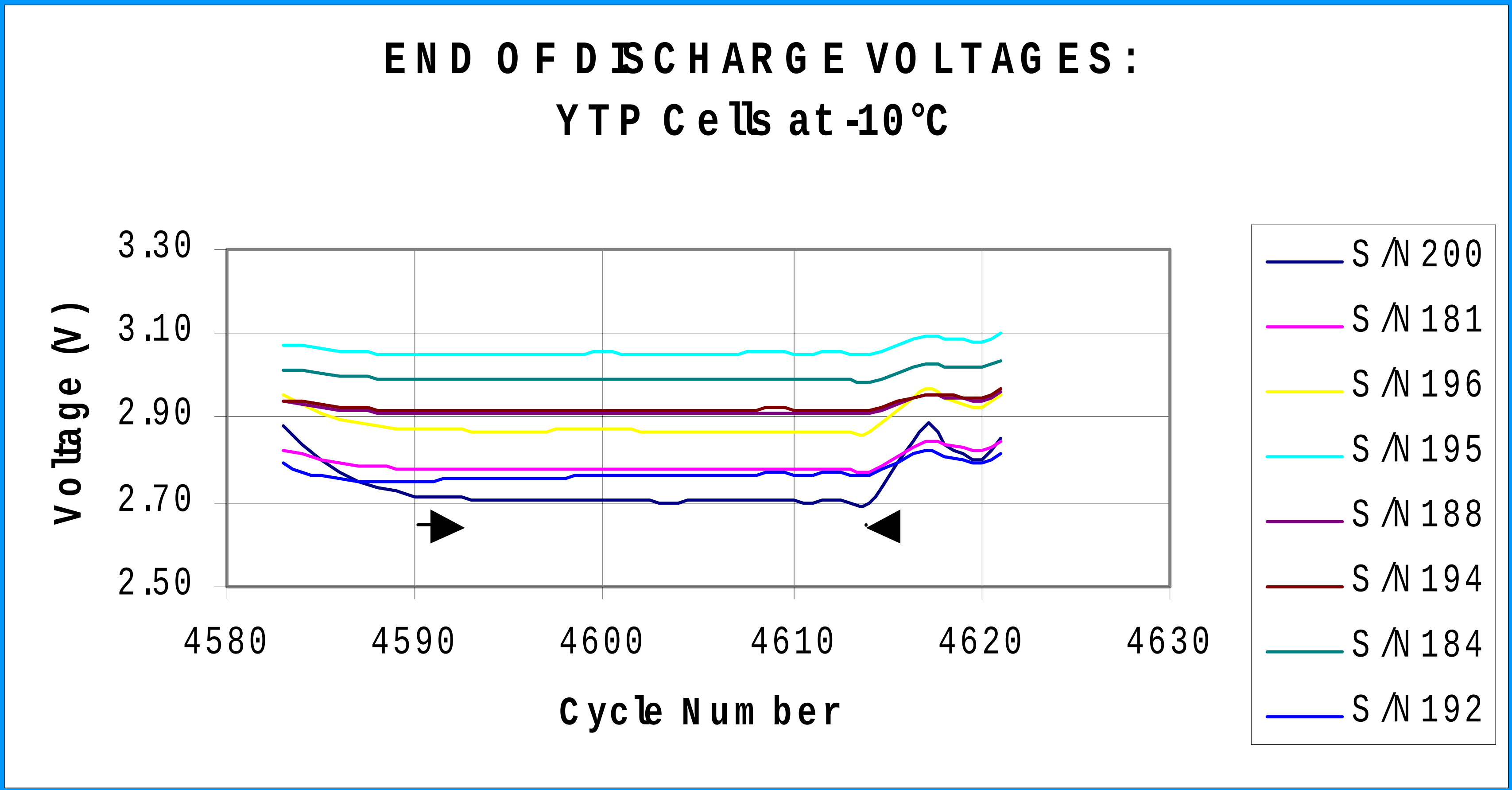

END OF DISCHARGE VOLTAGES:
YTP 20 Ah
Pack
Avg. Cell
Cycle Number
20°C
-10°C
Pack, V
Avg. Cell, V
0
10
20
30
40
0
2
4
6
8
0
2000
4000
6000
8000

END OF DISCHARGE VOLTAGES: SAFT 12 Ah





END OF DISCHARGE VOLTAGES:
MSA 10 Ah
Pack
Avg. Cell
Cycle Number
0
500
1000
1500
2000
2500
3000
3500
4000
40
30
20
10
0
8
6
4
2
-10°C
0°C
MALFUNCTION
PACK, V
AVG.CELL, V


END OF DISCHARGE VOLTAGES:
YTP Cells at -10°C
Voltage (V)
3.30
3.10
2.90
2.70
2.50
4580
4590
4600
4610
4620
4630
Cycle Number
S/N 200
S/N 181
S/N 196
S/N 195
S/N 188
S/N 194
S/N 184
S/N 192

Test Status

- One cell in the SAFT pack is showing 2.954V after 6226 cycles with low end of charge voltage of 4.09V.
- One cell in the YTP pack is showing low end of discharge (2.84V) and high end of charge voltage (4.5V) after 6714 cycles.
- One cell in the MSA pack is showing low voltage(2.905 decreasing to 2.77V) during discharge after 3441 cycles. The voltage is high during charge 4.47 increasing to 4.48V.
- Tests stopped and the health of cells under evaluation.

Reconditioning

- The low voltage cell increased to 3.6V from 2.77 V in the SAFT pack and pack voltage increased by 430 mV when reconditioned by discharging at C/20.
- The low voltage cell increased to 2.77V from 2.5 V in the MSA pack and the pack voltage increased by 800 mV when reconditioned.
- YTP pack did not show any significant effect.

Conclusions

- Li-ion cells manufactured by YTP, SAFT and MSA have completed 6714, 6226 and 3441 cycles, respectively.
- An increase in charge voltage limit was required in all cases to maintain the discharge voltage.
- SAFT and MSA cells were capable of cycling at -10°C and 0°C with an increase in the charge voltage limit, whereas Yardney cells could not be cycled.
- Reconditioning improved the discharge voltage of SAFT and MSA cells; it is important to note that the effect has been temporary as in Nickel-Hydrogen and Nickel-Cadmium batteries.
- Demonstrated that the charge operation with VT clamp at battery rather than at cell level is feasible.
- Continuation of testing depends on the health of the cells and on the funding situation.

DPA of 1.6 Ahr Li-ion Pouch Cells Using Coin Cells

NASA Space Power Workshop

Enoch Wang

US Government

11/27/01

Objective

- To identify the limiting electrode(s)
  - To shed understanding on failure mechanism

Why Coin cells?

- It gives more direct and definitive results in determining failed electrode(s)
- It gives both qualitative and quantitative info on electrodes degradation

Experimental

- Overview
  - Bring cells to “complete” state of discharge.
  - Open pouch cells in glovebox.
  - Observe condition of electrodes and other components.
  - Build button cells (Li metal half-cells) using portions of anodes & cathodes from each pouch cell.
  - Cycle button cells at low rate (C/10) and high rate (LEO rates).
  - Determine limiting electrode (anode or cathode).

Experimental (cont'd)

- Cycling conditions
  - Low rates to determine intrinsic capacity
    - C/10 Charge and Discharge for $LiCoO_2$
    - C/10 Charge and C/10 Discharge + trickle for MCMB

Cycling conditions (cont'd)

LEO rates to determine rate capability loss

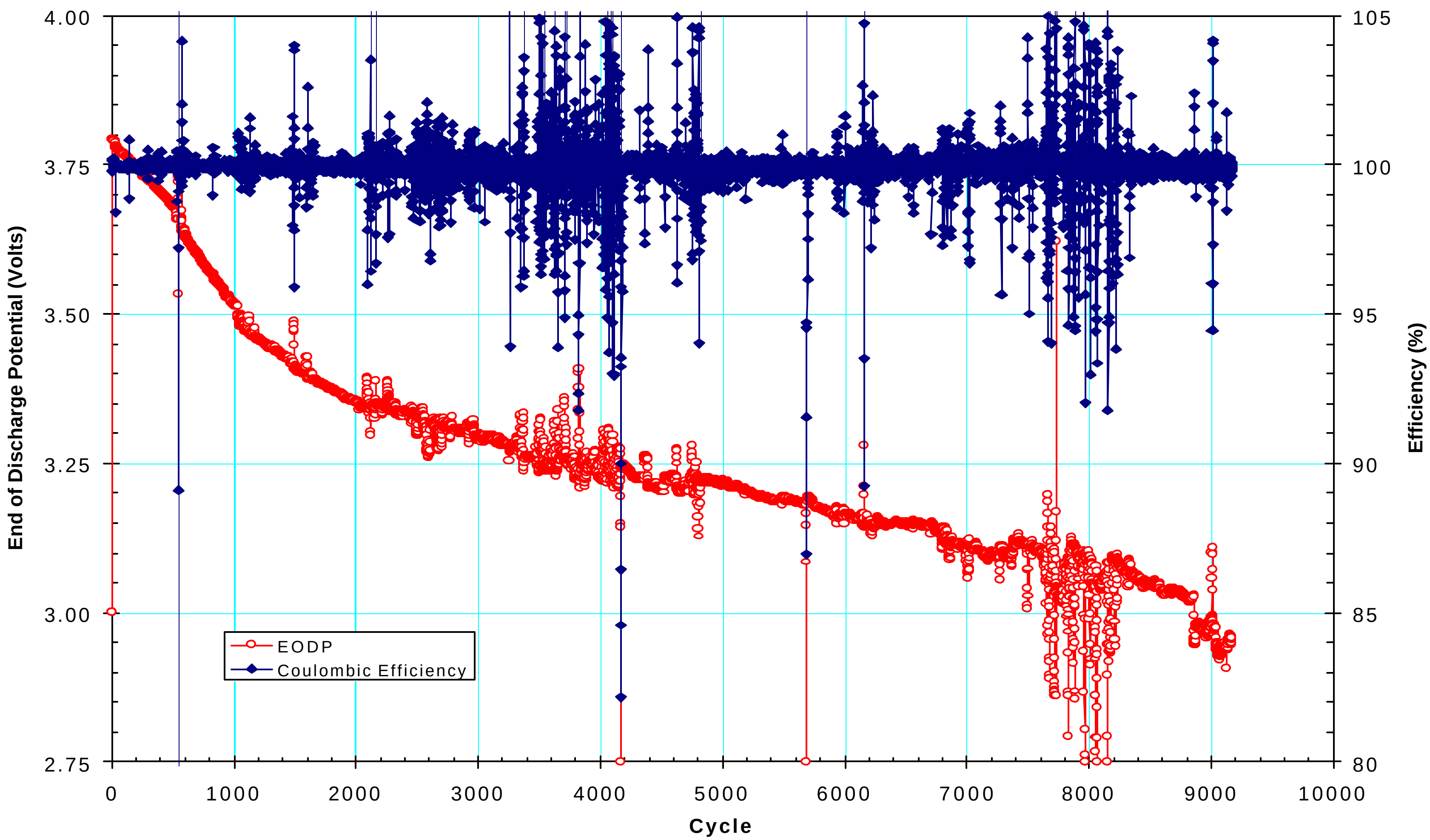
- 40% DOD
- Cathode
  - 36 min Discharge (loading) @2/3C to 2.8V
  - 54 min Charge (unloading) @ C to 4.2V
- Anode
  - 36 min Charge (unloading) @ 2/3C to 2.5V
  - 54 min Discharge(loading) w/ trickle @ C to 20 mV

Pouch Cells Background

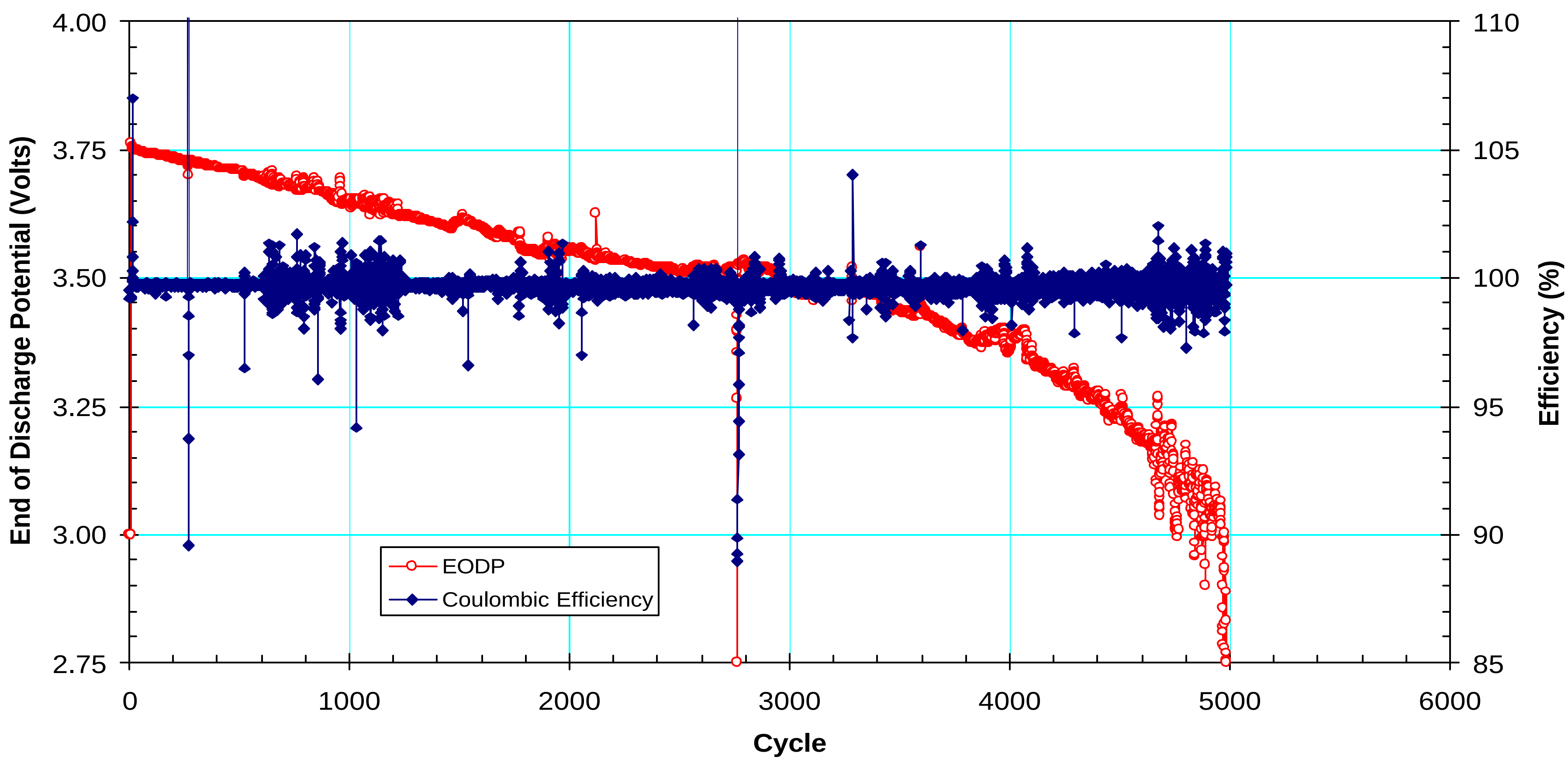
Pouch Cells	Positive	Negative	# cycles
LM6-D6	$LiCoO_2$ from vendor A	0.5% SP MCMB2528	~9000
LM7-G3	$LiCoO_2$ from vendor B	2% SP* MCMB2528	~4900
LM7-G5	$LiCoO_2$ from vendor B	2% SP* MCMB2528	~4600
LM7-M2	$LiCoO_2$ from vendor A	2% SP* MCMB2528	~4500

*bad batch of negative electrodes

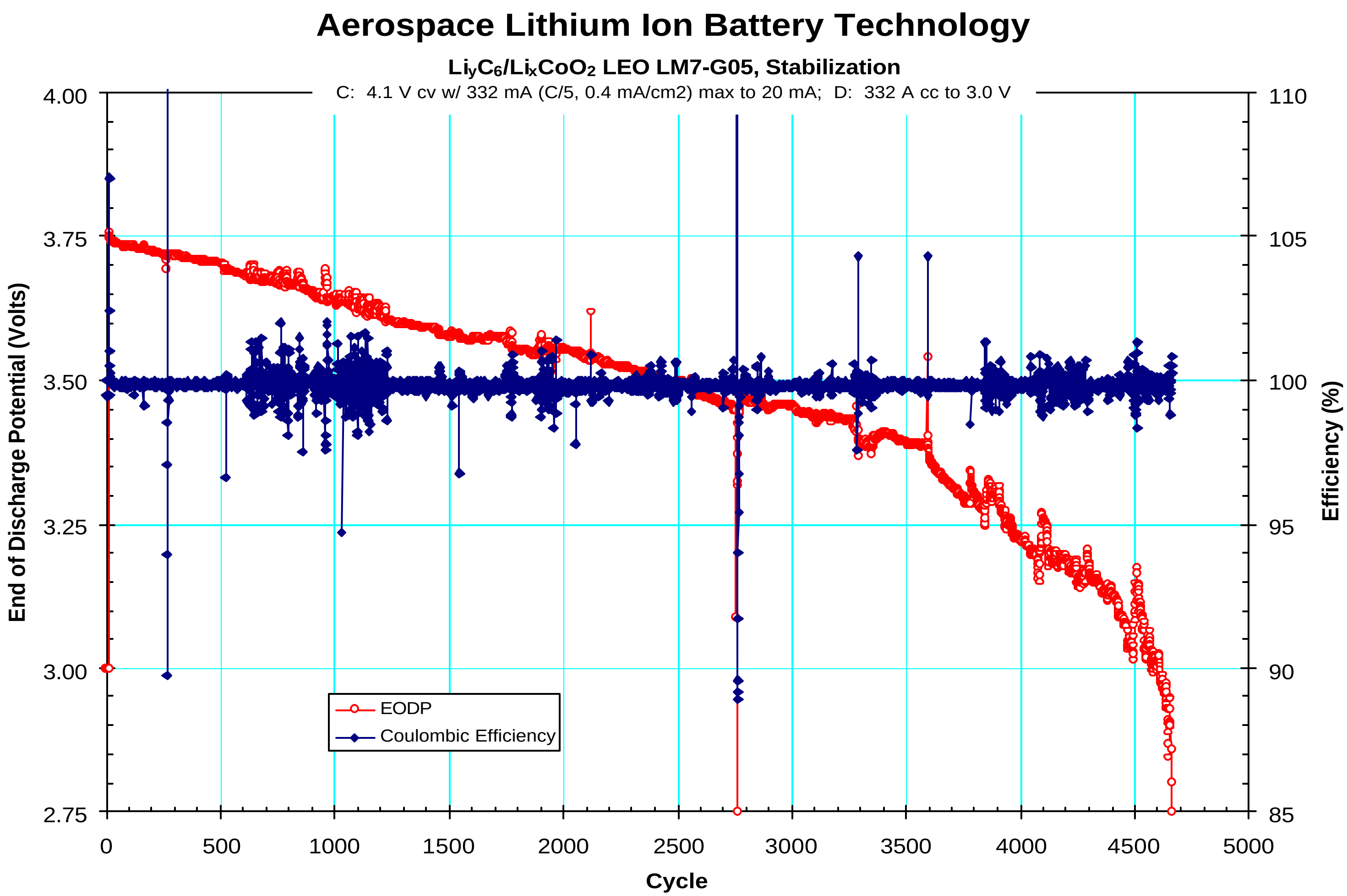
LM6-D06 Cycle Life



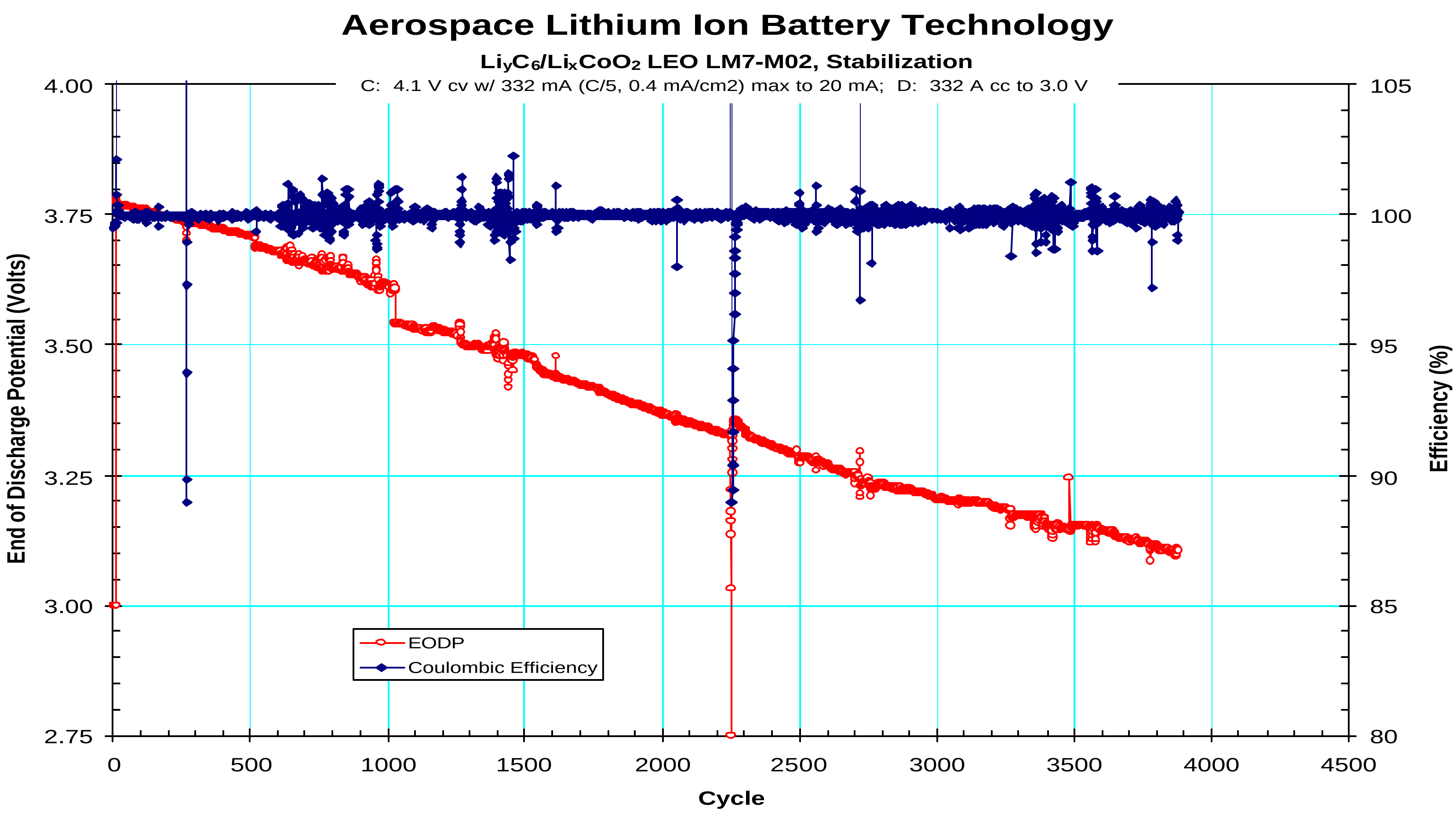
LM7-G03 Cycle Life



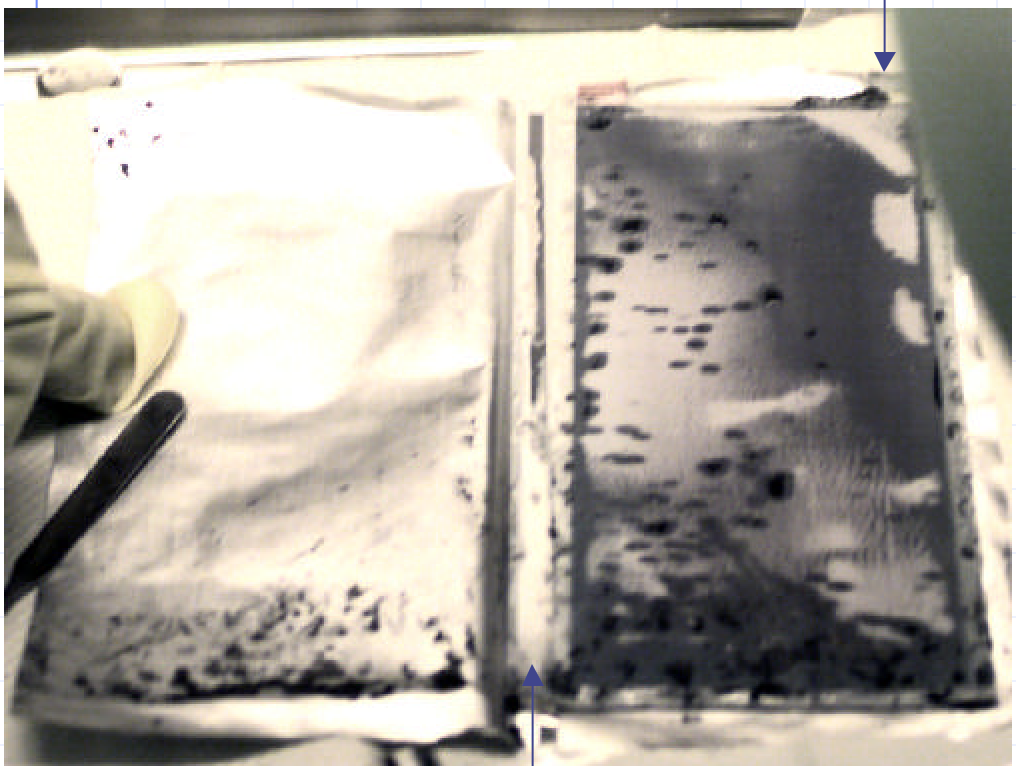
LM7-G5 cycle life

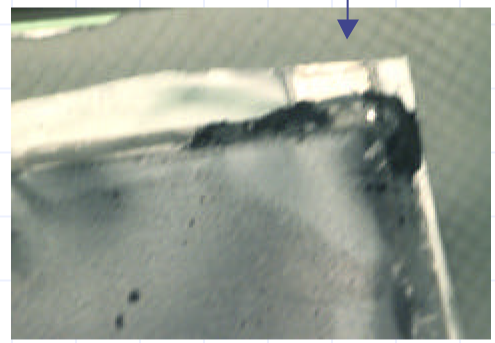


LM7-M2 cycle life



LM6-D06 Pouch





Observations

- Mossy Li deposits around perimeter of separator bag.
- Mossy Li deposits on pouch surface.
- Heavy deposits of mossy Li around cathode tab.
- Most of Li missing from reference electrode.

Results (contd.) LM6-D06 Anode

Edge #1 0.192 – 0.196 mm, 4k – 6k O

Edge #4

0.194 – 0.208 mm

1k – 5k O

Edge #2

0.192 – 0.202 mm

4k – 13k O

Edge #3 0.195 – 0.212 mm, 40k – 60k O

Observations

- Discoloration around perimeter of electrode
- No visible Li deposits on electrode surface
- Mossy Li deposits around perimeter of separator bag

Fresh Material

Thickness: 0.157 – 0.160 mm

Resistance: 5 – 10 O

Results (contd.) LM6-D06 Cathode

Cycled Cathode

Thickness: 0.160 – 0.165 mm

Resistance: 120 - 190 O

Fresh Cathode

Thickness: 0.151 – 0.154 mm

Resistance: 70 – 90 O

Observations

- Cathode appeared “fresh”.
- No visible Li deposits on electrode surface
- Mossy Li deposits around perimeter of separator bag

Results (contd.)
LM7-G03 Anode

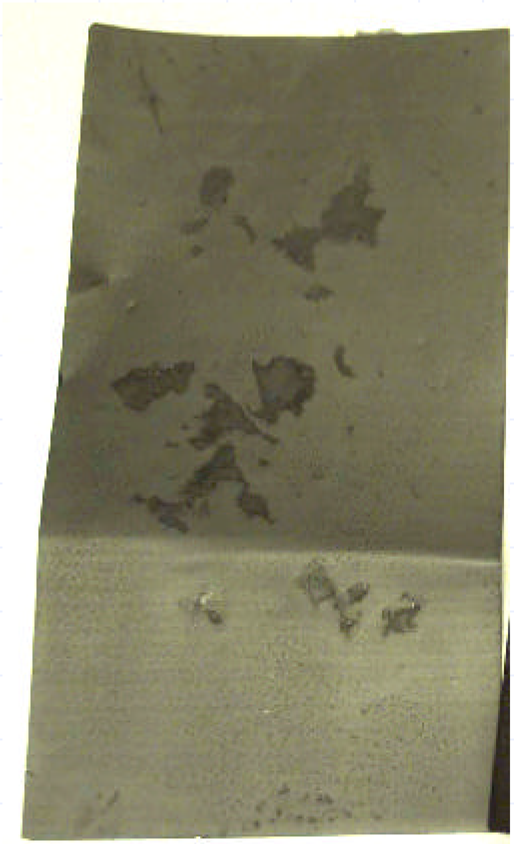
Observations

- Blotched areas
  - smooth hard texture
  - raised deposits
  - 20k - 40k Ω
  - reacted with H_2O

Fresh Material

Resistance: 5 – 10 O

Results (contd.)
LM7-G03 Cathode

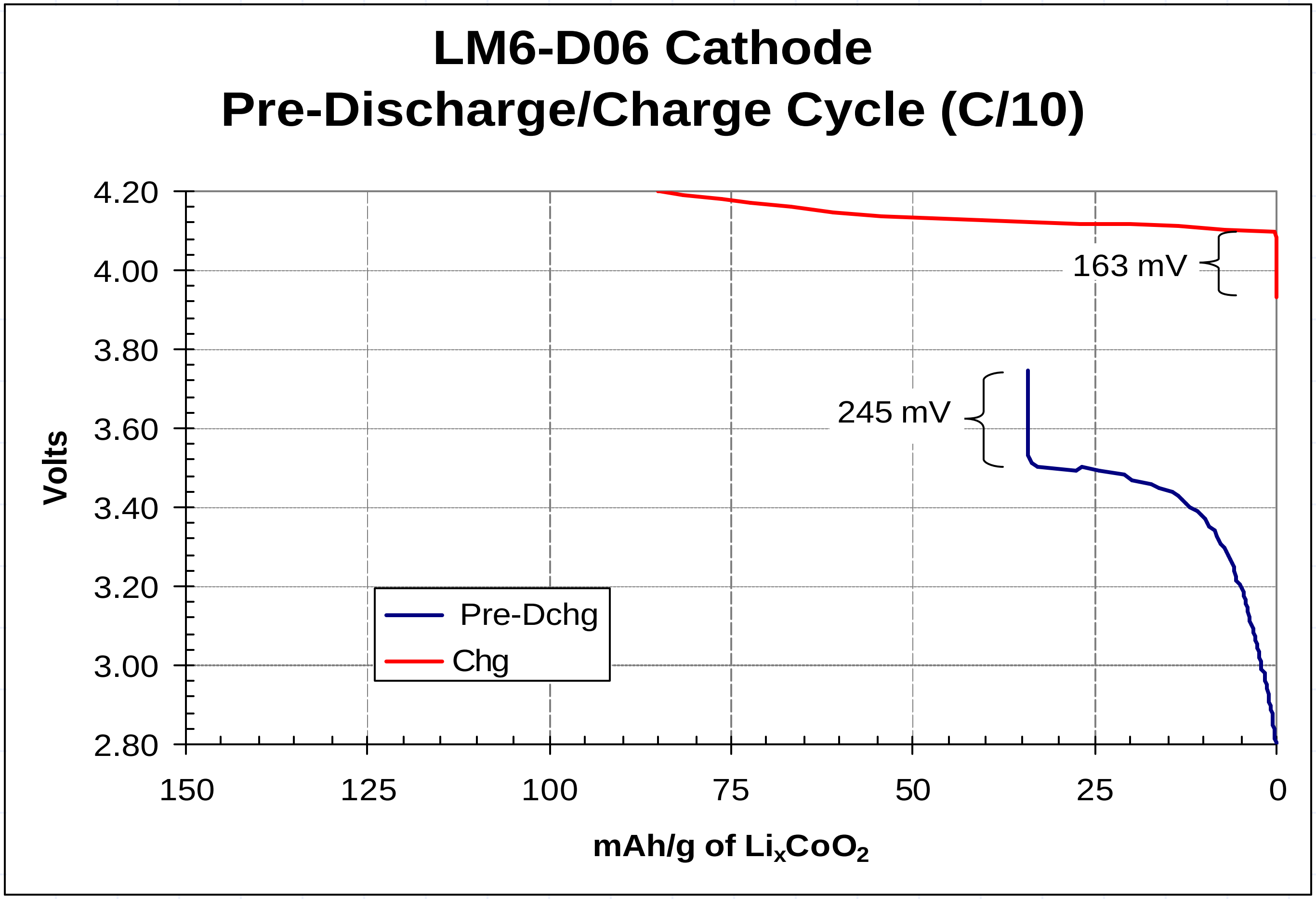


Observations

- Areas with dark discoloration (300 – 400 O)
- Side A (170 - 200 O)
- Side B (80 - 100 O)

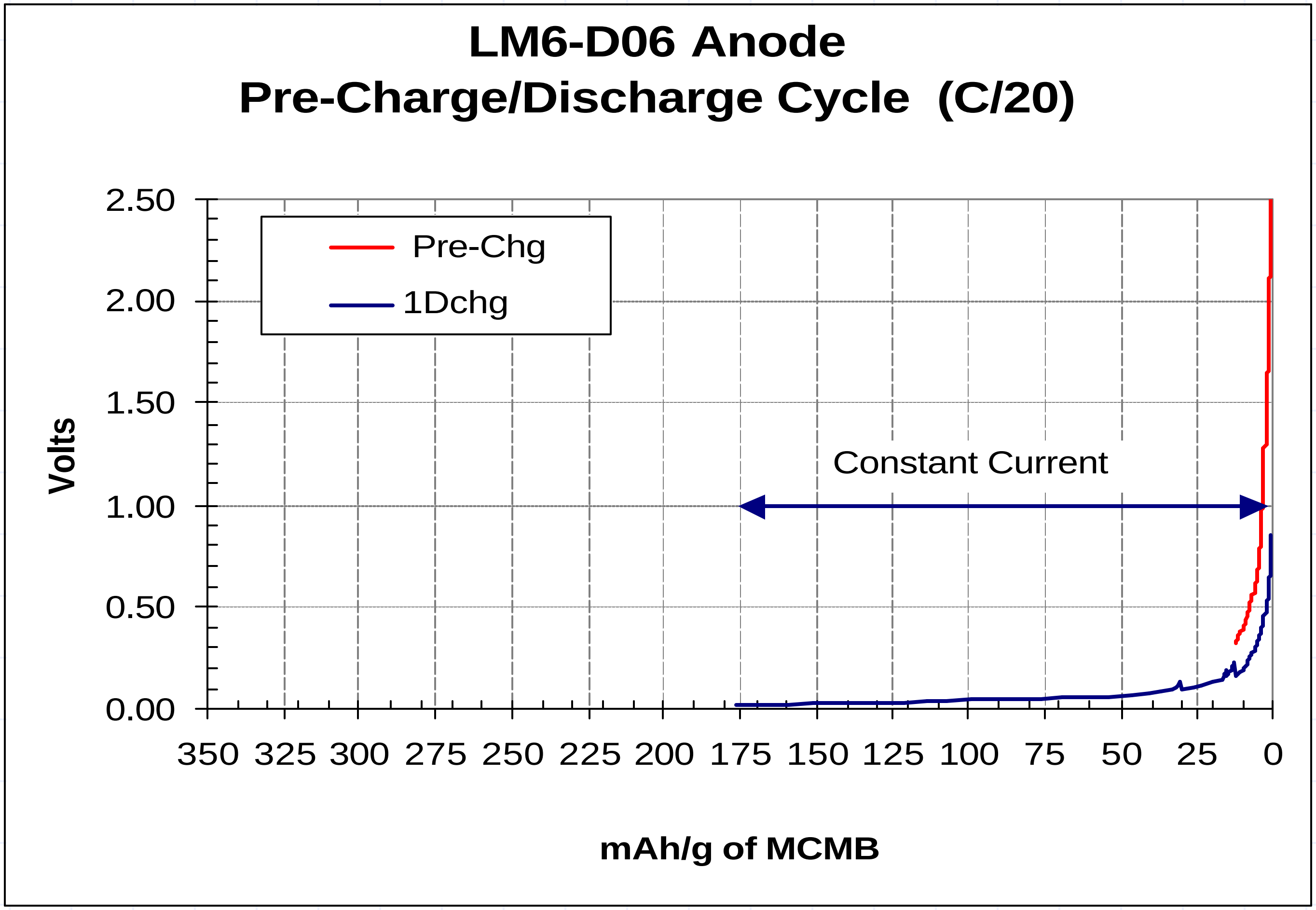
LM6-D06 Cathode

- Large polarization but NO loss of cyclable Li

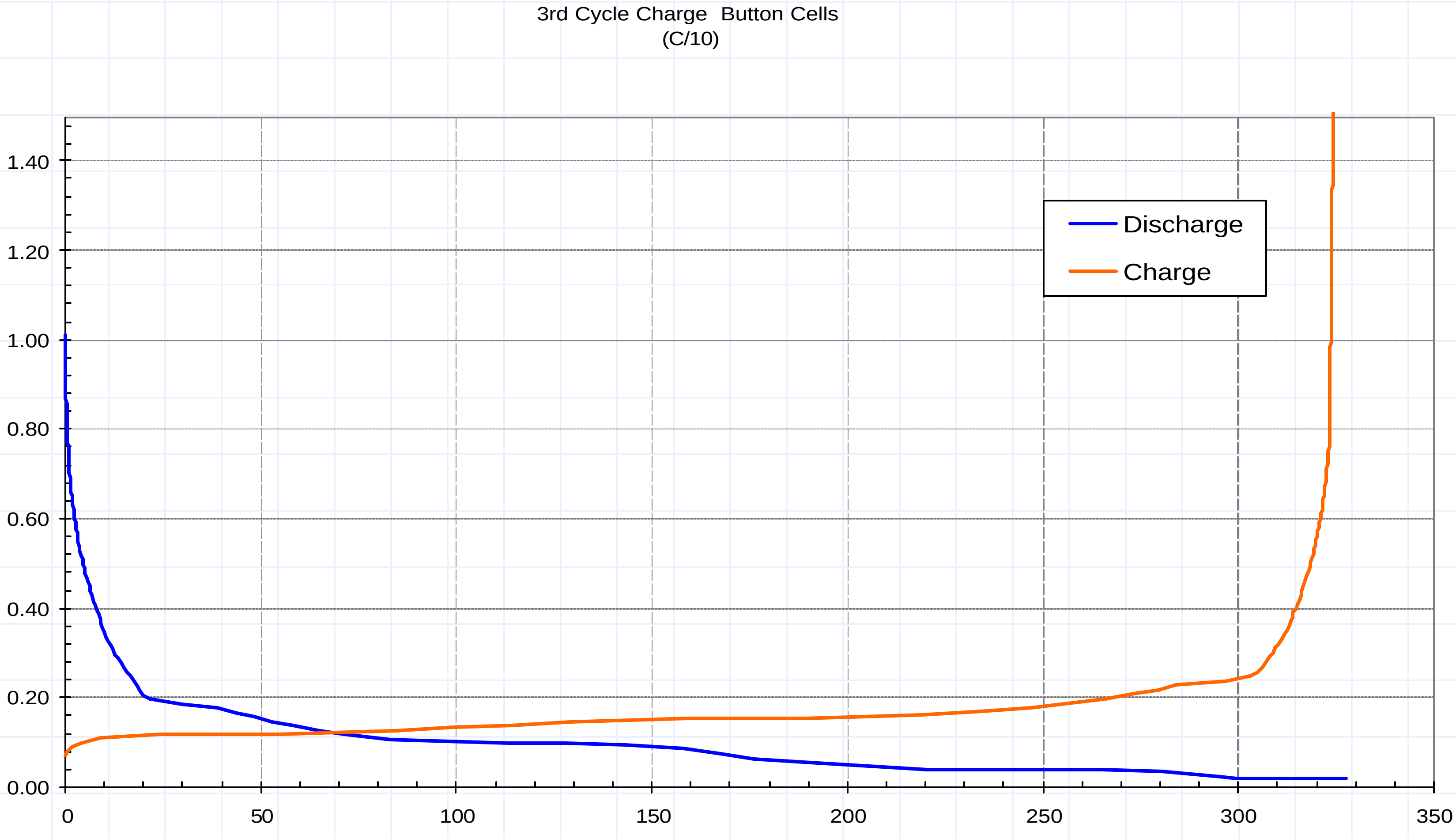


LM6-D06 Anode

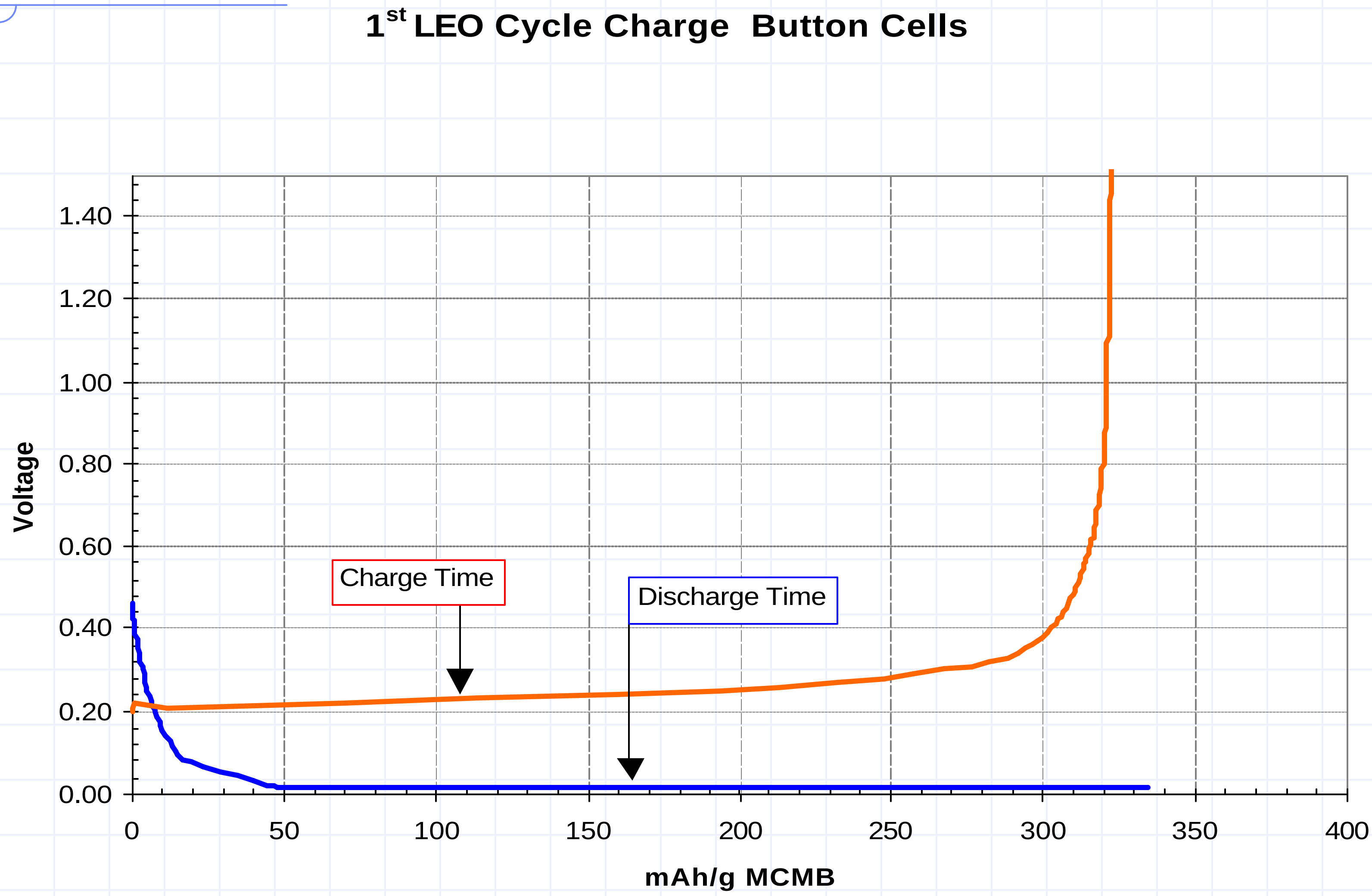
Negligible Li left in anode



Fresh anode @ C/10

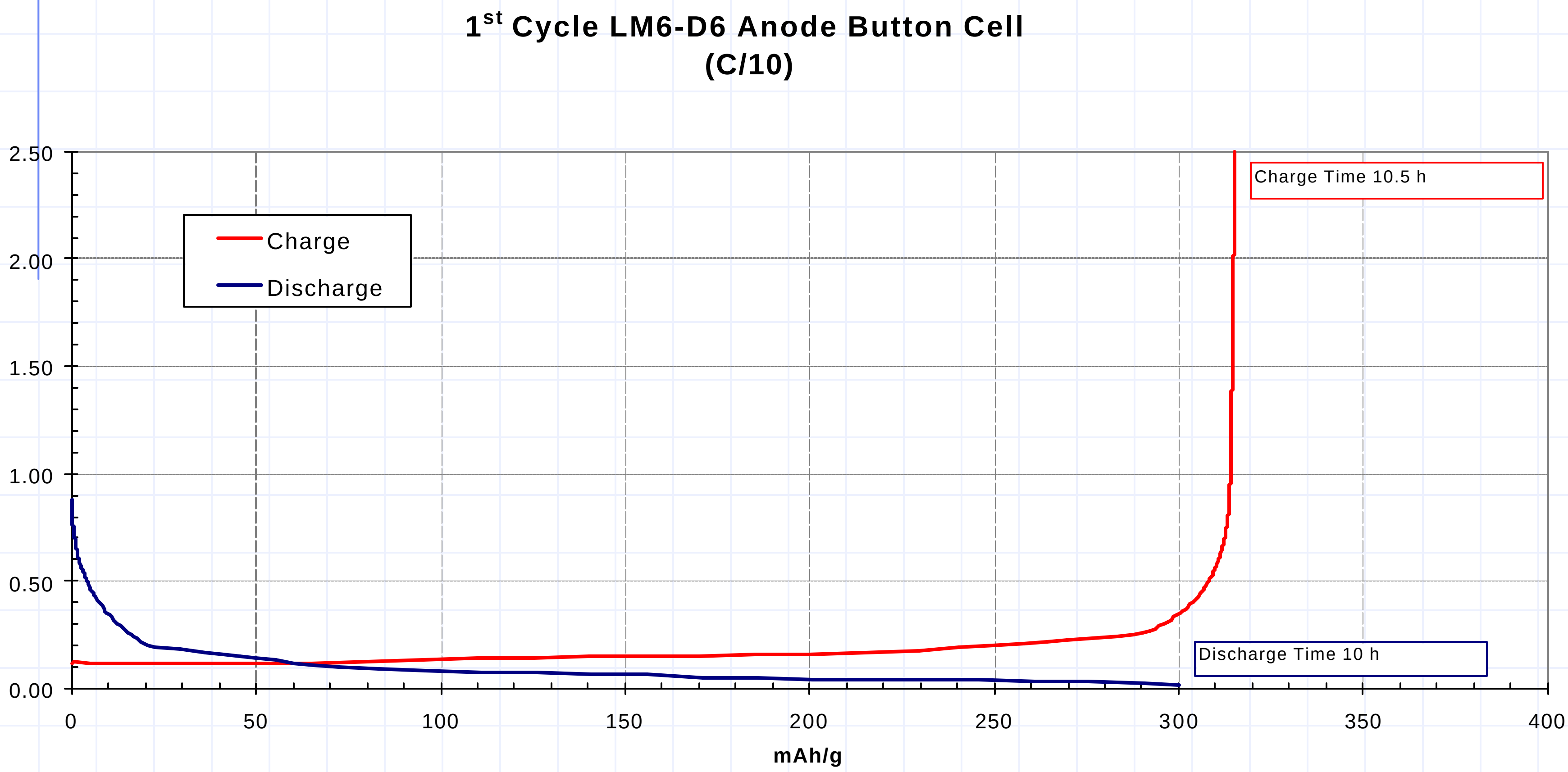


Fresh anode @ LEO rate



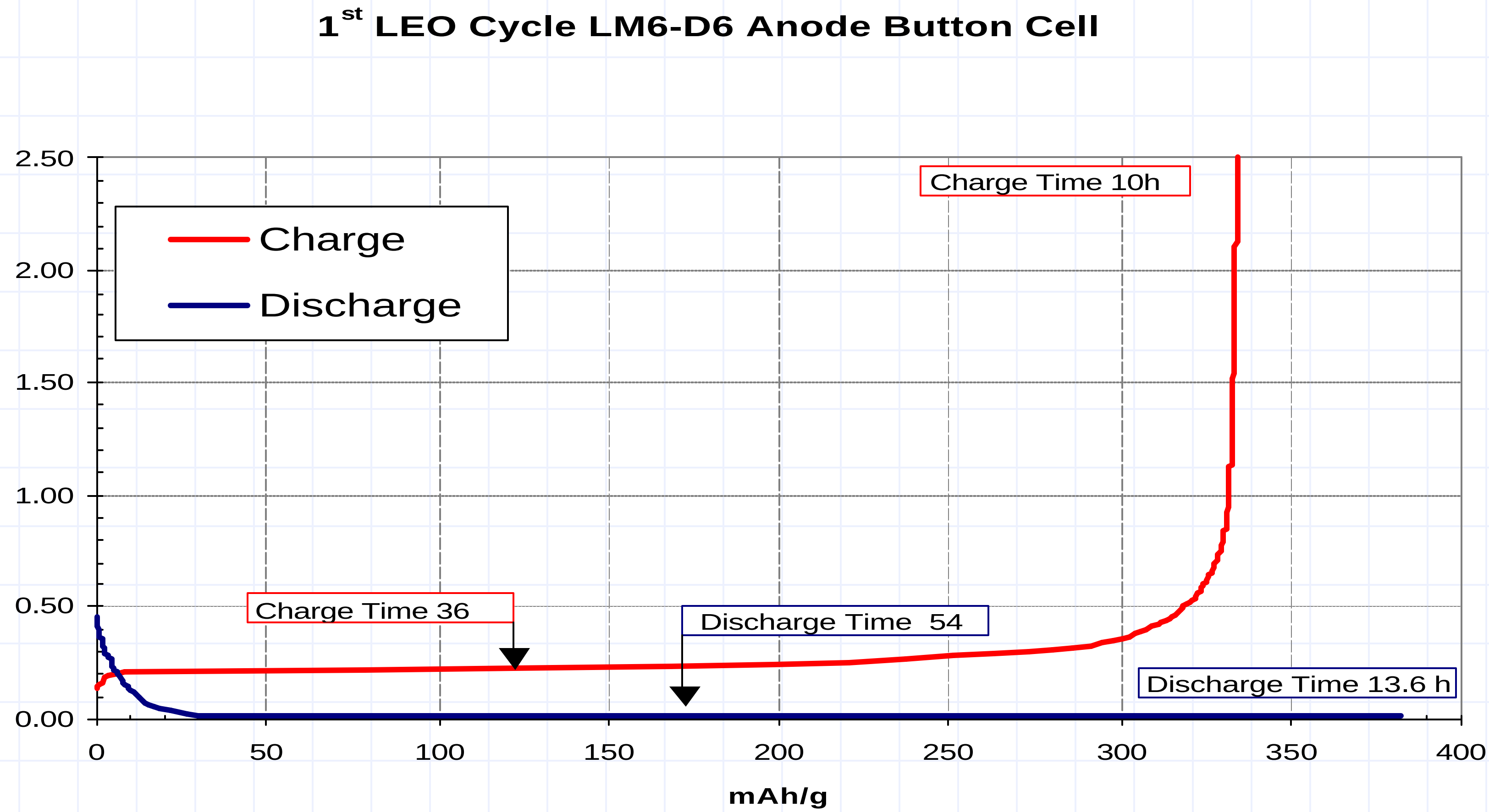
Coin Cell Results
LM6-D6 Anode

No degradation in intrinsic capacity

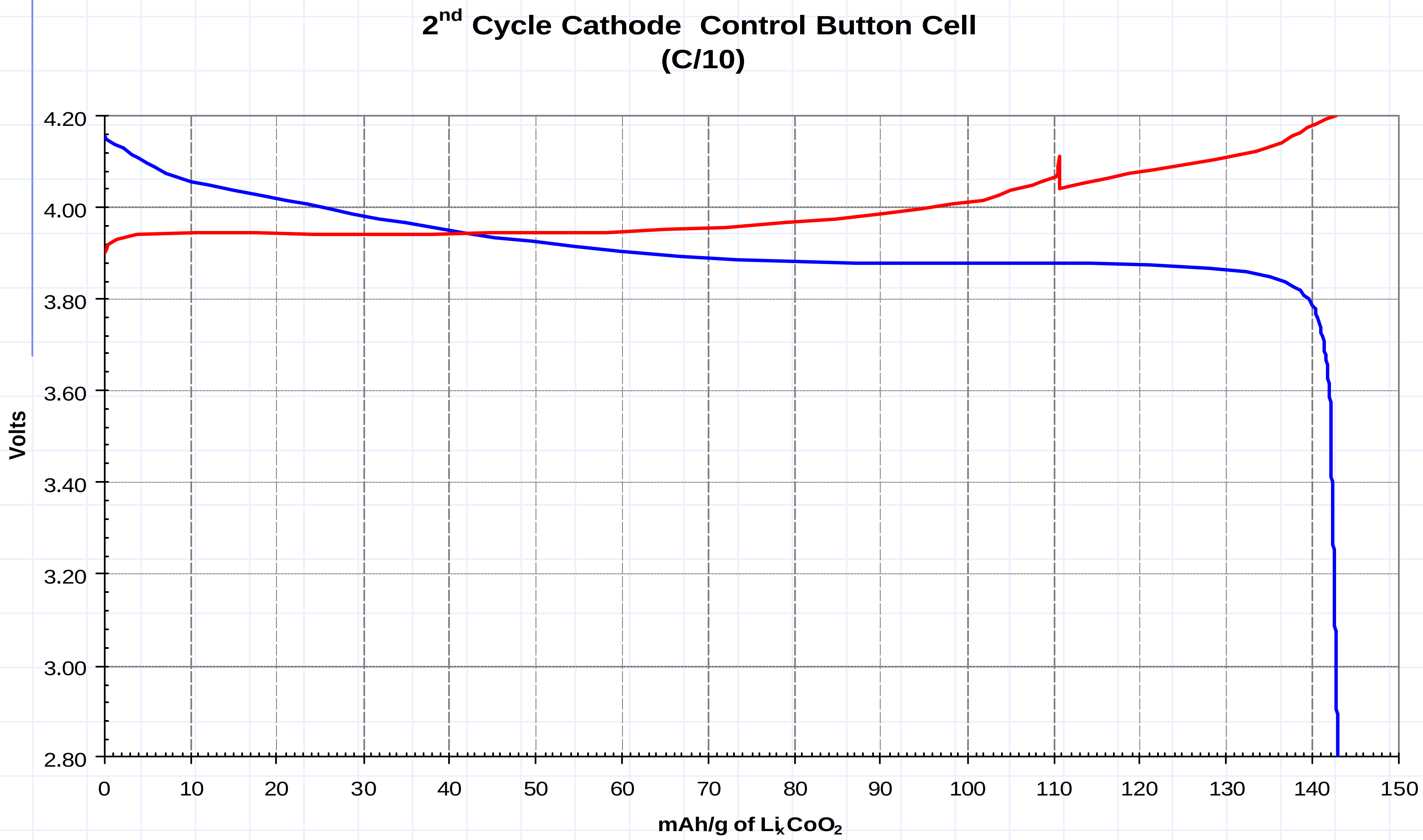


Coin Cell Results
LM6-D6 Anode

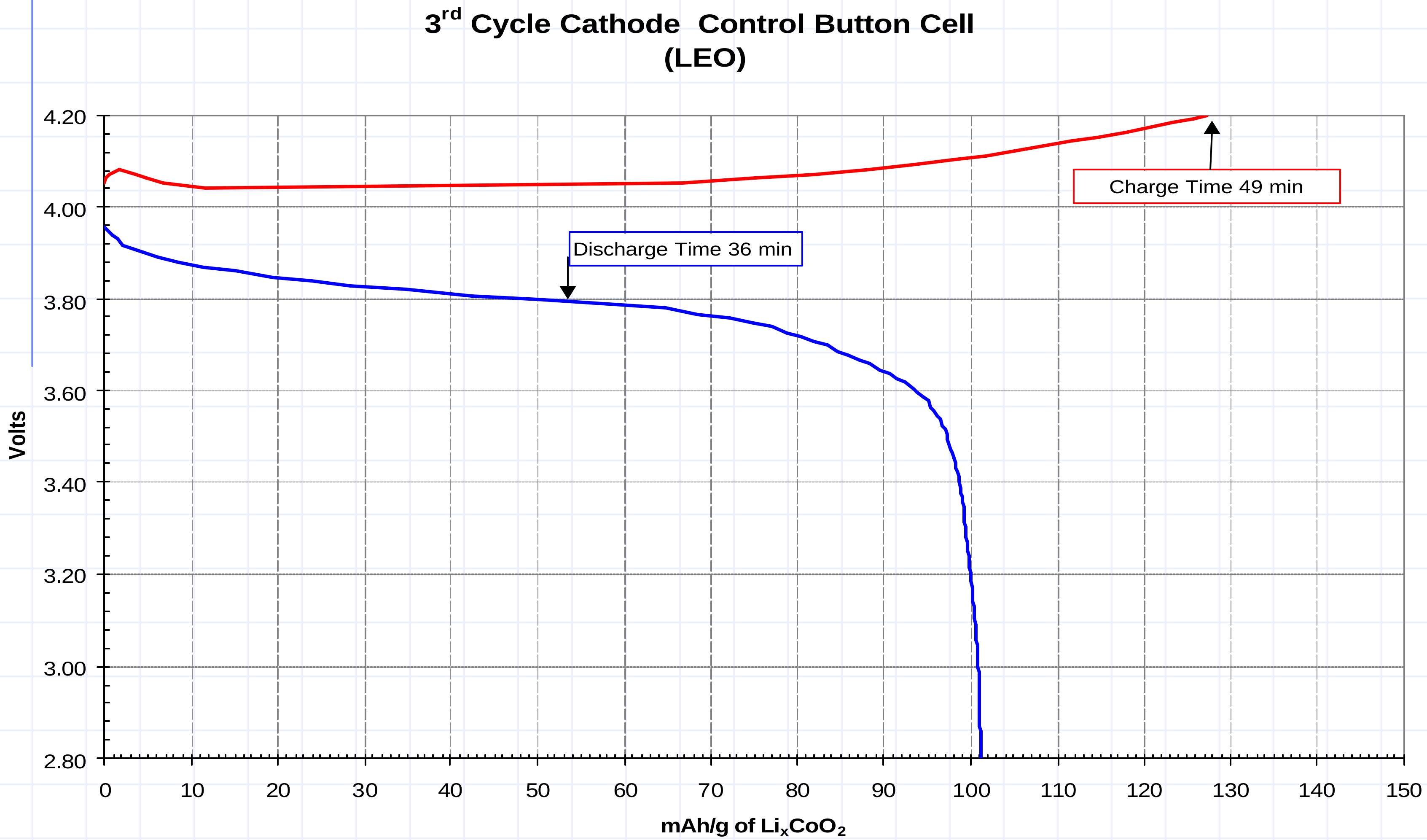
No degradation in LEO rate



Fresh cathodes at C/10

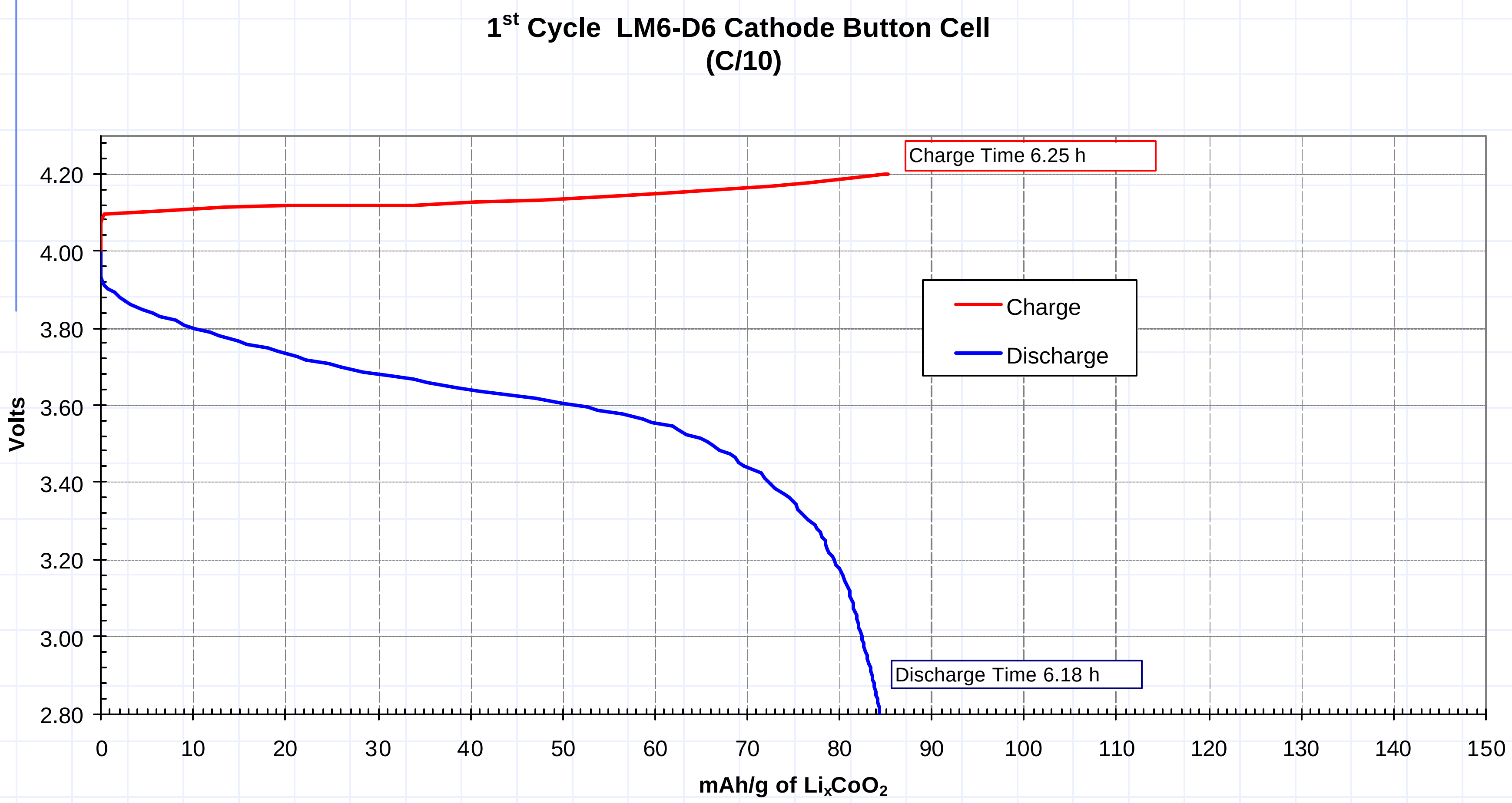


Fresh cathodes at LEO



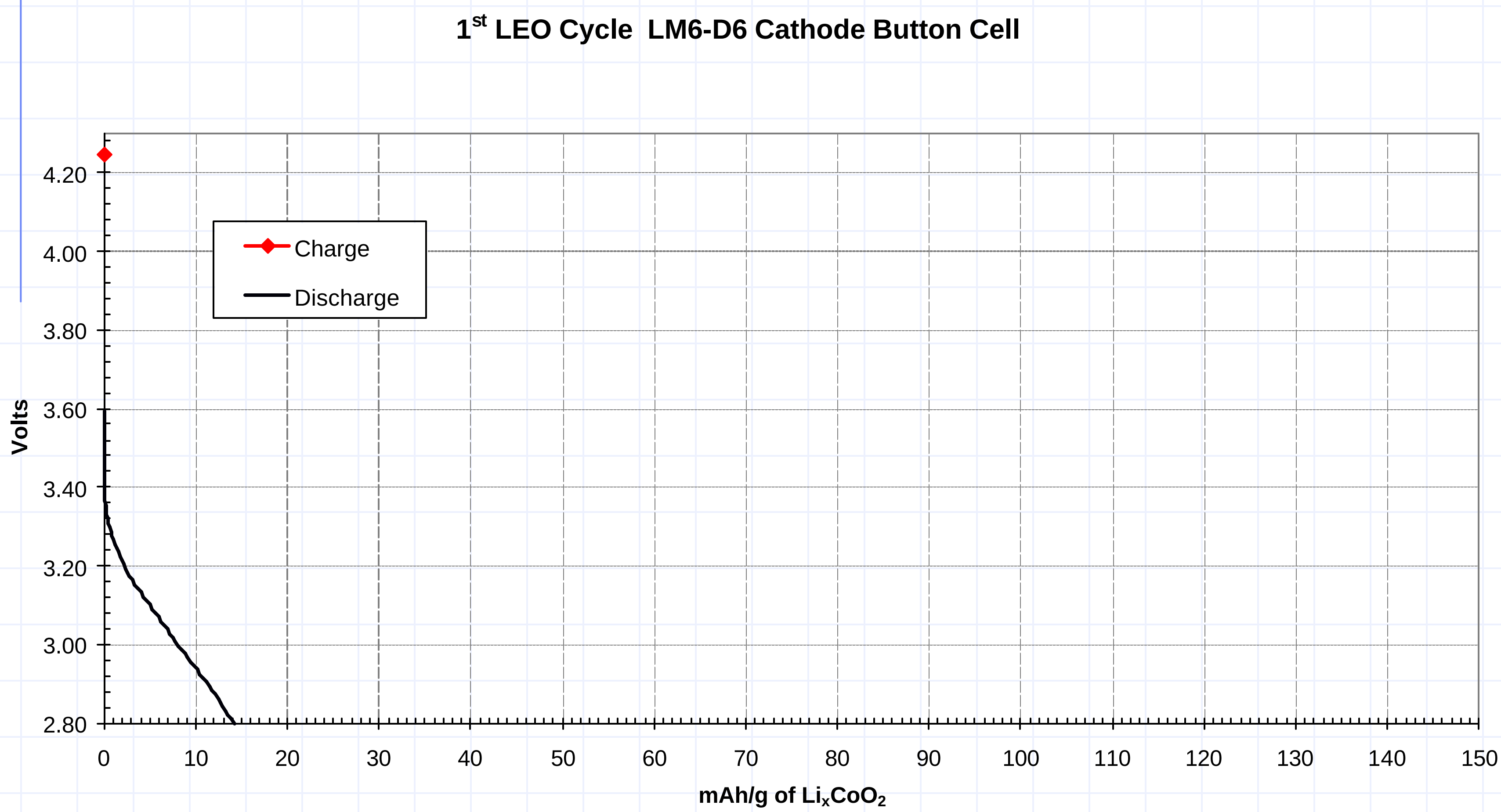
Coin Cell Results
LM6-D6 Cathode

Significant degradation in intrinsic capacity



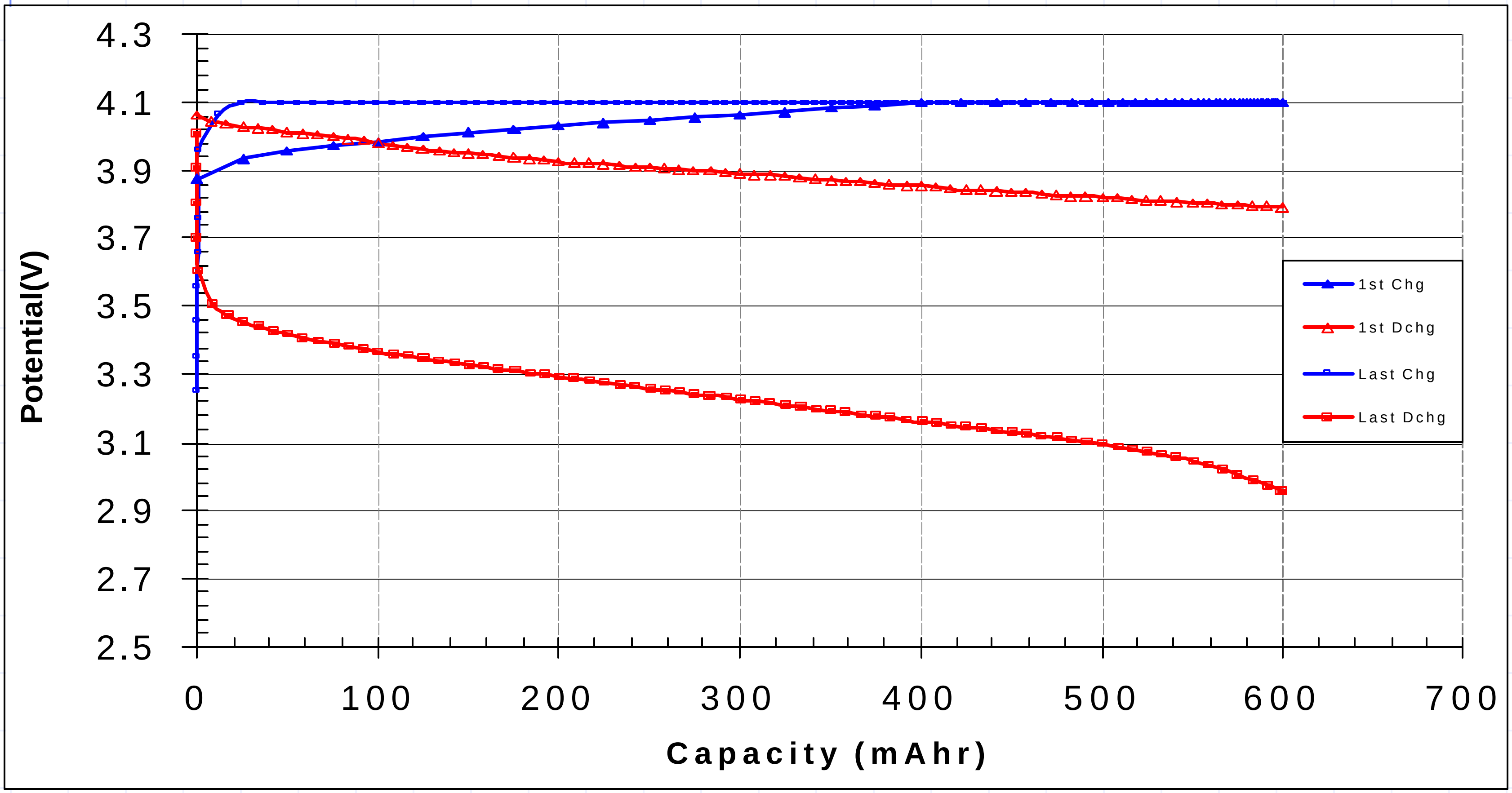
Coin Cell Results
LM6-D6 Cathode

Significant degradation in LEO rates



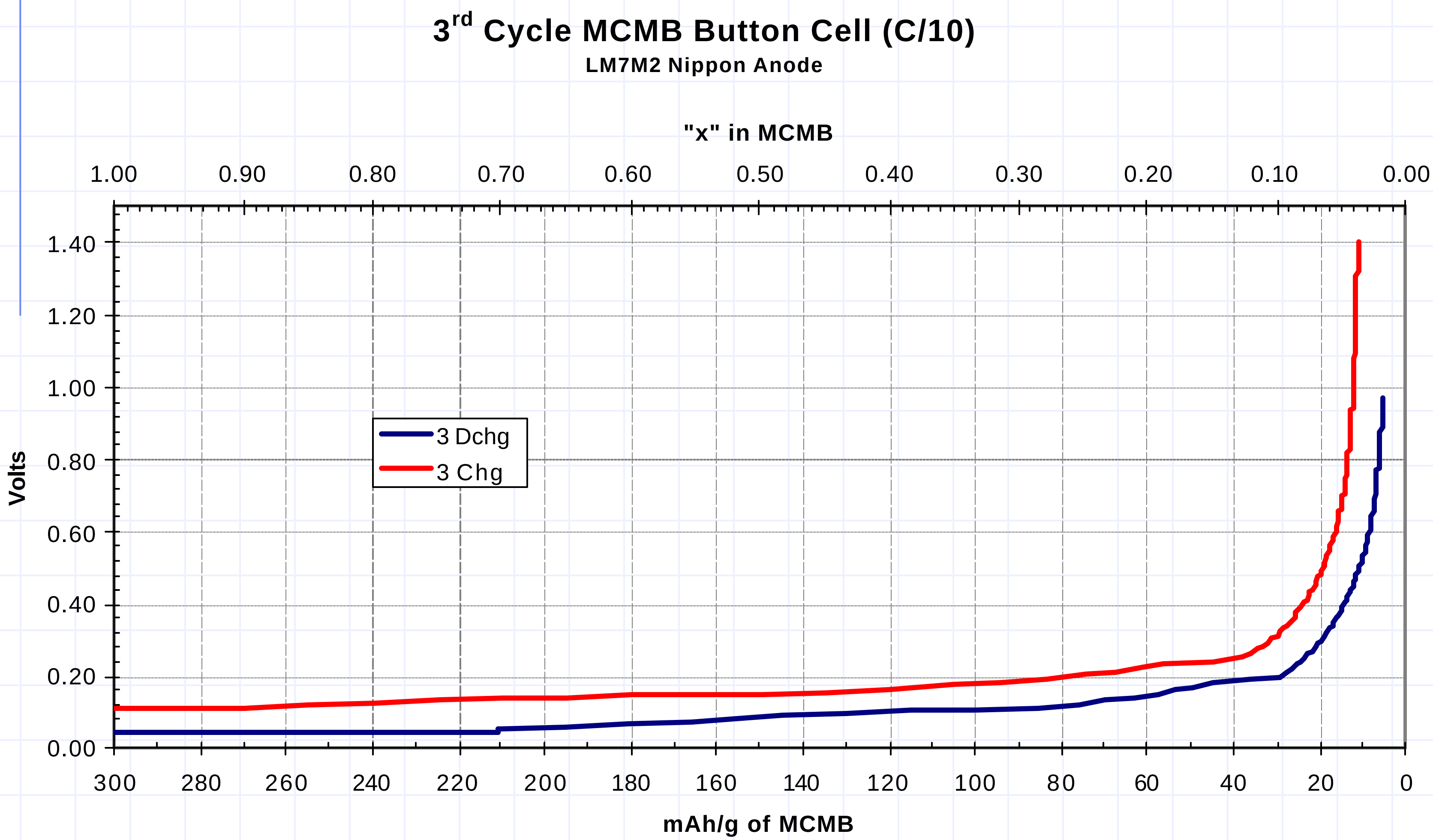
LM6-D06 LEO cycles in full cells

Full cell V curves indicative of predominant cathode polarization



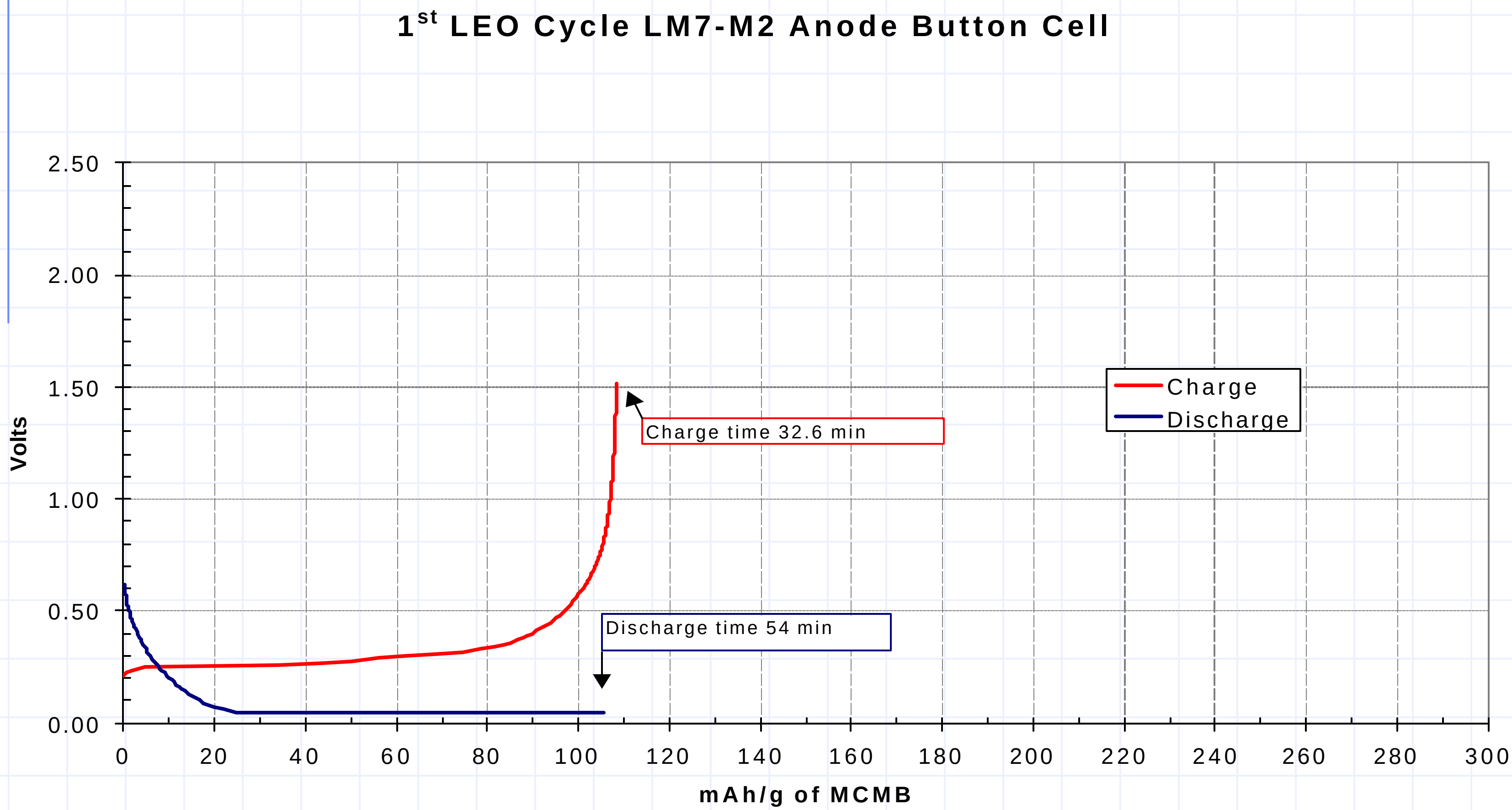
Coin Cell Results
LM7-M2 Anode

No loss in intrinsic capacity



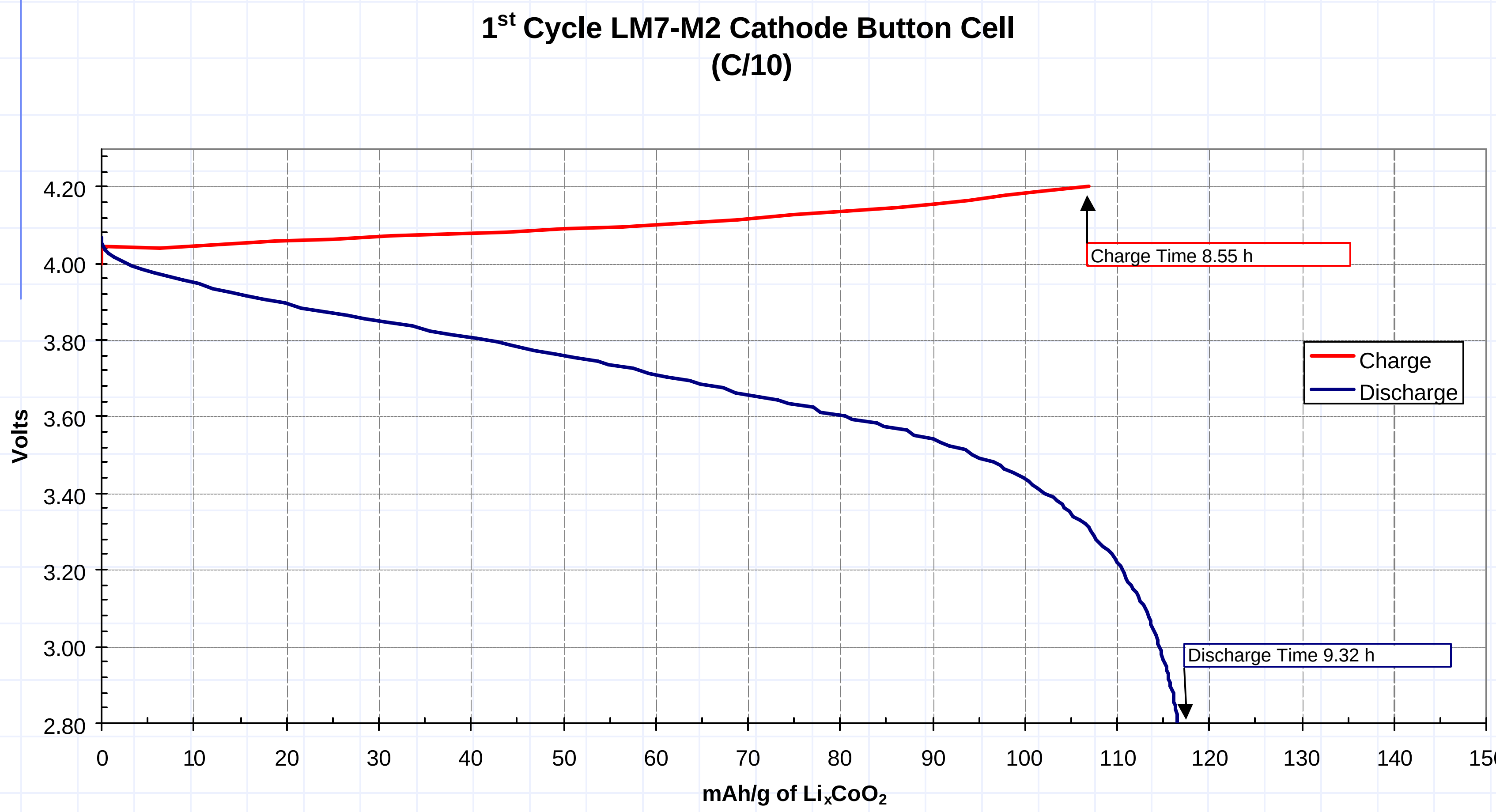
Coin Cell Results
LM7-M2 Anode

Some loss in LEO rate capability



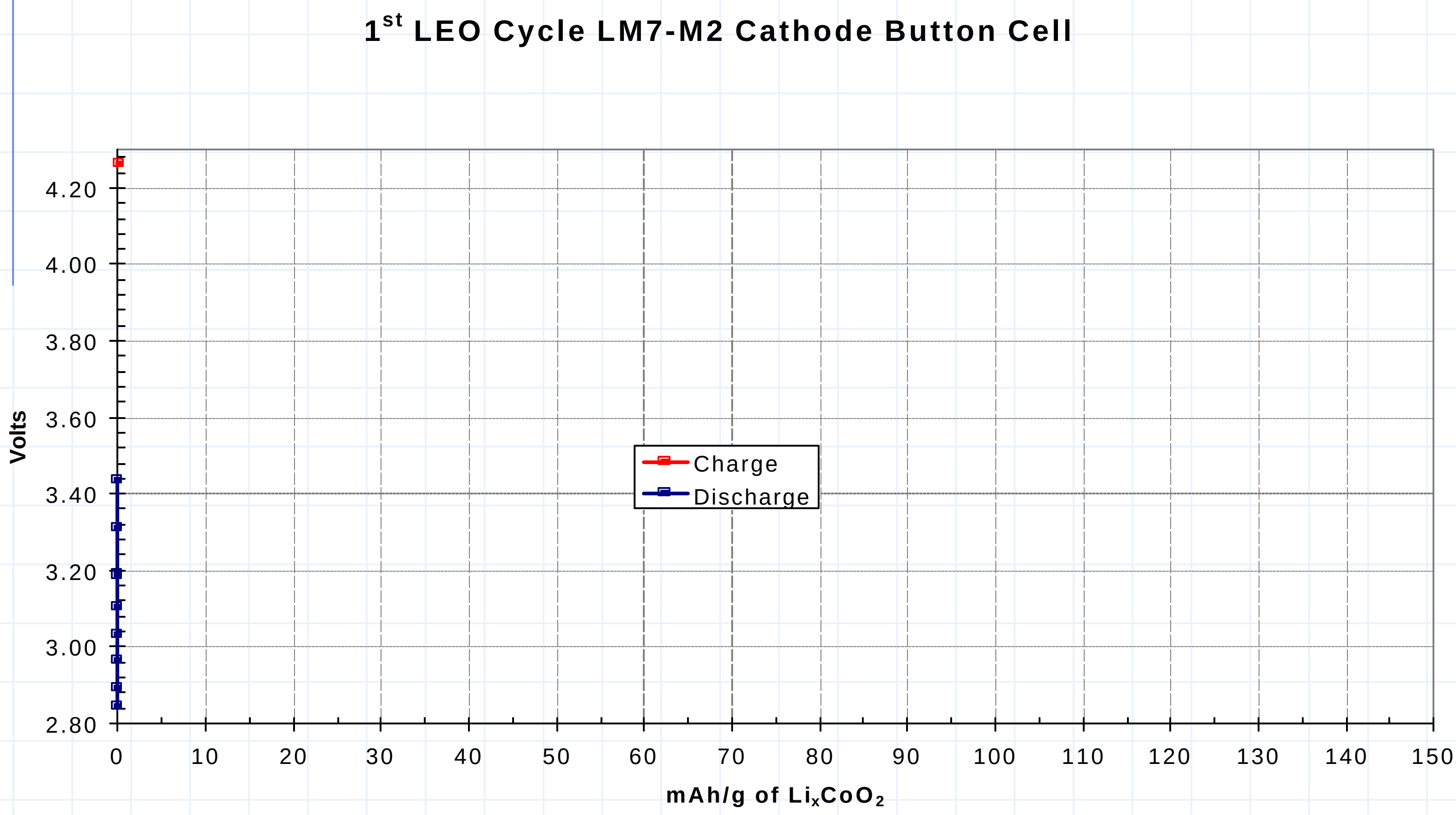
Coin Cell Results
LM7-M2 Cathode

Degradation in intrinsic capacity



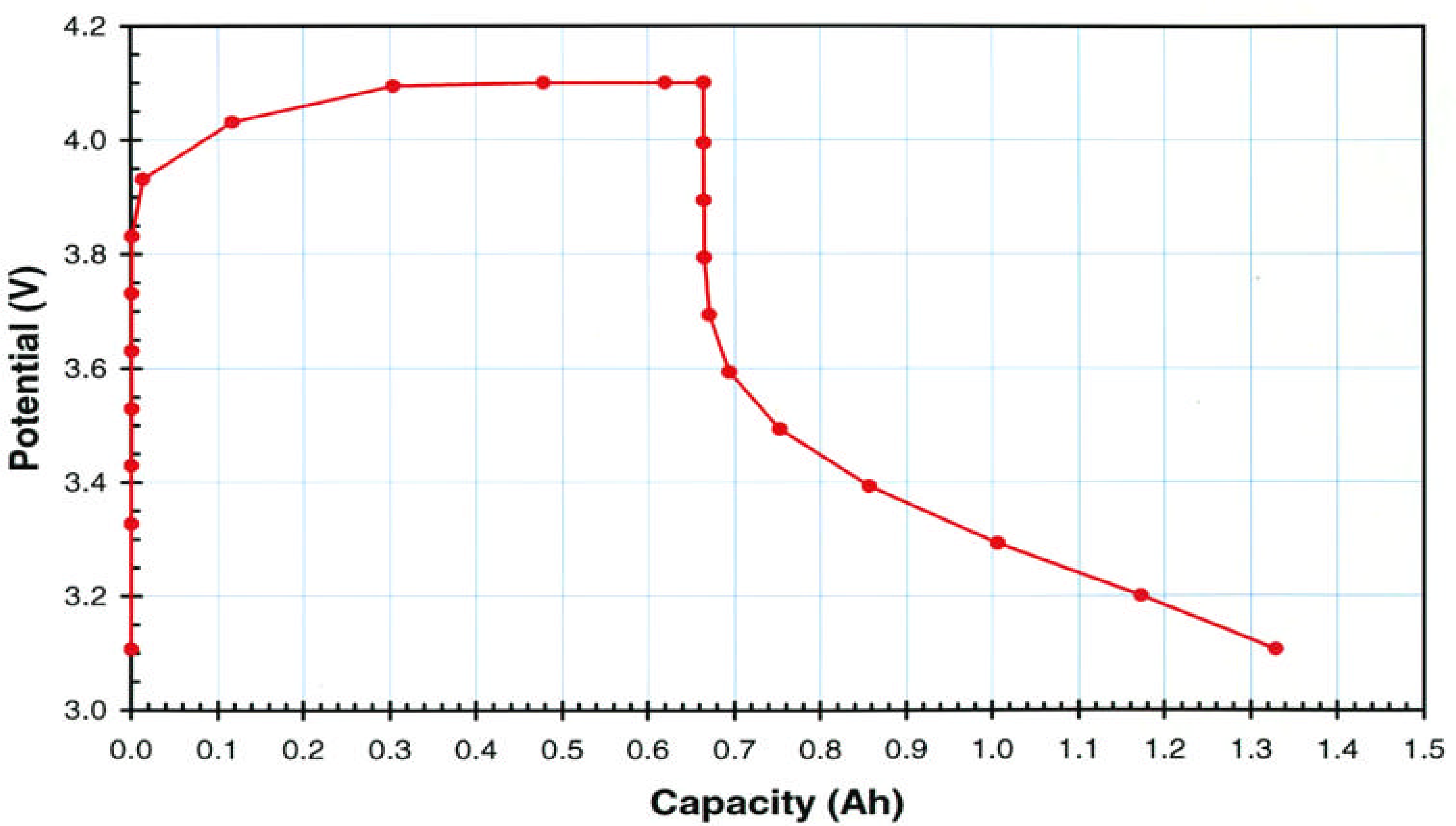
Coin Cell Results LM7-M2 Cathode

Complete loss of LEO rate capability



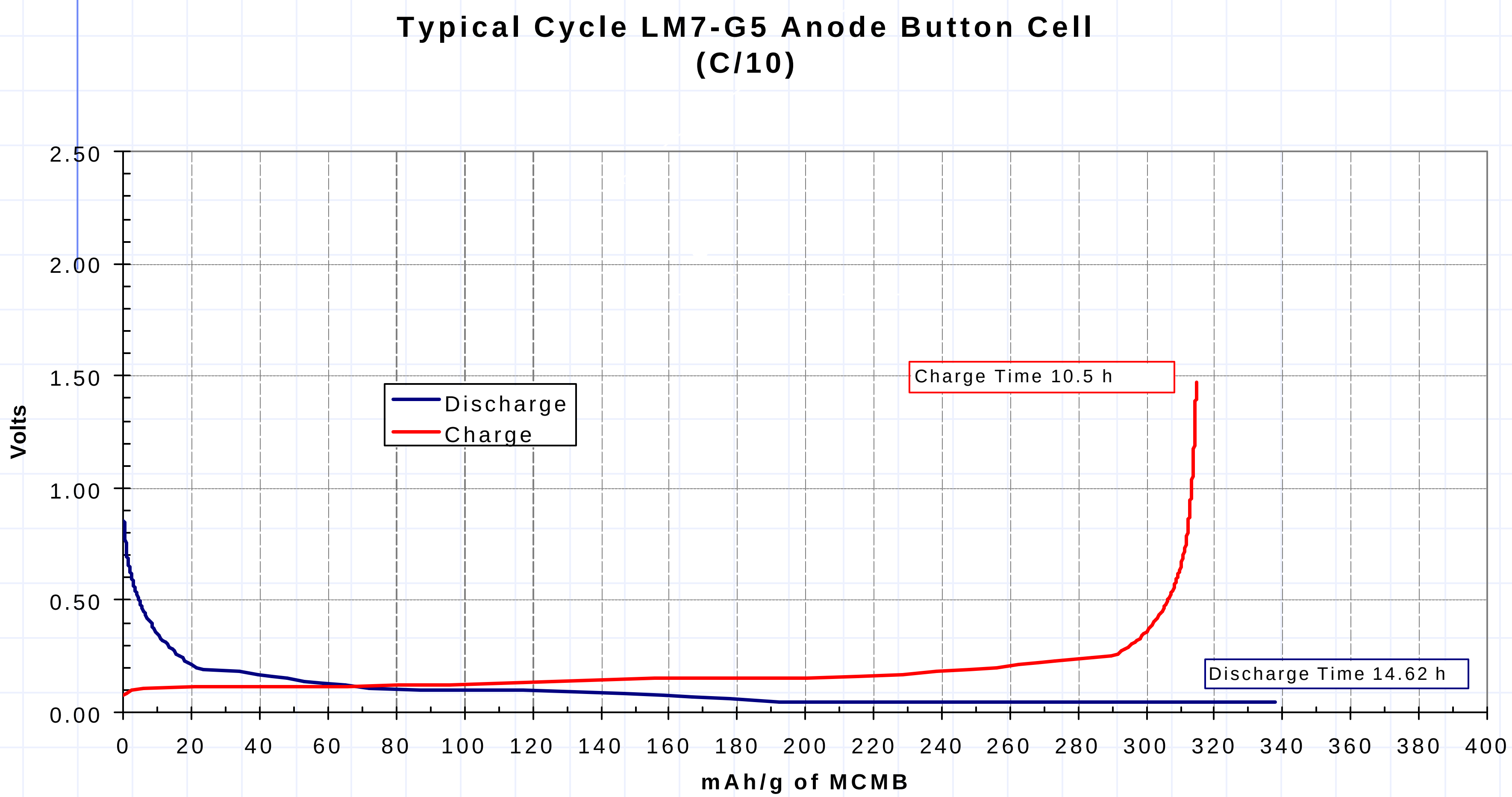
Full Cell Results
LM7M-2, LEO Cycle 3880

Full cell V curves indicative of predominant cathode polarization



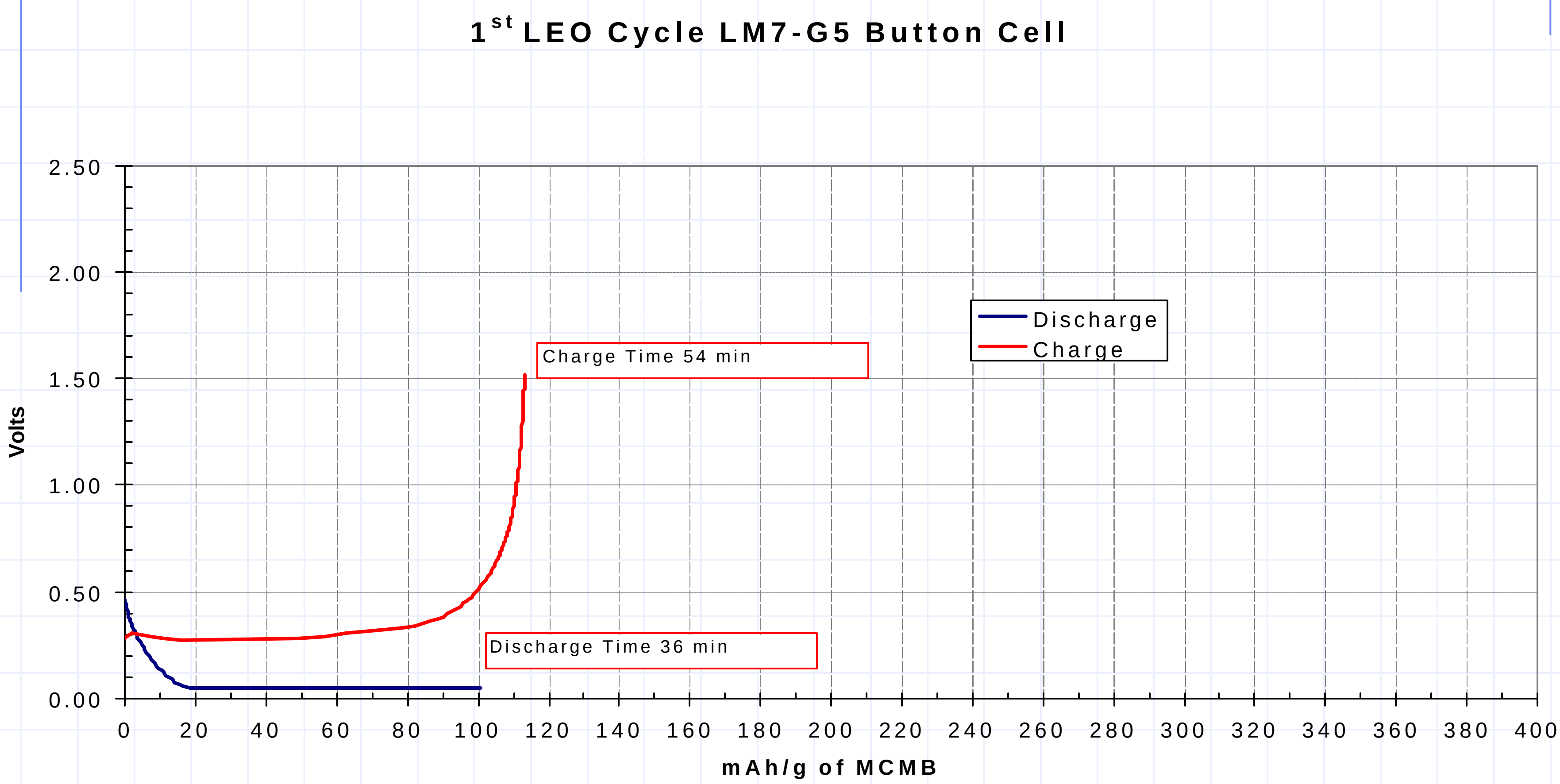
Coin Cell Results
LM7-G5 Anode

No loss in intrinsic capacity



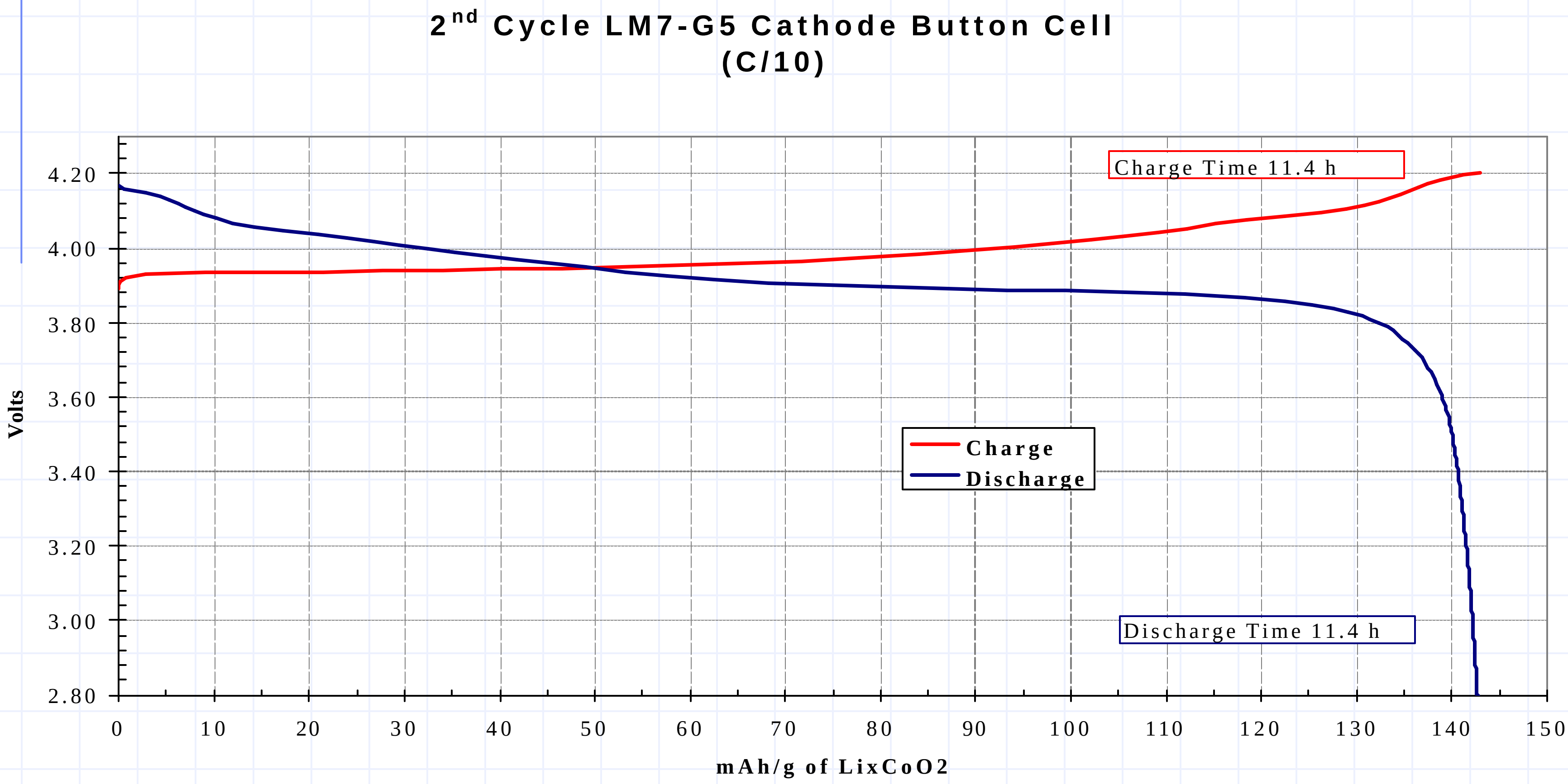
Coin Cell Results
LM7-G5 Anode

Degradation in LEO rate capability



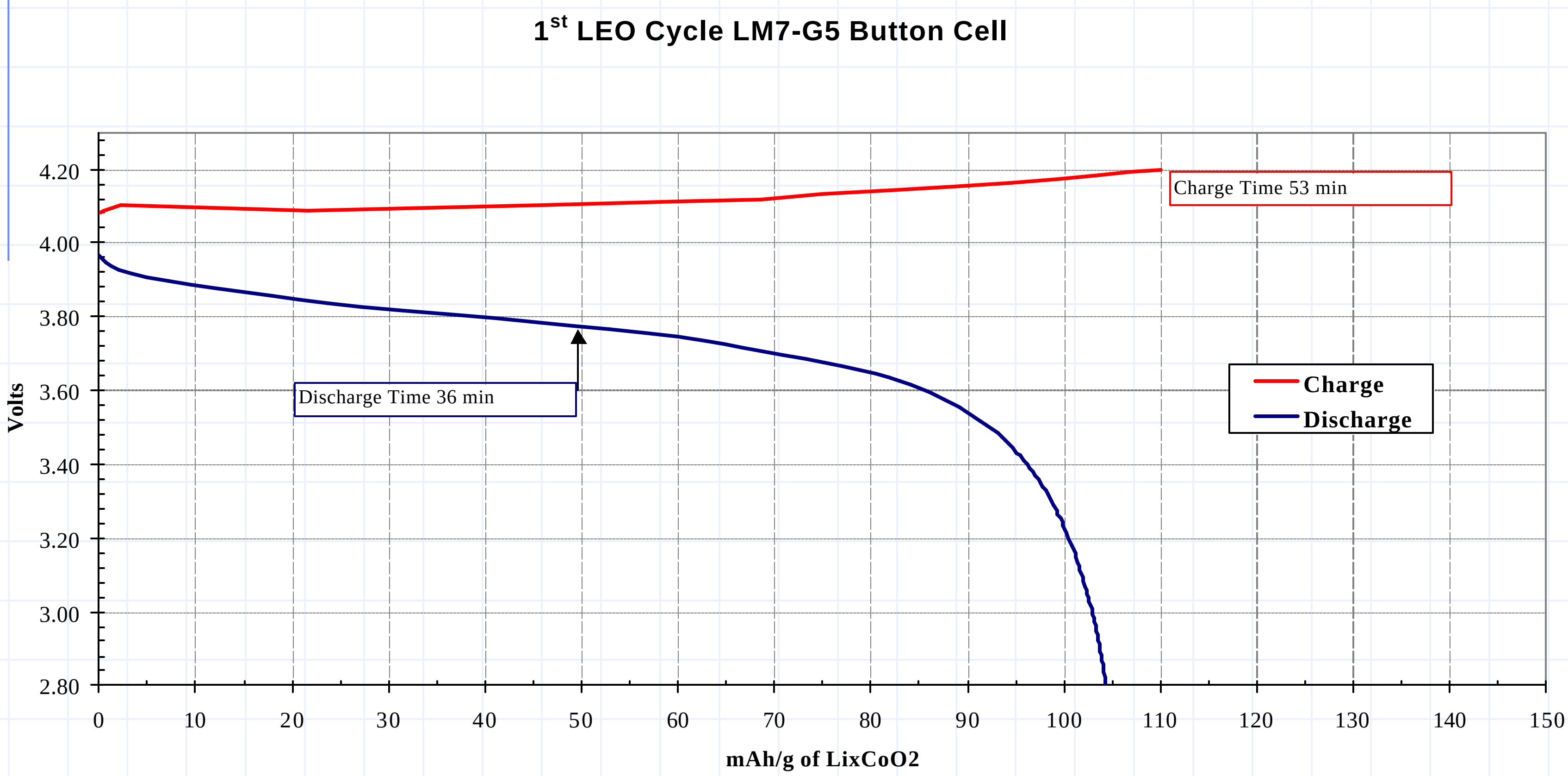
Coin Cell Results
LM7-G5 Cathode

No loss in intrinsic capacity



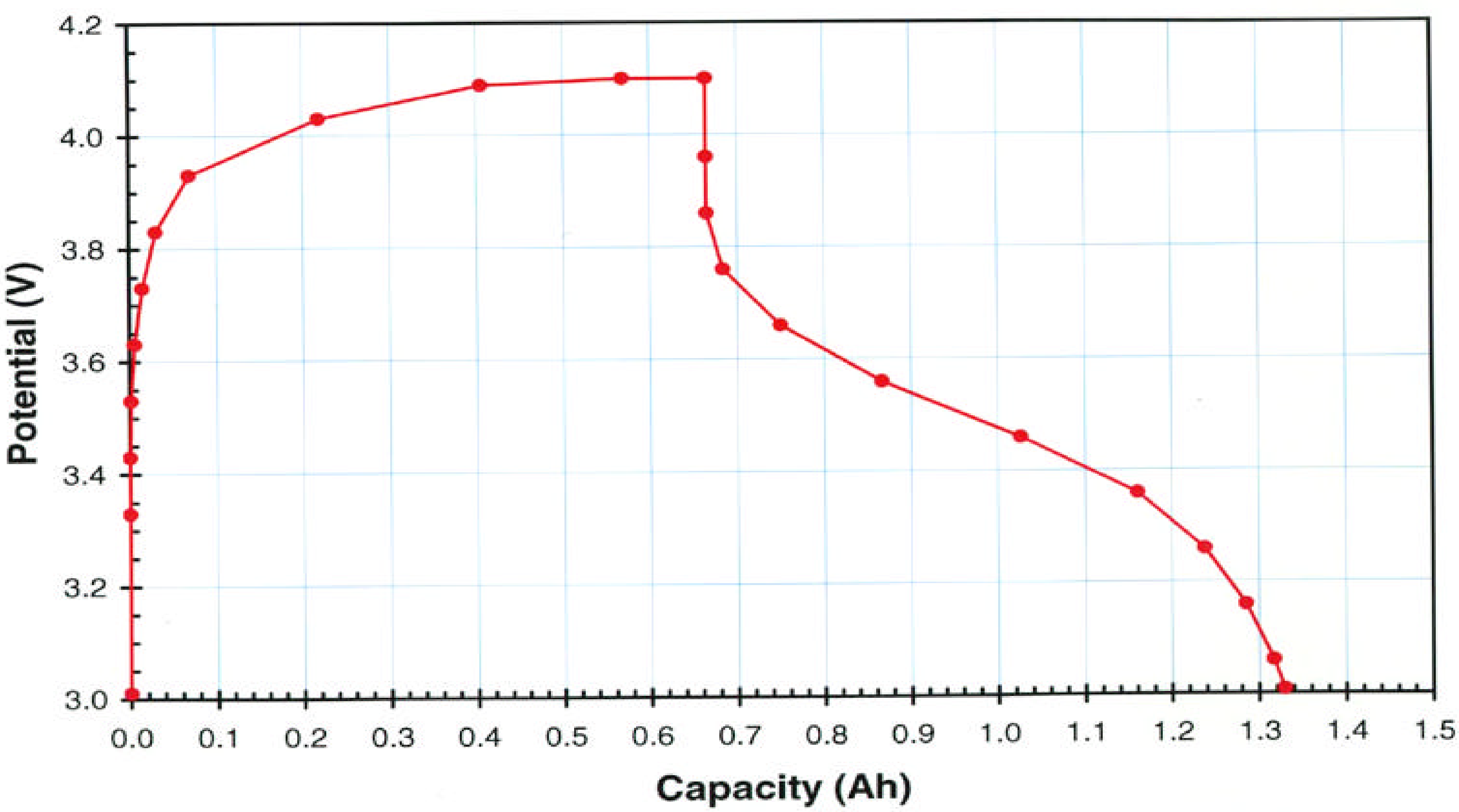
Coin Cell Results
LM7-G5 Cathode

No degradation in LEO rate capability



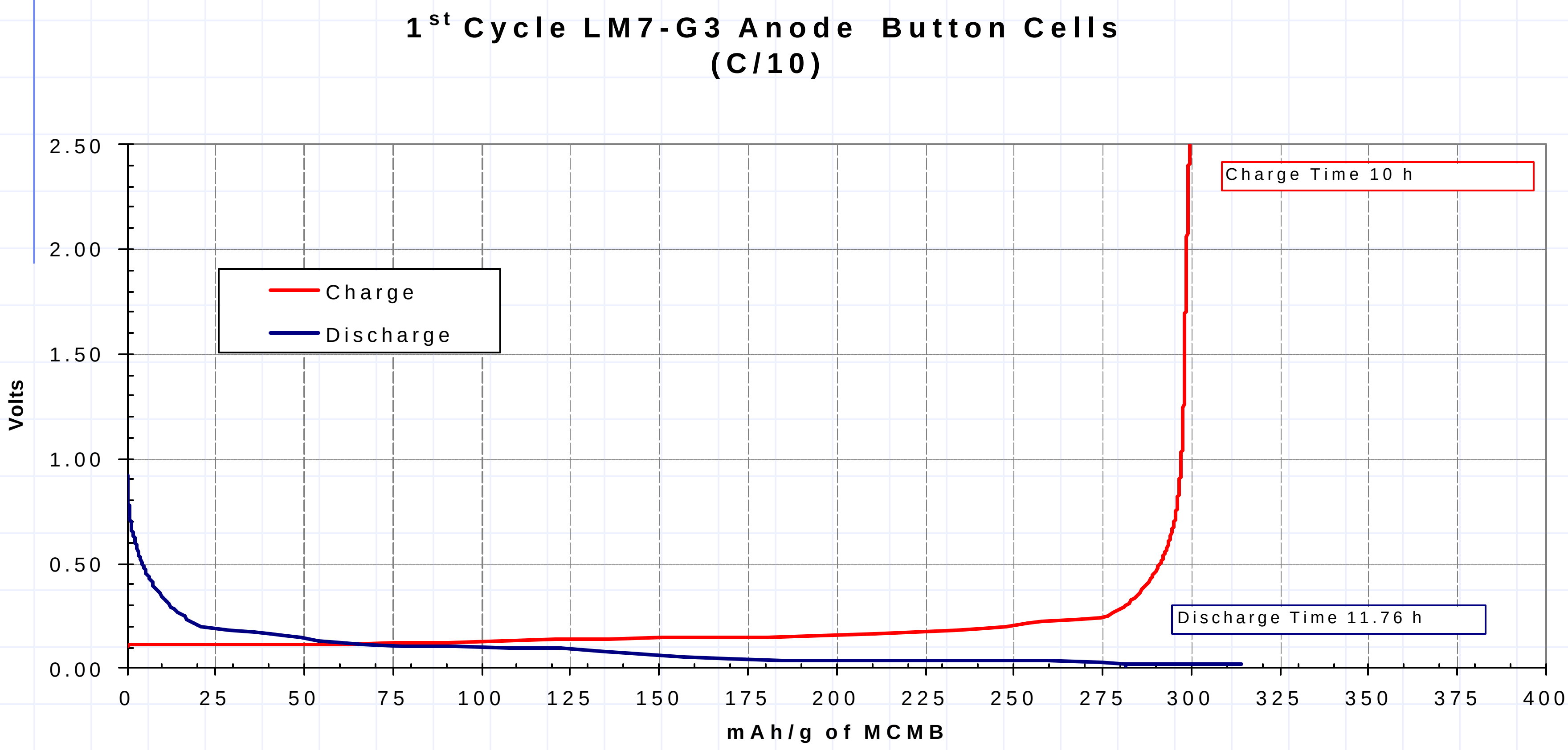
Full Cell Results
LM7G-5, LEO Cycle 4600

Full cell V curves indicative of predominant anode polarization



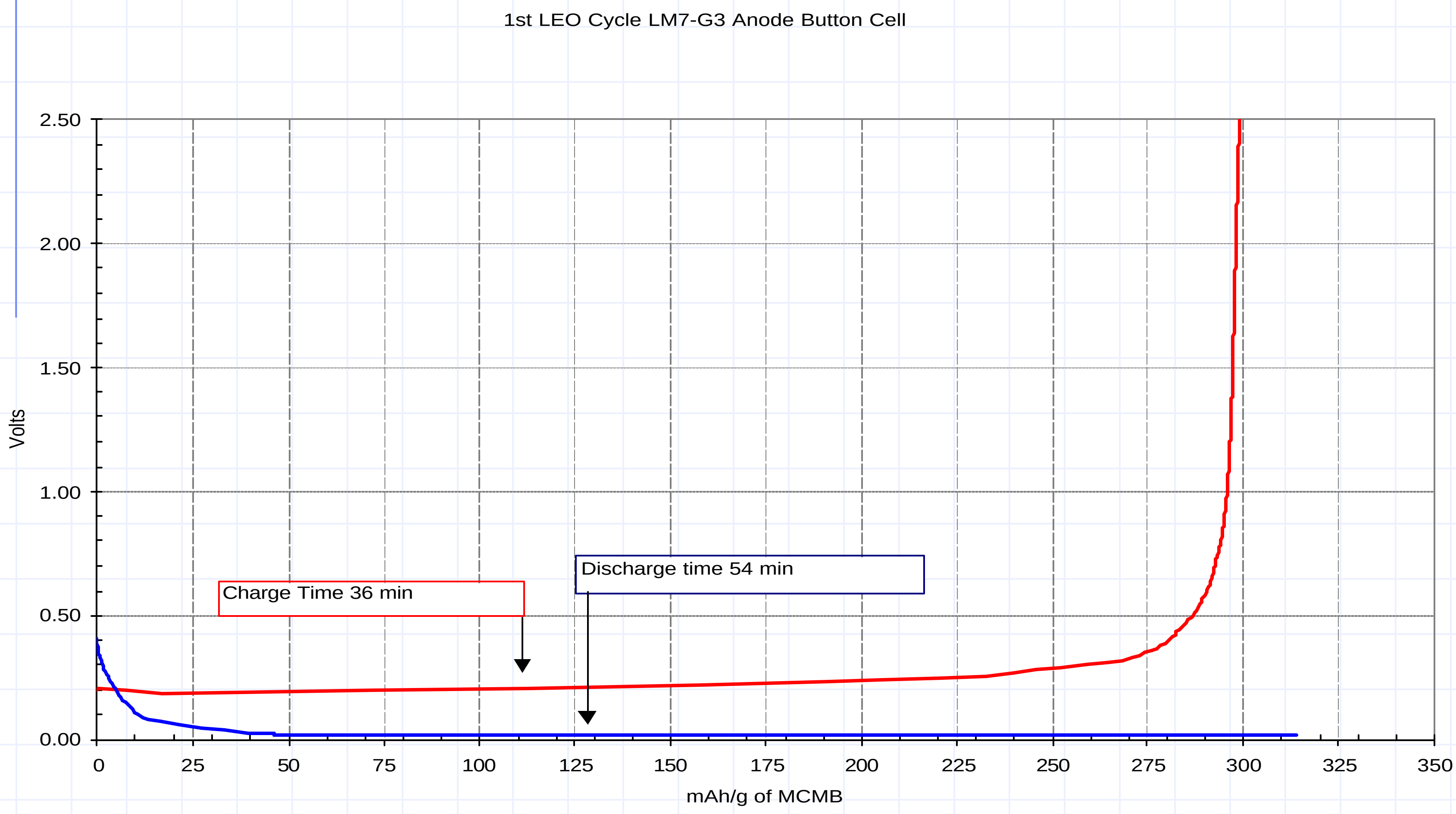
Coin Cell Results
LM7-G3 Anode

No loss in intrinsic capacity



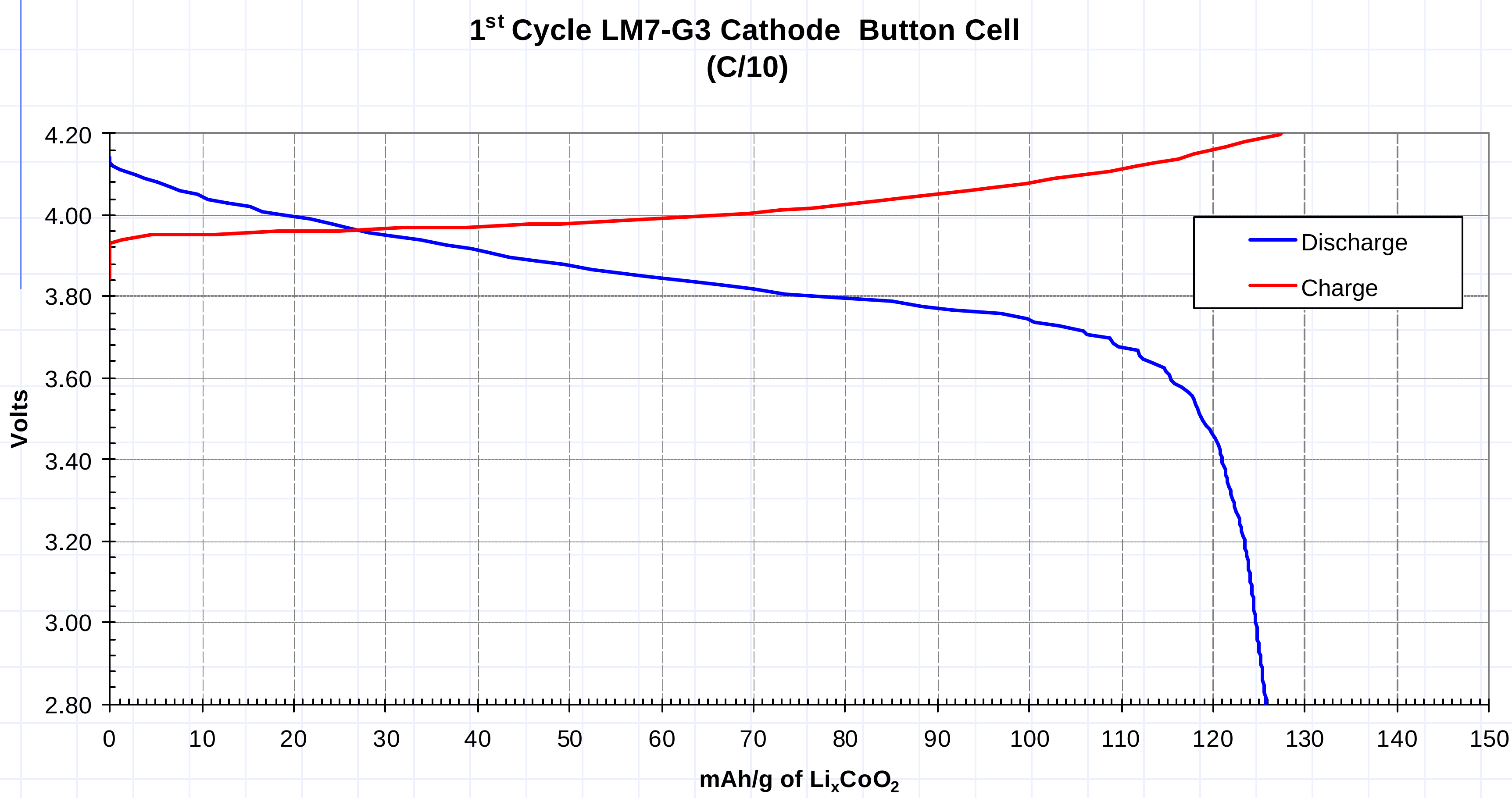
Coin Cell Results
LM7-G3 Anode

Some degradation in LEO rate capability



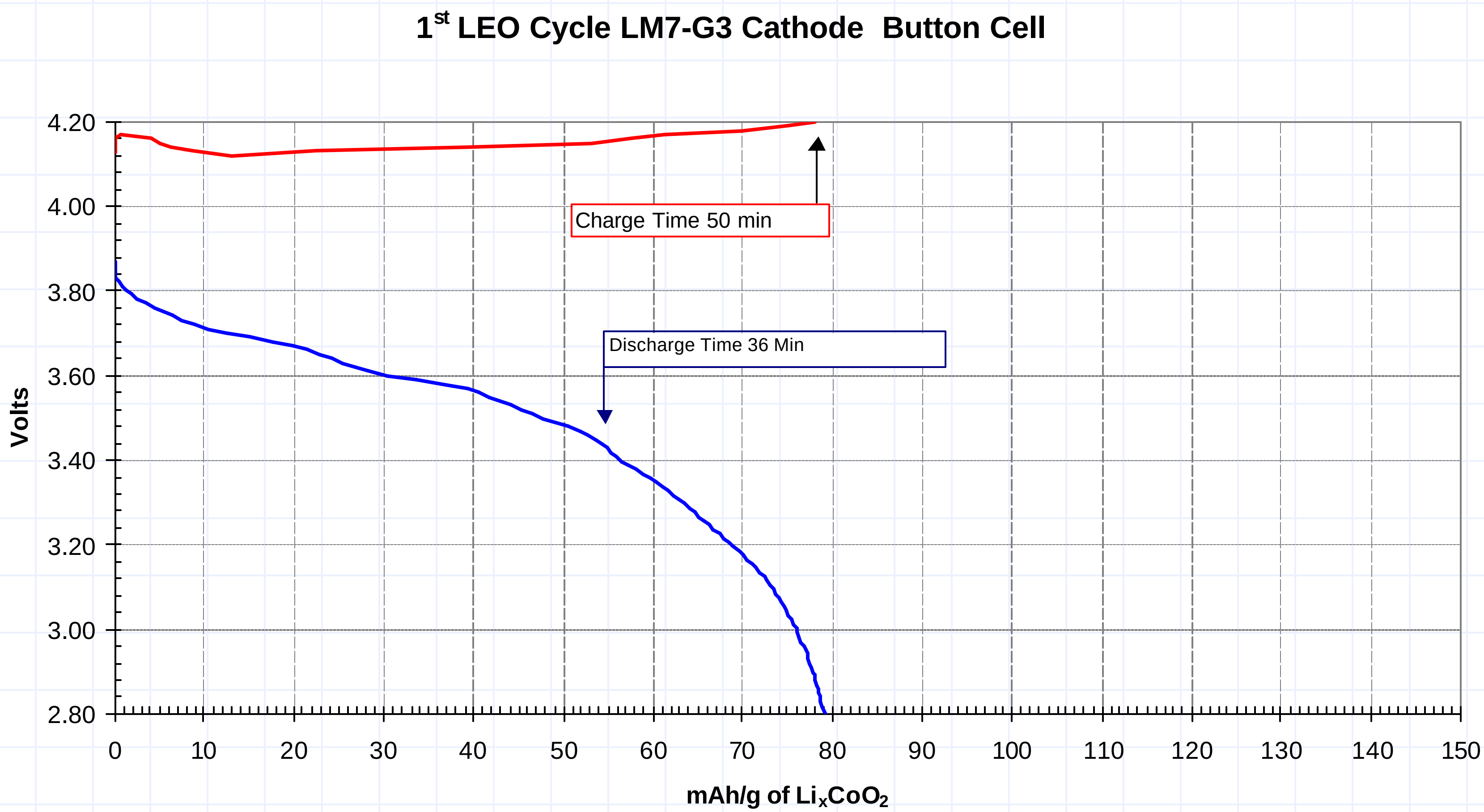
Coin Cell Results LM7-G3 Cathode

Some loss in intrinsic capacity



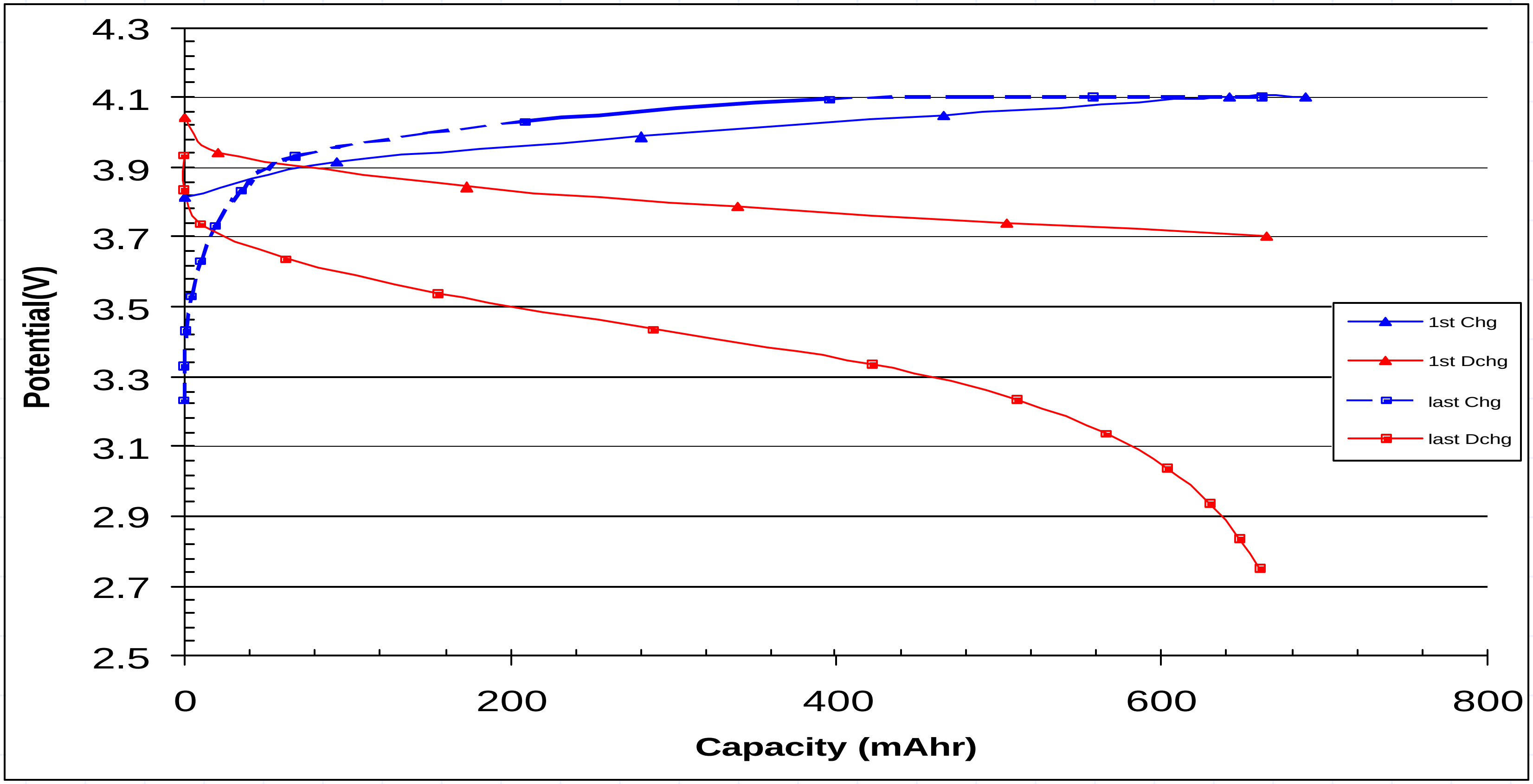
Coin Cell Results
LM7-G3 Cathode

Degradation in LEO rate capability



Results (contd.)
LM7-G03 LEO cycles

Full cell V curves indicative of cathode & anode polarizations



DPA Cells Summary

Pouch Cells	Coin half Cells	Intrinsic Capacity (mAh/g)	LEO Capacity (mAh/g)	Li Loss (x) on Cycling Li_xCoO_2
LM6-D6	Cathode Anode	85 (U) / 84 (L) 315 (L) / 299 (U)	***0 (U) / 14(L)*** 169 (L)/ 122 (U)	0.01
LM7-M2	Cathode Anode	121 (U) / 121 (L) 316 (L) / 312 (U)	***0 (U) / 0(L)*** ***105 (L)/ 108 (U)***	0.01
LM7-G3	Cathode Anode	128 (U) / 126 (L) 299 (L) / 314 (U)	***<78 (U) / 54(L)*** ***128 (L)/ 113 (U)***	0.01
LM7-G5	Cathode Anode	143 (U) / 143 (L) 337 (L) / 317 (U)	110 (U) / 54(L) ***101 (L)/ 113 (U)***	***0.16***
Fresh Electrodes	Cathode Anode	140 (U) / 140 (L) 330 (L) / 323 (U)	127 (U) / 54(L) 164 (L)/ 120 (U)	0.01

Li-ions accounting

	LiCoO2 eltd.		MCMB eltd.
initial	$LiCoO_2$		Li_0C_6
Charge	$Li_{0.5}CoO_2$	**conditioning**	$Li_{0.5}C_6$
Disch.	$Li_{0.9}CoO_2$	**100% DOD**	$Li_{0.1}C_6$
charge	$Li_{0.5}CoO_2$	LEO 40%DOD	$Li_{0.5}C_6$
Disch.	$Li_{0.7}CoO_2$		$Li_{0.3}C_6$

==

Capacity loss could be due to:

1) Loss of cyclable Li
2) Electrode(s) polarization

Preliminary Failure Mechanisms

- LM6-D6 and LM7-M2
  - Cathode severely polarized due to possible structural degradation
    - XRD of post-mortem $LiCoO_2$ electrodes showed broadened peaks
- LM7-G5
  - Anode polarized due to possible SEI destruction/repassivation
    - Loss of cyclable lithium
- LM7-G3
  - Both electrodes were polarized, with possible structural degradation of the cathode

Performance and Safety Tests on Samsung 18650 Li-ion Cells: Two Cell Designs

Yi Deng, Judith Jeevarajan, Raymond Rehm
Lockheed Martin Space Operations

Bobby Bragg
NASA Johnson Space Center

Wenlin Zhang
Schlumberger Perforating and Testing

Introduction

In order to meet the applications for space shuttle in future, two types of Samsung cells, with capacity 1800mAh and 2000mAh, have been investigated. The studies focused on:

- Performance tests

  Completed 250 cycles at various combinations of charge/discharge C rates

  Discharge capacity measurements at various temperatures

- Safety tests

  Overcharge and overdischarge

  Heat abuse

  Short circuit: Internal and external short

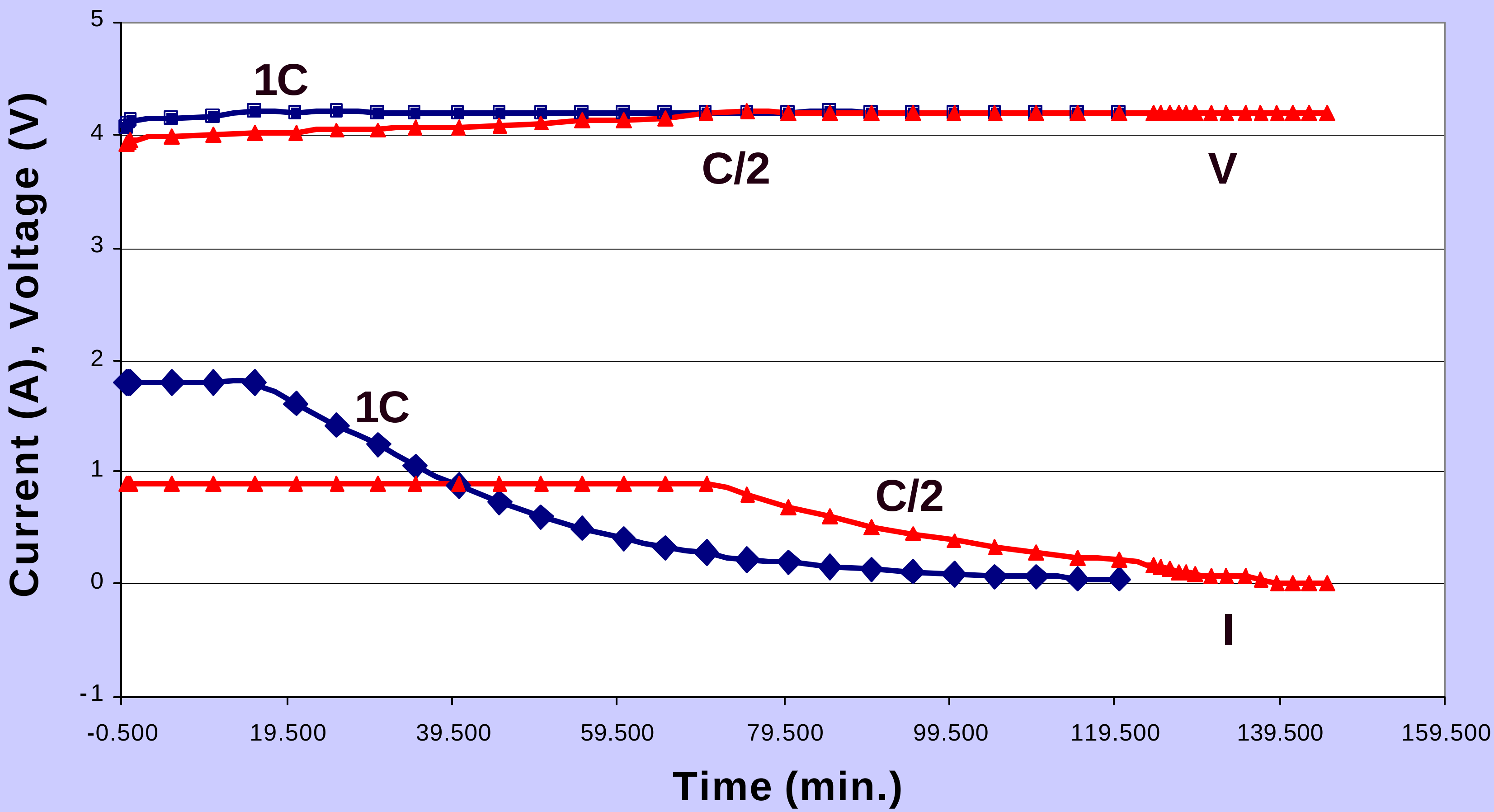
  Vibration, vacuum, drop tests

Information of cells

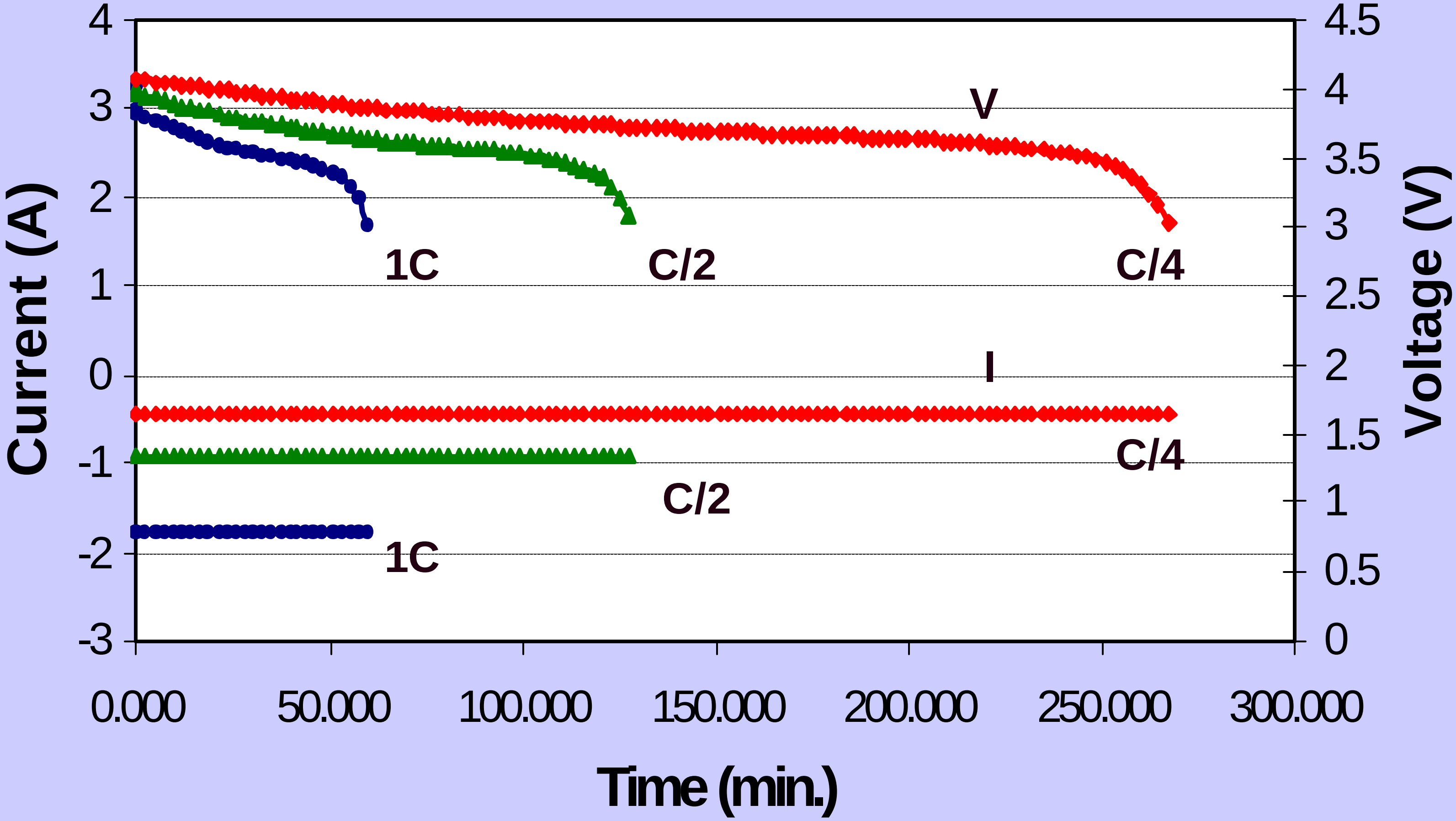
Model #	Capacity	Dimension		Weight	Energy density	
		Diameter	Height			
ICR18650-18	1800mAh	18.0±0.3mm	64.9±0.3mm	42g	403Wh/L	158Wh/Kg
ICR18650-20	2000mAh	18.0±0.3mm	64.9±0.3mm	43g	448Wh/L	172Wh/Kg

Performance tests

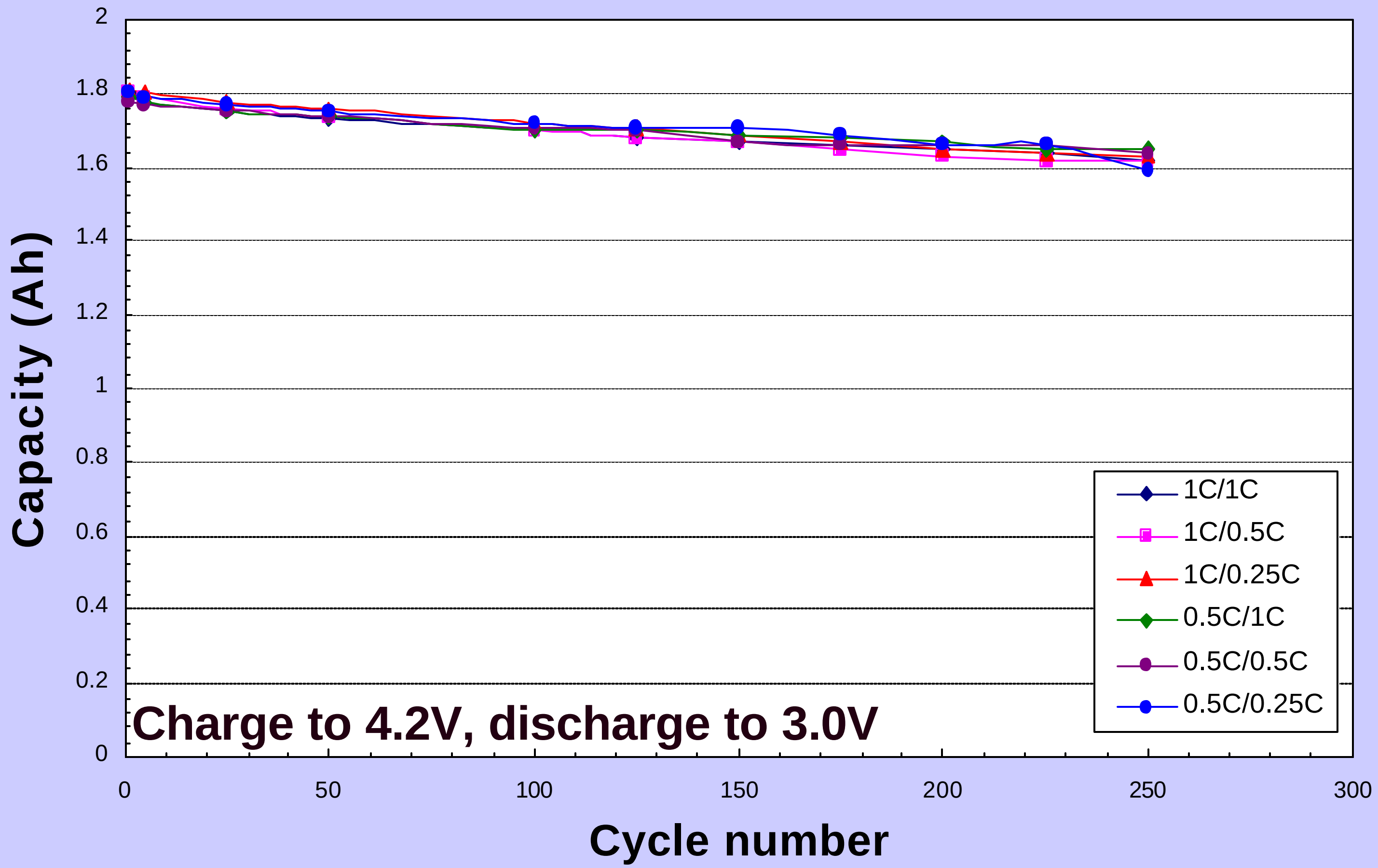
Plot of CC/Cv charge for 1.8 Ah Samsung Li-ion cells at two different rates at RT



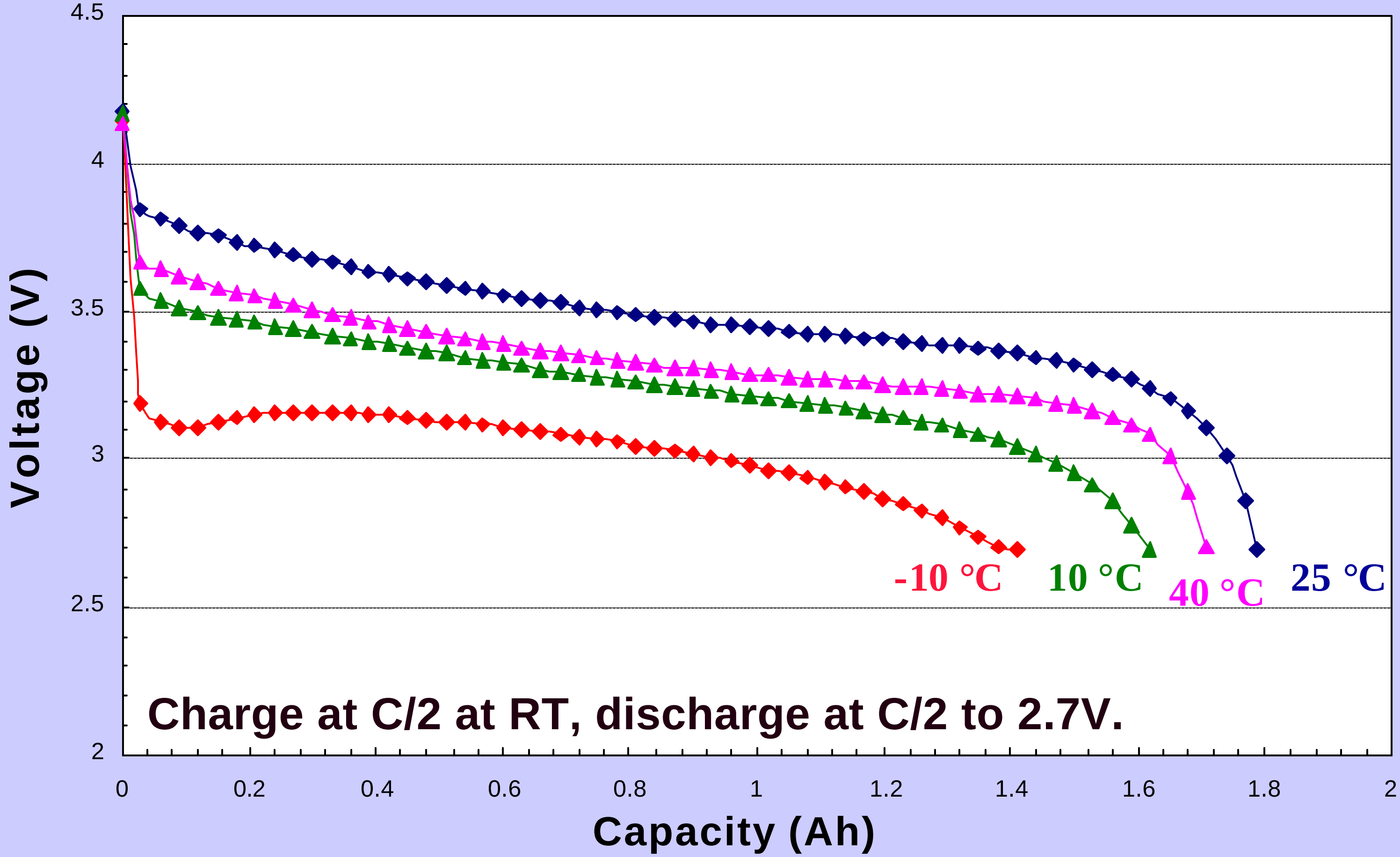
Plot of discharge of Samsung 1.8 Ah Li-ion cells at different C rate at RT



Cycle life tests for 1.8 Ah Li-ion cells at various C rate combinations of charge/discharge



Characterization of capacities of 1.8 Ah cells at various temperatures



Discharge capacity at different temperatures

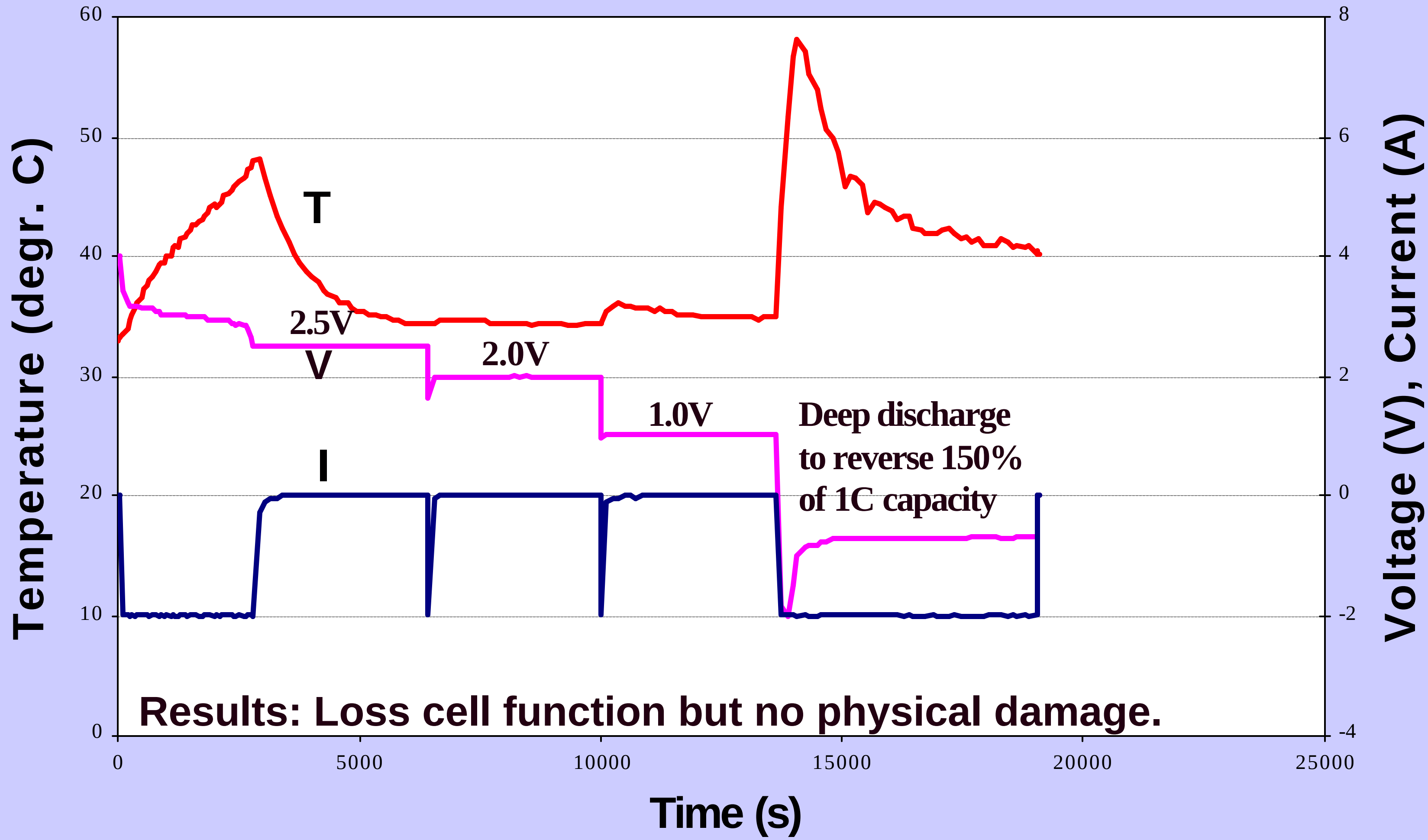
1.8 Ah cells			2.0 Ah cells		
Test temperature (°C)	**Capacity of discharge (Ah)**		**Test temperature (°C)**	**Capacity of discharge (Ah)**	
40	1.71	95.6%	40	1.82	95.8%
25	1.79	100%	25	1.90	100%
10	1.62	90.6%	10	1.75	92.1%
-10	1.41	78.8%	-10	1.34	70.5%

Summary for performance tests

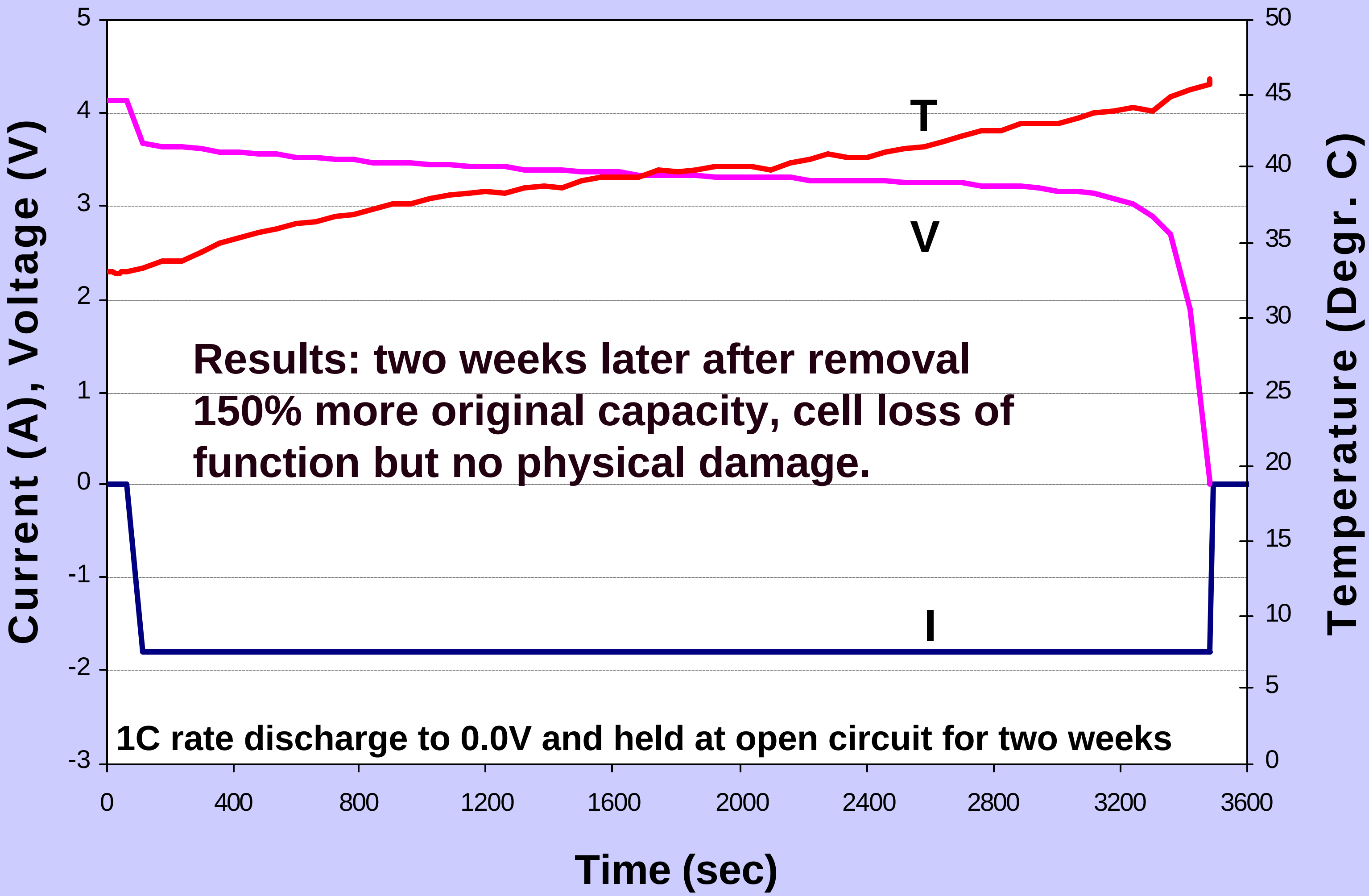
- In 250 cycles, the capacity drops with 100% DOD were 11%-12% both for 1.8Ah and 2.0Ah cells regardless combination of C rate at range from 1C to C/4.
- The optimum discharge capacity and energy were achieved at 25 °C

Safety tests

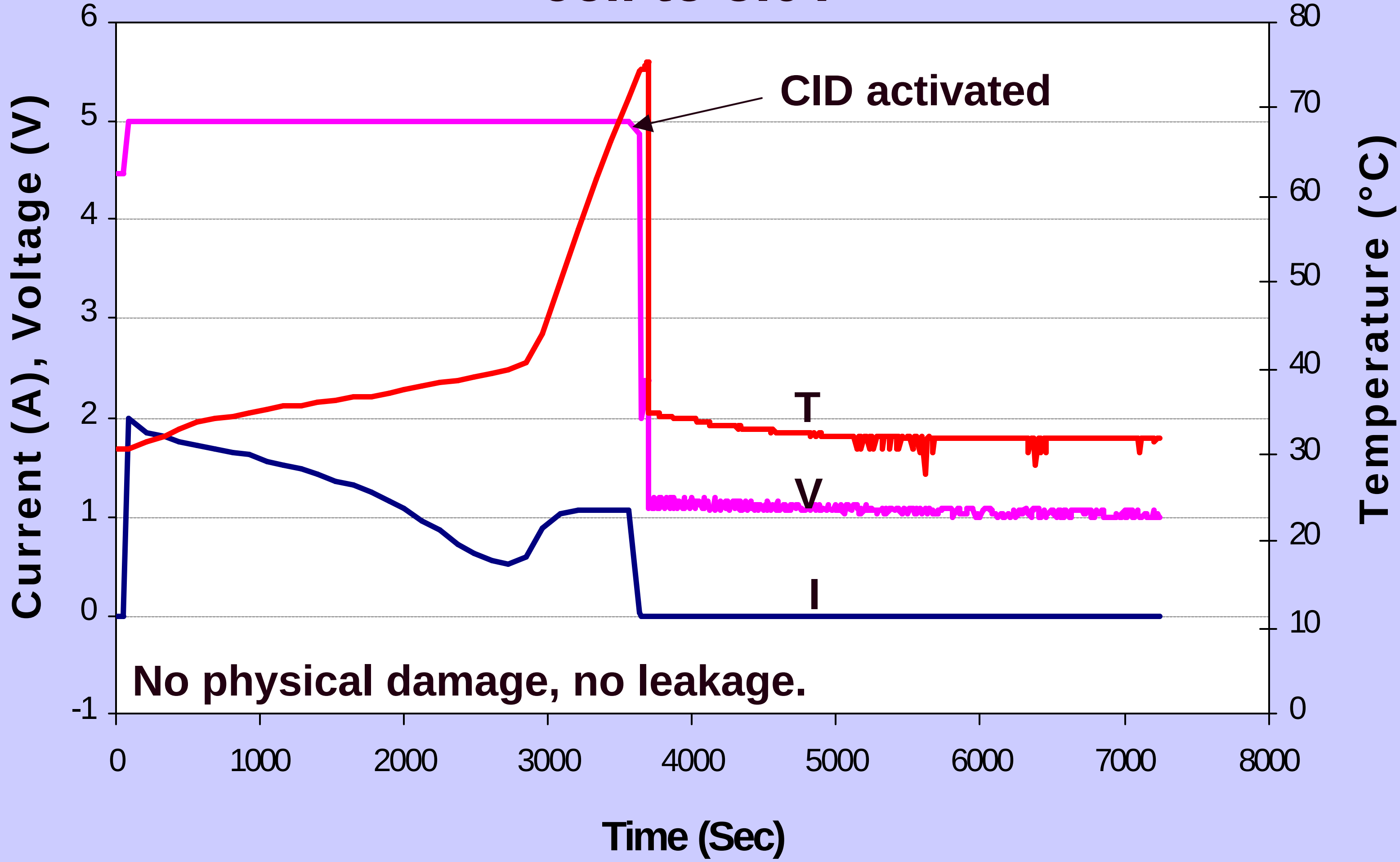
Over-discharge of Samsung 2.0 Ah li-ion cell at 1C rate into reversal

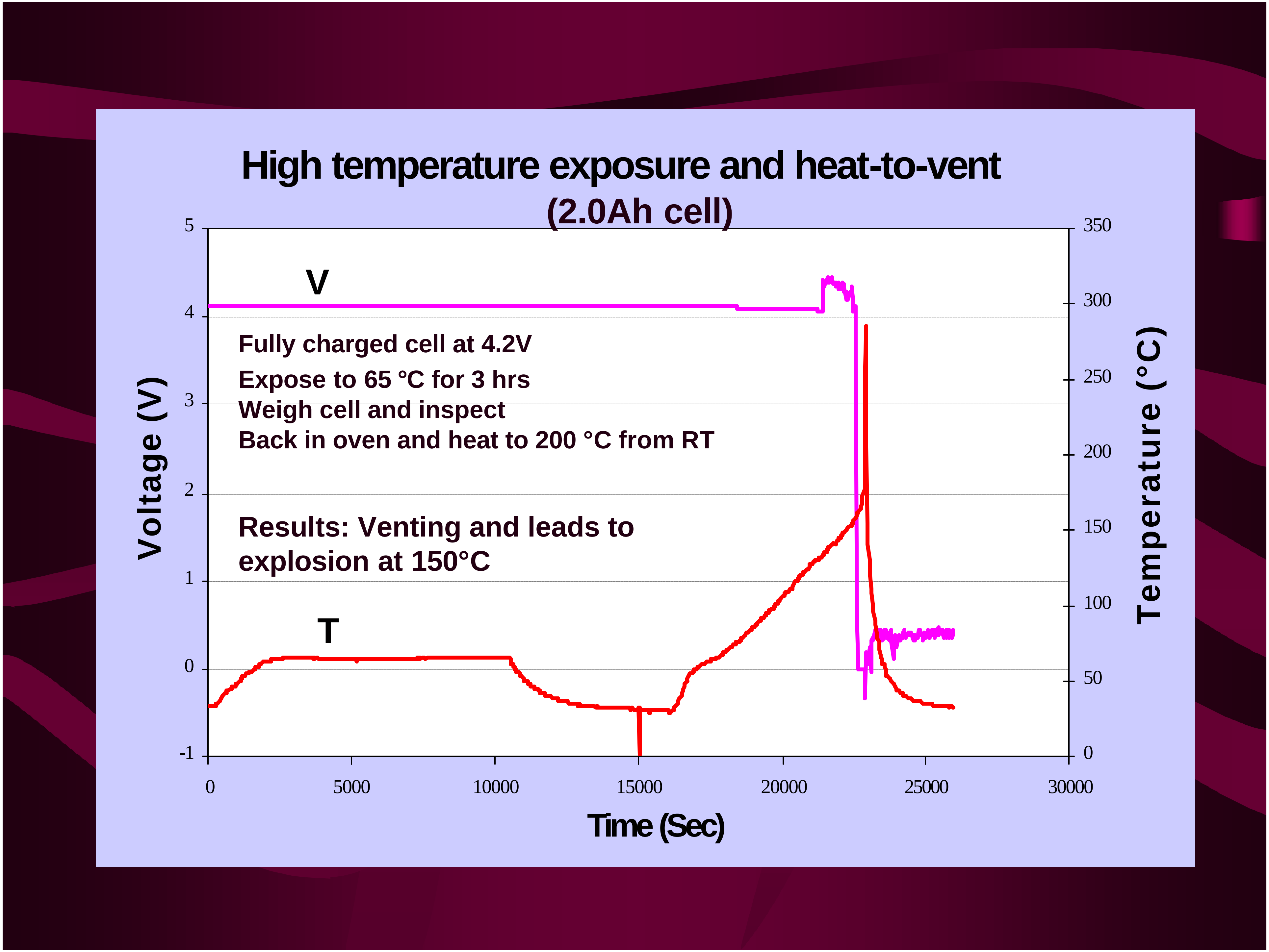


Over discharge 1.8 Ah cell to 0.0V



Constant voltage overcharge of 2.0Ah cell to 5.0V

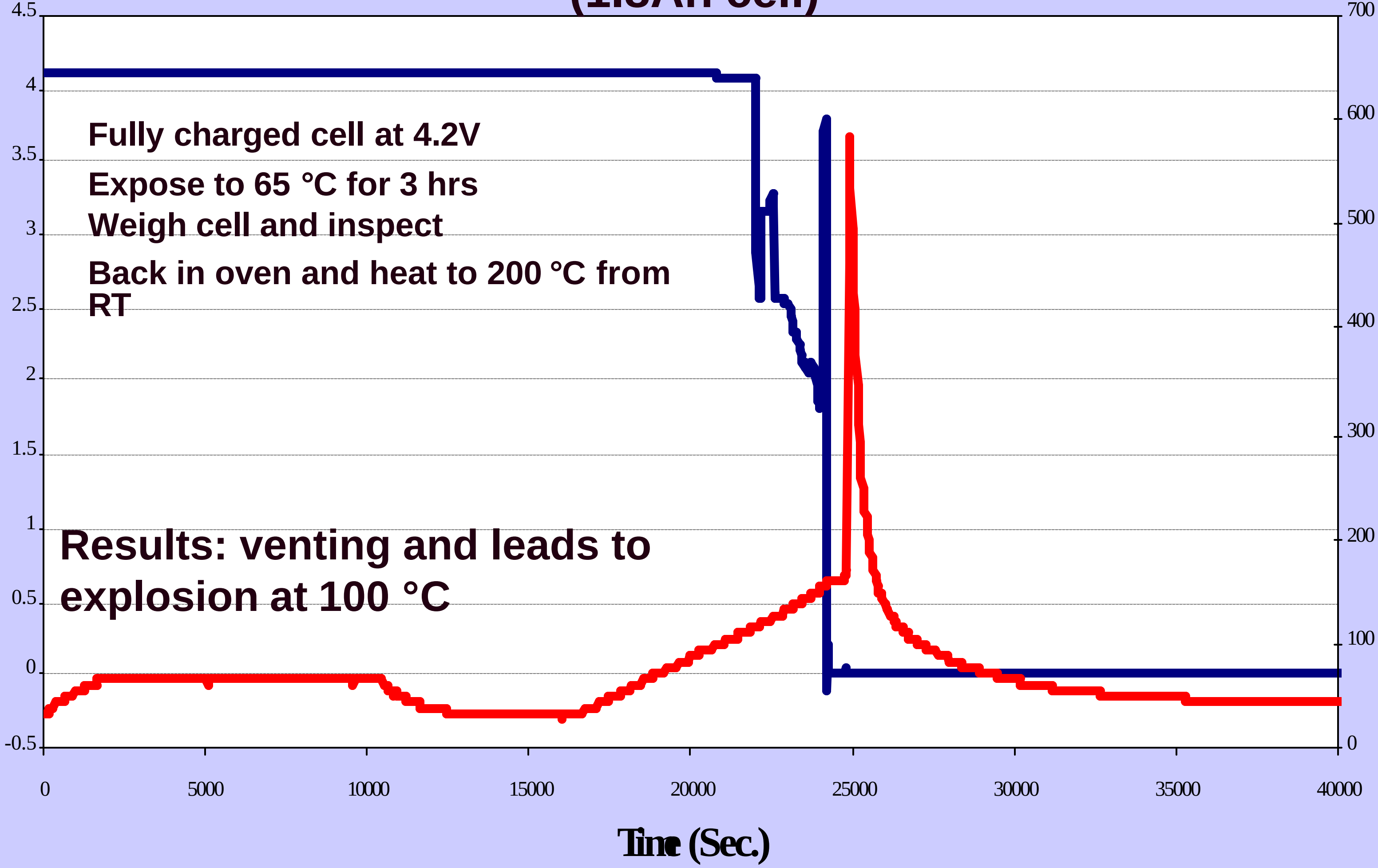




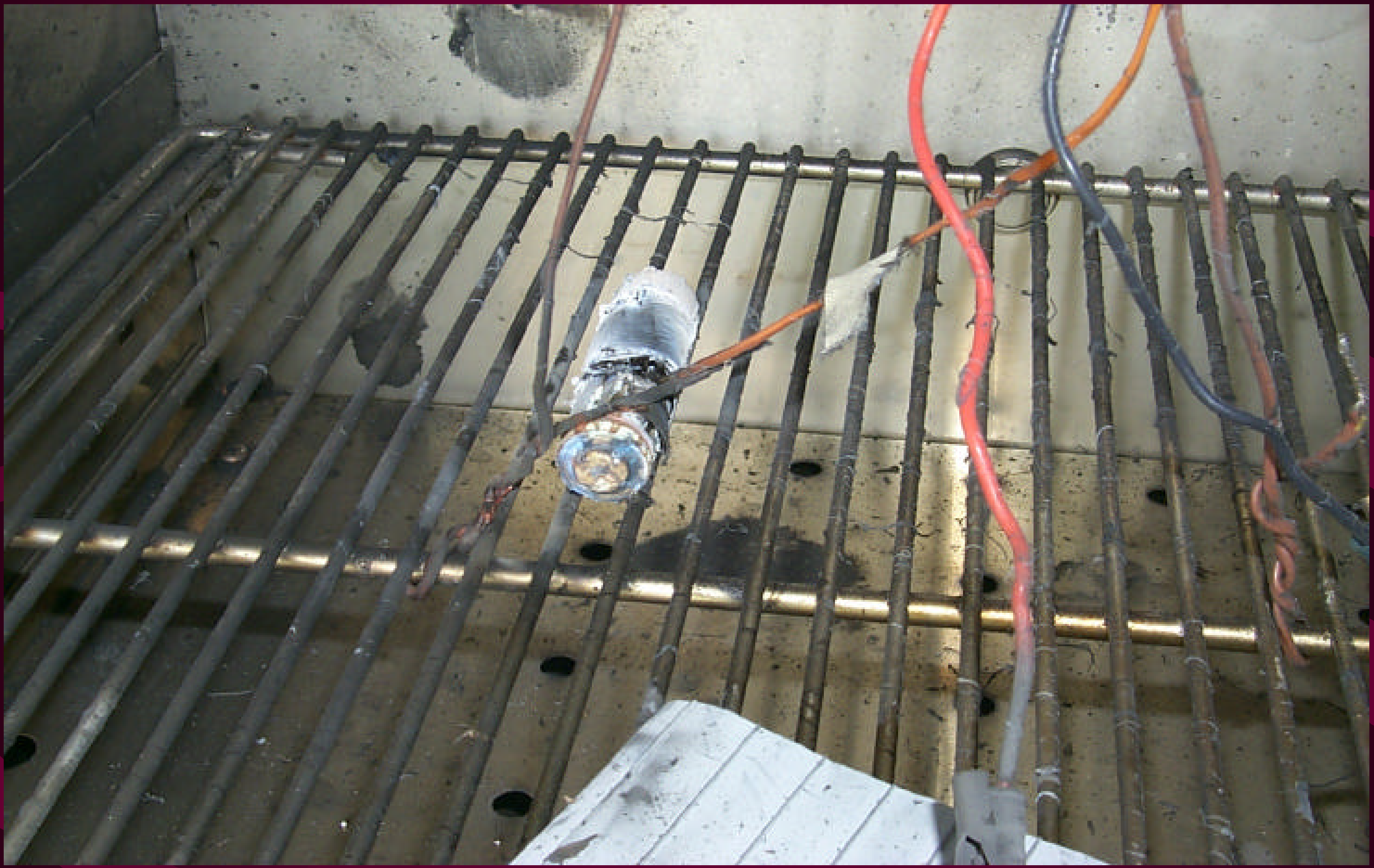
High temperature exposure and heat-to-vent
(2.0Ah cell)
V
Fully charged cell at 4.2V
Expose to 65 °C for 3 hrs
Weigh cell and inspect
Back in oven and heat to 200 °C from RT
Results: Venting and leads to explosion at 150°C
T
Voltage (V)
Temperature (°C)
Time (Sec)
5
4
3
2
1
0
-1
350
300
250
200
150
100
50
0
0
5000
10000
15000
20000
25000
30000

High temperature exposure and heat-to-vent

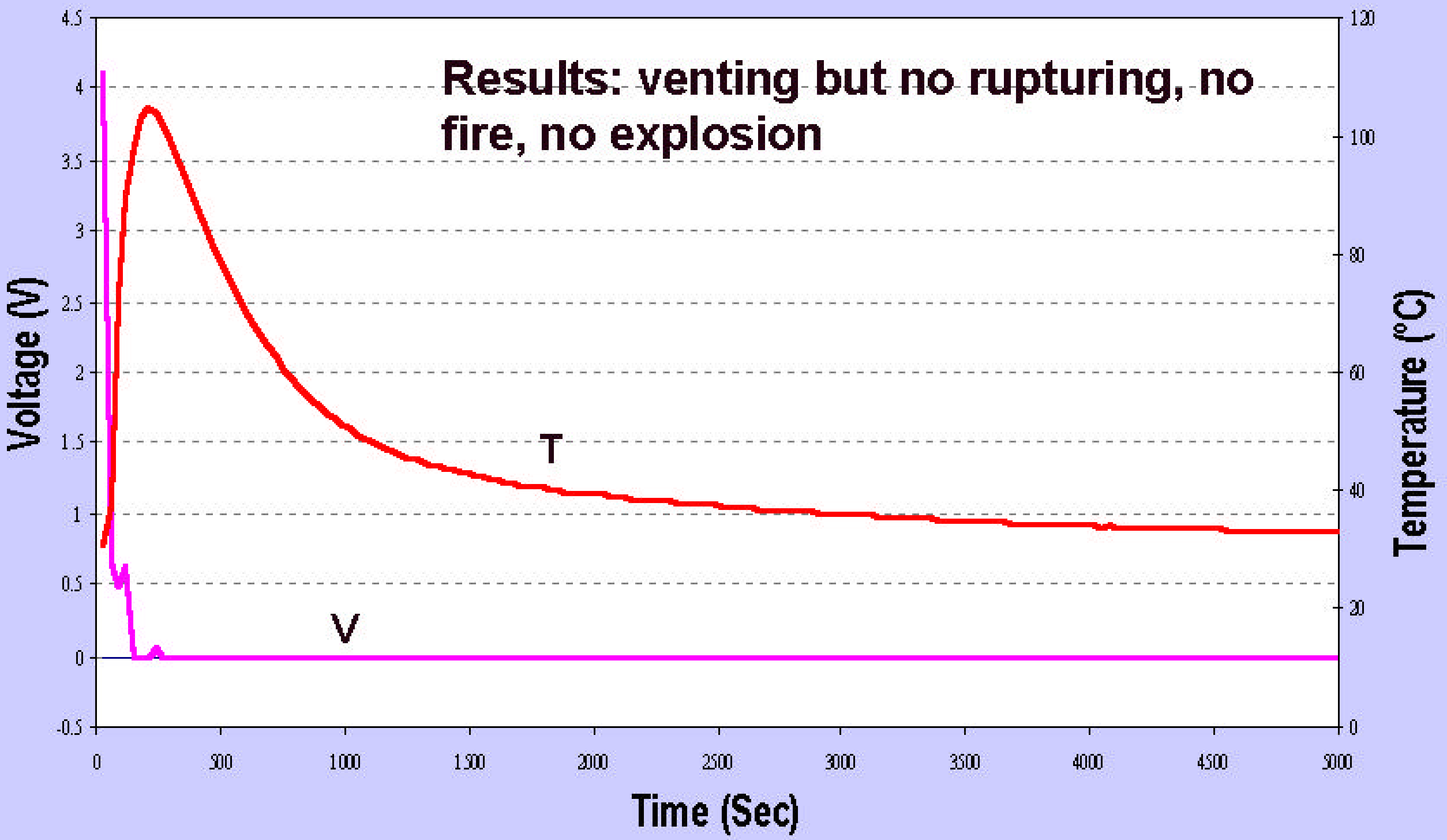
(1.8Ah cell)



Heat abuse test

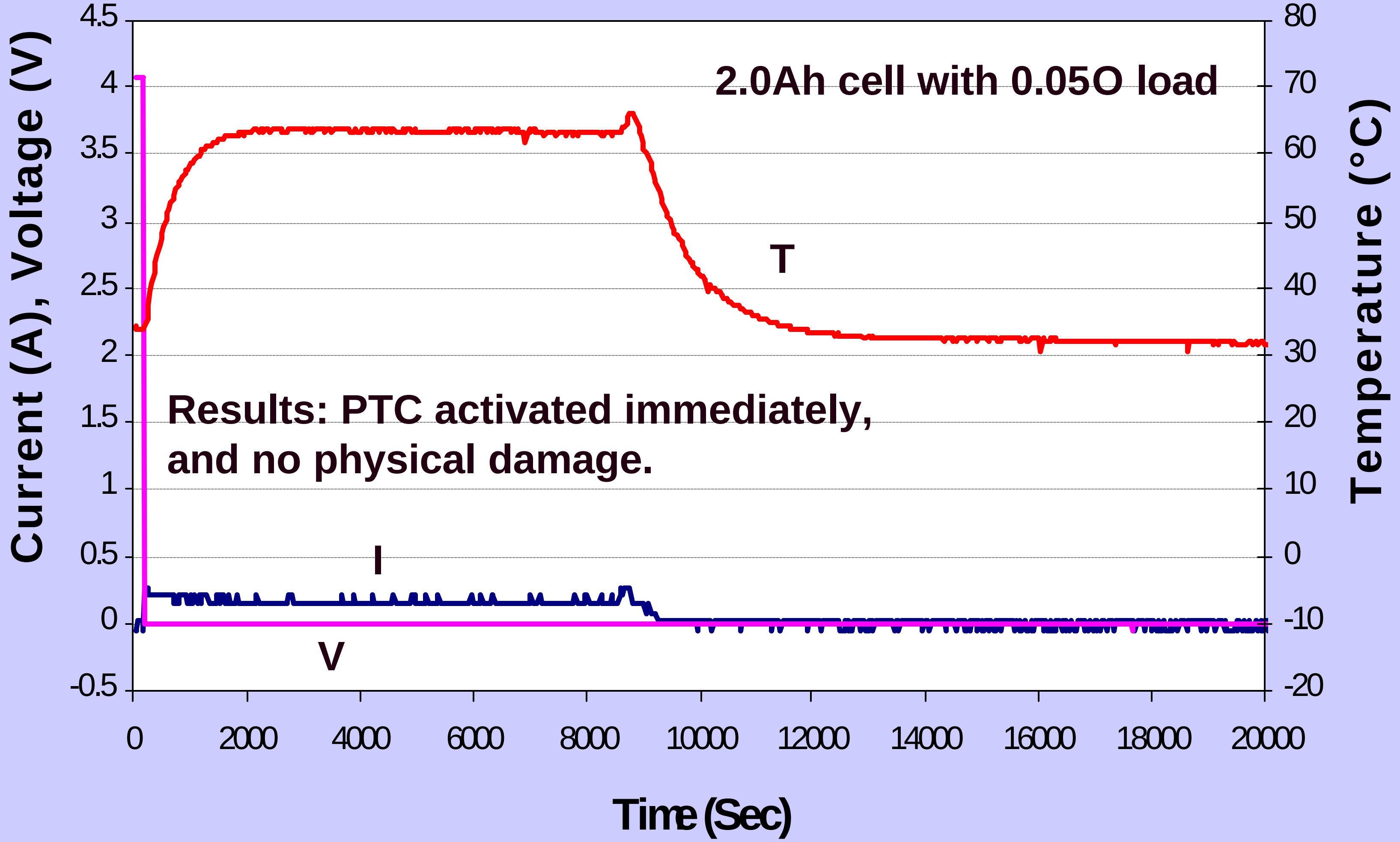


Short circuit: Internal Short



Internal short circuit test

Short circuit: External Short



Summary for safety tests

Safety test	1.8Ah cell test results	2.0 Ah cell test results
1C rate overcharge to 4.5V	passed	passed
1C overcharge to 5.0V	No fire, no explosion	No fire, no explosion
High rate (3C) discharge to 2.7V	passed	passed
1C overdischarge to 0V and reverse 150% of 1C capacity	No fire, no explosion	No fire, no explosion
65°C heating test	passed	passed
Exposure at temperature higher than 65°C to 200°C	Explosion at 100°C	Explosion at 150°C
Vacuum test (0.1 psia for 6 hrs)	passed	passed
Drop test (6ft randomly drop)	passed	passed
Vibration test (*see appendix)	passed	passed
Short circuit: internal short	No fire, no explosion	No fire, no explosion
External short	No fire, no explosion	No fire, no explosion

Appendix

Vibration tests in X, Y, and Z axes for 15 min. respectively at following vibration condition:

Frequency:	Level:
20-80 HZ	+3 dB/octave
80-350 Hz	$0.1g^2/Hz$
350-2000 Hz	-3 dB/octave

Acknowledgment

Thanks Samsung for supplying the li-ion cell samples.

PERFORMANCE AND SAFETY TESTING OF CYLINDRICAL MOLI LITHIUM-ION CELLS

NASA Battery Workshop
November 2001

Judith A. Jeevarajan, Yi Deng, Ray Rehm

Lockheed Martin/NASA-JSC

Walt Tracinski,

Applied Power International

Bobby J. Bragg

NASA-JSC

Moli 18650 Li-ion Cell Characteristics

Avg. Weight	Avg. Diameter	Avg. Length	OCV	CCV	Discharge Capacity
42.786 g	18.059 mm	64.973 mm	3.726 V	3.445 V	1.593 Ah (1.65 Ah)

Protective Features:

PTC-Positive Temperature Coefficient

CID-Current Interrupt Device

Shut-down Separator

Vent

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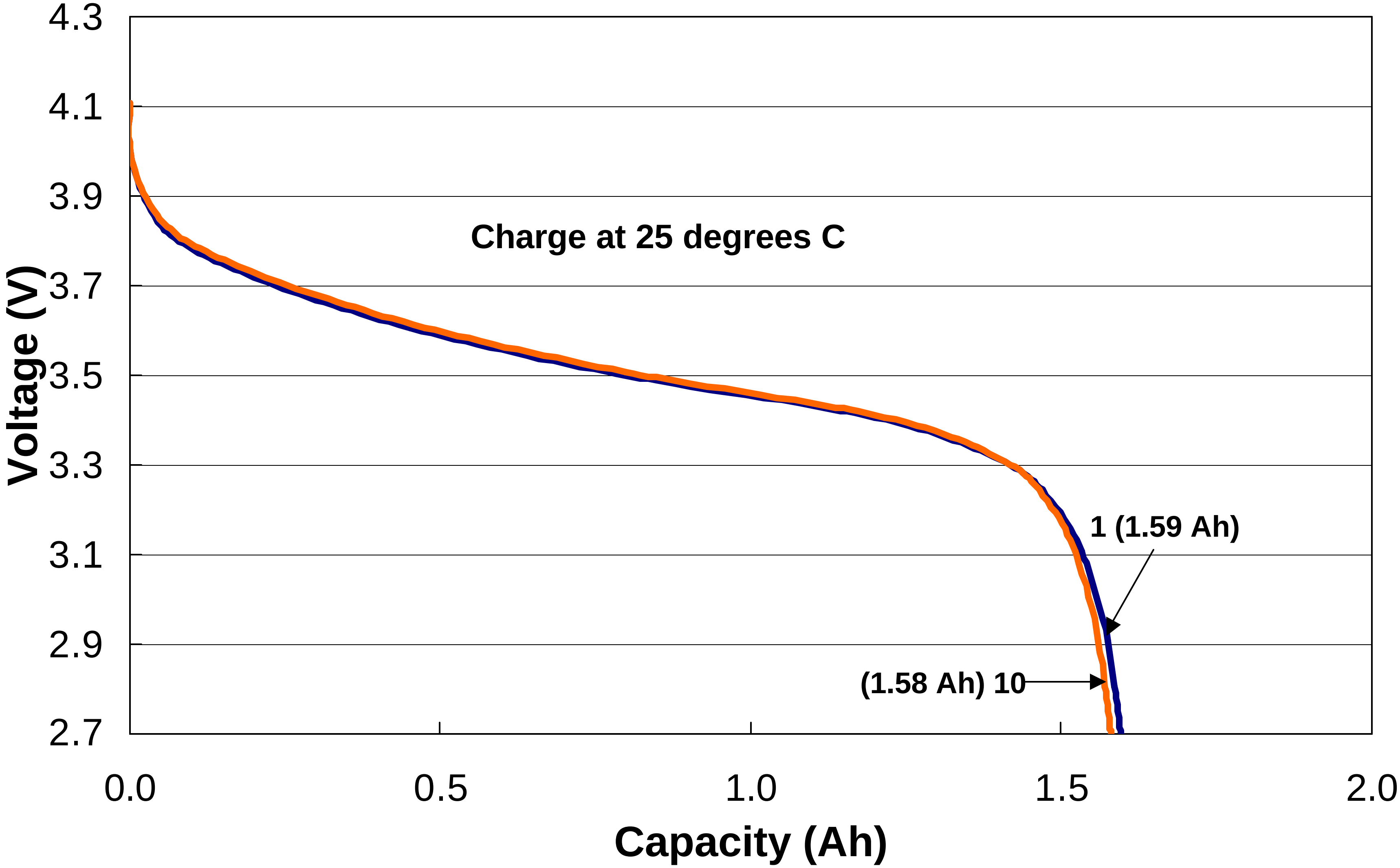
Discharge Capacity for Moli 18650 Li-ion Cell at 25 degrees C
(Charge and Discharge at 1 C Rate)



FORM SEAT 076 (08/26/1997)

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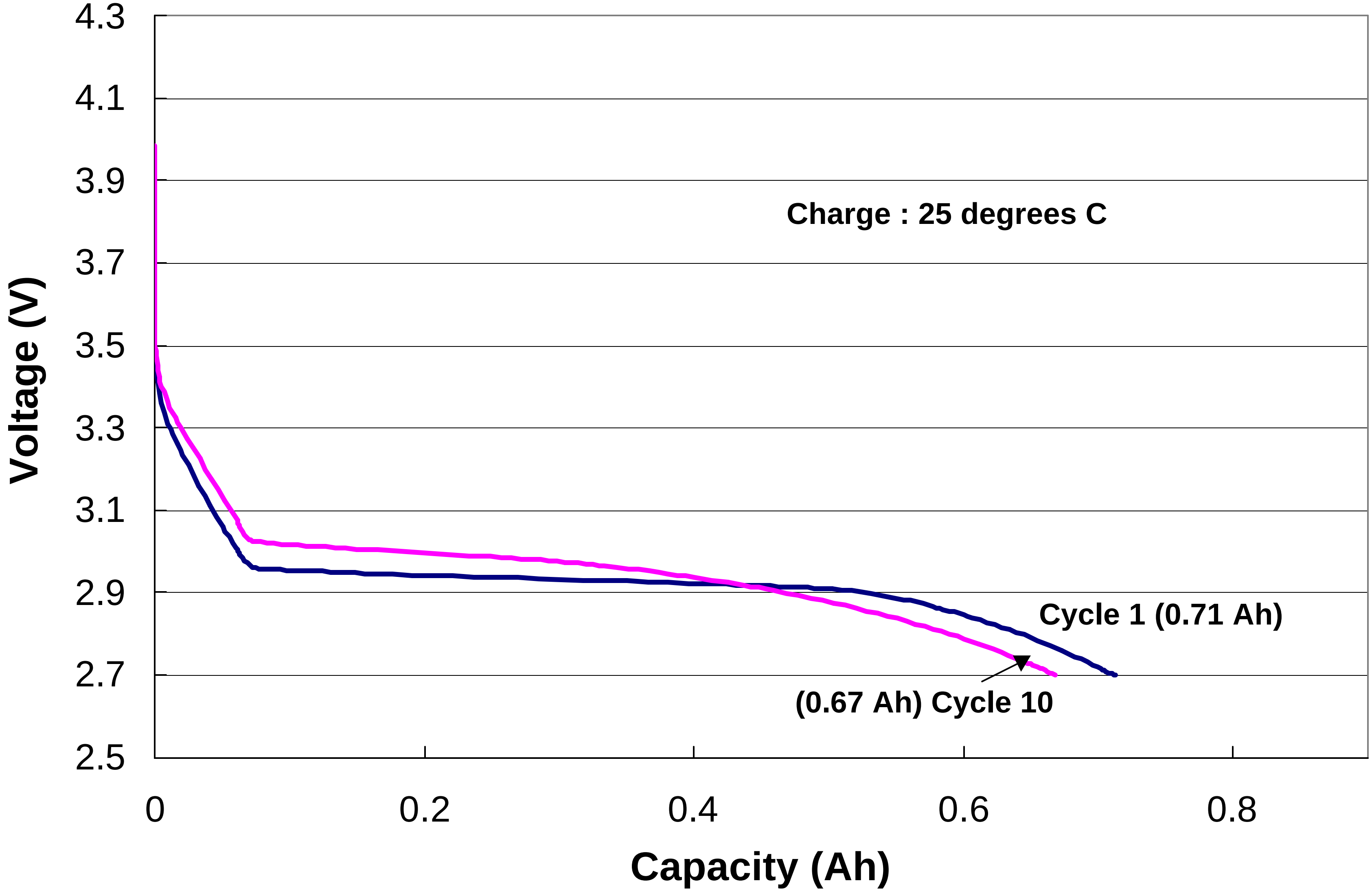
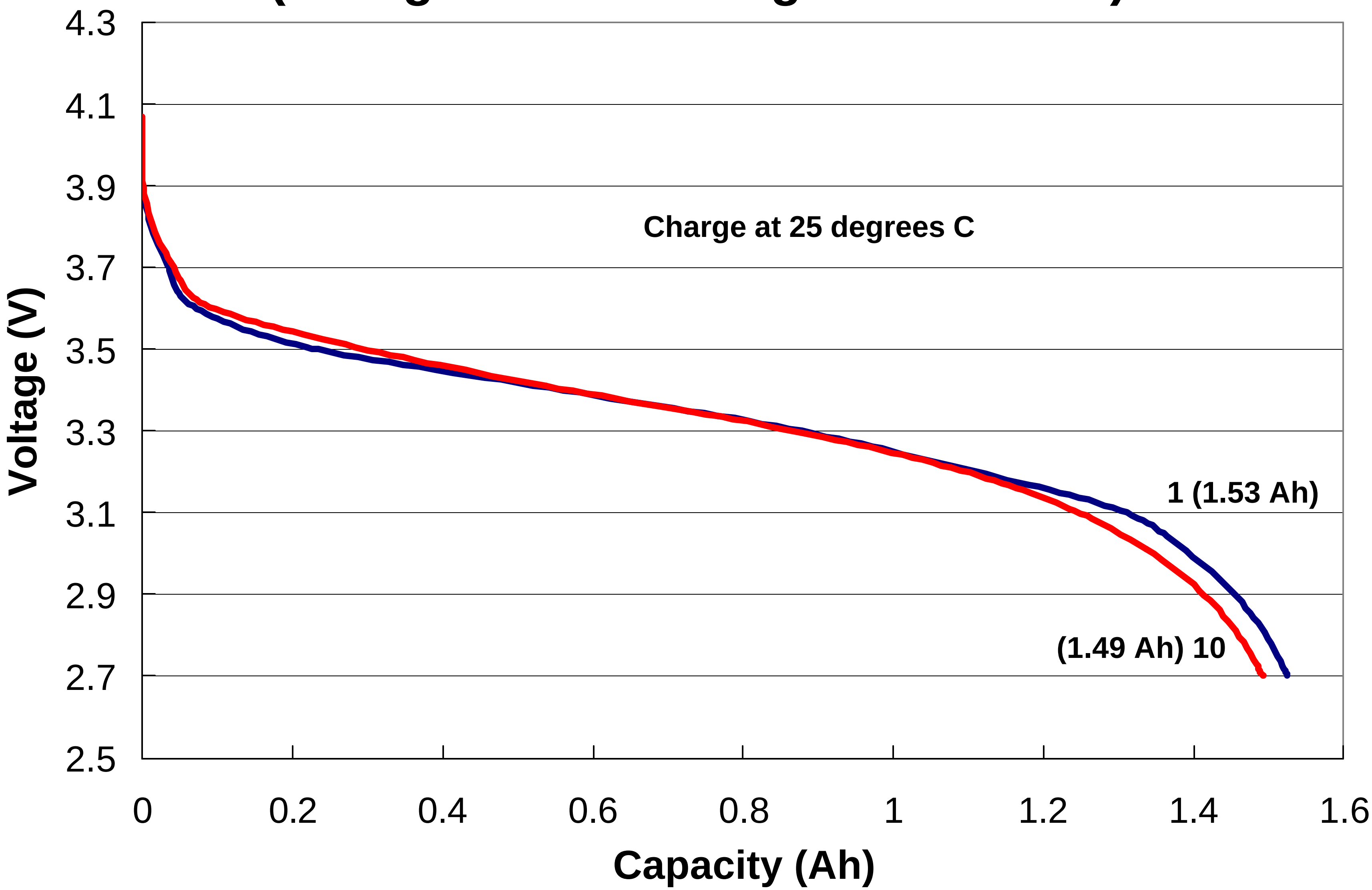
Discharge Cycles of Moli 18650 Li-ion Cell at –10 degrees C (Charge and Discharge at 1 C Rate)

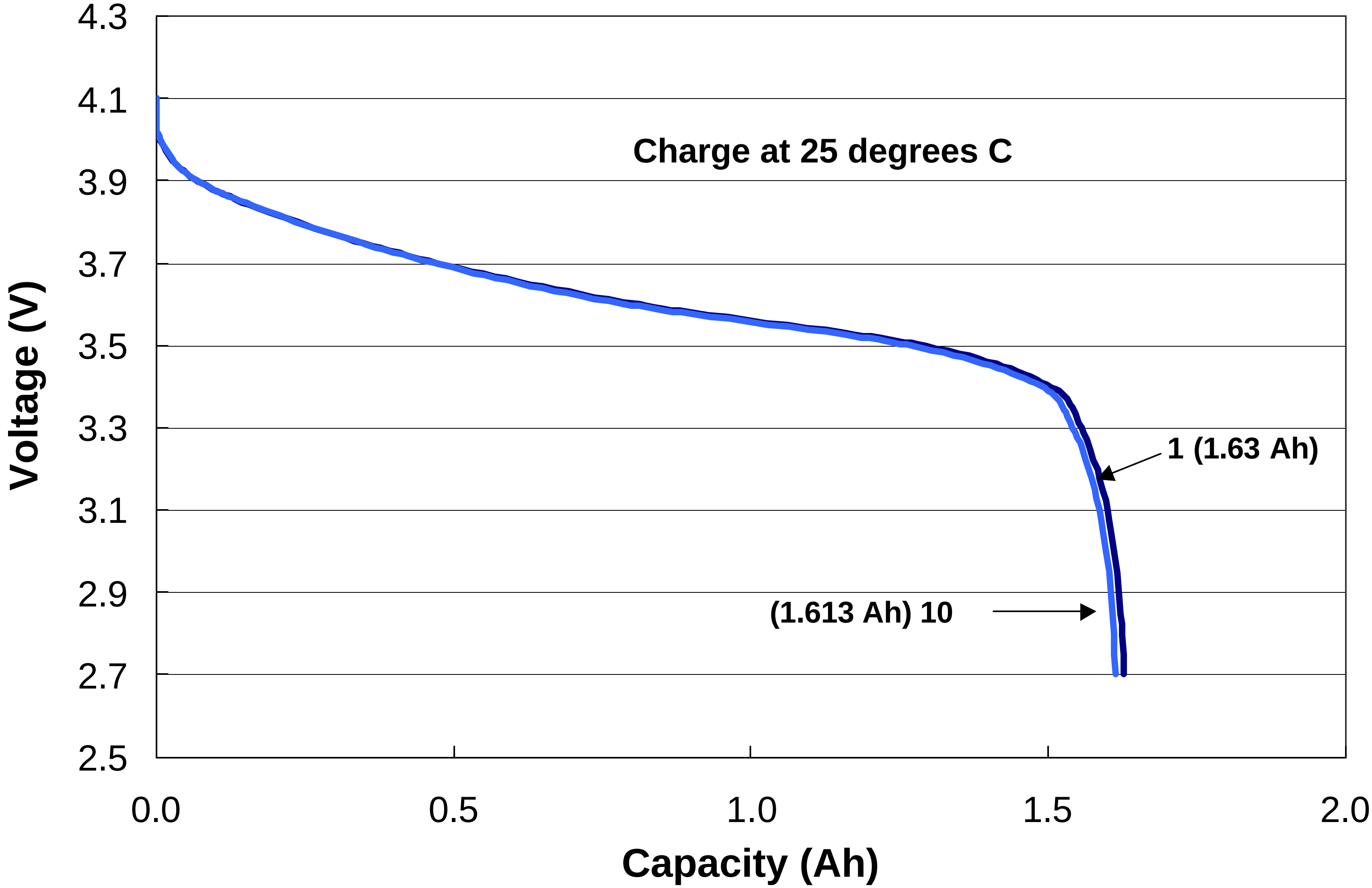


Performance of Moli 18650 Li-ion Cell During Discharge at 10 degrees C (Charge and Discharge at 1 C Rate)



LOCKHEED MARTIN

Performance of Moli 18650 Li-ion Cell at 45 degrees C (Charge and Discharge at 1 C Rate)



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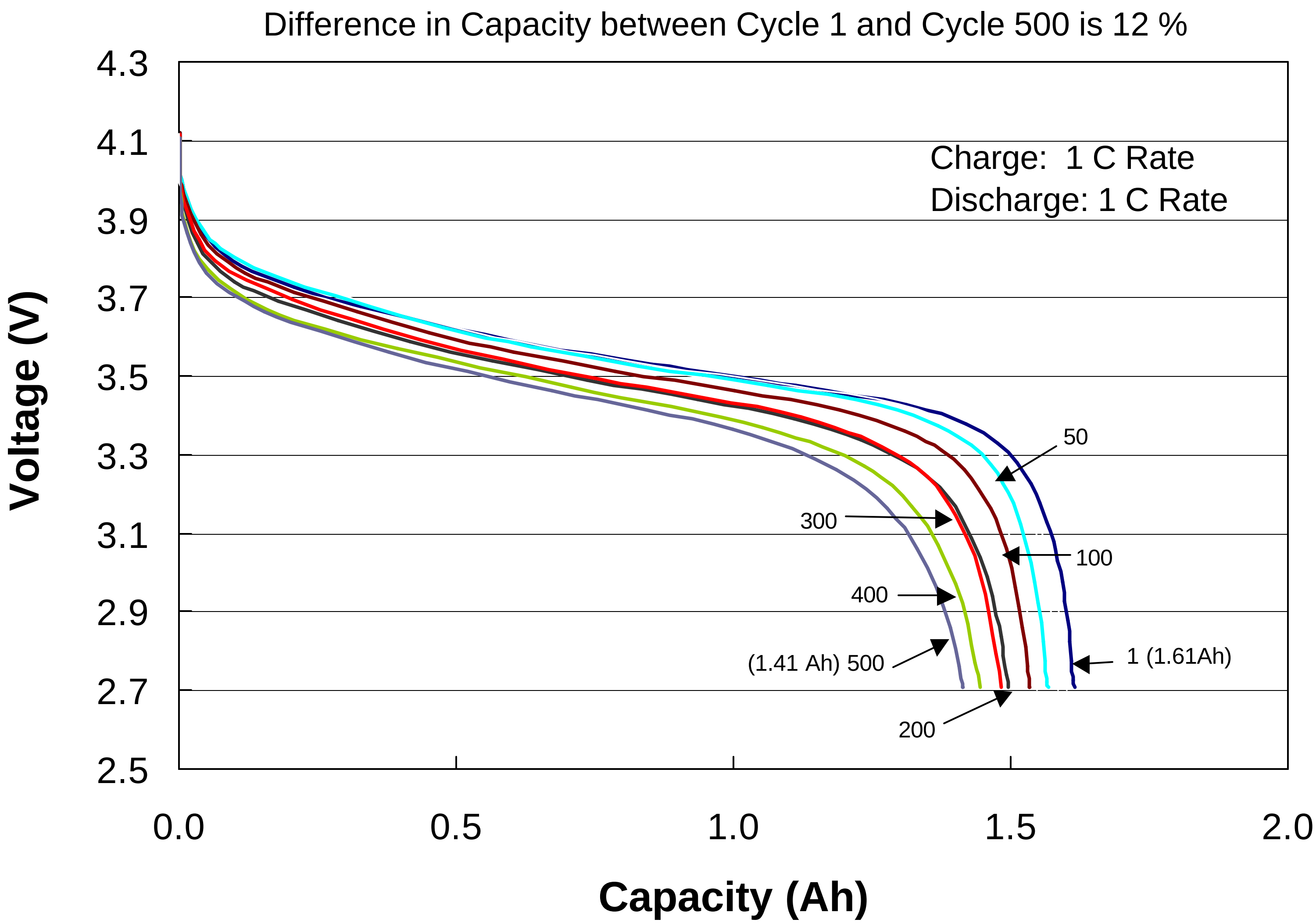
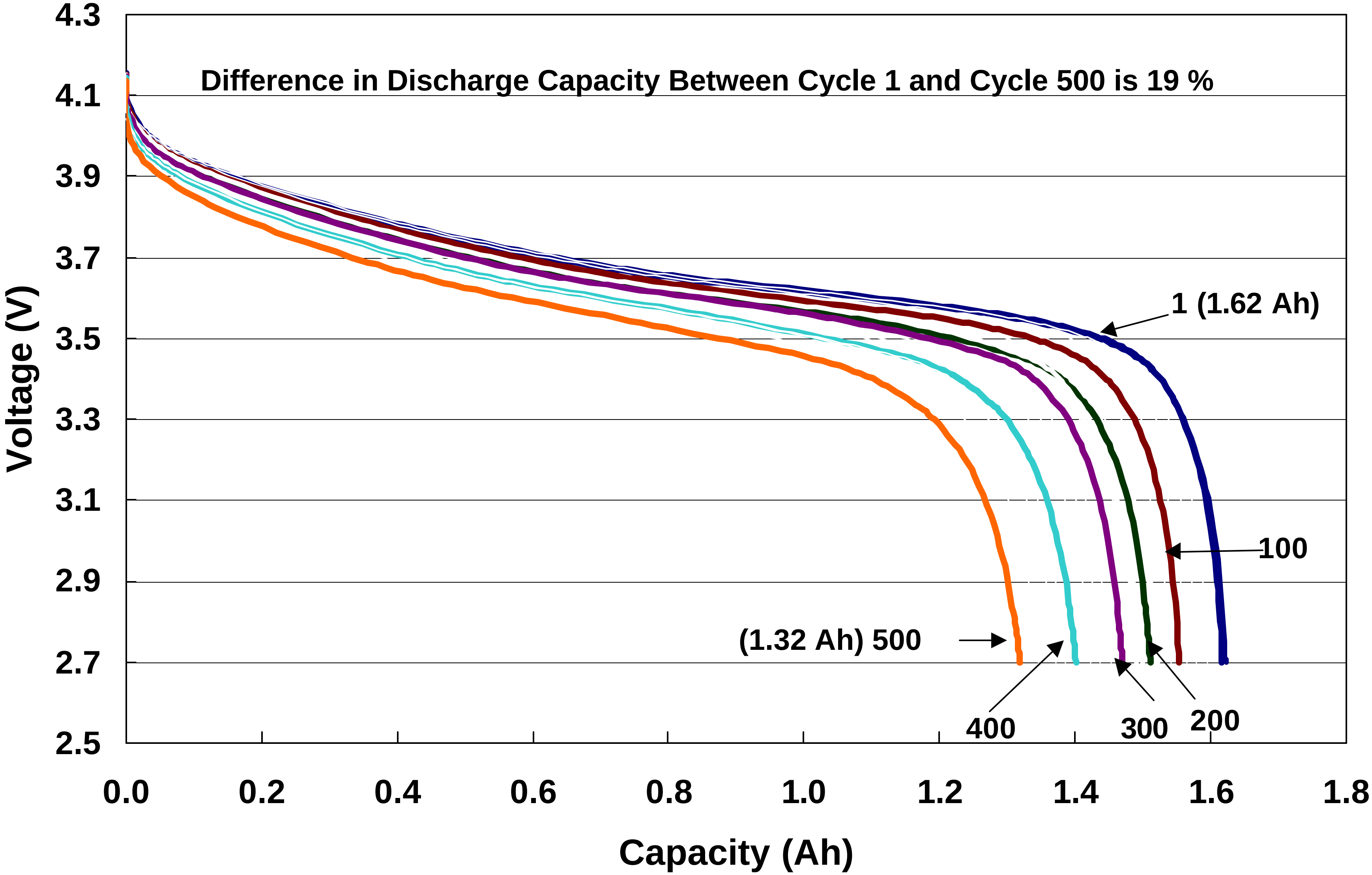
Cycle Life Test on Moli 18650 Li-ion Cell
(Temperature = 25 degrees C)



LOCKHEED MARTIN

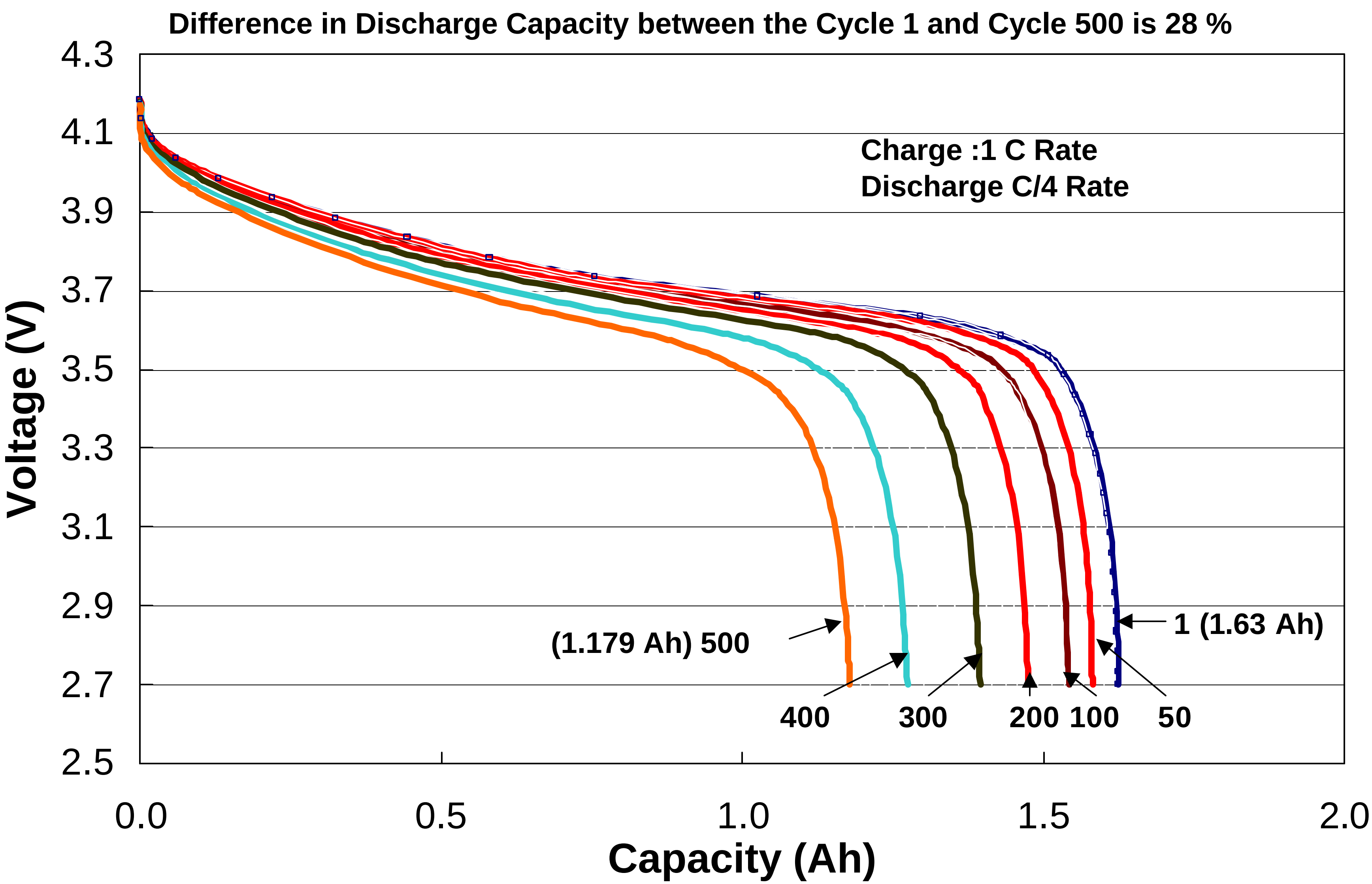
Cycle Life Test of Moli 18650 Li-ion Cell
Discharge Capacities at 1C Charge and C/2 Discharge
(Temperature = 25 degrees C)



FORM SEAT 076 (08/26/1997)

LOCKHEED MARTIN

Cycle Life Test for Moli 18650 Li-ion Cell
(Temperature = 25 degrees C)



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Characteristics of the Moli 18650 Li-ion Cell at Different Rates of Charge and Discharge at Room Temperature

Cycle Number	Charge Rate	Discharge Rate	Capacity	Difference
1 500	1C 1C	1C 1C	1.613 Ah 1.413 Ah	12 %
1 500	1C 1C	0.5 C 0.5 C	1.622 Ah 1.319 Ah	19 %
1 500	1C 1C	0.25 C 0.25 C	1.626 Ah 1.179 Ah	28 %
1 500	0.5 C 0.5 C	1C 1C	1.582 Ah 1.368 Ah	13.5 %
1 500	0.5 C 0.5 C	0.5 C 0.5 C	1.593 Ah 1.423 Ah	11 %
1 500	0.5 C 0.5 C	0.25 C 0.25 C	1.599 Ah 1.452 Ah	9 %

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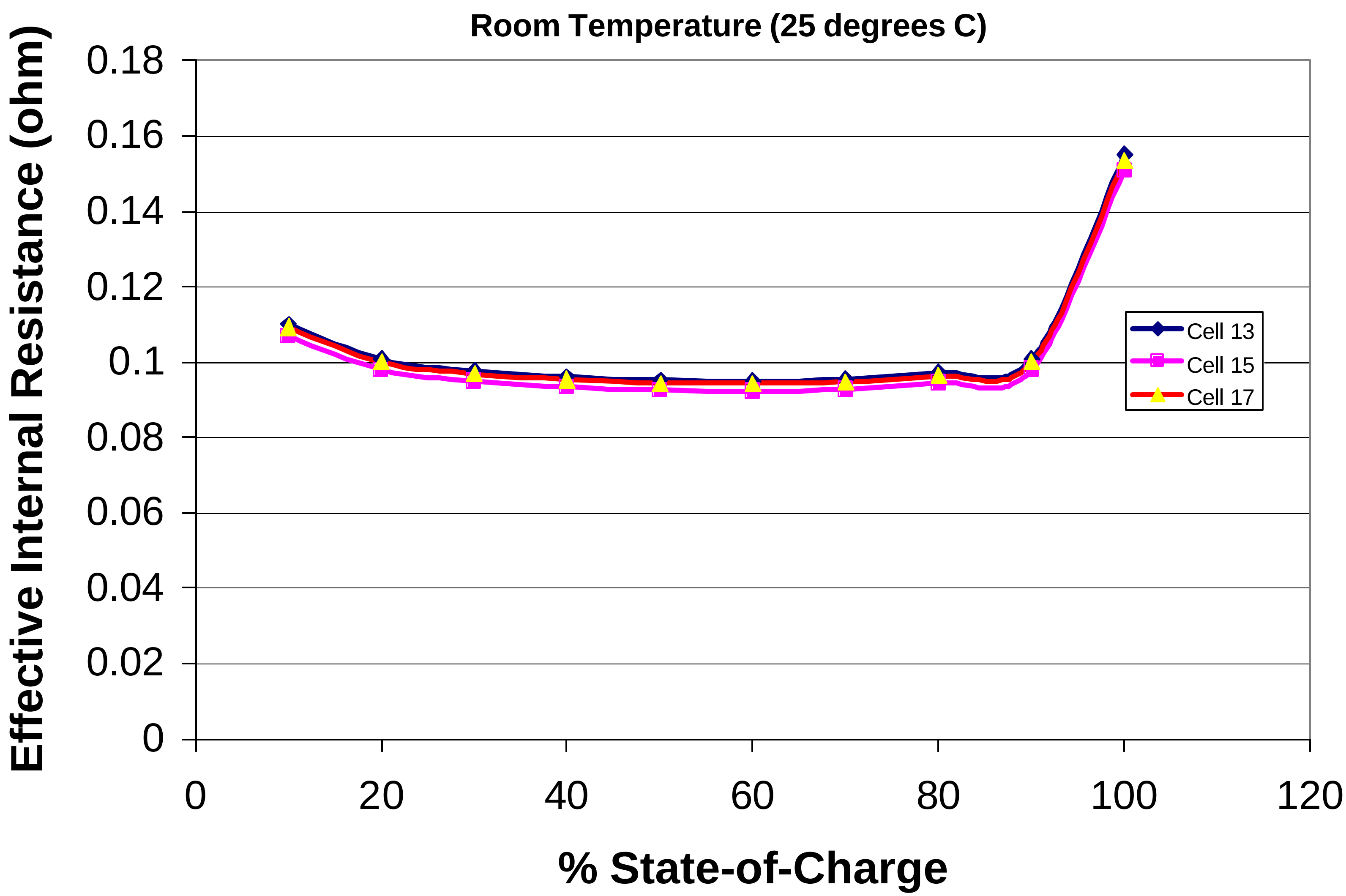
Effective Internal Resistance Characteristics for the Moli 18650 Li-ion Cell



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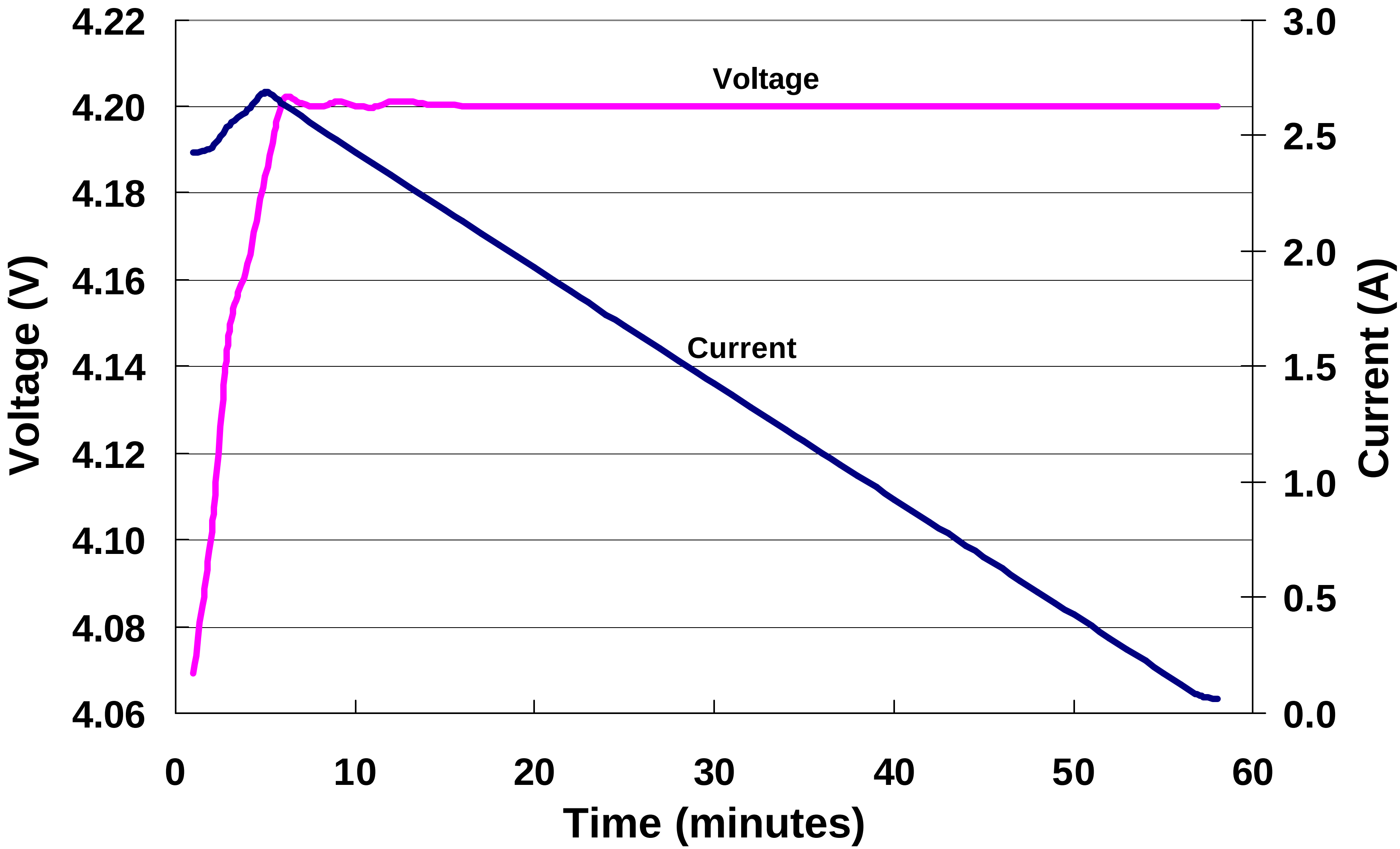
Fast Charge of Moli Li-ion 18650 Cell using a 3 C Current to 4.2 V



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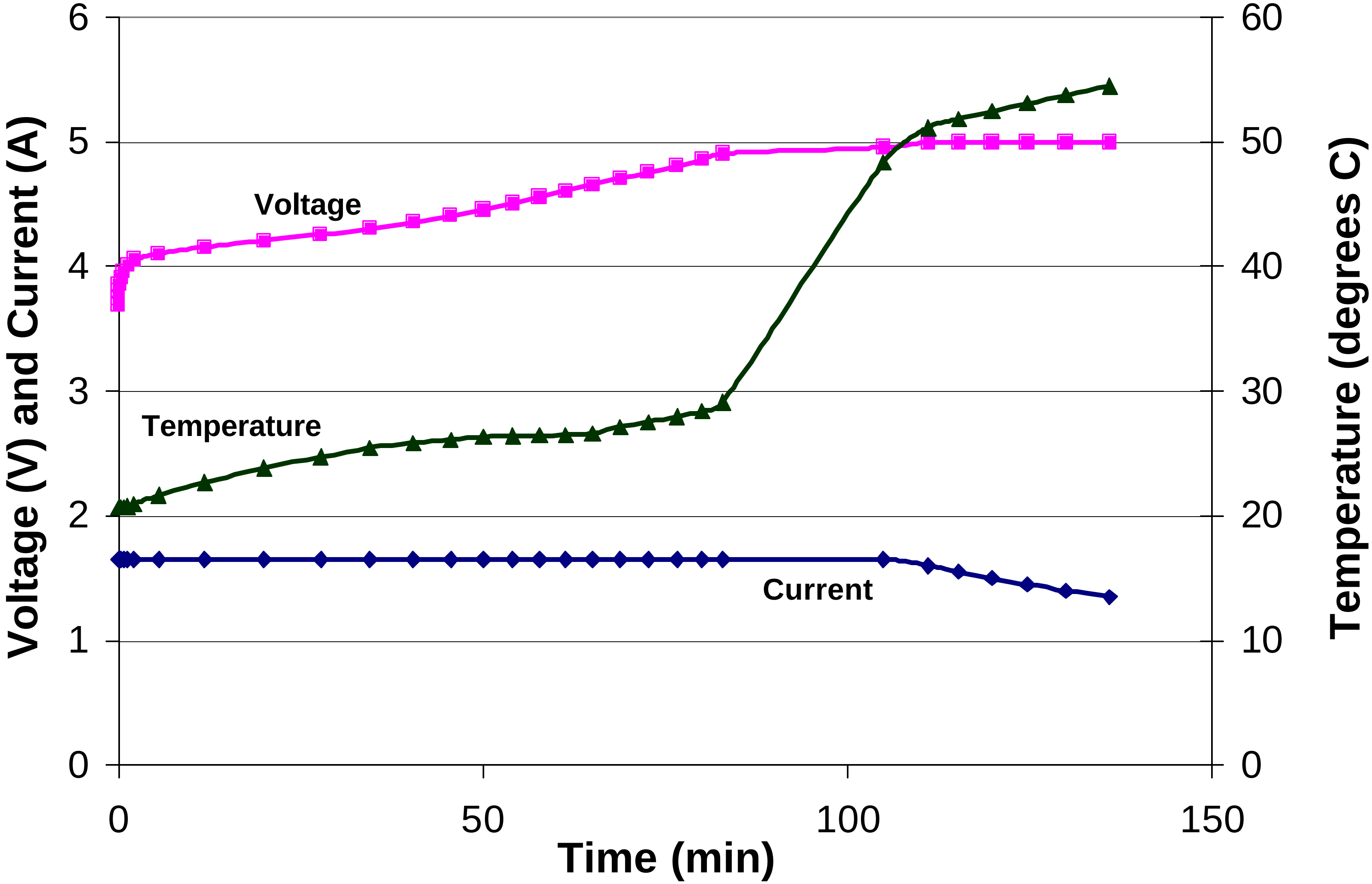
Overcharge of Moli 18650 Li-ion Cell to 5.0 V at 1 C Rate



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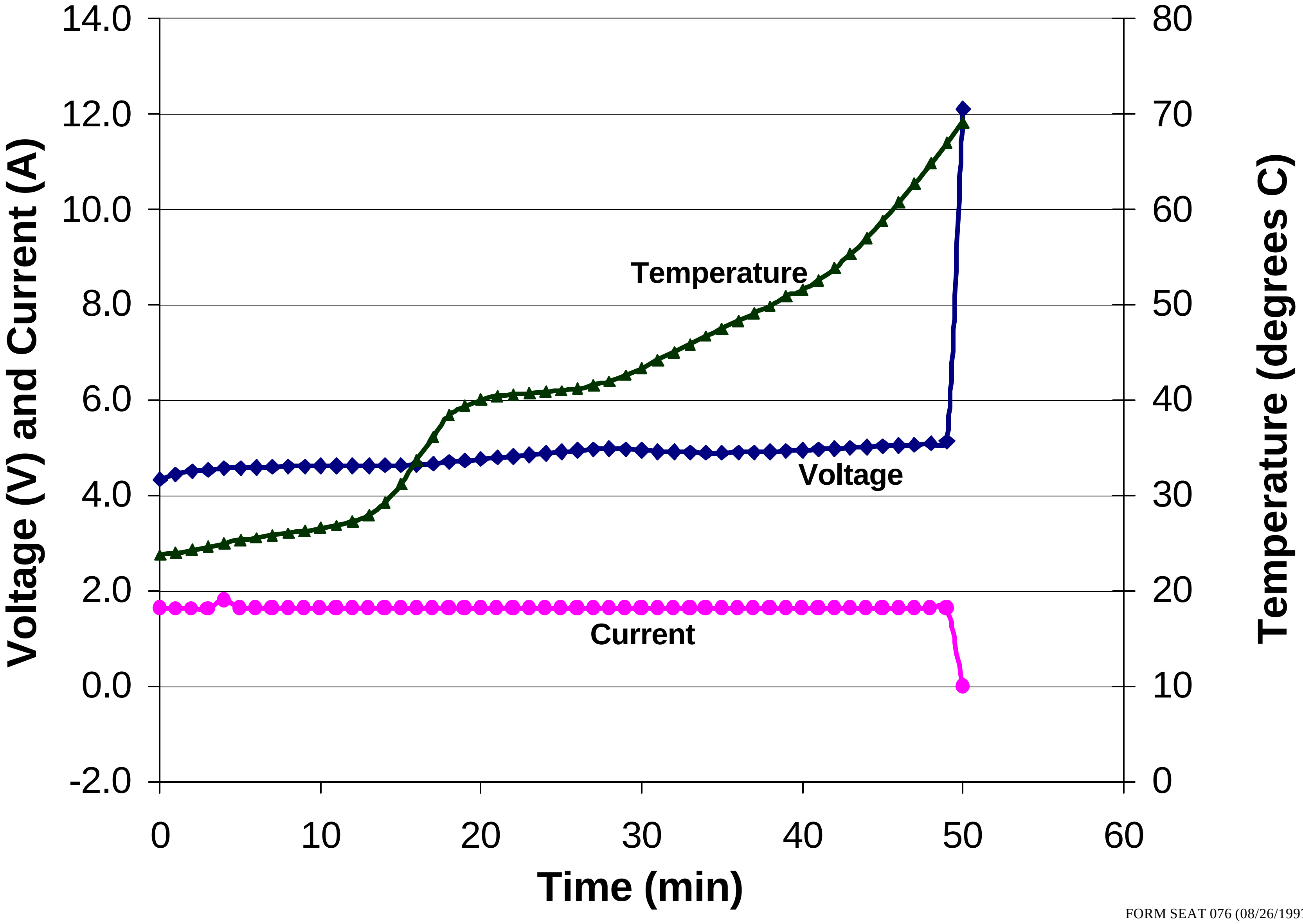
Overcharge Test of Moli 18650 Li-ion Cell to 12 V for 50 Minutes at 1C Rate



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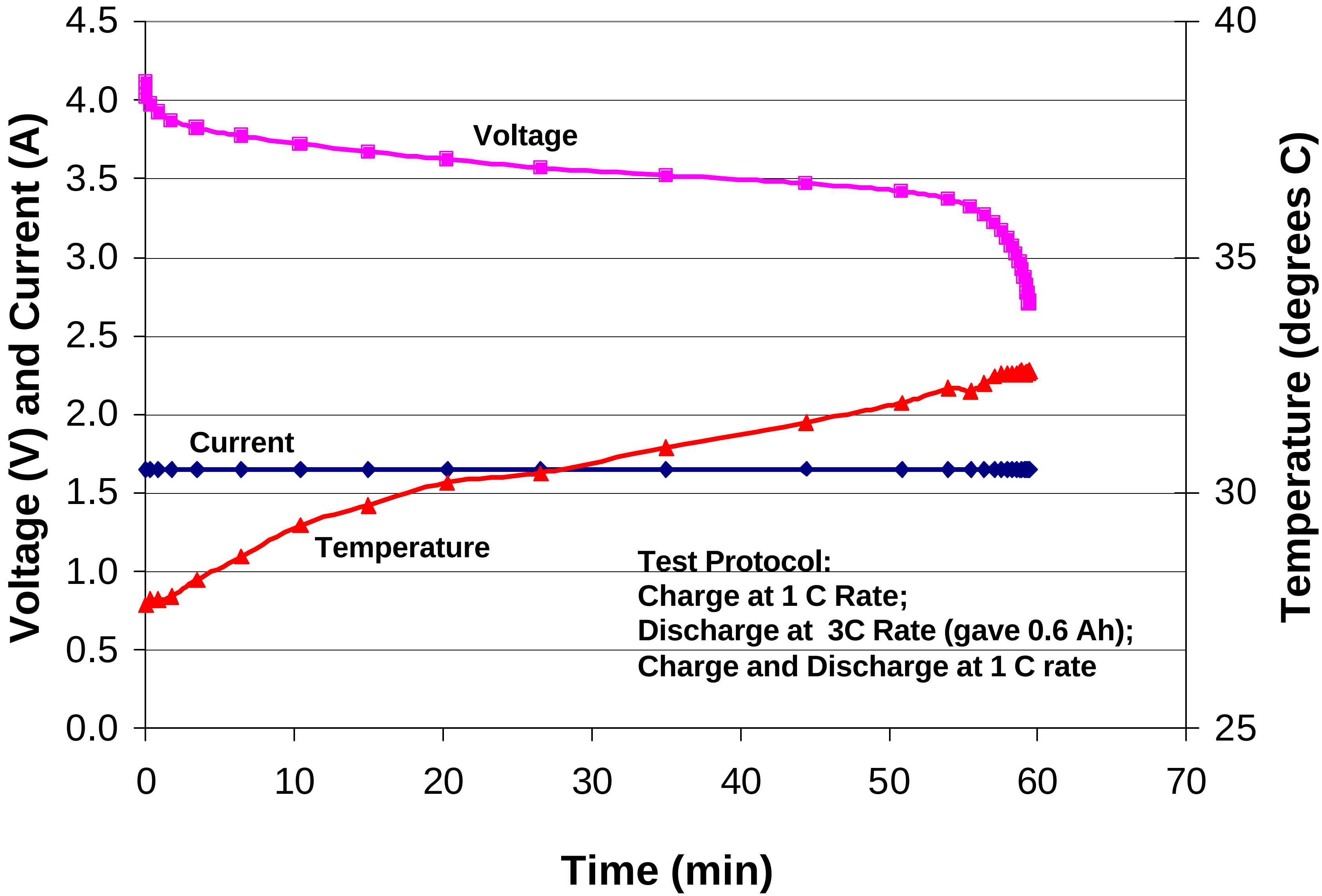
Discharge Cycle after Fast Discharge of Moli 18650 Li-ion Cell Using a 3 C Rate



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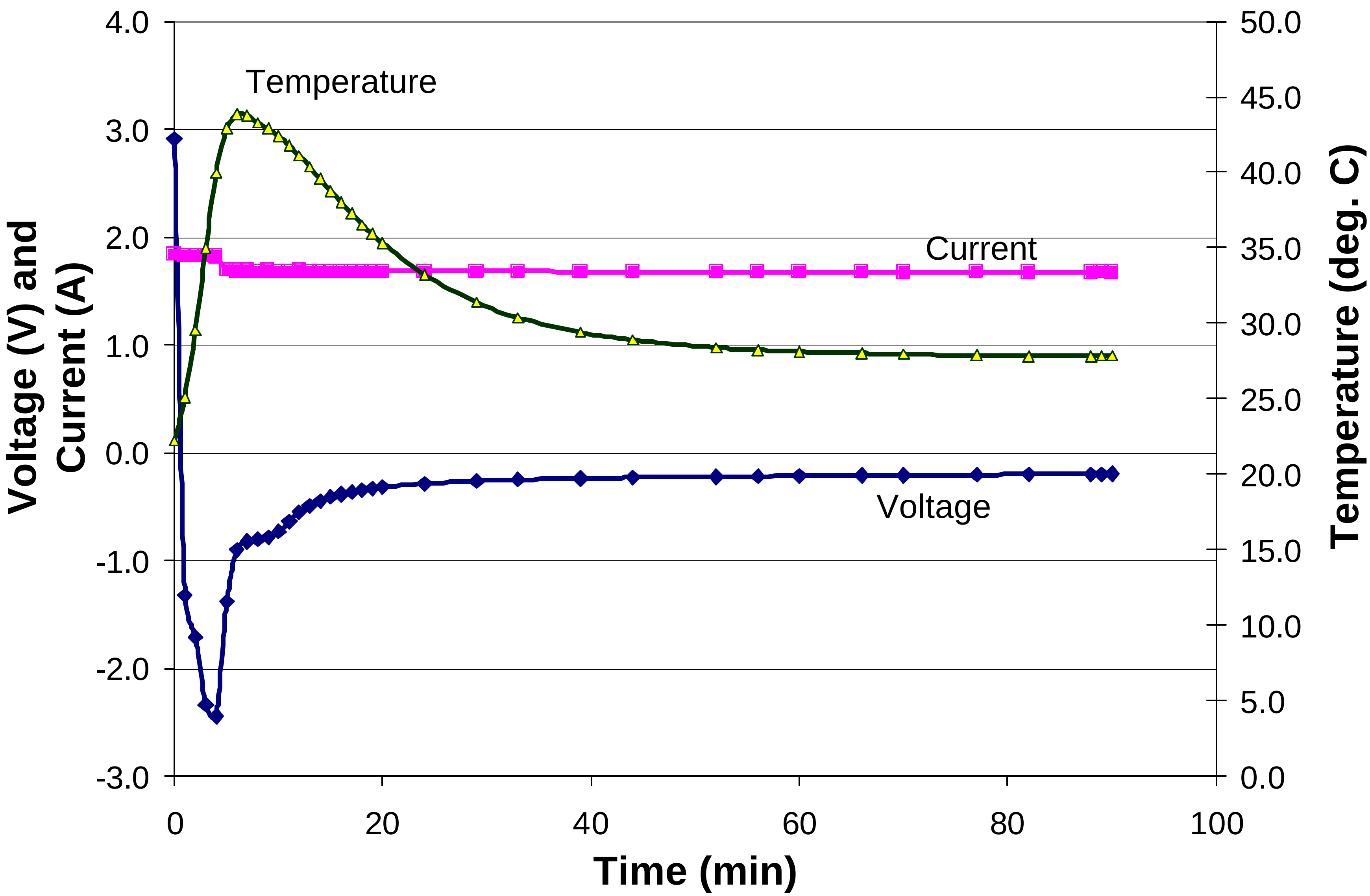
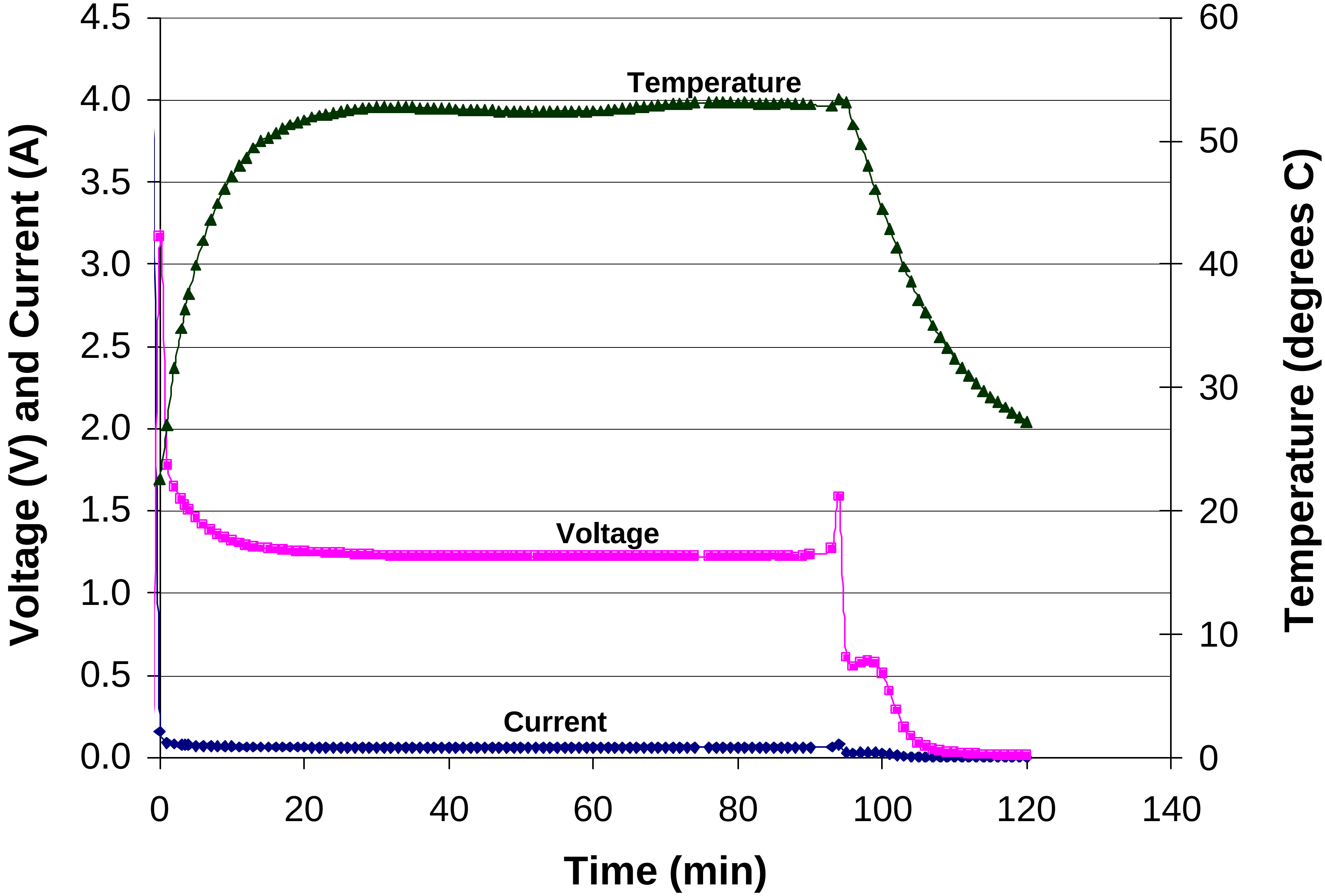
Overdischarge into Reversal of Moli 18650 Li-ion Cell

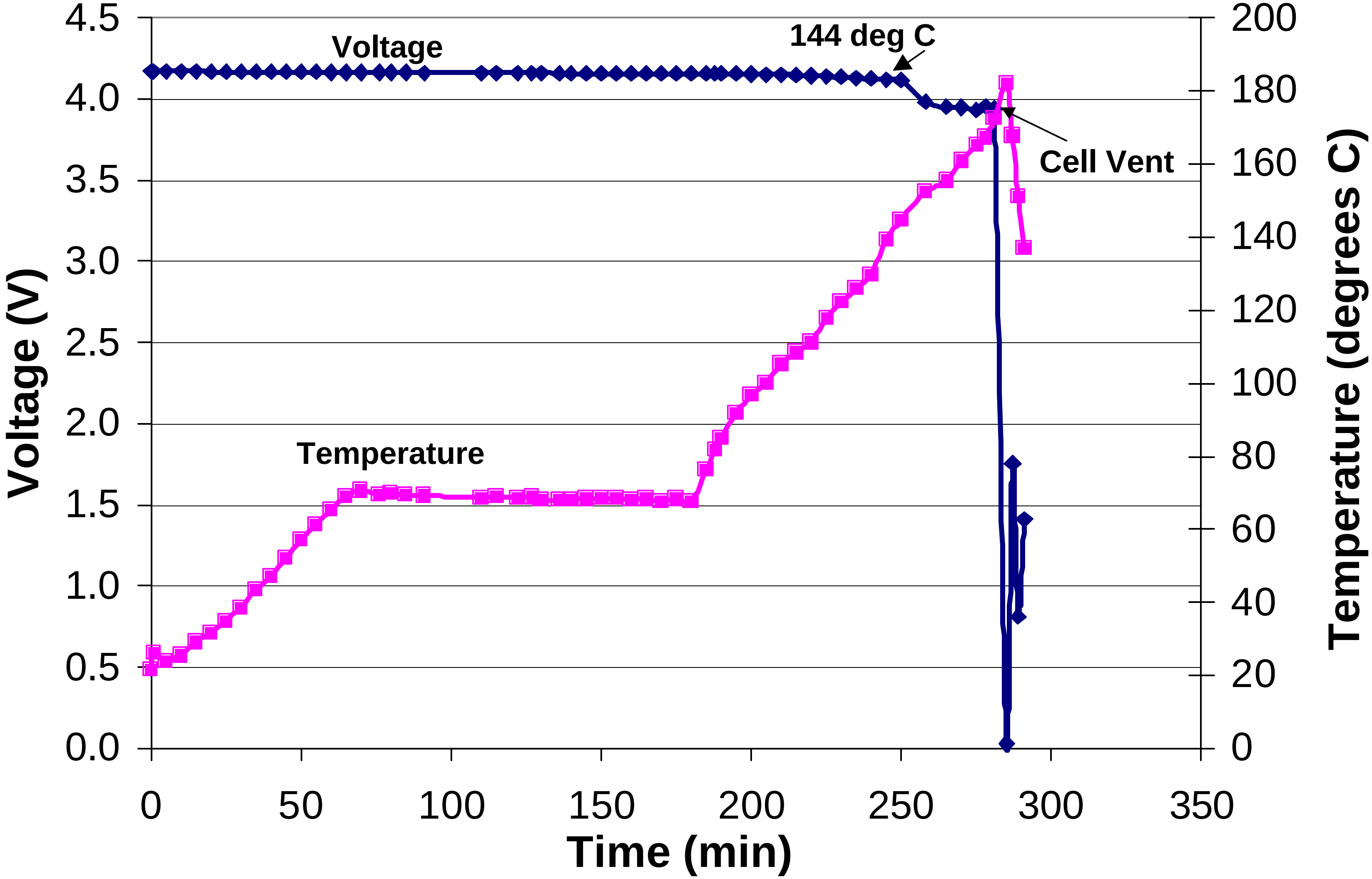


LOCKHEED MARTIN

External Short Circuit Test of Moli 18650 Li-ion Cells with 50 mOhms



Heat-to-Vent Test for Moli 18650 Li-ion Cell



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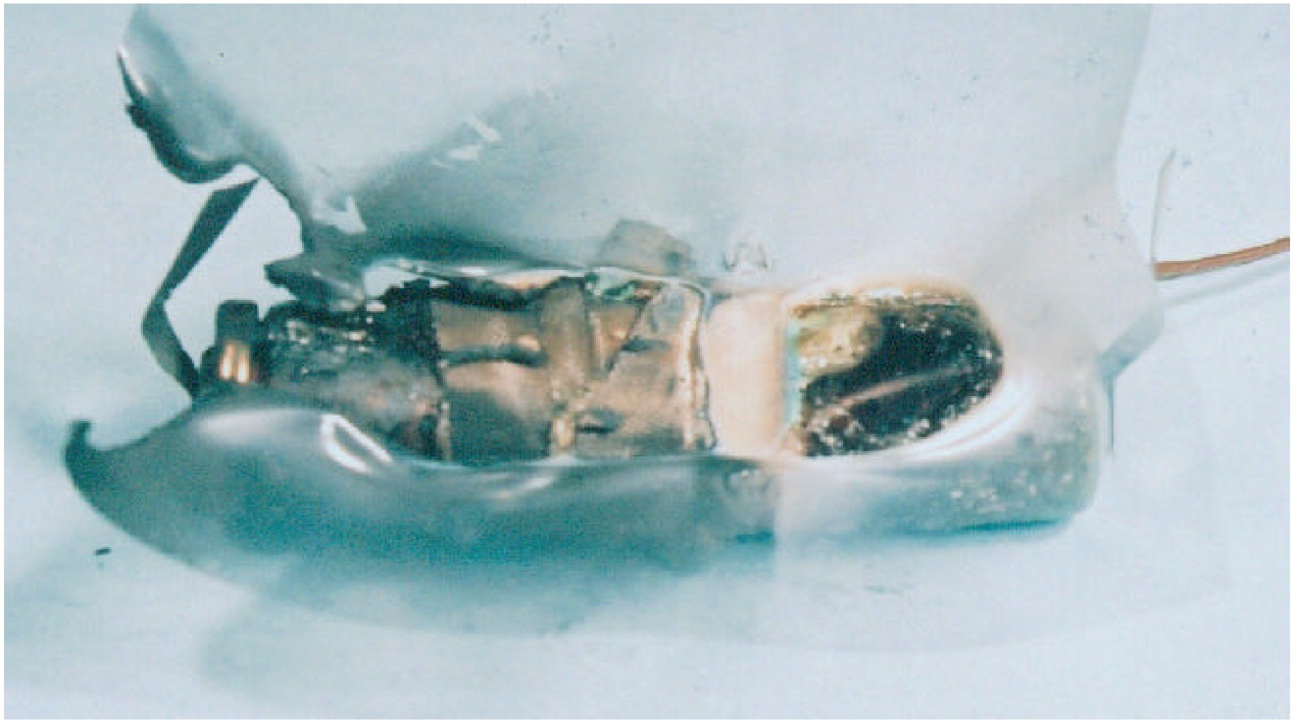
Heat-to-Vent Test of Moli 18650 Li-ion Cell

Cell that exhibited the worst case results

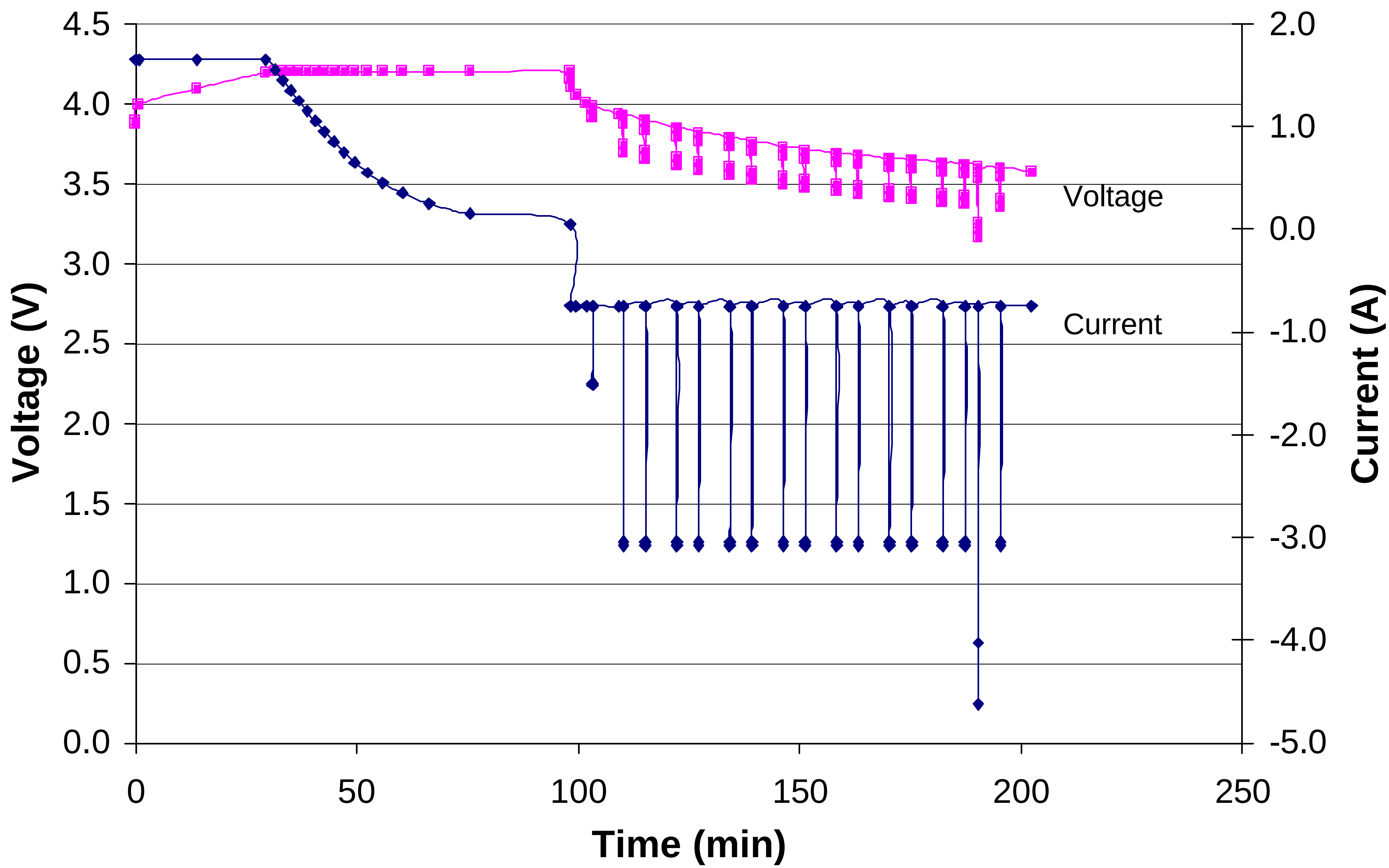
Simulated Internal Short Test of Moli 18650 Li-ion Cell

- Results dependent on nature of crush.
- Light crush did not cause any significant venting.
- Heavy crush caused significant venting with smoke and a small fire (no explosions).



LOCKHEED MARTIN

Moli 18650 Li-ion Cell Tested Using an EAPU Profile



Vibration Test for the Moli 18650 Lithium-Ion Cell

Frequency	Level
20-80 Hz	+3 dB/octave
80-350 Hz	0.1 g^2/Hz
350-2000 Hz	-3 dB/octave

- The Moli cells were subjected to the above vibration levels for 15 minutes in each of the independent x, y and z axes.
- Less than 5% changes in capacities recorded before and after the vibration was observed.

CONCLUSIONS

- The Moli lithium-ion cells were tested under normal and abuse conditions.
- The cells exhibit only 50 % of their original capacity at about –10 degrees C .
- The optimum charge discharge rate with the least percentage loss in capacity is C/2 charge and C/4 discharge.
- The cells did not explode or go into a thermal runaway during venting at very high temperatures.
- The cells exhibited good tolerance under the vibration conditions tested.
- The cells could potentially be used in the build up of large batteries that have high current pulse (up to 3C) applications.

ACKNOWLEDGMENT

Walt Tracinski – Applied Power International

Gerald Steward- NASA-JSC

Anita Thomas-Lockheed Martin/NASA-JSC

Pulse performance of Small Lithium Ion Cells

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Abstract

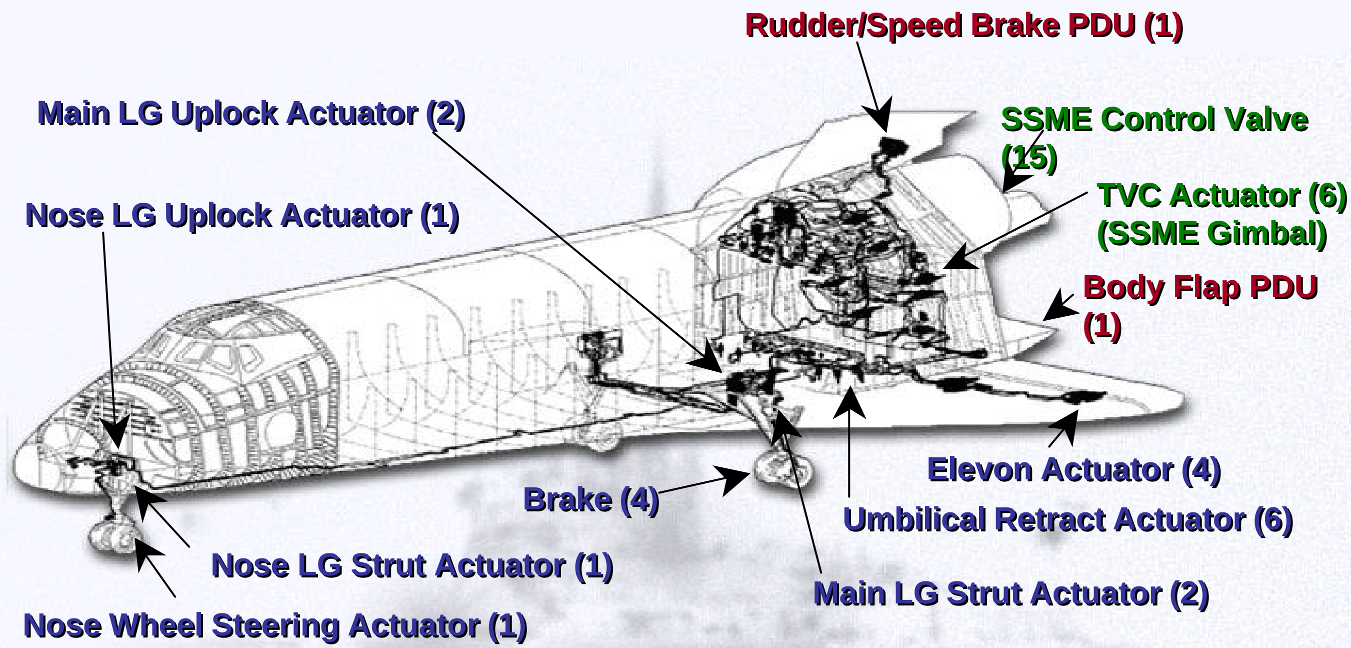
Five types of small commercial cells were subject to capacity and resistance measurements under pulsed conditions and under a worst case application conditions. Results indicate that an 82S-102P array of 18650 cells will exceed the power/energy requirements for a proposed Space Shuttle EAPU battery system.

EAPU Subsystem Summary

- Currently a hydrazine-fueled turbine-driven unit drives the Shuttle hydraulics.There are three redundant systems.
- Drives: thrust vectoring, propellant valves, body flaps, landing gear, nosewheel steering …
- Required during launch and de-orbit.
- NASA is looking at alternative battery solutions.
  - Safety
  - Reliability
  - Cost

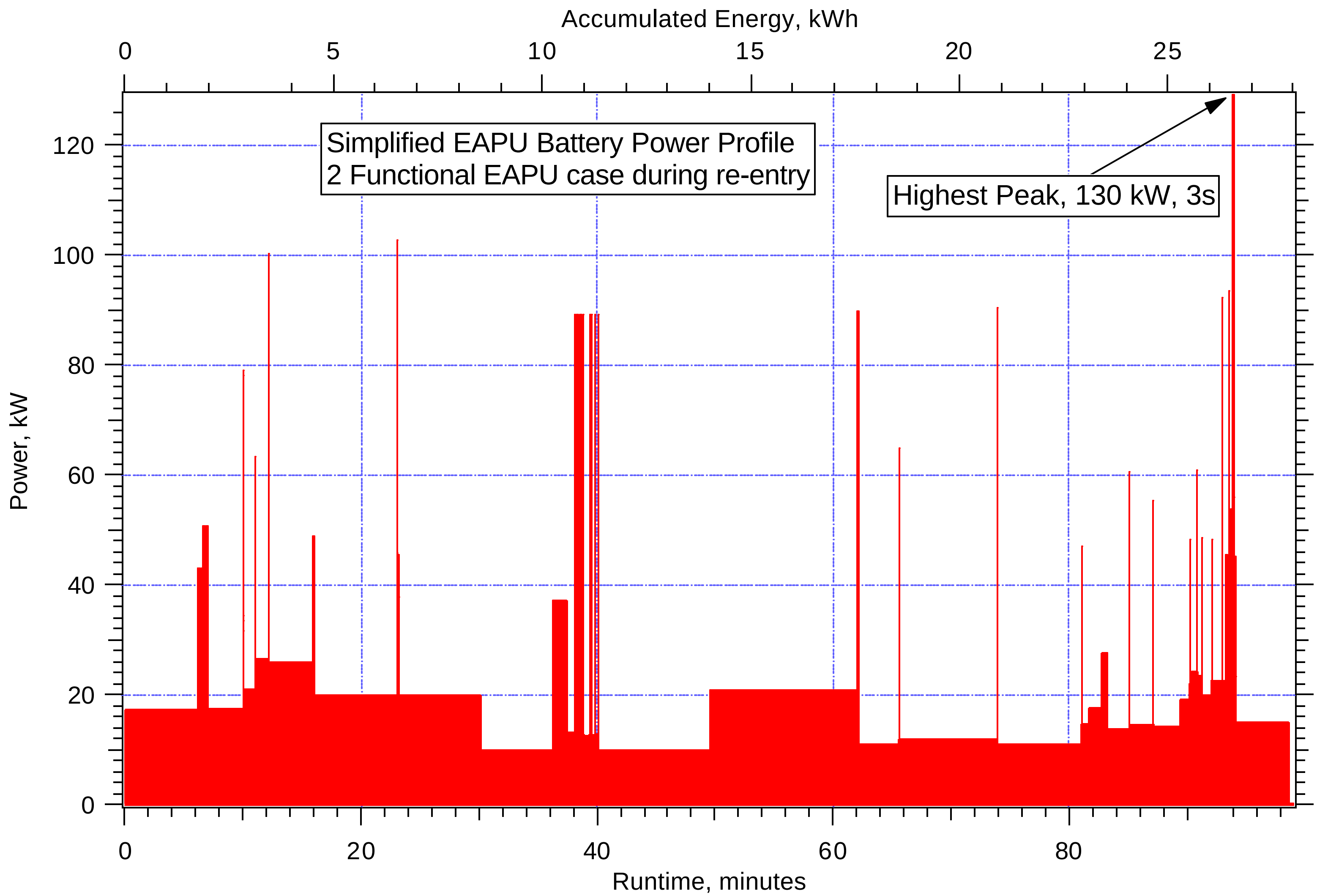
APUs Are Critical To Flight Control

41 Orbiter Flight Control and Auxiliary Actuators

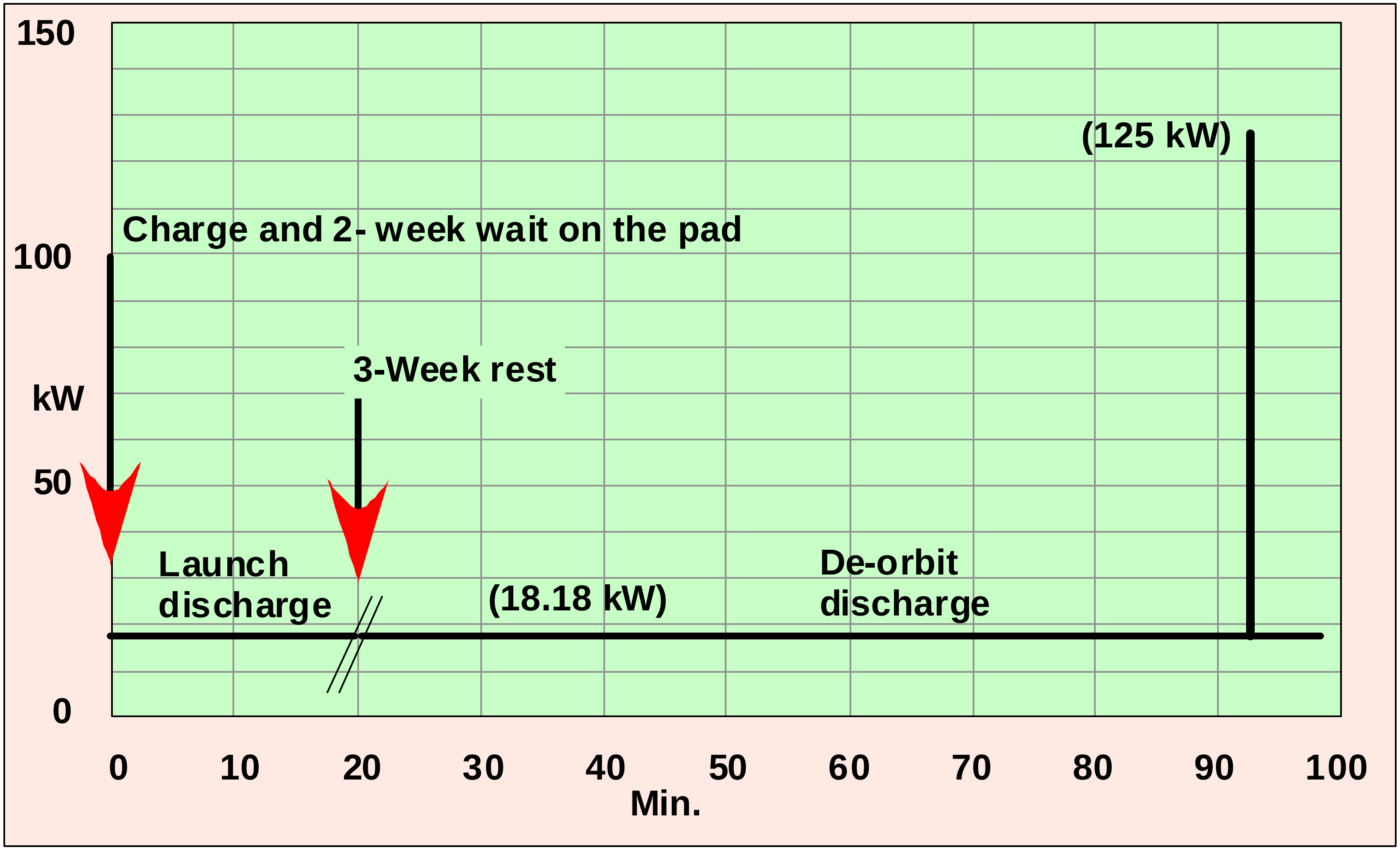


Catastrophic failure can occur during ascent or entry unless 2 of the 3 APUs are functioning perfectly

Latest Worst Case Mission Profile



Simplified Mission Profile Used



Cell Parameters Tested

- Self-discharge
- Mission performance (using the simplified profile)
- Capacity (to 4.4V)
- Series resistance in pulse conditions

Prior to this, a preliminary sizing analysis indicated that the EAPU power/energy requirements could be met with at minimum a 82S x 102 P array of Sony 18650 HC lithium ion cells. This allowed the battery requirements to be scaled to single-cell level.

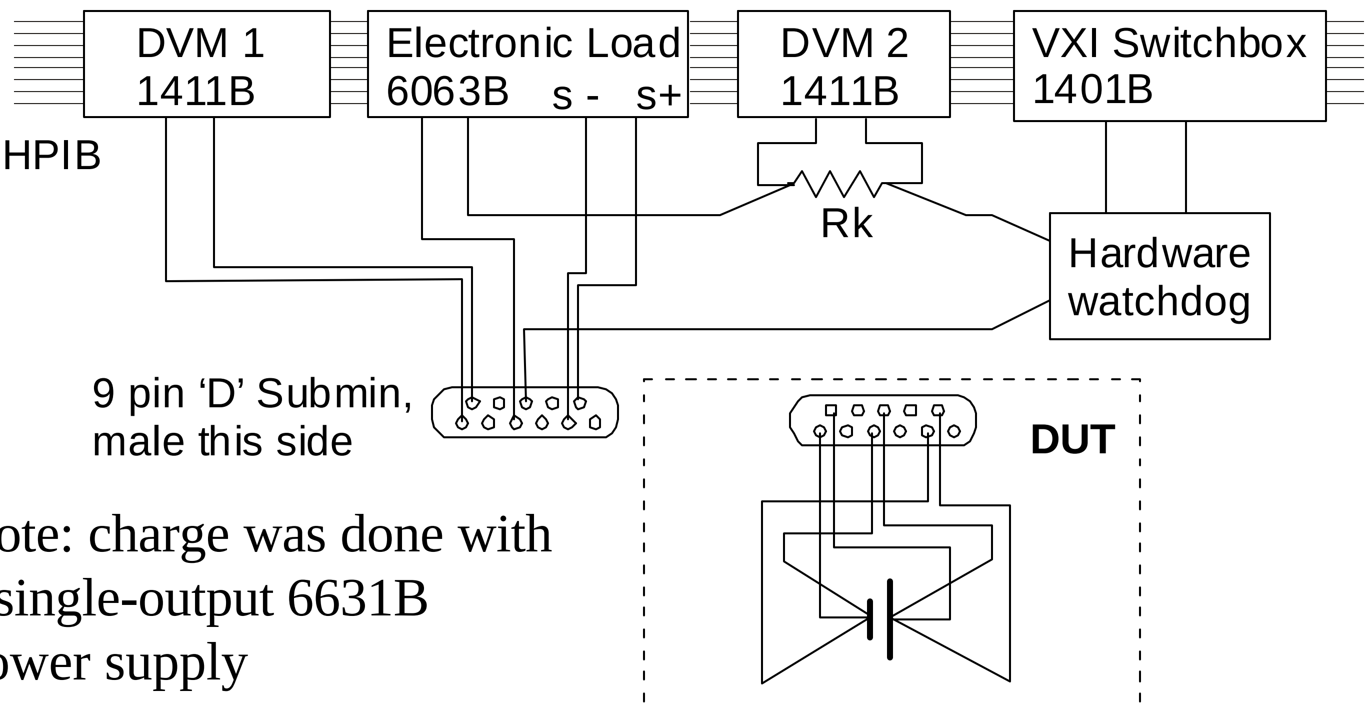
Battery - Cell Requirements

Parameter	Battery	Cell
S-series	82	1
P-Parallel	102	1
No. of cells	8364	1
Voltage range	205 - 360.8	2.5 - 4.4
Mass*	393 kg	0.0409 kg
Average discharge power	18.18 kW	2.17 W
Pulse power	125 kW	14.95 W
Min spec. voltage	230 V	2.805 V

*with a 1.16 parasitic mass factor assumed

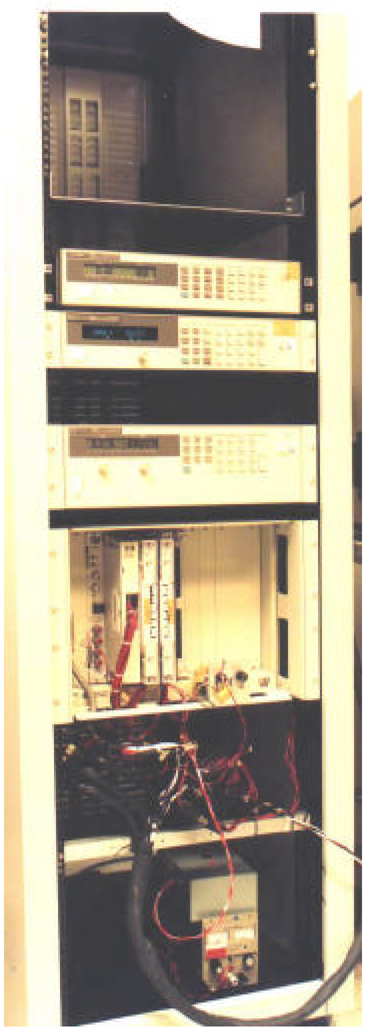
Test Set-Up

- Based on an existing test rig at COM DEV.
- Agilent (HP) equipment, 'VEE' test software.



Note: charge was done with a single-output 6631B power supply

Test Equipment



This test rack contains two power supplies 120 and 4A and 8V 10A, electronic load and the VXI rack which houses two precision digital voltmeters, a 64 channel switch multiplexer and four 32 channel switch cards. There is spare capacity for two more cards if expansion were required.

Kilovac relays are used to provide high current-switching capability.

Not shown are dumb loads and associated switches, and a PC with the Agilent 'VEE' software.

Two uninterruptible power supplies are used which have maintained operation up to 30 minutes. One long outage produced a graceful shutdown with all cell/battery connections open circuit.

The aim of the test rack was to provide a versatite, quickly reconfigurable facility for development work.

Test Cells and Test Plan

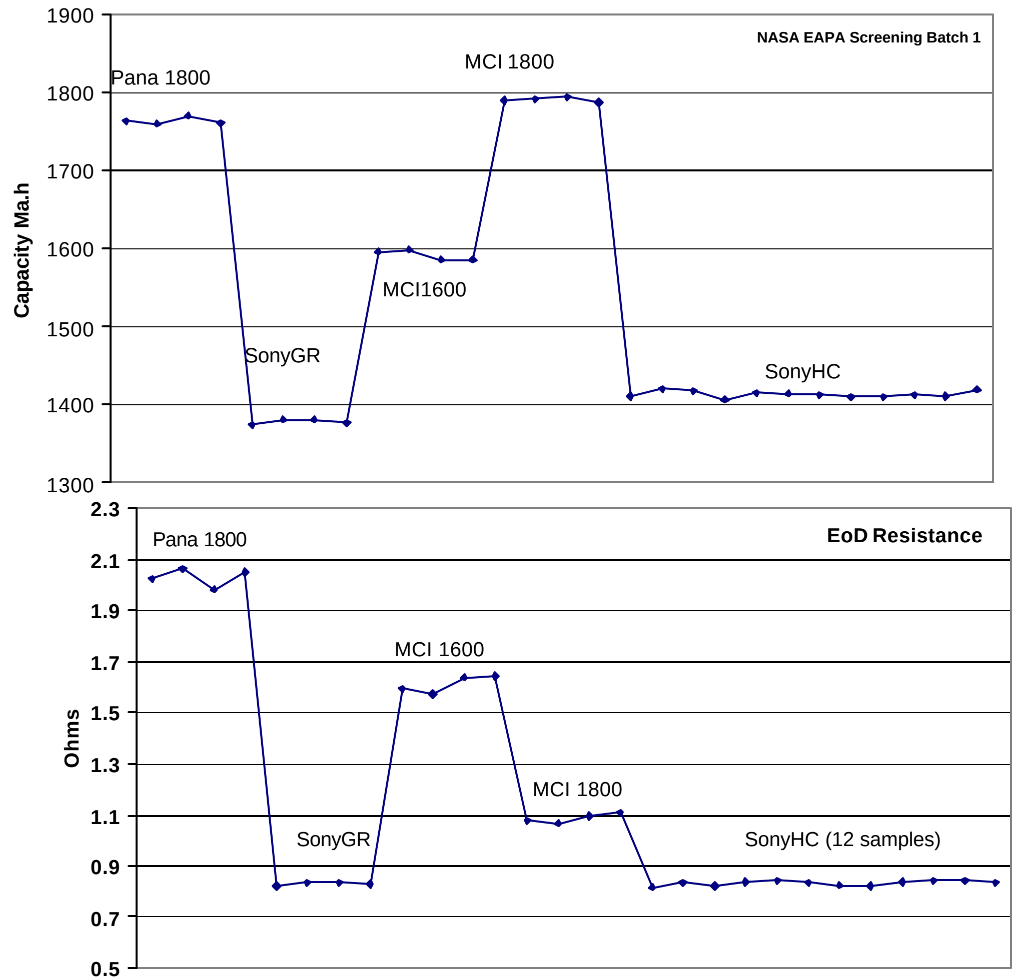
- Sony Hard Carbon, 1500 mAh,which has been our ‘standard’
- Sony Graphite 1500 mAh
- MCI 1600 mAh
- MCI 1800 mAh
- Panasonic 1800 mAh
- Tests were:
  - Initial screening with C/10 discharge
  - Charge to 4.4V with 10 mA taper charge
  - Pre-launch wait, 20°C for 2 weeks (measure self-discharge)
  - Launch phase. 20 minutes.
  - In-orbit wait, 3 weeks at 35°C (measure self-discharge)
  - De-orbit, 79 minutes, 3-second pulse at minute 73
  - Capacity and series resistance

Screening Summary

Screening was done on a standard formation tester with a charge and discharge at C/10 rate.

While the cells deliver about their stated nameplate capacity, there are differences in end of discharge resistance which show up in later tests.

Following this test the cells were charged to 4.2V.



Pre-launch Self-discharge

Prior to the Mission test, each cell was incrementally charged from 4.2 to 4.4V, 10 mA taper cut-off. Allowing chemical diffusion to finish (about 3-4 days) the cell voltages were measured about once a day.

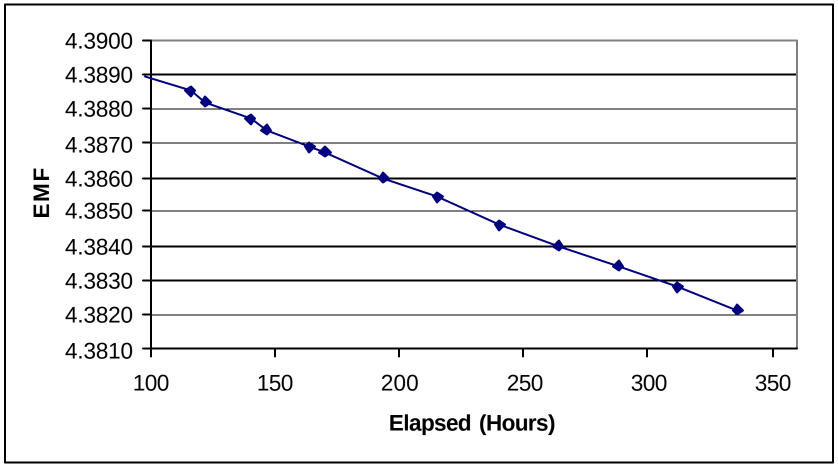
Self-discharge is measured simply in microvolts per hour.

This gave a good indication of the self-discharge loss and the differences between cell types.

Shown also is the actual curve for the Sony HC cells.

'Elapsed' is the time from end of charge.

Self-discharges by type	MicroV/h	Ratio
SonyHC	-28.6	1.0
SonyGR	-30.8	1.1
MCI 1600	-80.2	2.8
MCI 1800	-68.7	2.4
Pana 1800	-140.7	4.9



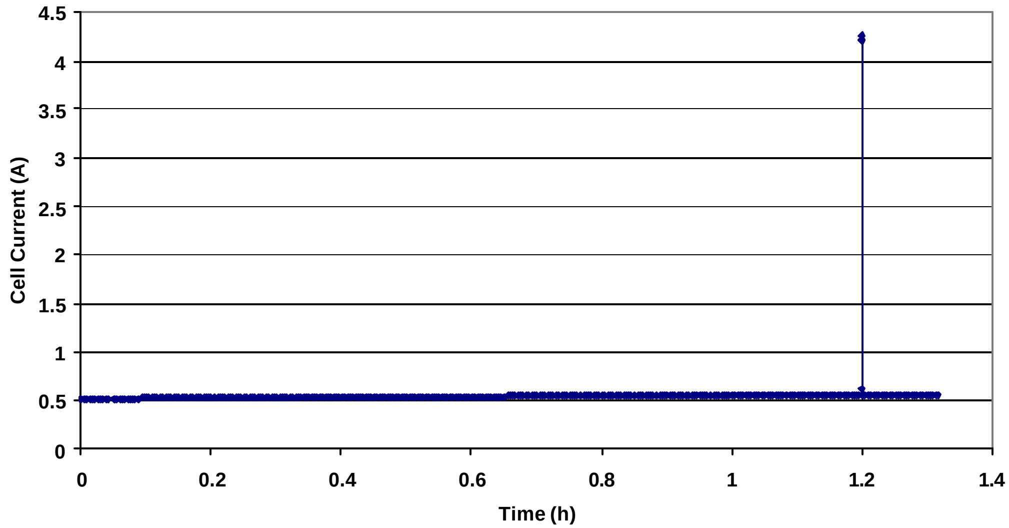
Launch/On-Orbit Phase

- Launch tested each cell in turn by imposing a 20 minute constant-power discharge of 2.17 Watt at 20°C.
- Following this the in-orbit maximum mission length of 21 days was imposed, at 35°C.

After launch	Volts
SonyHC	4.2859
SonyGR	4.2802
MCI 1600	4.1991
MCI 1800	4.2212
Pana 1800	3.7893

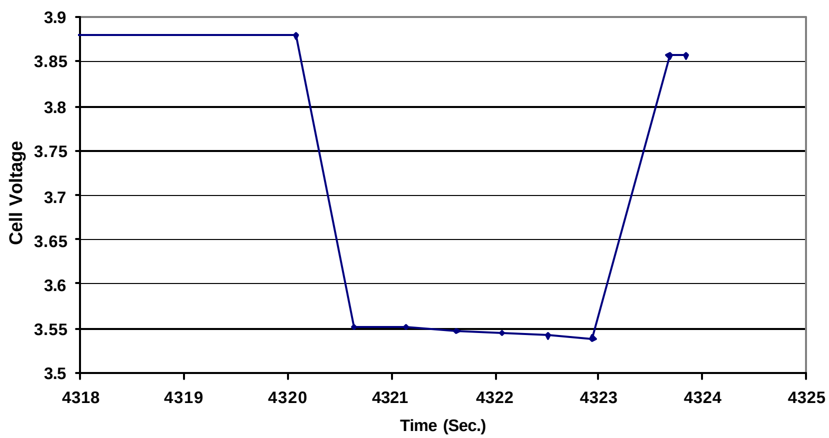
Cell	In-Orbit SD
SonyHC	-45.1
SonyGR	-39.2
MCI 1600	-41.8
MCI 1800	-60.7
Pana 1800	-47.6

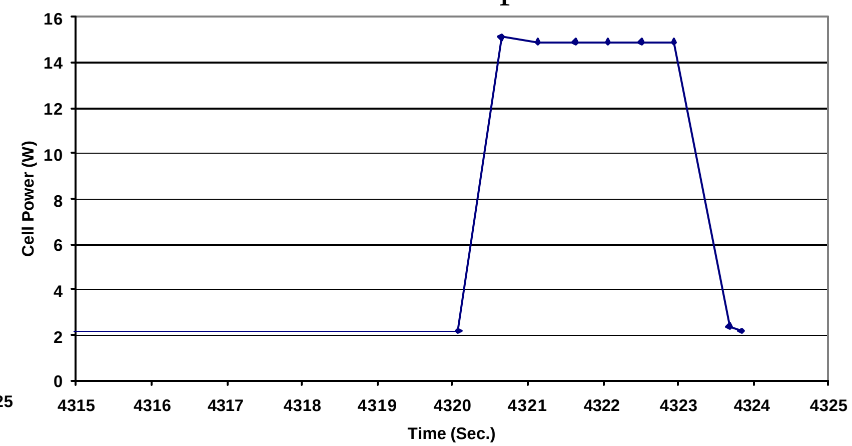
Descent



The 79 Minute de-orbit showing cell current (SonyHC)

Details of the 3-second pulse.





Summary

- The table summarises the main cell parameters, weights them and provides an overall score.
  - Rs is the average series resistance of the batches of four
  - Wh is the energy capacity
  - S_Dis is the pre-launch self-discharge
  - De-orbit EMF is the voltage, or remaining charge, upon landing

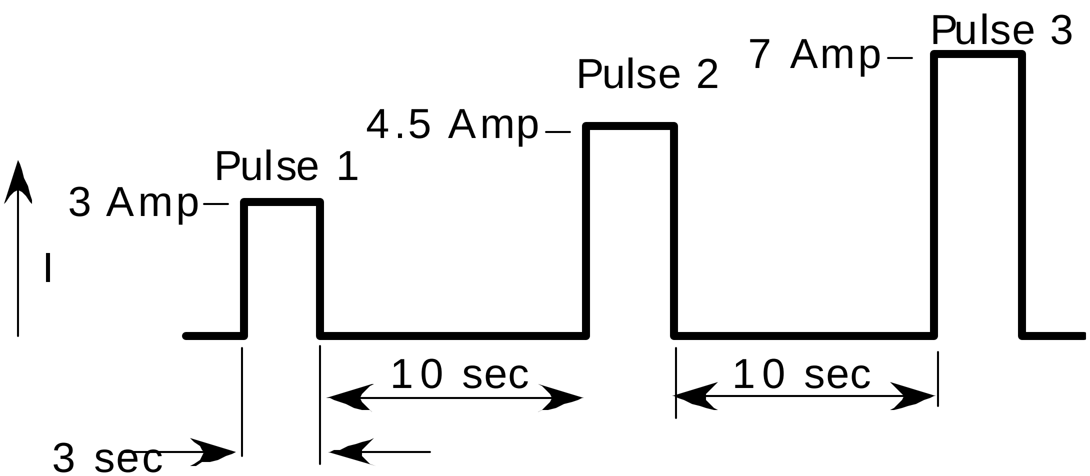
Cell Type	Rs, weight=2	Wh. Weight=1	S_Dis, weight=0.5	De-orbit EMF, weight=0.5	Score
SonyHC	1	1.00	1.00	1.00	4.50
SonyGR	1.16	0.97	1.08	1.00	4.82
MCI1600	1.59	1.03	2.80	1.02	6.62
MCI1800	1.90	1.08	2.40	1.02	7.10
Pana1800	1.29	1.22	4.92	1.02	7.27

(low is best)

Pulse and Capacity Tests

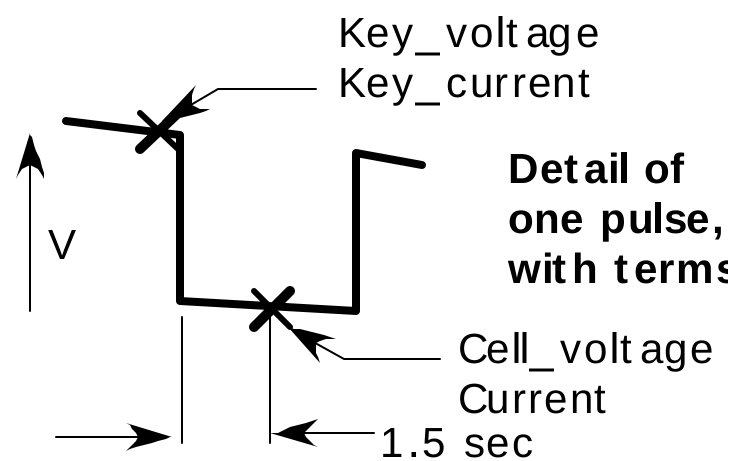
- Separate tests were conducted to measure capacity under mean orbit discharge rates (about C/2.5).
- During discharge, pulses were imposed to measure resistance.
- Tests done at 0°C, 20°C and 35°C.

The Three Pulses

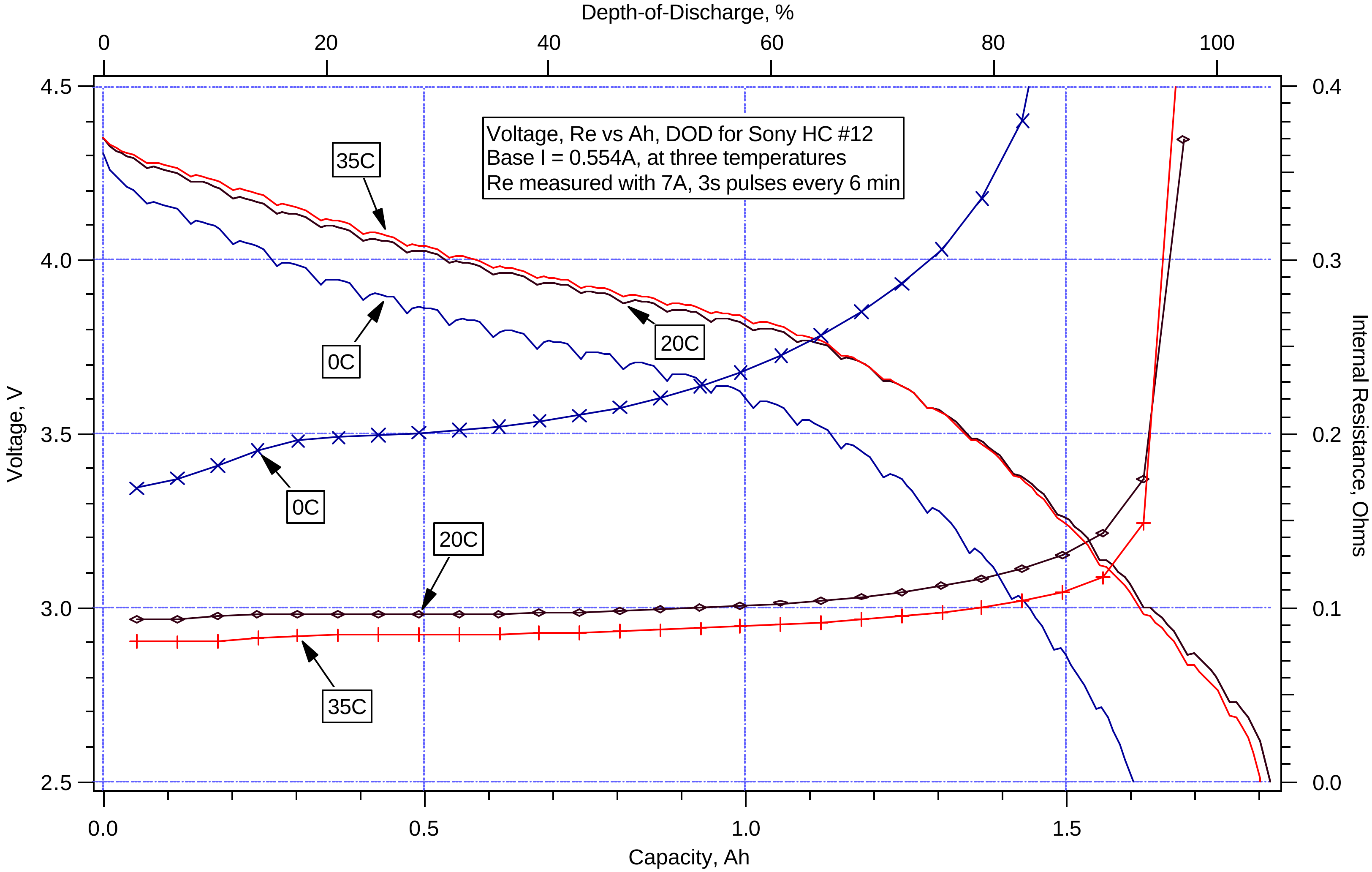


The sets of pulses were imposed every six minutes, all cells showed a slightly decreasing Rs from pulse to pulse, due to thermal dissipation.

$Rs = \Delta V / \Delta I$



Typical Performance of Sony HC Cell



Pulse Performance of Small Lithium-Ion Cells

Conclusions

- All cells would support the mission.
- It is the performance during pulse conditions that drives the battery size.
- The Sony hard carbon has the best overall score and would permit the smallest battery to meet the mission requirements
- The Sony HC cell has been extensively validated and qualified for space use. They have flown on:
  - Shuttle missions
  - STRV
  - Proba
- They are extremely safe

Low Temperature and High Rate Performance of Lithium-ion Systems for Space Applications

R. Gitzendanner, F. Puglia, C. Marsh

Lithion, Inc.

Pawcatuck, CT USA

Research Goals

- *As part of the Inter-Agency* Lithium-ion Development Program, *Lithion has undertaken an empirical analysis of the rate limiting steps in Lithium-ion cells*

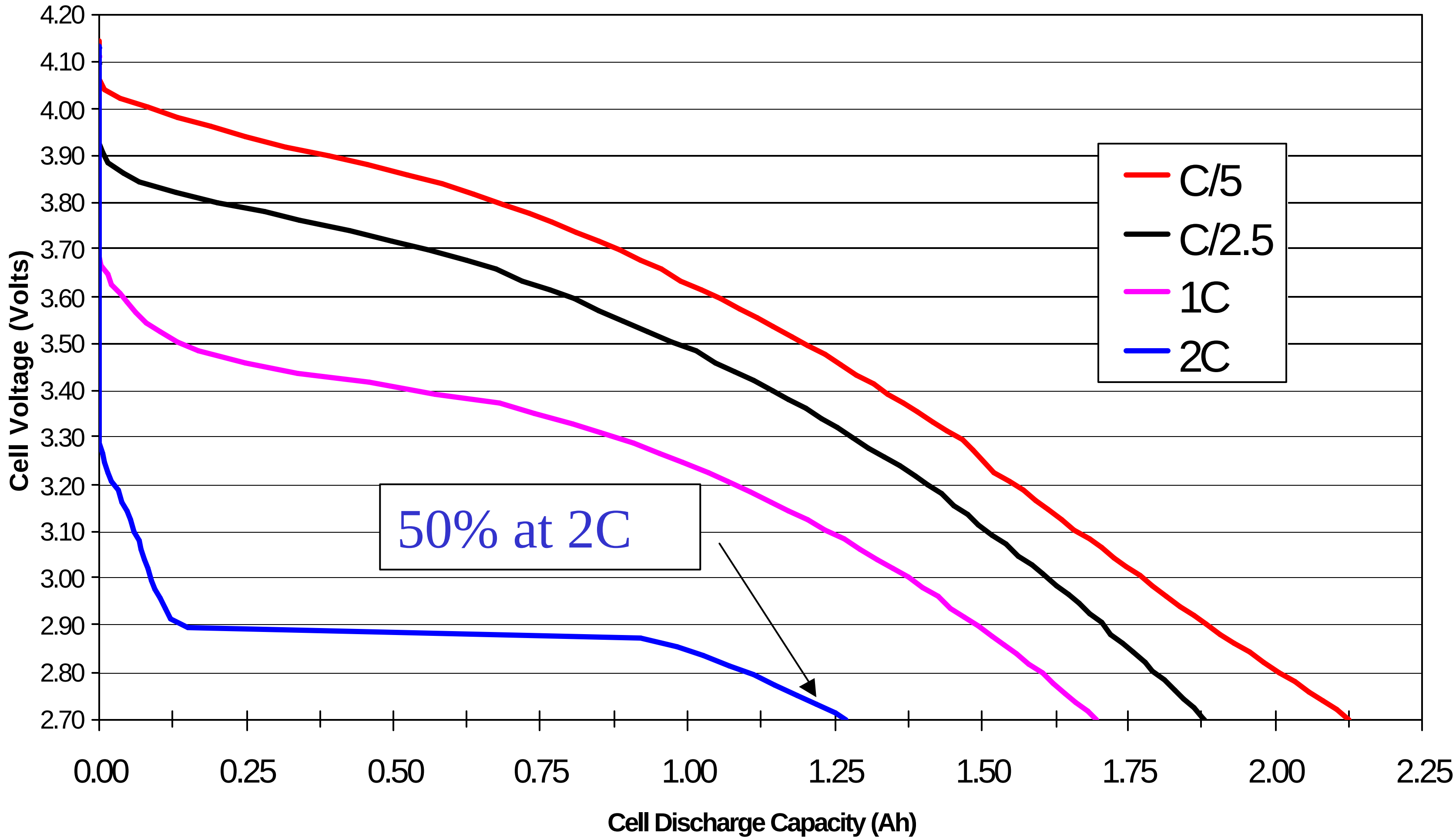
- *Goal is to improve High Rate performance:*
  - Continuous Discharge
    - Goal: >50% capacity @ 20C and 25°C (to 3.0V cutoff)
    - Goal: >50% capacity @ 5C and -20°C (to 2.5V cutoff)
  - Pulse Discharge (< 1 second)
    - Goal: > 100C at 25°C (above 2.0V)
    - Goal: > 10C at -20°C (above 2.0V)

Targeted Applications

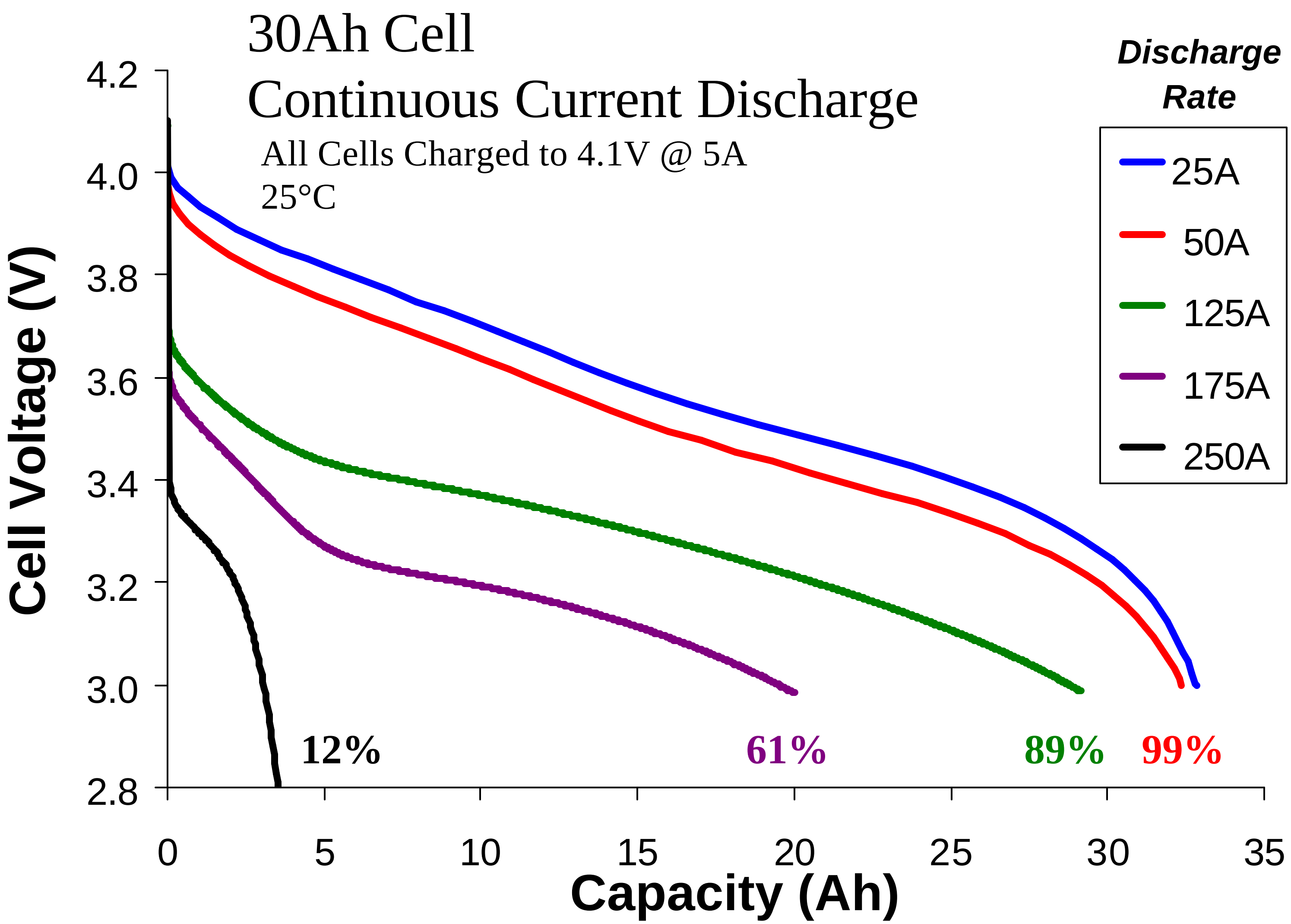
- *High Rate Pulse Power required for many applications*
  - Communications (Satellite, Radio, Terrestrial…)
  - Engine Start, Motor Drives, Actuators (Aircraft, Vehicular)
  - Military Lasers
  - Pulsed Radar…
- *High Rate Constant Current demands also necessary for many applications*
- *Typically battery design has been sized to meet highest rate requirement (oversized on capacity)*
  - Increase rate capability $\Rightarrow$ Decrease battery size

Rate Capability of a Commercial 22650 Cell

High Rate Continuous Discharge



High Rate Capability of Current 30Ah Cell



Experimental Approach

- *The empirical approach is undertaken in 6 separate experiments*
  1) Electrode Weight Loading, Anode Particle Size, & Ratio of Anode to Cathode (Complete)
  2) Anode Conductive Diluents (Complete)
  3) Separator Thickness and Porosity, & Binder Type (Modeling)
  4) Electrolyte Salt and Solvent, & Cathode Material (In Process)
  5) Mechanical Cell Construction Improvements (In Planning)
  6) Validation/Verification Experiments

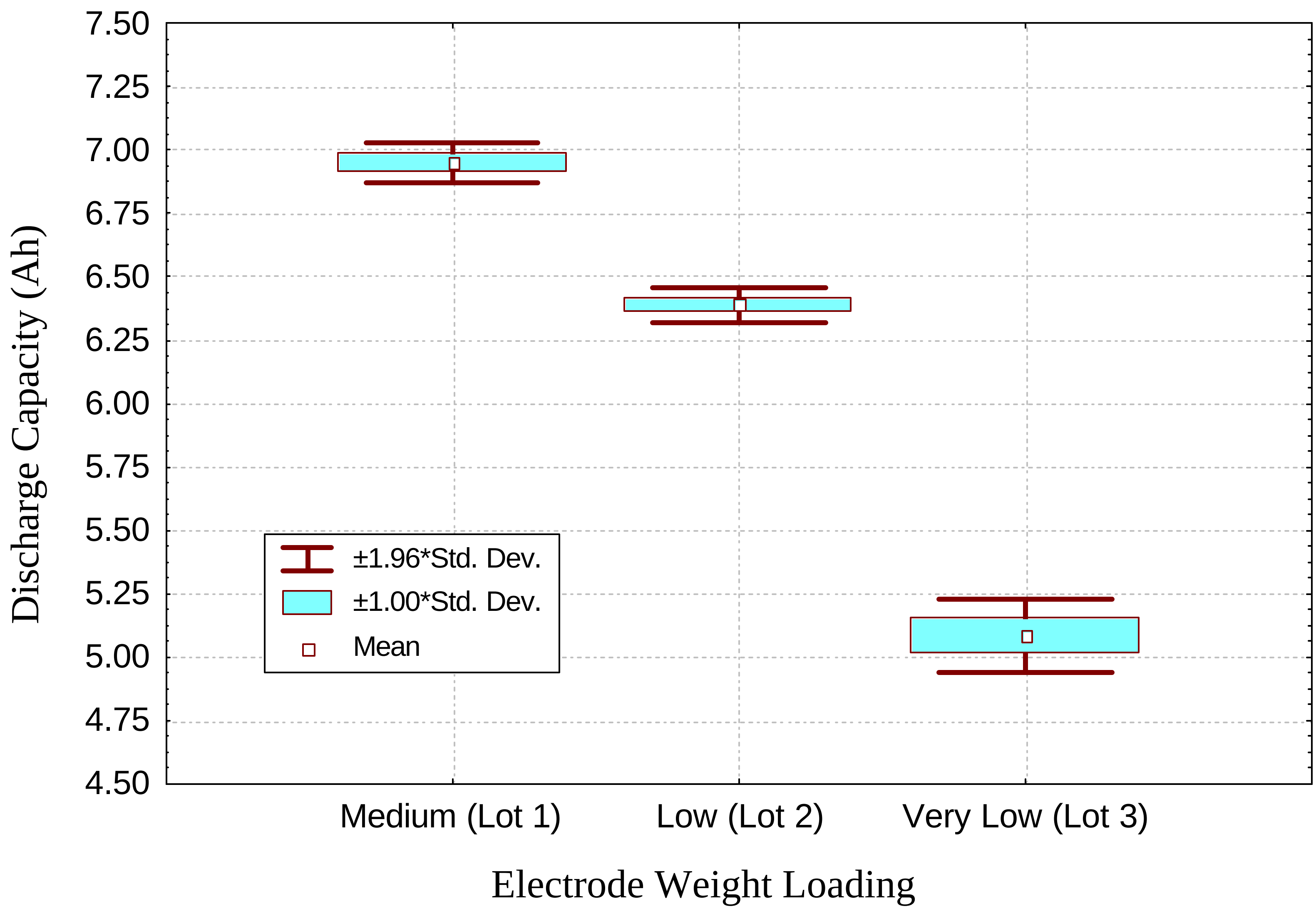
Experiment #1 Plan

- *Electrode Weight Loading, Anode Particle Size, & Ratio of Anode to Cathode*
  - Three Electrode Weight Loadings -- Full Factorial
    - Medium Loading (baseline chemistry)
    - Low Loading (~ 2/3 of baseline)
    - Very Low Loading (~ 1/3 of baseline)
  - Two Anode Particle Sizes -- Full Factorial
    - 10μm diameter nominal particle size
    - 6μm diameter nominal particle size
  - Three C/A Ratios -- Partial Factorial
    - Baseline
    - ~ 2/3 of Baseline
    - ~ 1/2 of Baseline

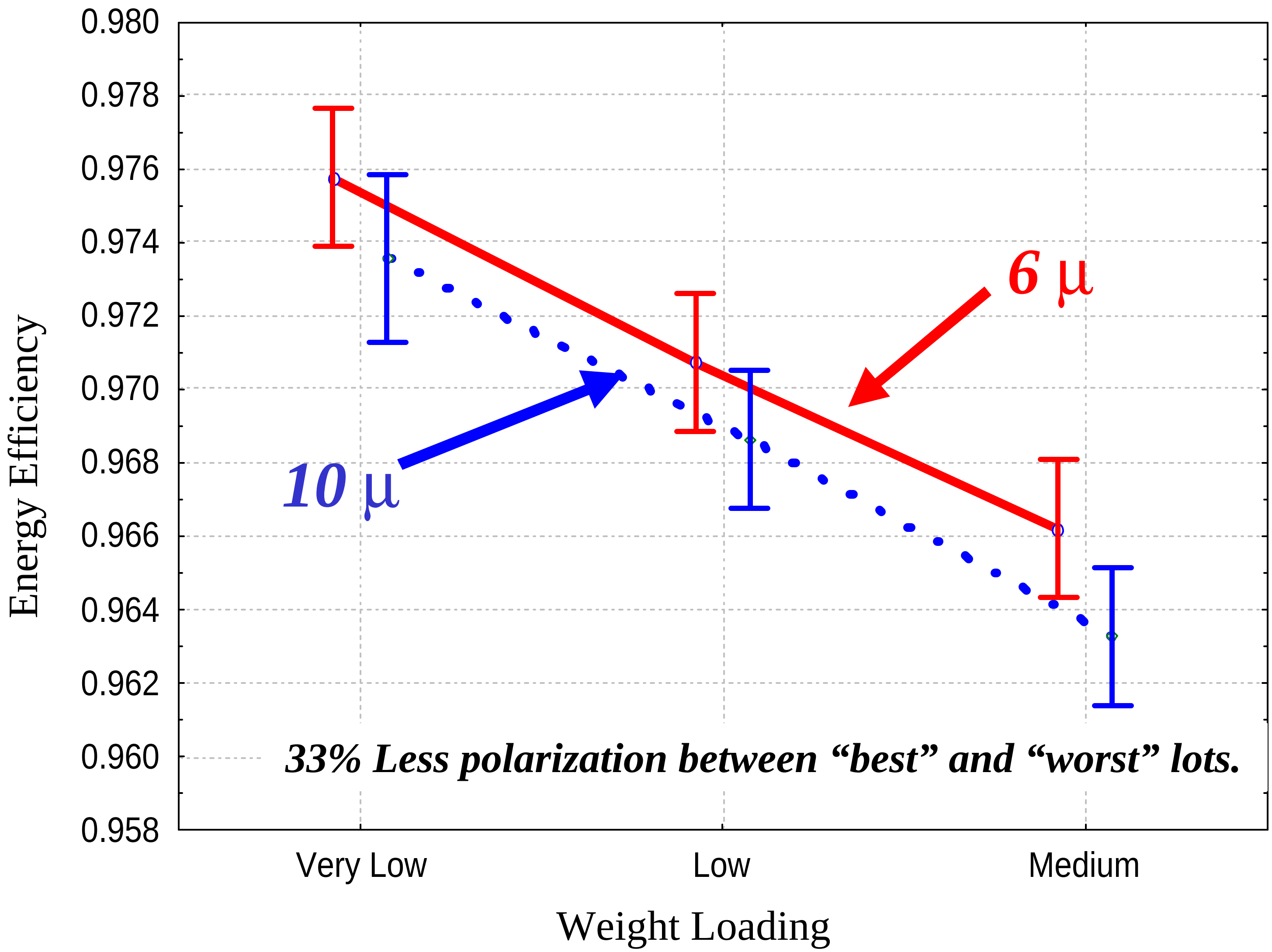
Experimental Testbed

- *10 Experimental Lots, 3 cells per Lot (typical)*
- *All Lots assembled and tested at same time*
- *All Lots used same prismatic cell hardware*
  - Cell volume maintained so Capacity varied as a function of Weight Loading and C/A Ratio
    - Baseline Lots had nominal 7Ah capacity
  - Cell **NOT** designed for High Rate
    - Terminals only 0.090" diameter Mo GTMS (limits continuous discharge to ~ 20C)
    - Verification cells planned to use improved terminal design

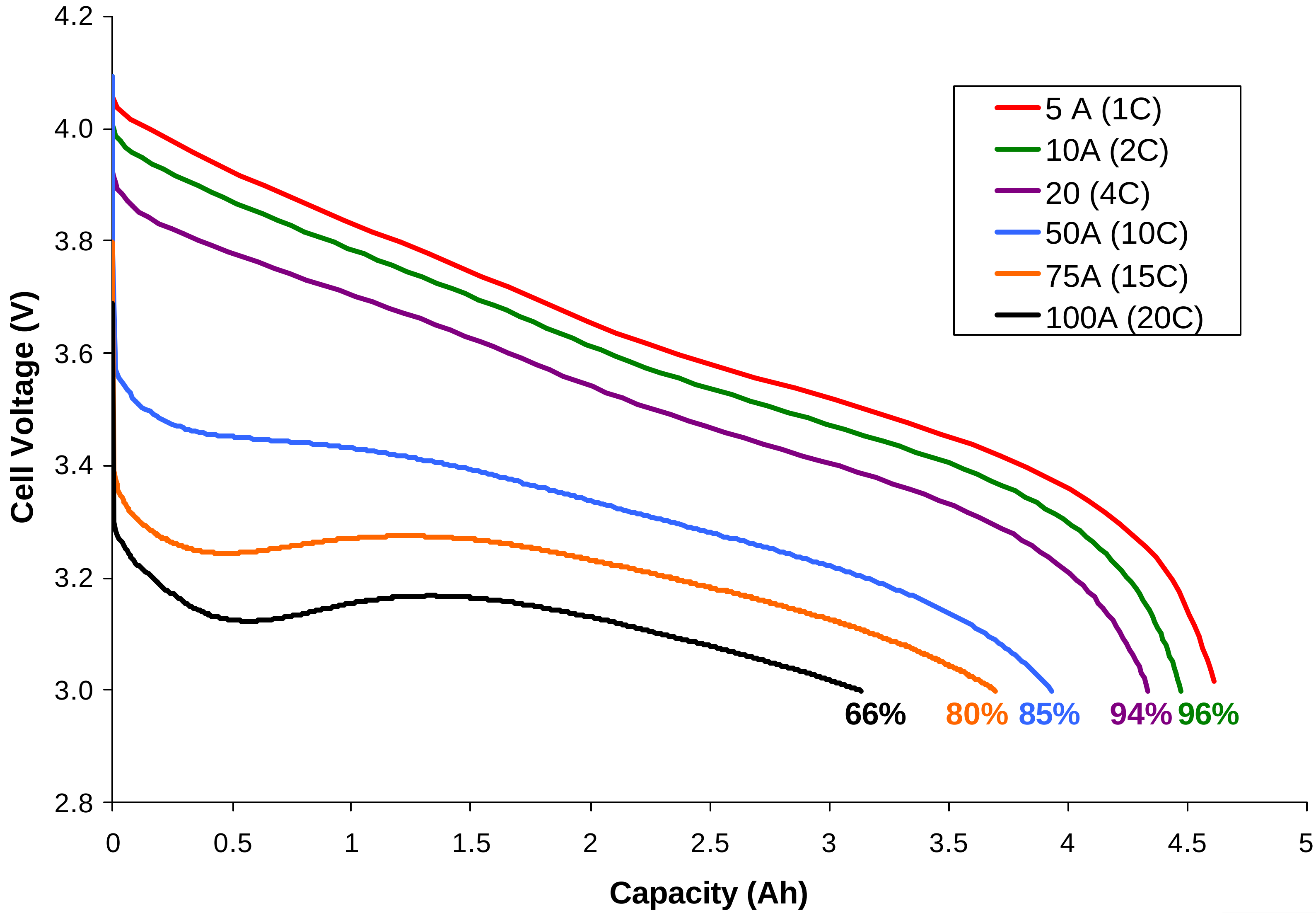
Effect of Weight Loading on Capacity



Effects on Efficiency

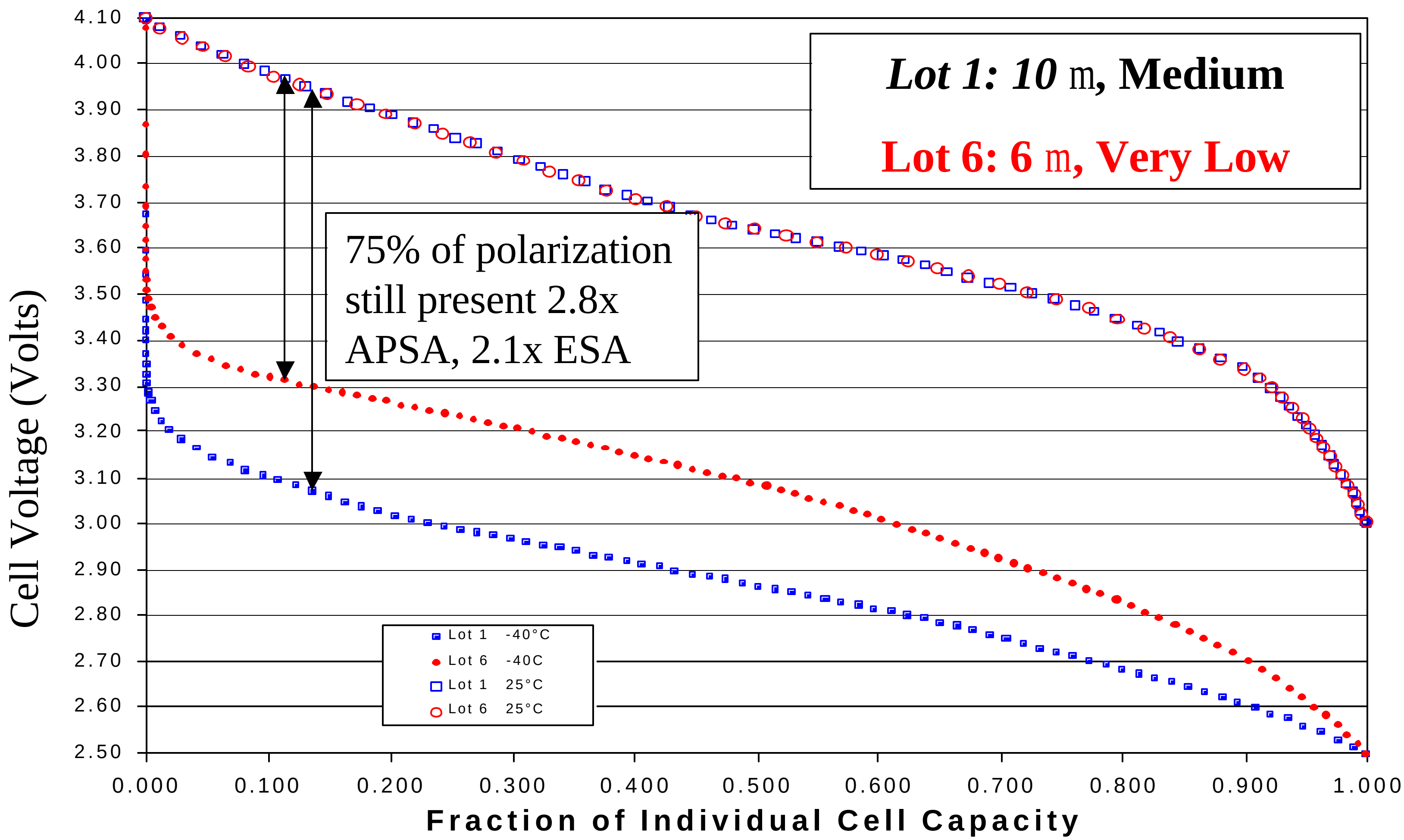


High Rate Constant Current Discharge



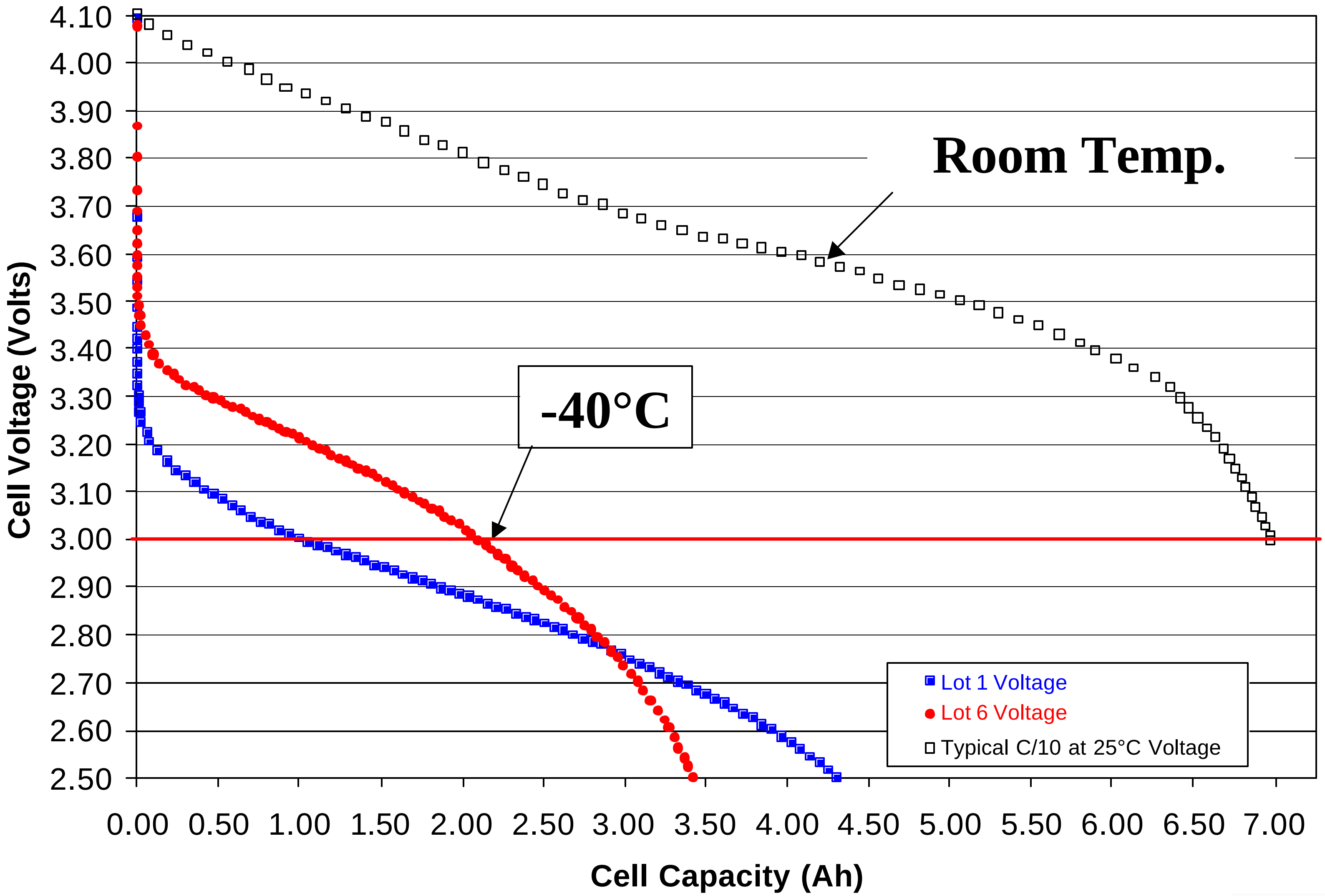
Lithion Inc.

Comparison of Lot 1 versus Lot 6
-40°C, C/10 Discharge (25°C Charge)

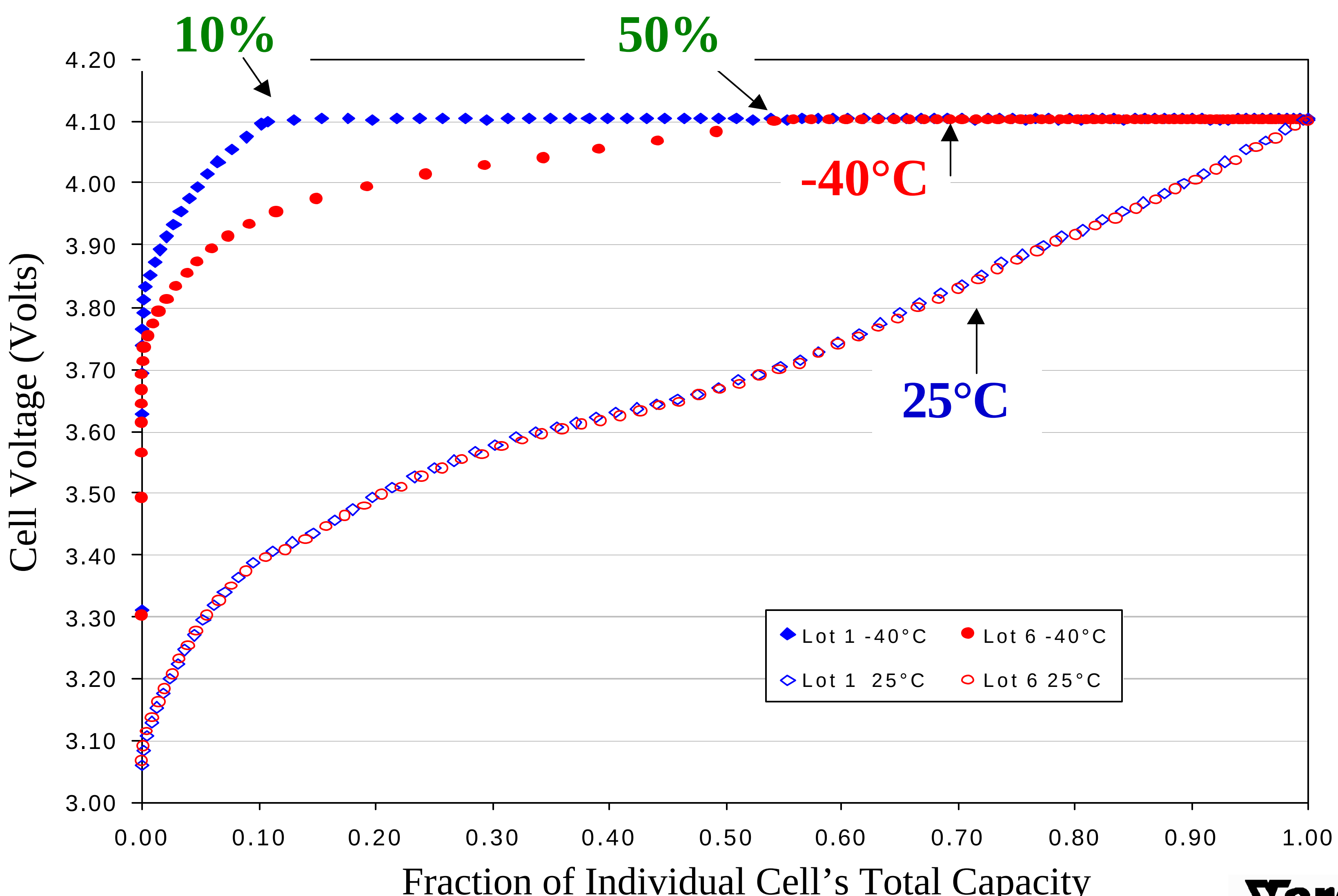


Yardney Technical Products, Inc.

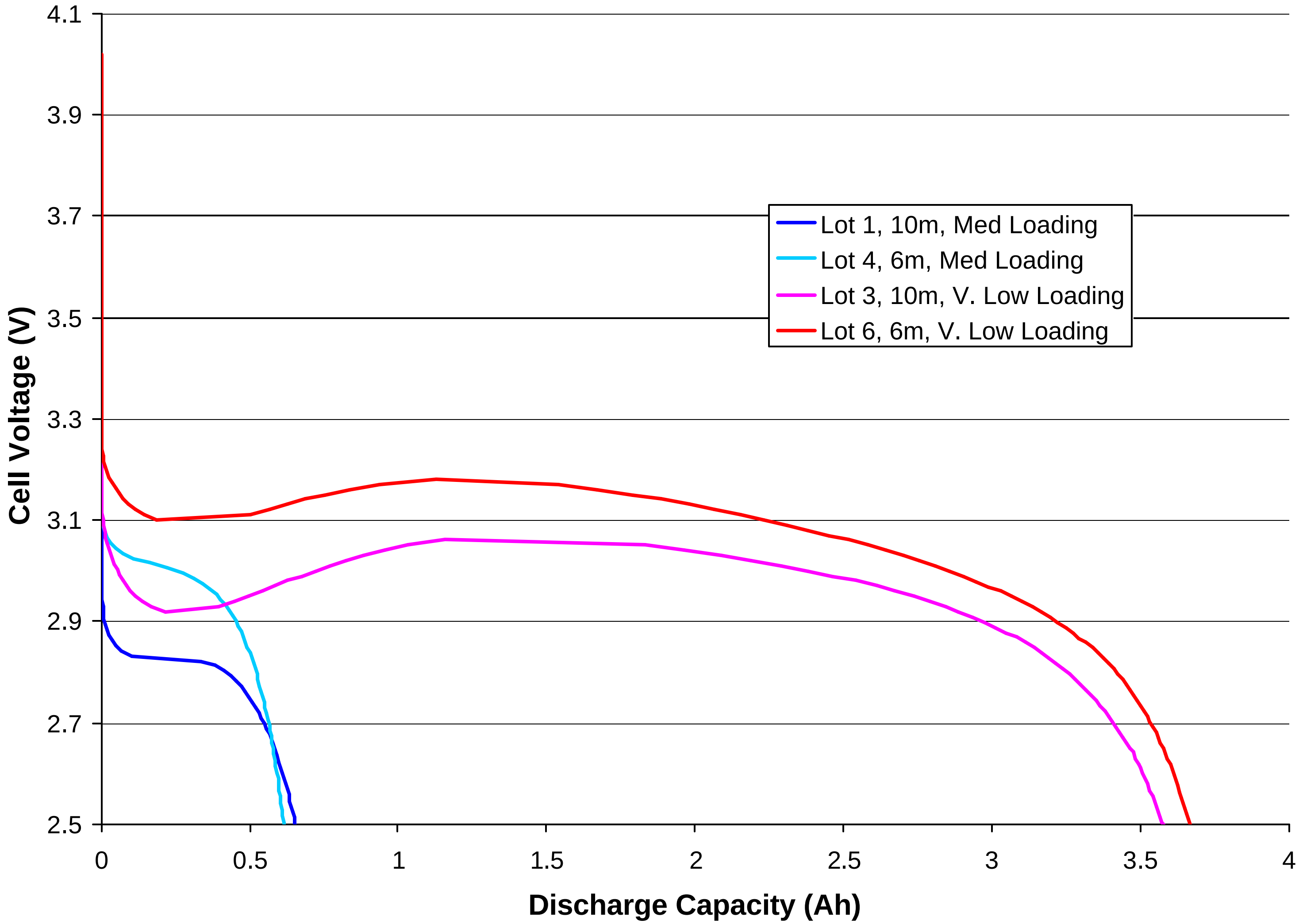
Comparison of Lot 1 versus Lot 6 -40°C, C/10 Discharge (25°C Charge)



Effect on Charging at -40°C

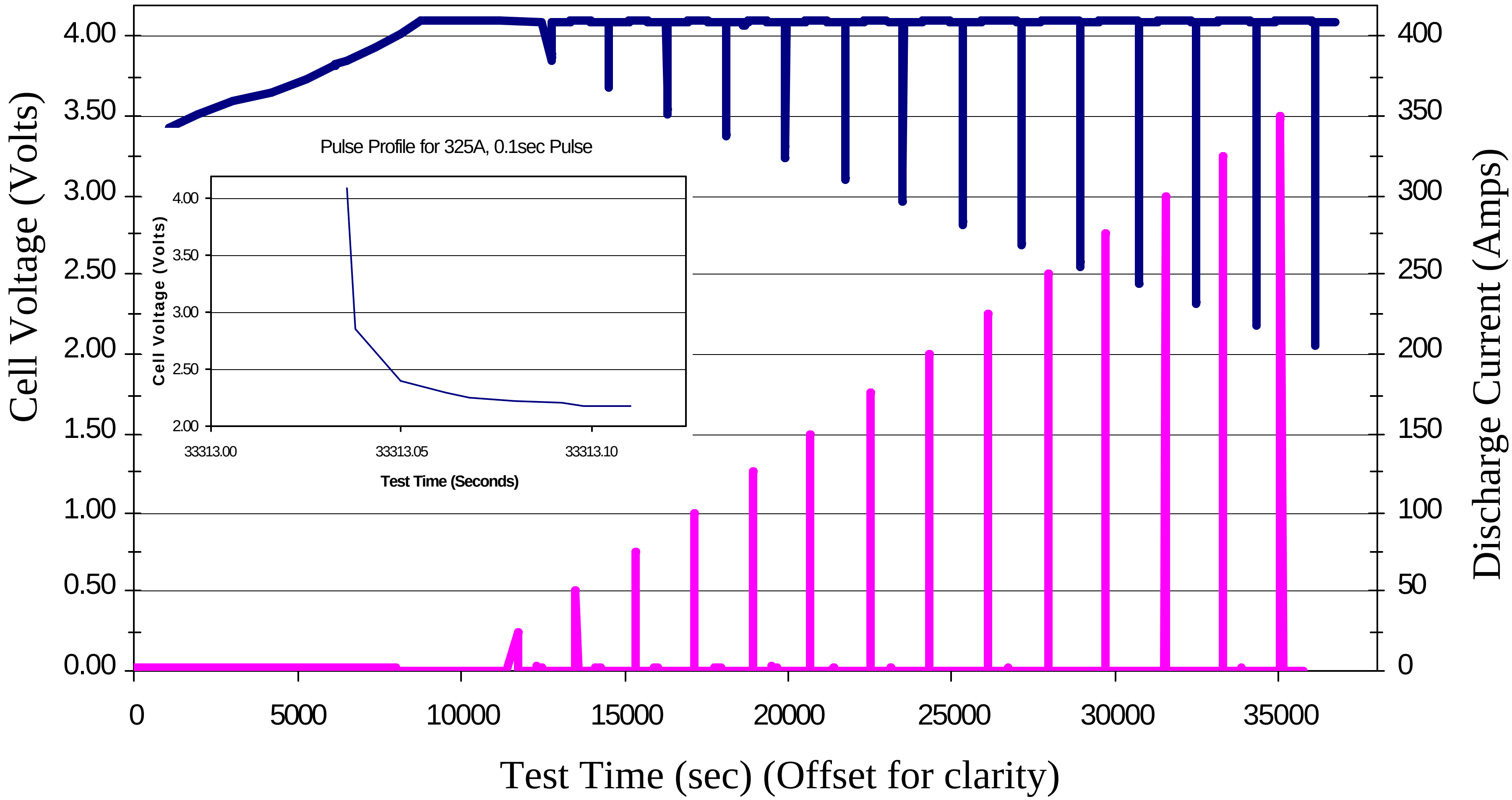


20A (4C) Discharge at -20°C

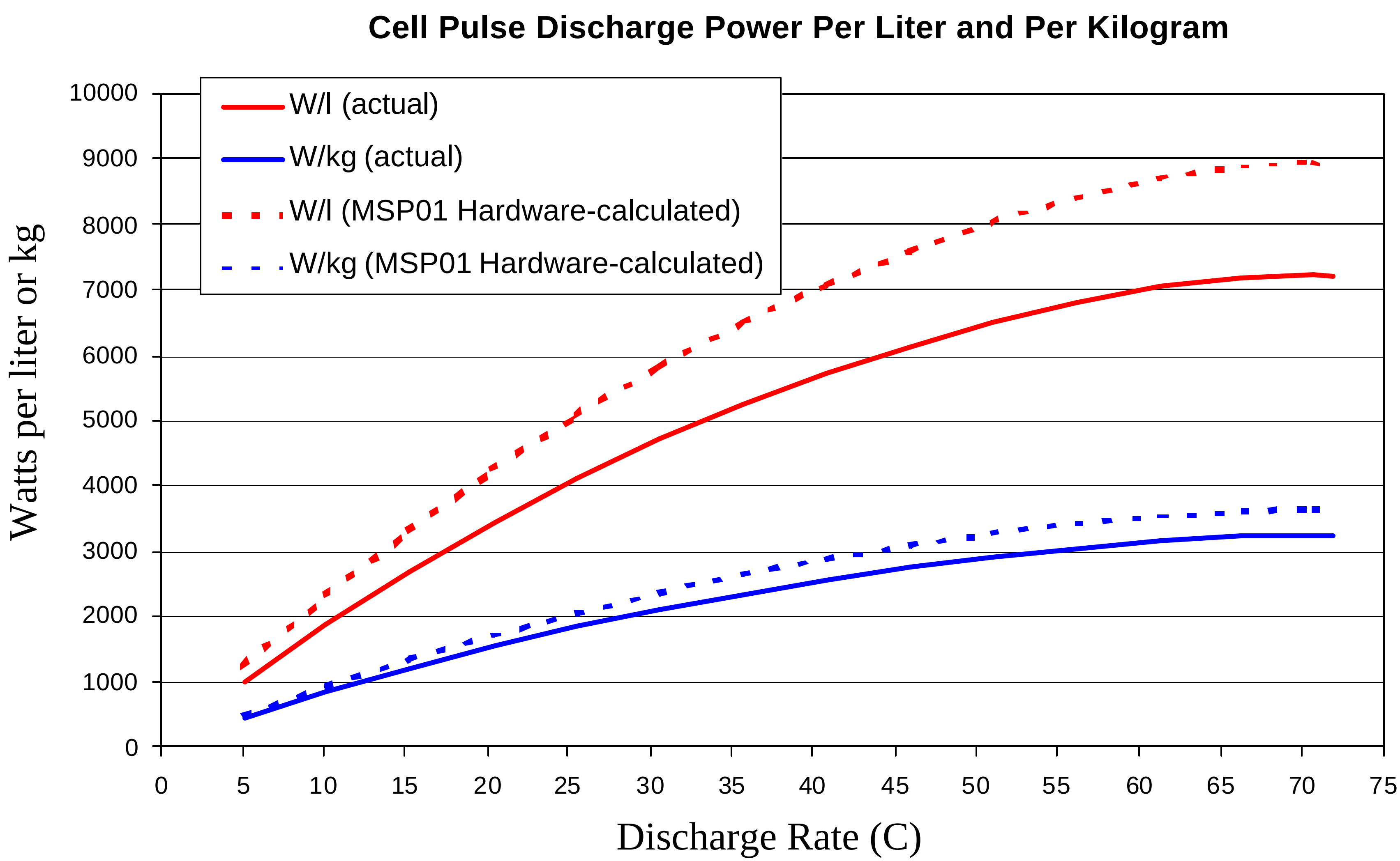


25°C High Rate Pulses

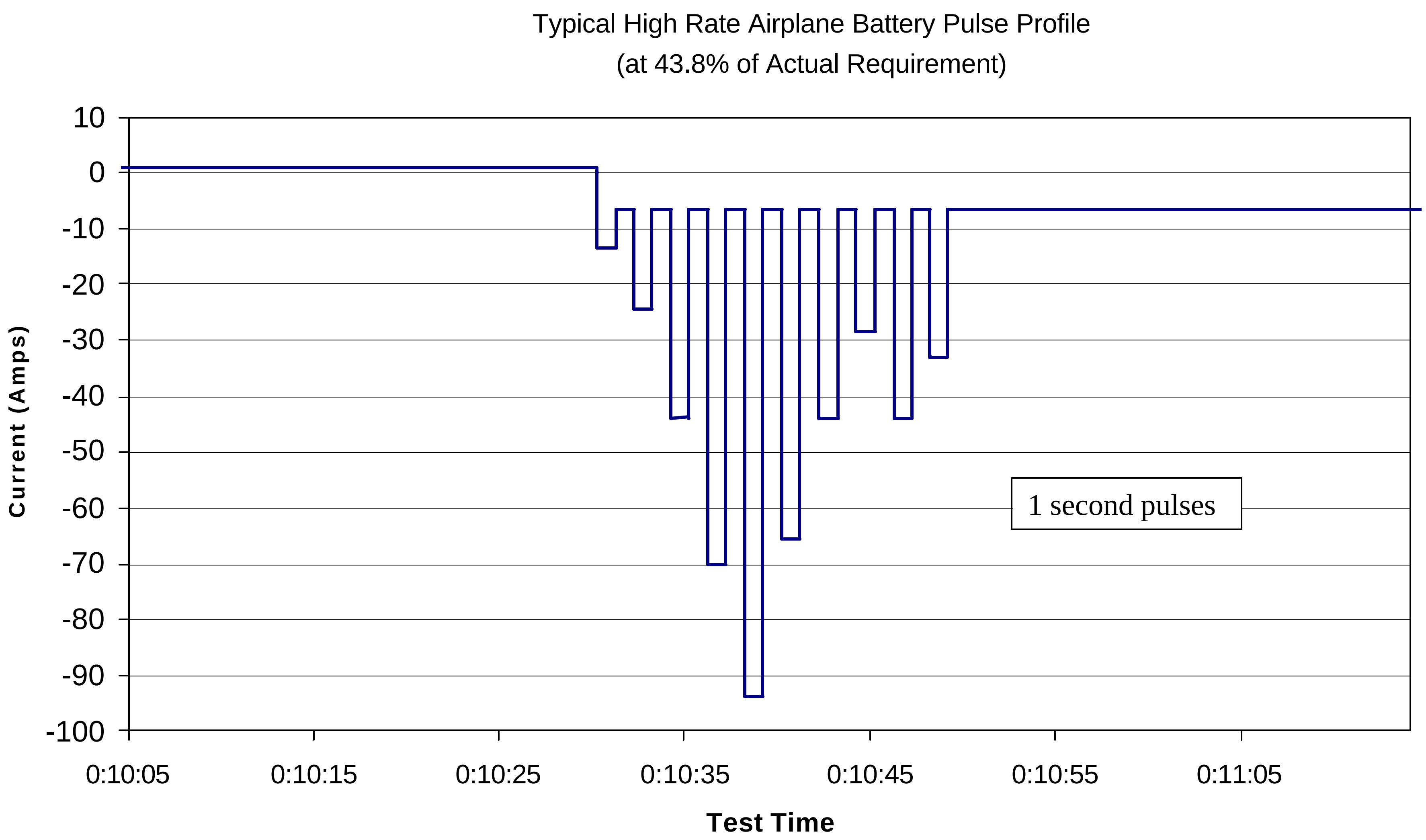
Lot 6 High Rate Pulses (0.1s at 25°C): 10A ® 350A
2C ® 75C



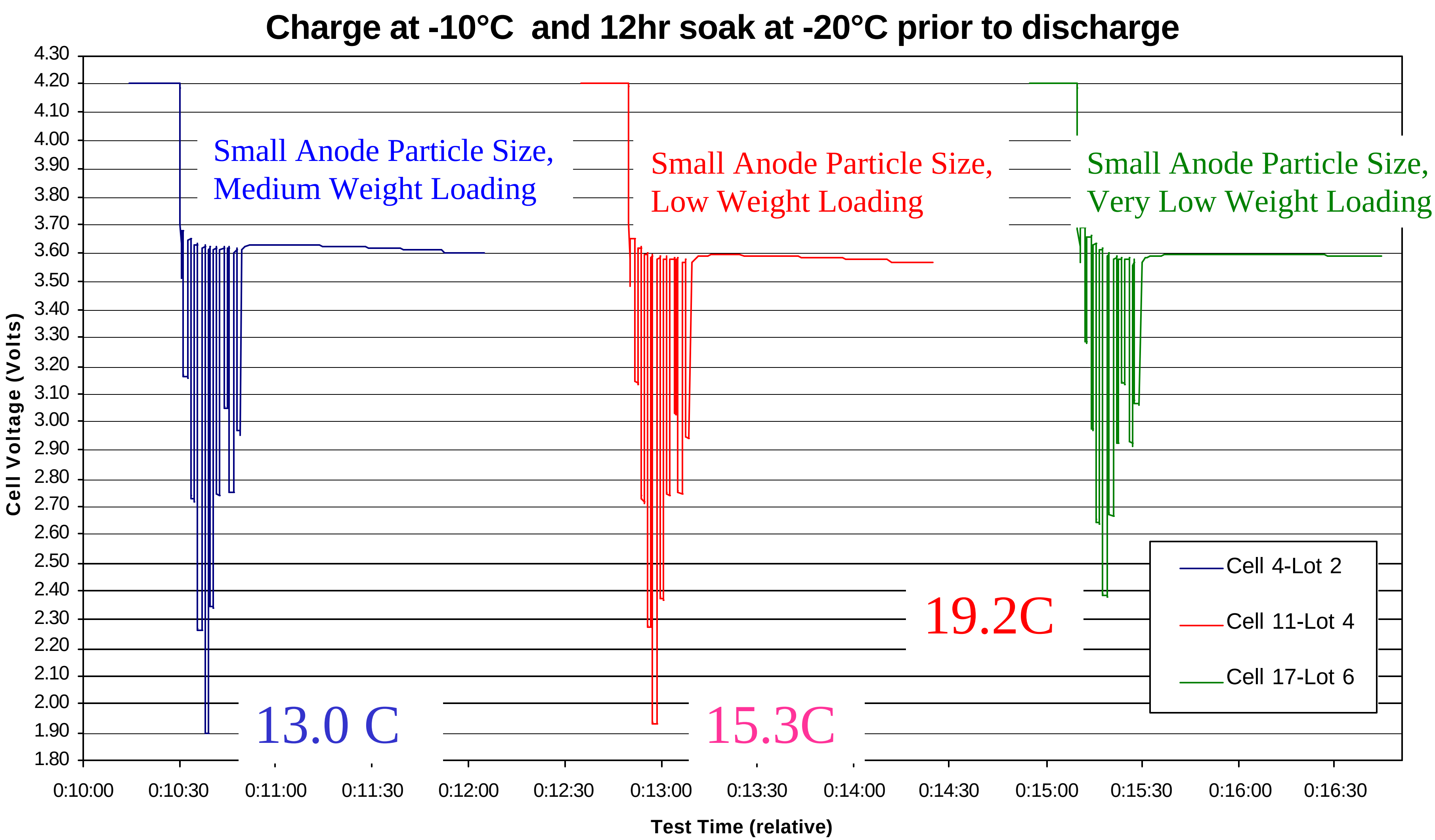
25°C High Rate Specific Power



High Rate Pulse Profile



High Rate Pulse @ –20°C



Summary

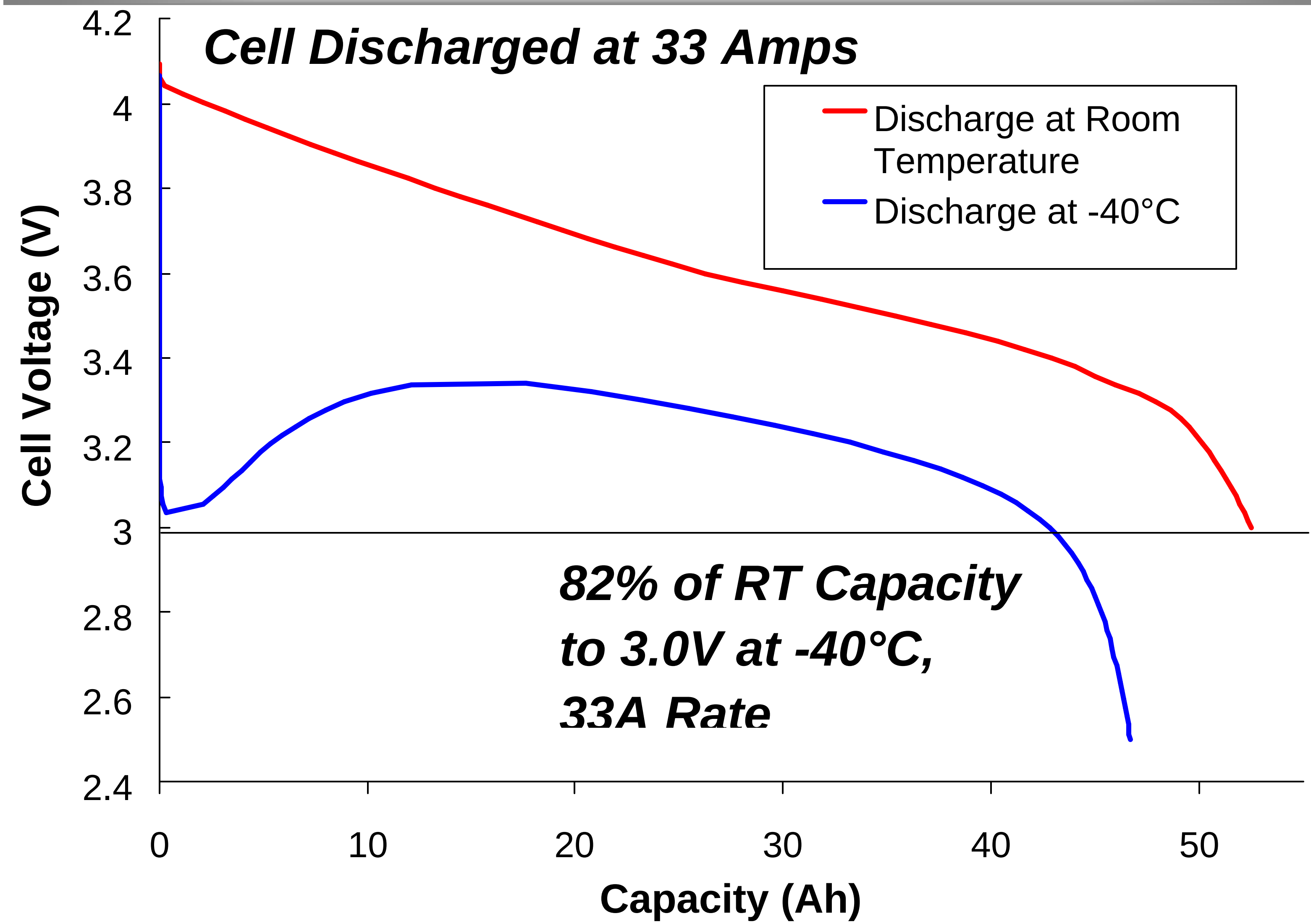
- *Lithion has investigated the first (of several) rate limiting steps in Lithium Ion performance*
  - Increased continuous discharge capability from ~5C to >20C
    - 63% of initial capacity available above 3.0 Volts!
  - Demonstrated pulse capability as high as 75C at voltages above 2.0 Volts
    - Power density of 3200 W/kg and 7200 W/l has been demonstrated!
    - Approaching 3700 W/kg and 9,000 W/l (in a 33Ah cell size)
  - Demonstrated discharge rates as high as 4C at –20°C (>70% capacity) and 2C at –30°C (>60% capacity)

These improvements in rate capability make Lithium Ion cells viable for many high rate, high power applications

Military Lasers, Radar Pulses, Electric Drive Systems (motors), Radio Communications, Actuators, etc

- *…and this is the first of the 6 experiments…*

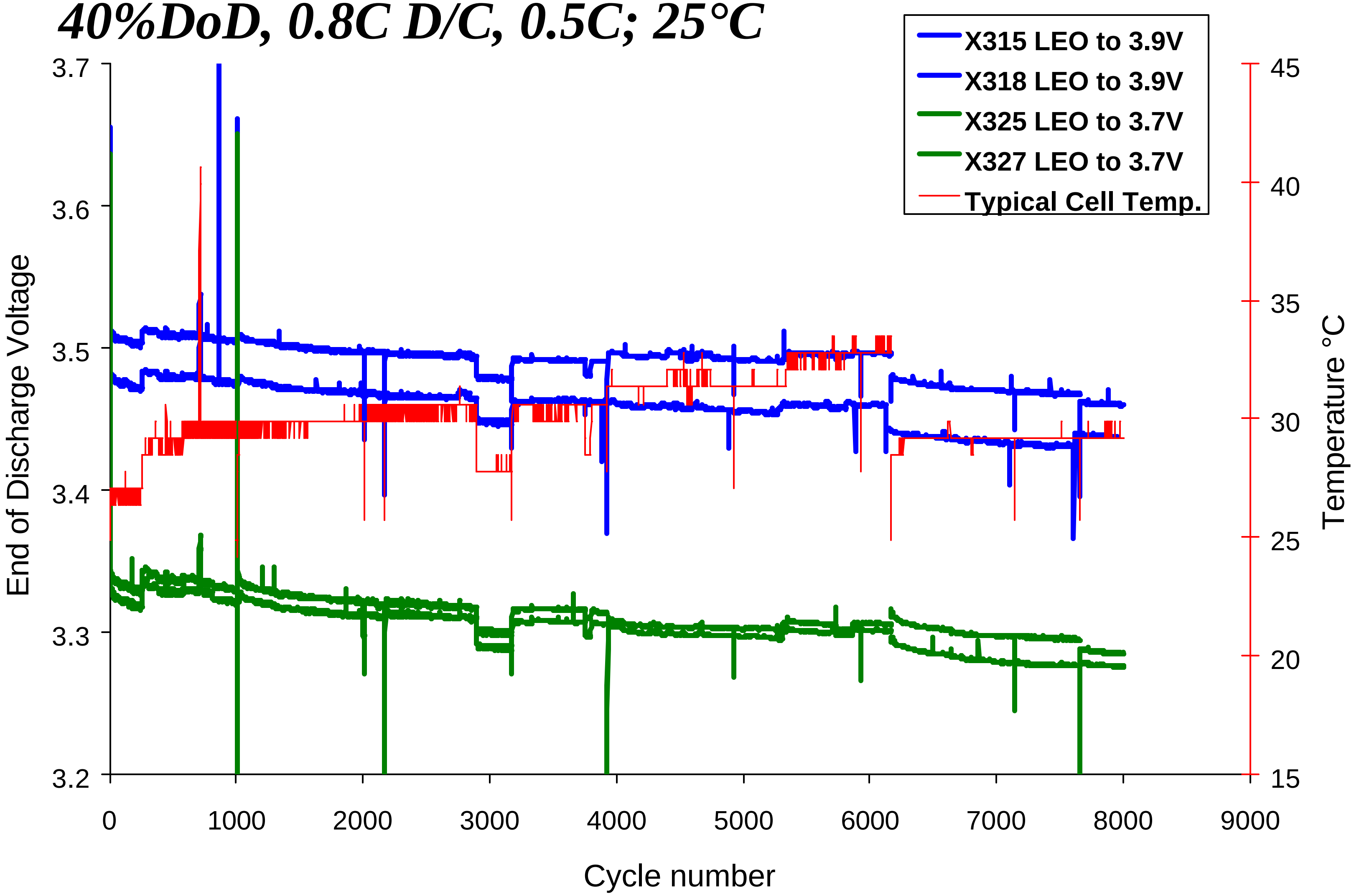
“Real-World” Application



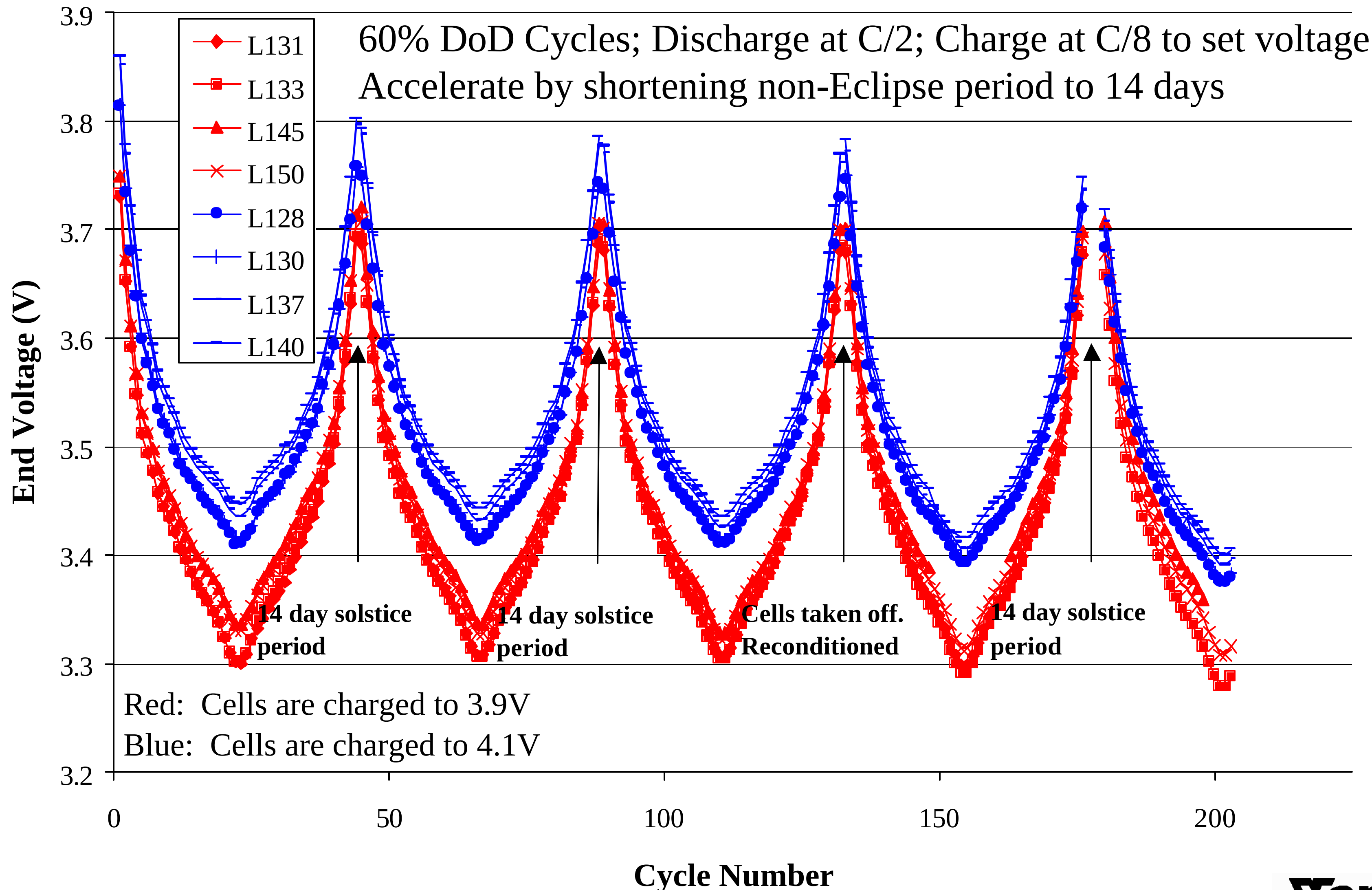
Update of LEO and GEO cycling

LEO Cycling at Lithion

40%DoD, 0.8C D/C, 0.5C; 25°C



GEO Cycling at Lithion



Other Ongoing Tests

- *5 Batteries developed for the MSP01 Mars Lander Program*
  - *Further Mars Mission Simulation Testing*
  - *Full Sky Astrometric Mapping Explorer (FAME)-NRL*
    - *Slightly elliptical GEO-type mission*
    - *Scheduled for launch in 2005*
  - *NASA Glen*
    - *LEO cycling at low temperatures*
  - *Wright Patterson Air Force Base*
    - *LEO cycling at Room Temperature (continuation of pack-level tests*
  - *Lockheed Martin Astronautics*
    - *LEO cycling at reduced charge voltages*

Acknowledgements

- *This effort is funded by the Air Force Research Labs at Wright Patterson Airforce Base, contract number F33615-98-C-2898*
- *Guidance and assistance from Steve Vukson (COTR on the program,(937) 255-7770) is greatly appreciated.*
- *Co-Workers and other staff at Yardney Technical Products*

Study of the effects of overdischarge on SONY 18650HC cells

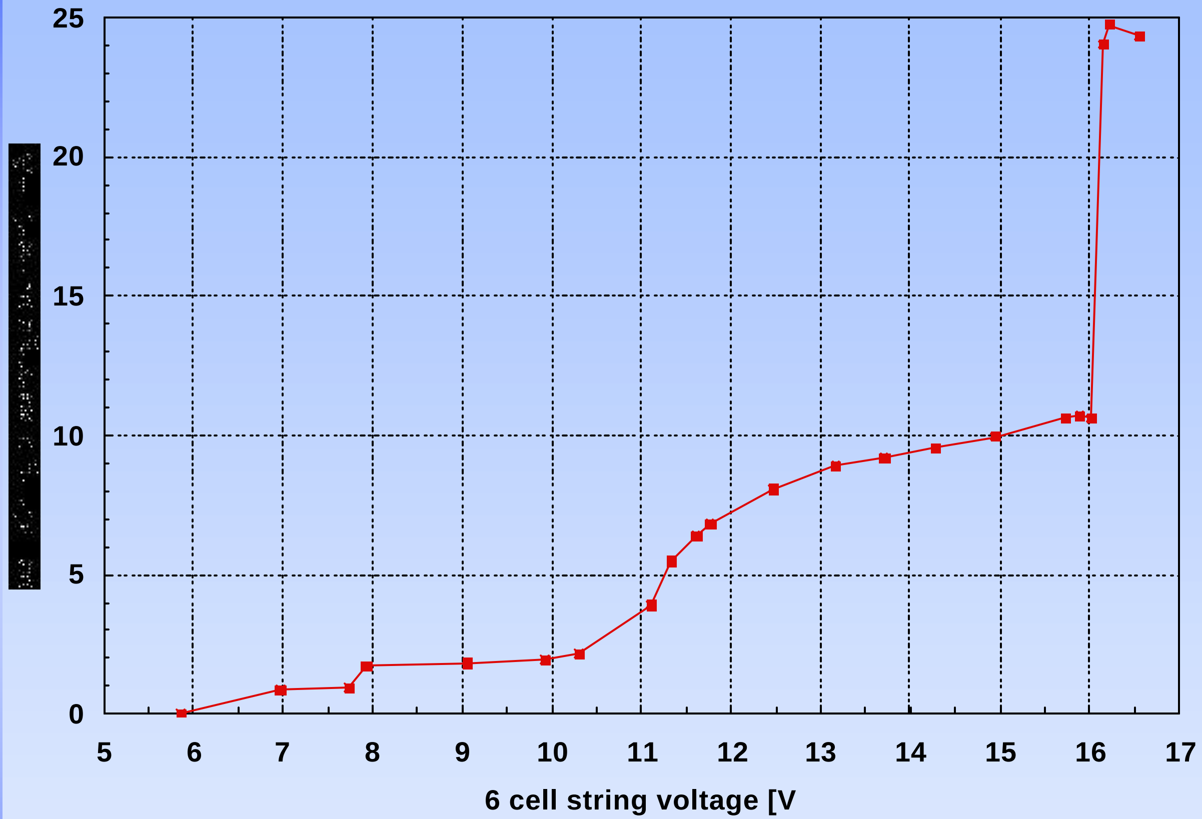
G. J. Dudley (ESA-ESTEC)

R. Spurrett (AEA Technology)

The Concern

- *Previously used secondary space battery cells can tolerate discharged to an open-circuit voltage of zero.*
- *Lithium-ion cells have minimum allowed open-circuit voltages of typically around 2.4 V, below which manufacturers warn of irreversible damage.*
- *This means that if the bus of a spacecraft with li-ion batteries collapses due to a fault condition, the spacecraft might not be recoverable.*
- *Several ESA scientific and earth-observation spacecraft are planning to use batteries of SONY 18650HC cells.*
- *The tests described here were an initial attempt to find out how long could a bus collapse last before the battery was unusable and the mission lost?*

Predicted battery drain as function of bus voltage



Opposite: The predicted battery drain current as a function of bus voltage for a particular spacecraft with a 28 V regulated bus, scaled to a single string of 6 series cells.

Below the minimum operating battery voltage (in this case 18 V), the battery drain will be determined by residual currents through non-linear semiconductor components of the BDRs, switches etc.

esa

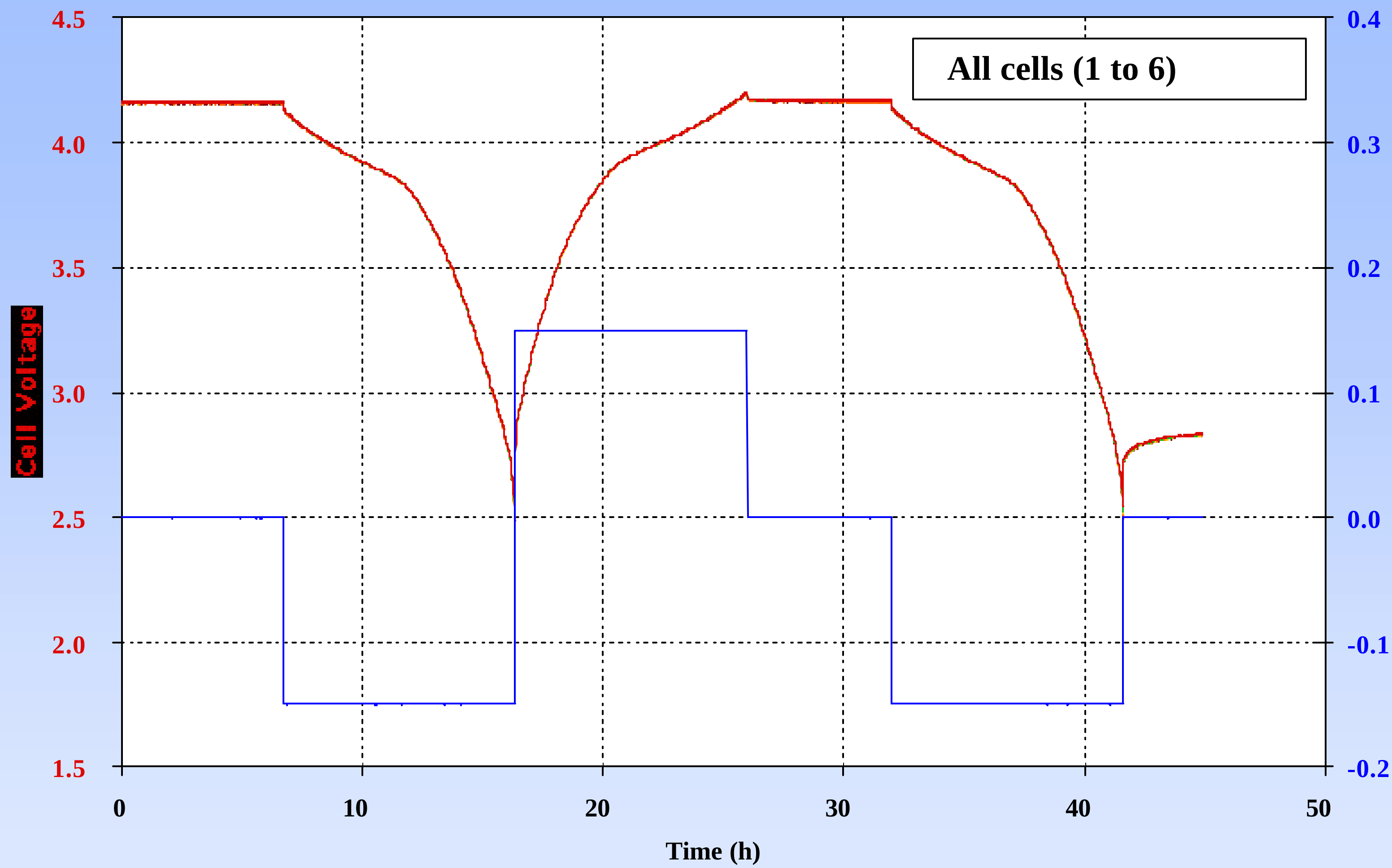
Possible effects of over-discharge

- *Apart form gross failures such as open or short-circuit cells, factors that are likely to be degraded as a result of overdischarge are:*
  - *Battery capacity*
  - *Battery resistance*
  - *Battery self-discharge rate*
  - *Spread of cell self-discharge rates*
- *The last one is important because this battery type relies on cells remaining 'naturally' balanced in state of charge.*

Test Plan

- *6 SONY 18650HC cells were selected by AEA Technology according to standard flight-battery procedures and connected in series.*
- *Test sequence:*
  - *BOL capacity/self-discharge/internal resistance check*
  - *Discharge at C/10 to 2.5V*
  - *Overdischarge according to realistic scenario, removing individual cells at intervals and continuing with remaining cells.*
  - *Repeat capacity/self-discharge/internal resistance check*
  - *Stress cycling (to give indication of remaining cycle life)*
  - *Cycling overdischarged cells together in series to check on state of charge balance.*

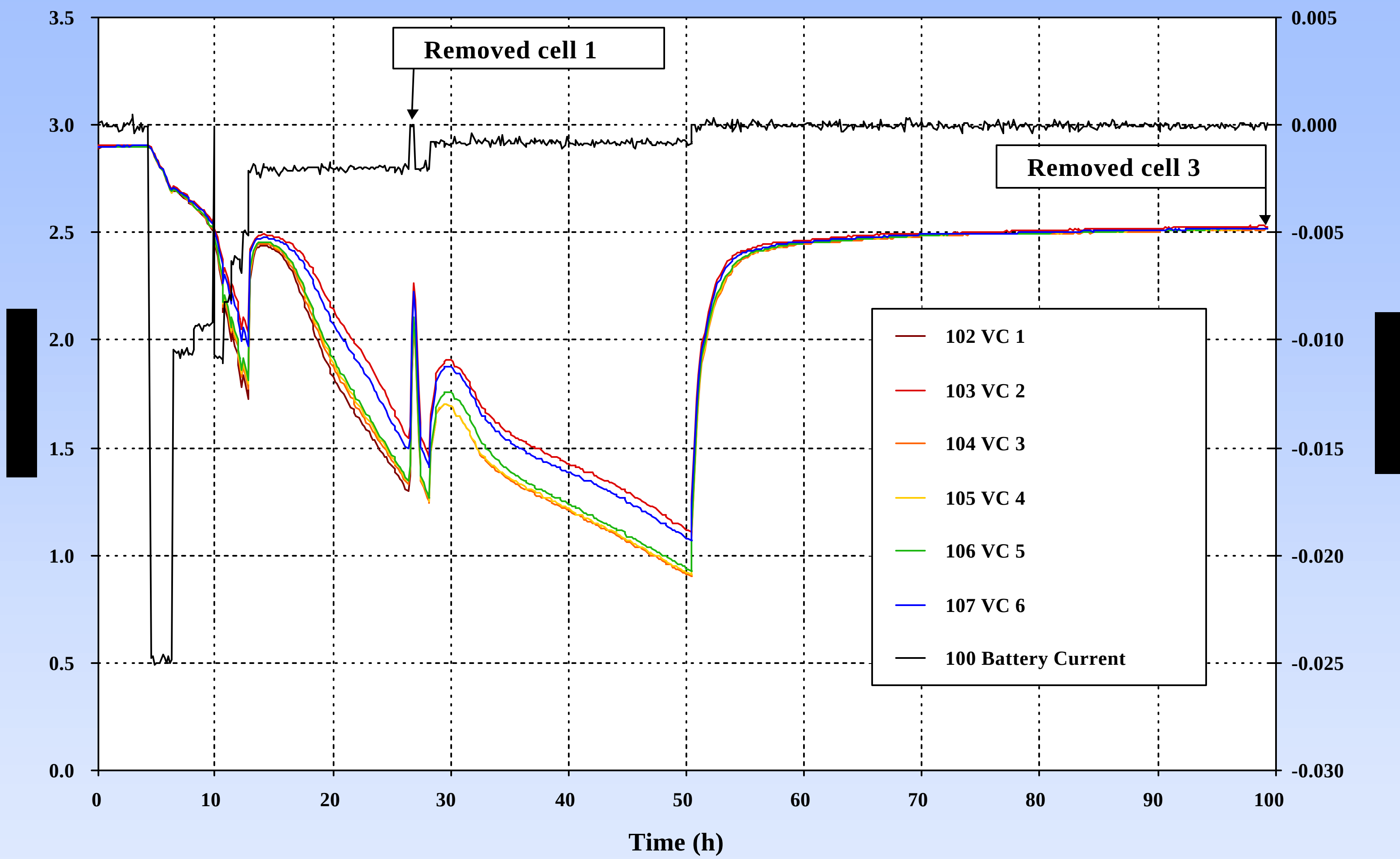
Initial capacity & self-discharge measurement



- Cell resistance estimated from charge--> discharge transients

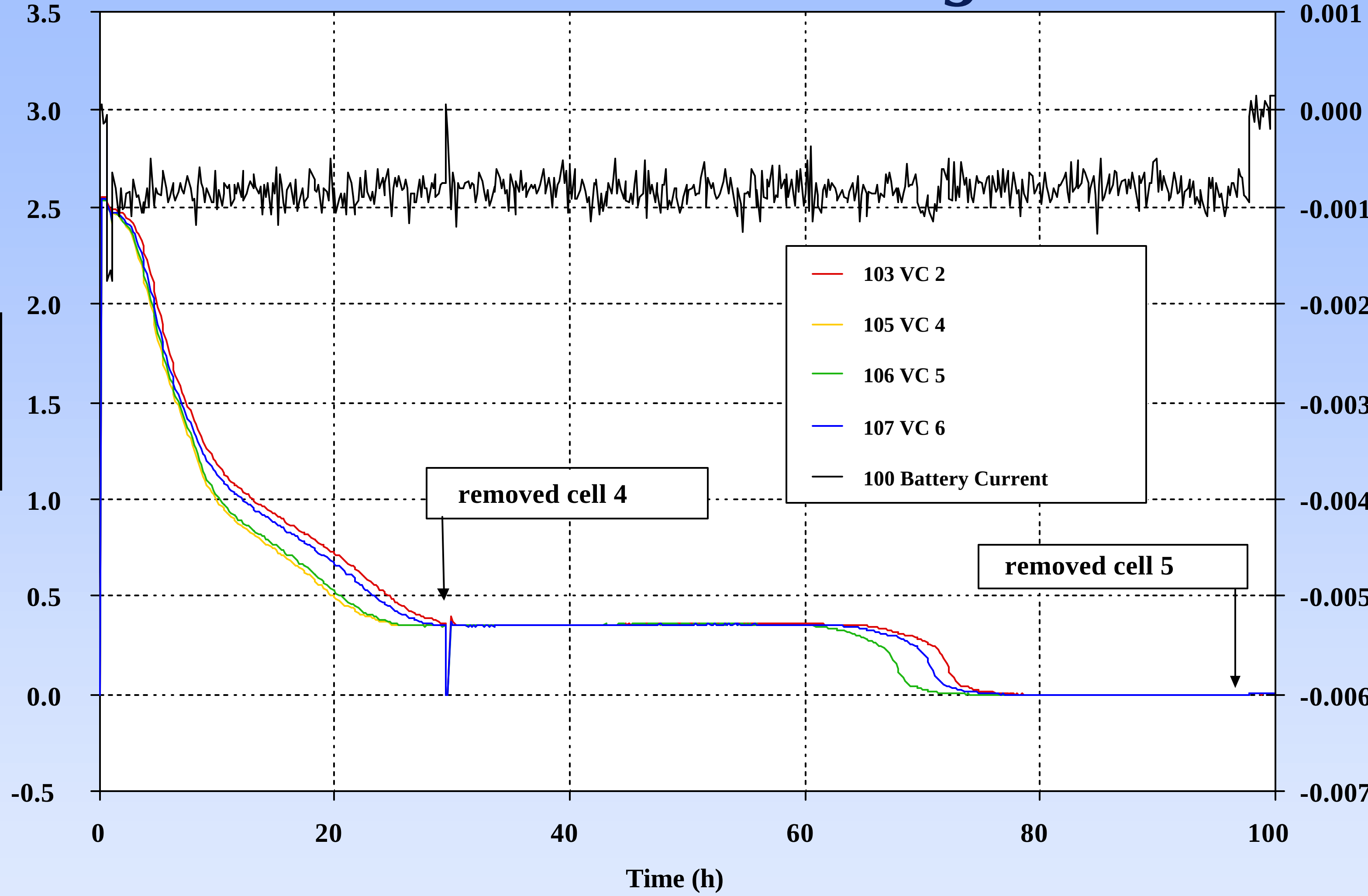
- Self-discharge estimated from difference between last discharge capacity and previous charge capacity over 6-hour open-circuit period.

First overdischarge



Because of rapid rise in cell internal resistance, the test reached the lowest current step sooner than expected and then went into open-circuit.

Second overdischarge



Overdischarge resumed at constant current of 0.8 mA. Cell 6 then left shorted for 3.5 months

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Test result summary

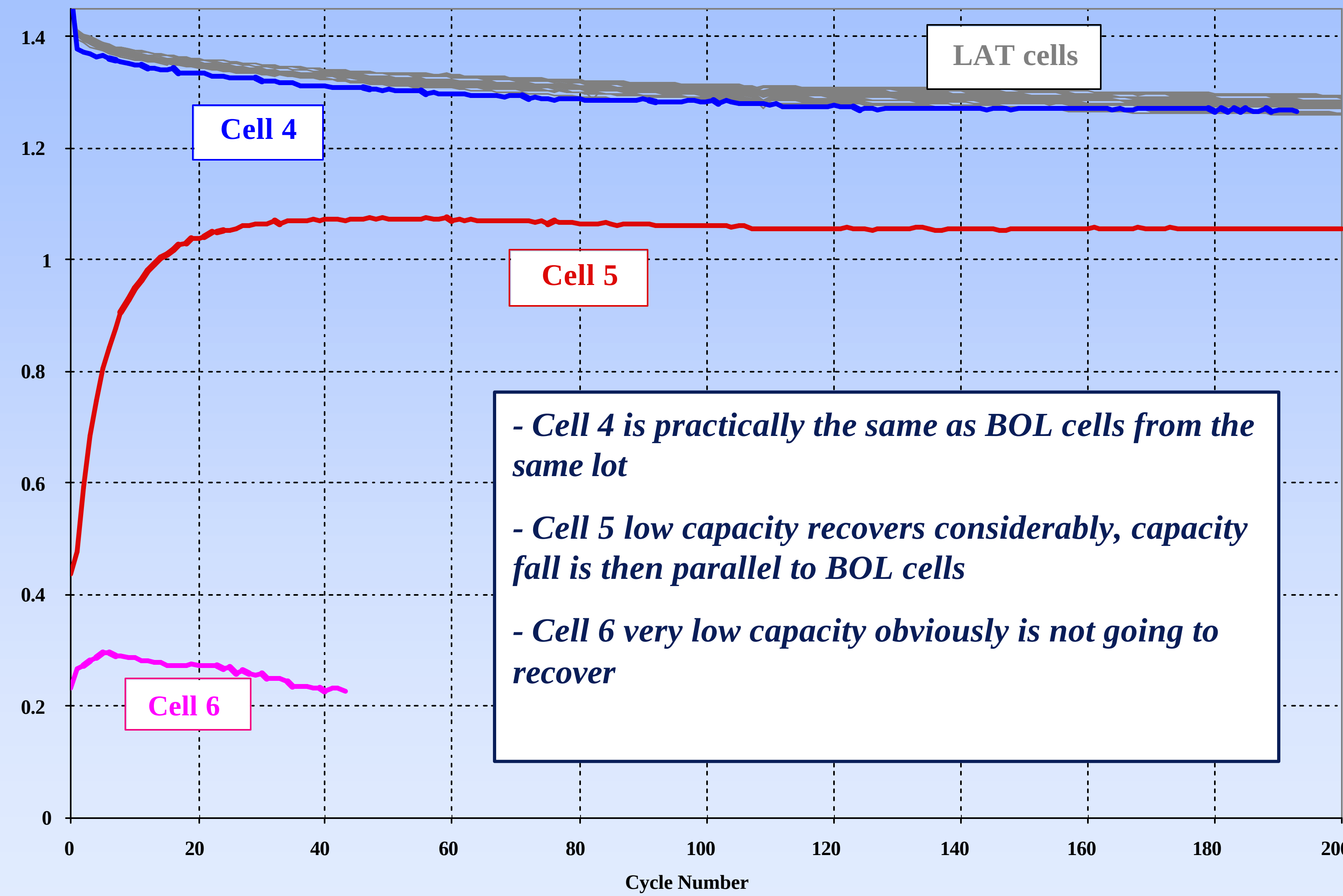
Cell	Before	1	2	3	4	5	6
Ah overdischarged	0	0.132	0.263	0.154	0.179	0.263	0.263
OCV after overdischarge	2.88	2.651	0.002	2.50	2.44	0.002	0.002
Cap 1st charge		1.5811		1.5966	1.6180	0.701	0.816¼
Cap 1st dch	1.4450 (1.4717*)	1.4732		1.4759	1.4860	0.369	0.318
Cap 2nd dch	1.4387	1.4553		1.4617	1.4639	0.439	0.335
Self-discharge current (mA)	1.0	3.2		2.4	2.3	[3.8]	[9.3]
Self-discharge current (mA)	1.0	3.2		2.4	2.3	[3.8]	[9.3]
Reoc (mohm)	115	115		122	117	678	927

Average of 24 cells from same lot during AEA Technology lot acceptance testing.

o *After leaving cell shorted for 3.5 months.*

Figures in square brackets are unreliable

Stress - cycling results



- Cell 4 is practically the same as BOL cells from the same lot

- Cell 5 low capacity recovers considerably, capacity fall is then parallel to BOL cells

- Cell 6 very low capacity obviously is not going to recover

Repeat tests after stress cycling

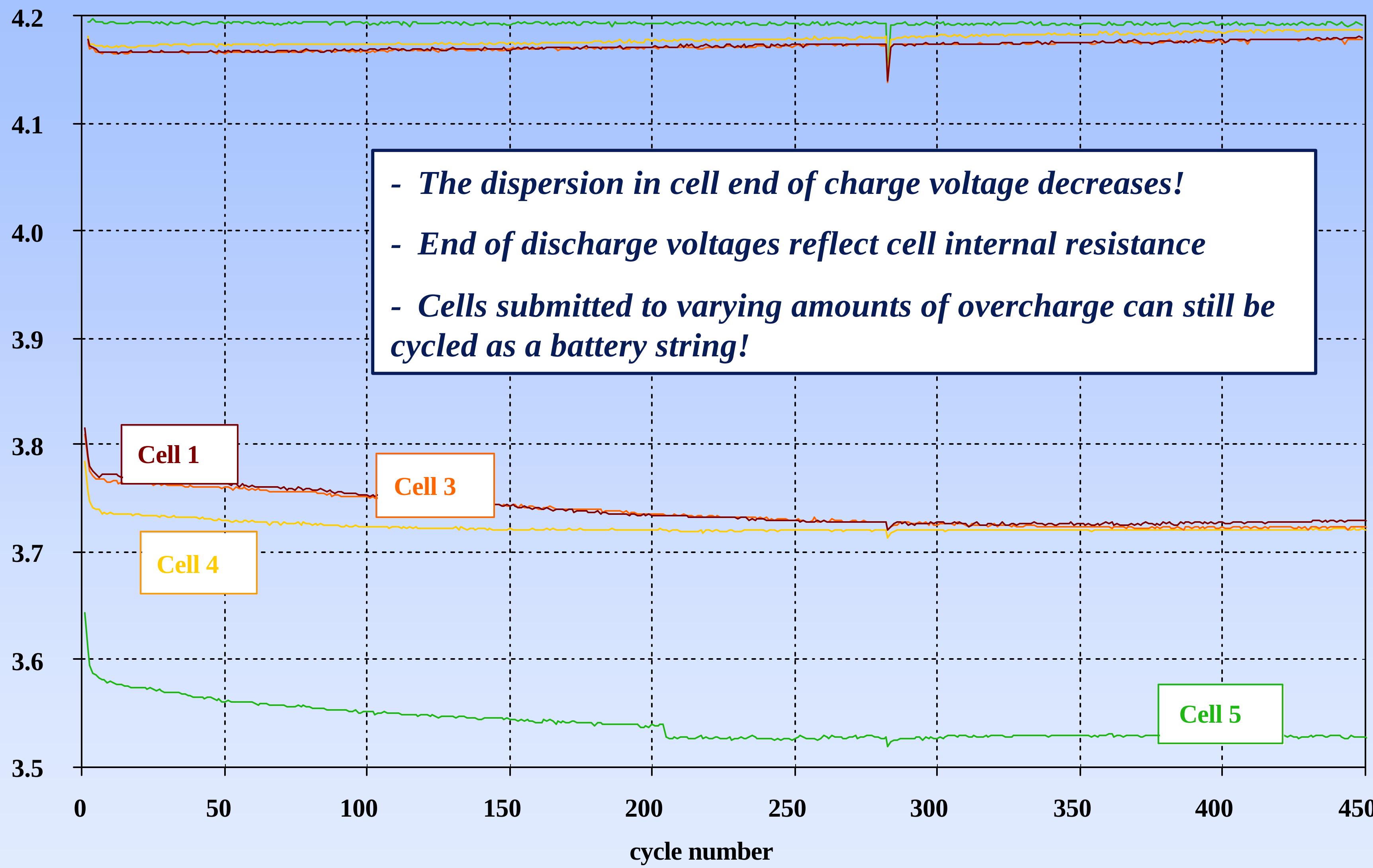
	BOL Cells	Cell 4	Cell 5
Stress cycle 5 cap	1.3904*		0.81
Stress cycle 200 cap	1.2774*		1.059
Cap 1^{st} dch	1.3471*	1.3546	1.2607
Cap 2^{nd} charge	--	1.3417	1.2585
Cap 2^{nd} dch	--	1.3537	1.2566
Self-discharge current (mA)	--	-2.0**	0.32
Reoc (mohm)	--	145	234
Voc eod	--	2.89	2.912
Repeat measurement			
Cap 1^{st} dch		1.3728	1.2717
Cap 2^{nd} charge		1.3708	1.2824
Cap 2^{nd} dch		1.3699	1.2701
Self-discharge current (mA)		0.15	2.05

Because of the observed capacity recovery during stress cycling, cells 4 and 5 were re-tested with the results shown opposite.

Self-discharge currents are again unreliable because of the unstable capacity

A further test gave higher, but still unreliable figures

Cycling cells 1, 3, 4 & 5 in series



Cells 1 & 3 conclusions

(<= 0.154 Ah overdischarge (relative to state of charge of a cell discharged at C/10 to 2.5 V))

- *Although cell 3 voltage on discharge fell to below 1V, open-circuit voltage was > 2.5V*
- *No evidence of degradation compared to BOL cells*

Cell 4 conclusions

(0.179 Ah overdischarge (relative to state of charge of a cell discharged at C/10 to 2.5 V))

- ***Unchanged capacity, internal resistance and stress cycling results show negligible signs of degradation compared to fresh cells. The observations that:***
- ***a: the open circuit voltage recovered to 2.44 after stopping the overdischarge and***
- ***b: the capacity measured during the first charge following overdischarge exceeded subsequent charge capacity by 0.173 Ah, (the same as the overdischarge within experimental uncertainty)***
- ***suggest that no irreversible electrochemical processes have occurred.***

Cell 5 conclusions

(0.263 Ah overdischarge (relative to state of charge of a cell discharged at C/10 to 2.5 V))

- *Internal resistance increased 6-fold resulting in large apparent loss of capacity.*
- *During stress cycling the internal resistance reduced to about double the normal value after 60 cycles and thereafter remained at this level.*
- *The 0.2 Ah deficit in capacity at the end of stress cycles can be accounted for entirely by the higher 'iR' drop associated with the elevated internal resistance.*
- *Downward trend in capacity after 60 stress cycles parallels closely the behaviour of fresh cells, suggesting that the cell's cycle life has not been compromised.*
- *The difference in capacity between the first charge following the overdischarge and the subsequent charge is again close to the overdischarged ampere-hours, suggesting that the majority of the overdischarged capacity is recoverable.*
- *This is remarkable in view of the fact that the cell was slightly reversed towards the end of overdischarge and the open circuit voltage was only 2 mV above zero.*

Cell 6 conclusions

(0.263 Ah overdischarge + 3.5 month short-circuit)

- *Capacity did not exceed 0.3 Ah during cycling. Cell unusable*

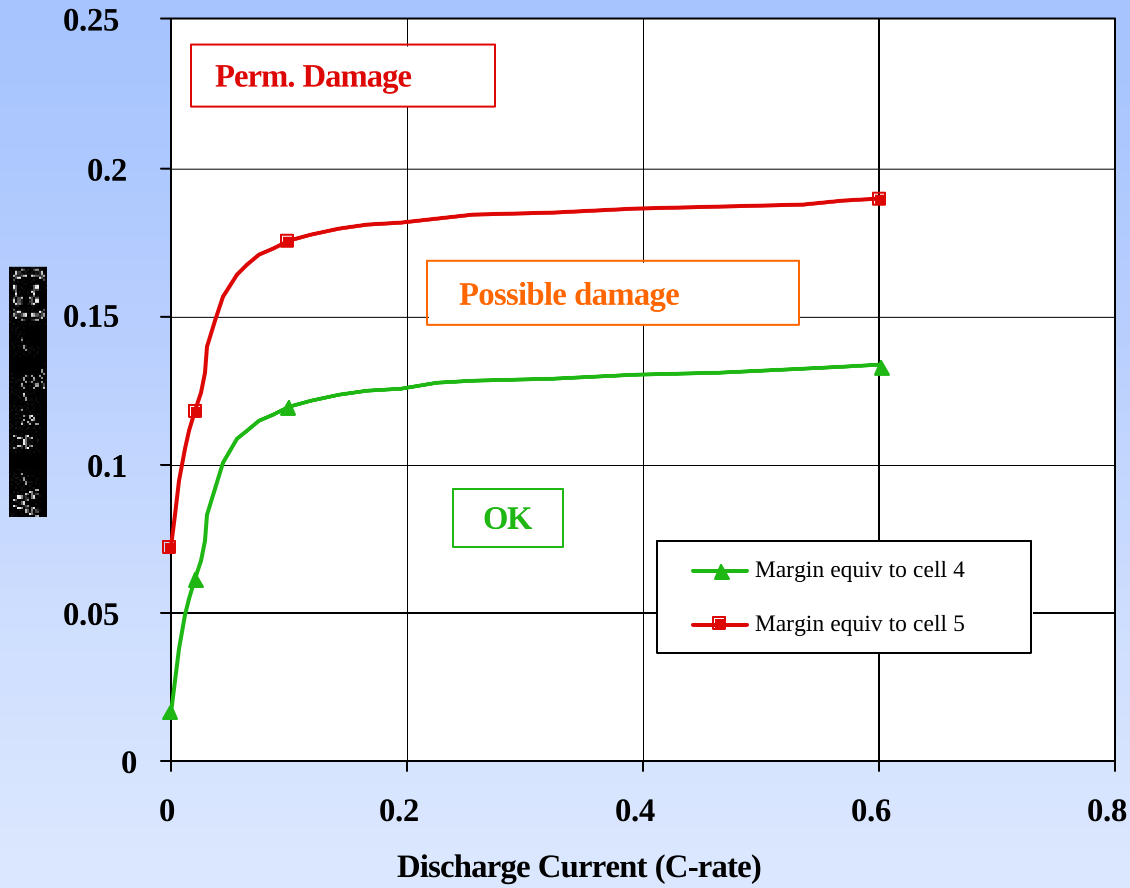
Result summary

- Cells overdischarged by not more than 0.179 Ah (relative to the state of charge of a cell discharged at C/10 with to 2.5 V) are not significantly damaged.
- Cells overdischarged by 0.263 Ah suffer a very large increase in internal resistance, but this recovers to about twice the normal value during cycling. Cycle life and self-discharge current is apparently not affected.
- Overdischarge up to 0.263 Ah does not affect self-discharge rate.
- Cells left shorted for 3.5 months still have capacity but are unusable

Conclusions

- Cells are not damaged provided the open circuit voltage (OCV) does not fall below 2.4 V.
- Large internal resistance increase at low states of charge means that:
  - Lower voltages under load are acceptable
  - It is hard to overdischarge cells in a short time period
- Cells are damaged if OCV < 2.4 V:
  - Danger to battery is low discharge currents for prolonged periods

Addendum: Practical Implications



Approximate Ah margin as function of discharge current with BDR cut-off set at 3.33 V/cell

For a specific spacecraft power system the battery overdischarge Ah margin depends mainly upon the discharge current at the moment the bus undervoltage limit is reached.

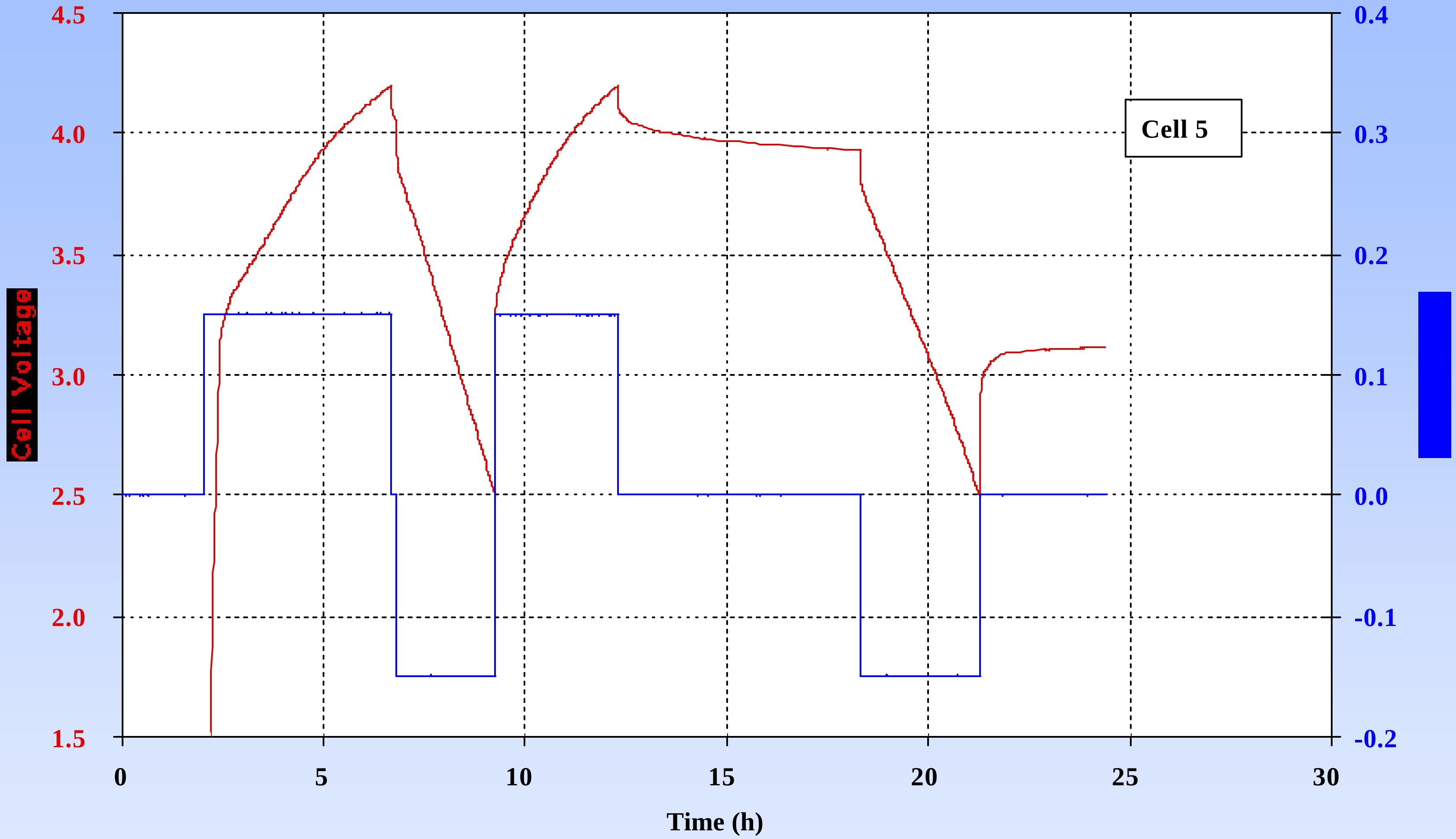
The example opposite has an undervoltage limit of 3.33 V/cell but a value of 2.5 V/cell would decrease the margin by less than 0.02 C.

For a particular spacecraft mission it then is in principle possible to estimate how soon batteries would be destroyed following a collapse of the bus.

Acknowledgements

- ***Horst Fiebrich and Ferdinando Tonicello of ESTEC provided inputs on the likely current seen by the battery at low bus voltages.***
- ***Carl Thwaite of AEA Technology is thanked for the LAT screening data and advice on test procedures.***

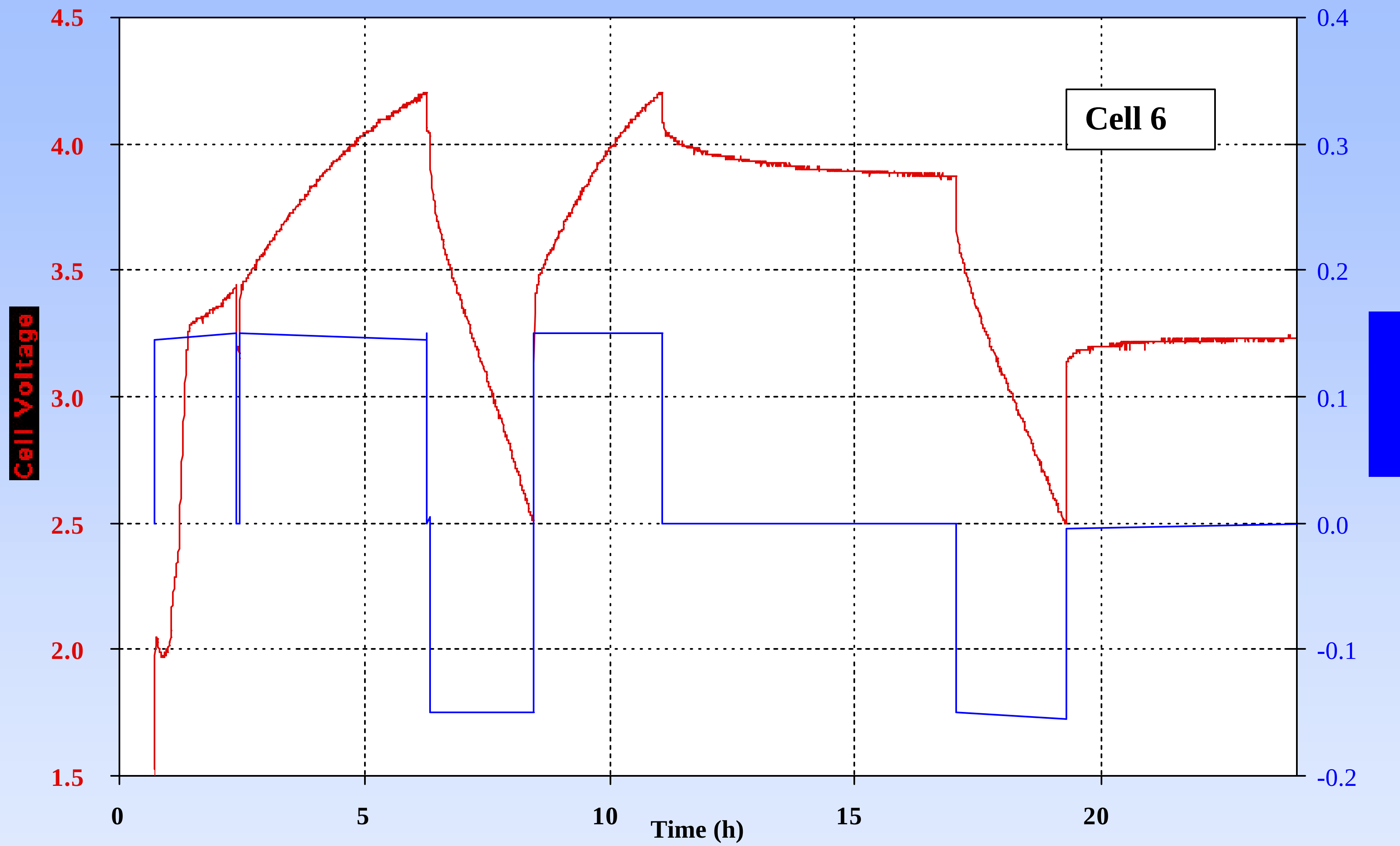
Cell 5 after overdischarge



Calculated self-discharge high because capacity was not stable

Final open-circuit EMF higher than BOL cells because of increased internal resistance

Cell 6 after overdischarge



Cell can still be cycled, albeit at low capacity (0.2 Ah)

Battery Safety Testing

Introducing the EV-ARC

Phill O'Kane & Martyn Ottaway

Thermal Hazard Technology

1 North House, Bond Avenue, Bletchley MK1 1SW, England.

www.thermalhazardtechnology.com

Accelerating Rate Calorimetry

- Devised by Dow Chemical in 1970’s
- Simulate worst case “runaway reaction”
- Widely used in Chemical and Battery Industry
- Applicable for most domestic batteries
- EV-ARC developed for larger batteries

THE QUESTIONS...

Is there a thermal hazard?

At what temperature does it begin?

How many processes; a simple or complex mechanism?

Is there an effect of impurity or additive?

How fast does it occur? The kinetics.

How big an event is it? The Thermodynamics.

What temperature will all control be lost?

What time is there before explosion?

How much pressure develops?

What is the rate of pressure rise?

i.e. IS MY PROCESS SAFE???!!!

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How and why batteries give out heat due to Discharge or Chemical Reaction

....and therefore how to develop batteries and new chemistries that are more safe.

How batteries might have batch differences

....and therefore how to monitor production process to keep batch variation down

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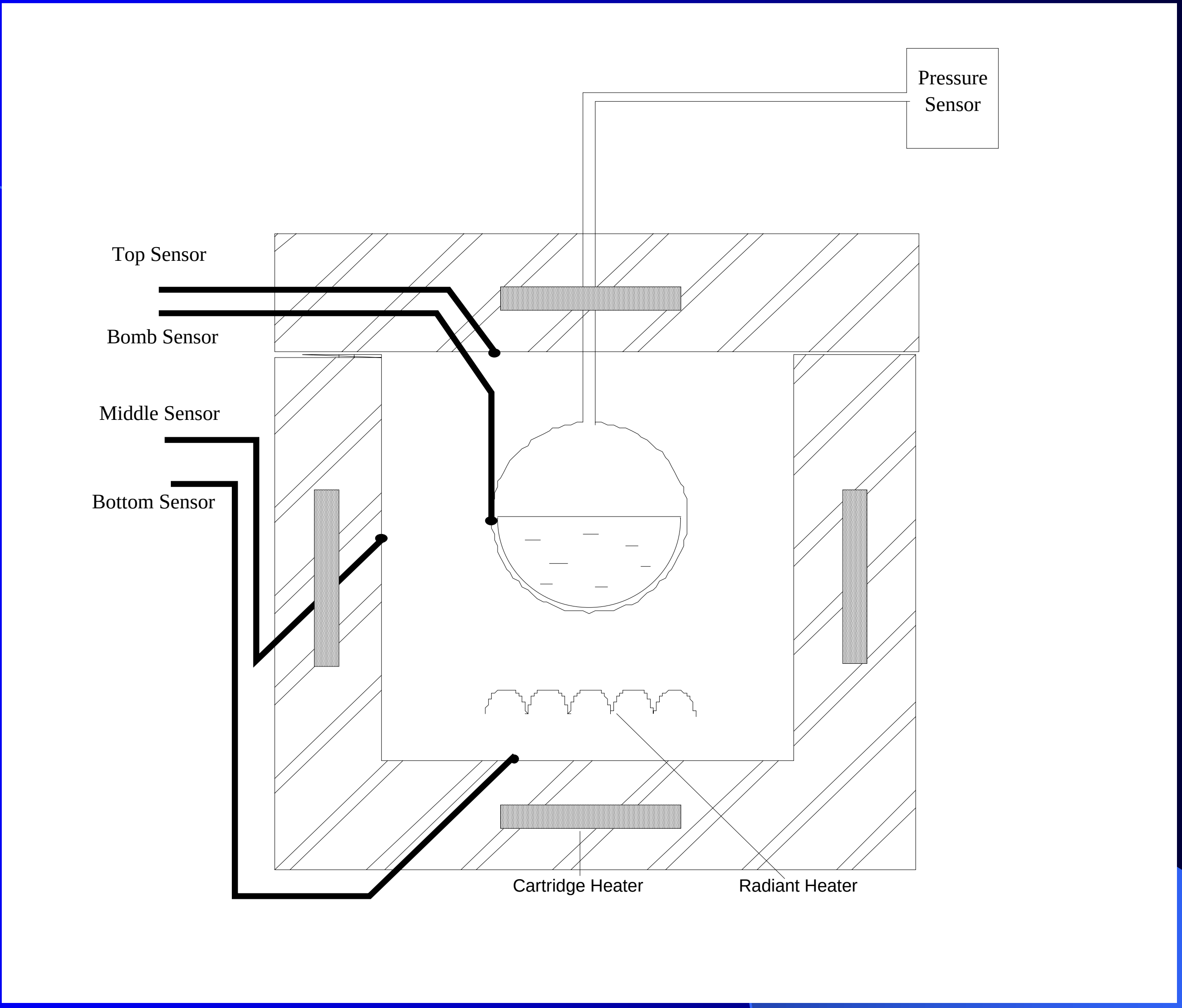

Pressure Sensor
Top Sensor
Bomb Sensor
Middle Sensor
Bottom Sensor
Cartridge Heater
Radiant Heater

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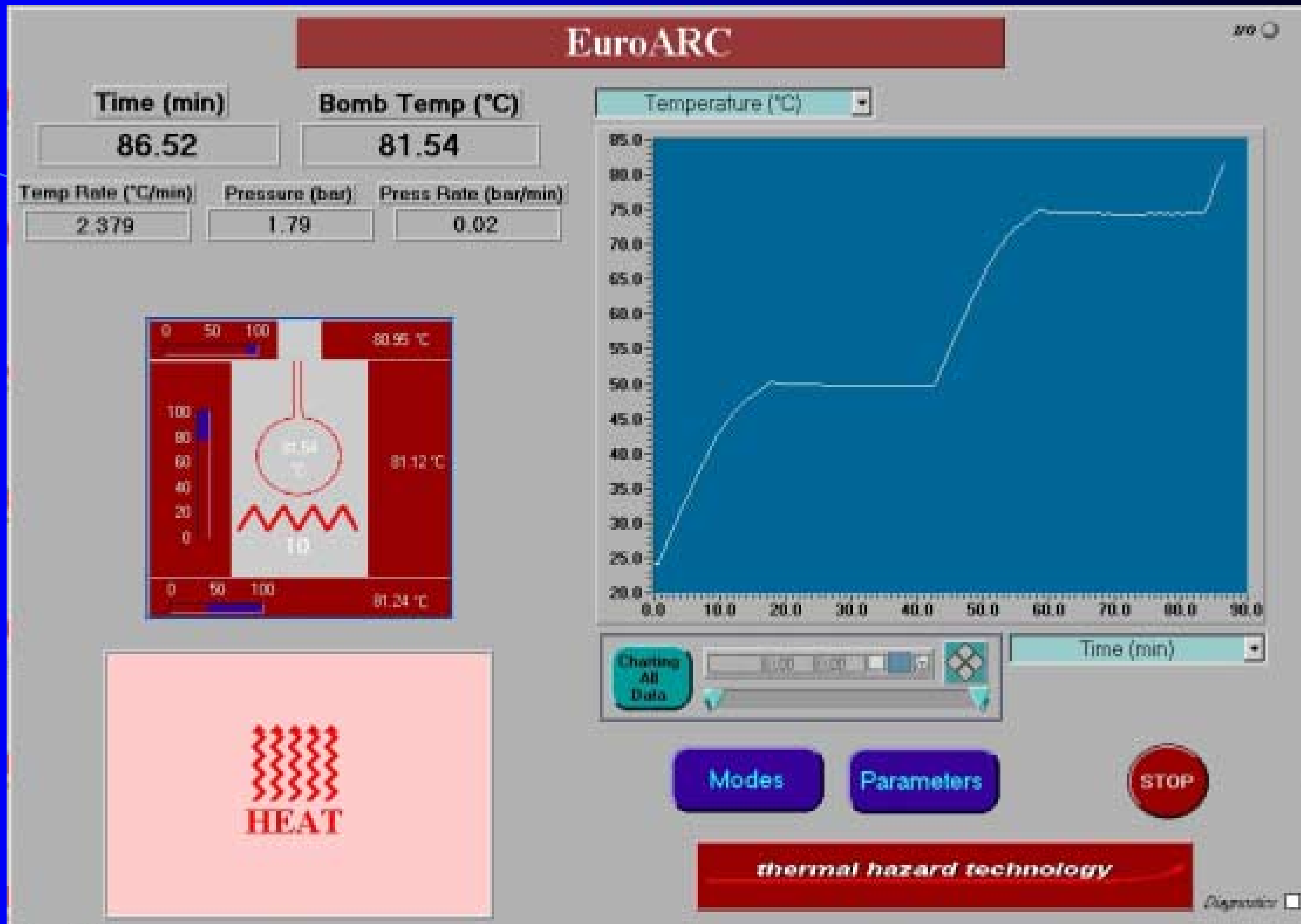
thermal hazard technology



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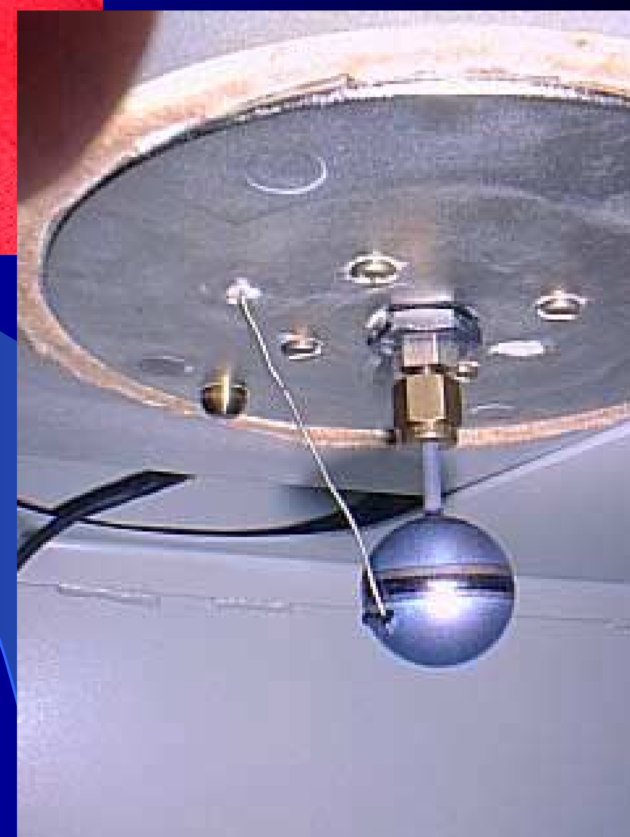
thermal hazard technology



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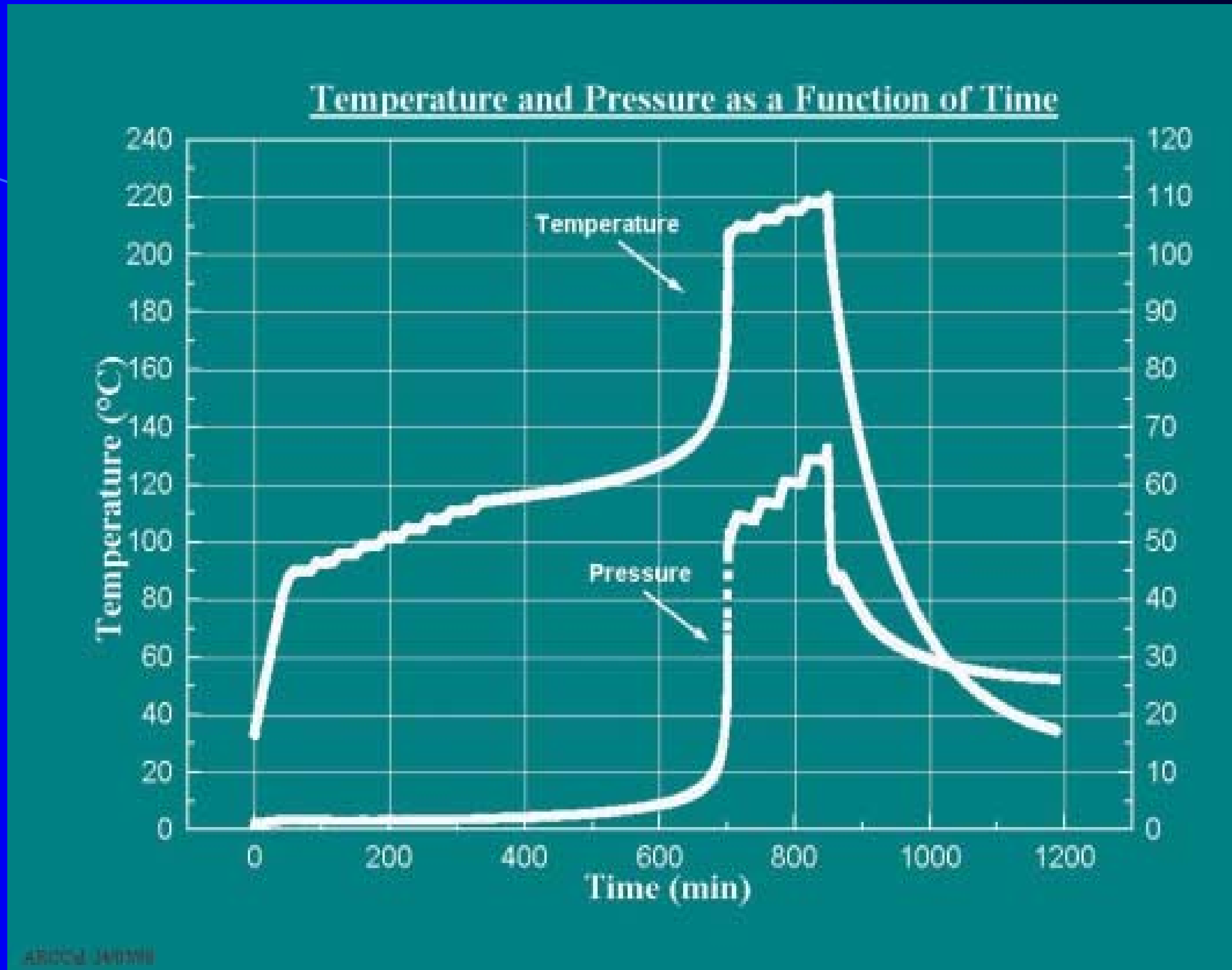
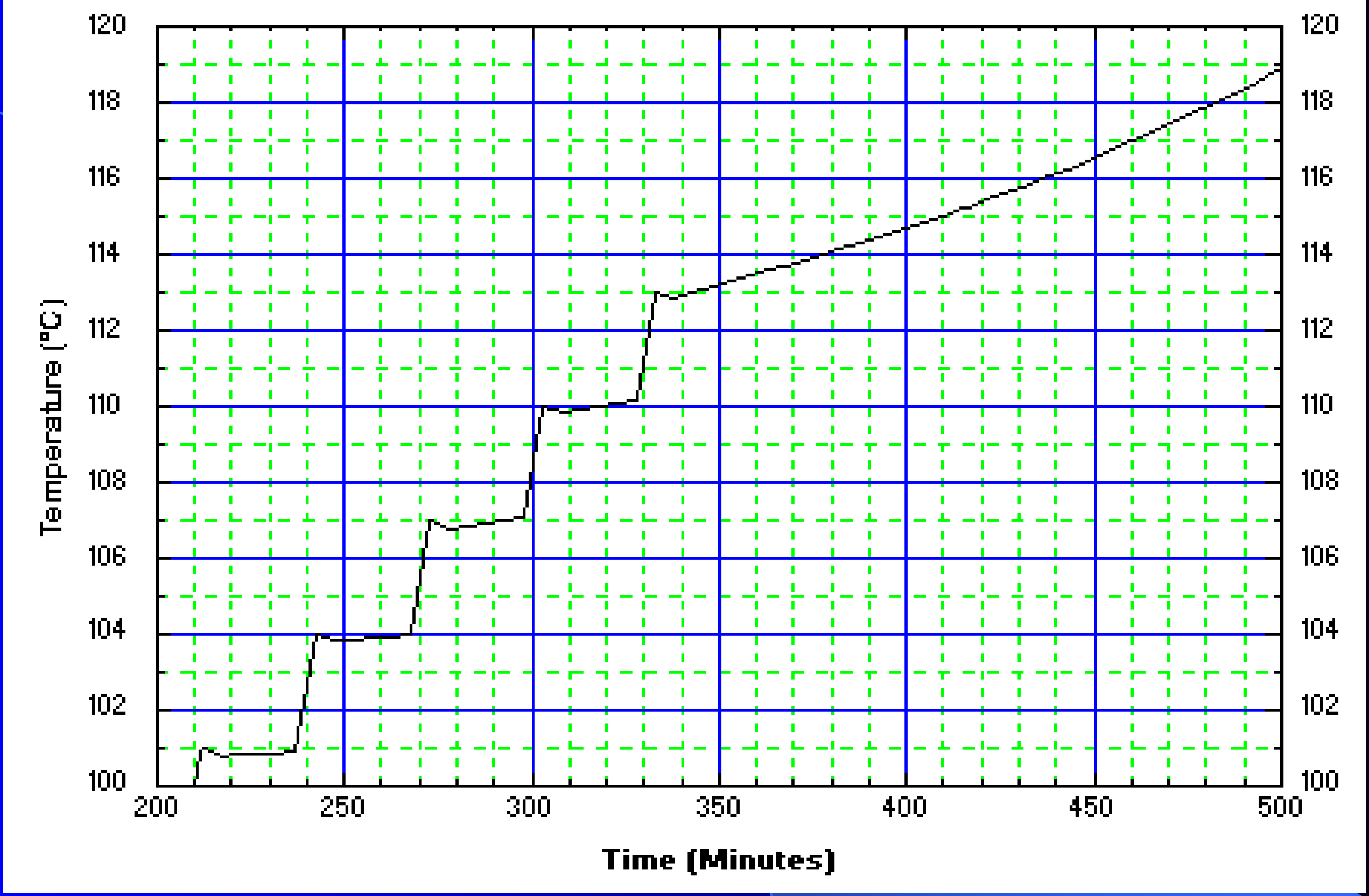
thermal hazard technology





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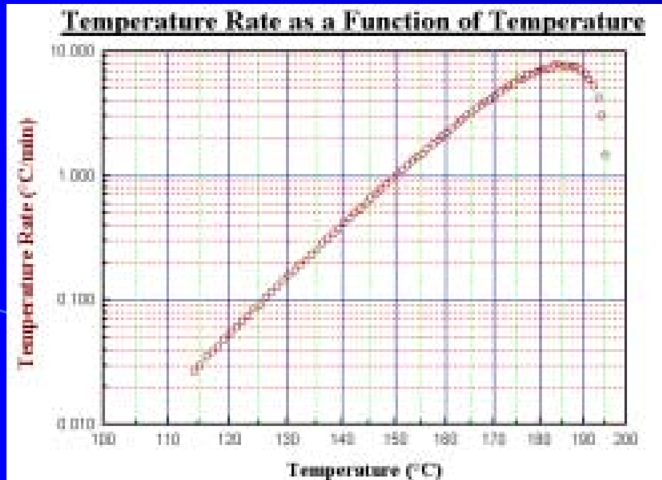

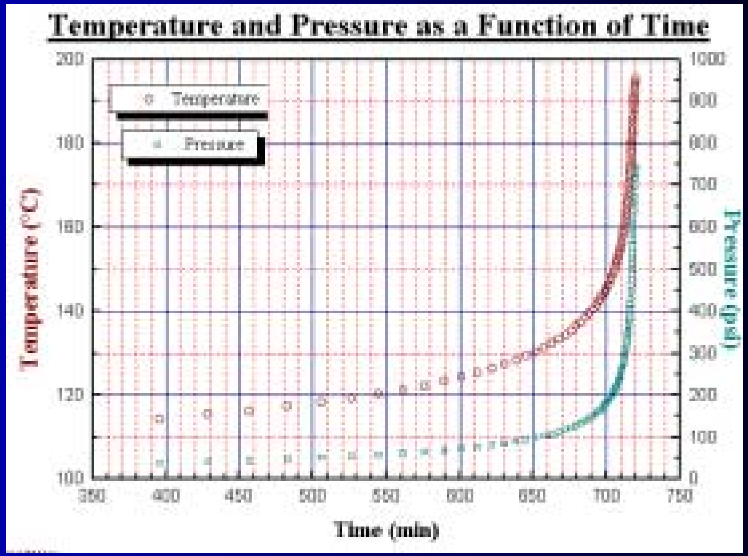

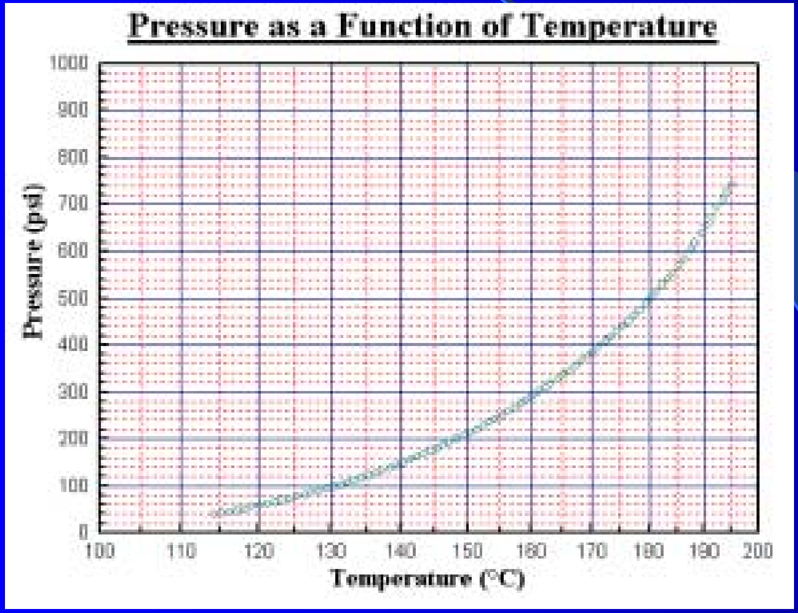

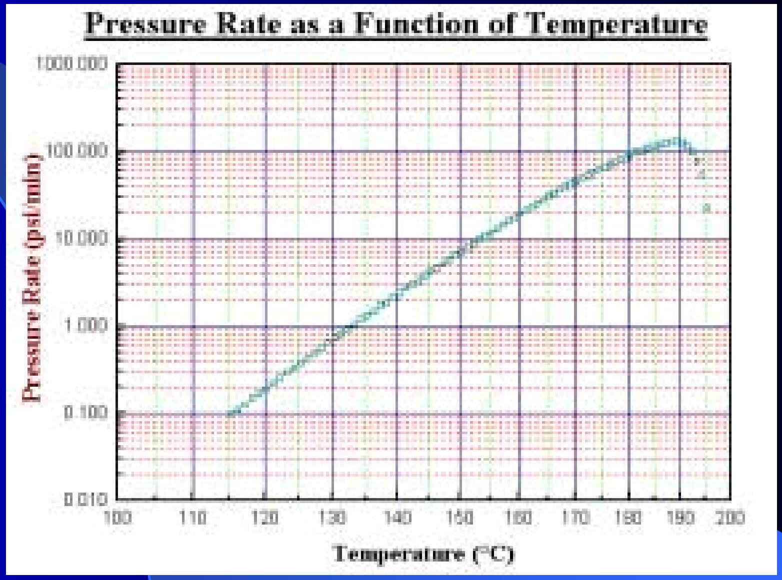

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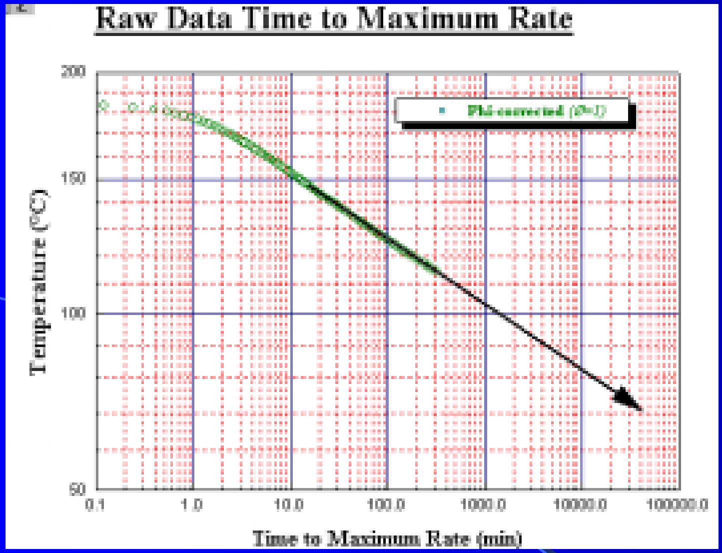
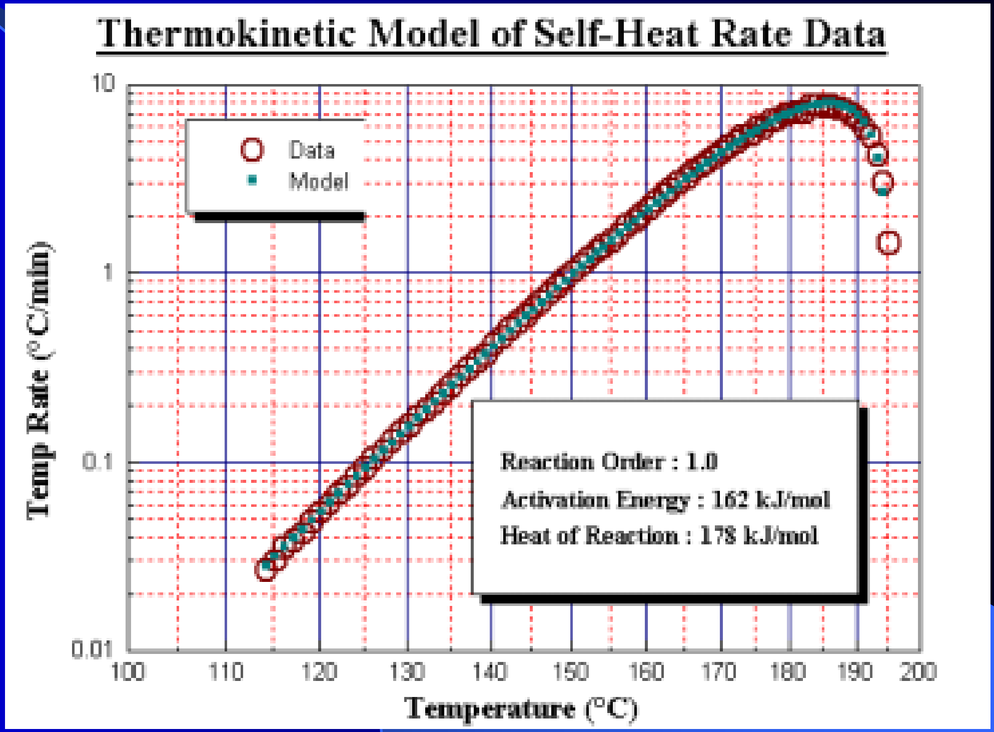
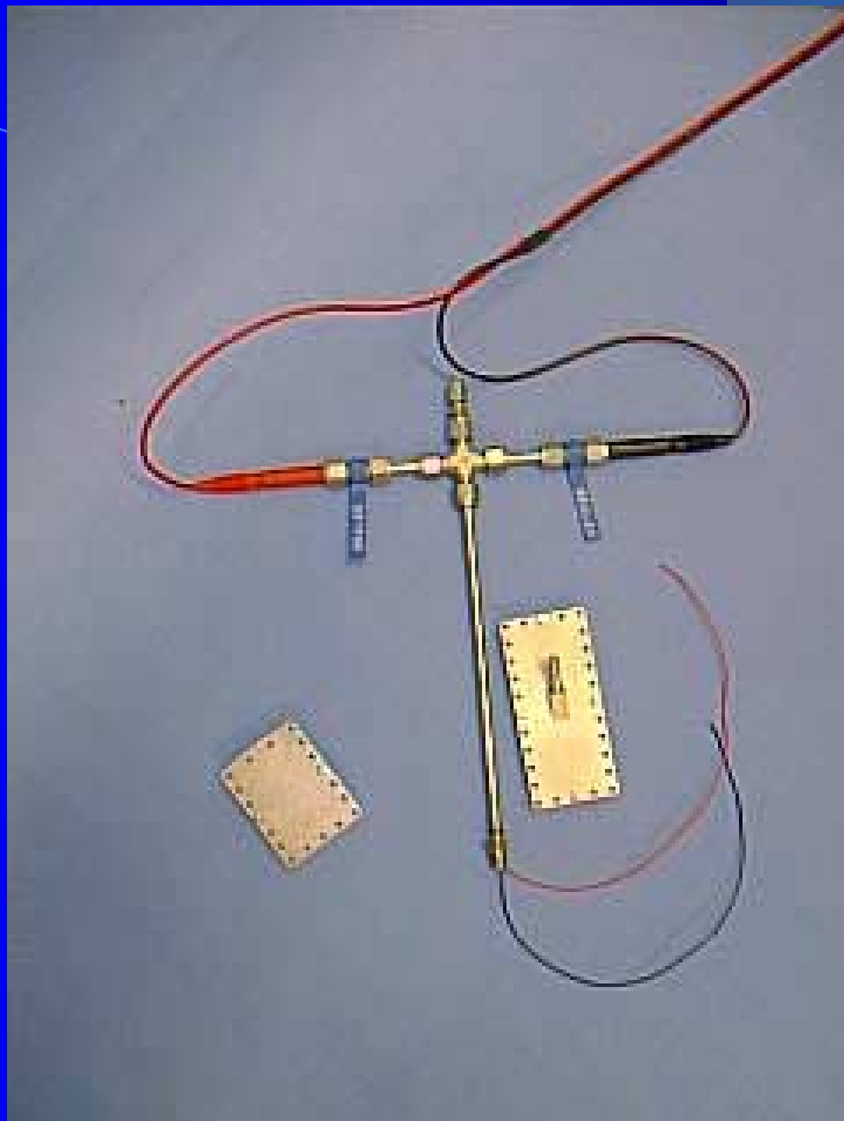
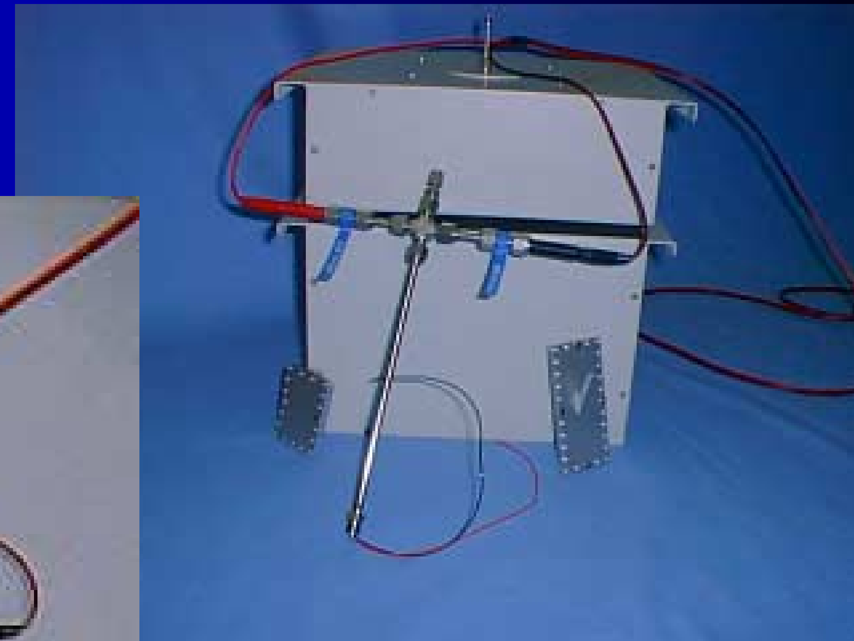


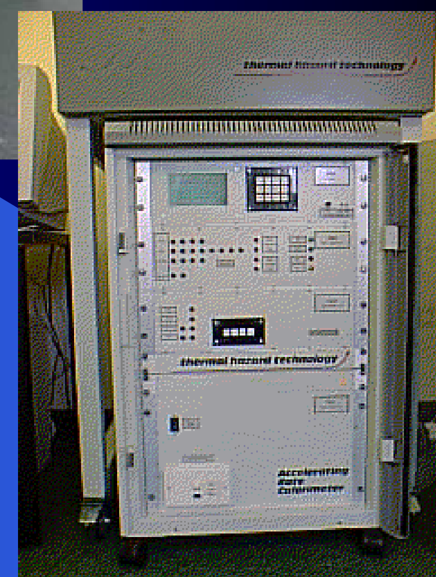


Development of Battery Safety and Test Options






CHARGE
DISCHARGE
SHORT
READY
POWER LEVEL
BSU
THERMOSTAT
thermal hazard technology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thermal hazard technology
accelerating rate calorimeter

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Summary

With a Battery Safety Option the Accelerating Rate Calorimeter may be employed to study

- batteries (at various charge levels)
- battery components
- batteries when shorted
- batteries when overcharged or overdischarged
- batteries when charged, discharged cycled

To obtain….. safety, lifecycle or electrochemical efficiency data

Using the ARC with Batteries

Prismatic, Polymer, Coin, AA, 3/4A 18650 etc

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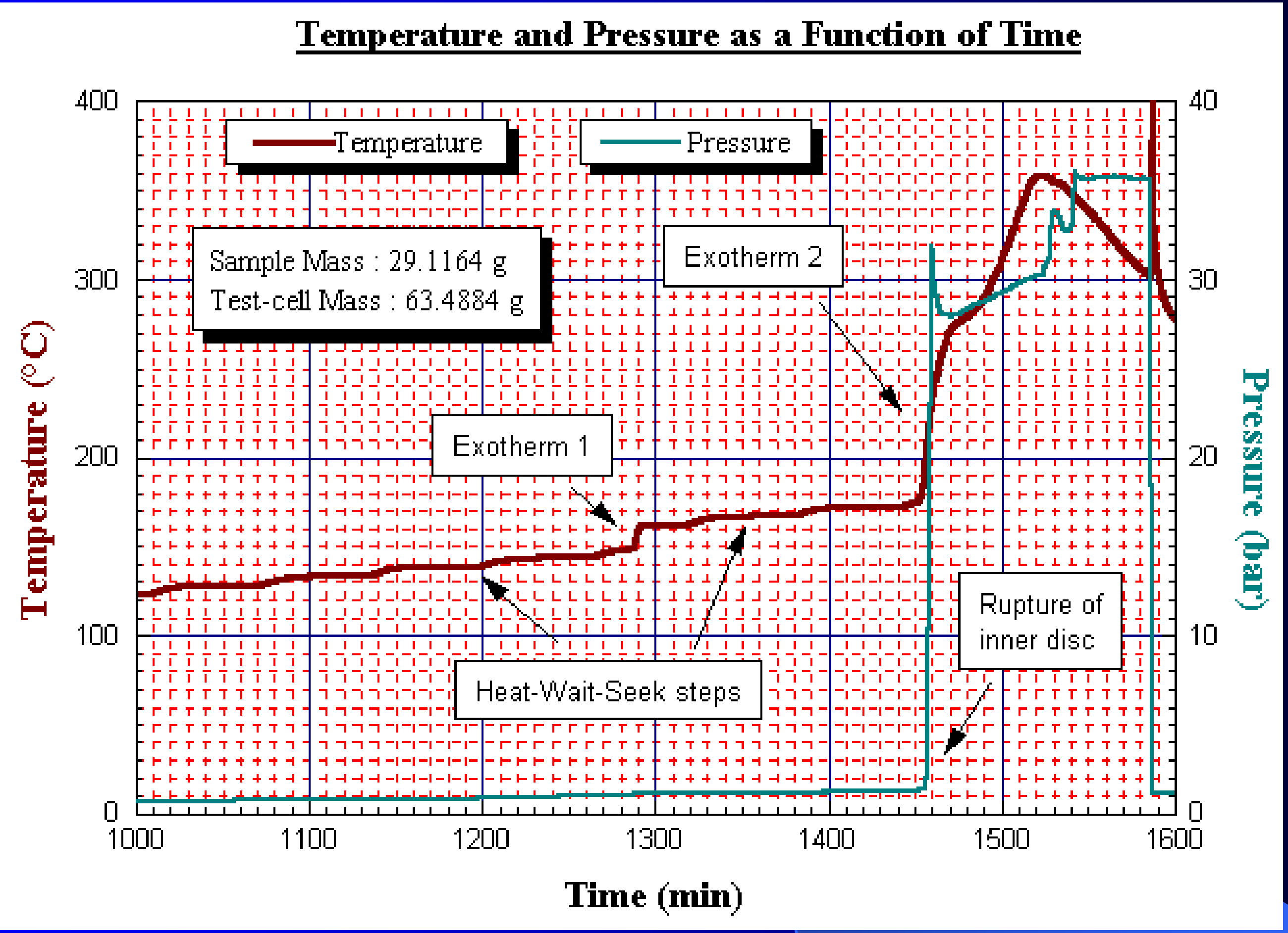
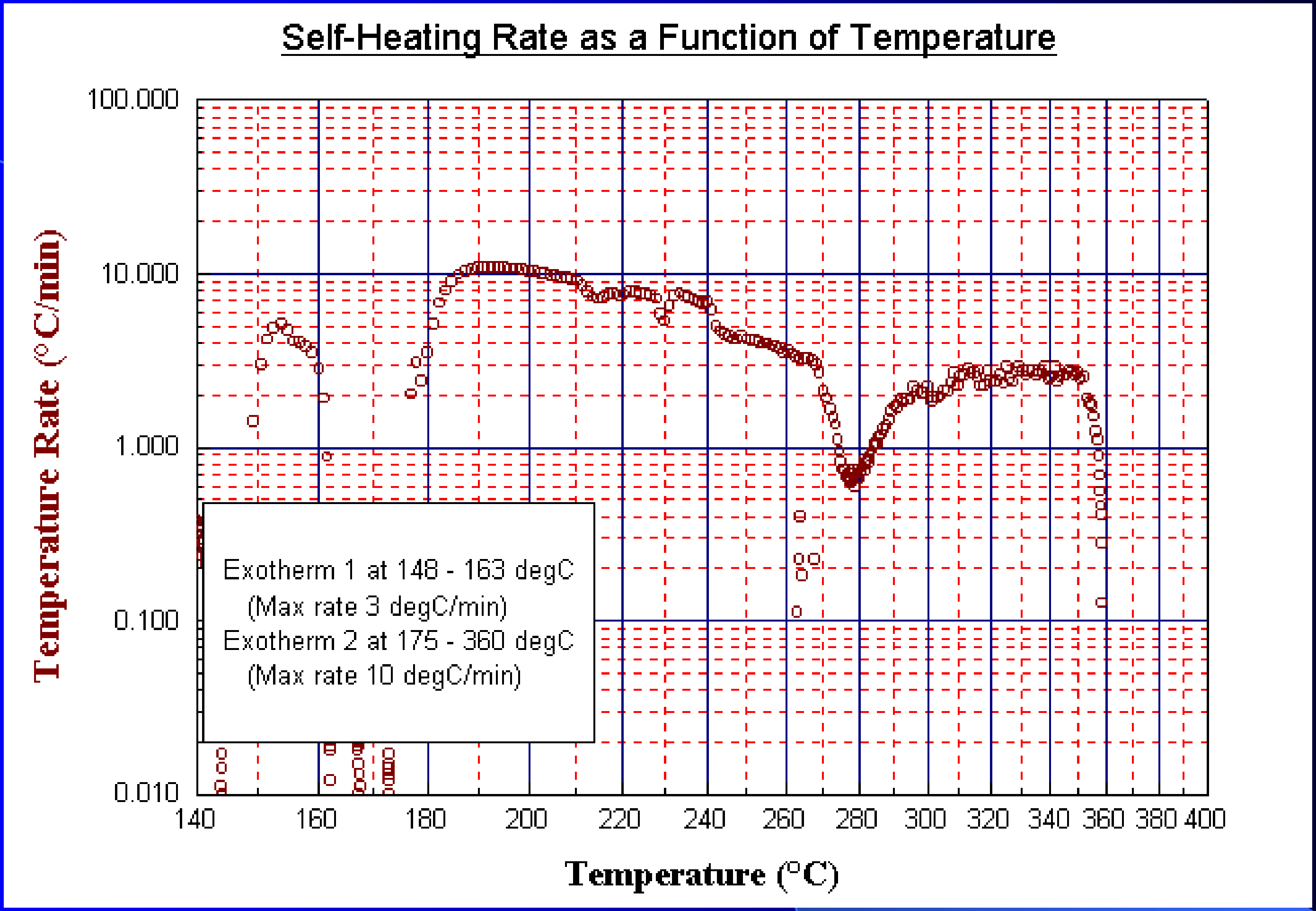
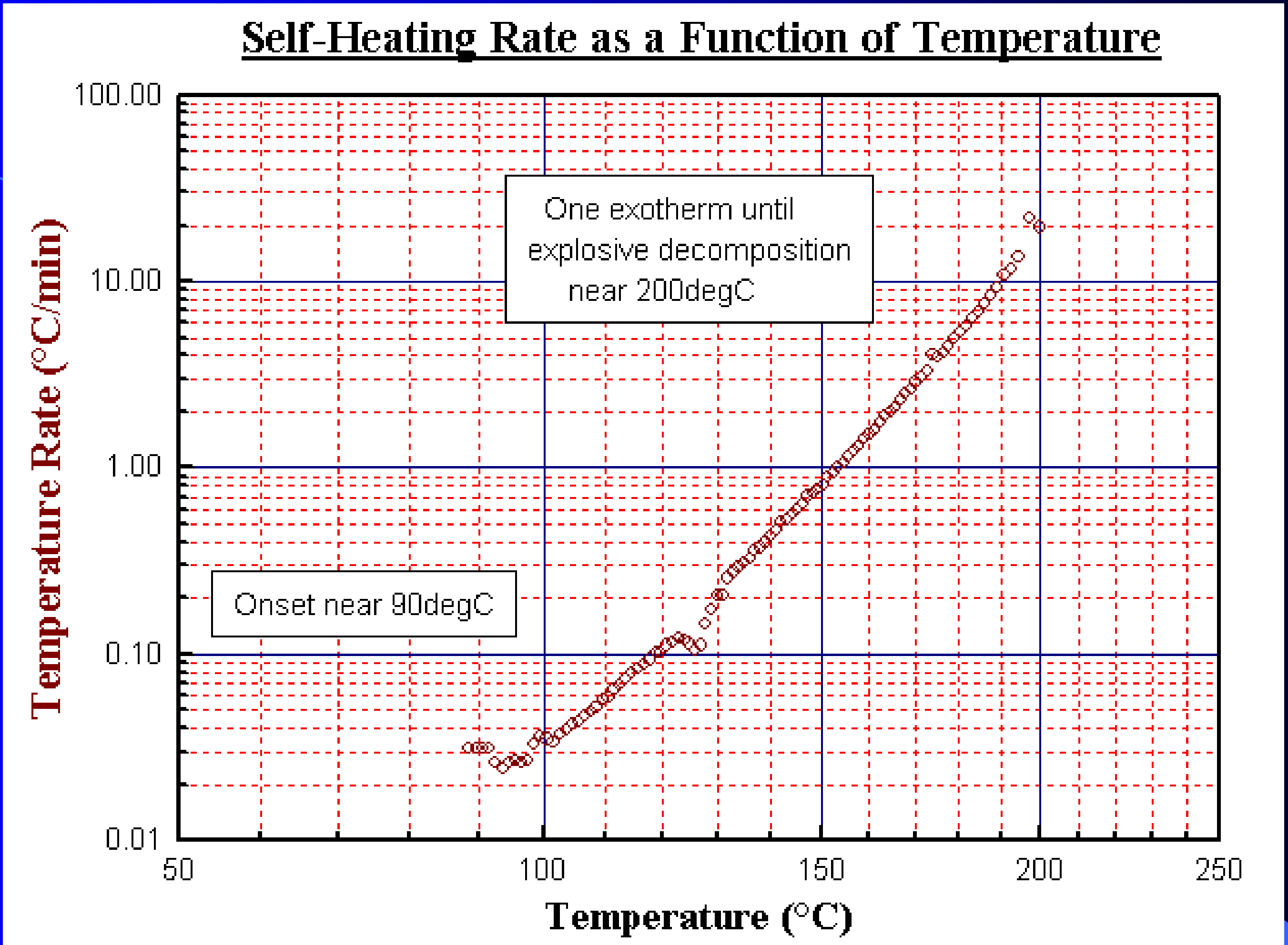




Self-Heating Rate as a Function of Temperature
Temperature Rate (°C/min)
100.000
10.000
1.000
0.100
0.010
Temperature (°C)
140
160
180
200
220
240
260
280
300
320
340
360
380
400
Exotherm 1 at 148 - 163 degC
(Max rate 3 degC/min)
Exotherm 2 at 175 - 360 degC
(Max rate 10 degC/min)


Self-Heating Rate as a Function of Temperature
One exotherm until explosive decomposition near 200degC
Onset near 90degC
Temperature Rate (°C/min)
100.00
10.00
1.00
0.10
0.01
50
100
150
200
250
Temperature (°C)

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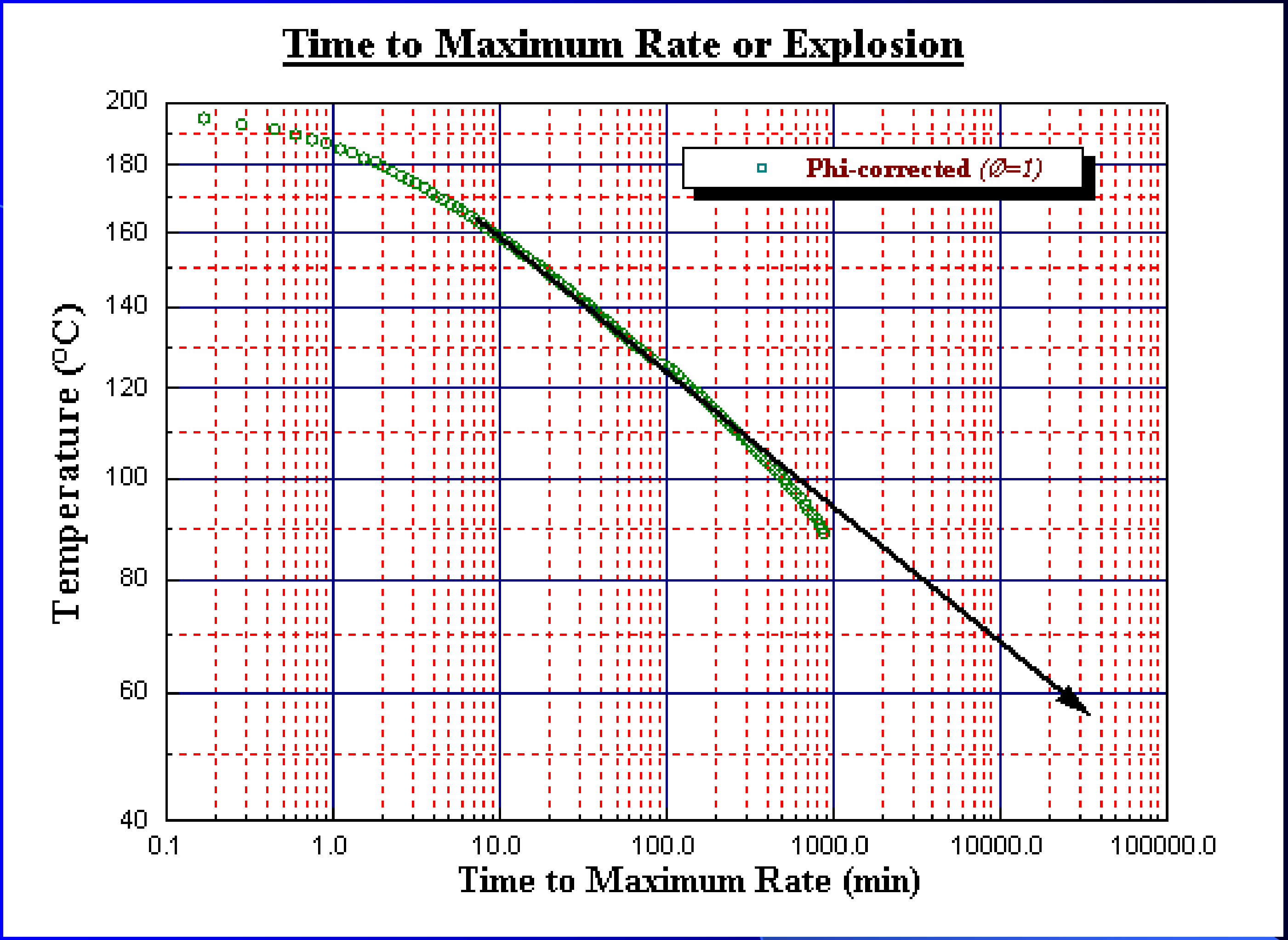
(Screen 10)


Time to Maximum Rate or Explosion
Phi-corrected (Ø=1)
Temperature (°C)
200
180
160
140
120
100
80
60
40
0.1
1.0
10.0
100.0
1000.0
10000.0
100000.0
Time to Maximum Rate (min)

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Design and Development of the EV-Accelerating Rate Calorimeter

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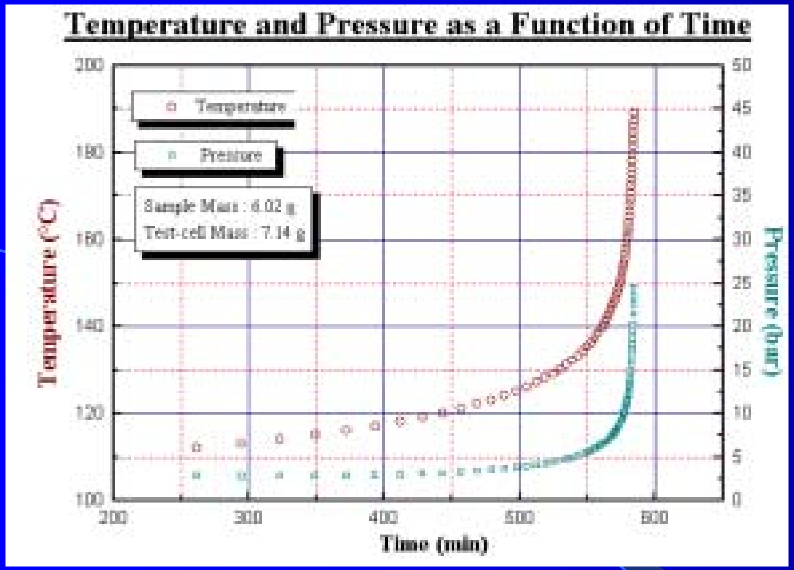
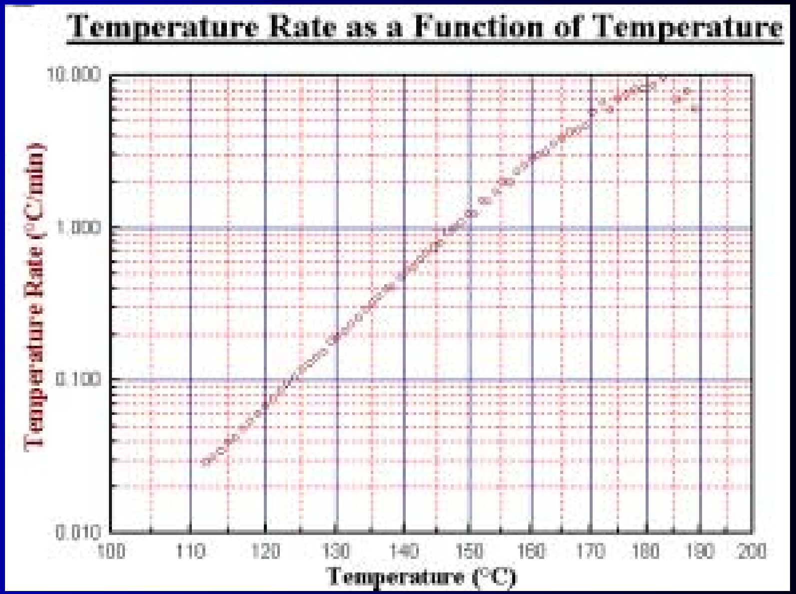
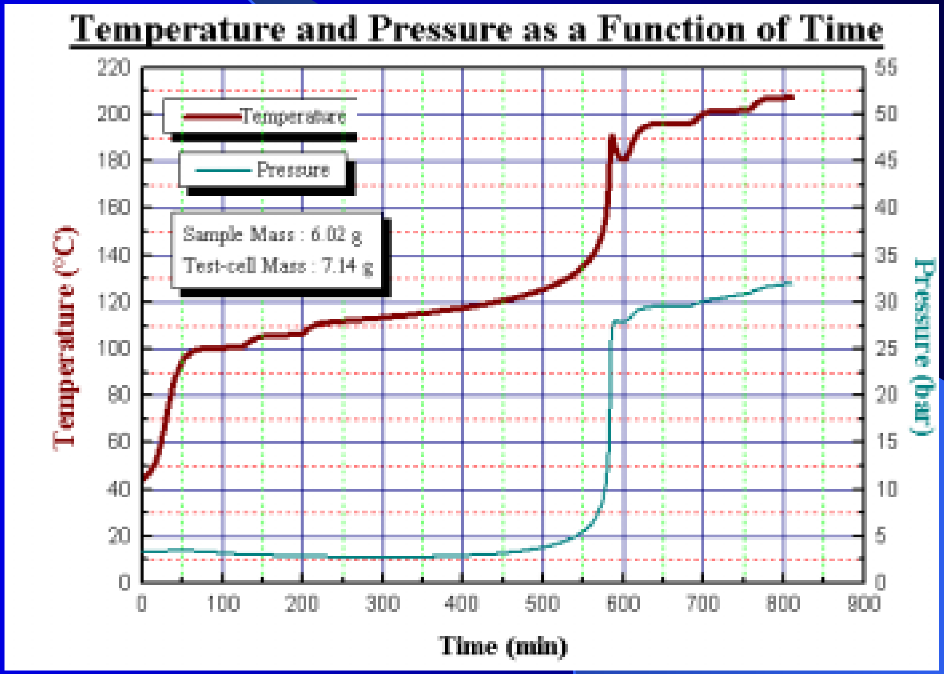






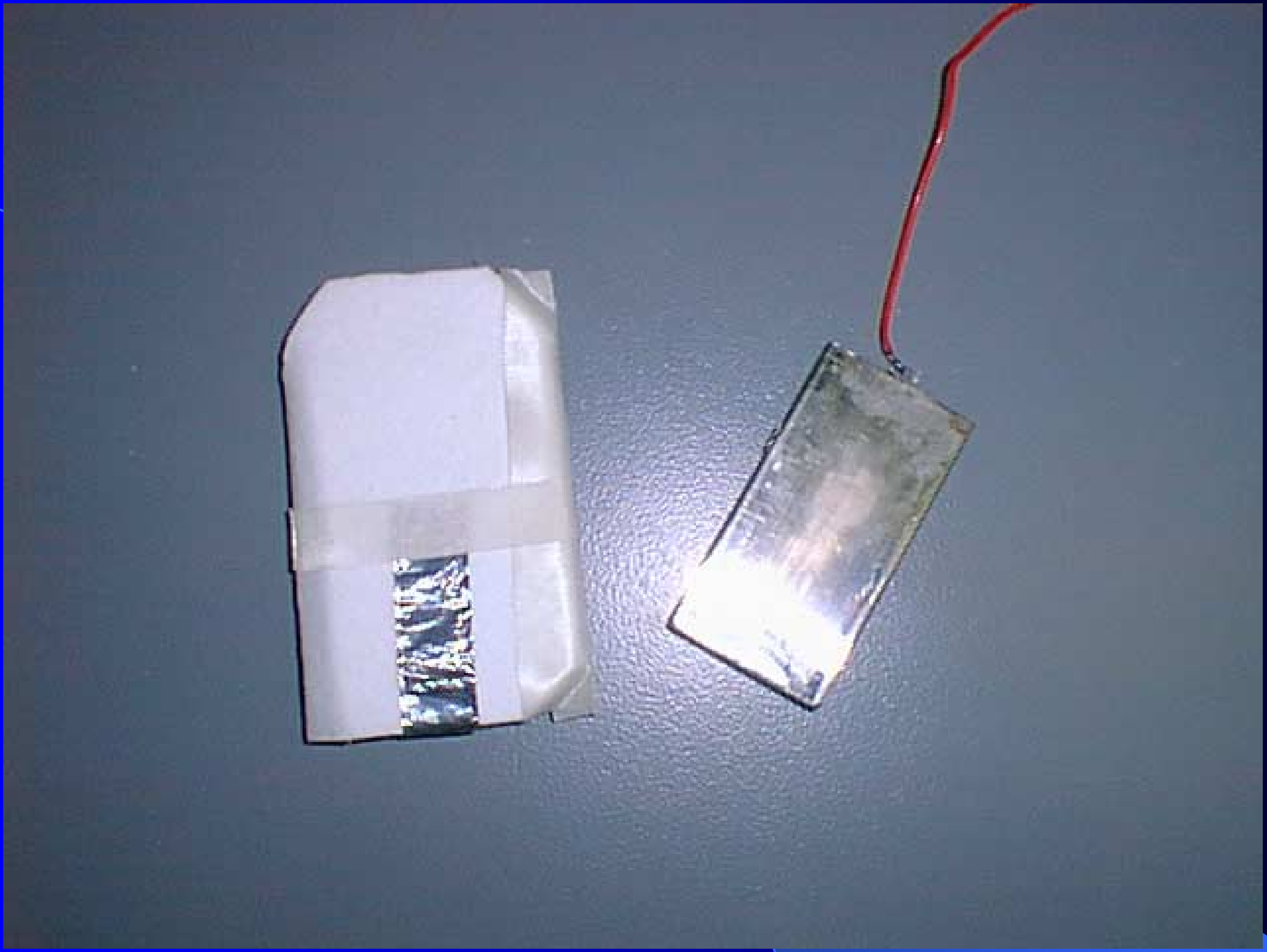
thermal hazard technology

Experimental Set-up

- Adiabatic Tests
- Isothermal Tests

Batteries are not allowed to runaway!

thermal hazard technology



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Electrothermal Dynamics

- Discharging
- Charging
- Cycling

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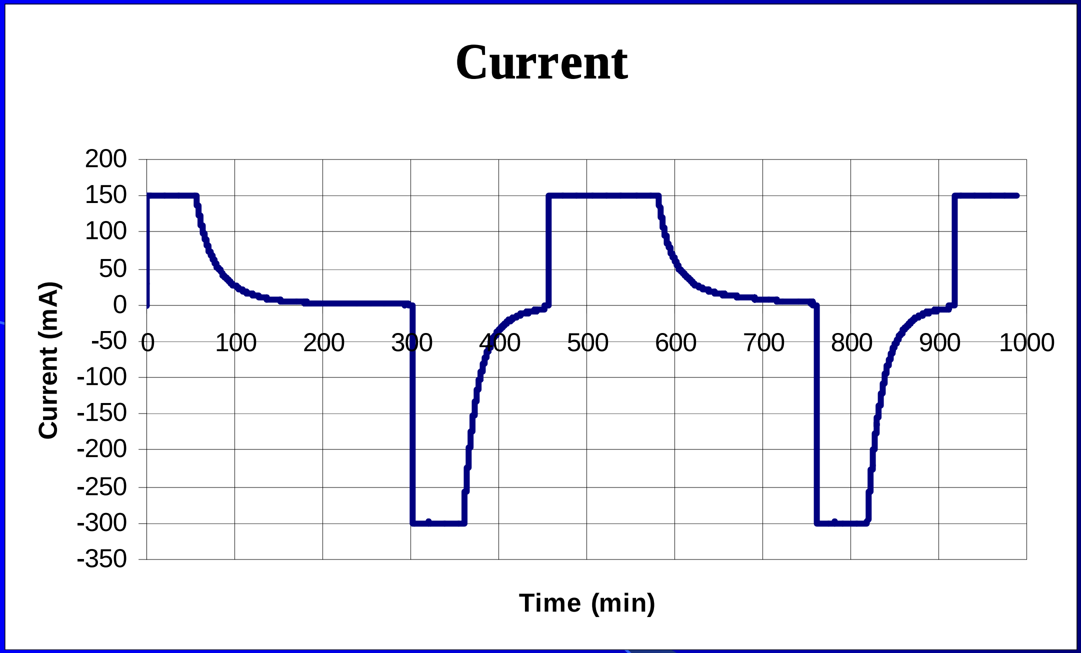

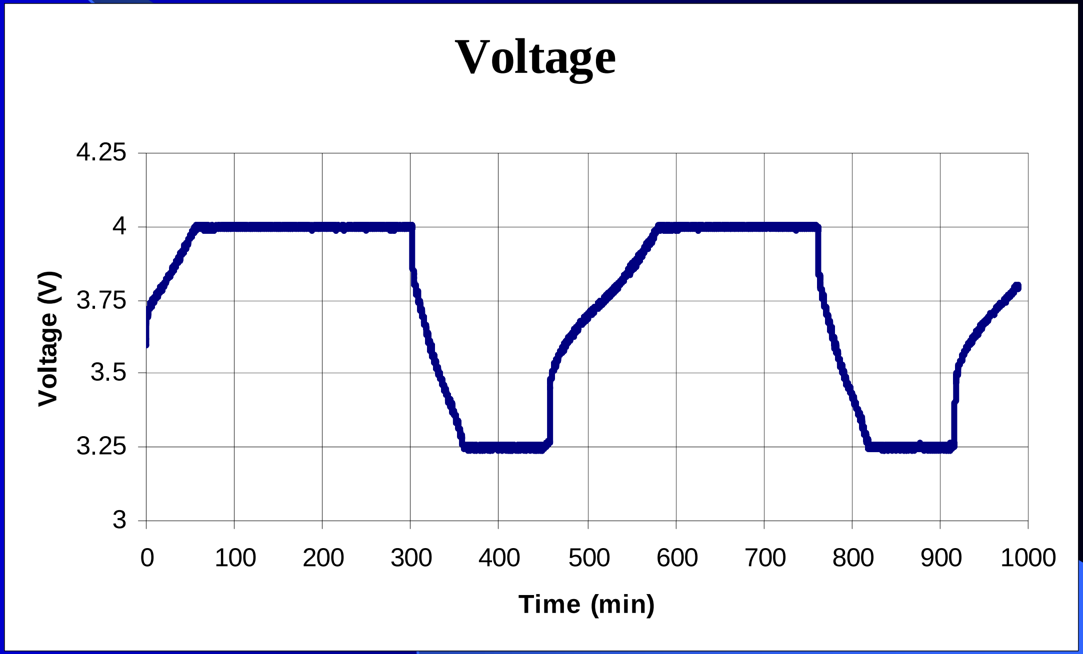

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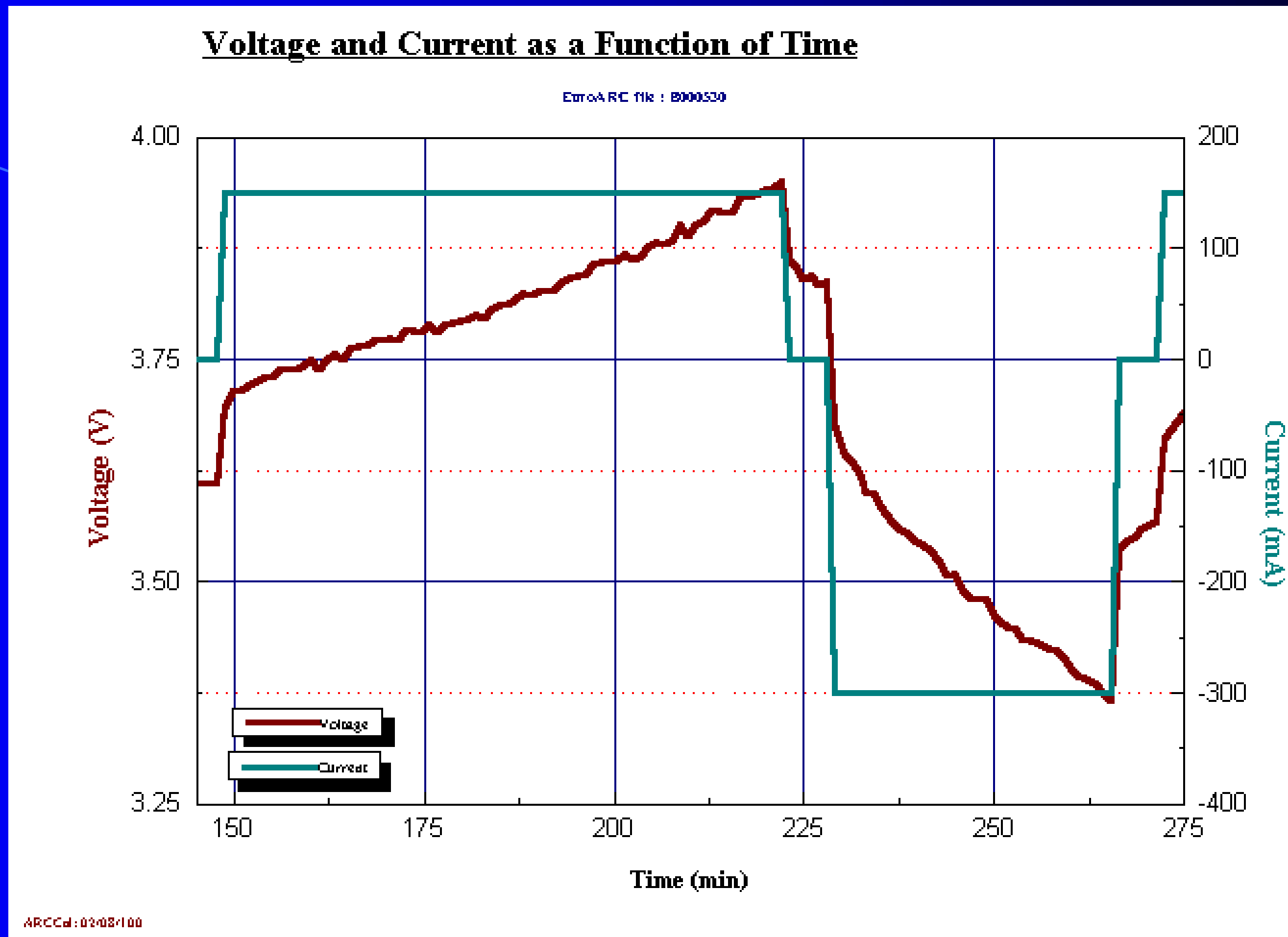

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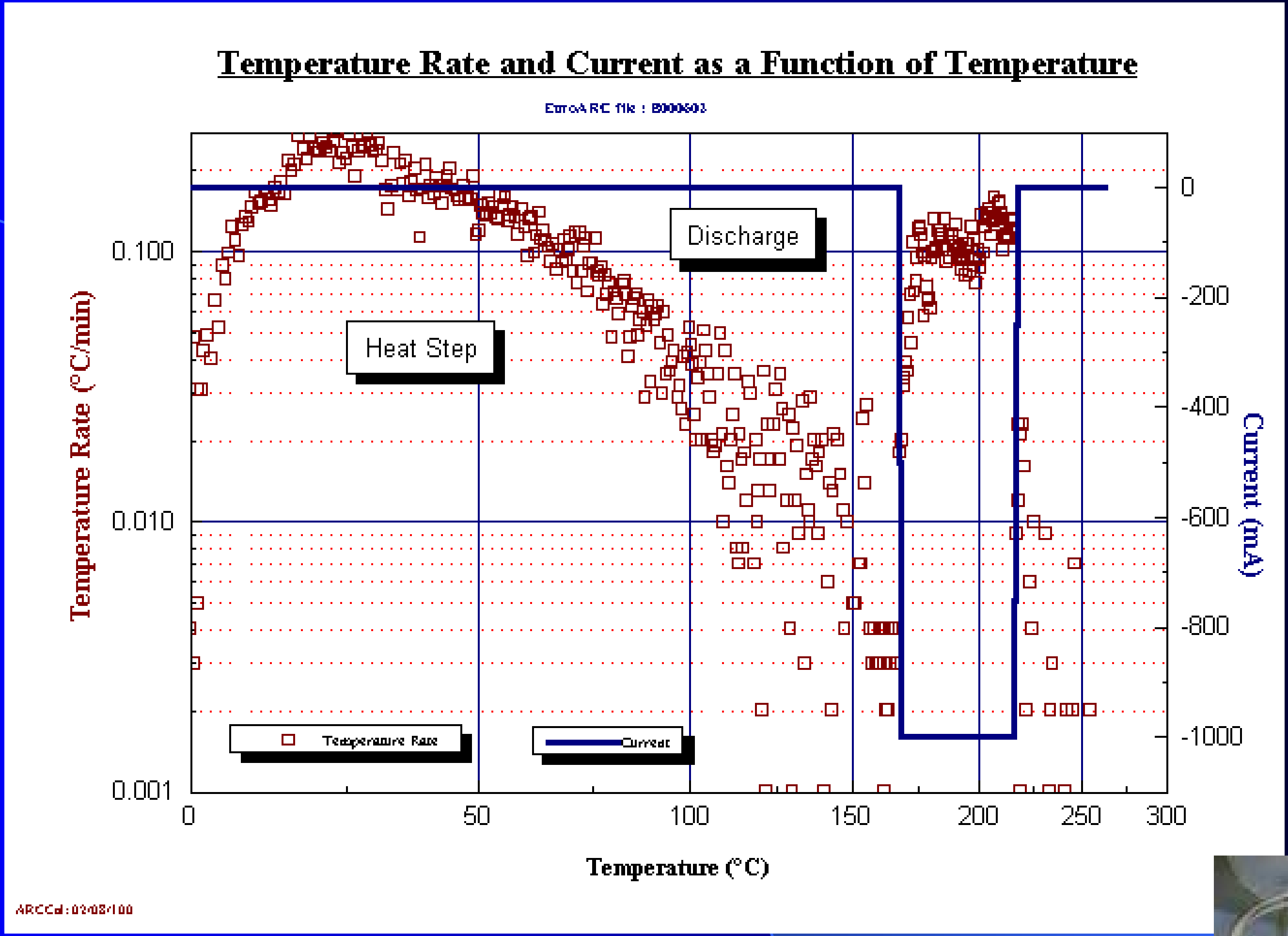

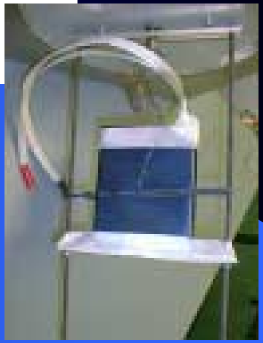

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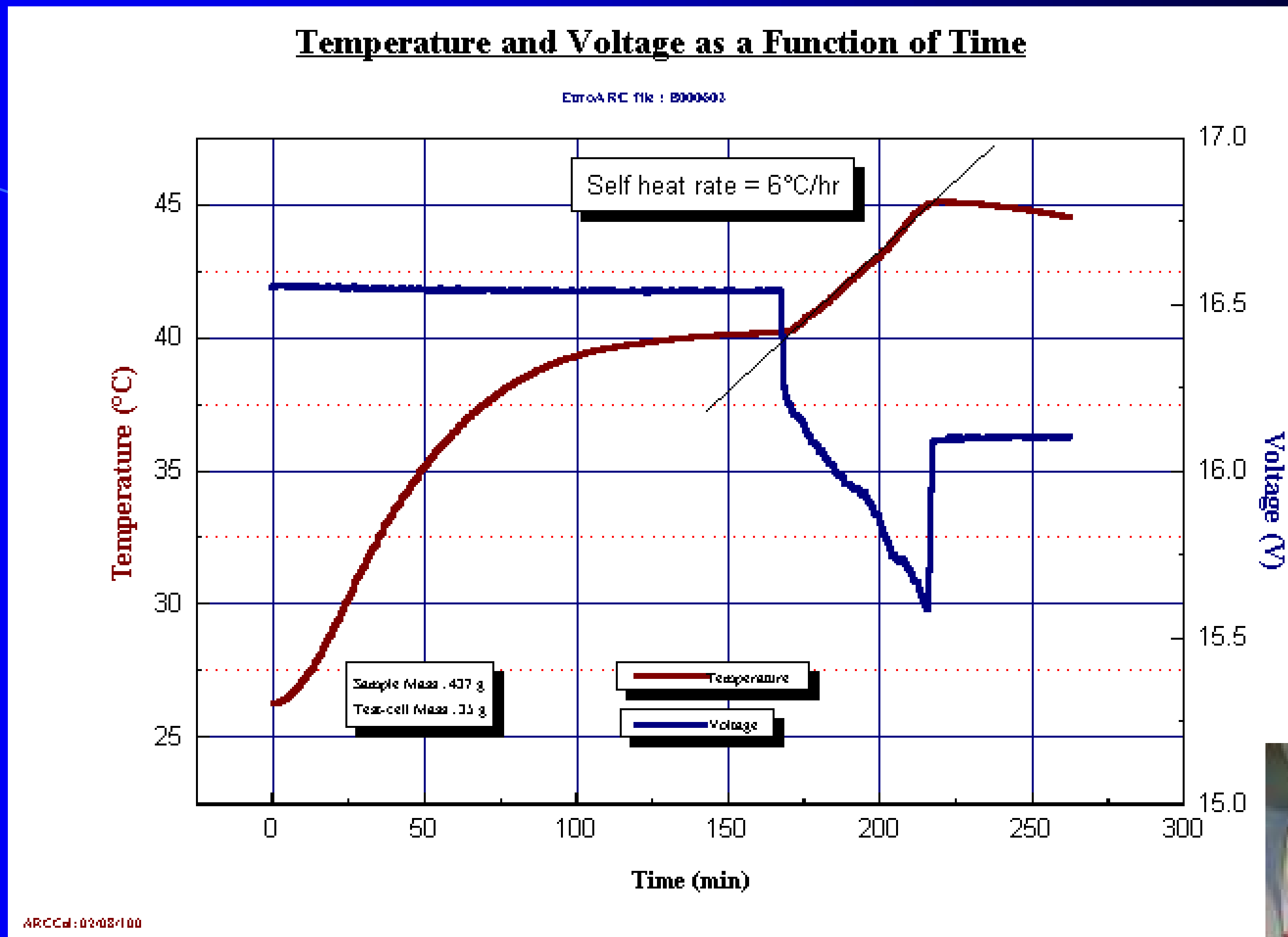

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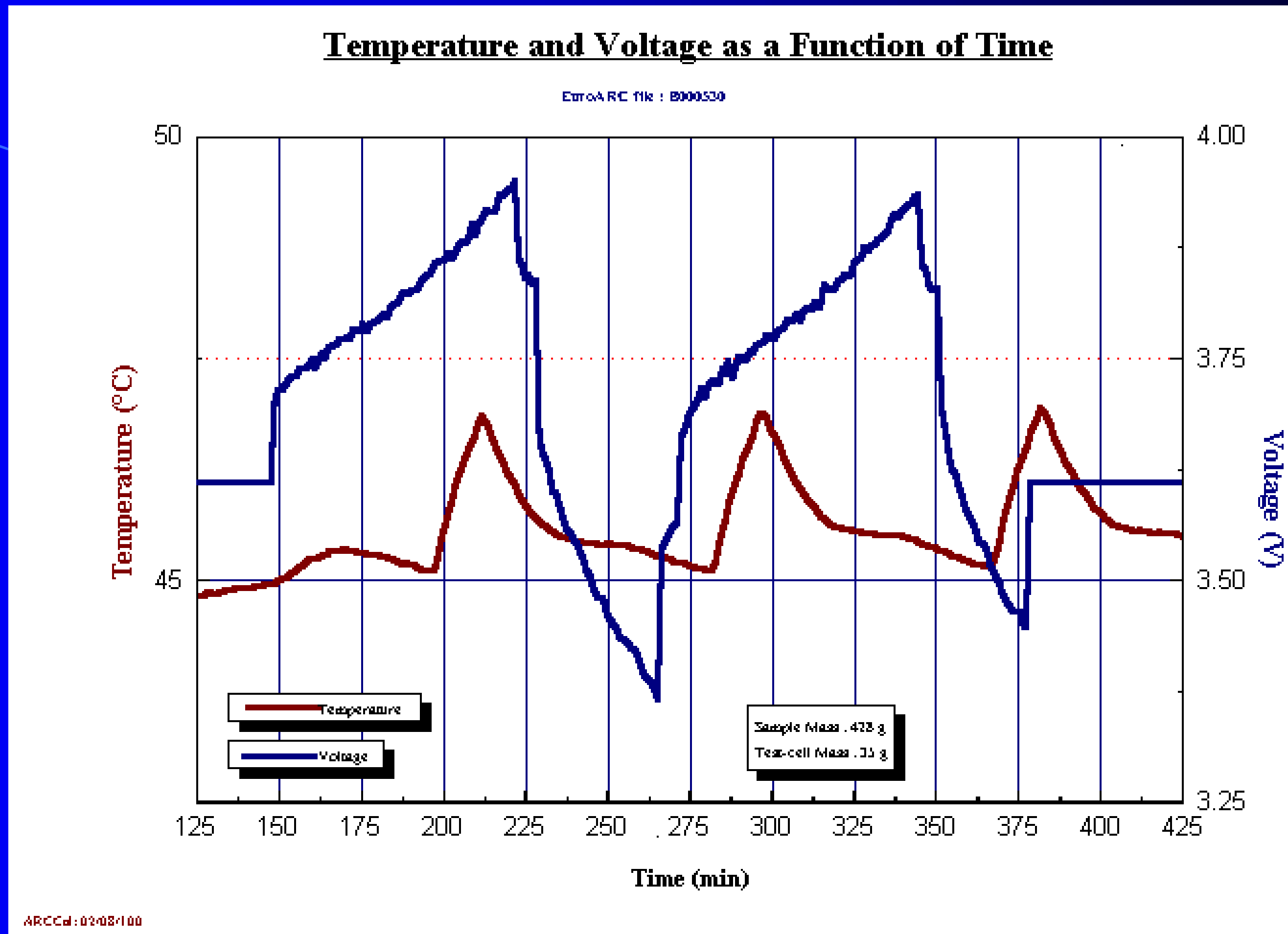

Electrothermal Abuse

- Over-voltage
- Shorting
- Heating

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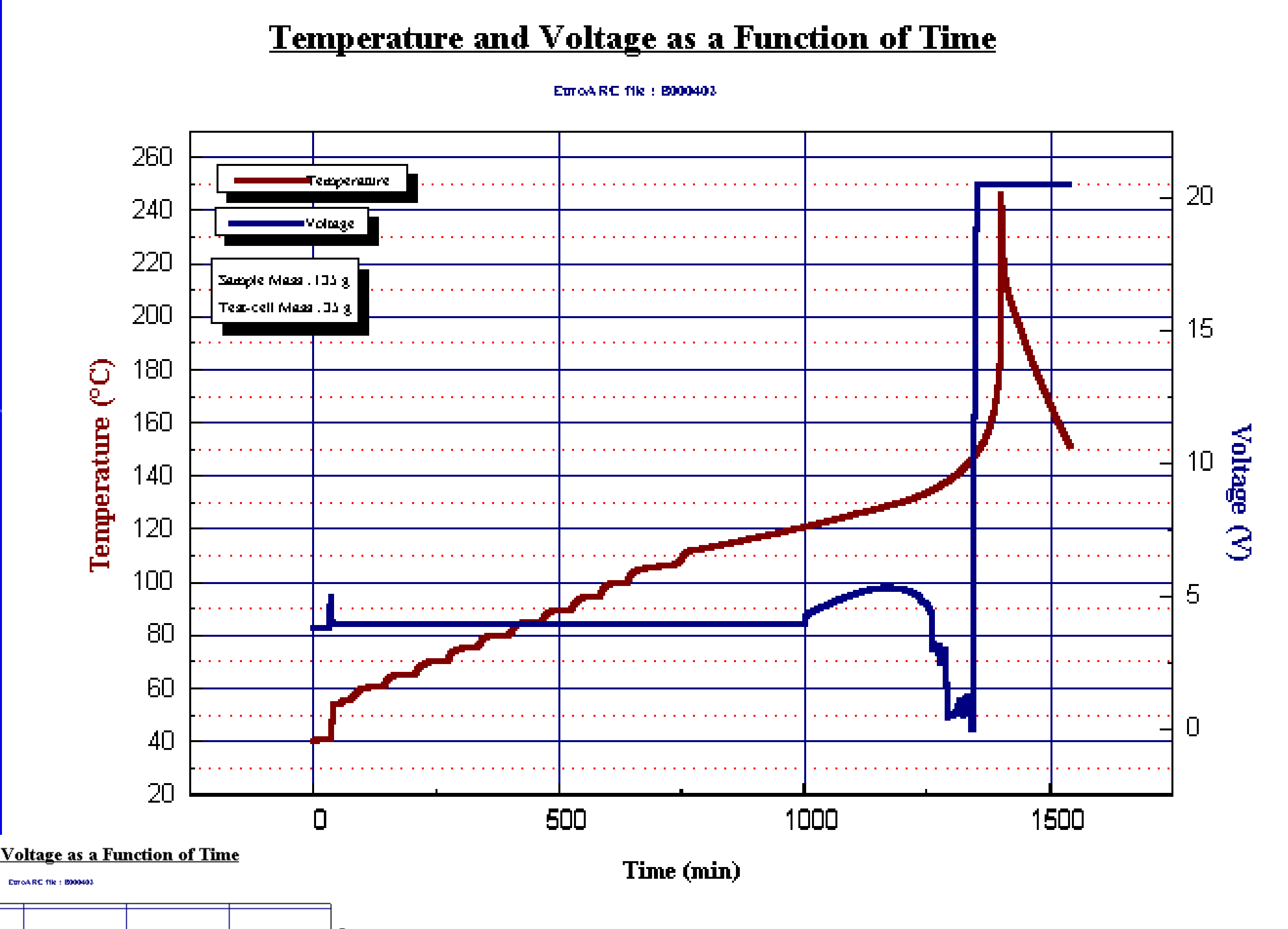

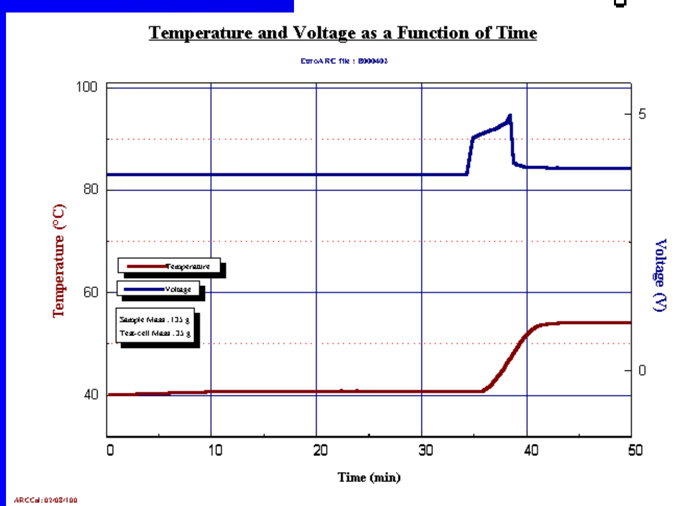

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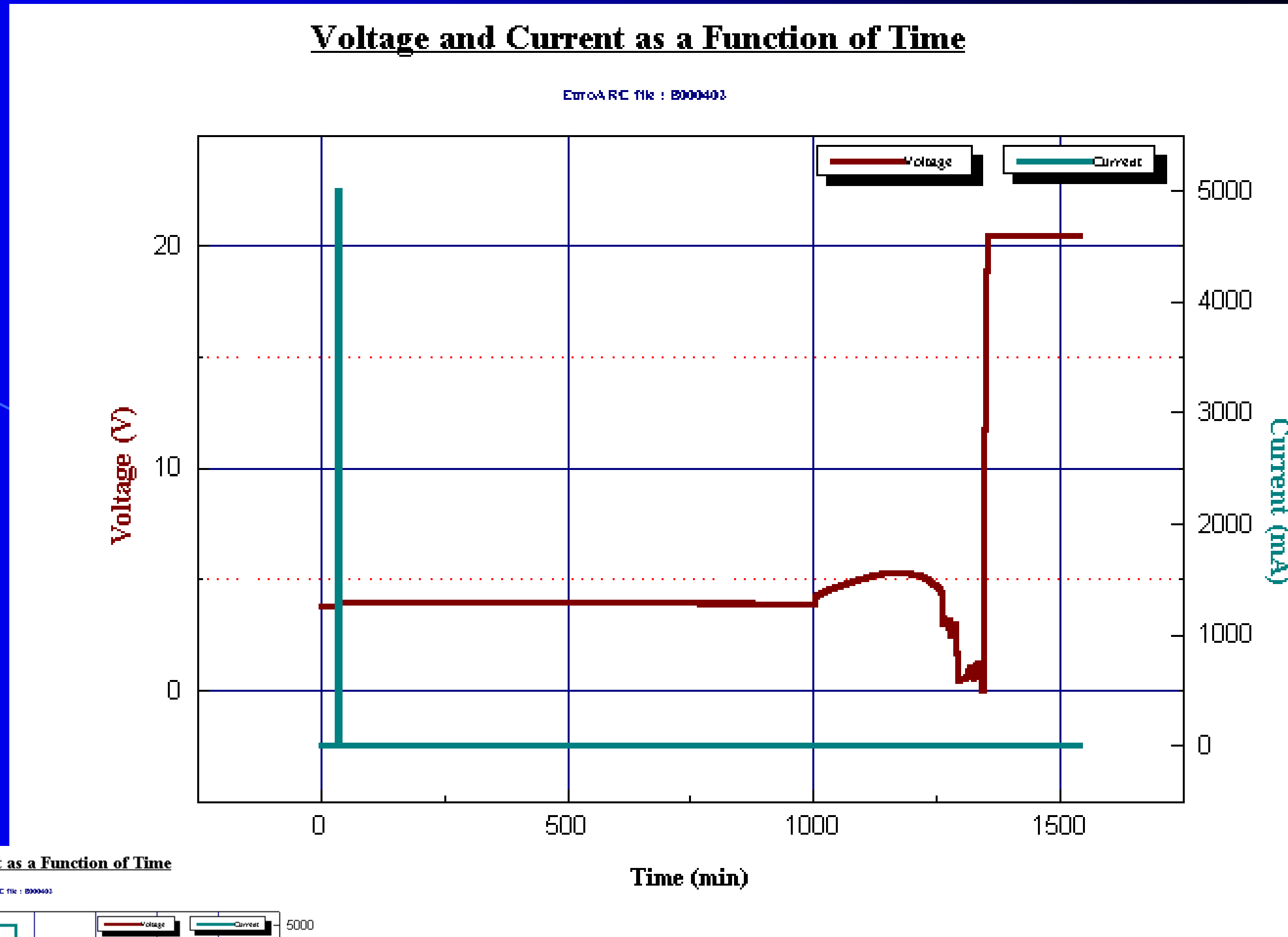
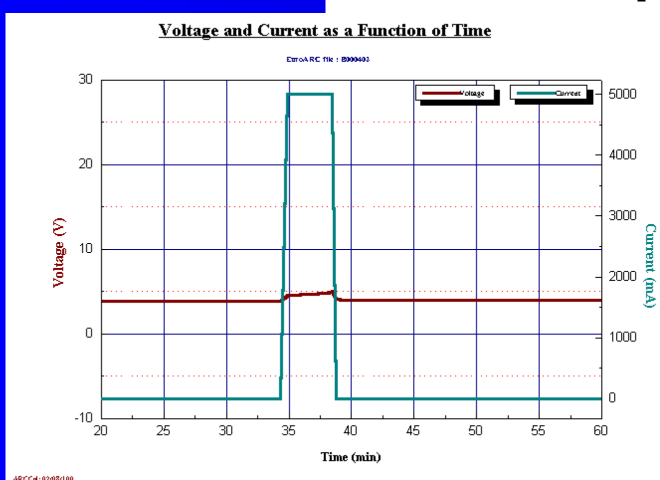
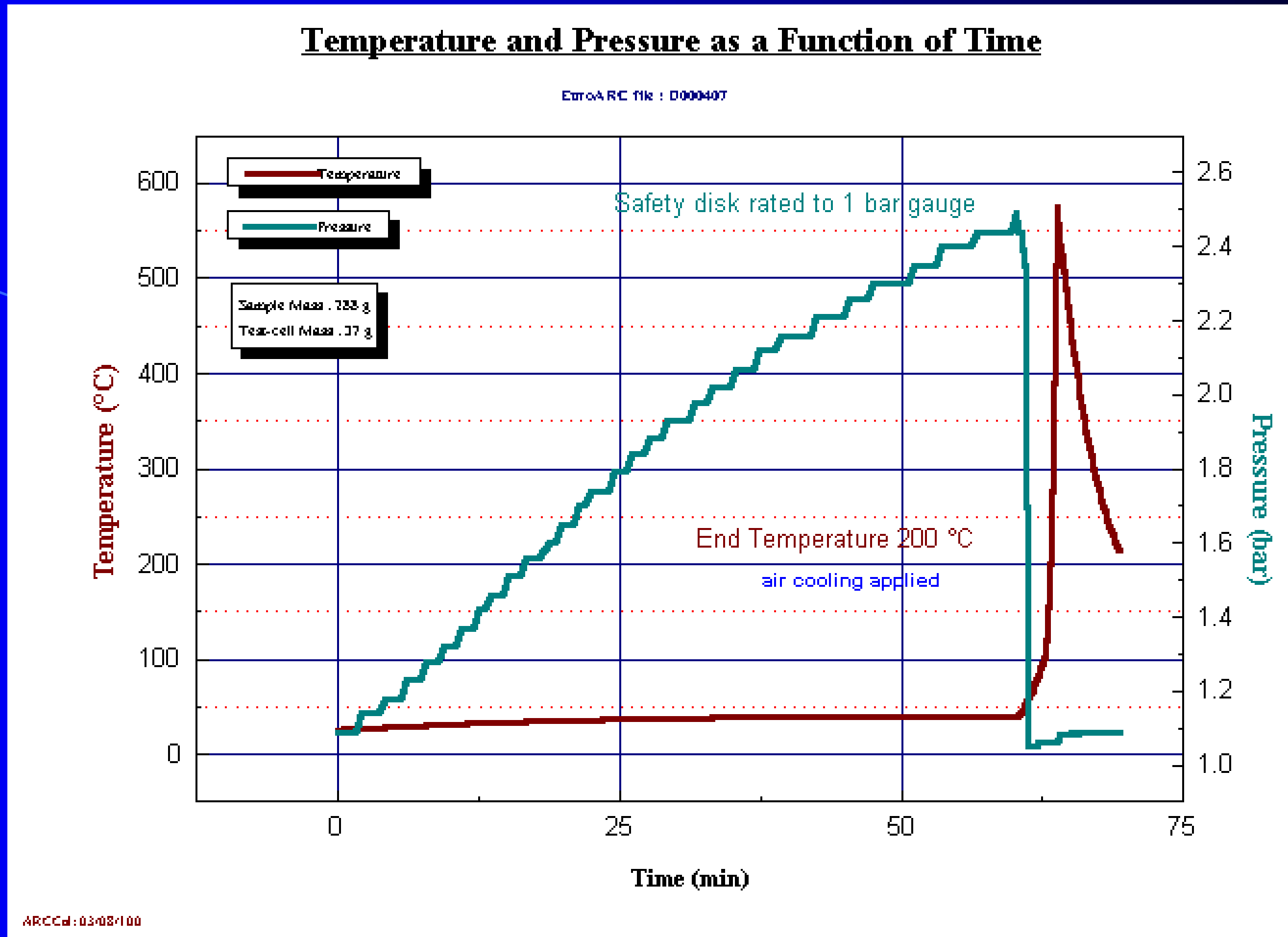


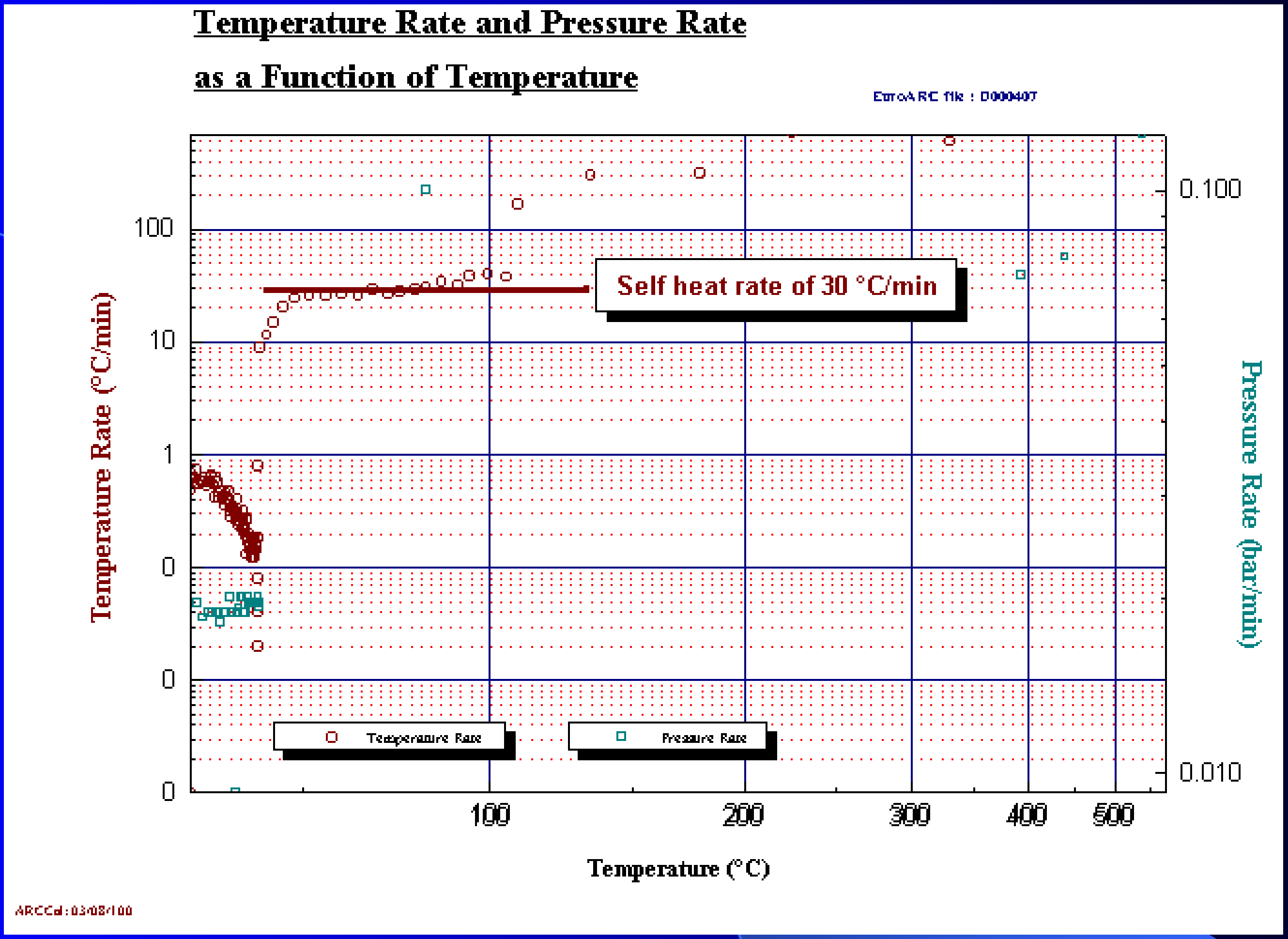


thermal hazard technology

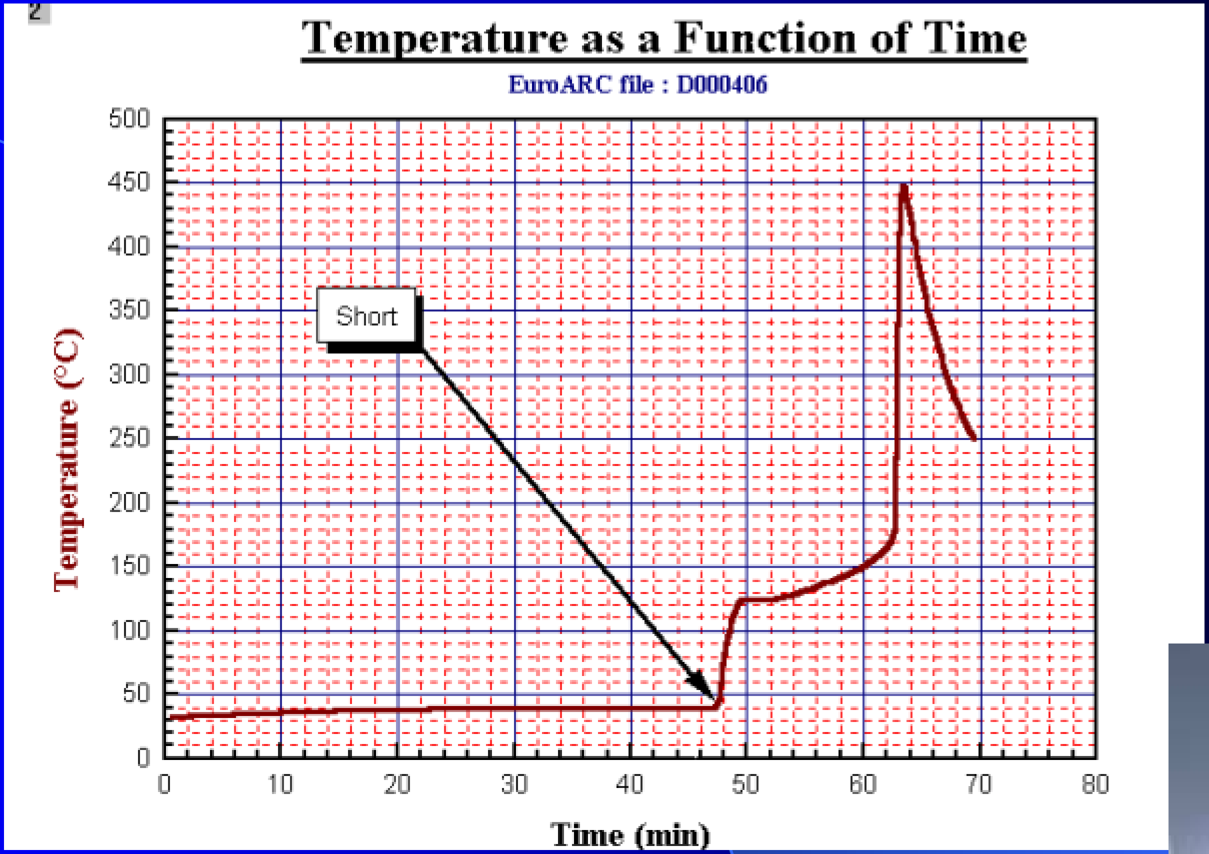


20V / 5A Over-voltage Applied Continuously on Single 26650 Li-ion Battery (4.1V)

thermal hazard technology



thermal hazard technology



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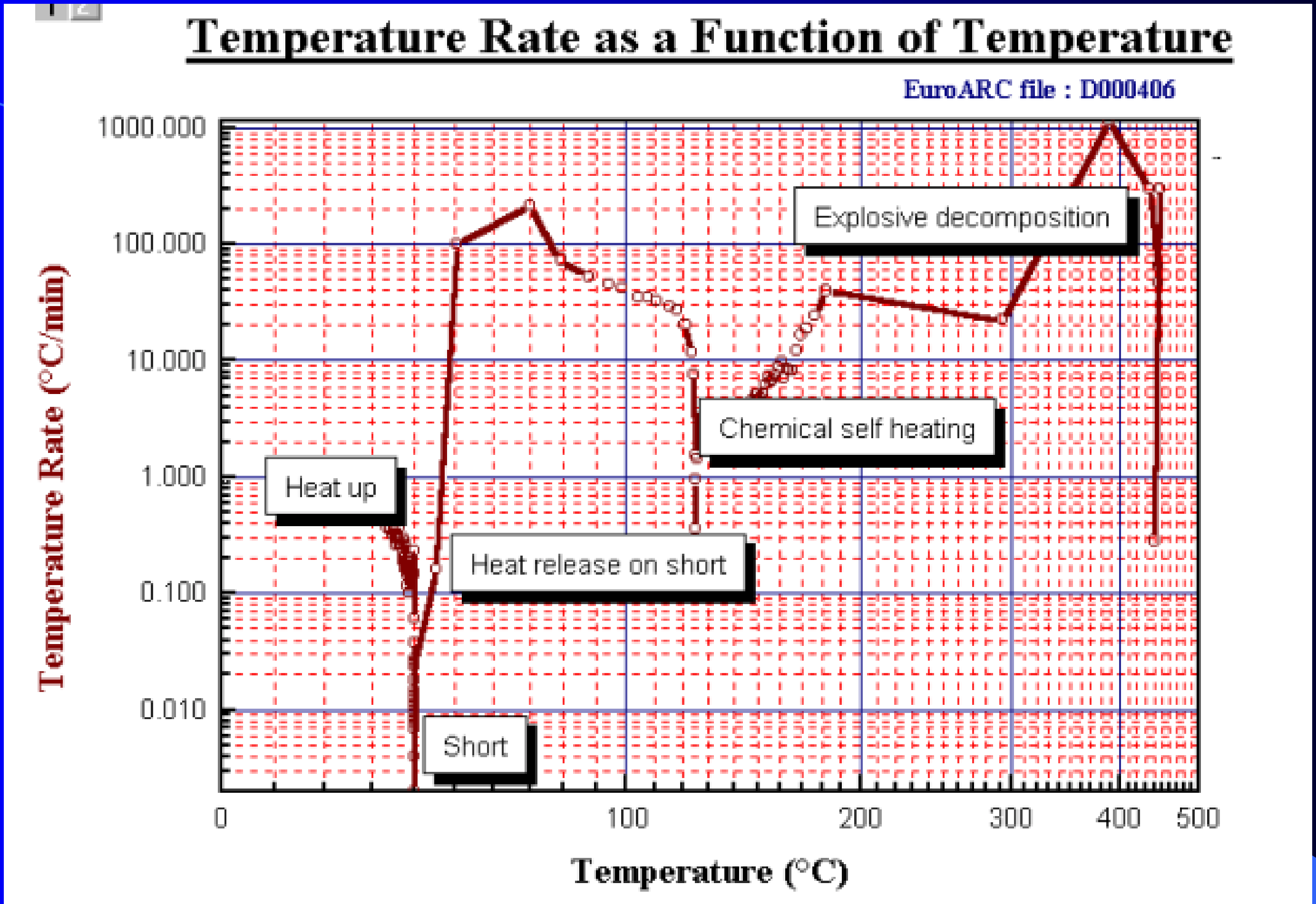

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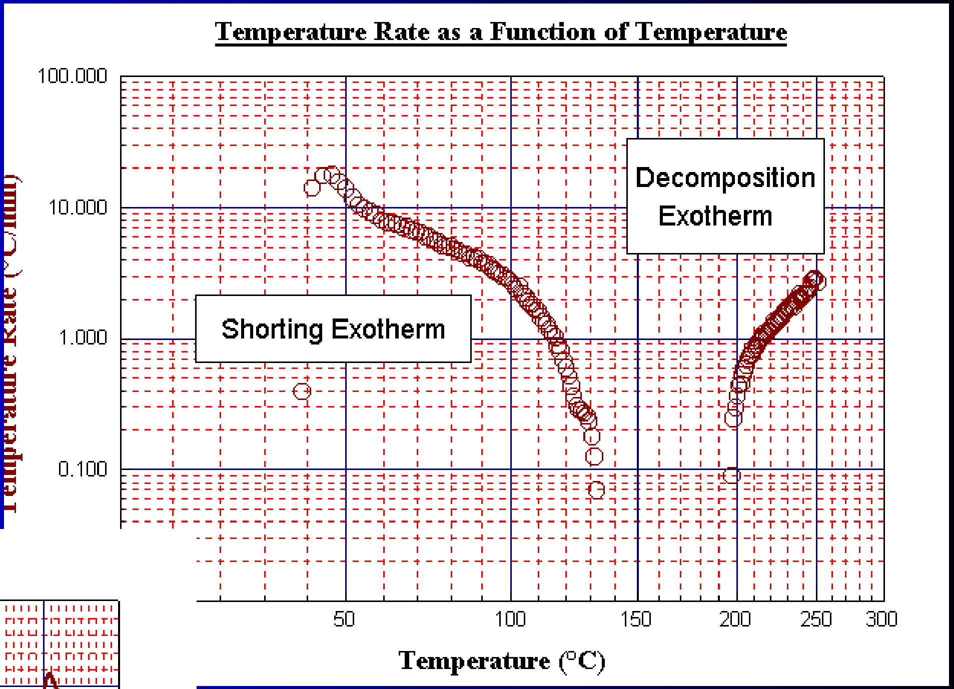

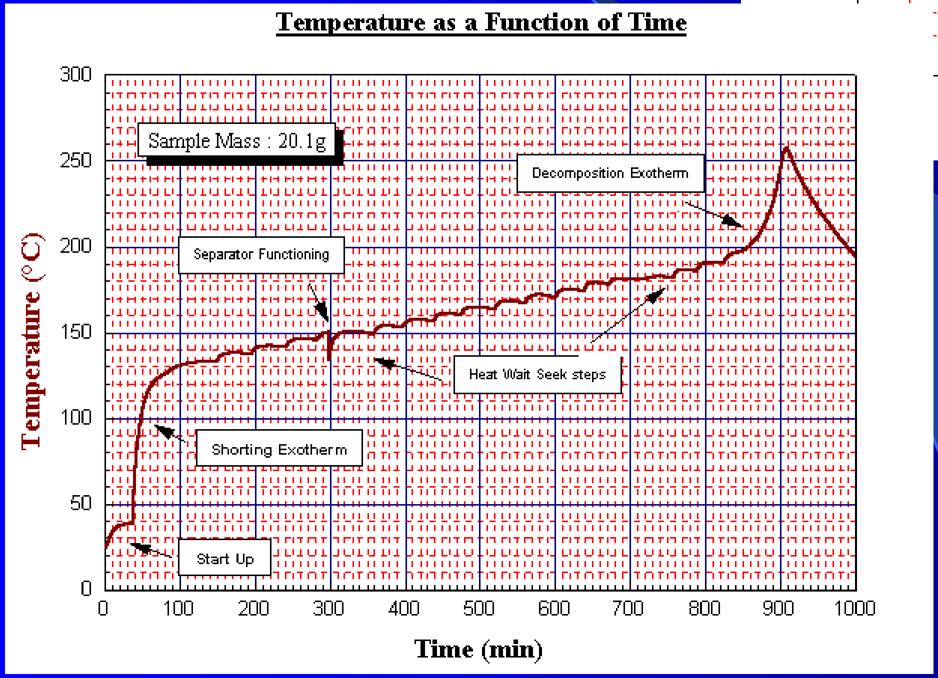

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Summary

Extended Volume Accelerating Rate Calorimeter

EVARC

- small scale and large scale batteries
- battery packs (voltages to 20V)
- electric vehicle (EV) batteries
- electrothermal dynamics (ETD)
- electrothermal abuse (ETA)

Electrothermal Performance and Safety Characterisation of Batteries

Performance of Li-S™ Cells Under LEO Test Regime and at Low Temperatures (to –40°C)

November 27, 2001

Spectrum Astro / Moltech Corporation

Product Attributes

Rechargeable Li-S Cells

Lightweight (lithium & sulfur) : Higher specific energy density than Li-ion

Rate capability exceeds Li-Ion

Environmentally benign

Low Material Costs

Technology Can be applied to:

Primary Batteries

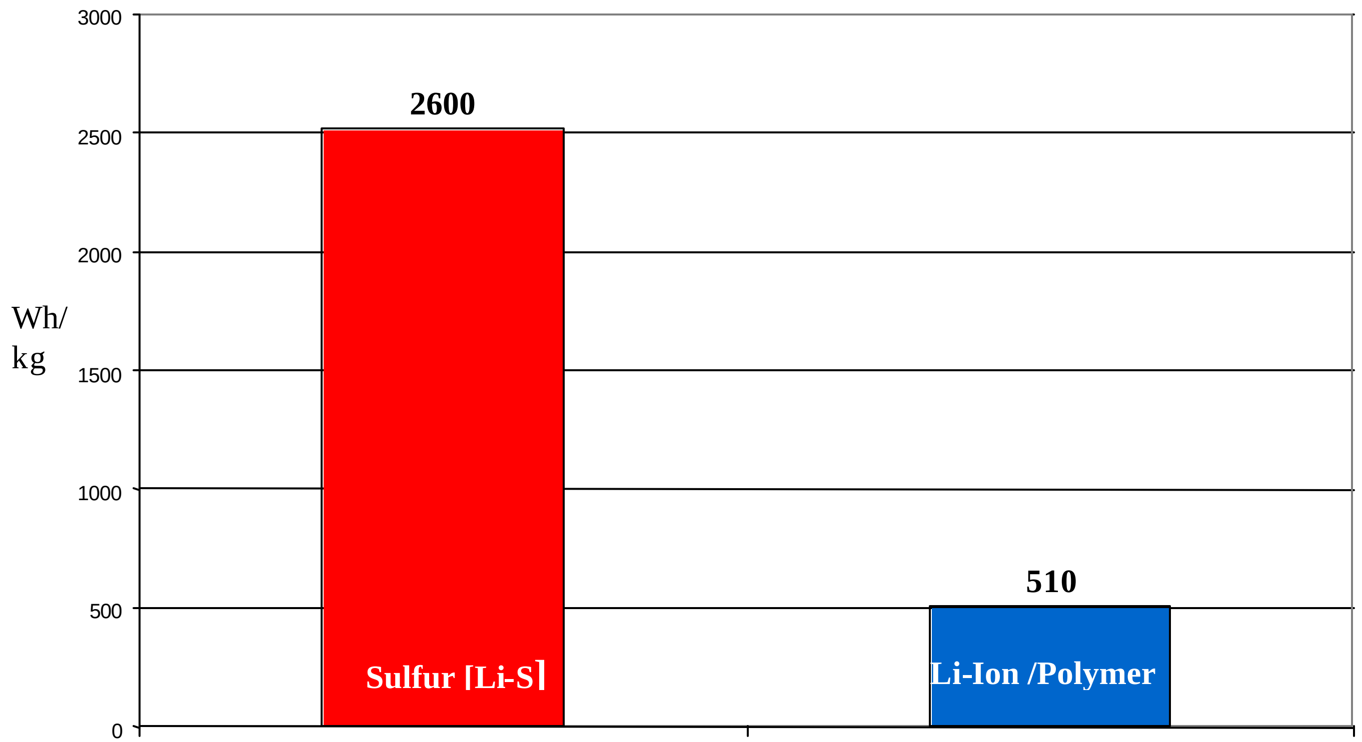
Super capacitors

SPECTRUMASTRO

MOLTECH CORPORATION

Theoretical Energy Density Comparison

Cathode Active Materials



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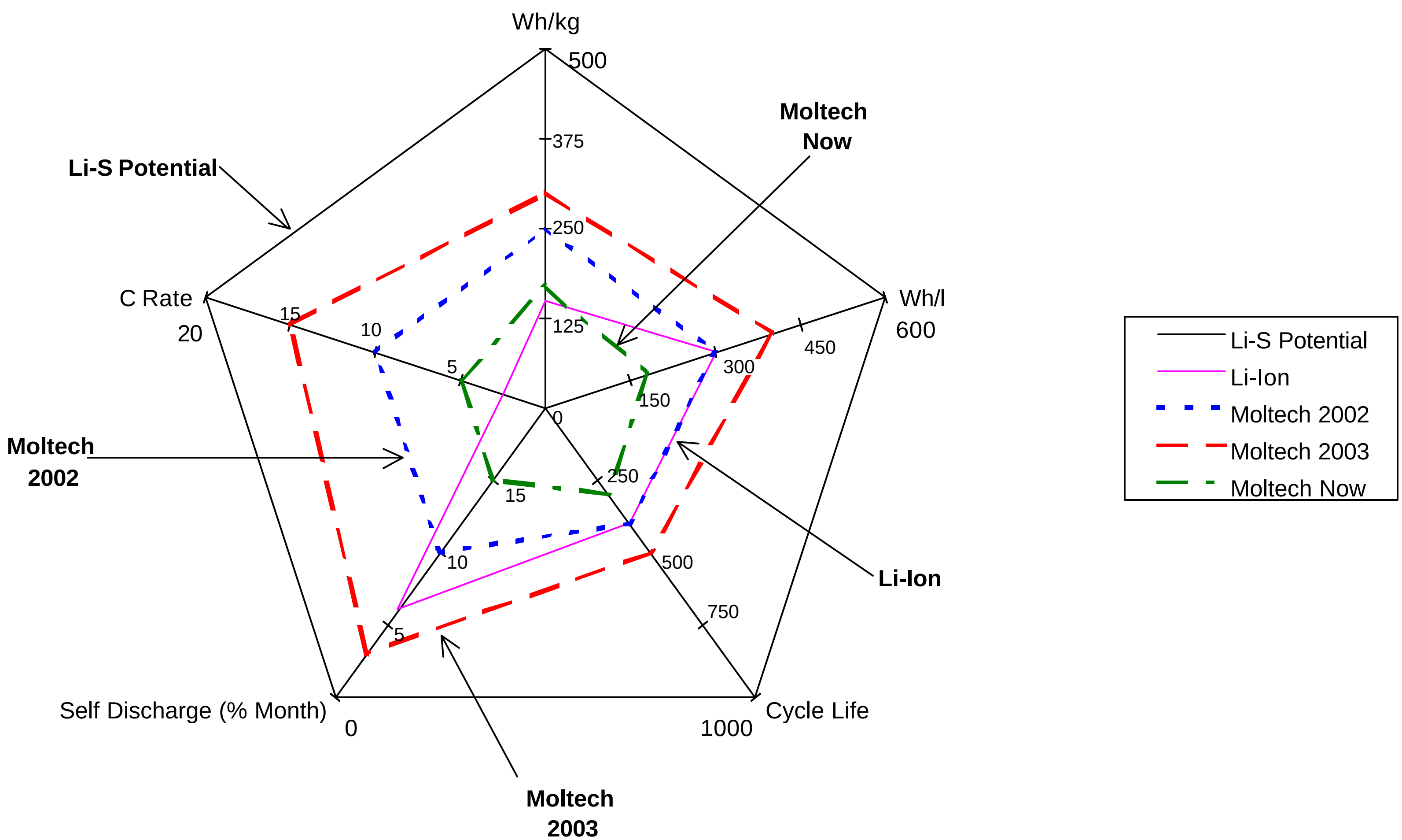
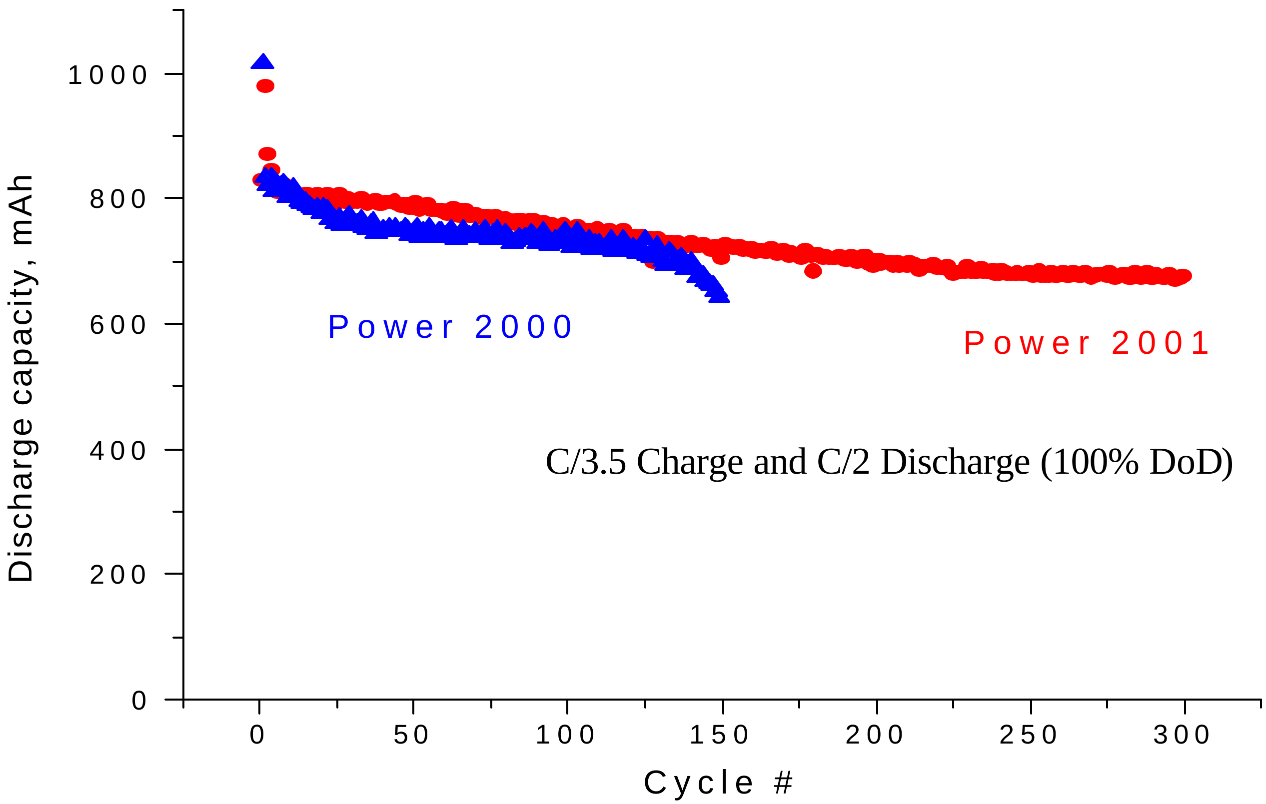
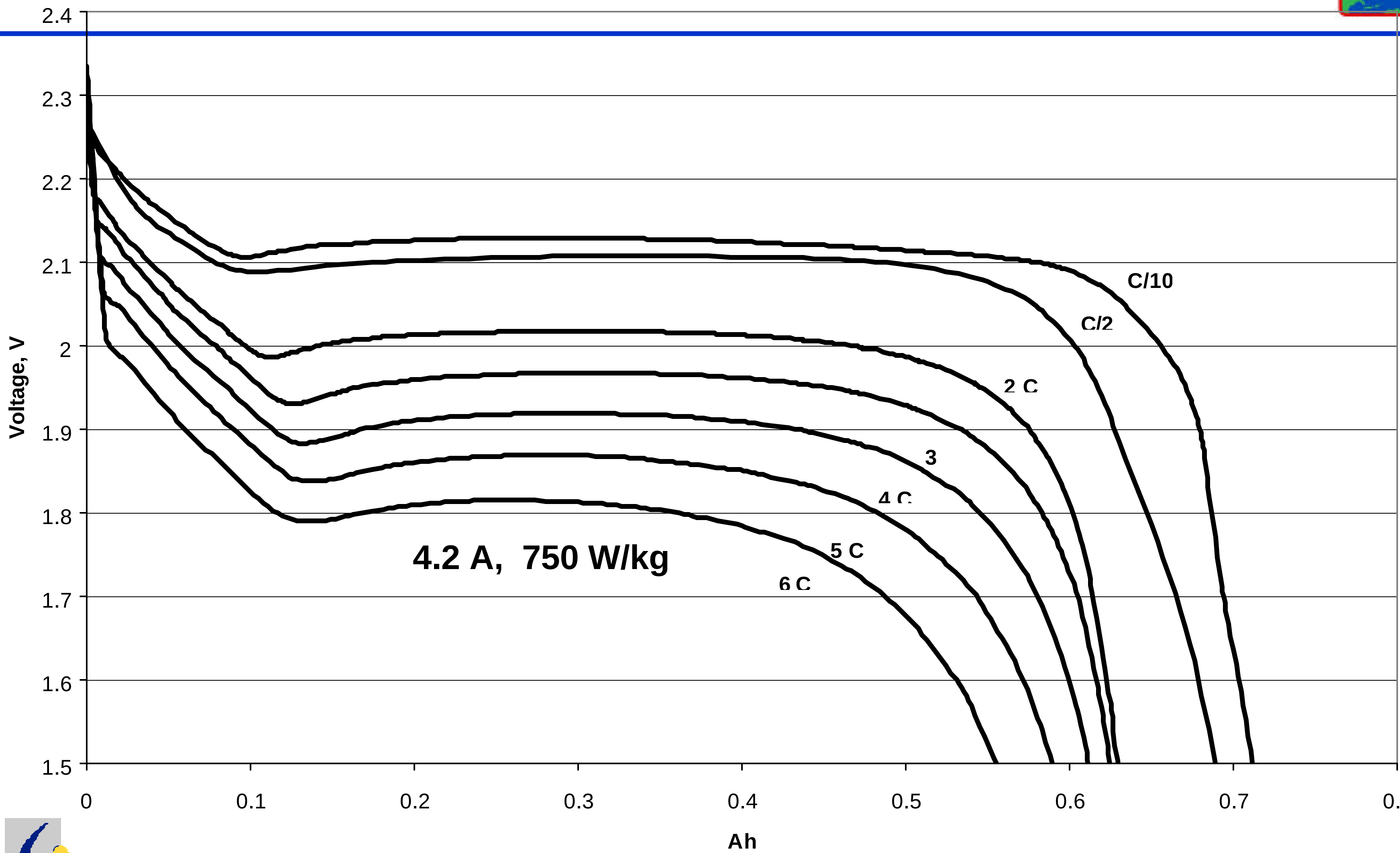
Li-S and Li-ion Cell Performance Comparison



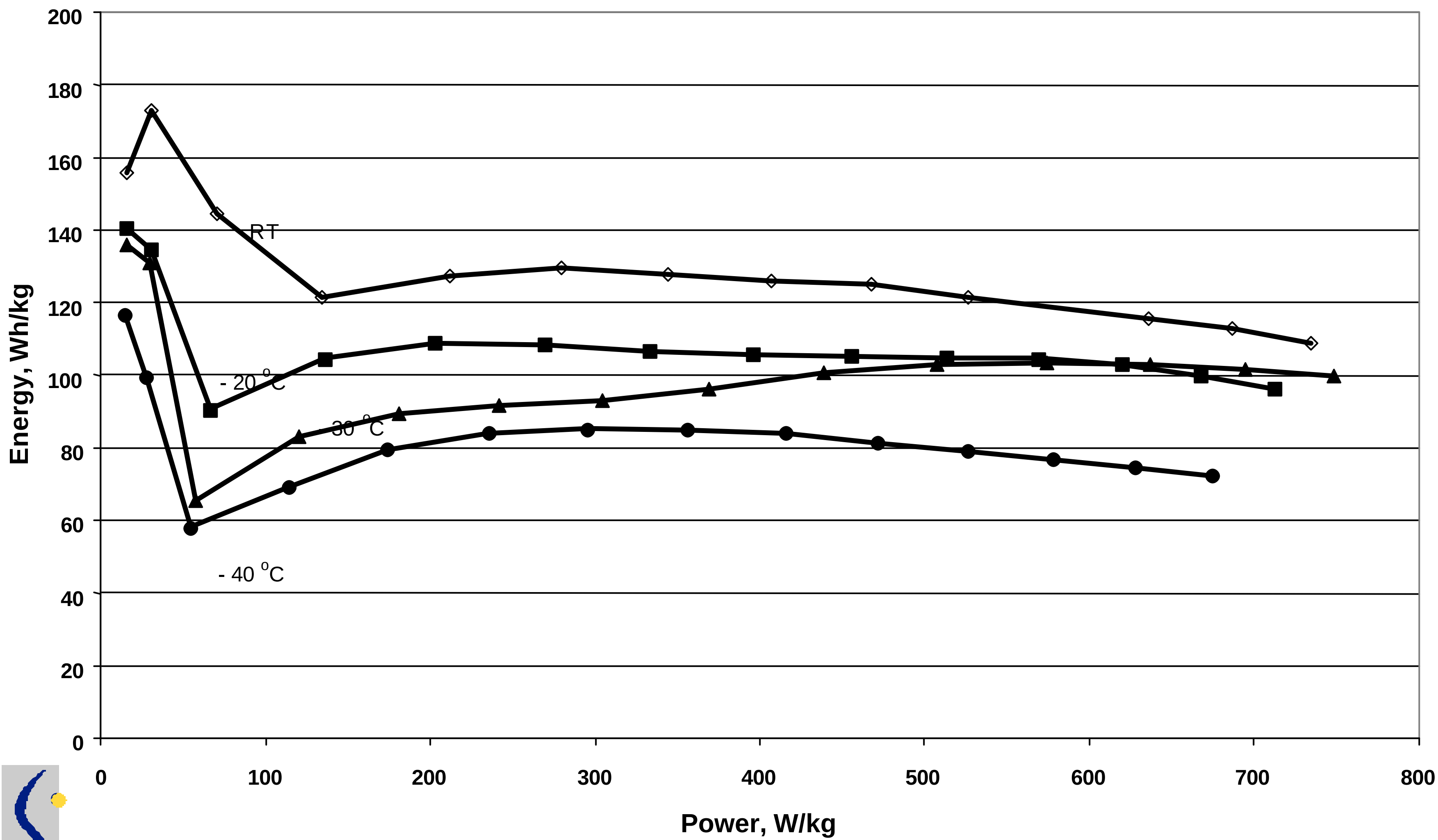
Cycle Life Evolution of Moltech Prototype Li-S Cells



Voltage vs Ah At Various Discharge Rates
Alpha-6 Improved Design



Cell Utilizing New Electrolyte Additive
Ragone Plots At Various Temperatures



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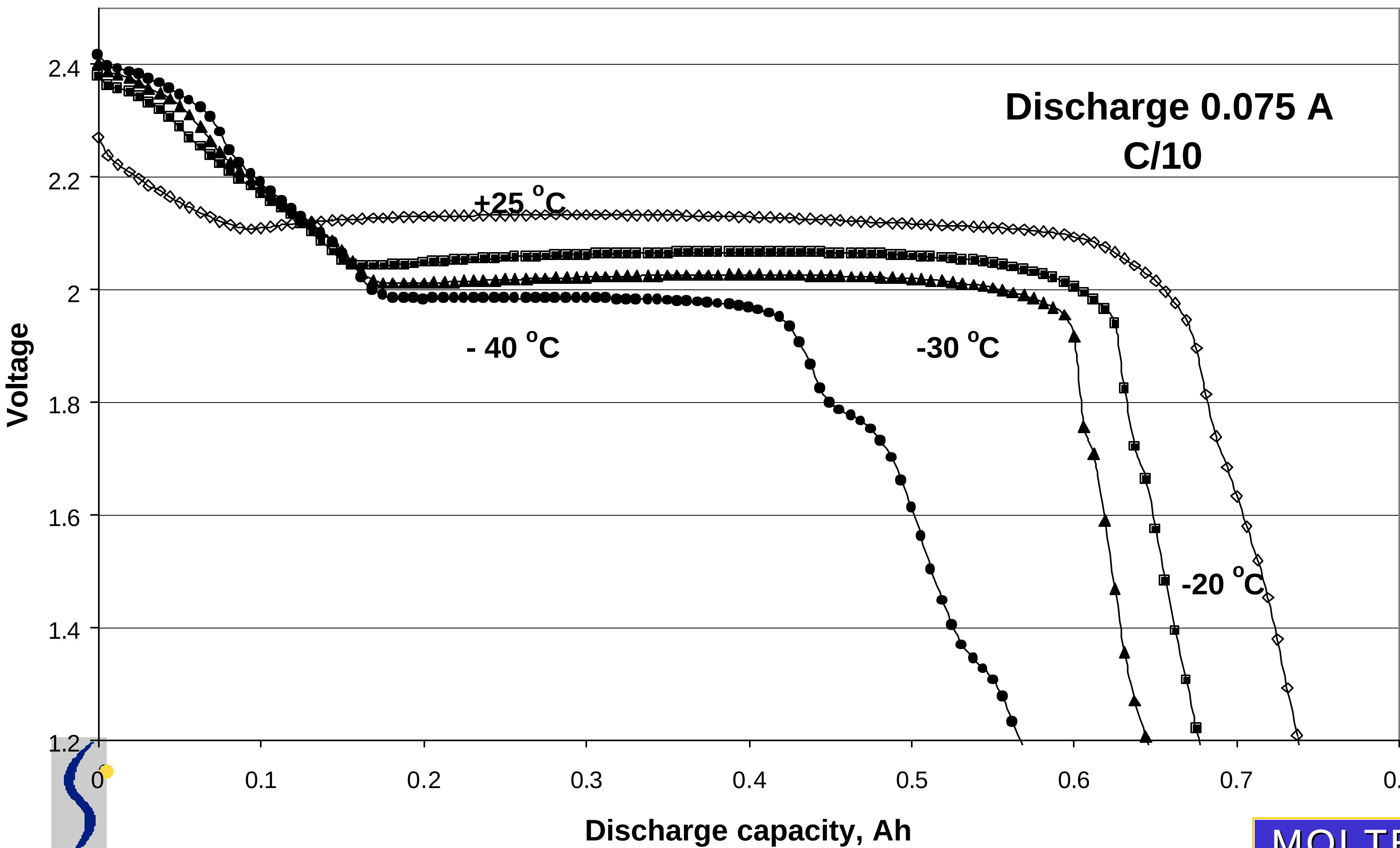
Voltage vs Discharge capacity at different temperatures



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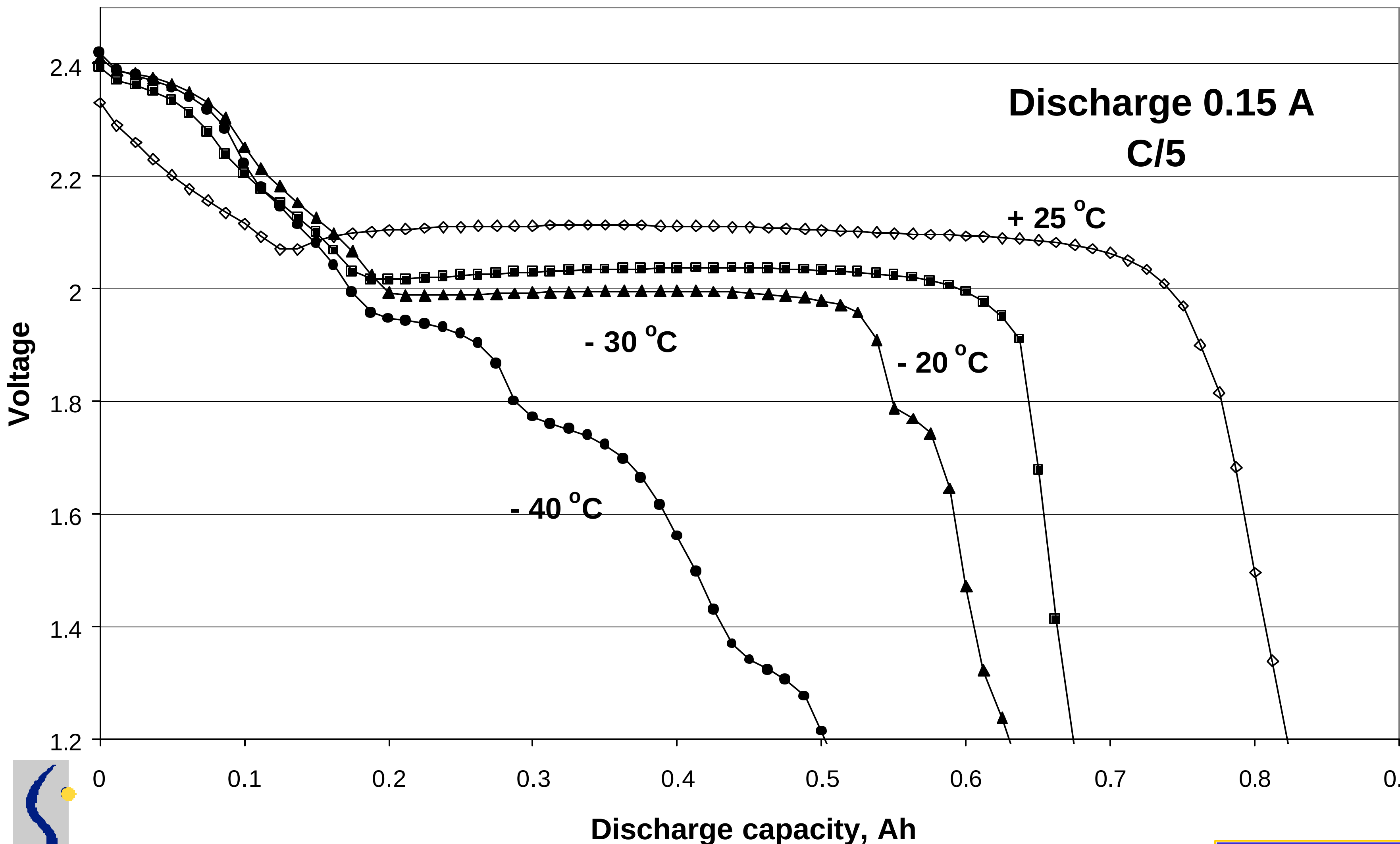
MOLTECH CORPORATION

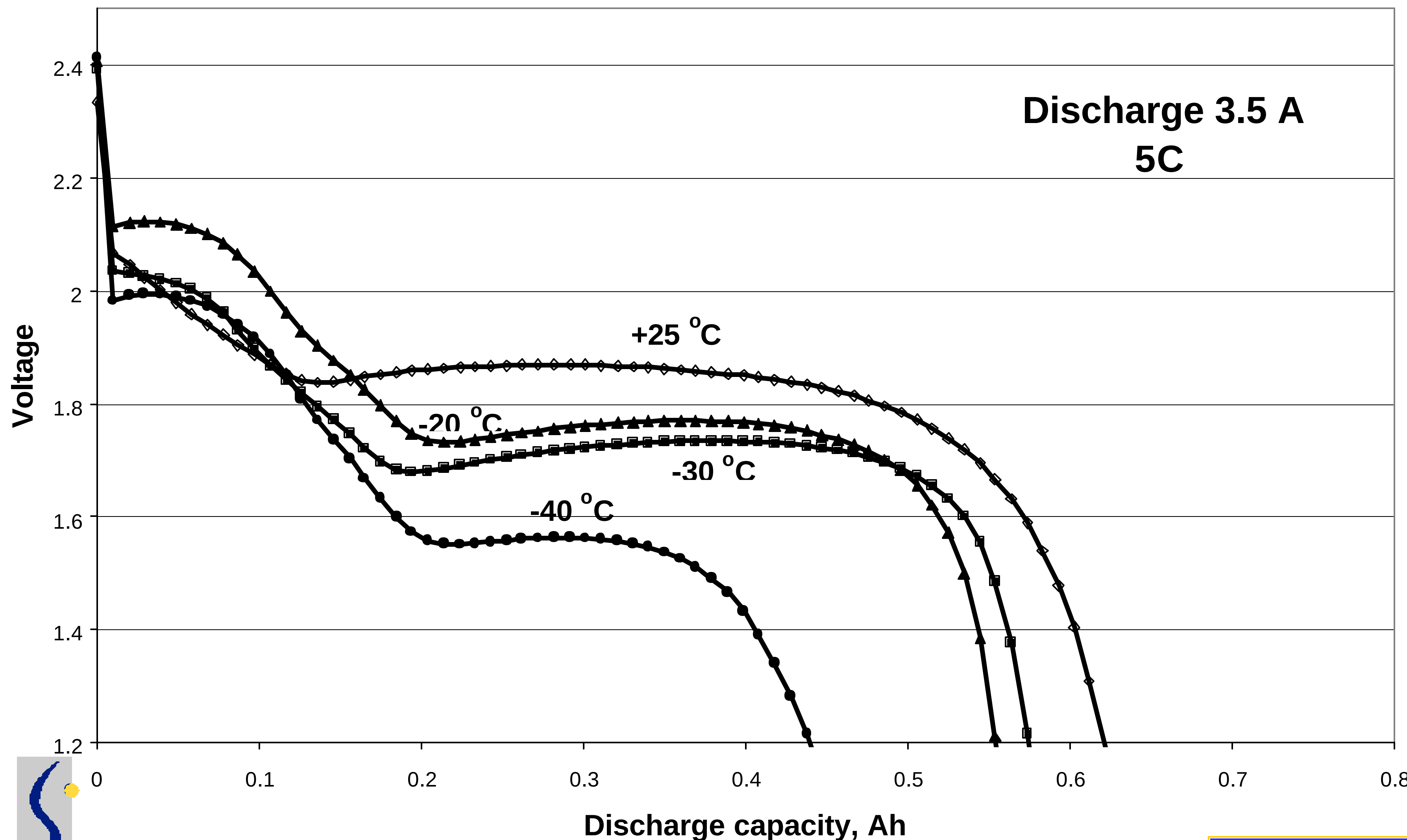
Voltage vs Discharge capacity at different temperatures



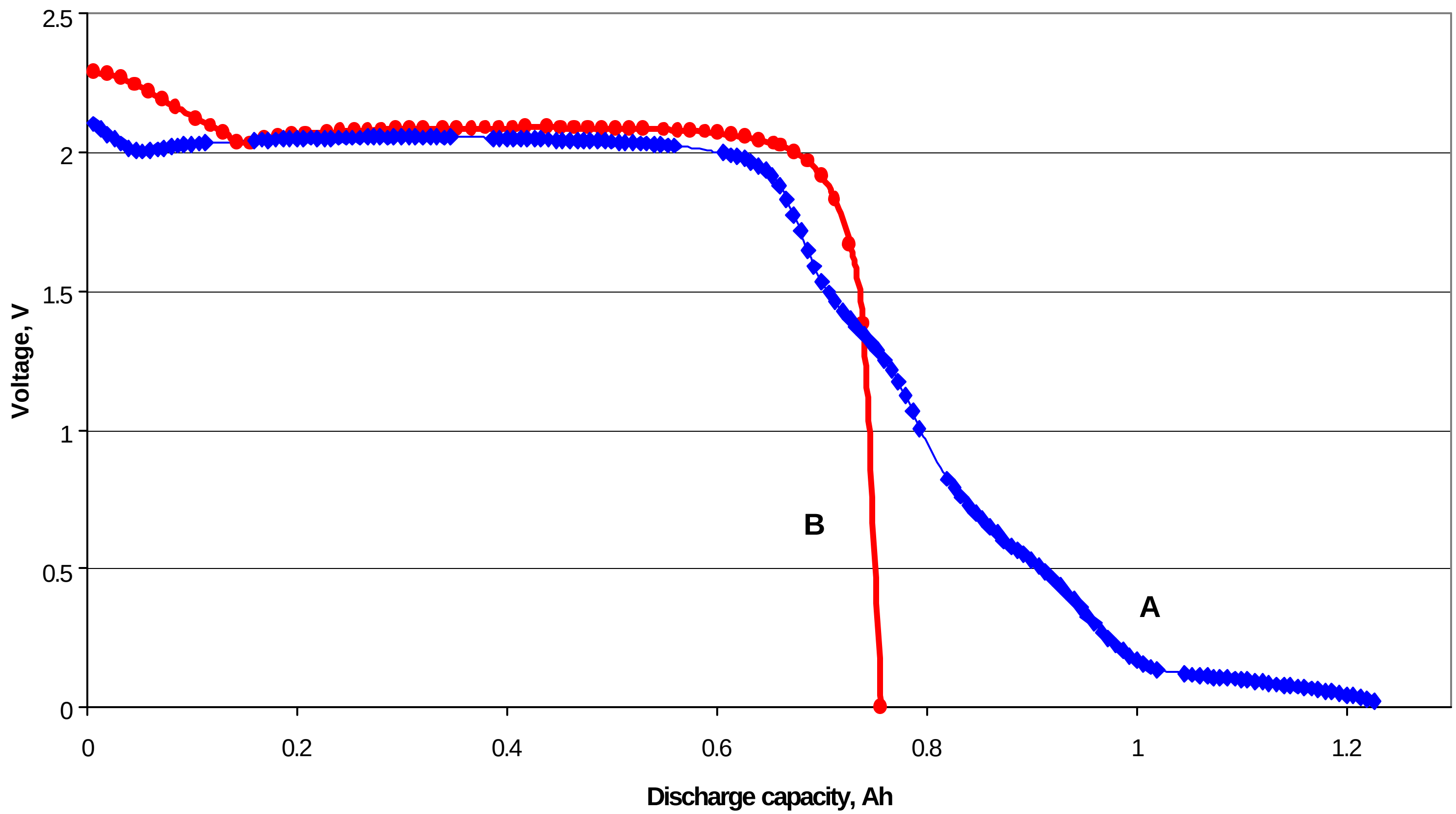
SPECTRUMASTRO

MOLTECH CORPORATION

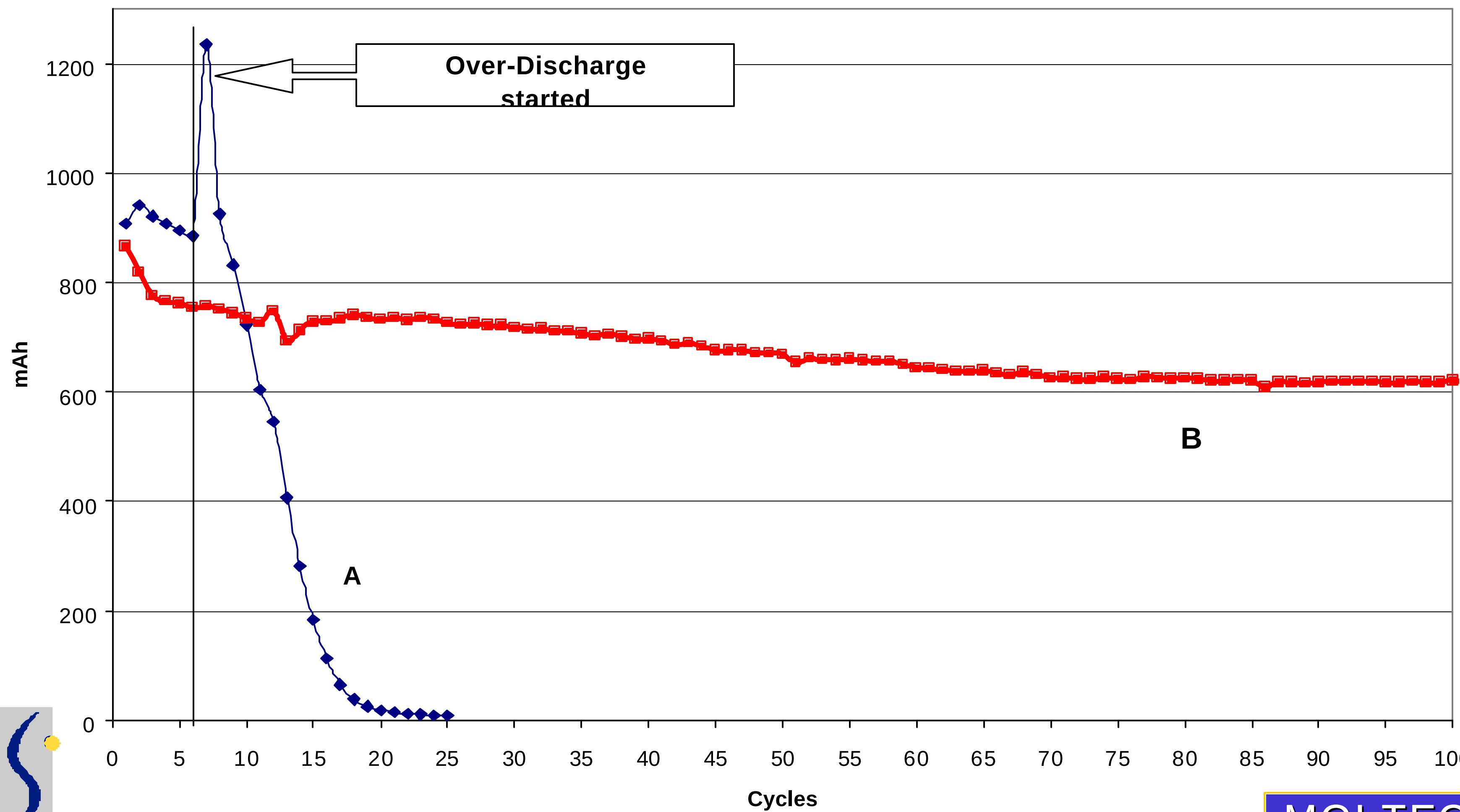
Voltage vs Discharge capacity at different temperatures



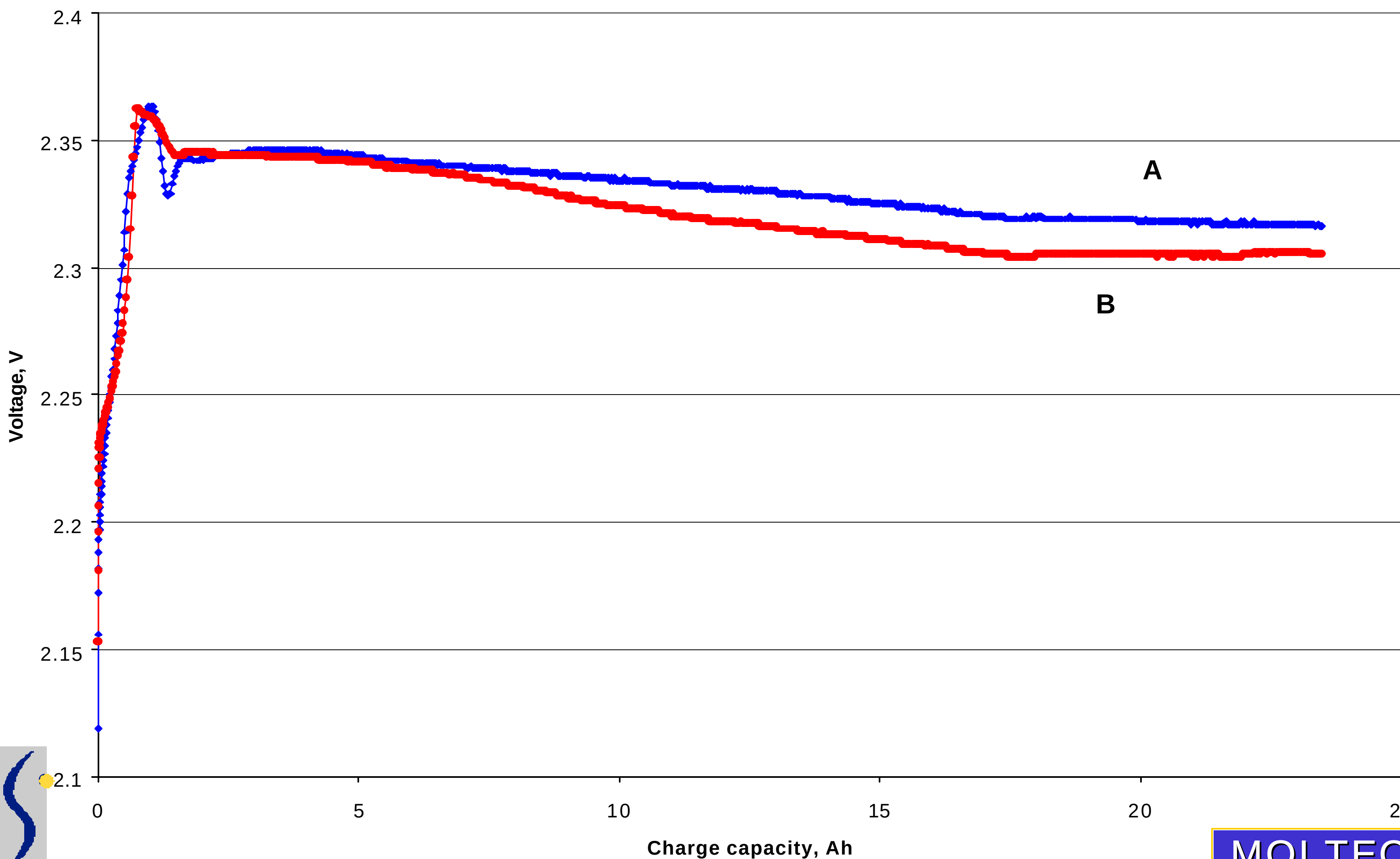
Over Discharge to 0V at 400mA/h



Continuous Cycling with Over Discharge to 0V



30 times Over Charge at 400mA/h

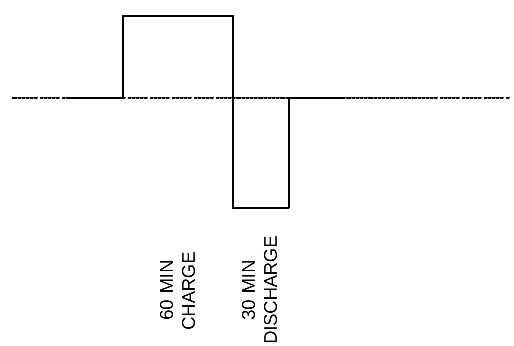


Li-S Cell Cycle Testing

Test Description

- **10 Sample Cells Were Placed in Cycle Testing**
- **Cells Had Been Previously Stored at Room Temp for 10 Months**
- **Cycle Consisted of 90 Minute Period; 60 Minute Charge, 30 Minute Discharge**
    - **Roughly 25% DOD**

TEST PROFILE

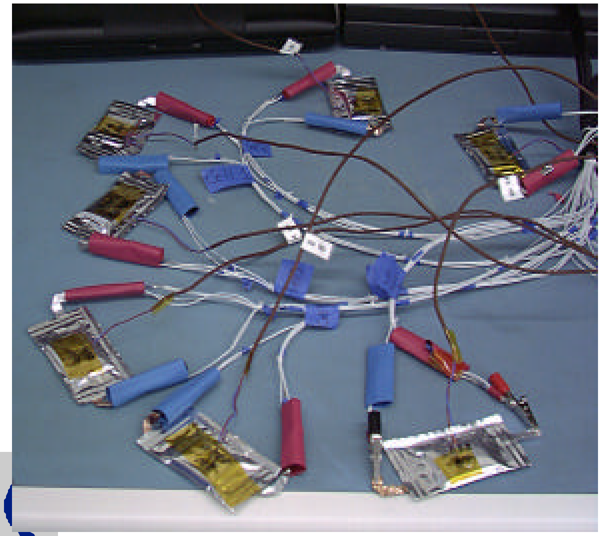


- **Individual Cell Voltages, Currents, and Temperatures Were Captured Throughout the Cycling**

Li-S Cell Cycle Testing (Cont'd)

Cells Then Placed Into Protective Enclosure For Cycling

Cells Individually Instrumented With Voltage, Current, and Temperature Monitors



Li-S Cell Cycle Testing (Cont'd)

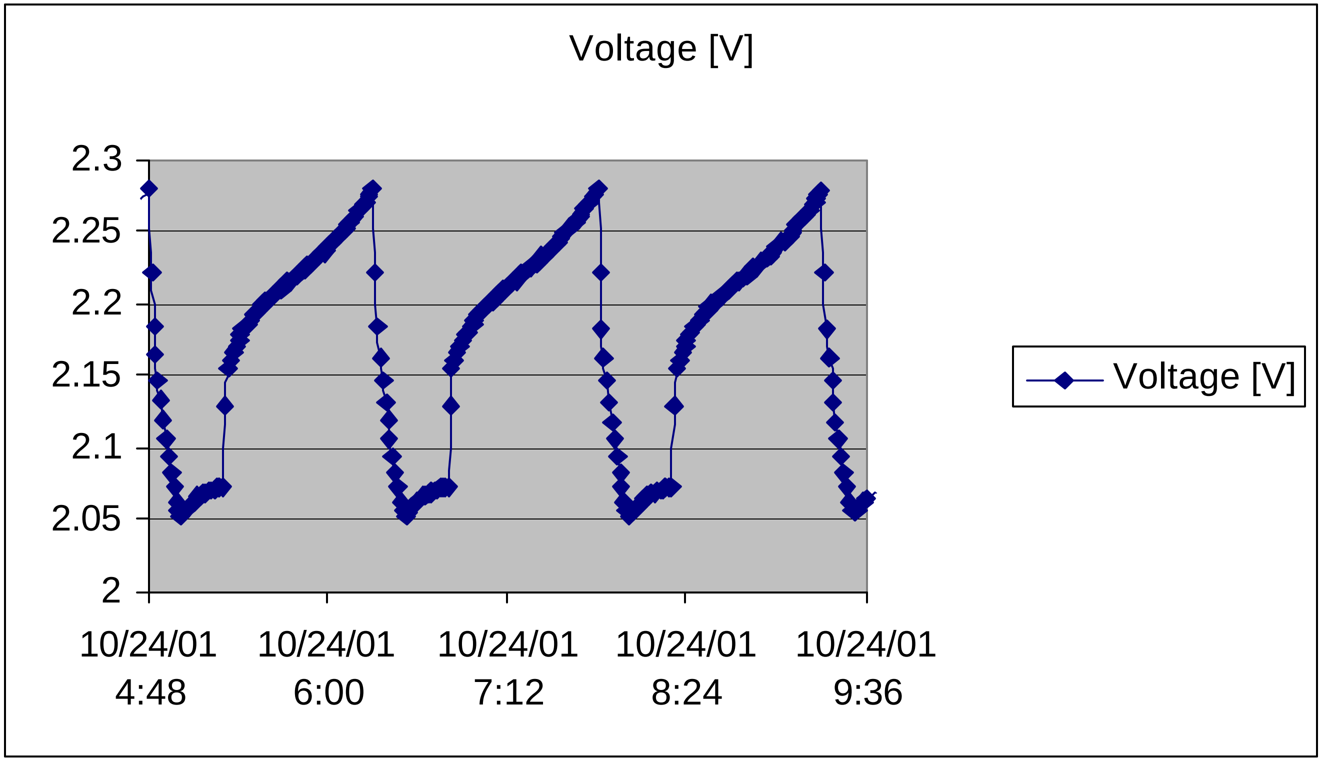
Cell Stabilization

The Cells Were Initially Stabilized Using the Following Process

- **Charge @ 250 mA for 3.5 hours (210 min.) (875mAh)**
- **Discharge @ 350 mA until cell reaches 1.8V**
- **Measure and record capacity from this discharge**
- **Repeat steps until 800 mA-h capacity is reached**

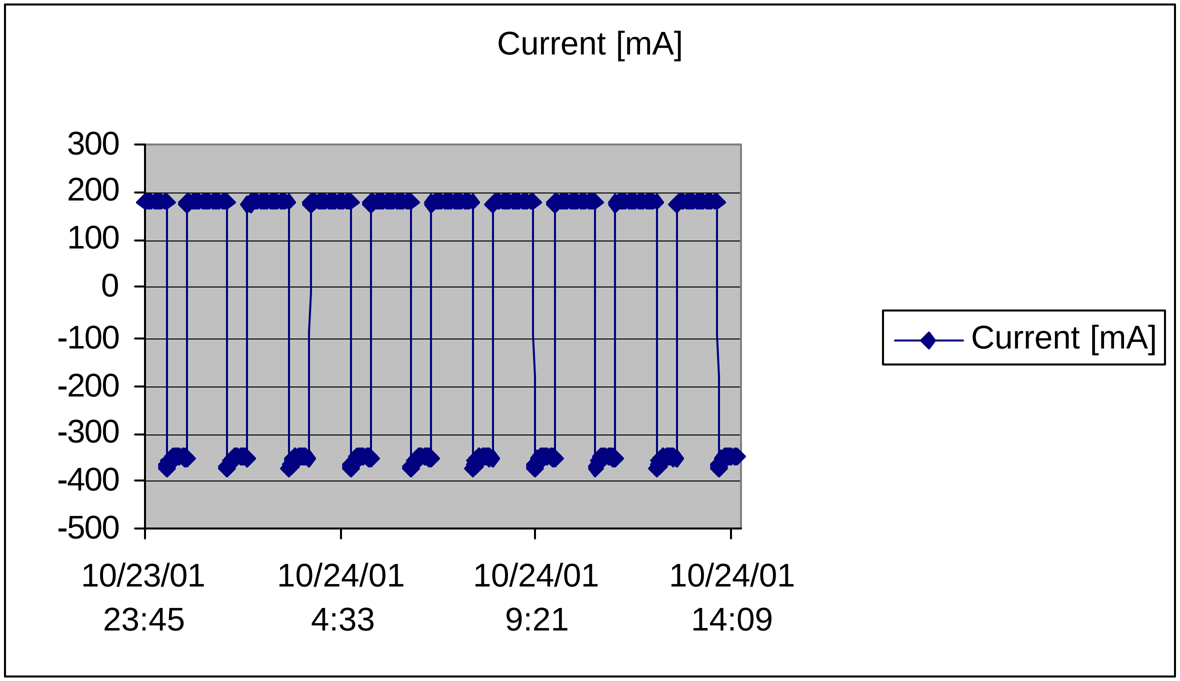
Li-S Cell Cycle Testing (Cont'd)

• **Cell Cycling Characteristics - Voltage**



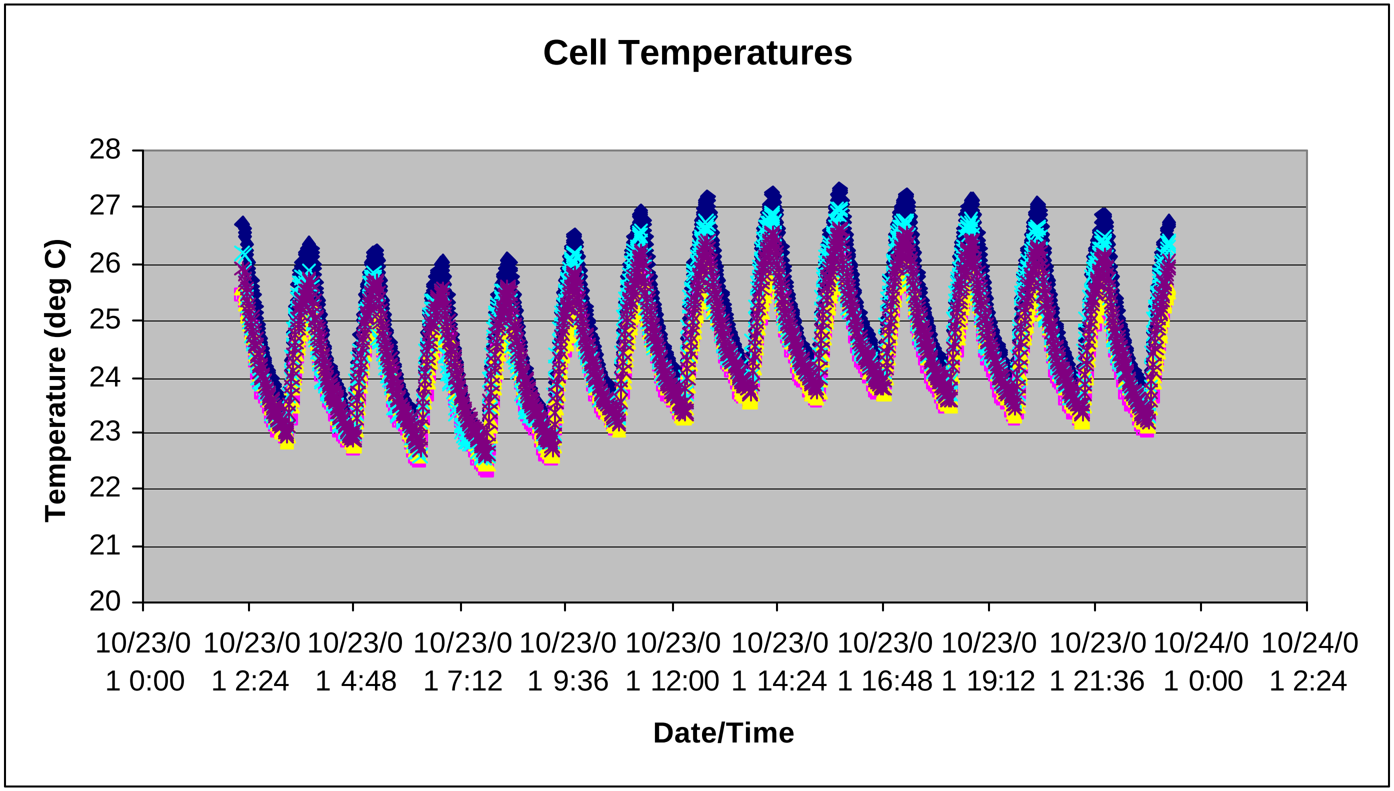
Li-S Cell Cycle Testing (Cont'd)

- **Cell Cycling Characteristics**



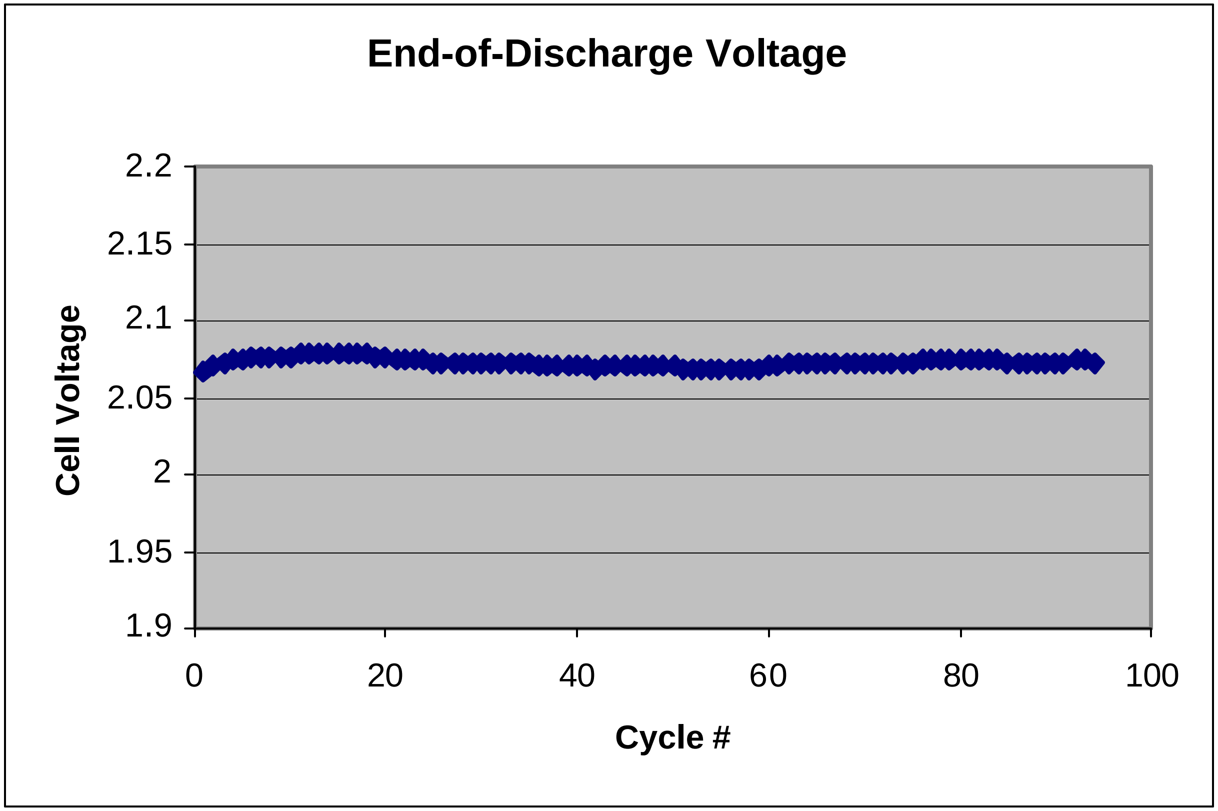
Li-S Cell Cycle Testing (Cont'd)

• **Cell Cycling Characteristics - Cell Temperatures**



Li-S Cell Cycle Testing (Cont'd)

- **Cells Successfully Completed 94 Cycles With No Noticeable Change in Voltage Characteristic**
- **Cycling Terminated Due to Test Equipment Issues**



Li-S Future Testing

Next Step

- Plan is To Commence Cycle Testing of Latest Generation of Cells at Moderate (25 - 50%) Depth-of-Discharge

Li-Polymer vs. Lithium-Sulfur

Items	Li-polymer	Lithium-Sulfur	
		a -6 Sample	Product in 2003
Operation Voltage	3.6V	2.1V	2.1V
Cycle Life to 80% at 100% DoD Discharge	>400	>300	>500
Specific Energy (Wh/kg)	120 -180	180	300
Volumetric Energy (Wh/l)	250 -350	170	400
Cell Capacity (mAh)	450 -900	800	1000 -2400
Operating Temperature	-10ºC to 65ºC	-40ºC to 65ºC 60% of RT at -40ºC	-40ºC to 65ºC Same or Better
Power (W/kg)	-	750W/kg or higher	same
Discharge Rate Capability	2C	>6C	same
Charge Rate	2hr at R.T.	3hr at R.T.	2hr at R.T.
Size and shape	Prismatic	Prismatic or cylindrical	Prismatic or cylindrical

Alpha Cell Development Plan

Alpha	**1-3**	**Metal foil cells (MFC)**
Alpha	**4**	**MFC with low impedance**
Alpha	**5**	**Spray metal tabs at cathode and anode**
Alpha	**6**	**PET substrate for cathode**
Alpha	**7**	**Coated Separator on cathode**
Alpha	**8**	**Thin film plastic cell**

Product Roadmap

a -4

160 Wh /kg
180 Wh /l
Cycles to
120, 80%

To 1999

a -6

180 Wh /kg
170 Wh /l
Cycles to
300, 80%

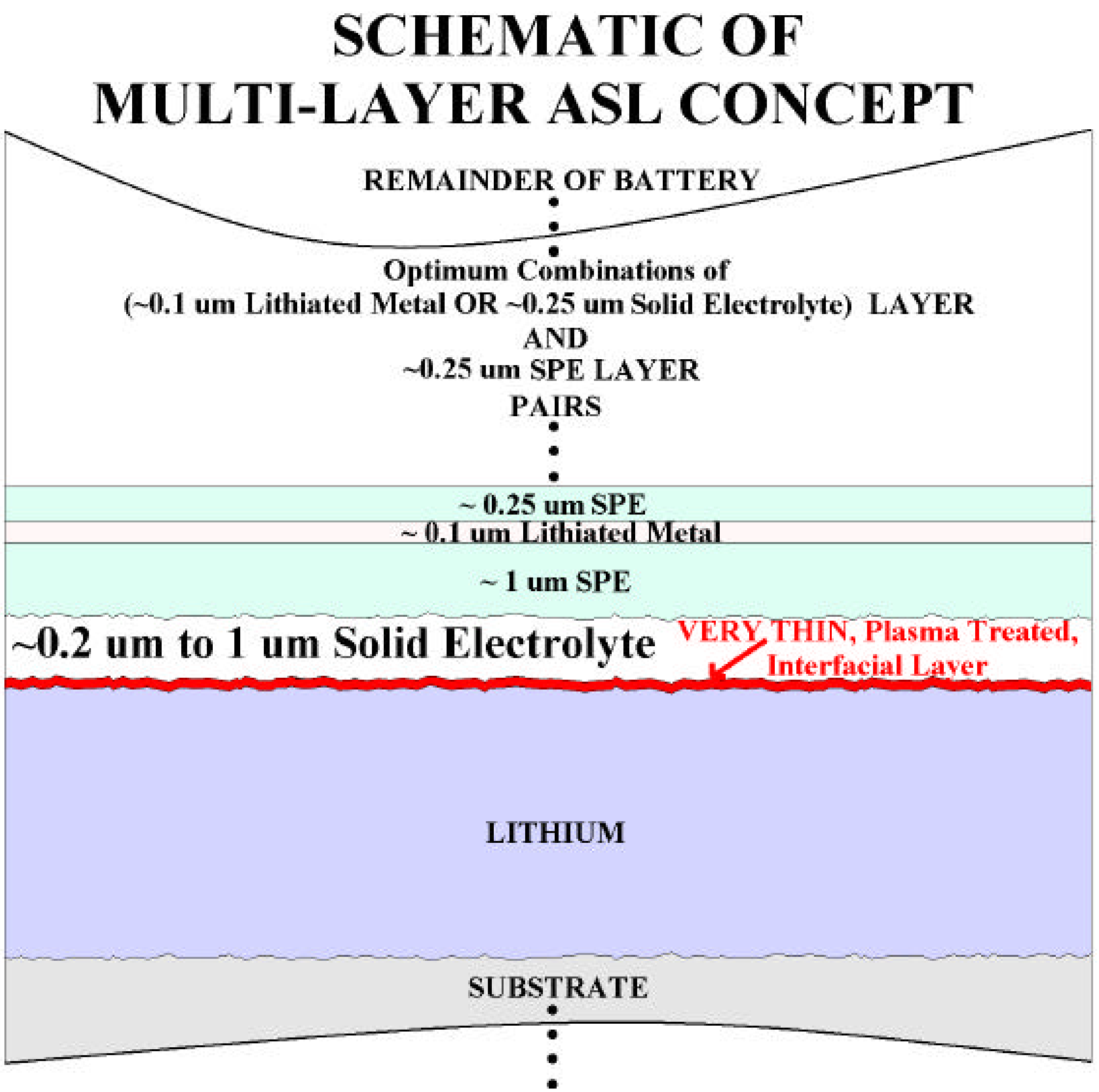
December 2001

a -8

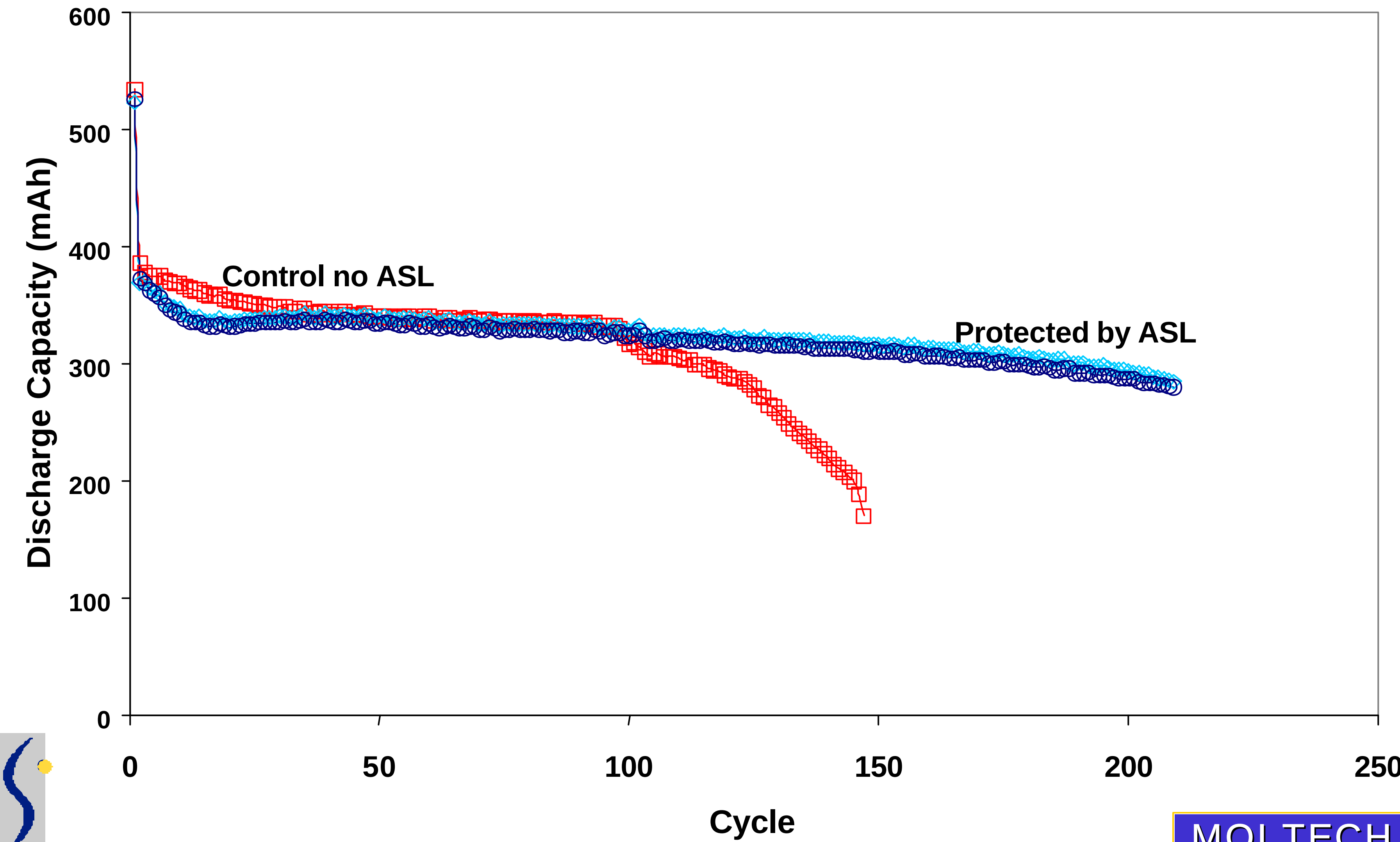
300 Wh /kg
400 wh /l
Cycles to
>500, 80%

December 2003

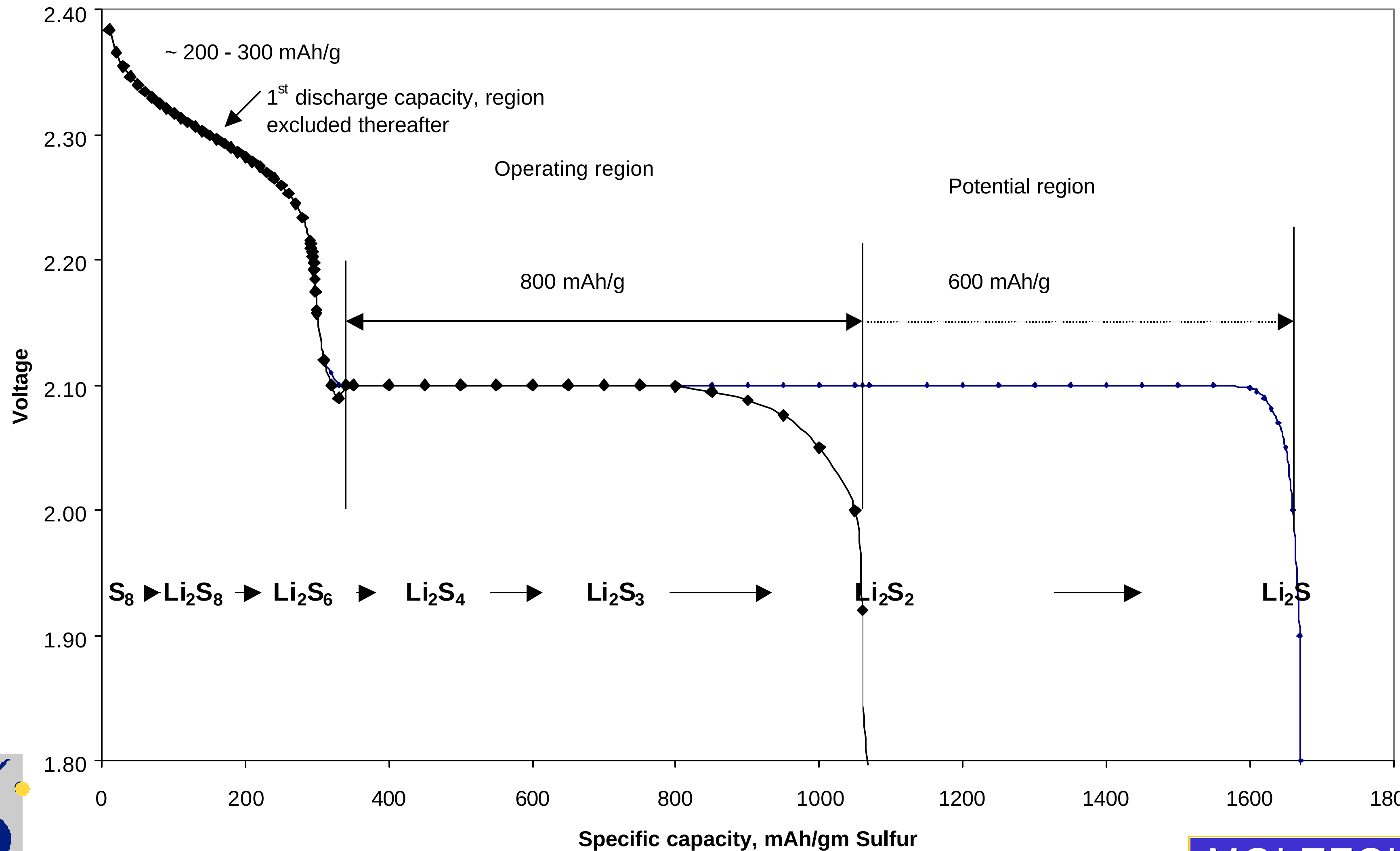
Anode Stabilization Layer Concept



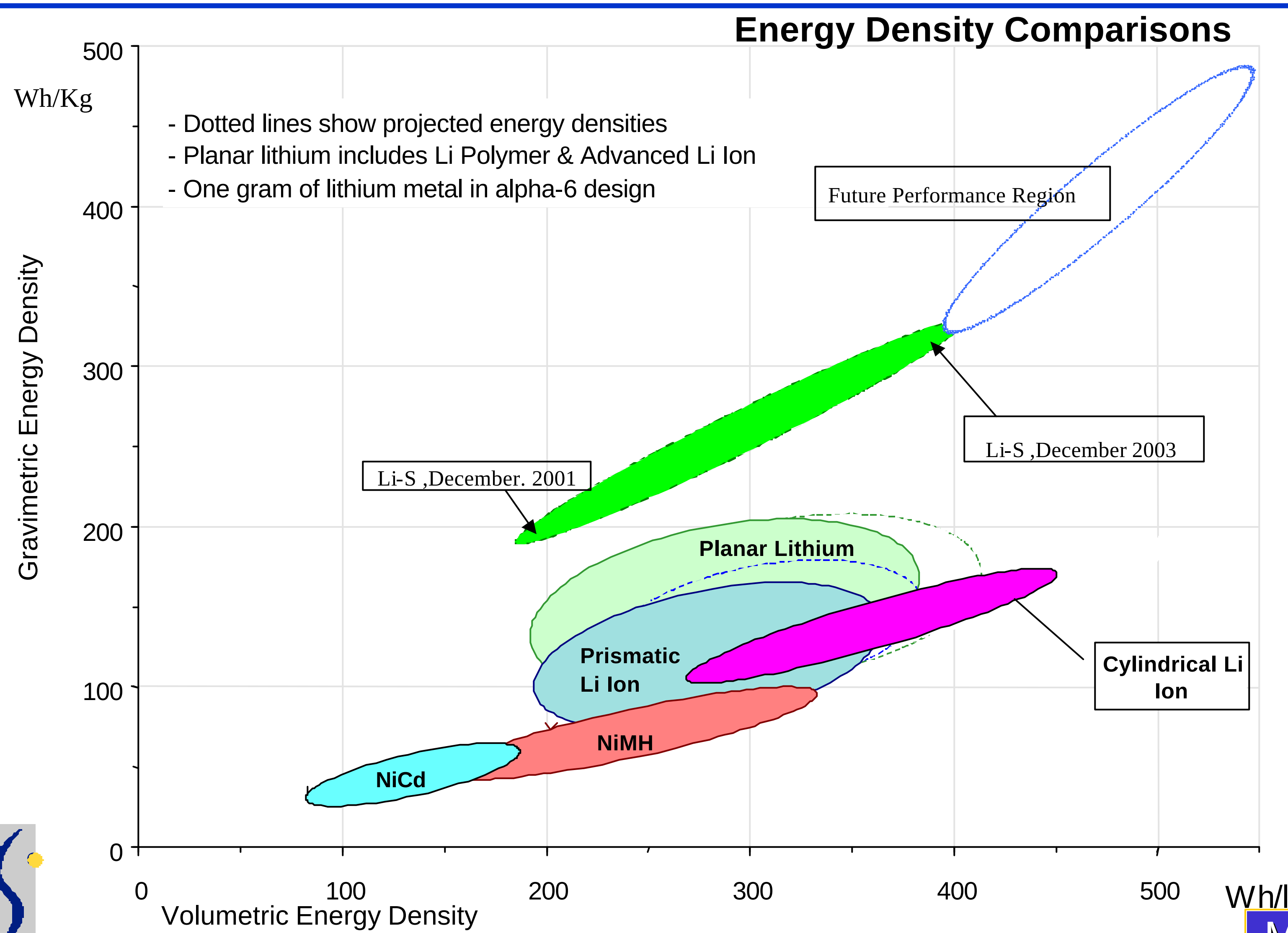
Cycle Life Comparison : Protected vs. Non-Protected



Lithium/Sulfur Discharge/Charge Chemistry



Li-S Compared to Other Systems



SPECTRUMASTRO

MOLTECH CORPORATION

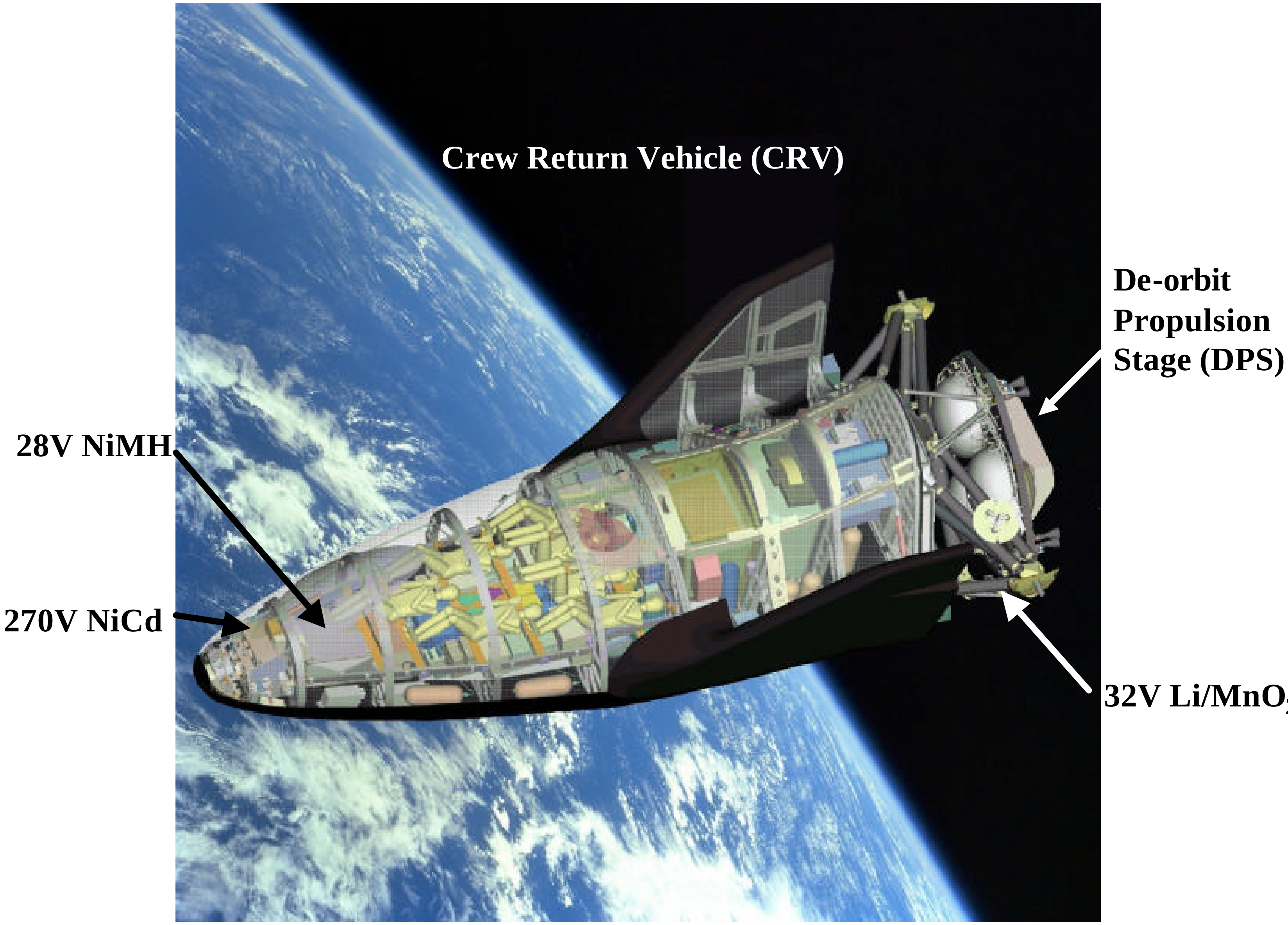
Development Status of 3 Battery Systems for the X-38 Crew Return Vehicle

by

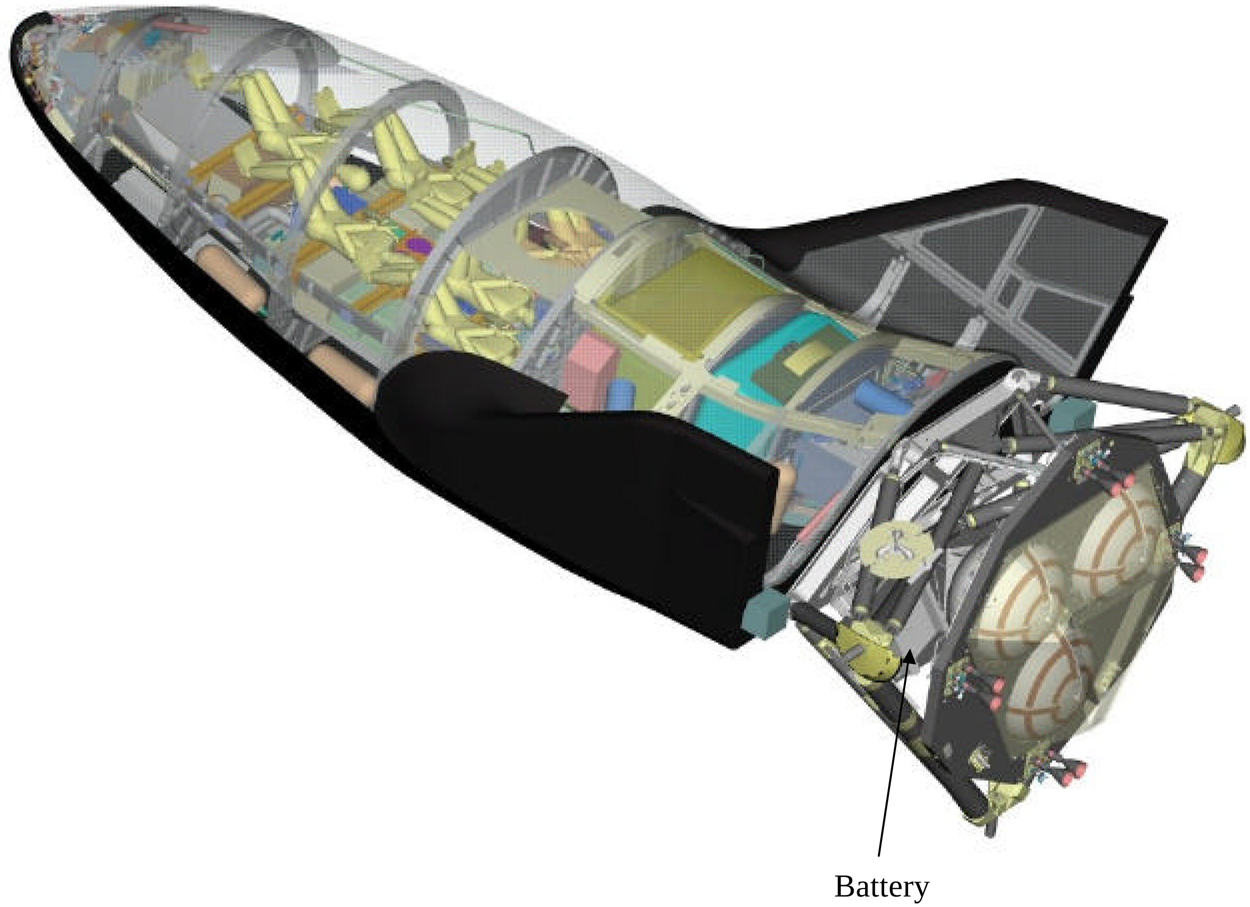
Eric Darcy/NASA-JSC

Presented at the

2001 NASA Aerospace Battery Workshop, Huntsville, AL


Crew Return Vehicle (CRV)
De-orbit Propulsion Stage (DPS)
28V NiMH
270V NiCd
32V Li/MnO_2

32V DPS Li Battery

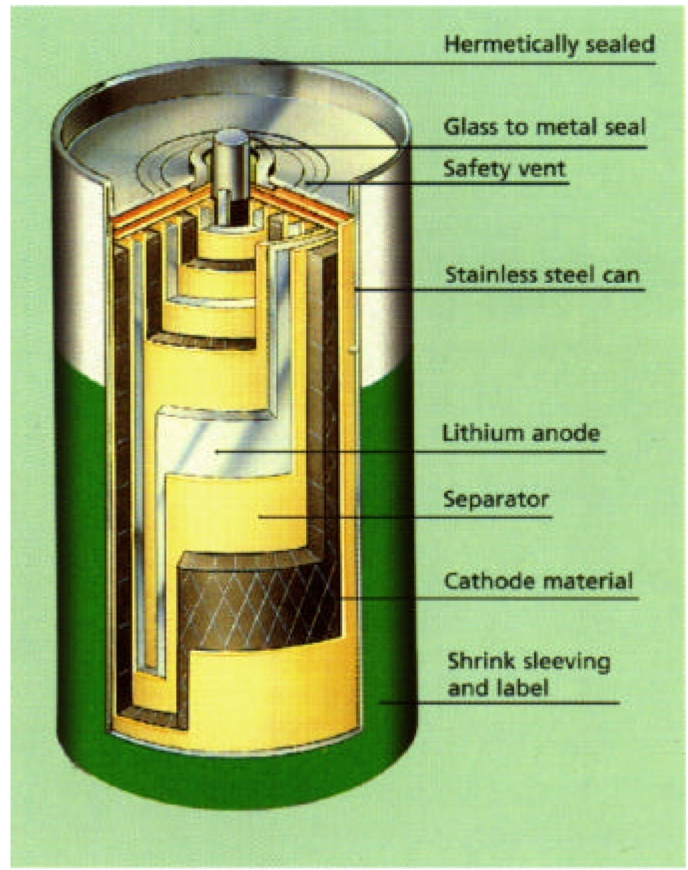


32V DPS Li Battery

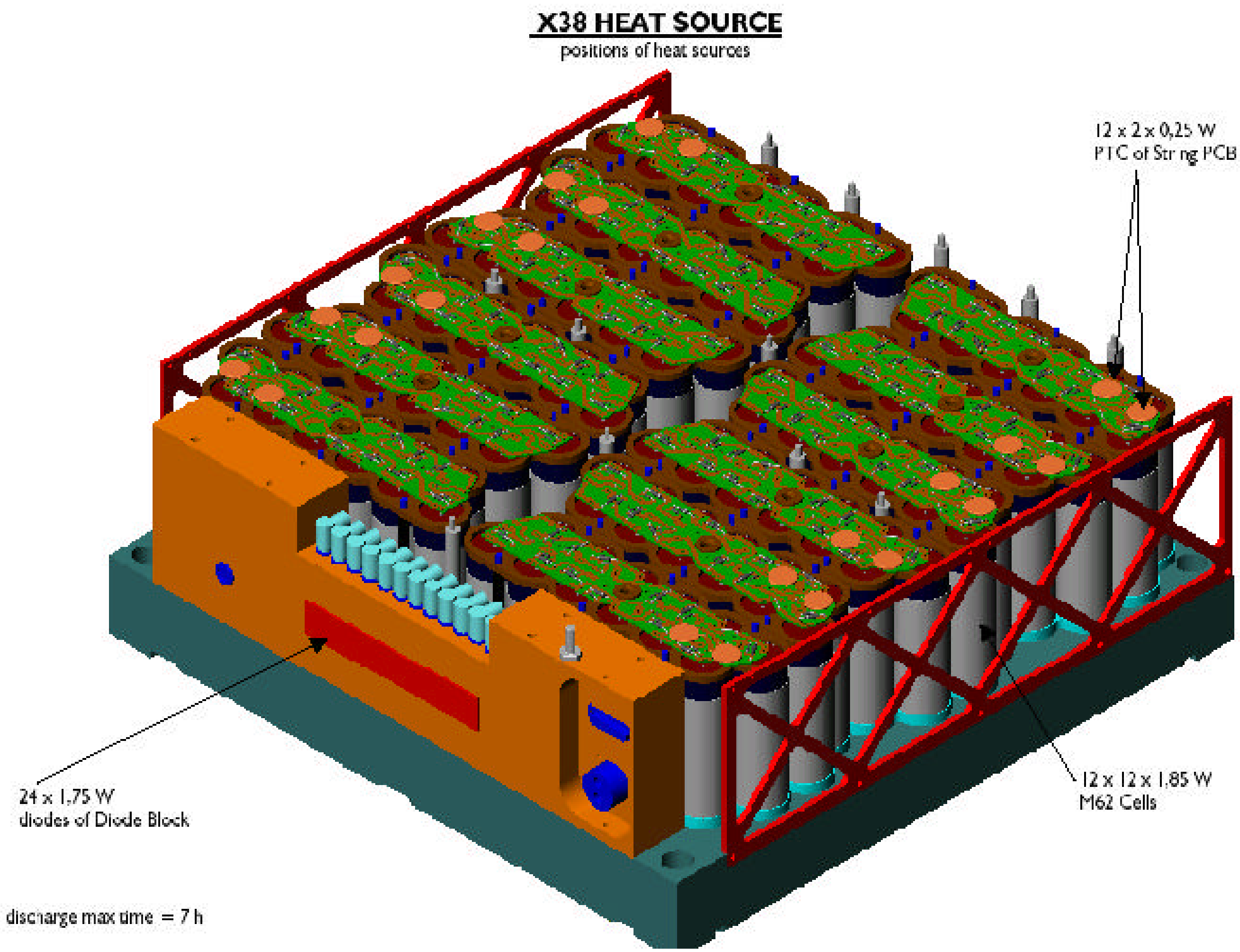
- Design Features (Vendor: Friemann & Wolf, Duisburg, Germany)
  - Li/MnO_2 31Ah cell (P/N M62) , 365g, 42 mm dia, 133 mm tall
    - At C/7 starting at 30 °C ⇒ 245 Wh/kg, 487 Wh/L
  - Battery String = 12 cells in series
  - Battery Module = 12 strings in parallel
  - Similar to ASTRO-SPAS battery design that flew on 4 Shuttle missions
    - Li/SO_2 cells replaced with identically sized Li/MnO_2 cells (20% more Wh)
    - Provisions for added battery capacity gauge circuit
    - Provisions for improved internal thermal conductivity and capacitance
  - Flight Battery Set = 4 Battery Modules
  - Voltage: Open Circuit = 40V, Closed Circuit = 24-33V
  - Capacity starting at 0 °C = 350 Ah/battery module
  - Capable of adiabatic discharge at 50A/module for 7 hours starting at < 30 °C
    - Composite phase change material heat sink sealed in base of battery
    - Provides >3300 kJ of latent heat at 42-44 °C
  - Battery Module Size
    - 590 mm wide, 580 mm deep, 223 mm tall ⇒ 169 Wh/L
    - 91.5 kg ⇒ 141 Wh/kg

M62 Cell Design Features

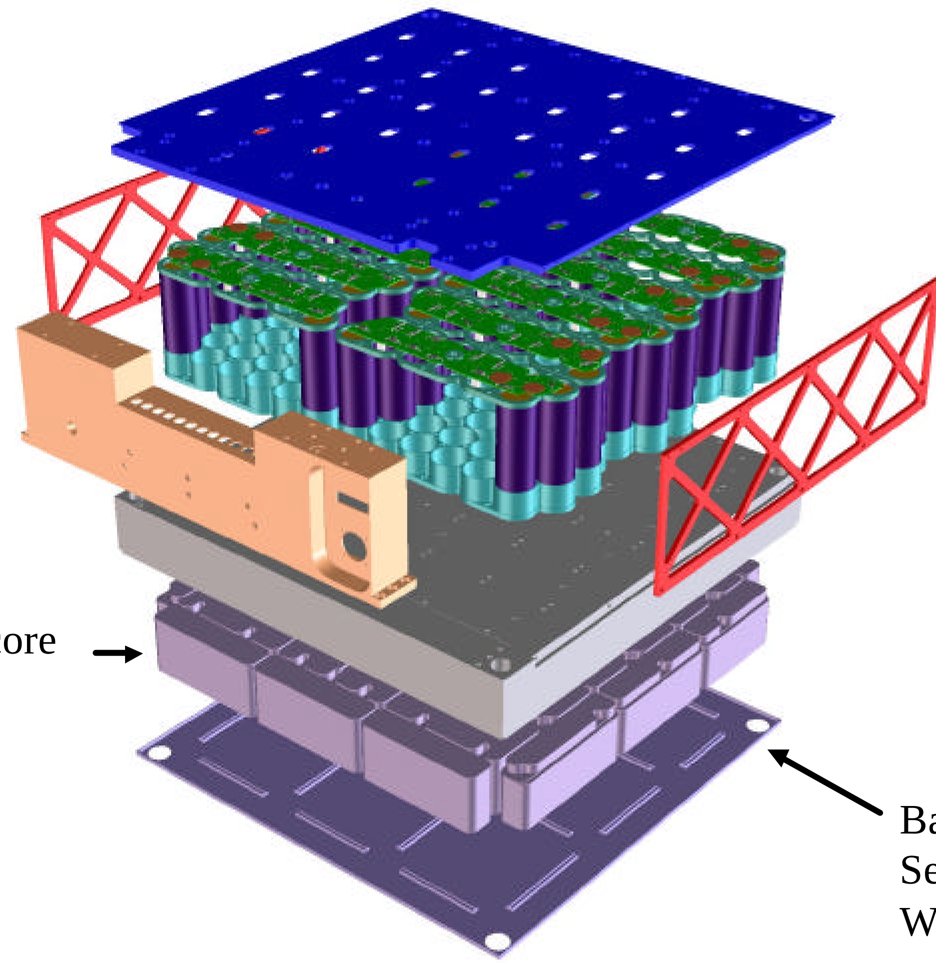
- Li foil anode, 10 g
- MnO_2, carbon, binder cathode mix, 160 g
- Double layer, polypropylene separator, 20 g
- Cylindrically wound coil with anode in contact with case, positive insulated from case with PTFE spacers
- Non-corrosive, organic electrolyte (with $LiClO_4$ salt)
- Glass-to-metal positive feed-thru
- Hermetic seal achieved by laser weld of lid to deep drawn can
- 304L SS can & lid with safety vent operating at 150 to 250 psia



32V DPS Li Battery Module (without cover)



32V DPS Li Battery Module



Carbon Fibercore
+ PCM Wax

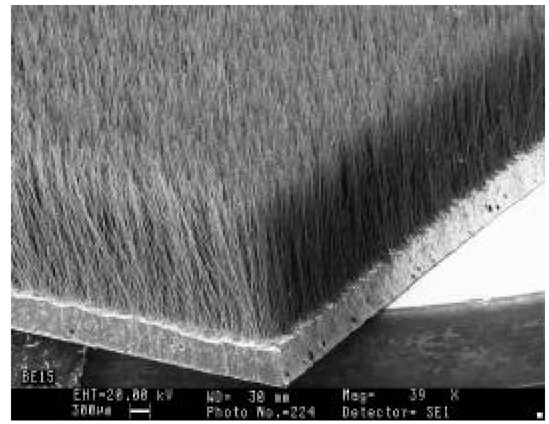
Battery Base Lid
Sealing PCM
With a Glue Joint

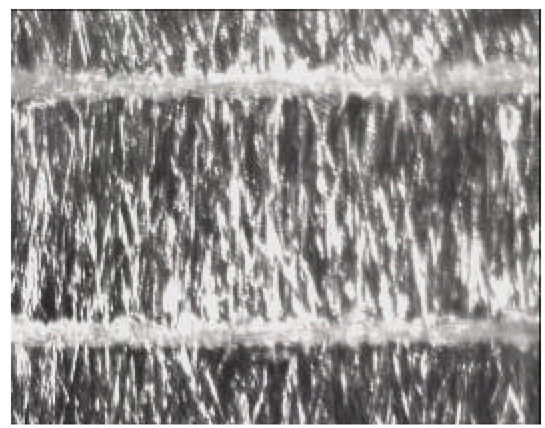
Adiabatic Discharge Possible with PCM Heat Sink

- Two Main Components of Battery
  - Upper Deck: Cells, polyswitches, and diodes dissipates heat
  - Base: PCM heak sink absorbs heat
- Thermal design requirements
  - High heat capacitance
    - Use latent heat of phase-change material (248 J/g) at 42-44 °C
    - Cp of composite heat sink ~ 2 J/g/C
  - Adequate thermal conductivity (Max $\Delta T < 9$ °C)
    - Conductive Al sleeves around base of each cell
    - Thermally conductive glue to bond sleeves/shell to battery base
    - Conductive Carbon Fiber Core Material with 90% porosity'
      - Increases thermal conductivity of pure PCM by factor of 50

PCM Composite Heat Sinks

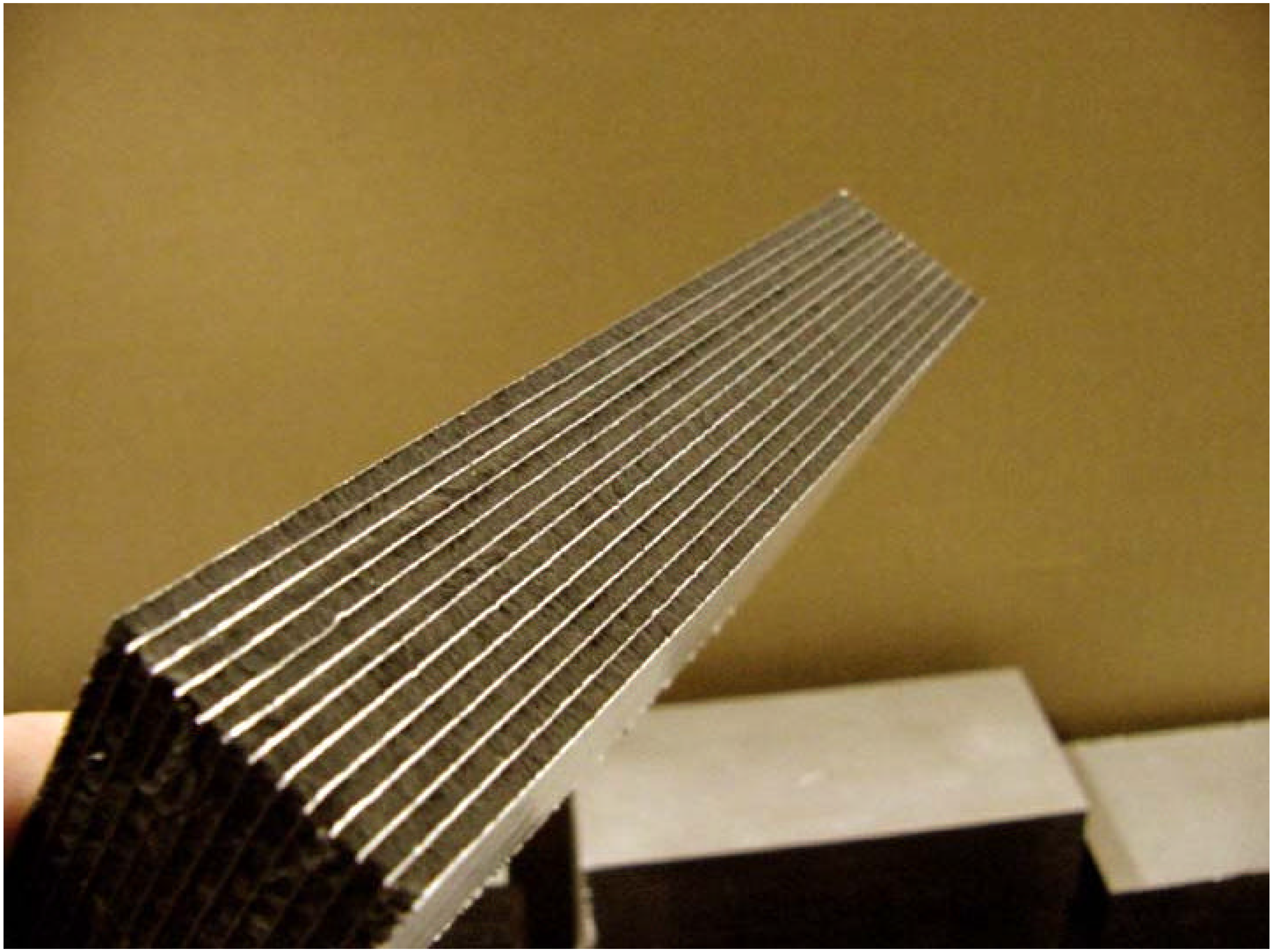
- Carbon-fiber core body
  - High thermal conductivity
  - Light honeycomb structural properties
  - Capillary control of voids relieves stress
- Lightweight packaging
  - Packaging mass = 20-50% of total heatsink mass
  - Specific latent heat > 150 J/g for total package
- Technology own by Energy Science Labs, Inc (ESLI), in San Diego, CA





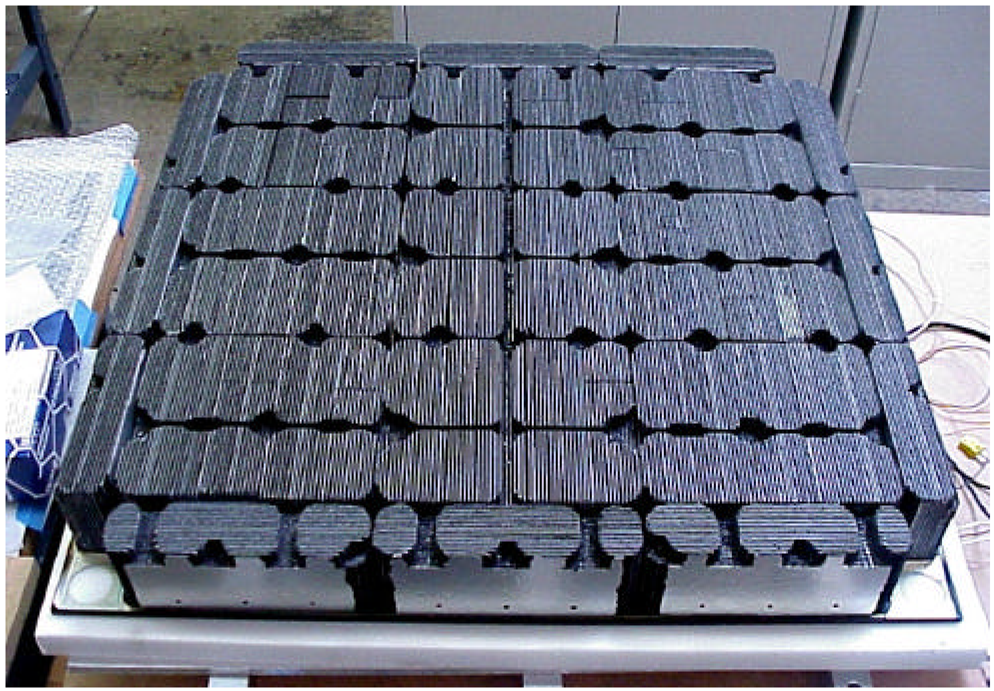
Carbon Fibercore Blocks for Qual Battery

Side view of carbon fibercore

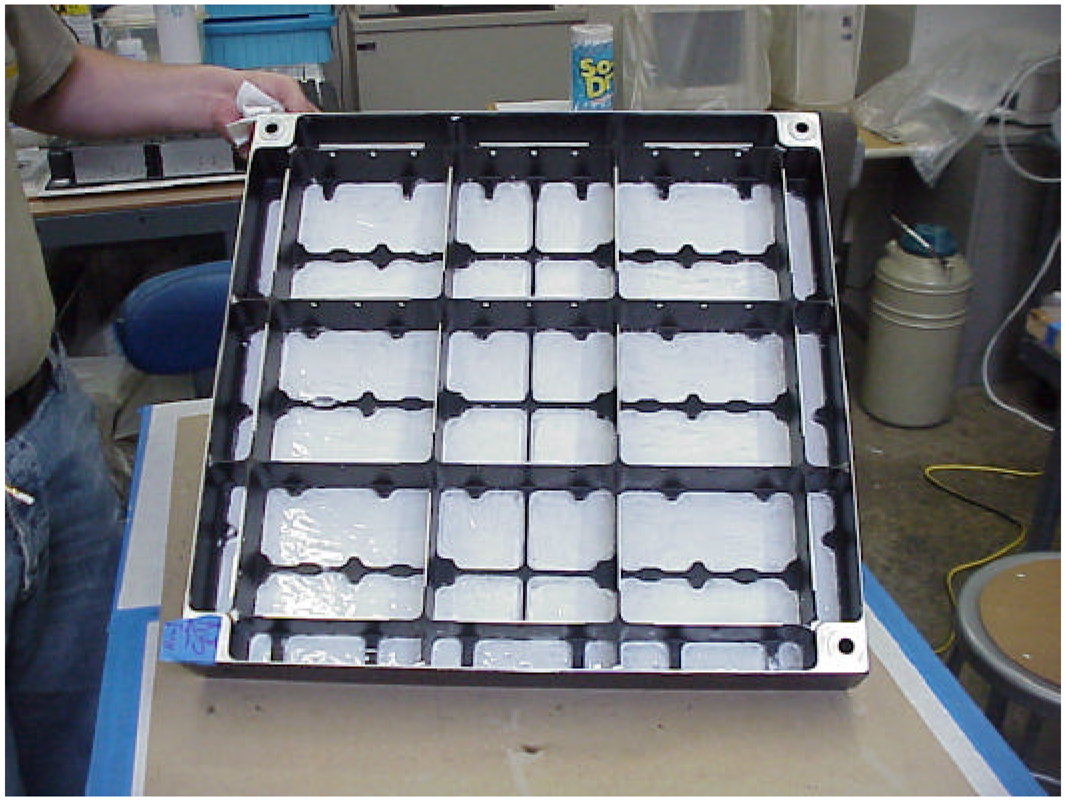


Battery Module Base Housing

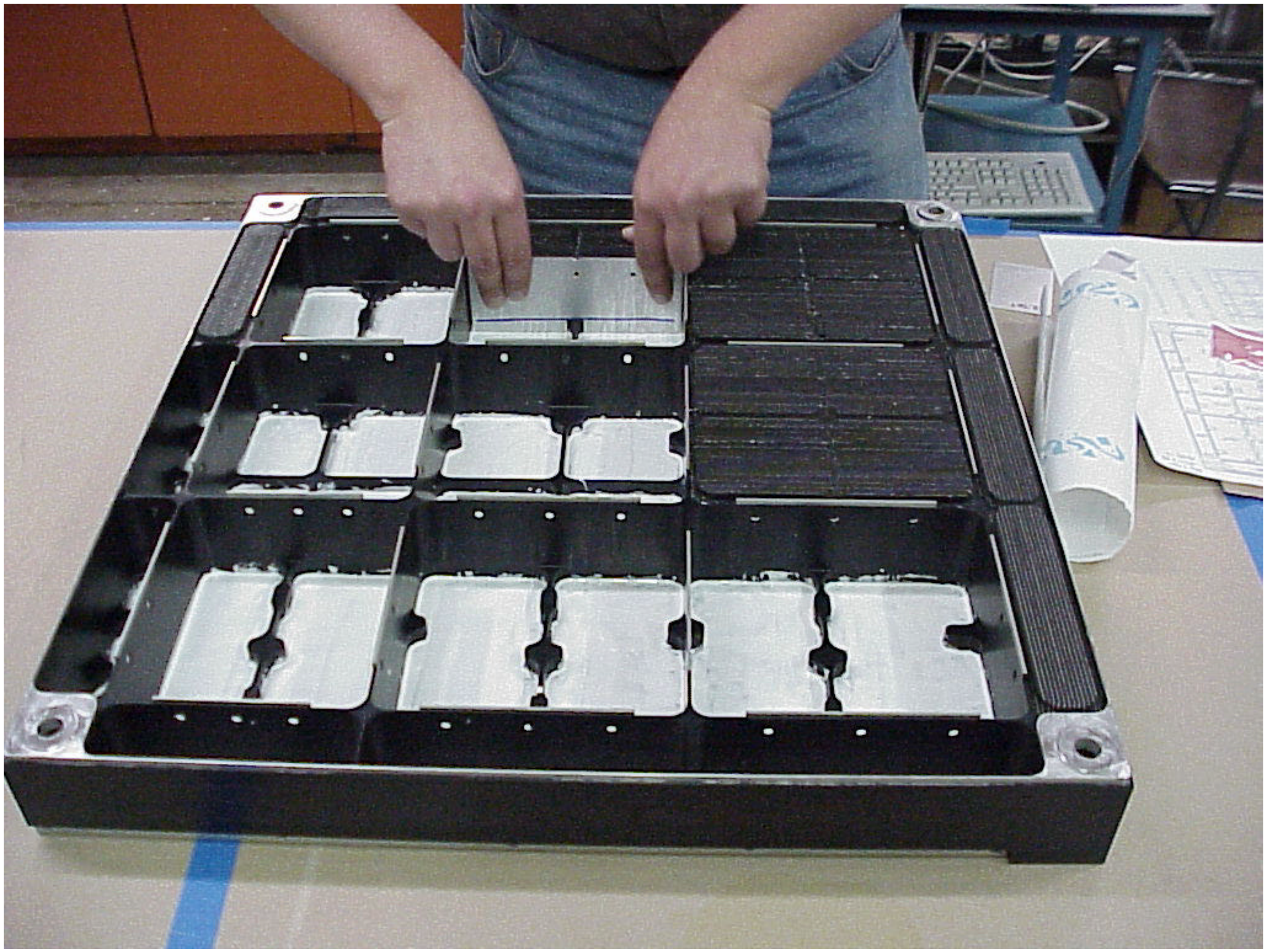
Carbon Fibercore Blocks on Lid of Base



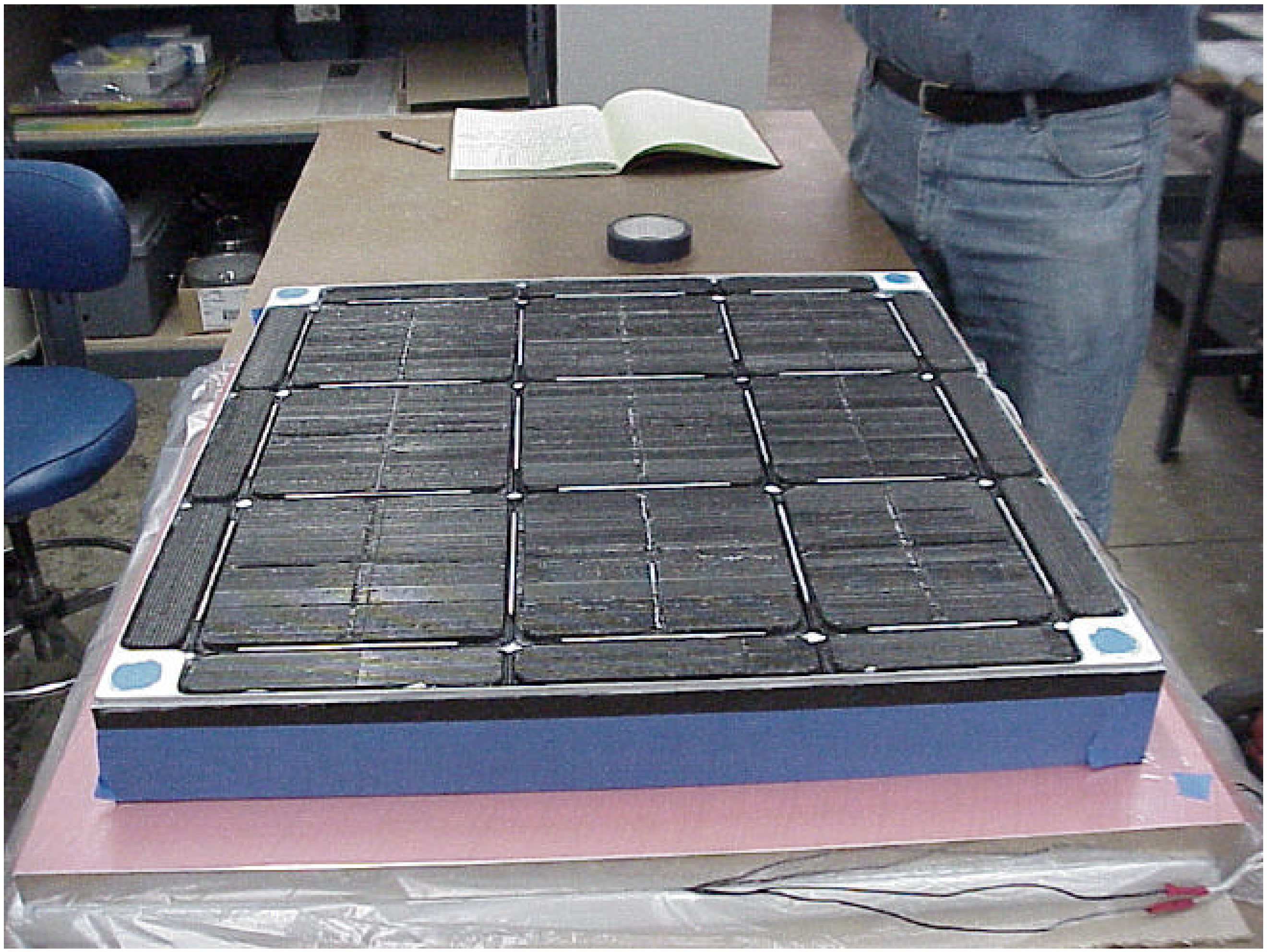
Base cavities are lined with epoxy glue



Fibercore blocs are hand fitted and glued to the base cavities



Battery base filled with fibercore blocks

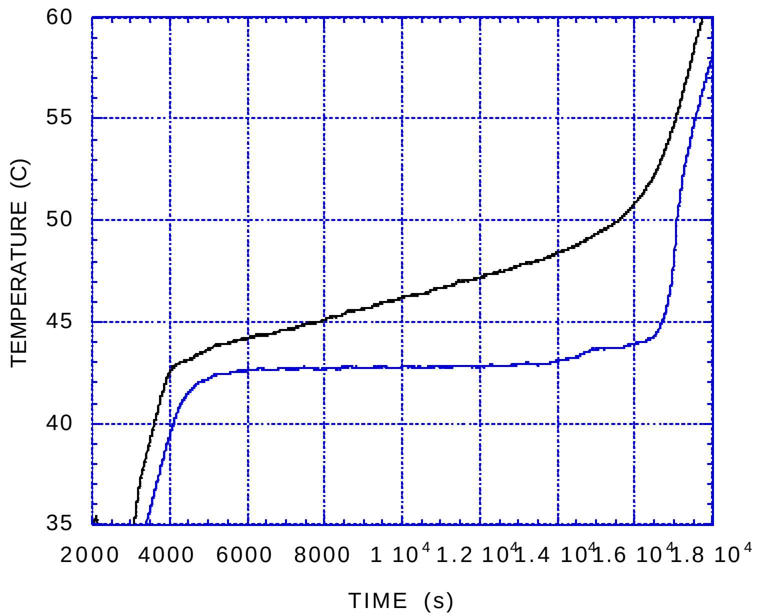


Ass'y and Acceptance of PCM Heat Sinks

- Lid is glued onto housing to complete unfilled assembly
- Vacuum baked to remove moisture
- Thermally shocked cycled followed by helium leak check
- Vacuum back-filled at 90 °C with liquid *n*-docosane ($C_{22}H_{46}$)
- Thermally cycled to measure capacitance with 350W heat source in two orientations

Melting Heat Sink Characteristics

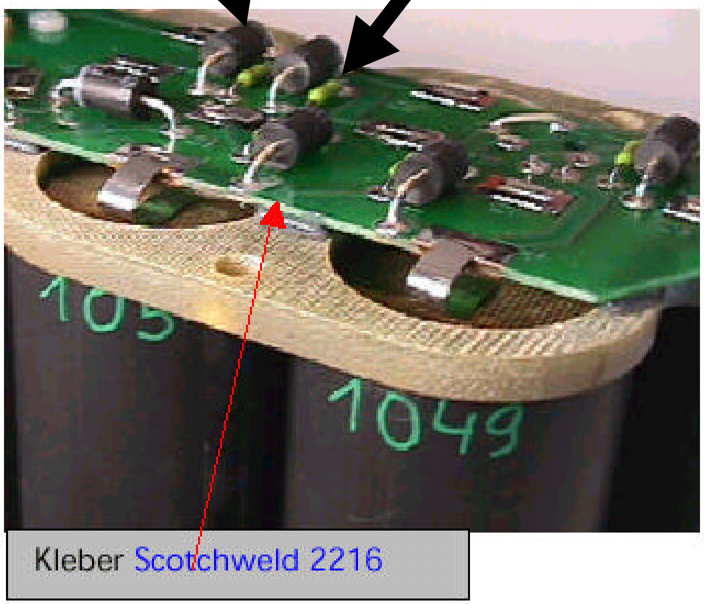
- Average of 4 Flight Heat Sinks
  - 3596 kJ of latent heat at 42-44°C
  - Melting over ˜ 3.5 hours at 300W
  - Specific latent heat = 133 J/g (includes structural mass of base)
  - Specific latent heat = 184 J/g (without 7.5 kg base mass penalty needed for battery w/o PCM)
- Battery Module Base = 27 kg
  - 14.5 kg (54%) PCM
  - 3.6 kg (13%) fibercore
  - 1.3 kg (5%) cover
  - 7.4 kg (27%) base housing

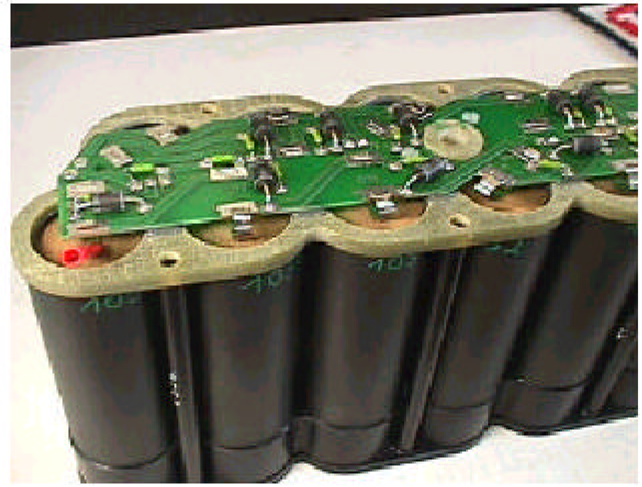


Assembly of Cell Strings

Bypass diode
Qty 1/cell

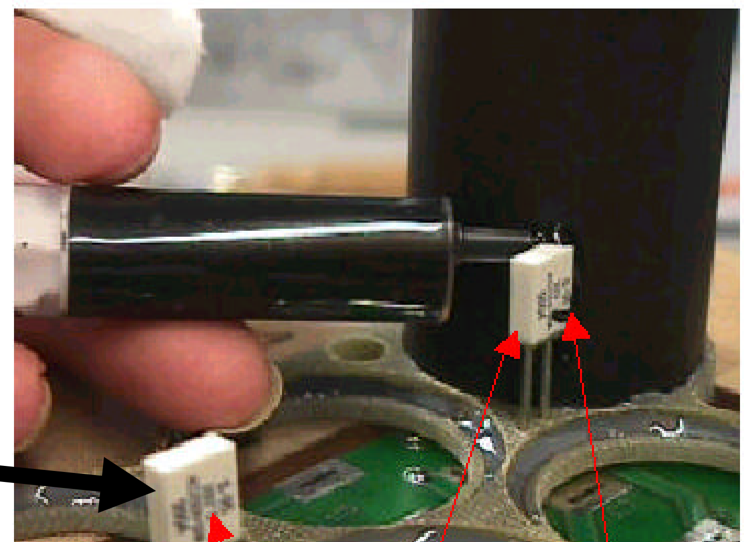
Picofuse
Qty 1/diode





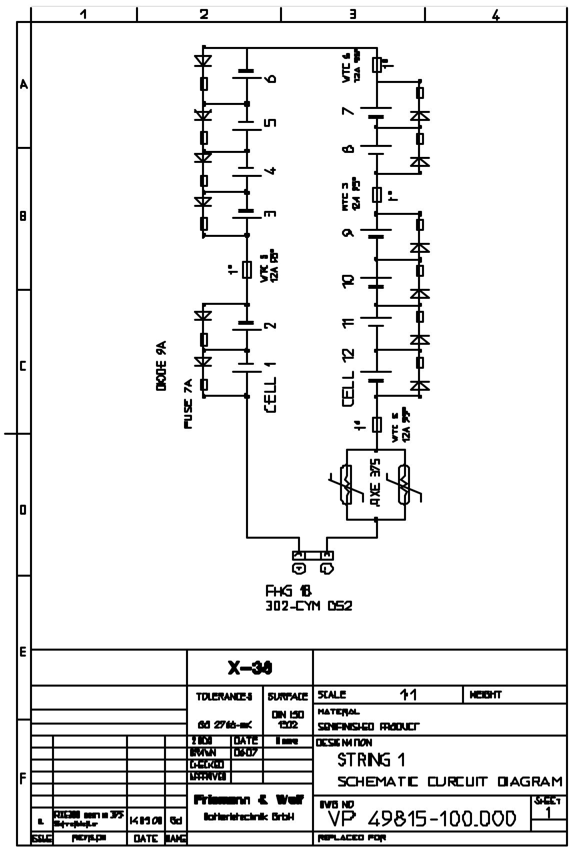
Polyswitch (not shown) Qty 2 in parallel/string

Thermofuse
Qty 4/string

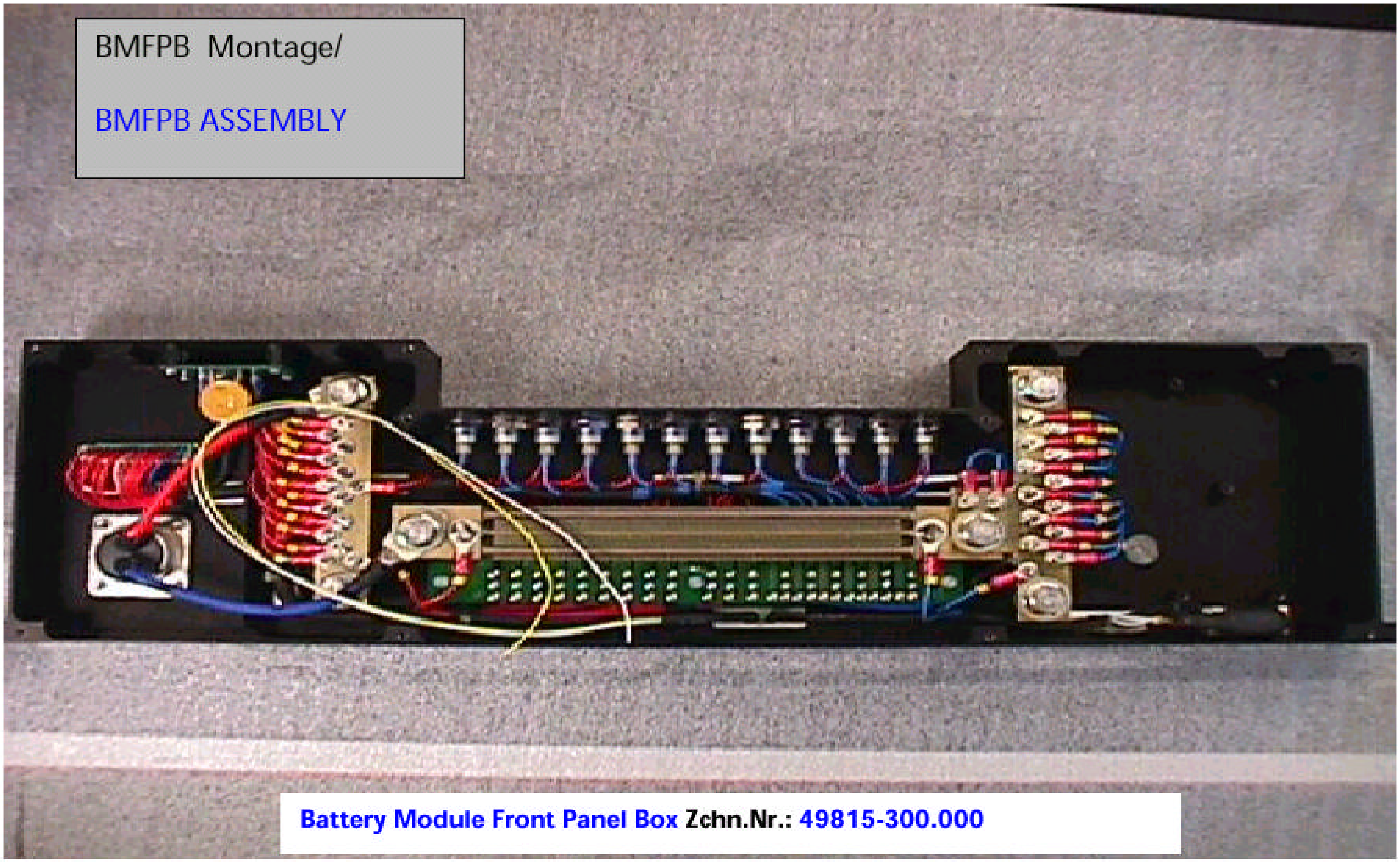


Electrical Schematic of Cell String

- 12 cells (P/N M62) in series
- 1 bypass Schottky diode/cell rated at 9A
- Each cell protected from a shorted diode failure by 7A fuse
- 2 polyswitches in parallel trip above 7.5A at 20 °C or at ~82 °C with 4.2A
- 4 thermofuses/string open at 90 to 100 ° C

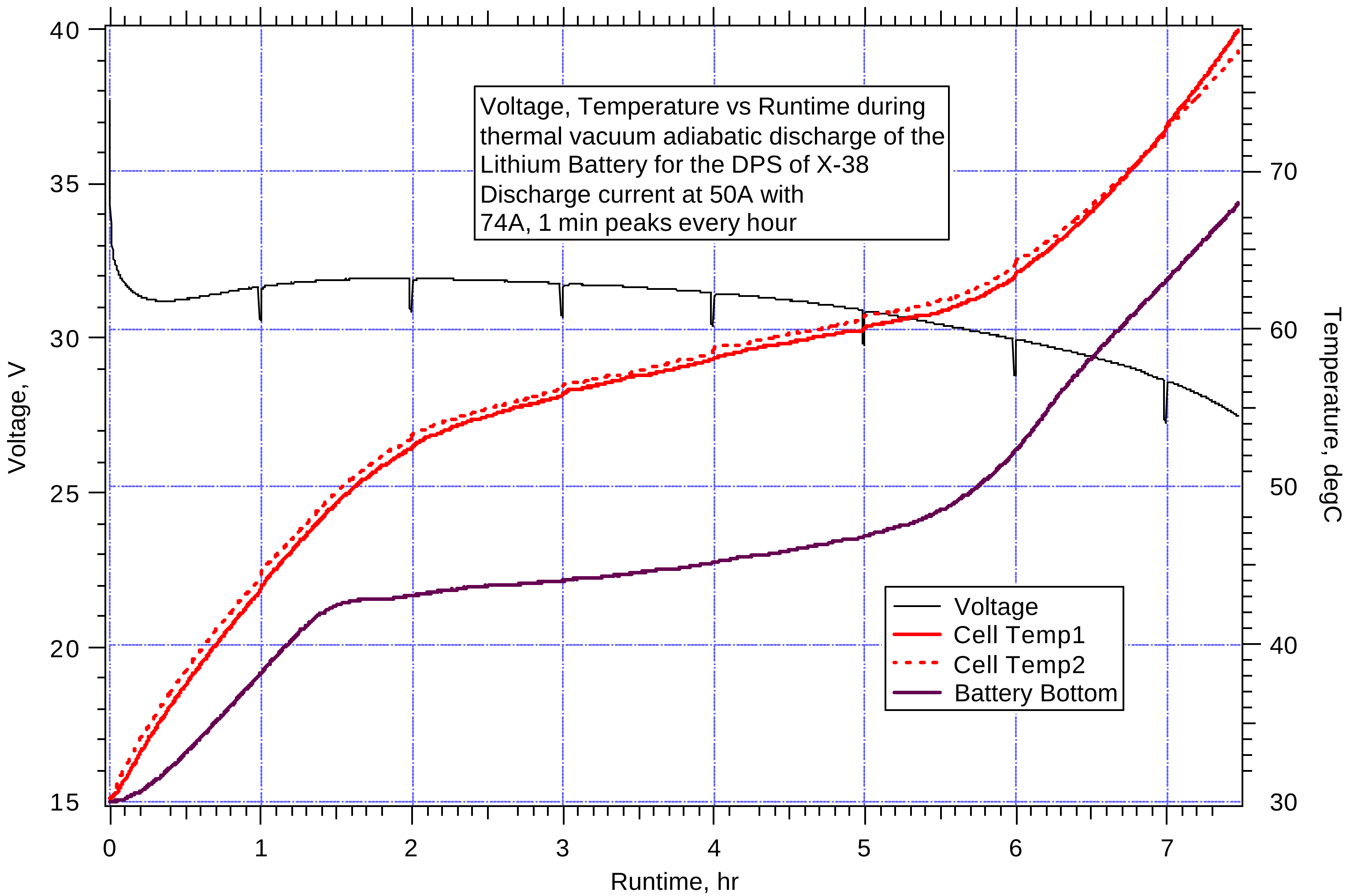


Battery Module Front Panel Box



Summary of Battery Qualification

- Qualification was successfully completed on 4/11/01
  - Battery passed shock (20g, 11ms) and vibration tests (~7 grms, 3 min/axis)
  - Battery ran for > 7 hours at 50A under adiabatic TV conditions
    - Started at 30 °C, ran for 7 hrs, 28 min until cell temperatures reached 80 °C
    - PCM composite heat sink stabilized battery temperatures at 42-50 °C for 3.5 hours
  - Three "firsts" were achieved for manned spacecraft!
    - Largest (12 kWh) lithium battery module
    - Largest (3600 kJ) PCM heat sink
    - Largest lithium battery capable of adiabatic discharge


Voltage, Temperature vs Runtime during thermal vacuum adiabatic discharge of the Lithium Battery for the DPS of X-38
Discharge current at 50A with
74A, 1 min peaks every hour
Voltage
Cell Temp1
Cell Temp2
Battery Bottom
Voltage, V
Temperature, degC
Runtime, hr
40
35
30
25
20
15
70
60
50
40
30
0
1
2
3
4
5
6
7

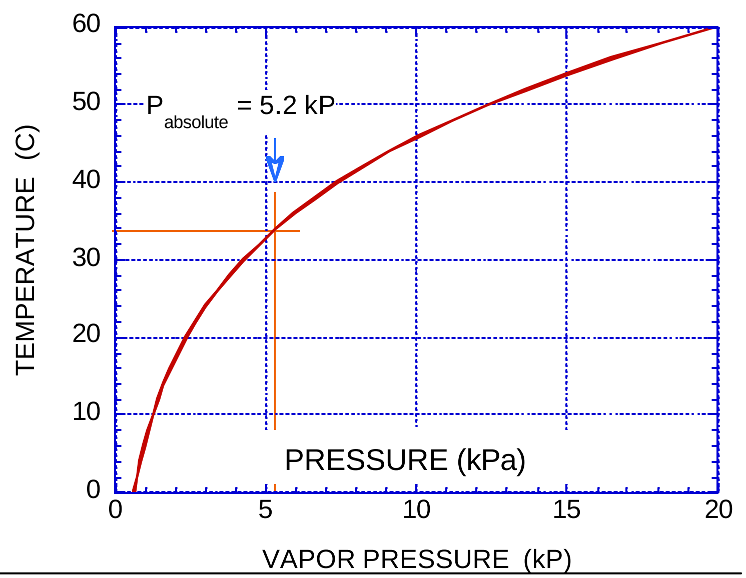
Future Plans

- Flight battery production underway
  - Quantity of 4
    - All 4 PCM bases have passed all acceptance tests
  - Refurbishment of Qual unit also underway
- Delivery expected in March 2002
- Vaporizing heat sink alternative looks very promising
  - Completed SBIR Phase I with ESLI
  - Could reduce battery heat sink from 27 to ~10 kg
    - Replace 14.5 kg of melting wax with ~1.5 kg of vaporizing water
  - Will award Phase II in Jan 2002

Water Heat of Vaporization

- Water latent heat of vaporization is 10x higher than paraffin latent heat of melting
  - But only one cooling cycle

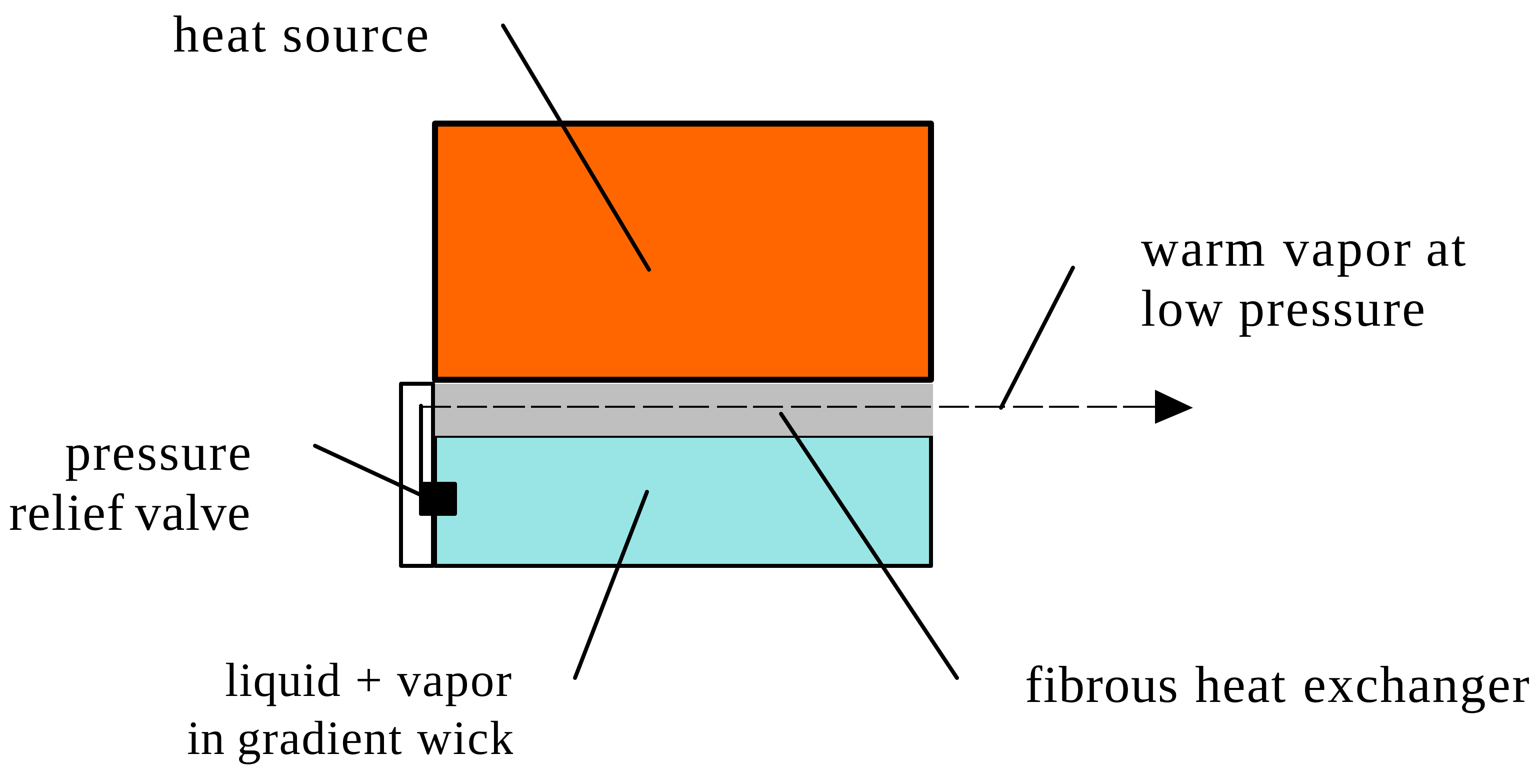
Temp. (C)	Pressure (bar)	Heat-vap (kJ/kg)
2	0.007	2497
22	0.026	2449
42	0.081	2402
62	0.217	2354
82	0.51	2304
102	1.08	2252



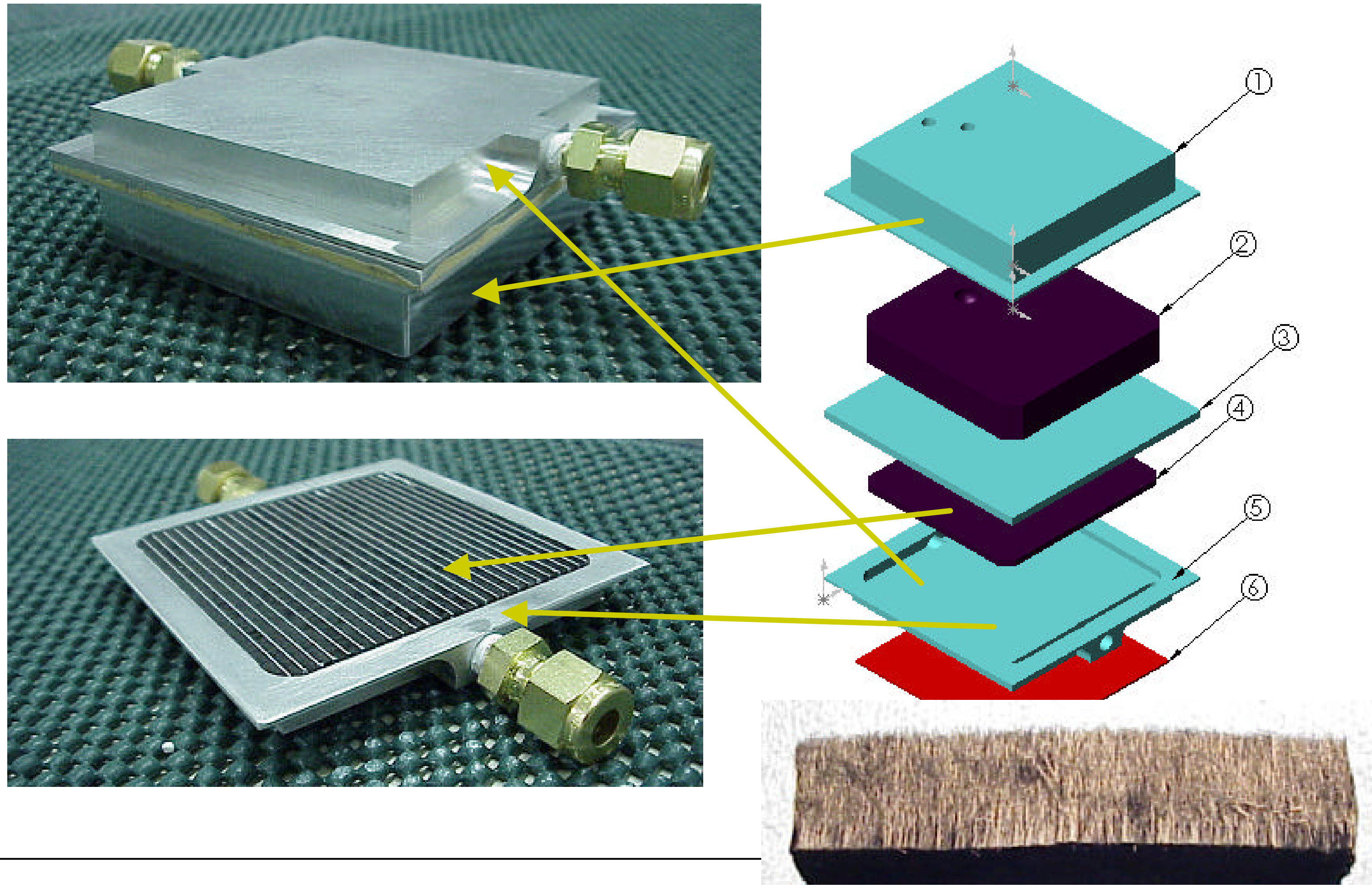
Vaporizing Heat Sink (VHS) Concept

- Relief Valve
  - Allow coolant to vaporize through a pressure-relief valve whose P sets the heat sink T
- Conductive Wick
  - Assures that all coolant remains in good thermal contact with the heat transfer surface in microgravity
- Recuperator
  - Channel the expended low pressure vapor back through the heat transfer surface to better utilize the vapor (reheat, atomize)

Vaporizing Heat Sink Schematic

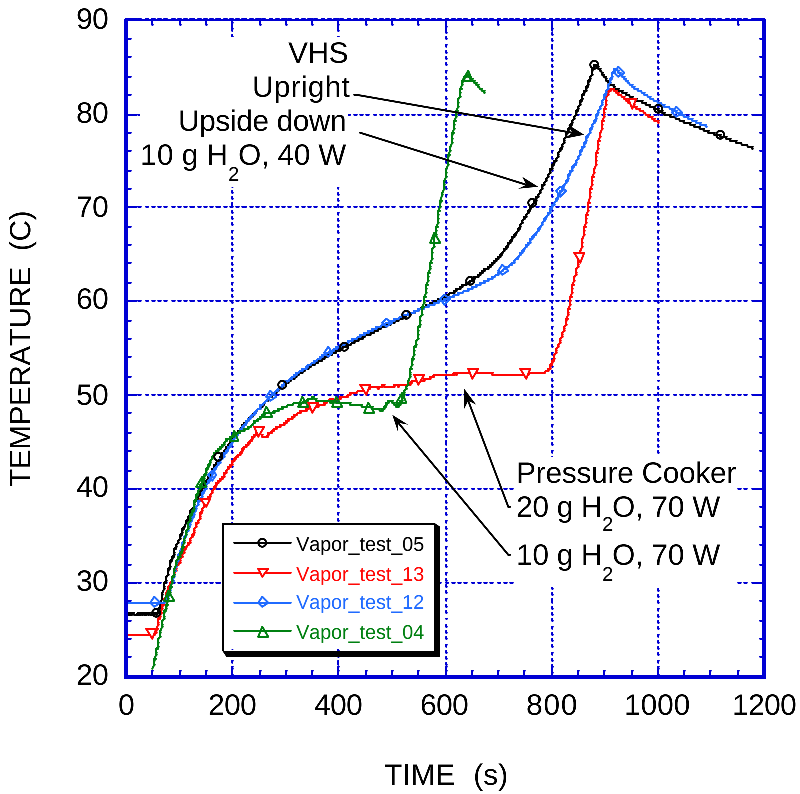


Prototype VHS with Wick and Recuperator



VHS Concept Demonstrated by Test

- Simple, uniform wick allows the heatsink to perform well against gravity (upside down, heater above)
- Thermal resistance in wick (k~ 1 W/K-m) causes steady increase in VHS temperature
  - Wick dries out across thickness
- Expect to reduce the gradient in either of two ways:
  - Higher conductance (k ~ 5)
  - Capillary gradient wick




28V NiMH

28V NiMH Battery System Requirements

- Specification Summary
  - Closed circuit voltage: 24 to 33V
  - Power: 3.6 kW
  - Energy: 3.6 kW for 3 hours = 10.8 kWh
  - Capacity: 387 Ah at 129 A rate to 24V while >10 °C
  - Charger built into each battery module using X-38 28V bus power
    - C/8 charger rate using < 3.5 kW power consumption
  - Capacity gauge circuit built into each battery module
    - Measure battery voltage, current, and temperature
    - Calculates and tracks %Ah remaining
    - Communicates to
      - DAU via a RS-422 interface
      - GSE via a RS-232 interface
  - Total mass: < 335 kg (738.5 lbs)
  - Max crate dimensions: 34.31” depth, 25.37” width, 12.13” height

28V In-Cabin Battery for V201

- NiMH 3.7Ah cell (P/N TH-4000) from Toshiba, Japan
  - Cell used in EMU helmet light battery
  - Cell extensively performance and abuse tested for X-38
  - Demonstrated 308 Wh/L, 90 Wh/kg at C/4 rate and 25 °C
  - 52 g, 17 mm diameter, and 67 mm long
- Battery String = 24 cells in series
- Battery Module = 16 strings in parallel
- Flight Battery Set = 8 Battery Modules in a Crate
  - Estimated at 300 kg, 173 L ⇒ 48 Wh/kg, 83 Wh/L
- Voltage: Open Circuit = 33.6V, Closed Circuit = 24-33V
- Capacity starting at 10 °C = 474 Ah
- Capacity gauge and charger circuit in each module accepting 28V
  - One charge control chip (ICS1702) per string using reverse pulse charging
  - One capacity gauge control chip (MTA11200) per module
- Battery Vendor: Yardney Technical Products, Pawcatuck, CT

LIMITED CONTROL

THIS DOCUMENT IS VALID ONLY IF ACCOMPANIED BY RELATED PROCUREMENT OR TEST DOCUMENTATION (PURCHASE ORDER, WORK ORDER, ETC.)

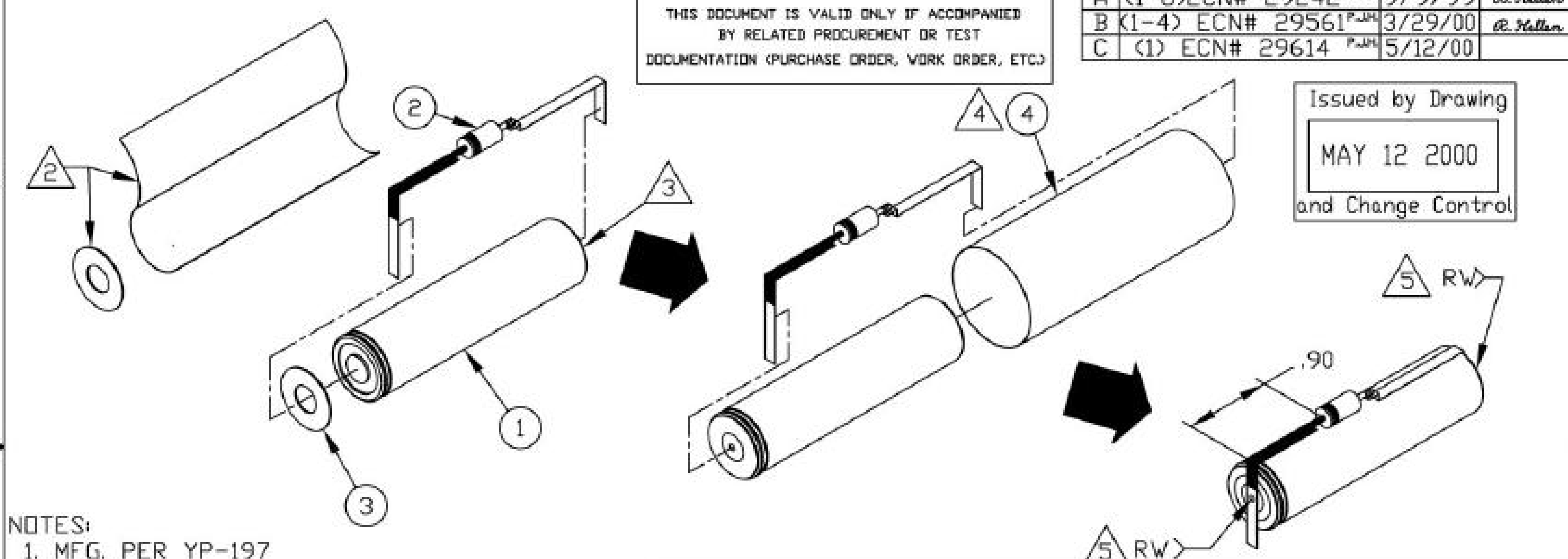
REVISIONS

REV	DESCRIPTION	DATE	APPROVED
A	(1-6)ECN# 29242 S.M.C.	9/9/99	R. Hellen
B	(1-4) ECN# 29561 P.J.H.	3/29/00	R. Hellen
C	(1) ECN# 29614 P.J.H.	5/12/00	

Issued by Drawing

MAY 12 2000

and Change Control



NOTES:

1. MFG. PER YP-197
2. REMOVE AND DISCARD ORIGINAL SHRINK WRAP AND INSULATOR.
3. IDENTIFY PER YEC-933, CLASS F, TYPE VS.
4. INSULATE ITEM 1 USING ITEM 4.
5. RESISTANCE WELD PER YP-897

ITEM NO.	QTY REQ'D	CAGE NO.	PART NO. OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION
4	1		(74006)	TUBING, KYNAR, SCD, 2.88 LG., YEC-2199
3	1		50951	INSULATOR
2	1		50953	DIODE ASSEMBLY
1	1		50943	CELL, NI-MH

NEXT ASSY	USED ON
50946	CRV
APPLICATION	

THIRD ANGLE PROJECTION

UNLESS OTHERWISE SPECIFIED INTERPRET DIMENSIONING PER ANSI Y14.5M. DIMENSIONS ARE IN INCHES. TOLERANCE: FRACTIONS ± ANGLES ± 2° 3 PLACE DECIMALS ± .005 2 PLACE DECIMALS ± .01 1 PLACE DECIMALS ±

MATERIAL: NOTED

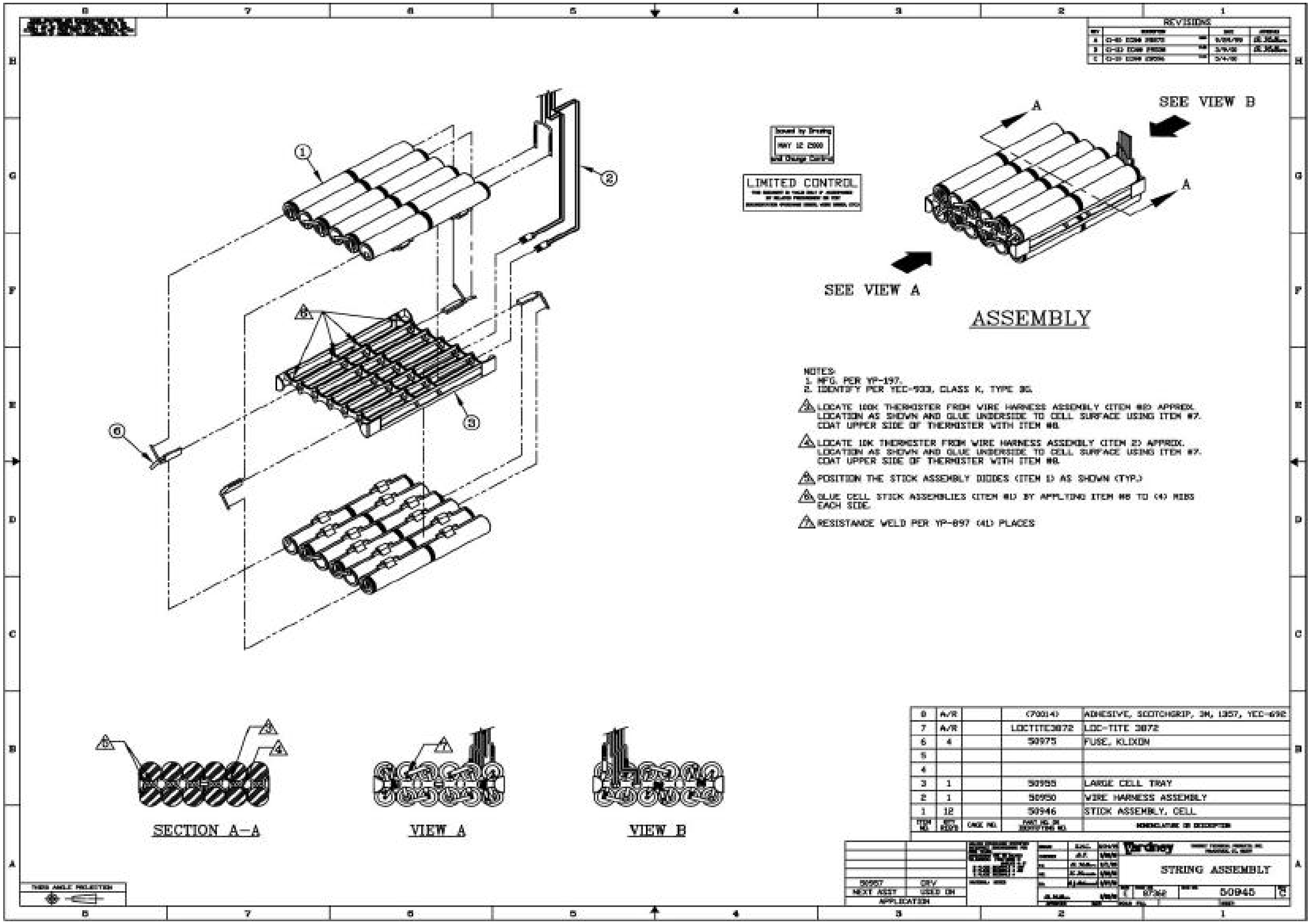
DRAWN	S.M.C.	8/2/99
CHECKED	B.T.	8/26/99
P.E.	R. Hellen	9/1/99
M.E.	K. Hoccata	8/26/99
Q.A.	B.J. Richmond	8/27/99
APPROVED	R. Hellen	8/23/99

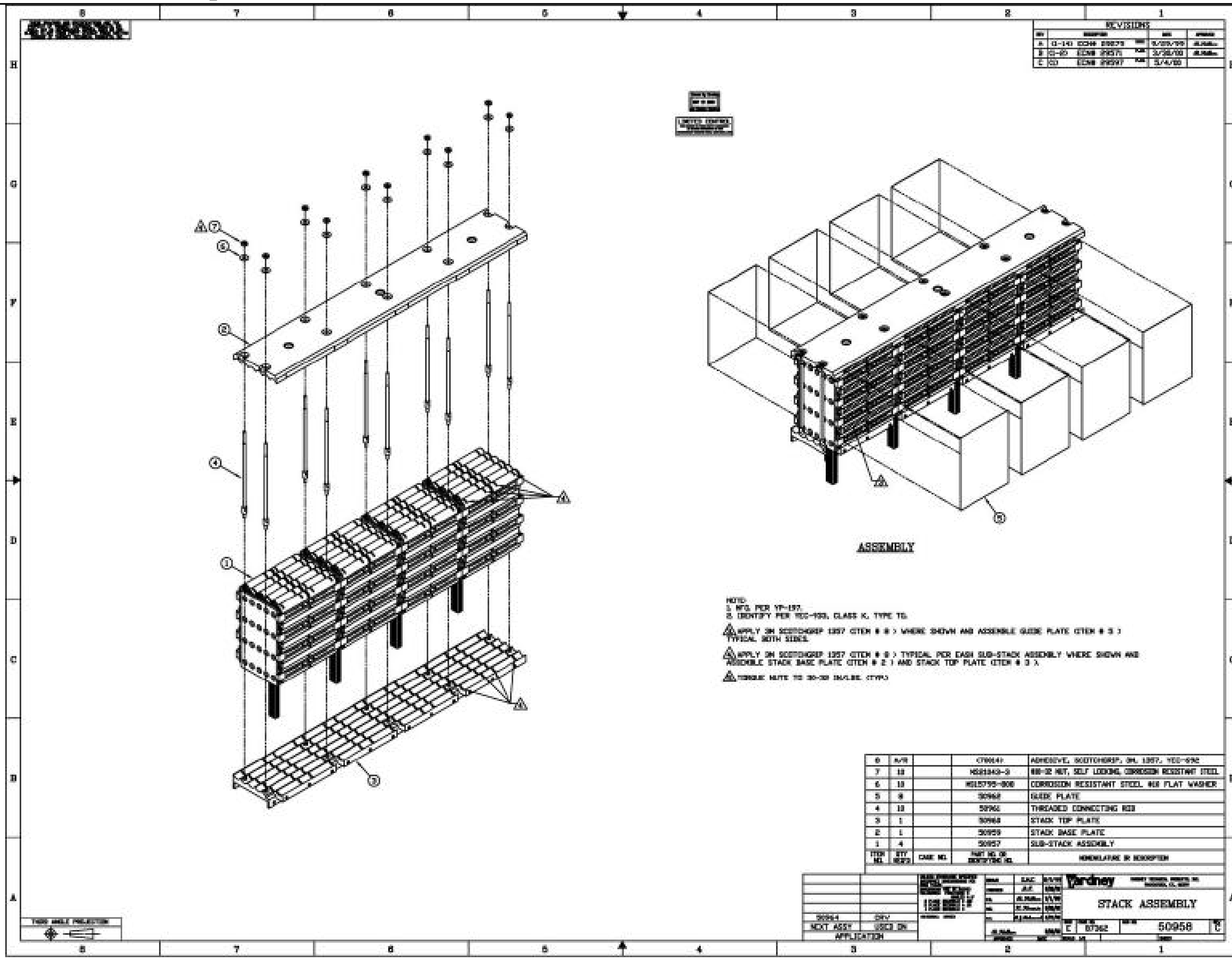
Yardney — YARDNEY TECHNICAL PRODUCTS, INC. PAWCATUCK, CT. 06379

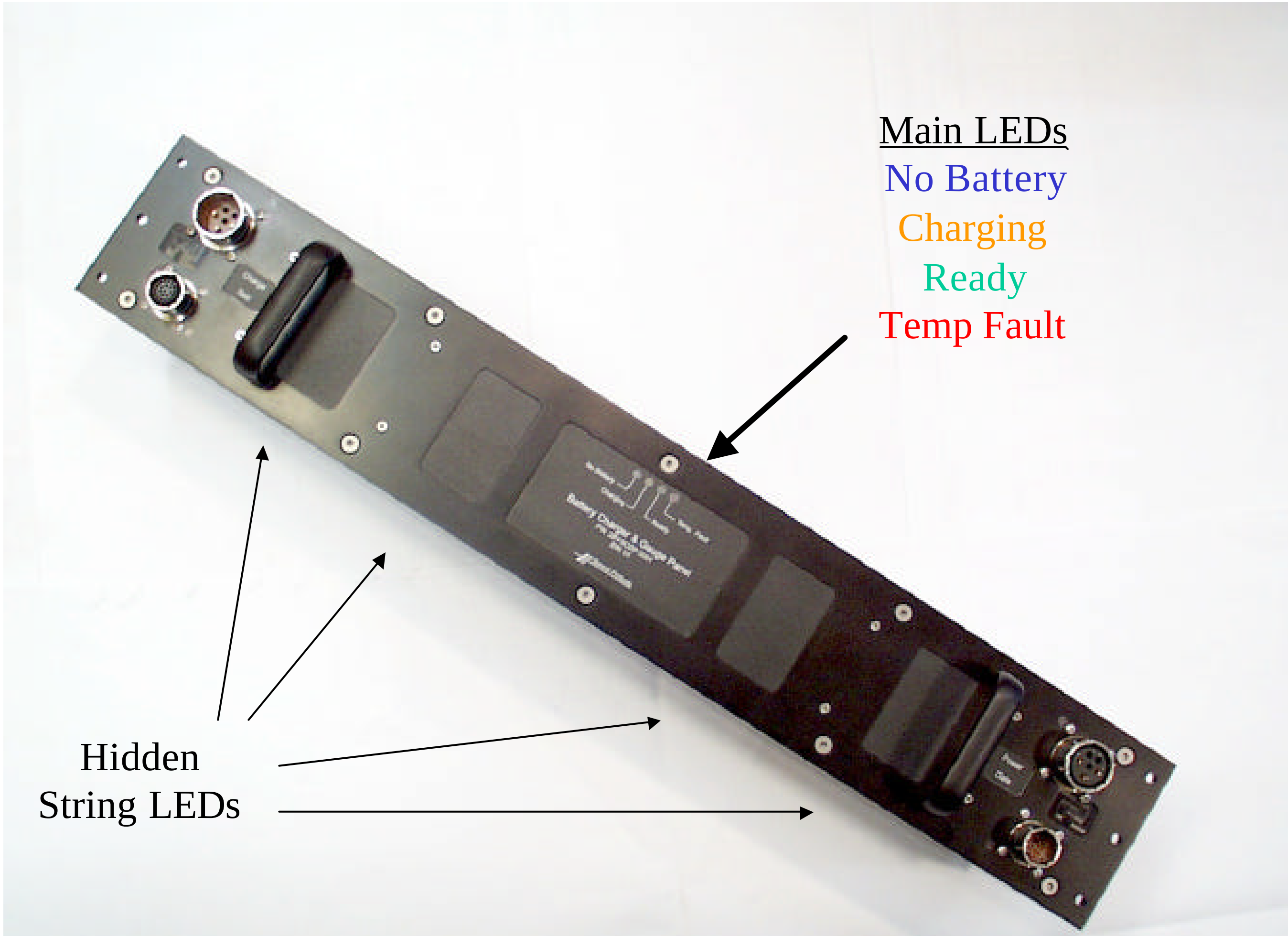
CELL/DIODE ASSEMBLY

SIZE: B | CAGE NO.: 87362 | DWG. NO.: 50954 | REV: C

SCALE: FULL | SHEET

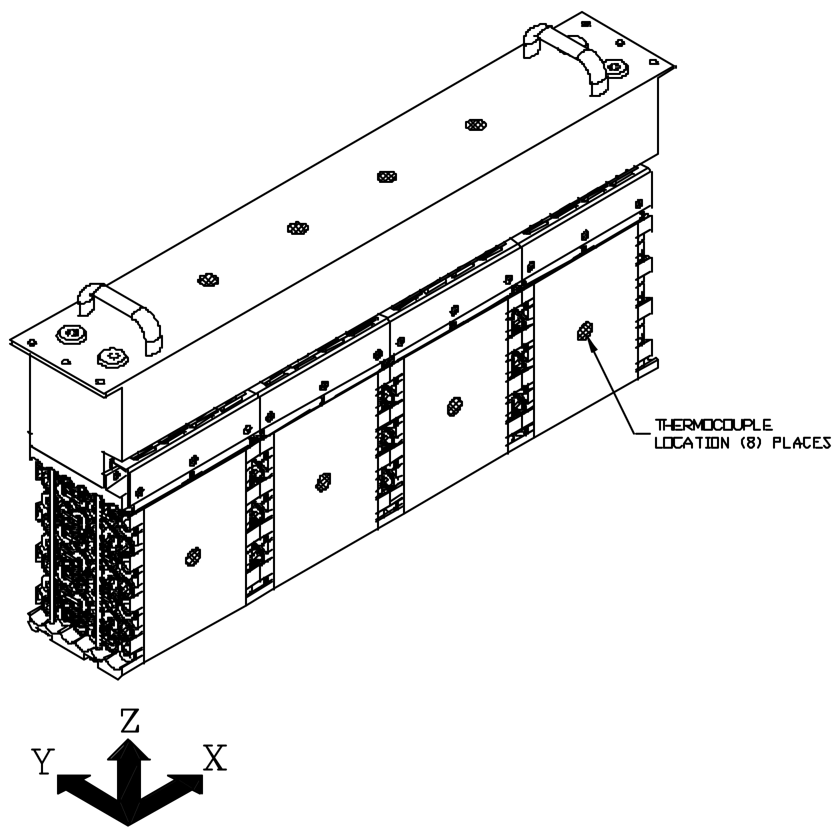

REVISIONS
SEE VIEW B
A
A
LIMITED CONTROL
SEE VIEW A
ASSEMBLY
NOTES:
1. MFG. PER YP-197.
2. IDENTIFY PER YEC-933, CLASS K, TYPE 3G.
3 LOCATE 100K THERMISTER FROM WIRE HARNESS ASSEMBLY (ITEM #2) APPROX. LOCATION AS SHOWN AND GLUE UNDERSIDE TO CELL SURFACE USING ITEM #7. COAT UPPER SIDE OF THERMISTER WITH ITEM #8.
4 LOCATE 10K THERMISTER FROM WIRE HARNESS ASSEMBLY (ITEM 2) APPROX. LOCATION AS SHOWN AND GLUE UNDERSIDE TO CELL SURFACE USING ITEM #7. COAT UPPER SIDE OF THERMISTER WITH ITEM #8.
5 POSITION THE STICK ASSEMBLY DIODES (ITEM 1) AS SHOWN (TYP.)
6 GLUE CELL STICK ASSEMBLIES (ITEM #1) BY APPLYING ITEM #8 TO (4) RIBS EACH SIDE.
7 RESISTANCE WELD PER YP-897 (41) PLACES
SECTION A-A
VIEW A
VIEW B
8 A/R (70014) ADHESIVE, SCOTCHGRIP, 3M, 1357, YEC-692
7 A/R LOCTITE3872 LOC-TITE 3872
6 4 50975 FUSE, KLIXON
5
4
3 1 50955 LARGE CELL TRAY
2 1 50950 WIRE HARNESS ASSEMBLY
1 12 50946 STICK ASSEMBLY, CELL
CAGE NO.
Yardney
STRING ASSEMBLY
NEXT ASSY
USED ON
APPLICATION
50945


ASSEMBLY
STACK ASSEMBLY
50958

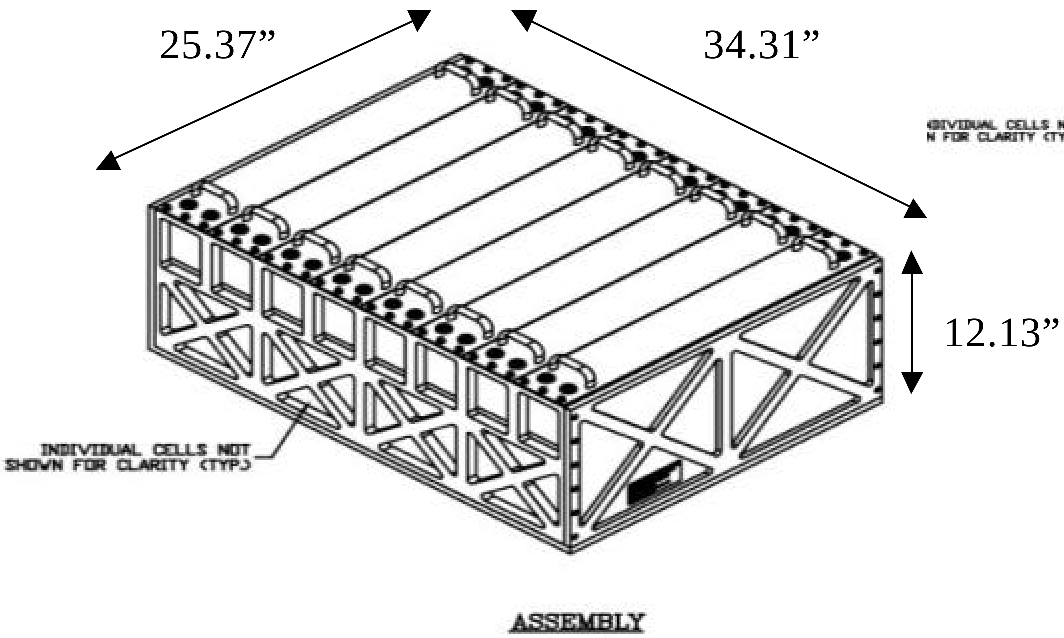


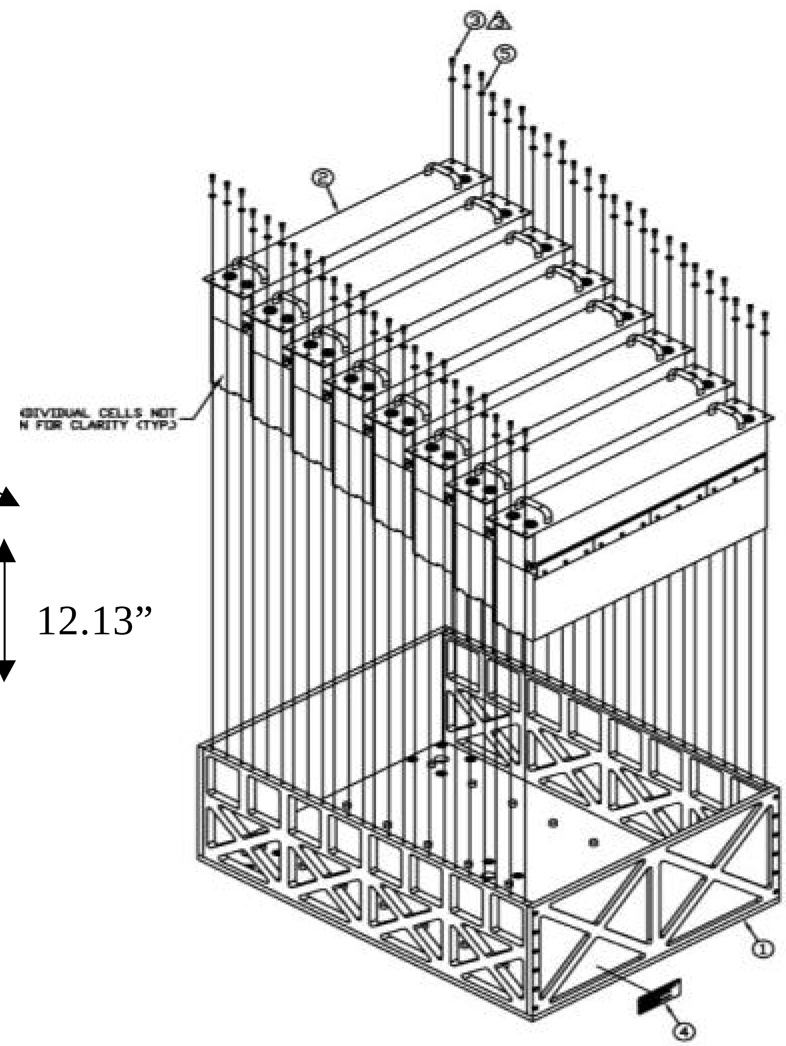
Battery Charge & Gauge Panel

28V, 50 Ah NiMH Battery Module



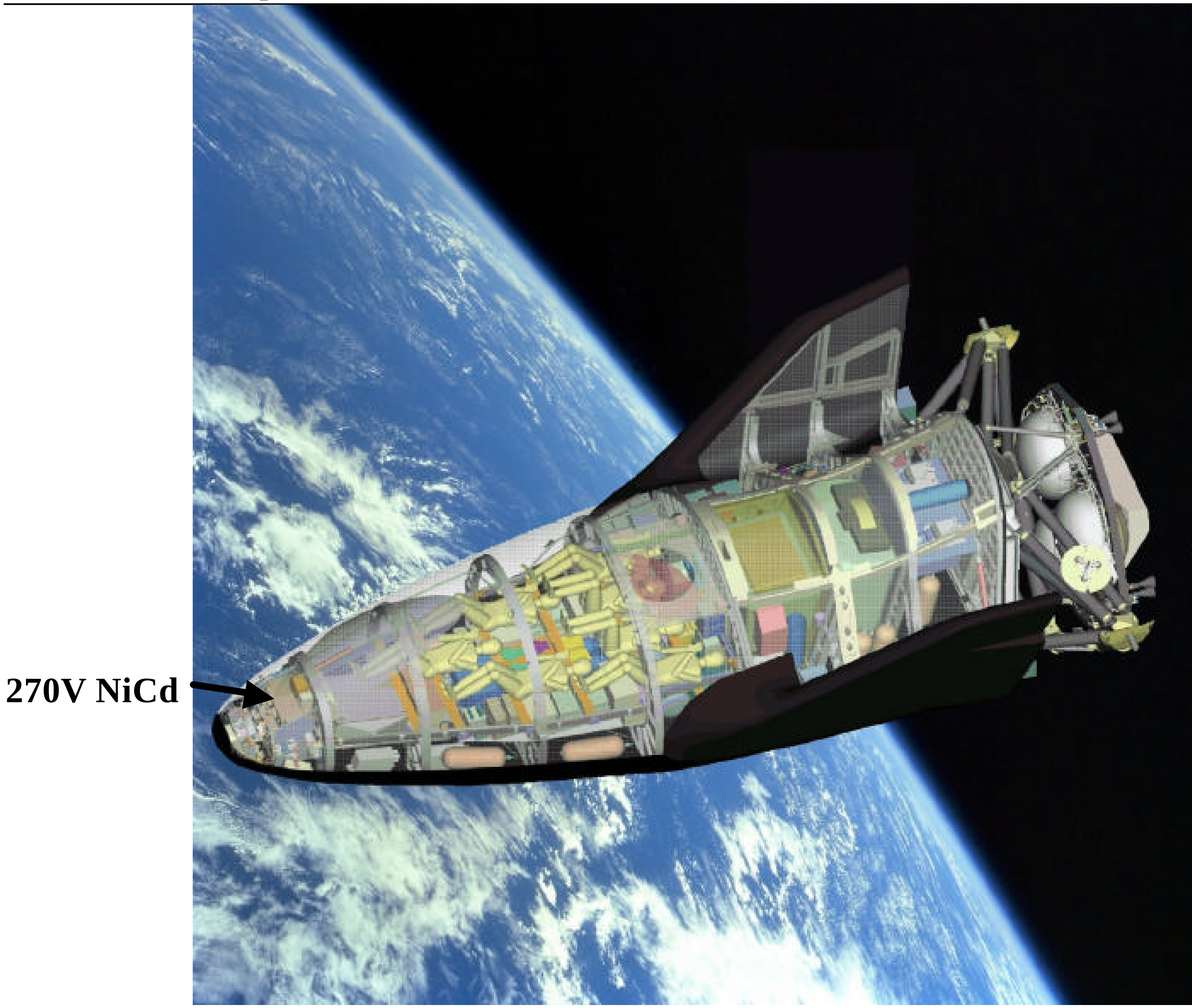
28V Flight Battery Stack and Crate





Status and Future Plans

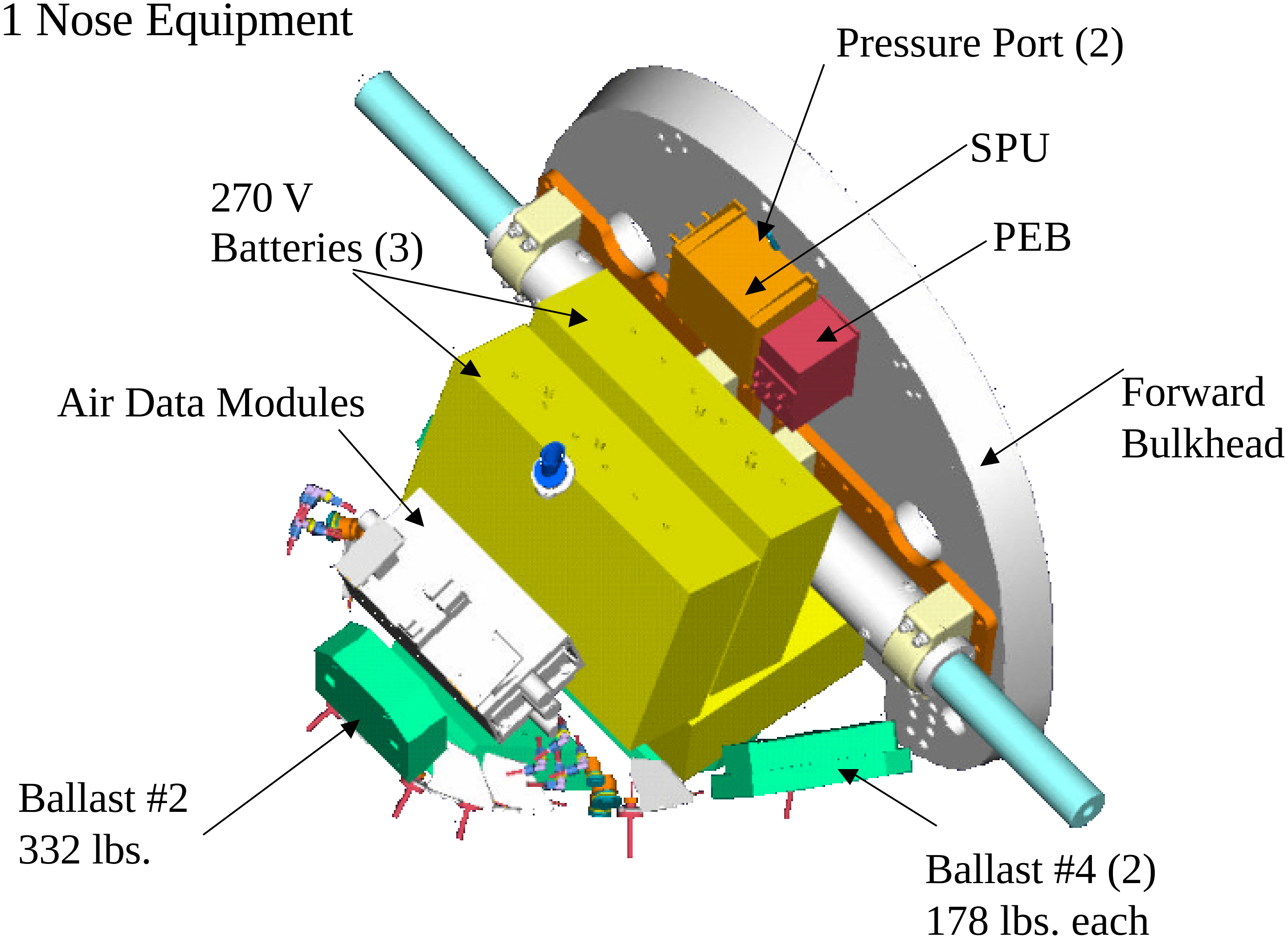
- Battery vibration failure during qualification forced a redesign
  - Battery charge & gauge panel design flaw was root cause
- Re-test is this week at YTP
- Assembly of 8 flight battery modules to follow after completion of qualification


270V NiCd

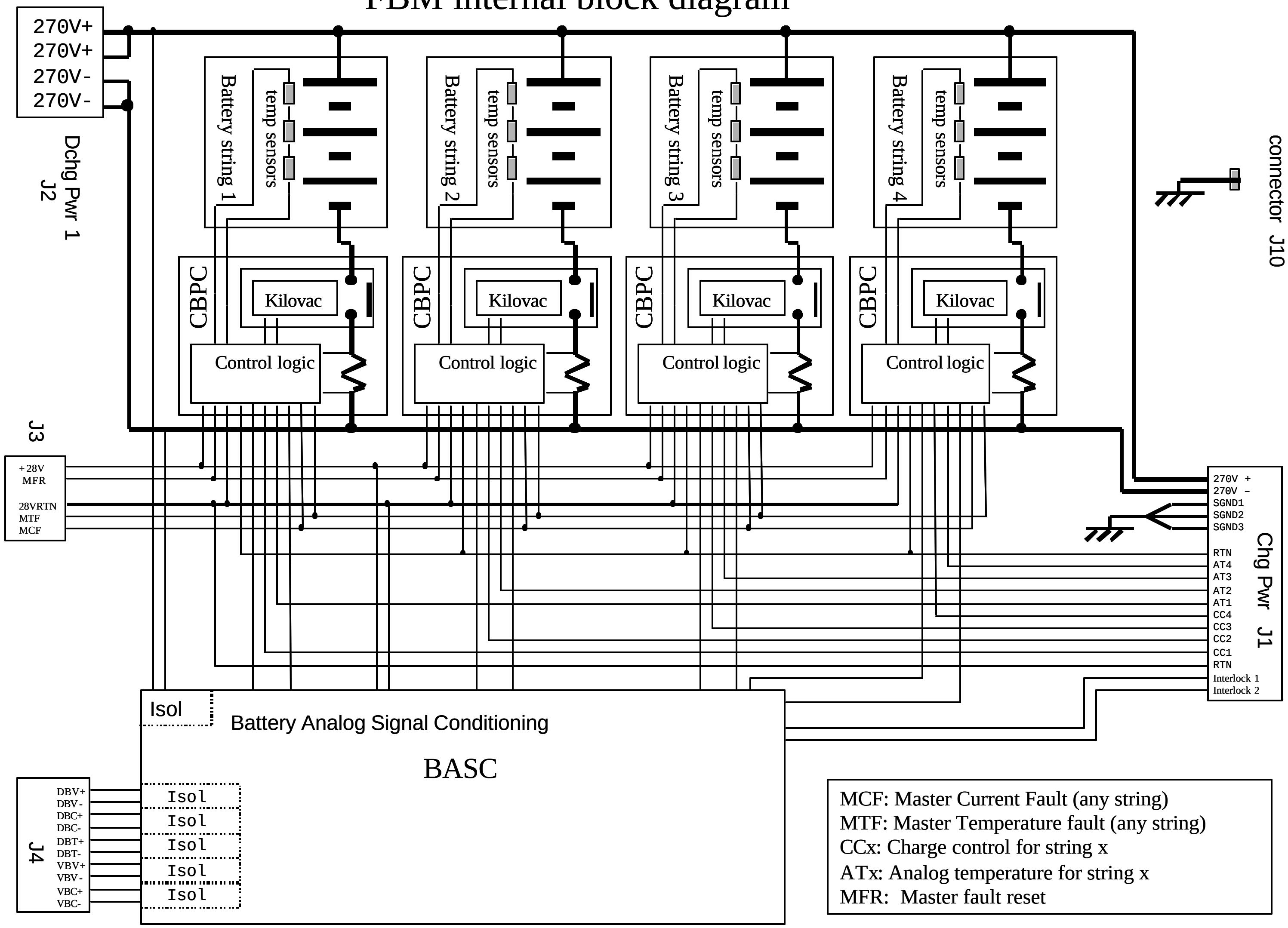
270V Battery Module Requirements & Status

- Performance Requirements
  - 270 +30/-70V during discharge, 306-350V during charge
  - Divide into 3 batteries modules each capable of 5.07 Ah (4.10 Ah for EMAs)
    - 6A for 1640 sec
    - 6A baseline with 170A, 100 ms peaks every 1 sec for 220 sec
    - Four 6A to 55A ramps over 15 sec for untwisting the parafoil
    - Four 6A to 45A ramps over 15 sec for steering the parafoil
    - One 6A to 45A ramp over 7 sec for the flare
  - 34.85 kW max peak power/battery module
  - Outside cabin, vacuum exposed for 3 years (14 days for V201)
  - Mass < 85 kg/battery module
  - Not to exceed volume; 25.25” wide x 16.25” deep x 6.75” tall
  - All 3 battery modules located in nose of vehicle
- Development Status
  - Contract awarded to AZ Technology (Huntsville, AL)-SRI (Arab, AL)
  - Assembly of qualification battery module nearly complete
  - Prototype 270V string charging and discharge performance validated
  - Completed cell acceptance on 5700 cells

V201 Nose Equipment



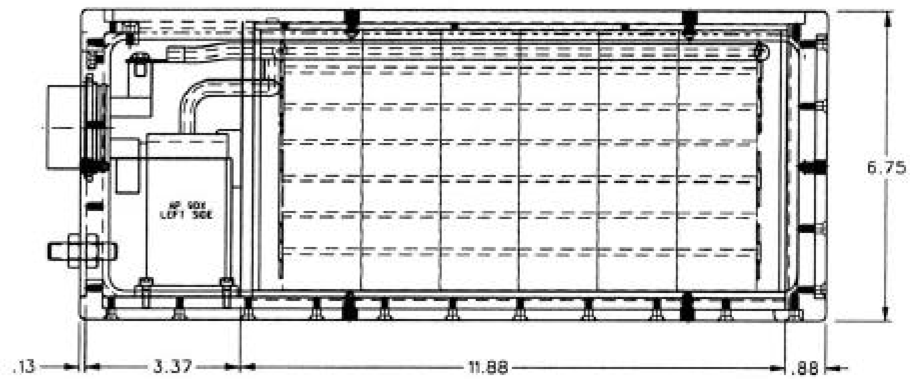
FBM internal block diagram



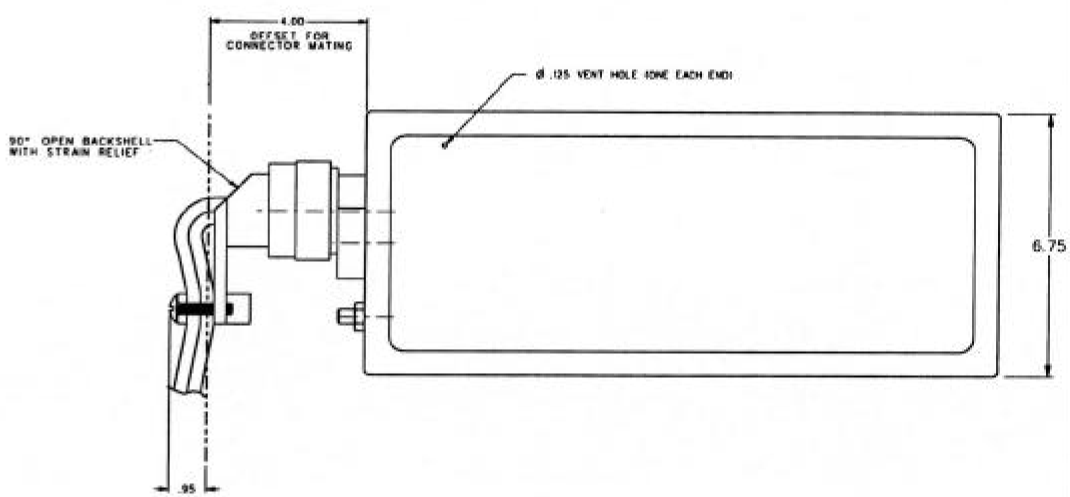
MCF: Master Current Fault (any string)
MTF: Master Temperature fault (any string)
CCx: Charge control for string x
ATx: Analog temperature for string x
MFR: Master fault reset

Baseline Design of 270V Battery

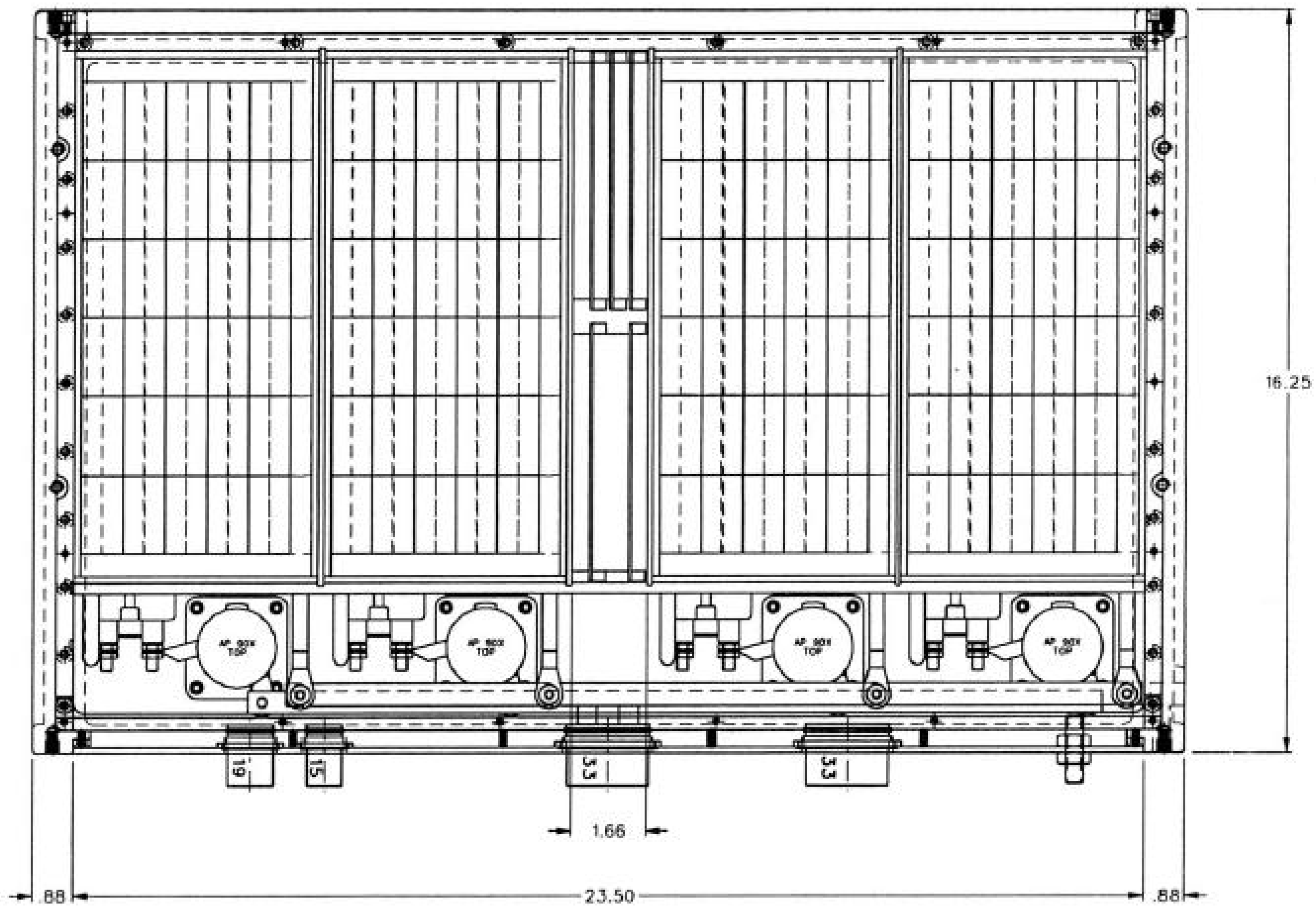
- Cell: SubC NiCd from Sanyo (P/N CP-2400SCR)
  - New cell design intended to replace Sanyo's N-1900SCR
- Battery String = 210 cells in series
- Battery Module = 4 strings in parallel
- Flight Battery Set = 3 Battery Modules
- Voltage: Open Circuit = ~285V, Closed Circuit = 200-280V
- Redundancy Plan: Consistent with EMA 2 failure tolerance
- Estimated Battery Module Mass = 85 kg
- Mass and volume estimates do not include interface to bulkhead



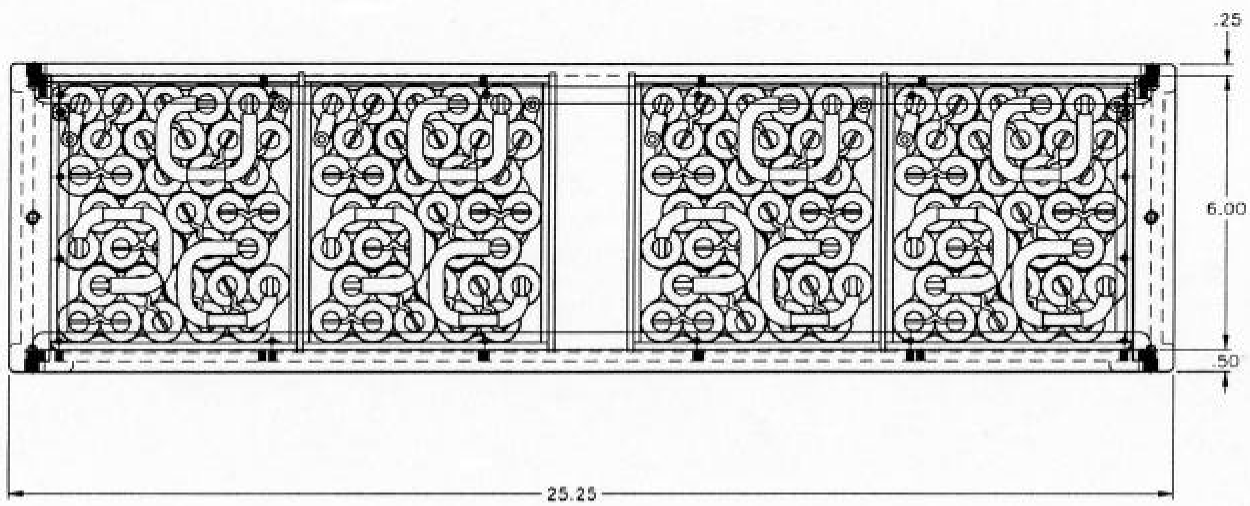
RIGHT SIDE VIEW



RIGHT SIDE VIEW



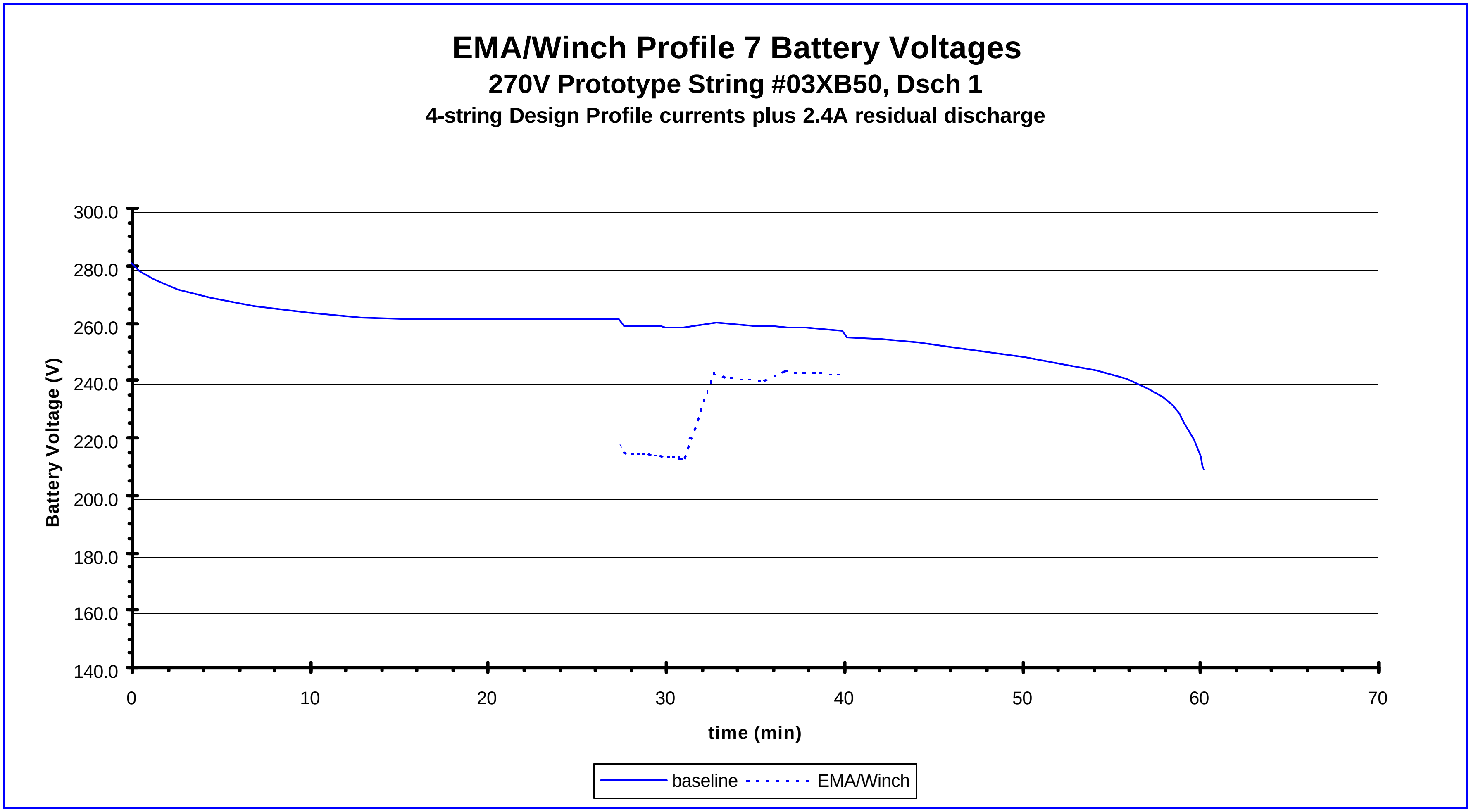
TOP VIEW



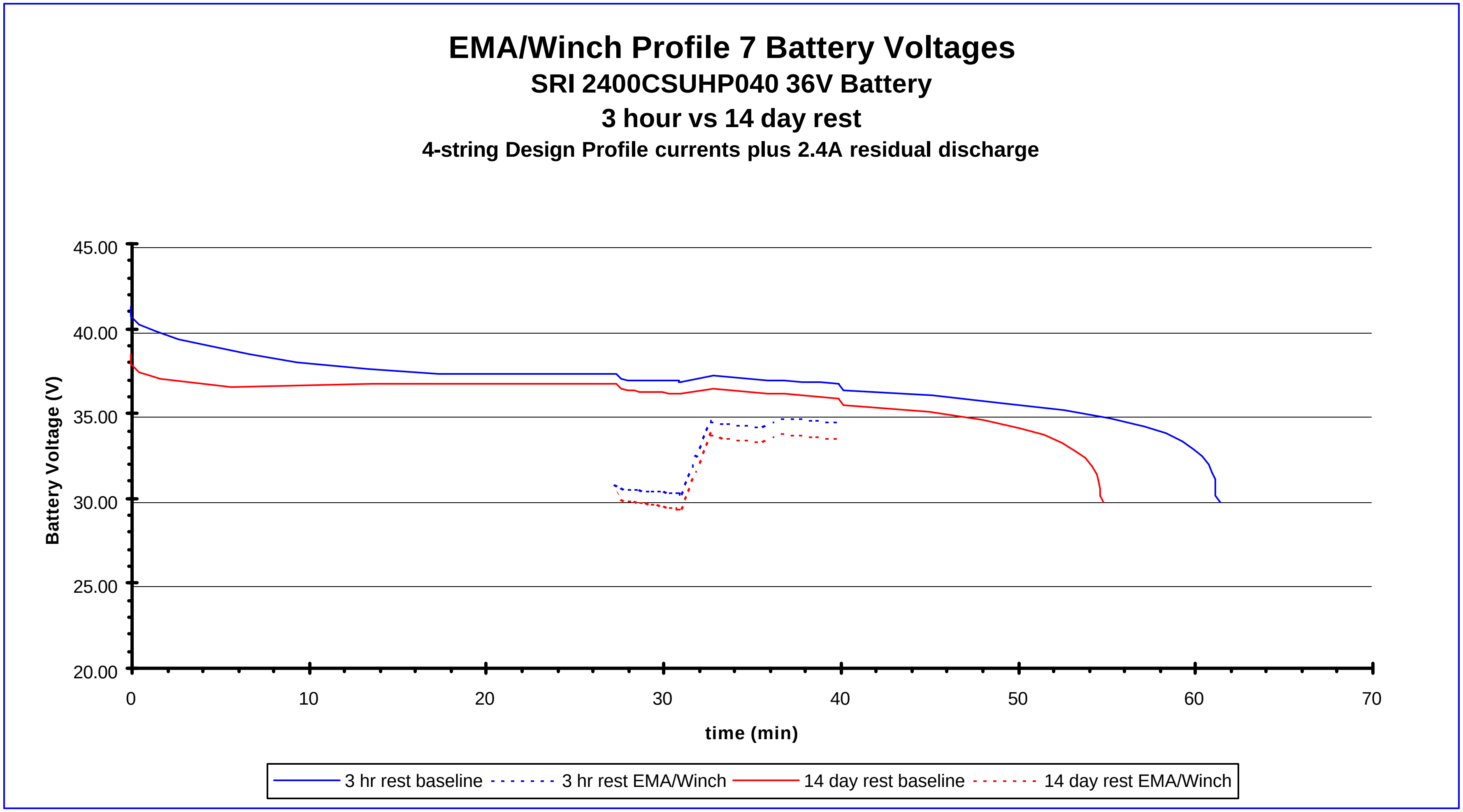
FRONT VIEW

CONTACTORS AND SHUNTS REMOVED FOR CLARITY

Prototype 270V String Validation Test



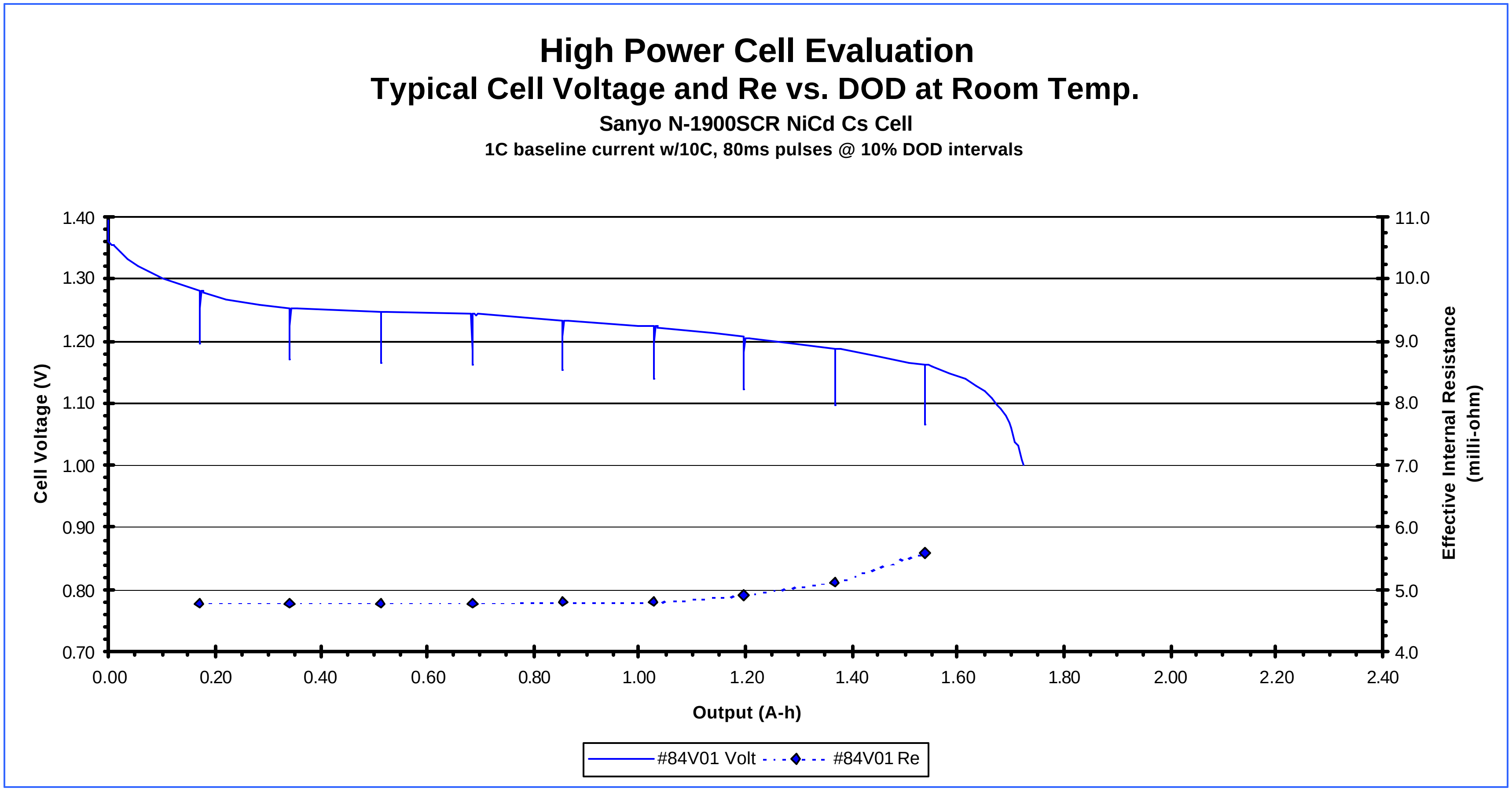
Performance and capacity retention test



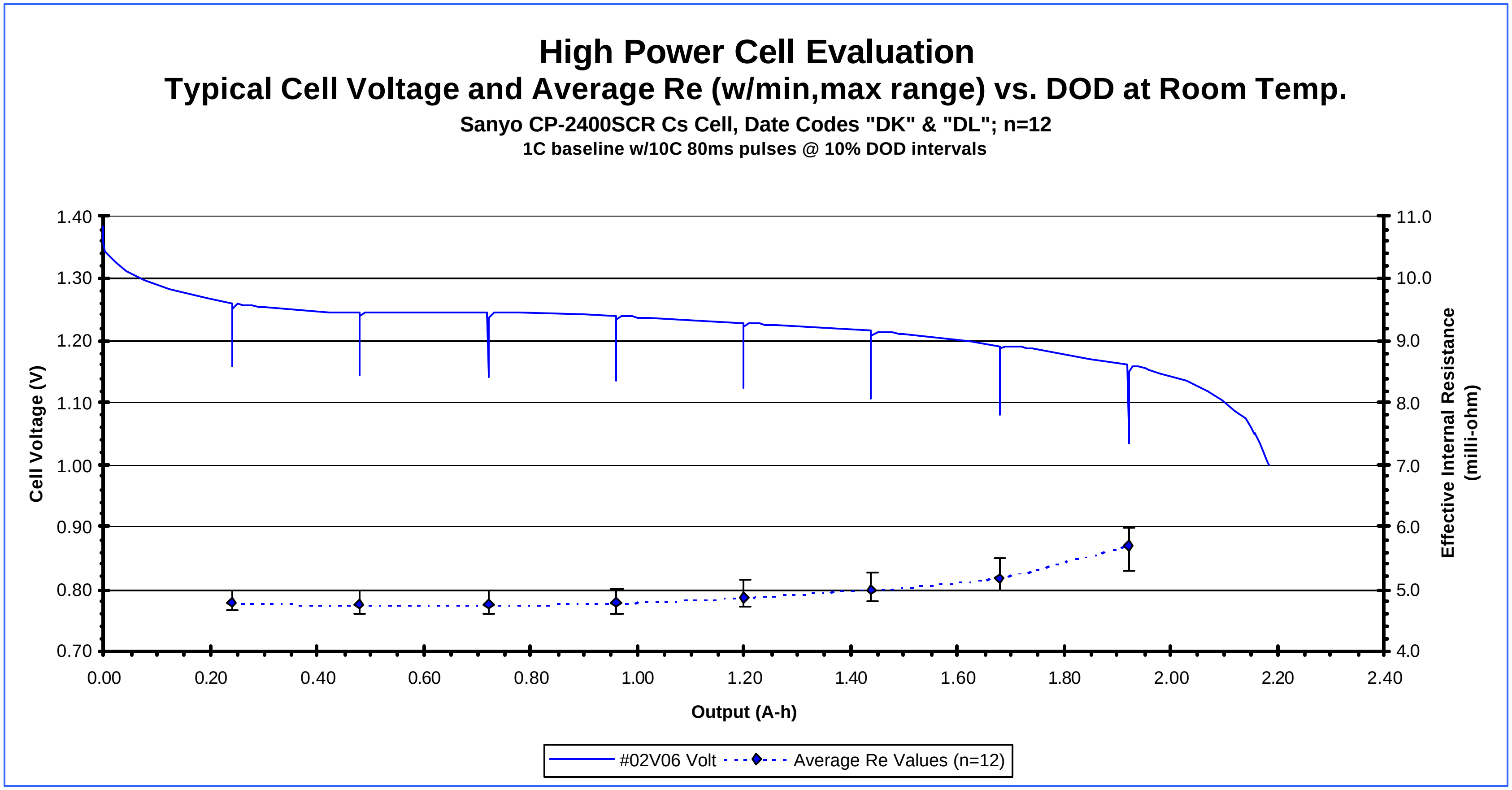
Comparison of N-1900SCR and CP-2400SCR

ATTRIBUTE	N-1900SCR	CP-2400SCR
Physical		
Size dia X ht (in)	0.873 X 1.651	0.870 X 1.673
Mass (g)	55	58
Design		
Electrode types (neg/pos)	Sinter/sinter	Sinter/sinter
Jellyroll winding lead	180° opposed lead	>360° pos lead
Current Collectors (neg/pos)	Disk/disk	Disk/disk
Can wall thickness (in)	0.013	0.011
Vent mechanism	Spring backed disk	Spring backed disk
Vent Pressure (psig)	230 to 290	190 to 310
Burst Pressure	910 to 950	800 to 850
Performance, typical		
1C Capacity (A-h)	1.8	2.2
Eff. Internal Resistance (80ms pls)	4.8	4.8

Old Cell

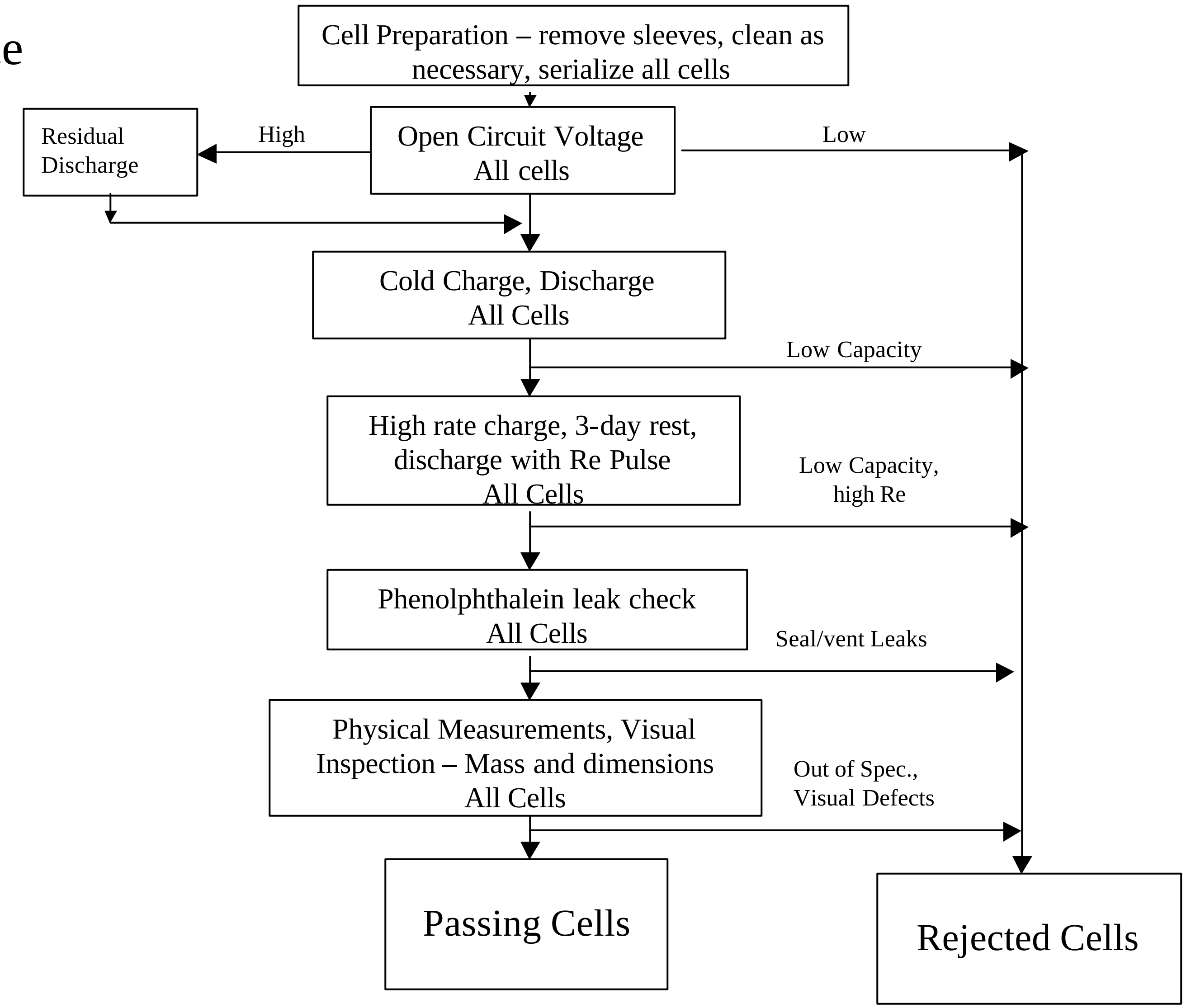

High Power Cell Evaluation
Typical Cell Voltage and Re vs. DOD at Room Temp.
Sanyo N-1900SCR NiCd Cs Cell
1C baseline current w/10C, 80ms pulses @ 10% DOD intervals
Cell Voltage (V)
1.40
1.30
1.20
1.10
1.00
0.90
0.80
0.70
0.00
0.20
0.40
0.60
0.80
1.00
1.20
1.40
1.60
1.80
2.00
2.20
2.40
Output (A-h)
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
Effective Internal Resistance (milli-ohm)
#84V01 Volt
#84V01 Re

New Cell

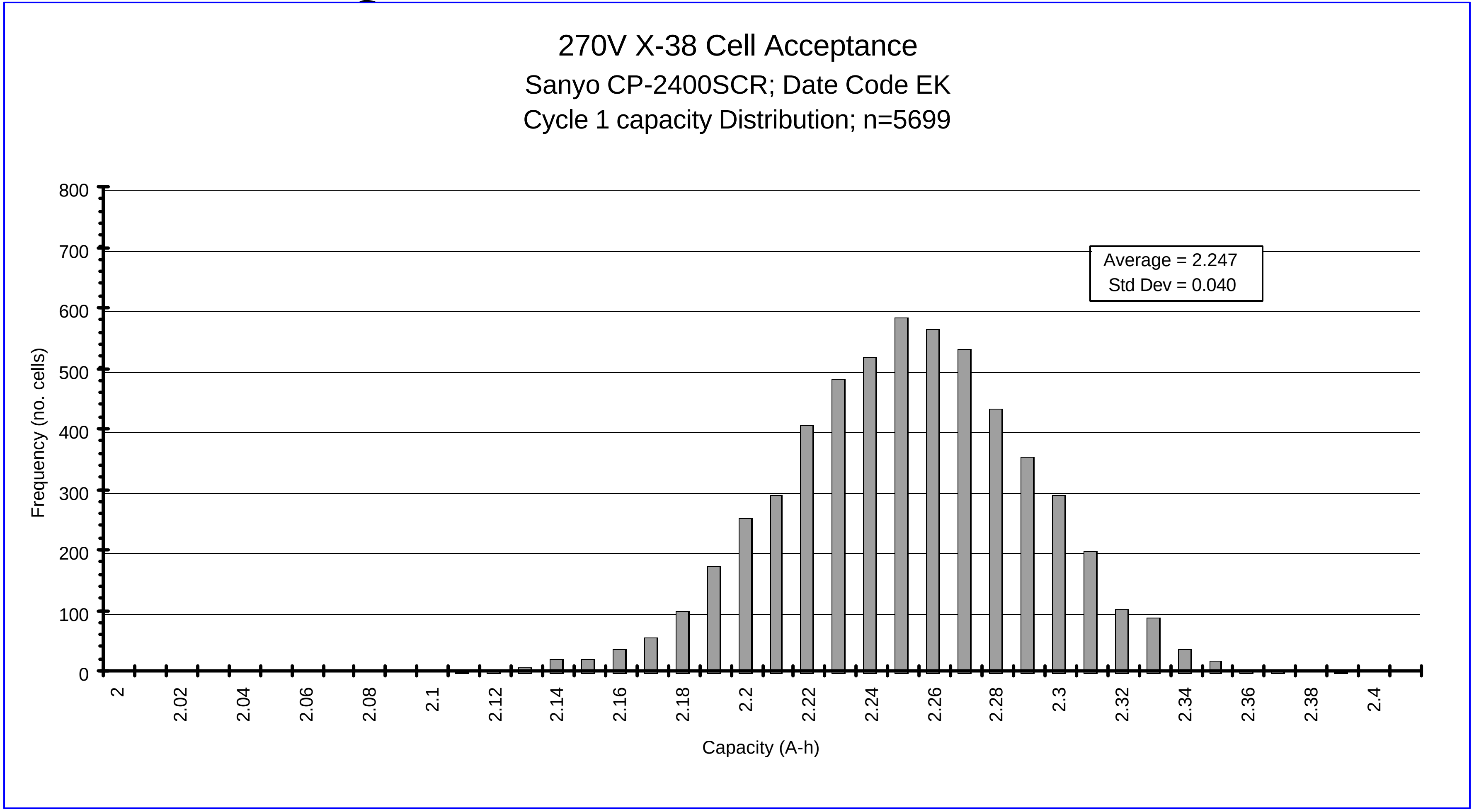


New cell provides 20% more Ah for only 1% more volume and 7% more mass

Cell Acceptance



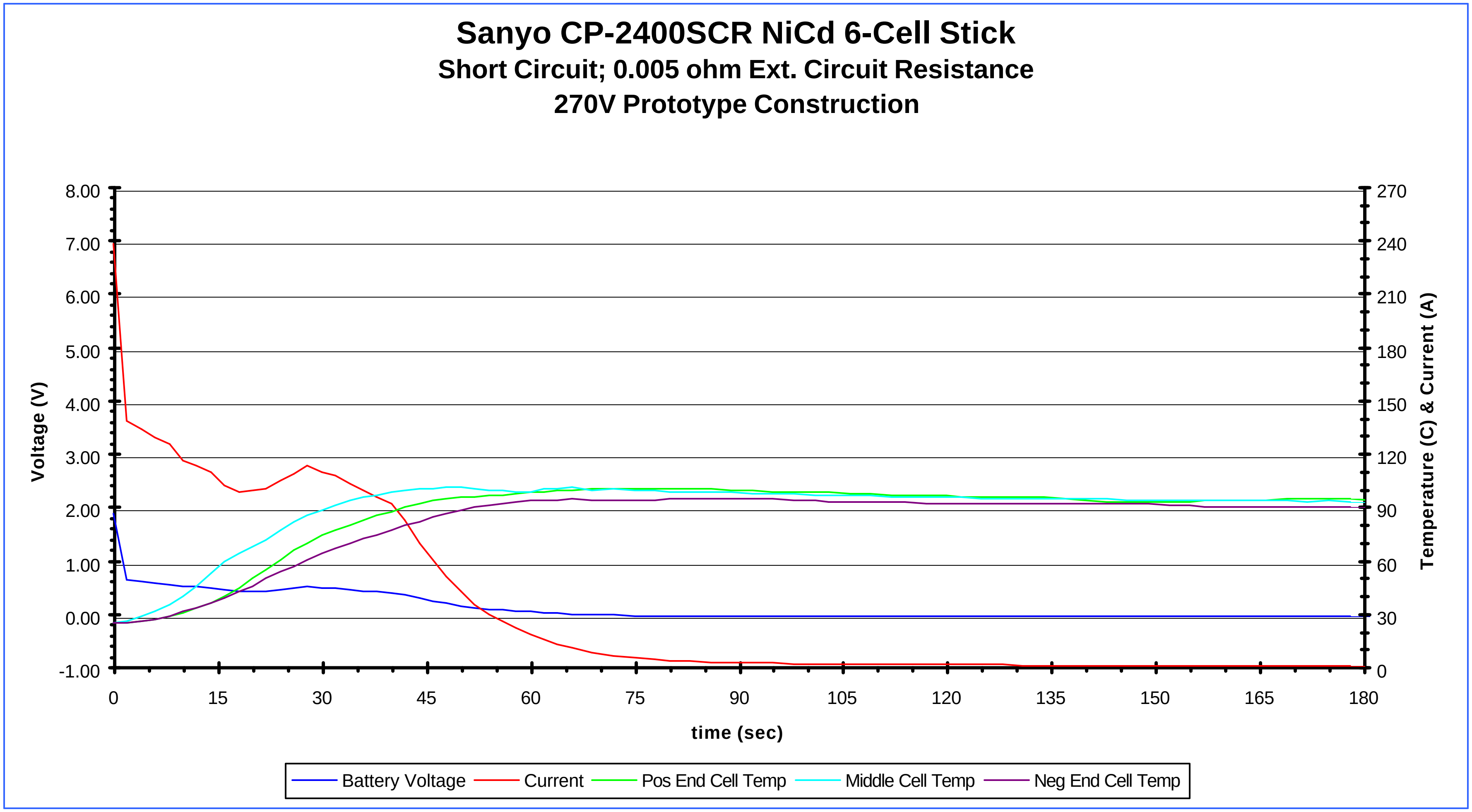
Cell Acceptance



Cell Acceptance Summary

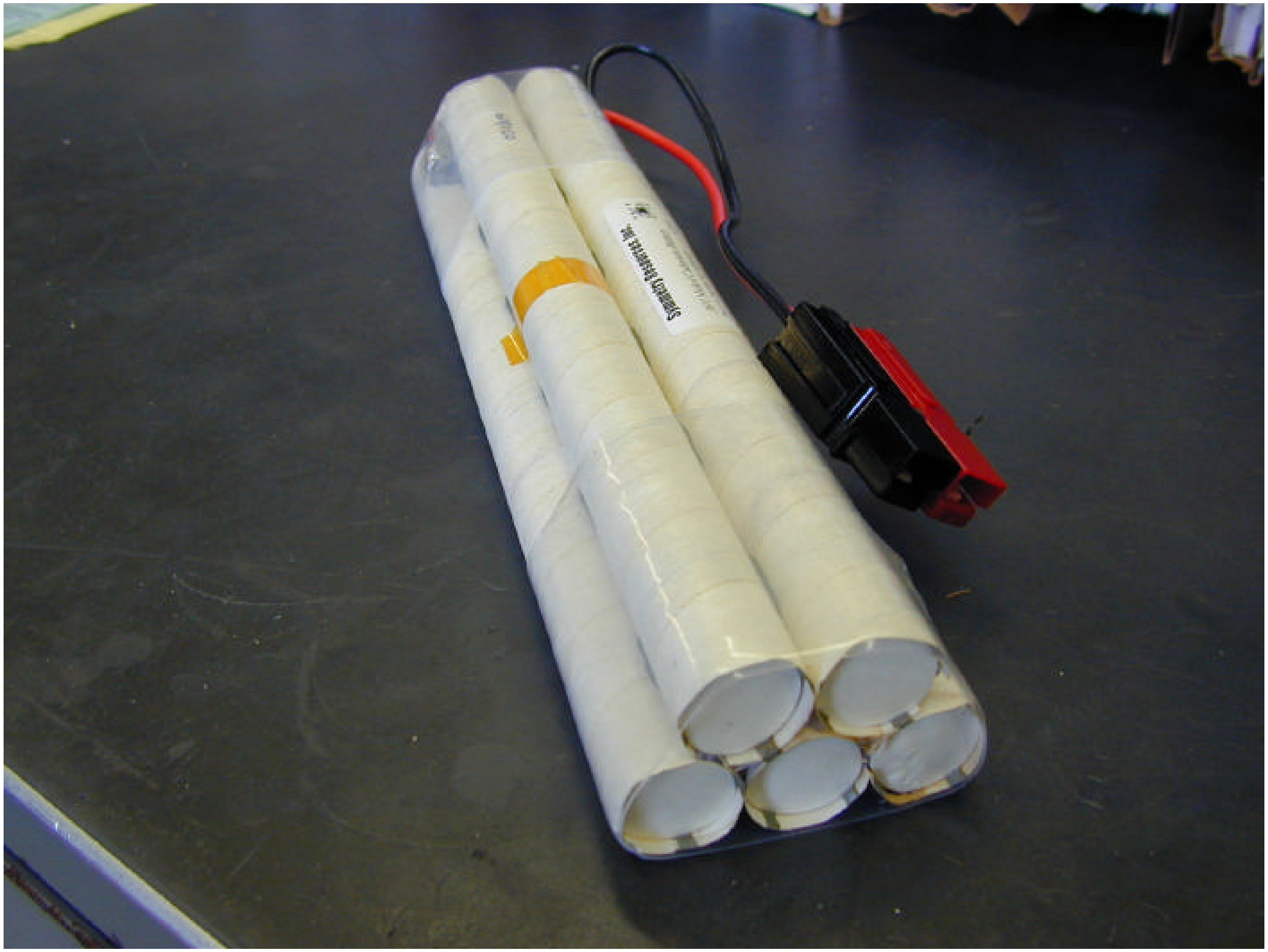
Cell Acceptance Testing for Sanyo CP-2400SCR Cs NiCd Cells										
for 270V X-38 Battery Modules										
Sanyo Cell Lot Identification "EK" (Nov., 2000)										
Summary, all cells n=5700										
	OCV Chk (P/F)	1 st Cycle Cap. (A-h)	2 nd Cycle Cap. A-h	Int. Res. (mohms)	Leak Test (P/F)	Mass Chk (P/F)	Dimension Chk P/F	Visual Defect (P/F	Cyc1 minus Cyc 2 A-h	Calc V @42.5A
Average		2.247	2.199	5.211					0.047	1.006
StDev		0.040	0.031	0.169					0.027	0.008
Max		2.388	2.302	6.030					0.359	1.035
Min		2.076	1.869	4.660					-0.090	0.966
# - 3 sigma		15	5	2					39	12
# + 3 sigma		4	1	19					2	3
Fail criteria	<0.90	<2.10	<2.00	<6.0	F	F	F	F		
TPI-011 Rev. A # Fail		2	1	1	2	0	3	71		

Short Circuit Test

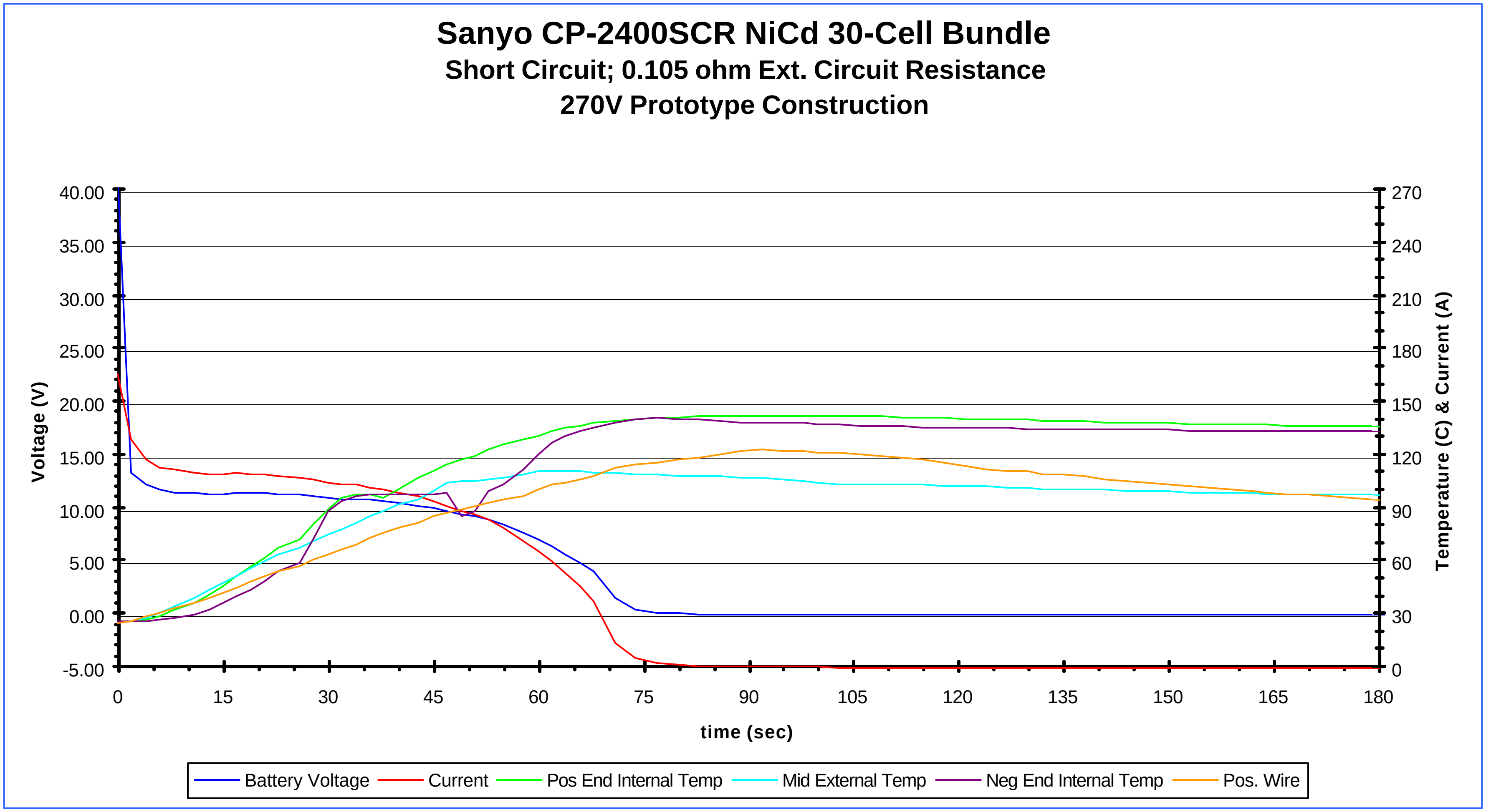


Stick short circuit tests results in no smoke, flames, or fire!

30-Cell Bundle – after short circuit test!



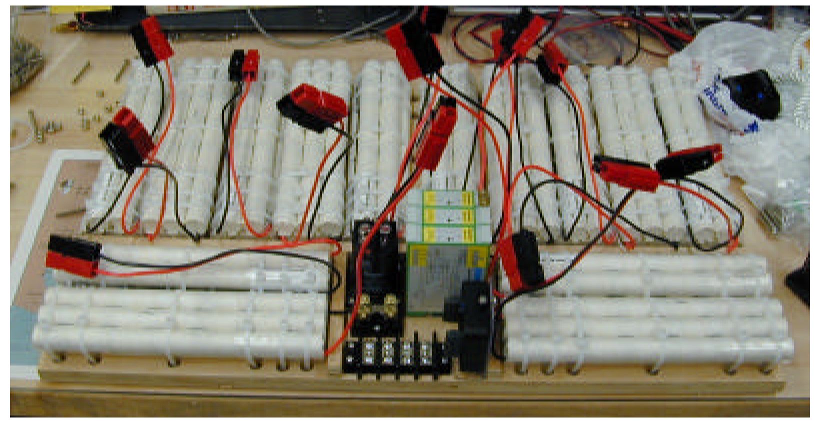
Short Circuit Test



30-cell bundle short circuit tests results in no smoke, flames, or fire!

Pallet Drop Battery

- Half-Battery (2, 270V strings)
- Package in Pelican Case
- Powered parafoil winches during pallet drop tests of 7500 sq.ft parafoil in near Yuma, AZ
- Excellent performance using 30 cell bundle as building block
- Good shock tolerance



Future Plans

- Manuf Readiness Review in late Nov
- Complete Qualification in Jan 2002
- Deliver Qual Module in Jan 2002
  - Perform corona test with EMA and HVSU at Moog
  - Integrate into V131R for drop test with 270V winches
  - Use it for EMA, Winch, and Ironbird testing
- Deliver 4 Flight Battery Modules by May 2002

Small Cell Battery Approach Works!

- High Safety
  - Small cells are safer than larger cells
  - Protective devices necessary are small and available
- Good Performance
  - Automated production of commercial cells are highly homogenous
- Low Cost and Rapid Development
  - Low total cell cost more than offsets cell screening costs needed
  - No cell development needed, only characterization
  - Cell and string level testing applicable to total battery

PERFORMANCE OF SMALL, COMMERCIAL, PRIMARY CYLINDRICAL, ALKALINE CELLS

By

Sonja N Baldwin, Andrew J. Markow
David J. Surd and C Richard Walk

BAE SYSTEMS
Applied Technologies, Inc.
Battery Technology Center
1601 Research Blcd
Rockville, Md. 20850

The new high tech commercial devices, like cellular phones, digital cameras, laptops, camcorders and palm pilots require more energy and power than the devices we have been using in the past. The manufacturers of small cylindrical cells want a significant share of these large new markets and are, therefore, making cell improvements to meet these new requirements. For these devices, they are concerned with operation in the 0.5-2.0 watt range. The cell improvements began in the late 1990's with the Duracell Ultra, Energizer e^2, Panasonic digital and similar improvements by other manufacturers to their standard product line.

Since the aerospace community may have some interest in these commercial products, we have attempted with this paper to present performance information for recently developed small cell technologies. Comparisons between manufacturers will not be made. The paper will be concerned only with the present state of the technologies.

The date presented in this paper, unless otherwise indicated, represents the discharge data for the median cell of a group of from 6 – 15 standard cells. We will start with the standard "AA" as the baseline. Figure 1 shows the performance for various discharge rates at 24°C. Performance begins to degrade at rates shorter than the 100 hour rate and at the 10 hour rate only about ½ the cell capacity is delivered to a reasonable cutoff voltage. Figure 2 shows the performance of the same type cells at the 1000 hour discharge rate as a function of temperature. Performance begins to degrade below 0°C and below –20°C less than ½ the capacity is delivered. Only ½ the capacity is delivered at 90°C at this rate but at 70°C the full capacity is delivered.

Figure 3 shows the performance of the high tech "AA" cells at various discharge rates. To a 0.8 volt cutoff and the 31.6 hour discharge rate the cells deliver a capacity of about 2.7 Ah, while the standard cells deliver about 2.4 Ah. At the 3.16 hour rate the high tech cells deliver 1.3 Ah while the standard cells deliver 0.8 Ah. At the 1000 hour rate (Figure 4) the high tech cells perform like the standard cells, which is no great surprise because they are designed for rates of less than 10 hours.

Manufacturers use essentially the same technology in their "AAA", "C", and "D" cells as they do in their "AA" cells, so these cells are supposedly a scale up or down of the "AA" cells with the same label. This does not necessarily mean that the performance of other cell sizes is just a multiple of the "AA" size. It only means that the technology is the same.

One other cell size that will be mentioned is the “AAAA”(Quad A) size. In the past this cells size has only been used in 9 V batteries and has not been offered commercially. It is now being offered commercially for applications like medical devices, laser pointers, target sites, personal safety devices, pen lights, etc. It performs similar to the high tech alkaline cells at various temperatures. At the 1000 hour rate it delivers about 700 mAh to a 0.8 volt cutoff. At the 31.6 hour discharge rate at 24°C the performance drops off by about 20%, which is similar to the performance of the high tech “AA” alkaline cells, (see Figures 9 & 10).

The Li/FeS_2 cell technology presently comes in the “AA” cell size and is only sold by Energizer. It is being marketed as a cell for cameras. The open circuit voltage of these cells is about 1.8 volts and at low discharge rates discharges at two plateau voltages (see Figure 5). At low rates this cell only delivers about 2.5 Ah but even at the 1 hour rate the cell still delivers more than 2.0 Ah above 0.8 volts,. The alkaline high tech cells cannot deliver 2.0 Ah at discharge rates shorter than the 10 hour rate. At the 1000 hour discharge rate over 2.0 Ah of capacity is delivered at temperatures as low as –40°C,.(see Figure 6).

“AAA” size Li/FeS_2 cells have been made in evaluation quantities, but it does not appear that this cell will be produced until a significant market is developed for it. At the present time, the “AA” Li/FeS_2 cell sells in the commercial marketplace for 2 to 3 times more than that of the alkaline high tech cells. Its outstanding performance in the camera market (which will be shown later in the paper) may justify its higher cost.

Because of their high cell voltage (greater than 3.0 volts), good pulse capability and high energy density Li/MnO_2 2/3A cells and CR2 cells were developed. The 2/3A cell contains the maximum amount of lithium metal that can be shipped uncontrolled. Because of the good performance capabilities of the Li/MnO_2 technology the smaller CR2 cell was marketed. The 2/3A cell has a rated capacity of about 1800 mAh while the CR2 has a capacity of about ½ that. At rates greater than the 500 hour rate the 2/3A cells deliver most of their capacity above 1.7 volts. There is then a gradual drop off in delivered capacity from the 500 hour rate to the 0.5 hr rate where about 1.0 Ah of capacity is delivered. For such a small cell this is an excellent capacity for a cell operated at 2.6 A (0.5 hr rate). At the 1000 hr rate as a function of temperature, the 2/3A cell performance falls off about 20 % at –20°C & 90°C. At –40°C, the performance drops off another 10%, (see Figures 7 & 8). Performance of the CR2 cells is similar to those of the 2/3A, (see Figures 11 & 12).

To provide a rough idea of how the different cells, described above, perform in pulse applications consider Figure 13. This chart shows how the different technologies perform in the ANSI photoflash test. The ANSI photo flash test had been 1.8 ohms applied 15 seconds/minute until the voltage dropped to 0.9 volts. The new ANSI photoflash test is 1 A applied 10 seconds/minute; 1 hour/day. The flashes obtained for the cells tested under the 1.8 ohm regime are shown in red, while the flashes obtained in the 1 A test are shown in blue.

We hope that the data presented in this paper will give the user some insight into the changing world of battery cells in the commercial market place and help the user select the right battery for his application.

Battery System Studies in a Virtual-prototyping Environment

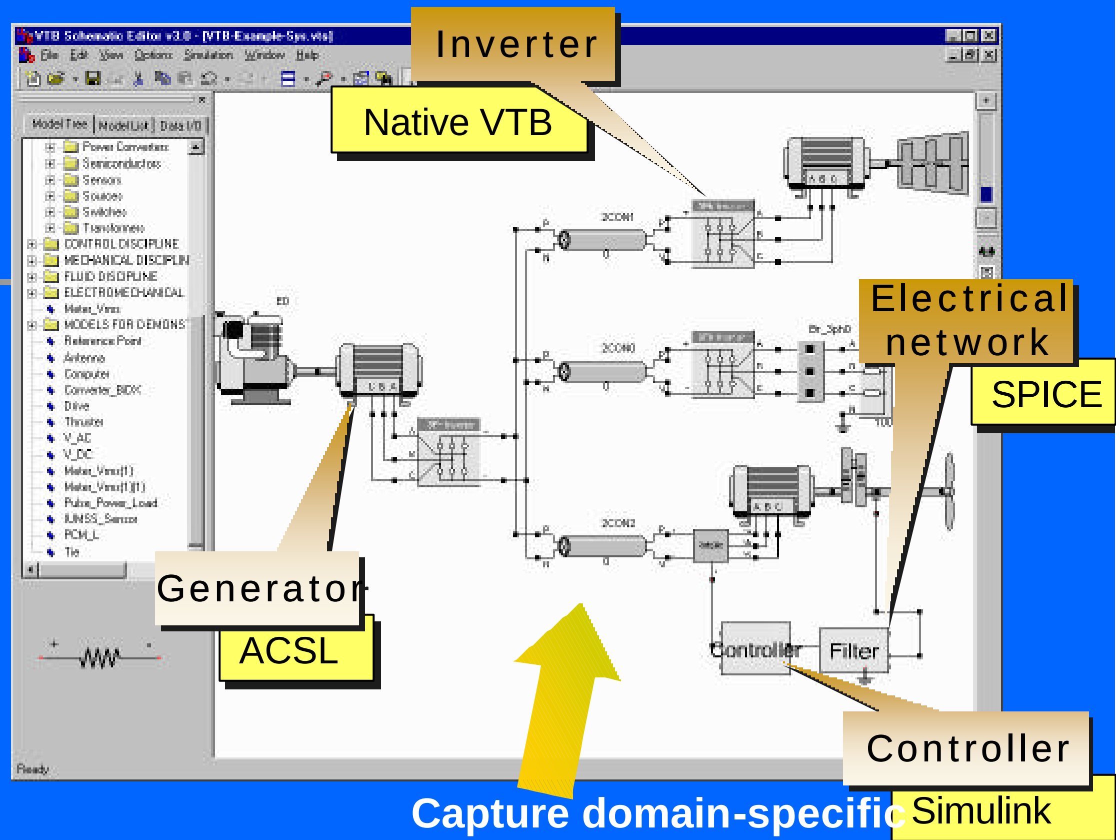
Presented by Roger A. Dougal

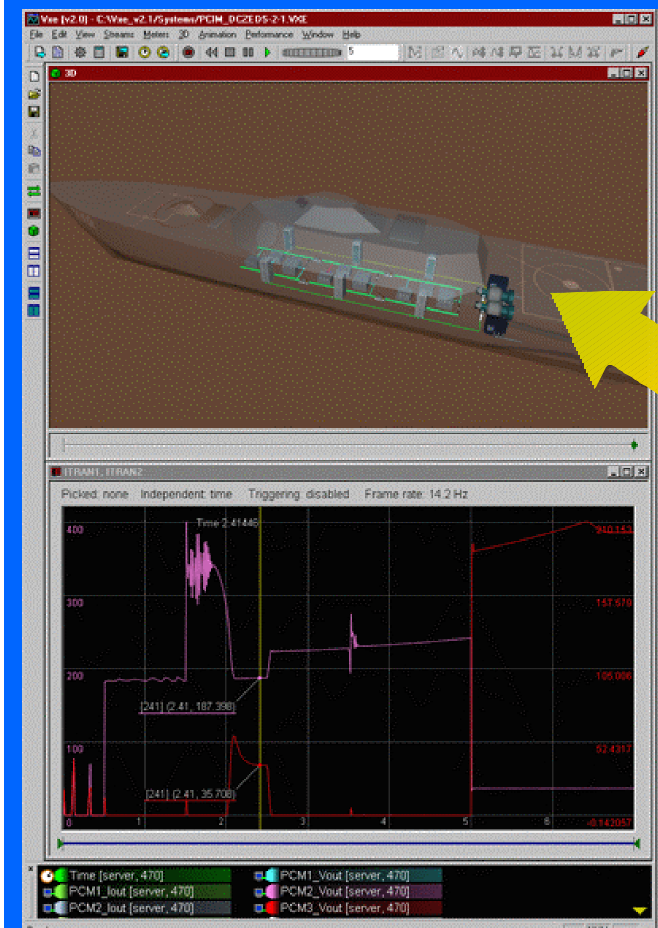
Contributors:
Zhenhua Jiang, Shengyi Liu, Roger A. Dougal, Lijun Gao,
John W. Weidner, Ralph E. White

Outline

- Introduction to VTB
- Battery Models in VTB
- Satellite power system simulations
- Comparisons of different configurations
- Interactive demonstration

Virtual Test Bed





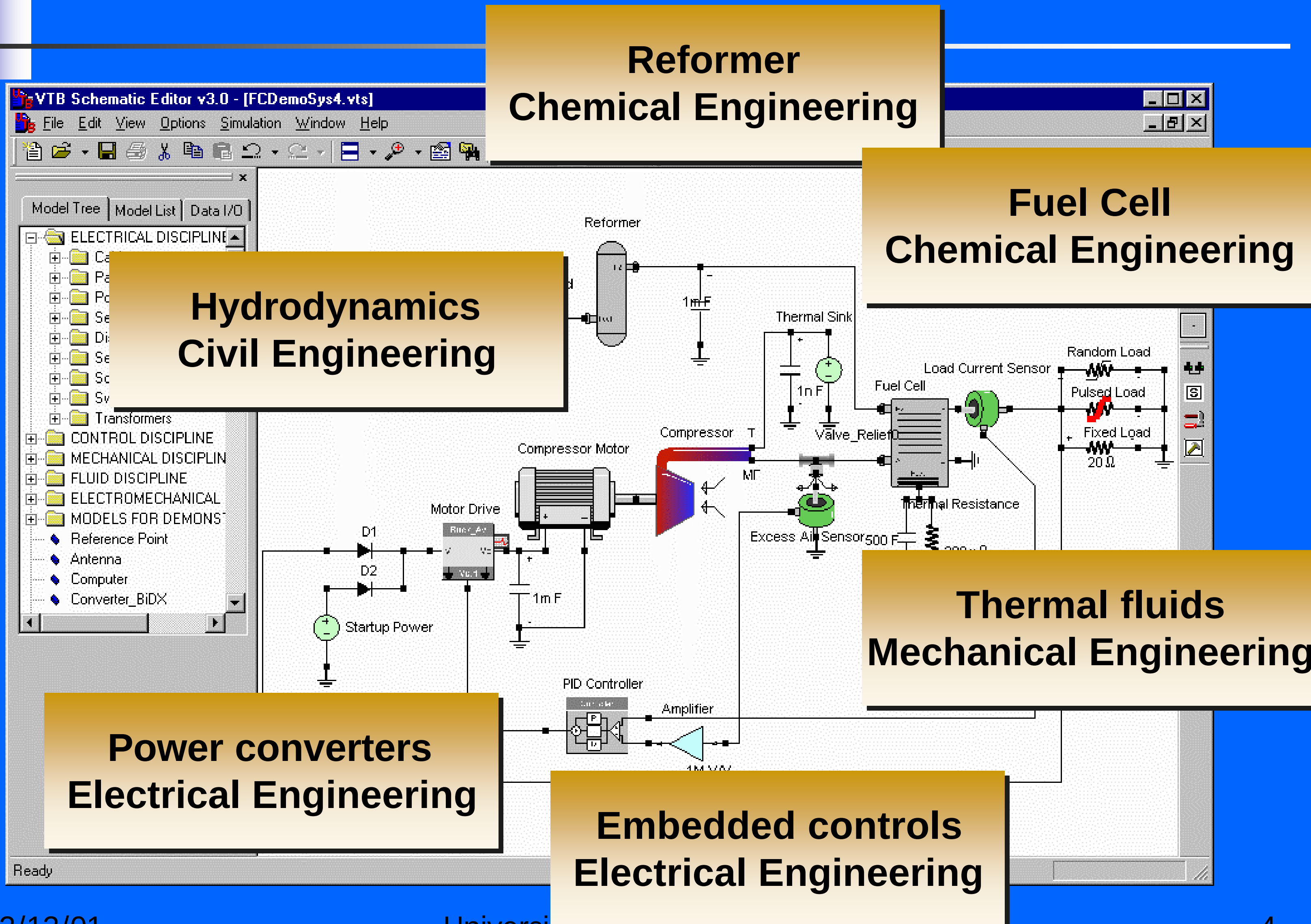
Advanced visualizations increase comprehension

Capture domain-specific expertise and preserve utility of existing models and modeling skills

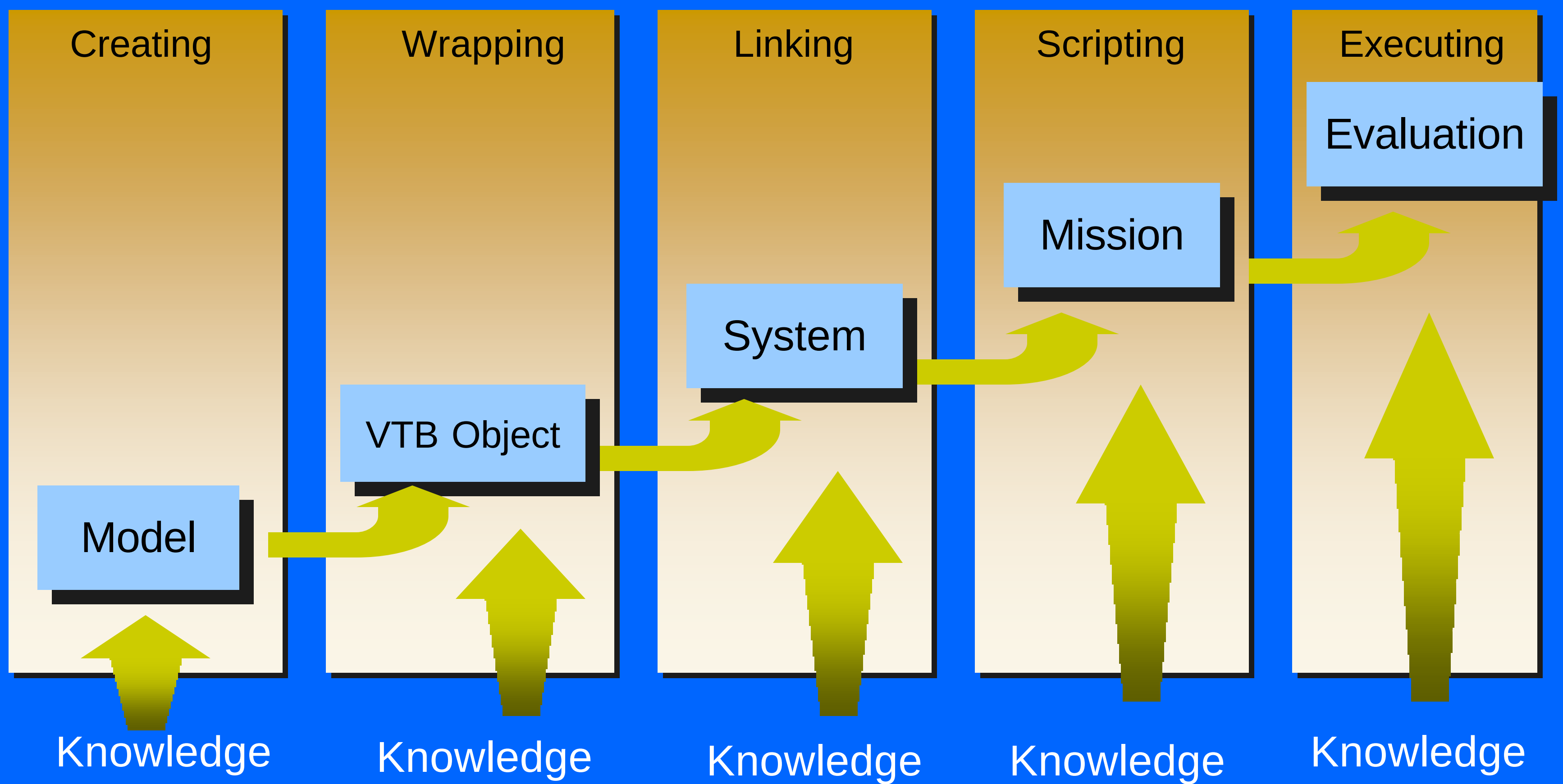
VTB

- Is an environment for integrating the work of interdisciplinary teams
- Provides a "common language" for expression of problems and solutions
- Enables virtual prototyping and tuning of complex dynamic systems.

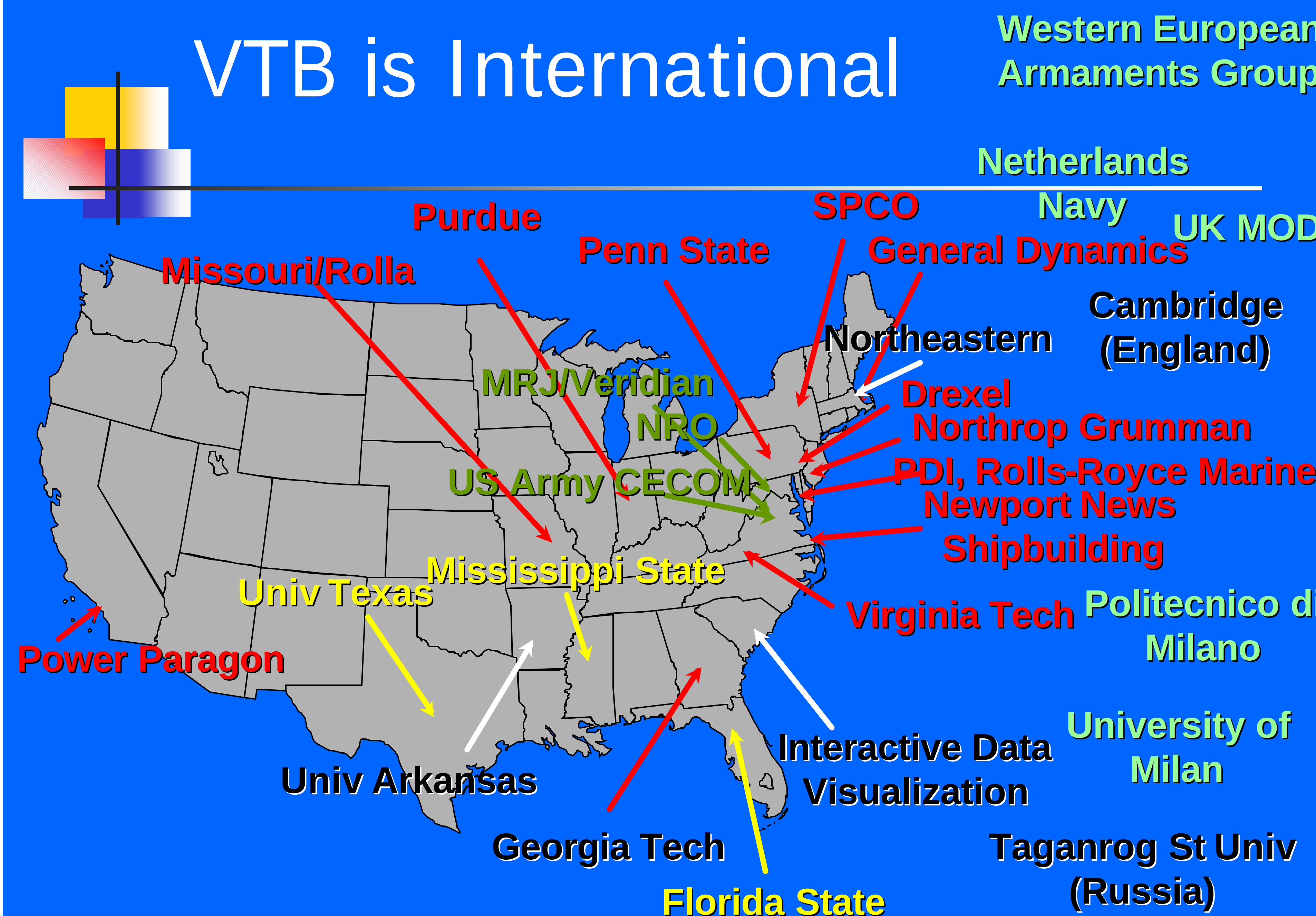
VTB accelerates interdisciplinary system design by integrating knowledge



VTB facilitates interdisciplinary and distributed team work by **capturing** and **amplifying** user knowledge at every step of the system modeling and simulation process



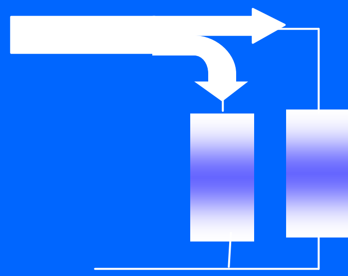
VTB is International



VTB uniquely supports all three types of object couplings, even for imported and hardware objects

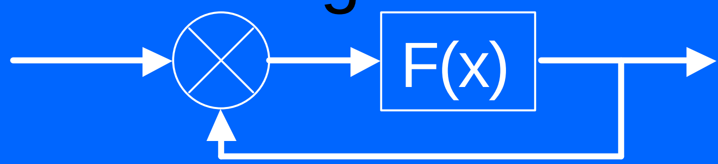
Natural Coupling

- Enforce physical conservation laws



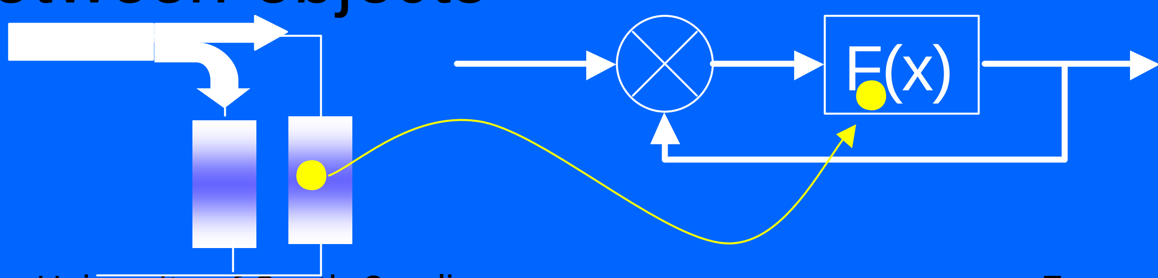
Signal Coupling

- Directed flow of information through objects



Data Coupling

- Pass data between objects

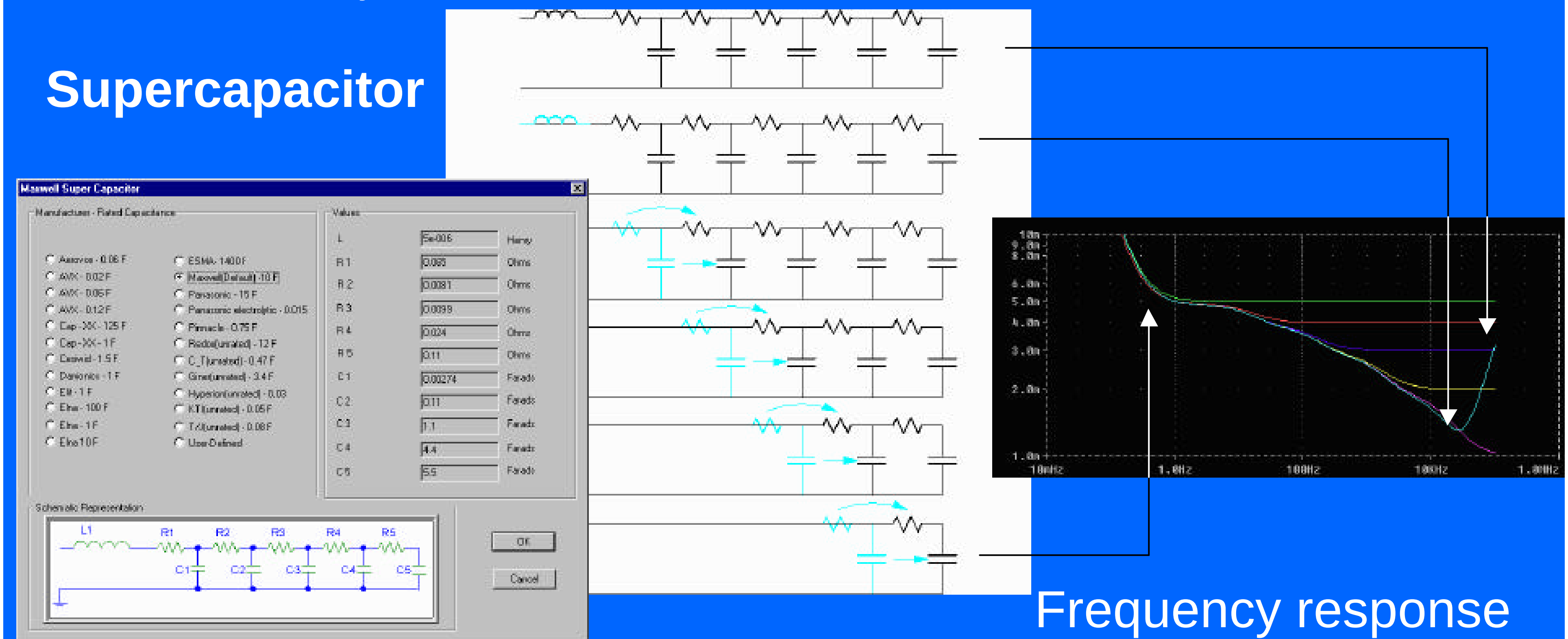


Advanced VTB Features

Variable Model Order

- Different types of studies require different levels of model detail
- VTB allows automatic model order reduction to speed computing. Resolution is appropriate to the particular study objective.

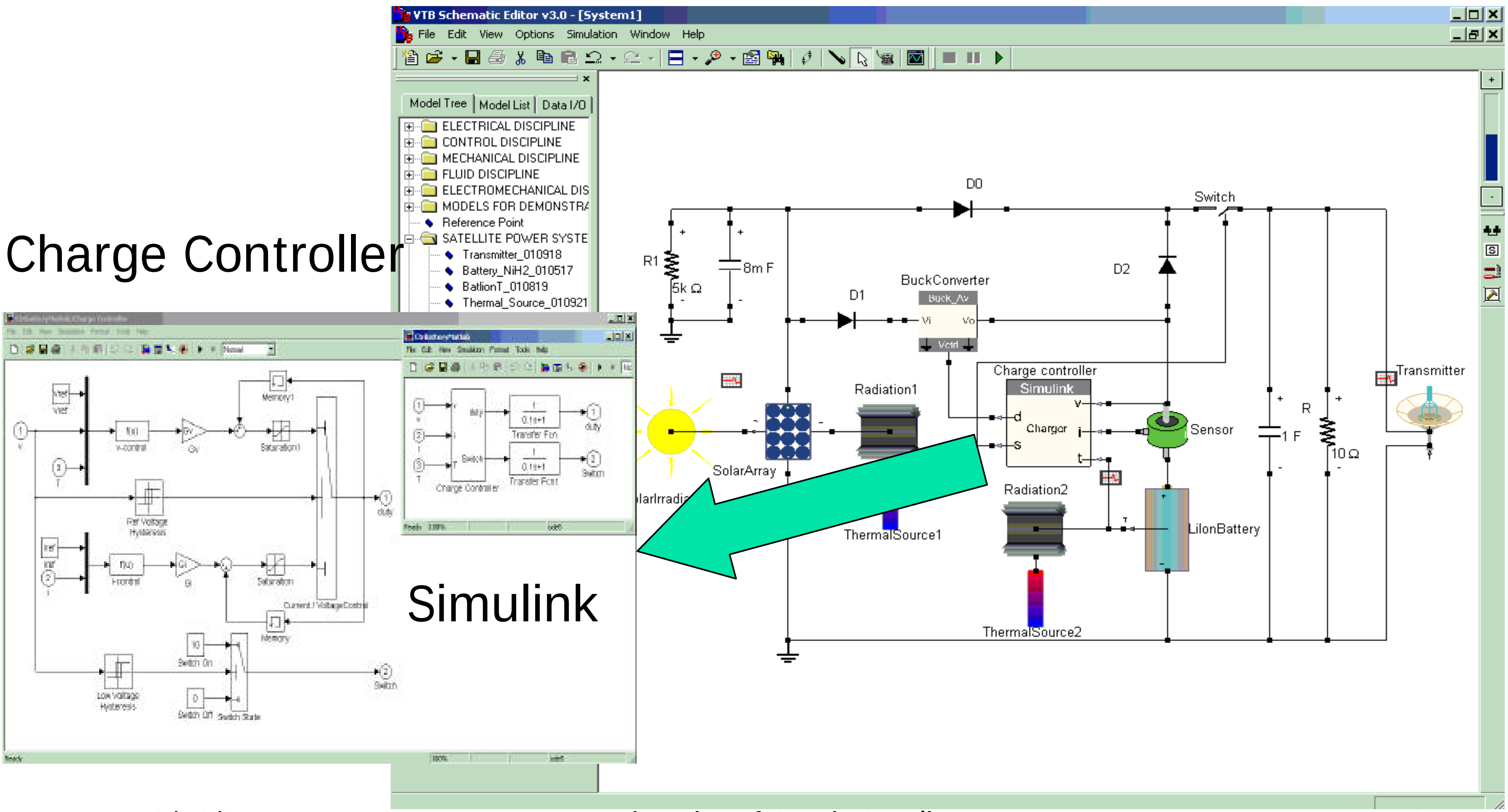
Supercapacitor



Frequency response

Battery Performance Models in a System Context

Charge Controller

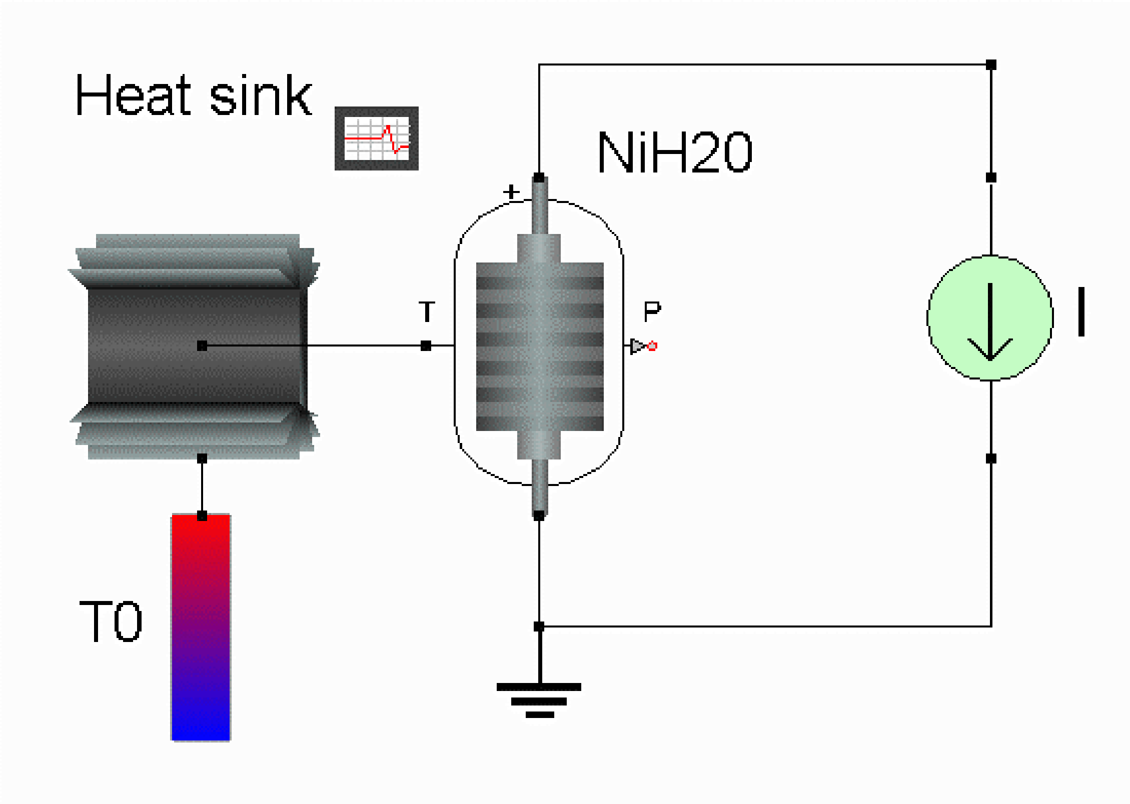


Simulink

What is in a battery model?

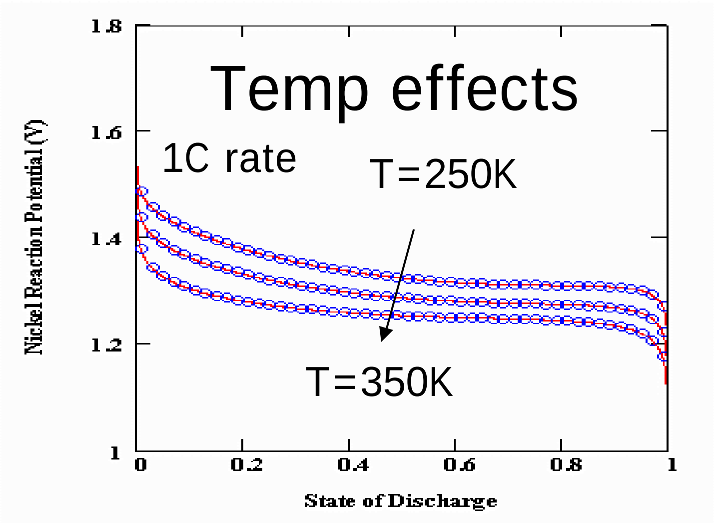
- Electrochemical effects
- Thermal effects, including heat exchange with ambient
- Pressure effects
- Transient response characteristics
- ….full diffusion based physics….on the way

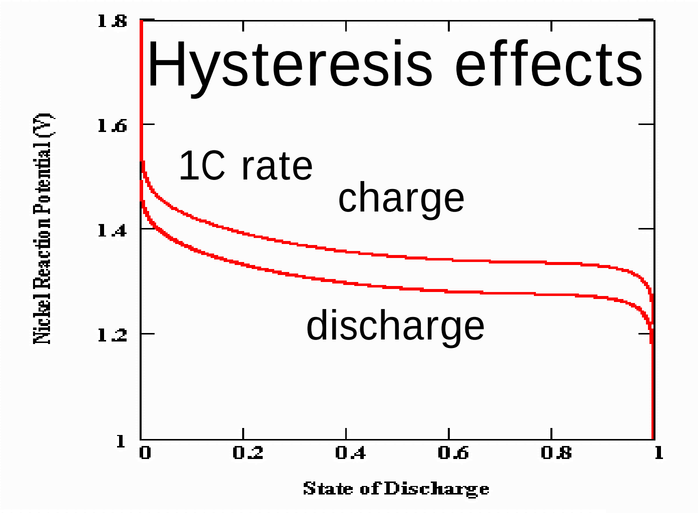
Charge/Discharge Characteristic Tests

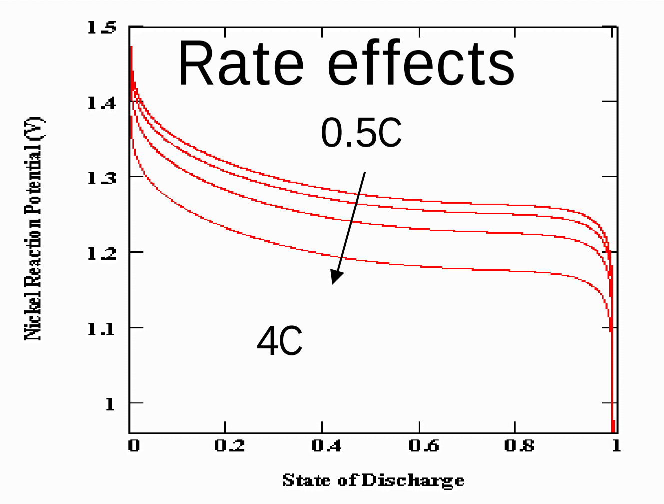


Models capture known physics

NiH$_2$ battery: discharge curves



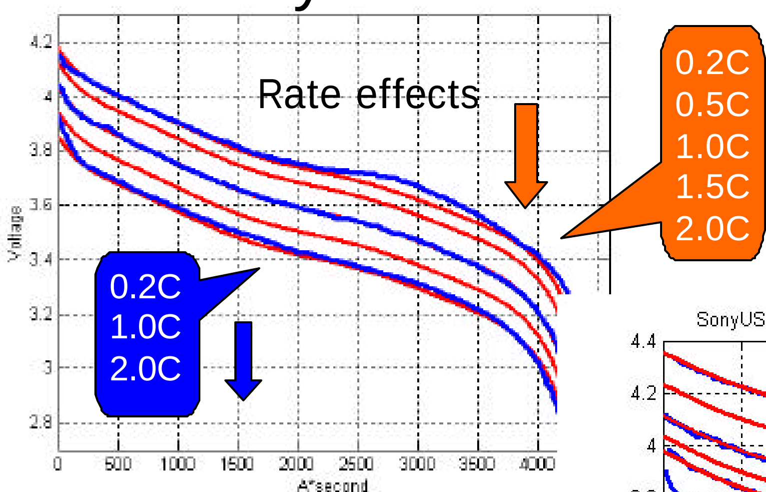




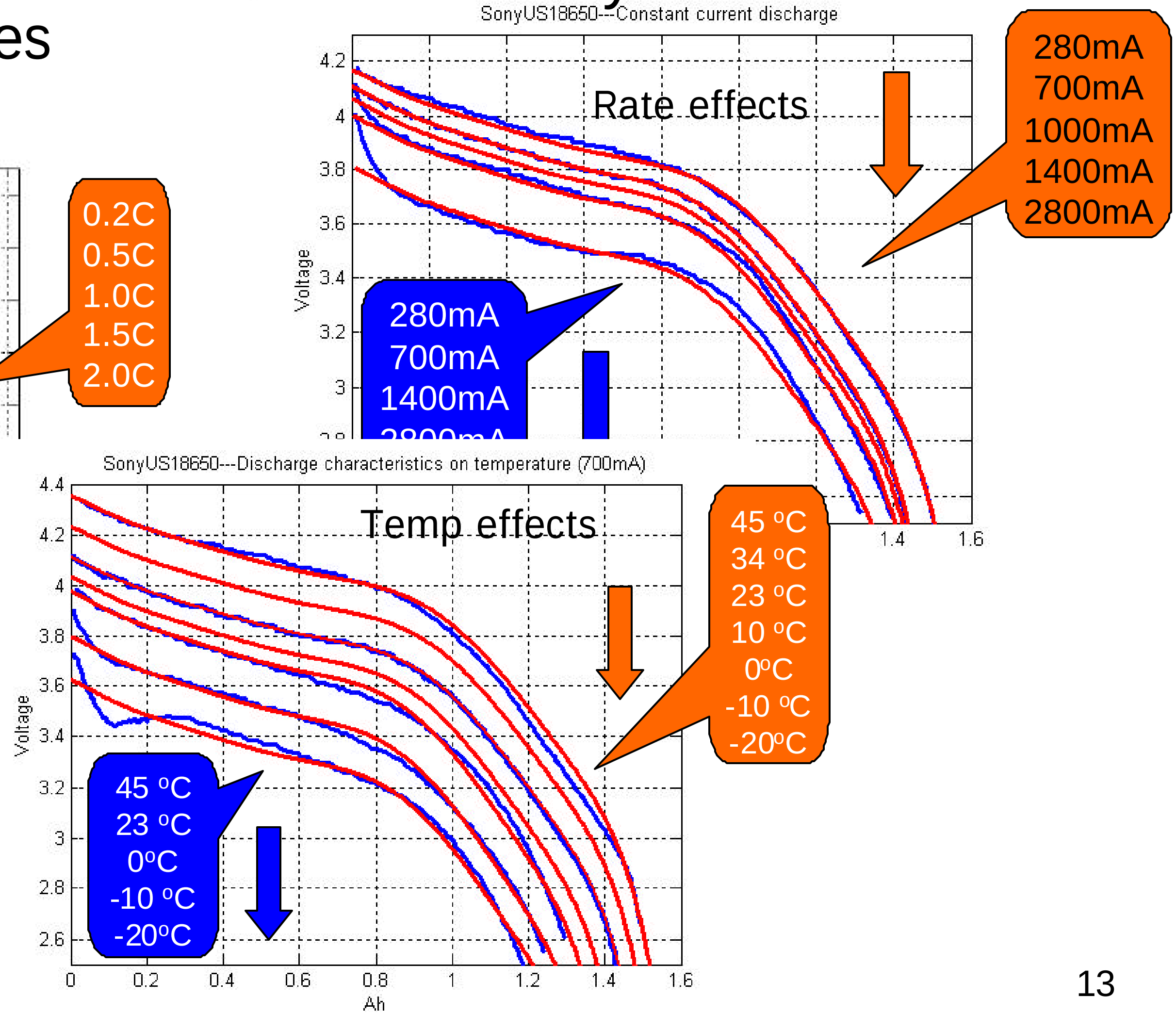
Models capture known physics

Lithium ion batteries

Polystor

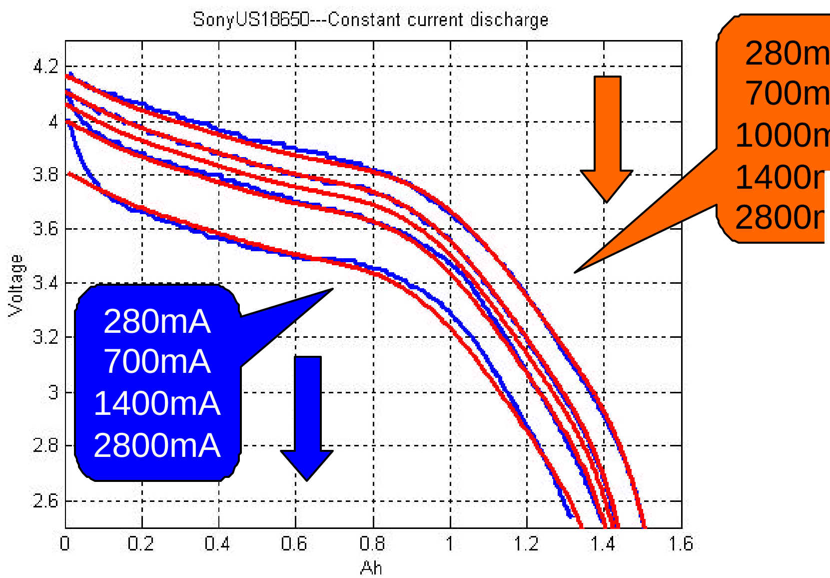


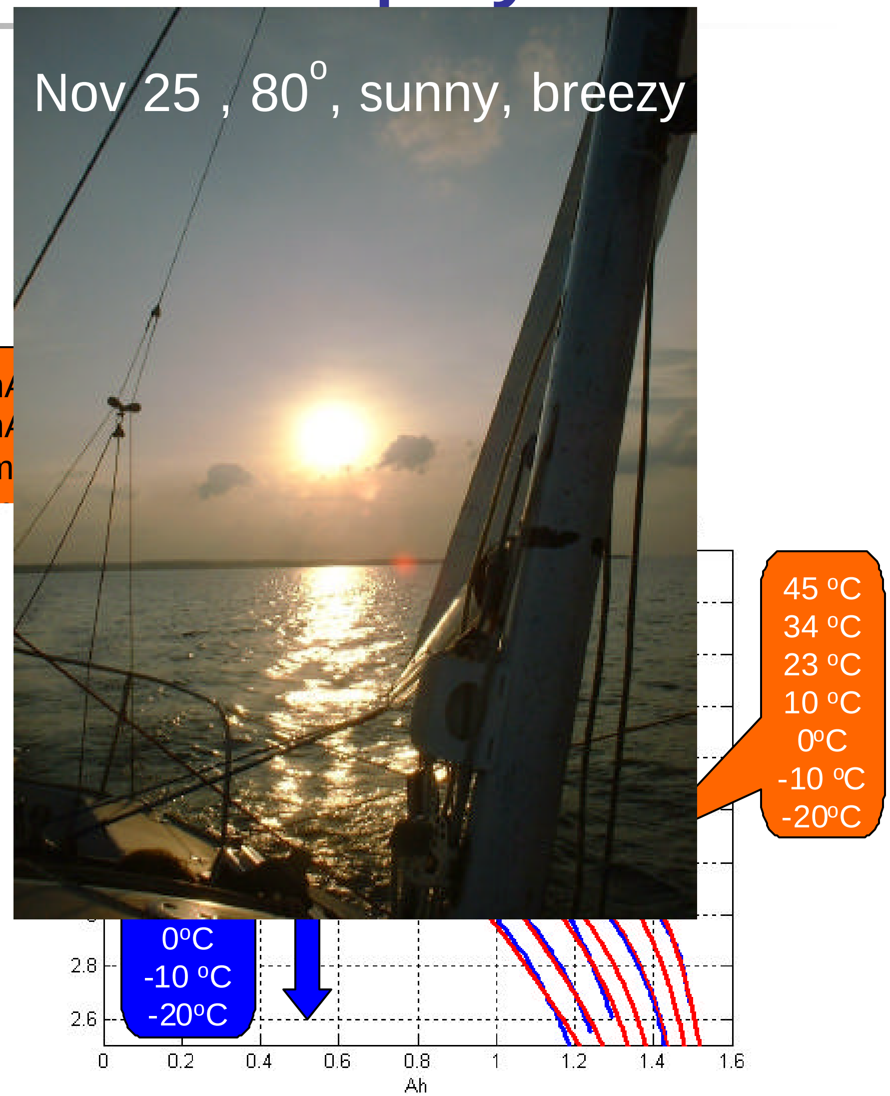
Sony



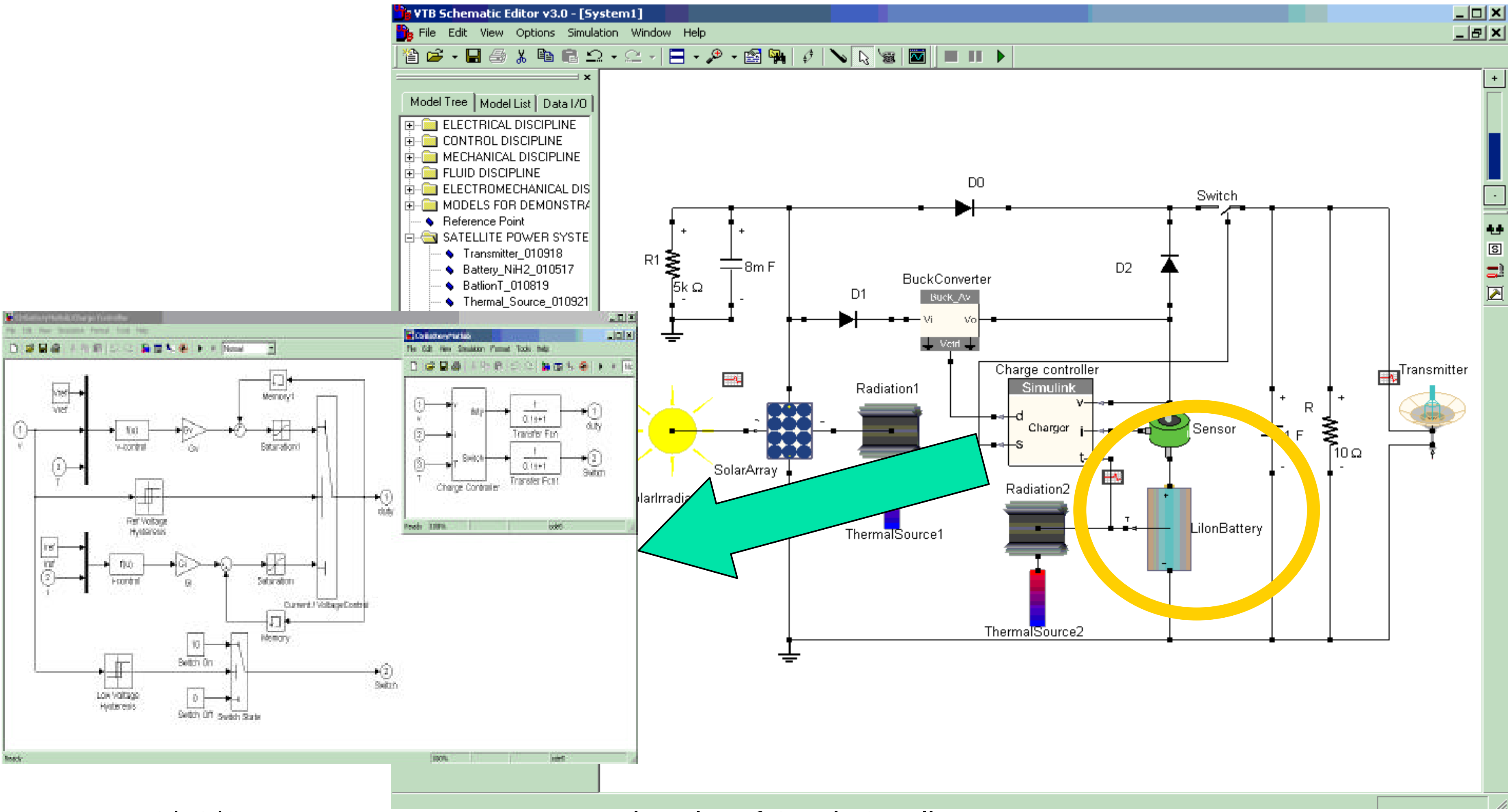
Models capture known physics

Unexpected data?

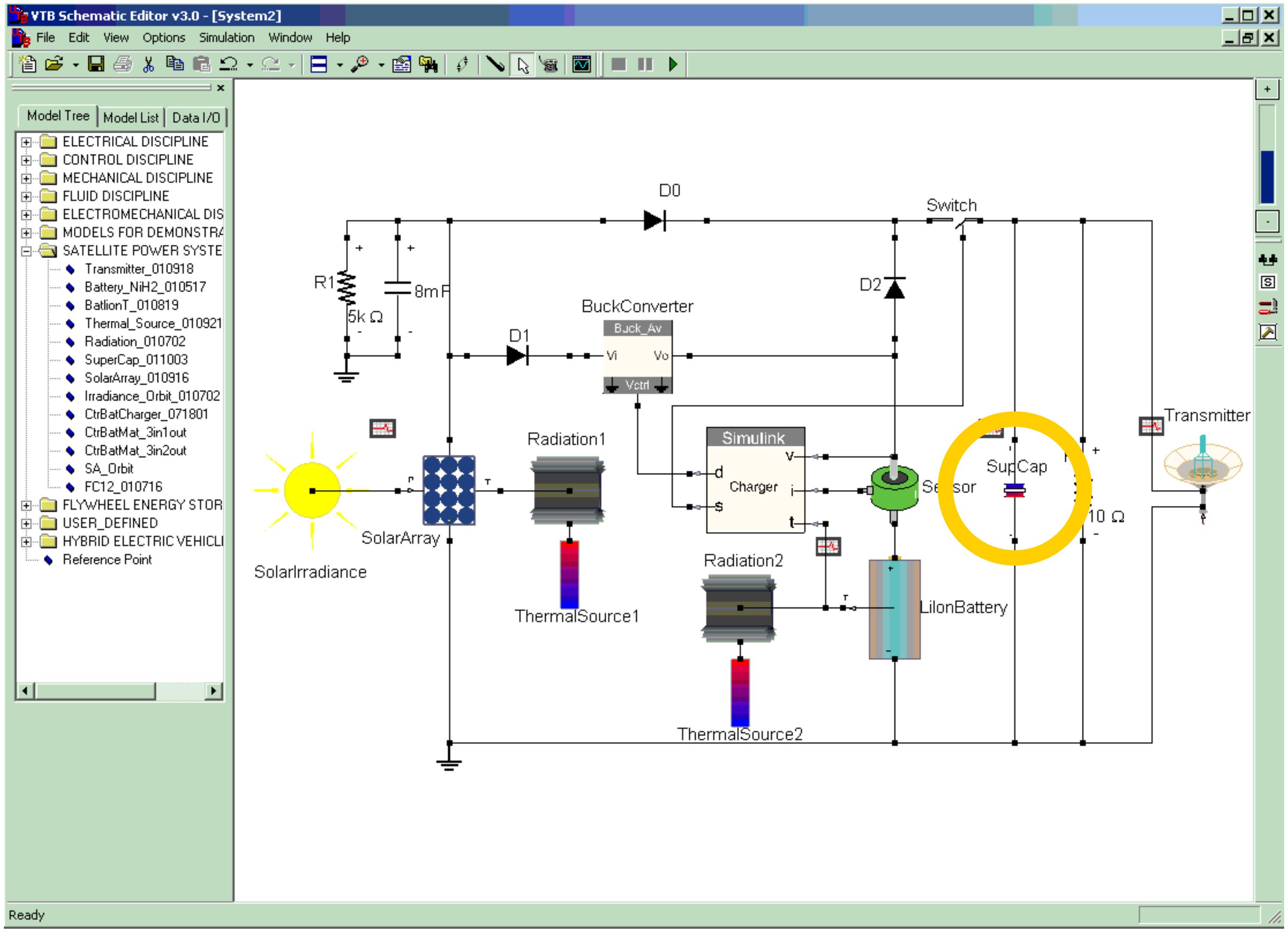




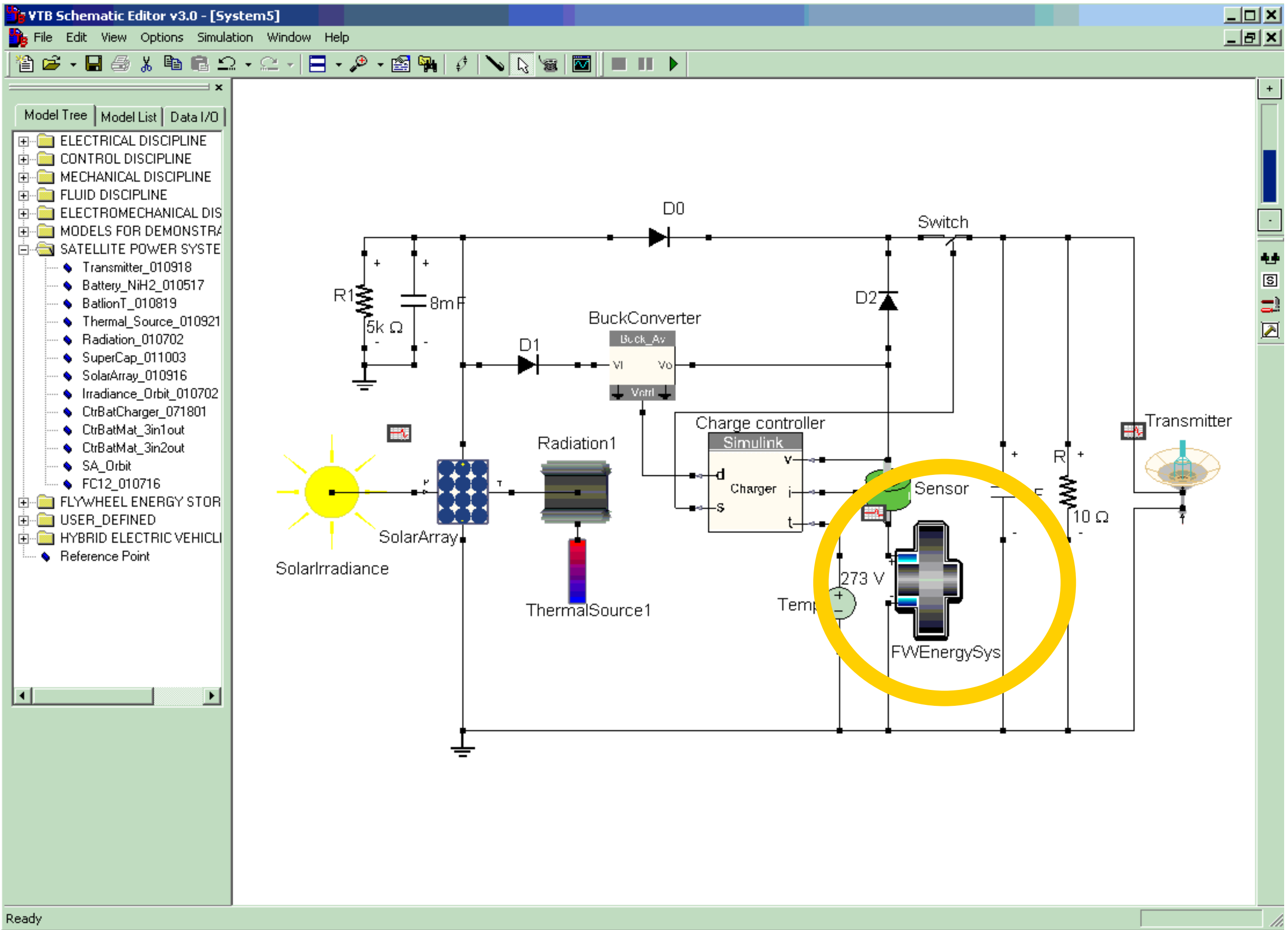
System Comparisons



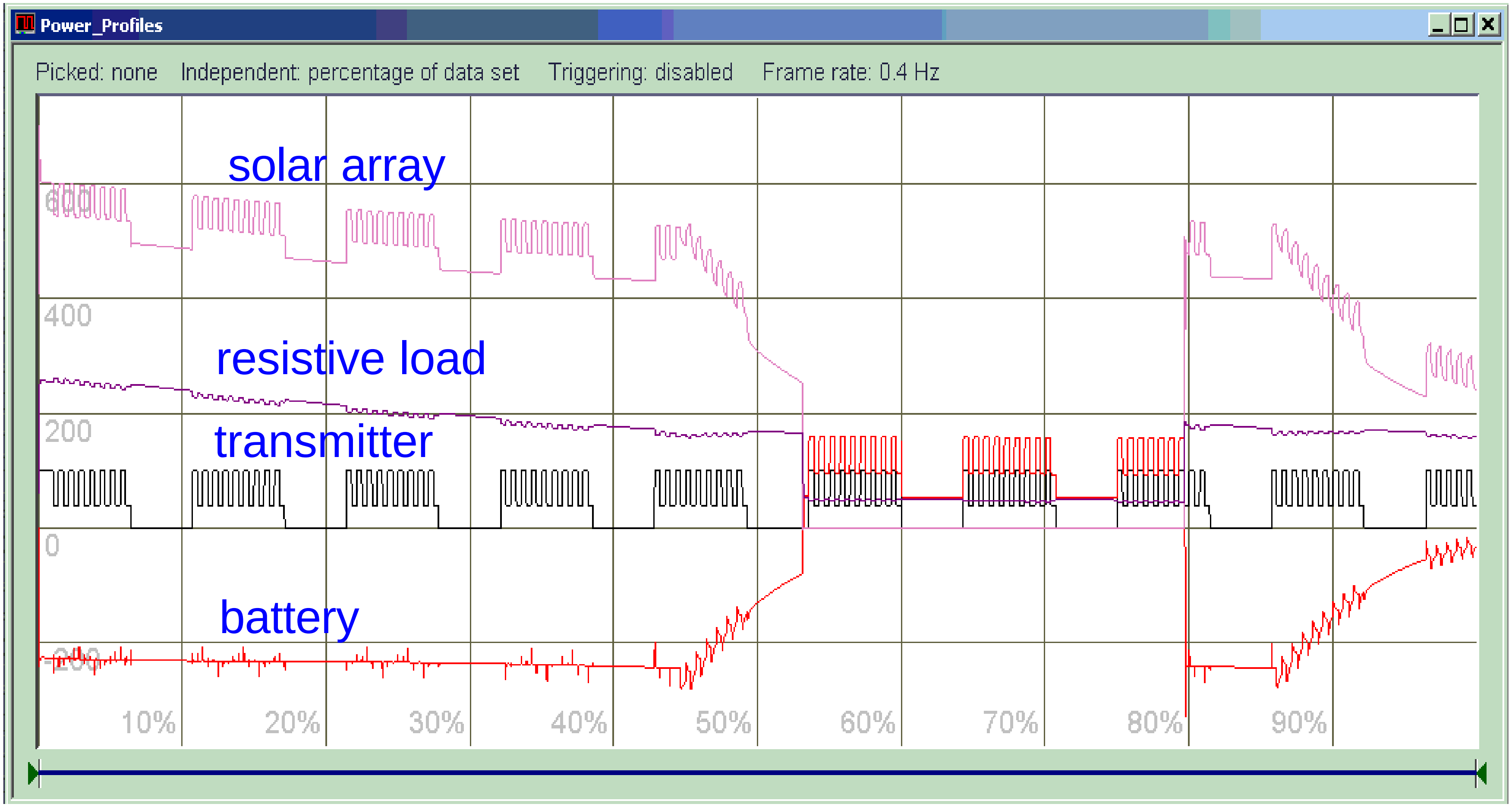
Design Alternative 1: Add Supercapacitor



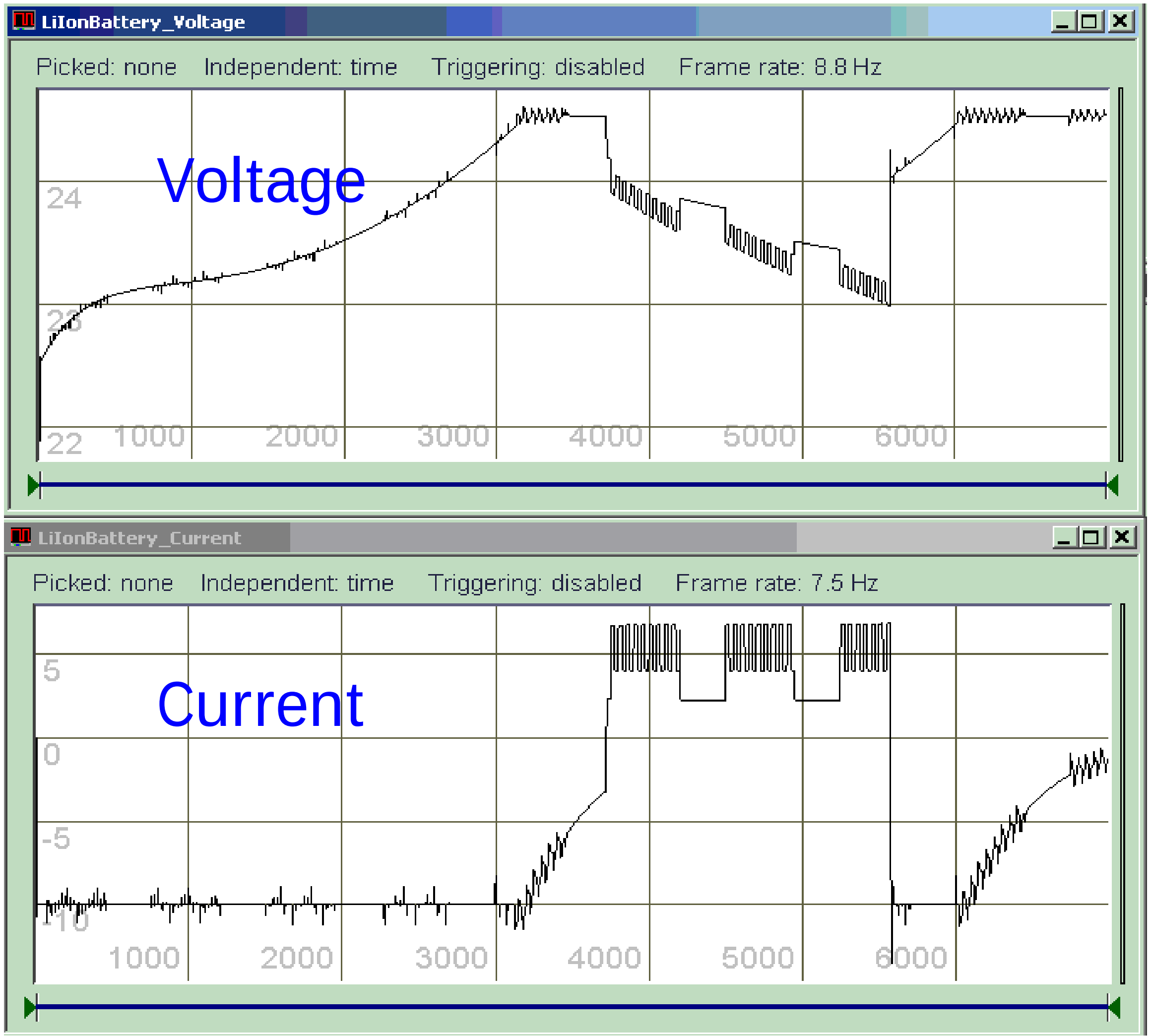
Design Alternative 2:
Use Flywheel instead of Li battery



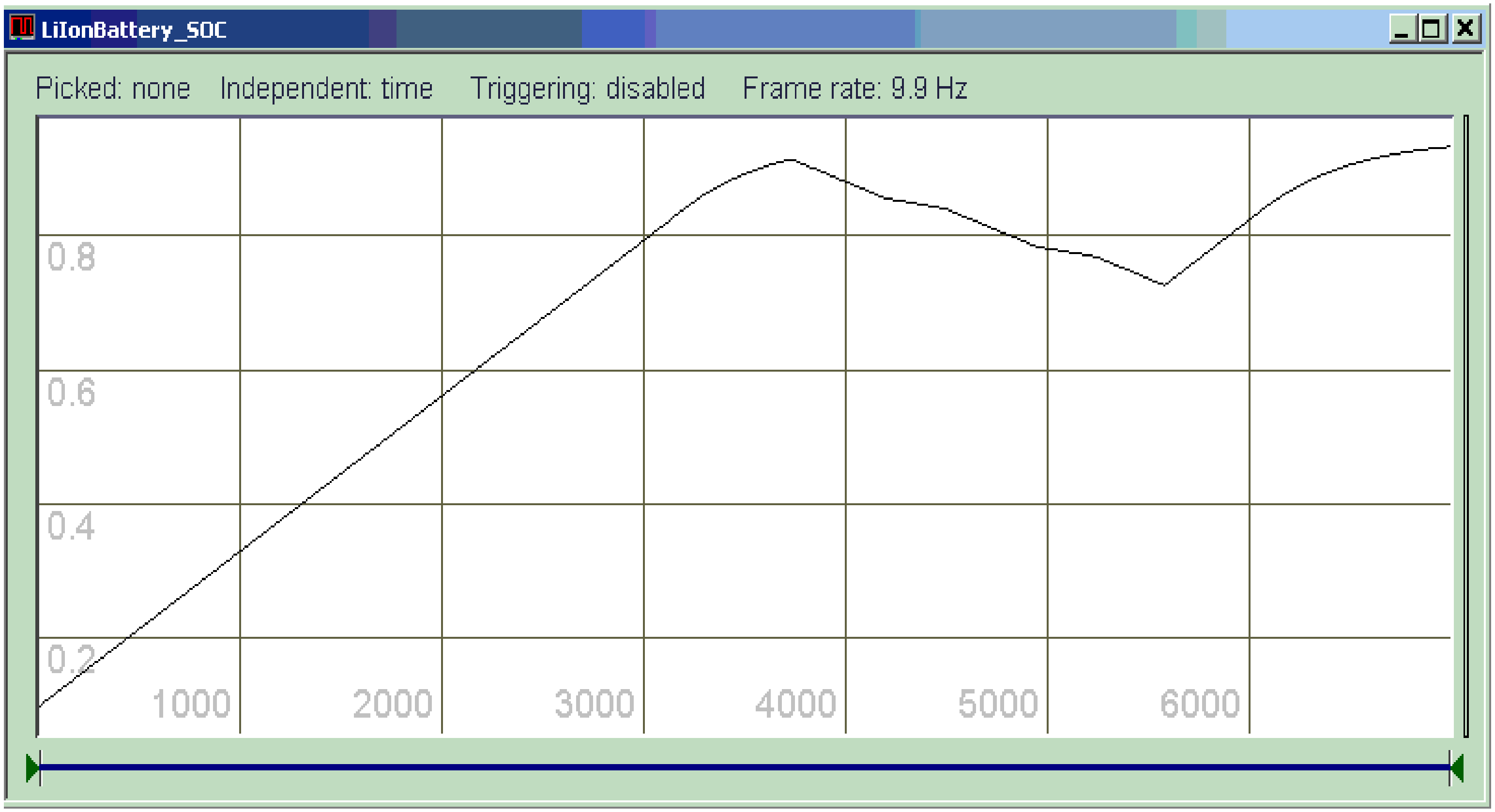
Power profiles – Li battery



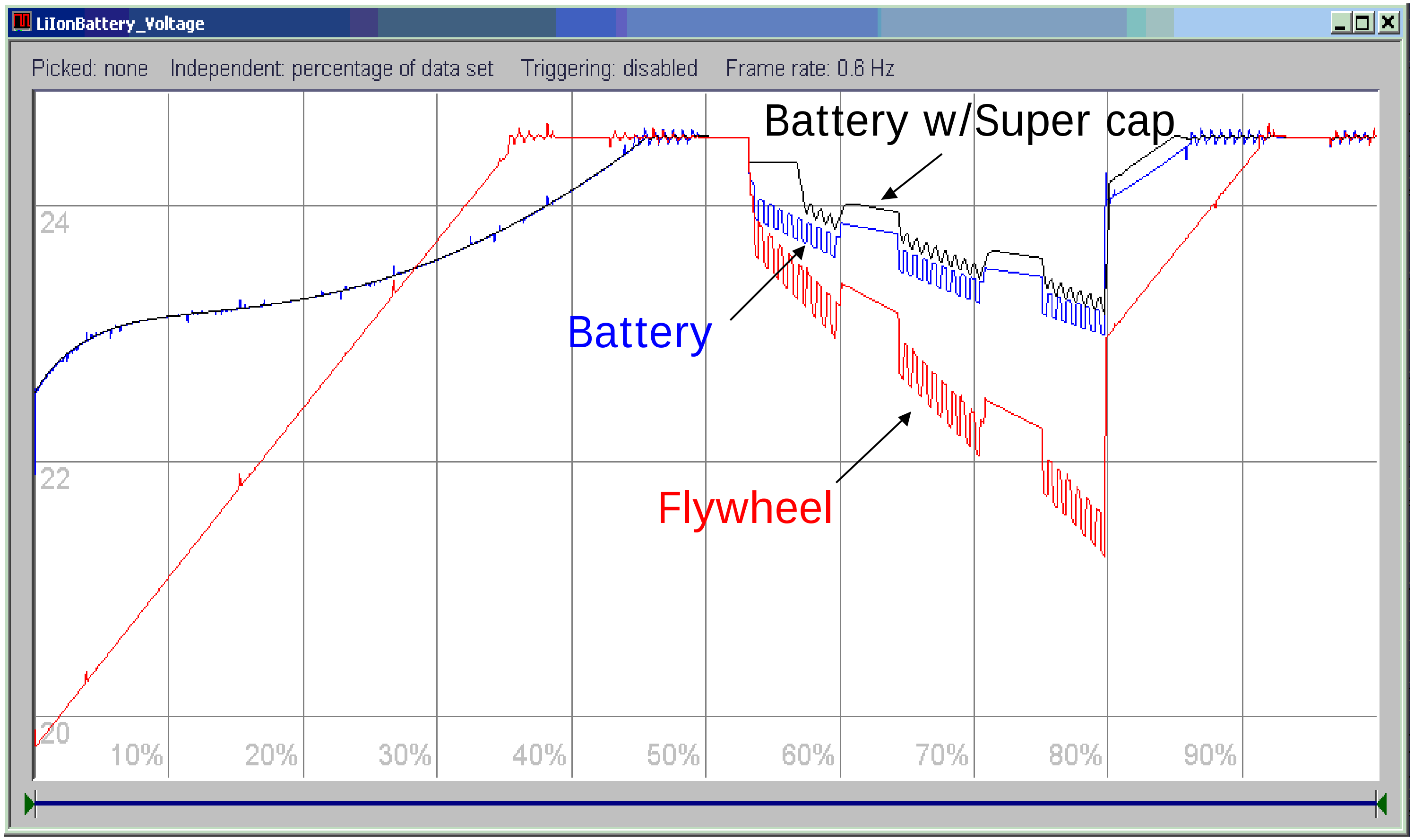
Battery voltage and current



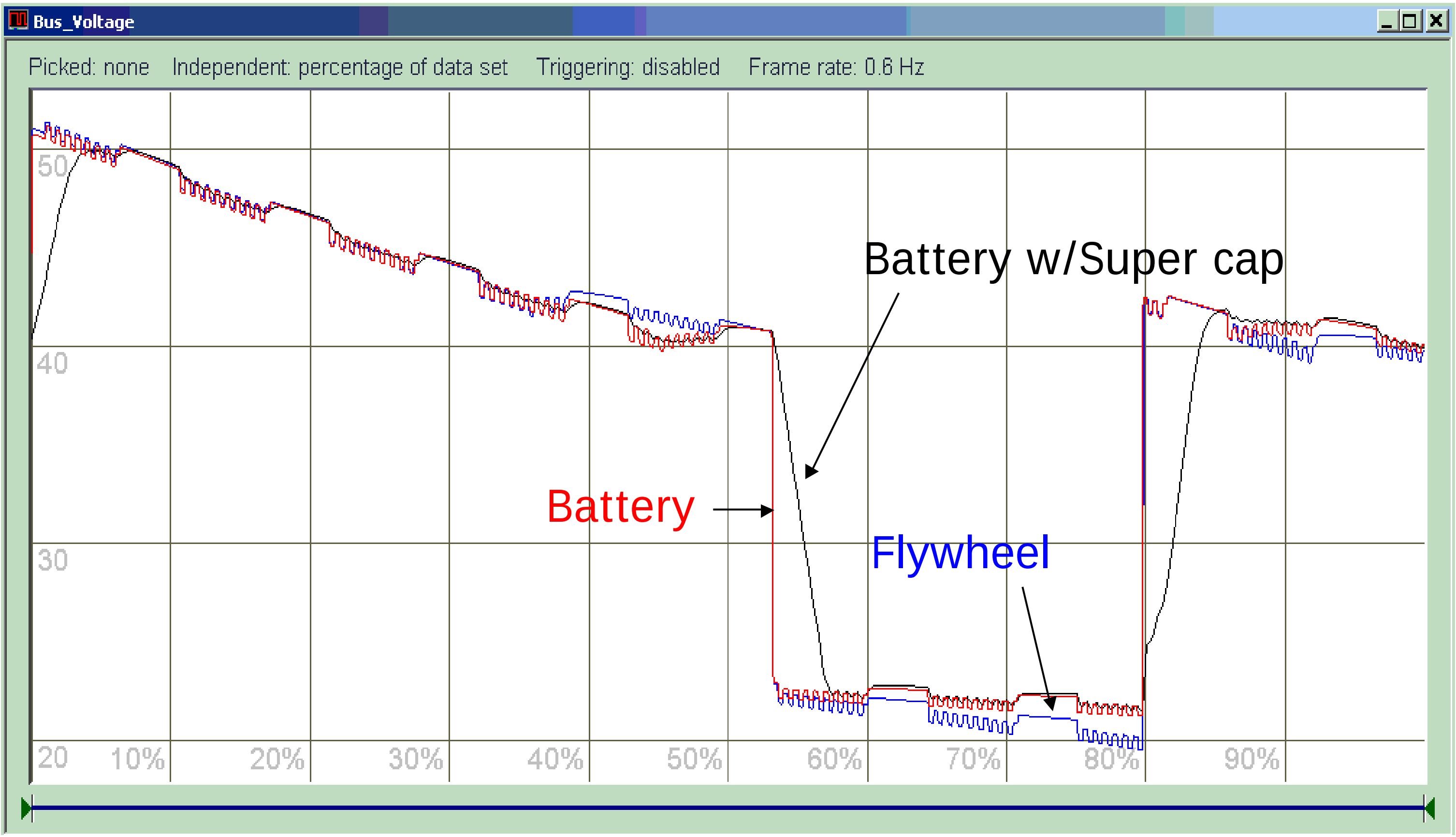
Battery state of charge



Terminal Voltages of energy storage devices



Comparison of the bus voltages



VTB belongs to the users

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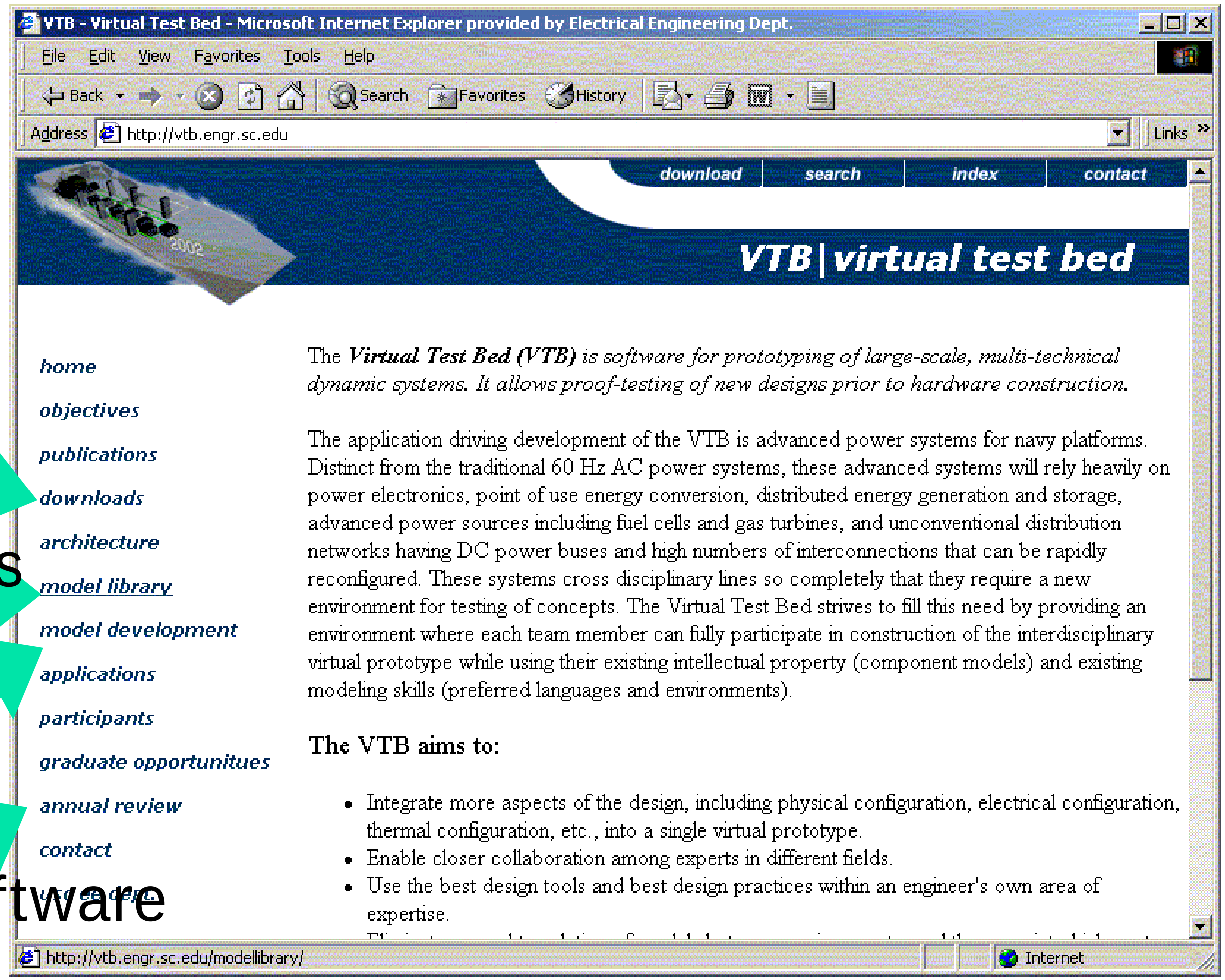

Demonstration