Capacity Loss Studies on High Capacity Li-ion Cells for the Orbiter Advanced Hydraulic Power System

Judith A. Jeevarajan

Bradley W. Irlbeck

NASA- JSC

May 9-13, 2004

- Introduction
- Physical and Electrochemical Characteristics
- Performance Evaluation

A. Rate Performance
B. Internal Resistance
C. Performance at Different Temperatures

- Safety Evaluation

A. Overcharge
B. Overdischarge
C. External Short
D. Simulated Internal Short
E. Heat-to-Vent
F. Vibration
G. Drop Test
H. Vent and Burst Pressure

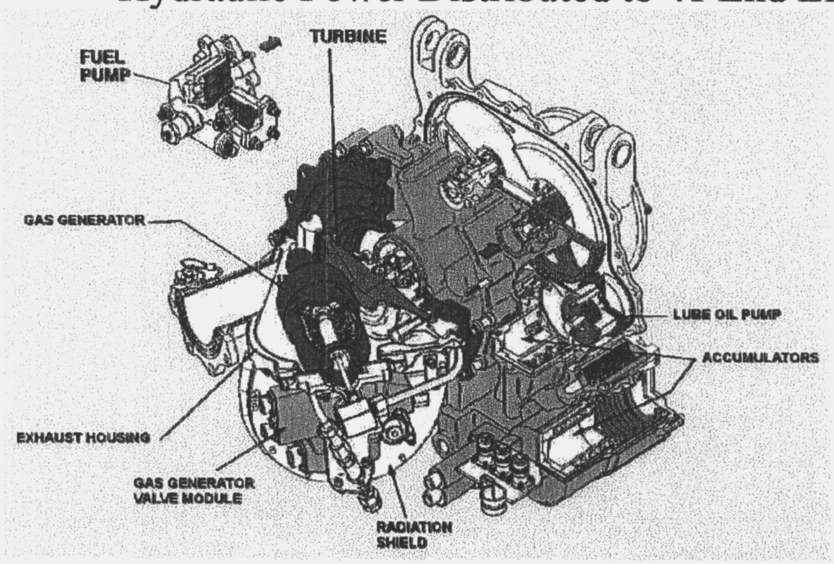
Orbiter Hydrazine APU Description

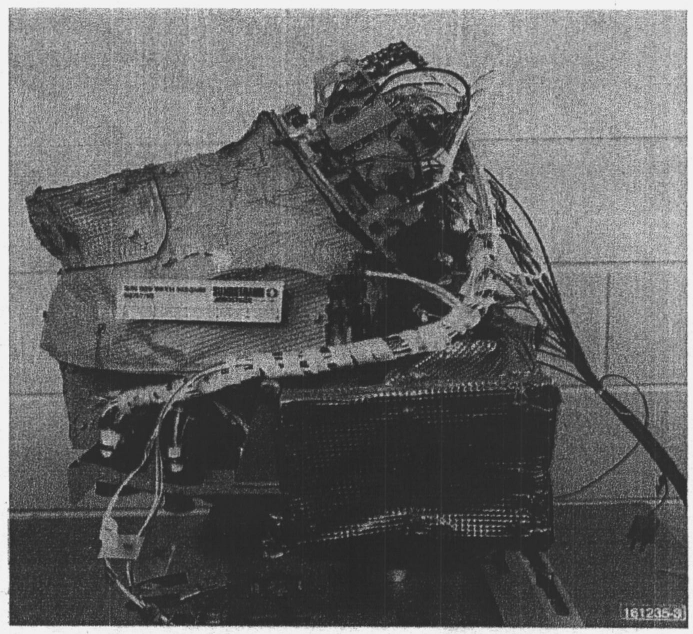
Hydrazine APU Used Throughout the Shuttle Program to Power Hydraulic Systems

- Operates During Ascent, On-Orbit Flight Control System Checkout, and Descent
- Converts Chemical Hydrazine Fuel to Shaft Power to Drive a Hydraulic Pump
  - Catalytic Reaction Drives a High Speed Turbine; Speed Reduced to Hyd Pump via a Gearbox

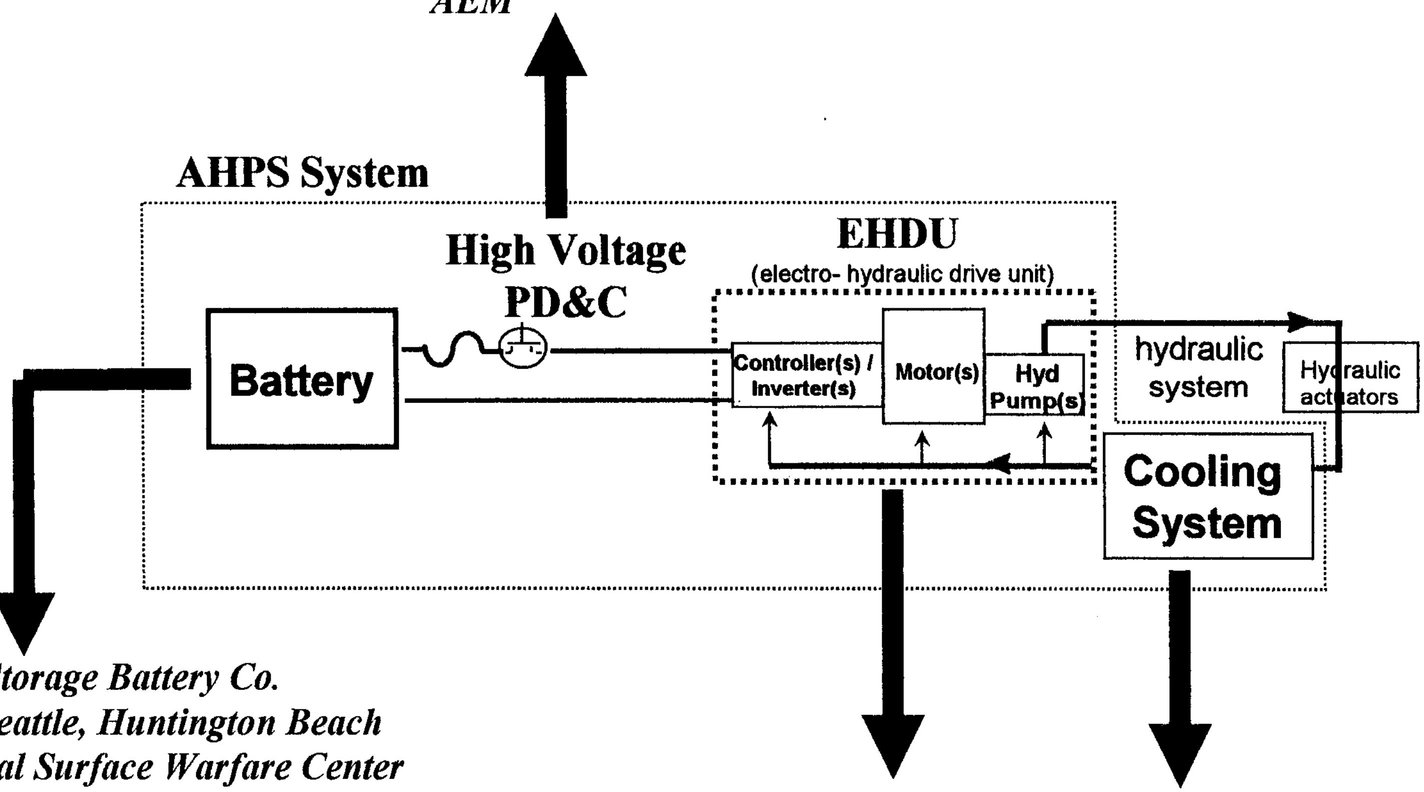
Three Hydraulic Systems Distributed Throughout the Orbiter Power Hyd Actuators

- Variable Displacement, Piston Pump Converts APU Shaft Power to 3000 psi / 69 gpm Fluid Power (120 hp max)
- Hydraulic Power Distributed to 41 End Effectors



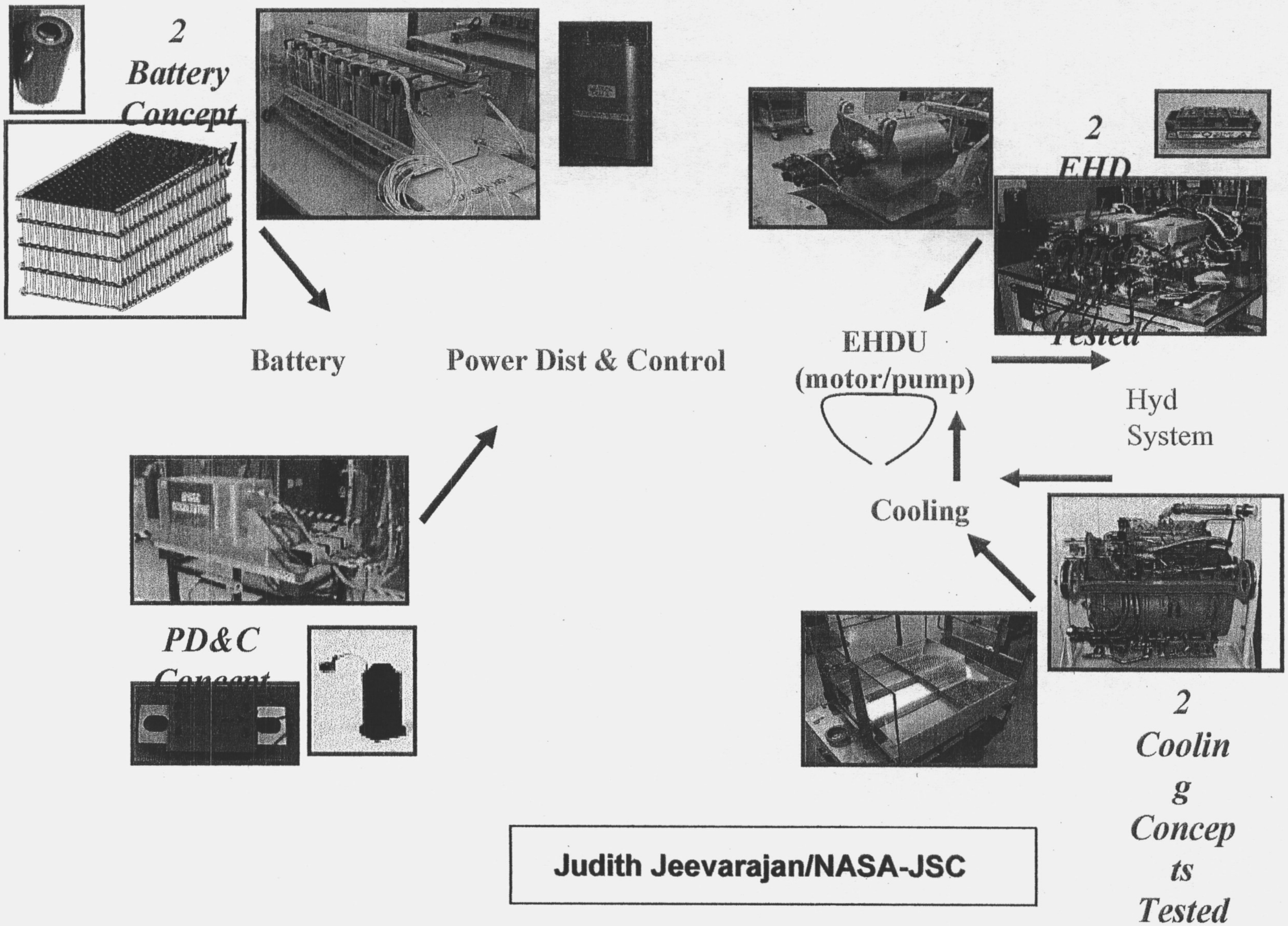


NASA GRC
Boeing – Rocketdyne, Huntington Beach
AEM



Japanese Storage Battery Co.
Boeing – Seattle, Huntington Beach
Crane Naval Surface Warfare Center
Sandia National Labs
Schlumberger
Aeroenvironment
COM DEV Space
NASA JSC ESTA
AEA
SRI

Moog Space Products – Buffalo, NY
Hamilton Sundstrand – Rockford, IL & Windsor Locks, CT
Boeing - Huntington Beach
NASA White Sands
NASA JSC ESTA
~~NASA MSFC~~



Judith Jeevarajan/NASA-JSC

Objective: Determine Long Term Effects of "Storage" Temp & State of Charge (SOC) On Cell Capacity & Resistance

Description: Test Began in April, 2002 When 12 Cells Were Placed in Temperature Chambers and Stored Open Circuit at Various Temperatures and SOC (2 cells per condition). Testing Scheduled to End Sept 04 (~840 days)

Standard Discharge Cycles Performed Periodically to Trend Capacity Loss and Resistance Growth.

Capacity Loss Test Performed at NSWC in Crane, IN

Test Matrix

Cell Designation	Condition Description	Storage Temp	Storage SOC	Capacity Check
112, 113	**Vehicle Between Missions Cold**	**5 C (41 F)**	**5 – 10%**	**30 days**
114, 115	**Vehicle Between Missions Nom.**	**25 C (77F)**	**5 – 10%**	**30 days**
116, 117	**Orbit Cold**	**25 C (77 F) 25 C (77 F)**	**5 – 10% 75 – 80% (2.5 mo @ 5-10%, 15 days @ 75-80%, repeat)**	**0, 2.5, 3 mo (repeat)**
118, 119	**Orbit Nominal**	**25 C (77 F) 40 C (104 F) (2.5 mo @ 25C, 15 days @ 40C, repeat)**	**5 – 10% 75 – 80% (2.5 mo @ 5-10%, 15 days @ 75-80%, repeat)**	**0, 2.5, 3 mo (repeat)**
120, 121	**Orbit Hot**	**25 C (77 F) 65 C (149 F) (2.5 mo @ 25C, 15 days @ 65C, repeat)**	**5 – 10% 75 – 80% (2.5 mo @ 5-10%, 15 days @ 75-80%, repeat)**	**0, 2.5, 3 mo (repeat)**
122,l 125	**Post Landing Hot**	**25 C (77 F) 65 C (149 F) (2.5 mo @ 25C, 1 day @ 65C, repeat)**	**5 – 10% 75 – 80% (2.95 mo @ 5-10%, 1 day @ 75-80%, repeat)**	**0, 2.95, 3 mo (repeat)**

Standard Discharge Cycle

Standard Discharge Cycle Performed Periodically to Trend Capacity Loss and DC Resistance Growth.

Standard Discharge Cycle Consists of:

- Return to Room Temperature
- Discharge Fully
- Charge Fully to 4.1 VDC
- Discharge at C/2 Constant Current With 2.7 C Pulses at 60, 70, 80, 90 and 100 Minutes (95 amps constant with pulses to 513 amps)
- Upon Reaching 3.0 VDC, Decrease Current to C/10 and Continue Discharge Until Reaching 3.0 VDC
- Charge to Desired SOC
- Return to Desired Storage Temperature

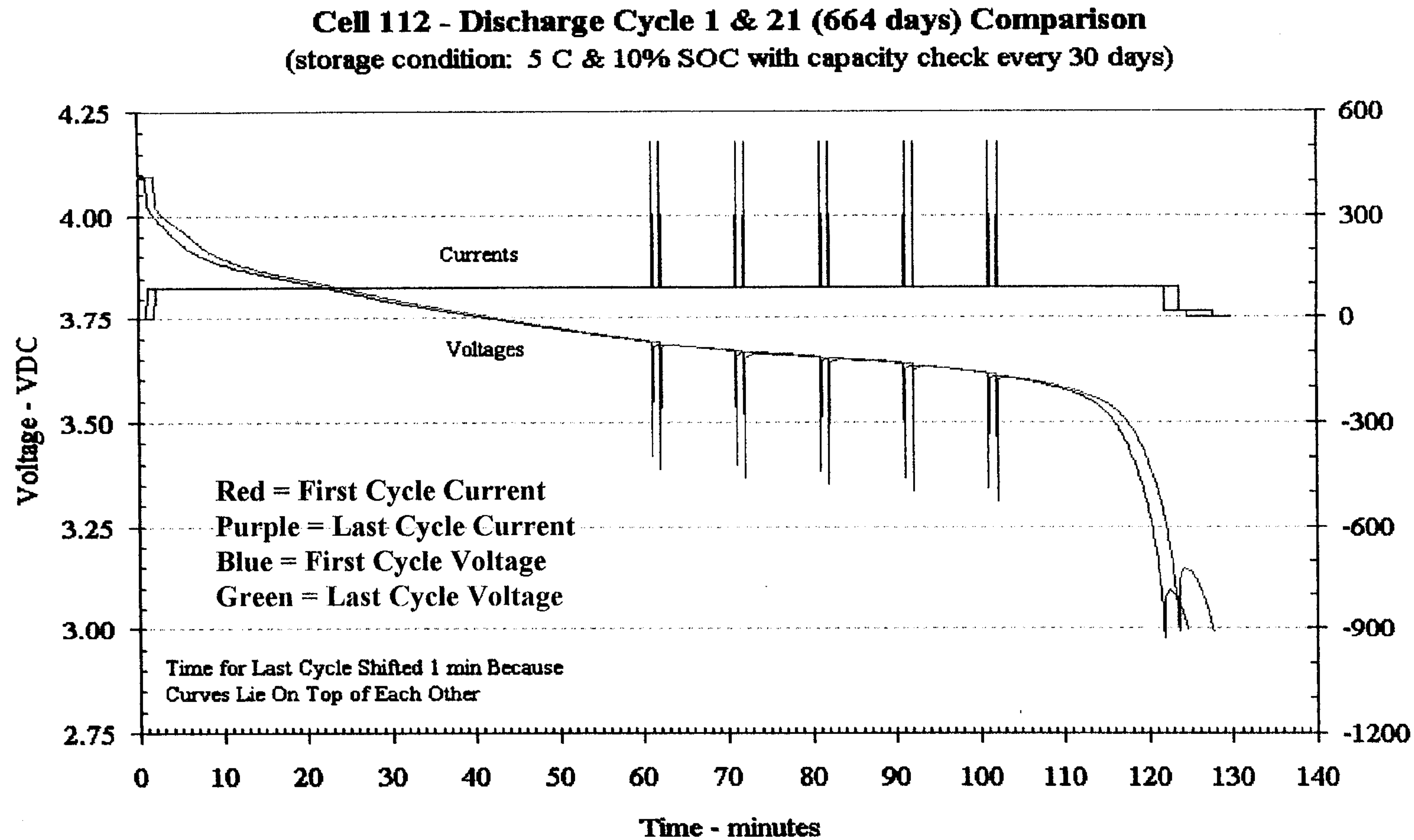
Resistance Calculated Based on dV / dI for the 2.7 C Pulses

- Trends Reported in Following Pages are for the 100 minute Pulse

Comparison of Standard Capacity Cycles

The first *vs* last discharge curves for one of the two cells from each of the six storage groups was compared.

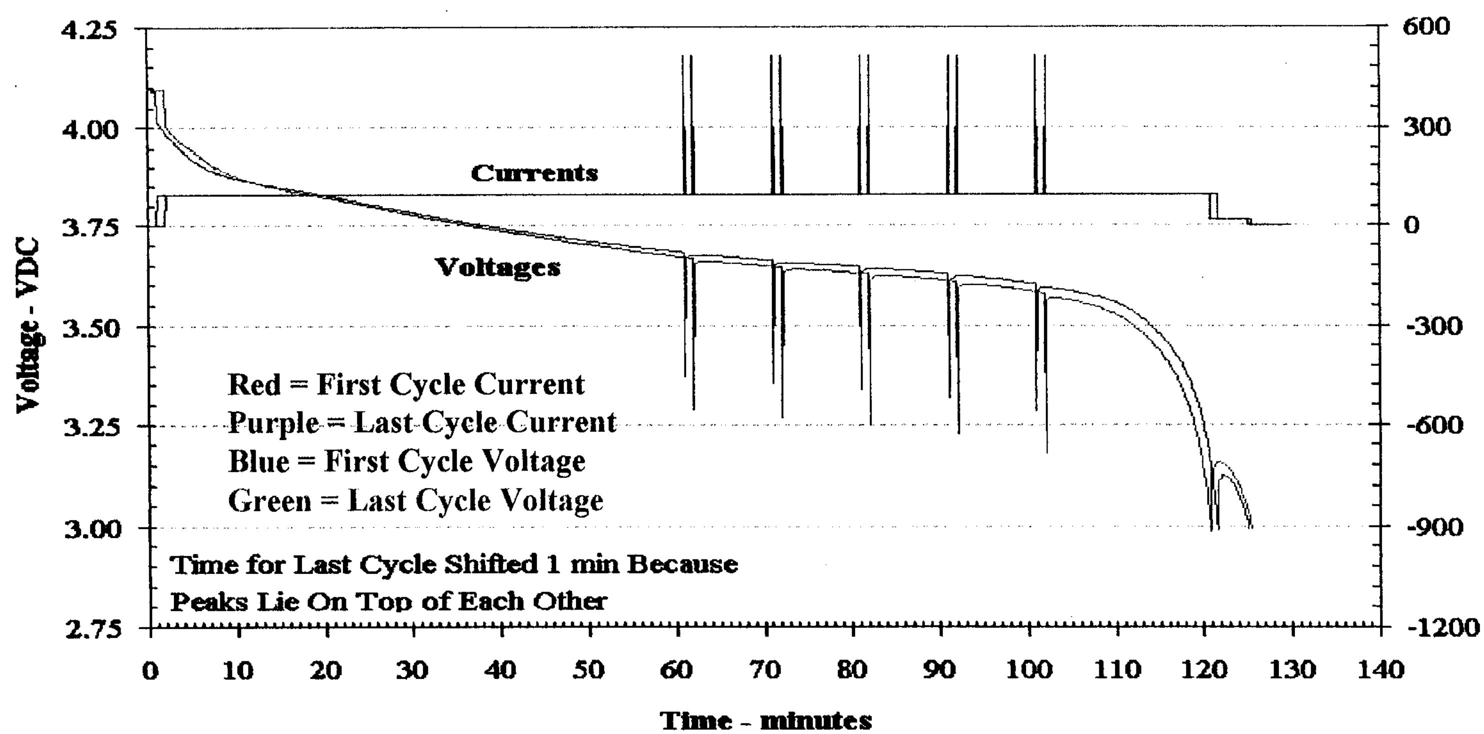
Comparison of Discharges Under Ground Storage Conditions at 5 °C & 10% SOC



Judith Jeevarajan/NASA-JSC

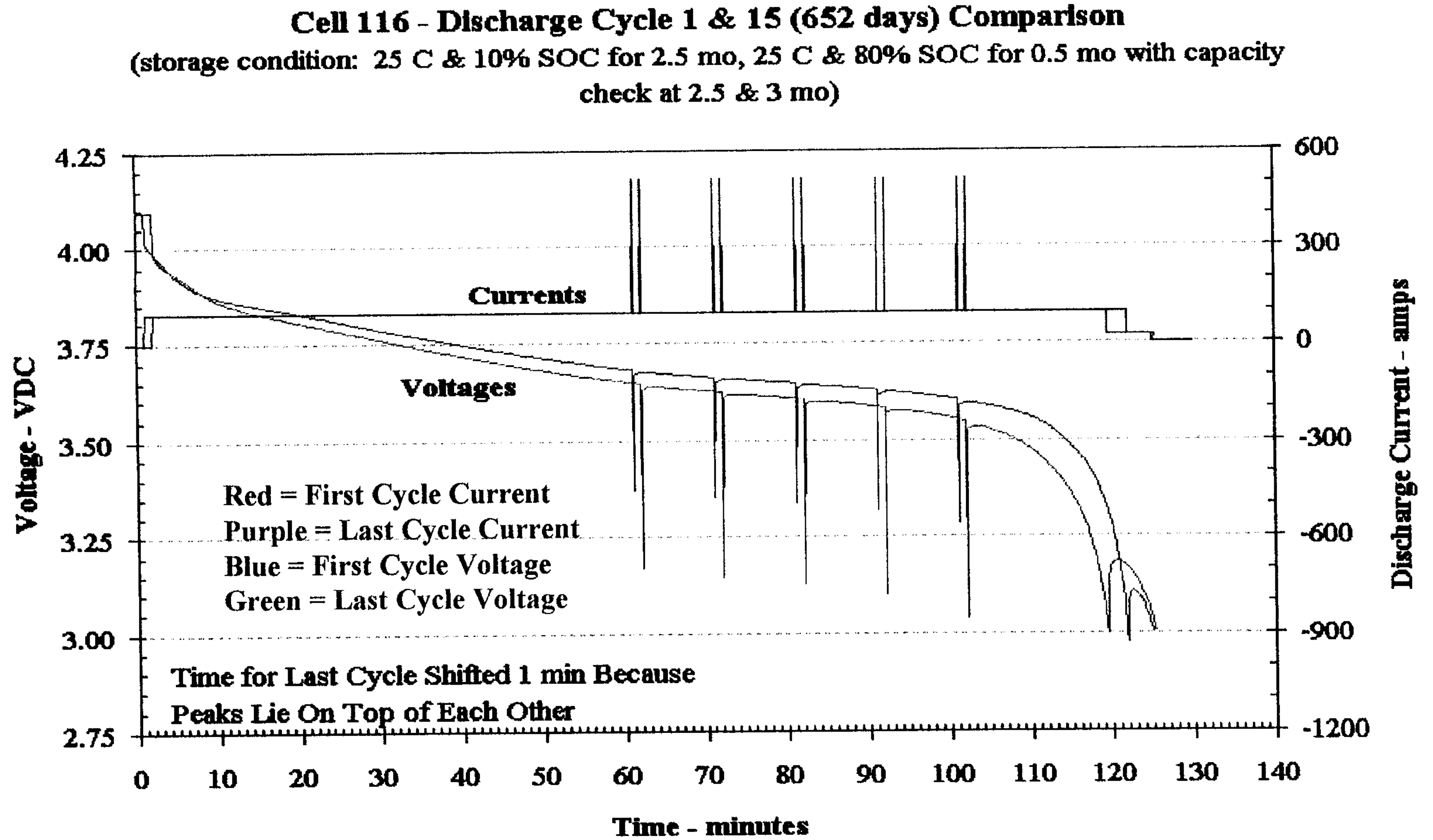
Comparison of Discharges Under Conditions of Ground Storage at 25 °C & 10% SOC

Cell 114 - Discharge Cycle 1 & 21 (650 days) Comparison
(storage condition: 25 C & 10% SOC with capacity check every 30 days)



Judith Jeevarajan/NASA-JSC

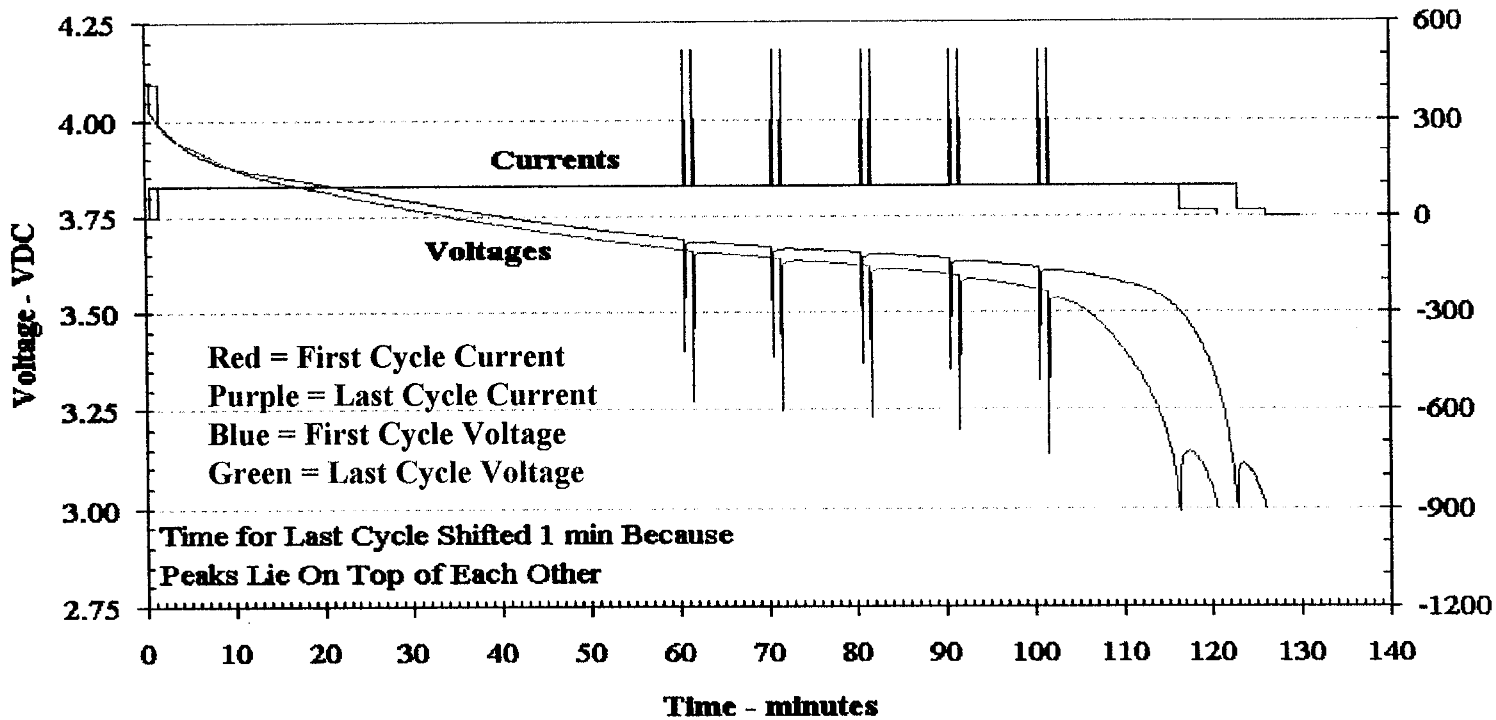
Comparison of Discharges Under Conditions of On-Orbit at 25 °C & 10%/80% SOC



Judith Jeevarajan/NASA-JSC

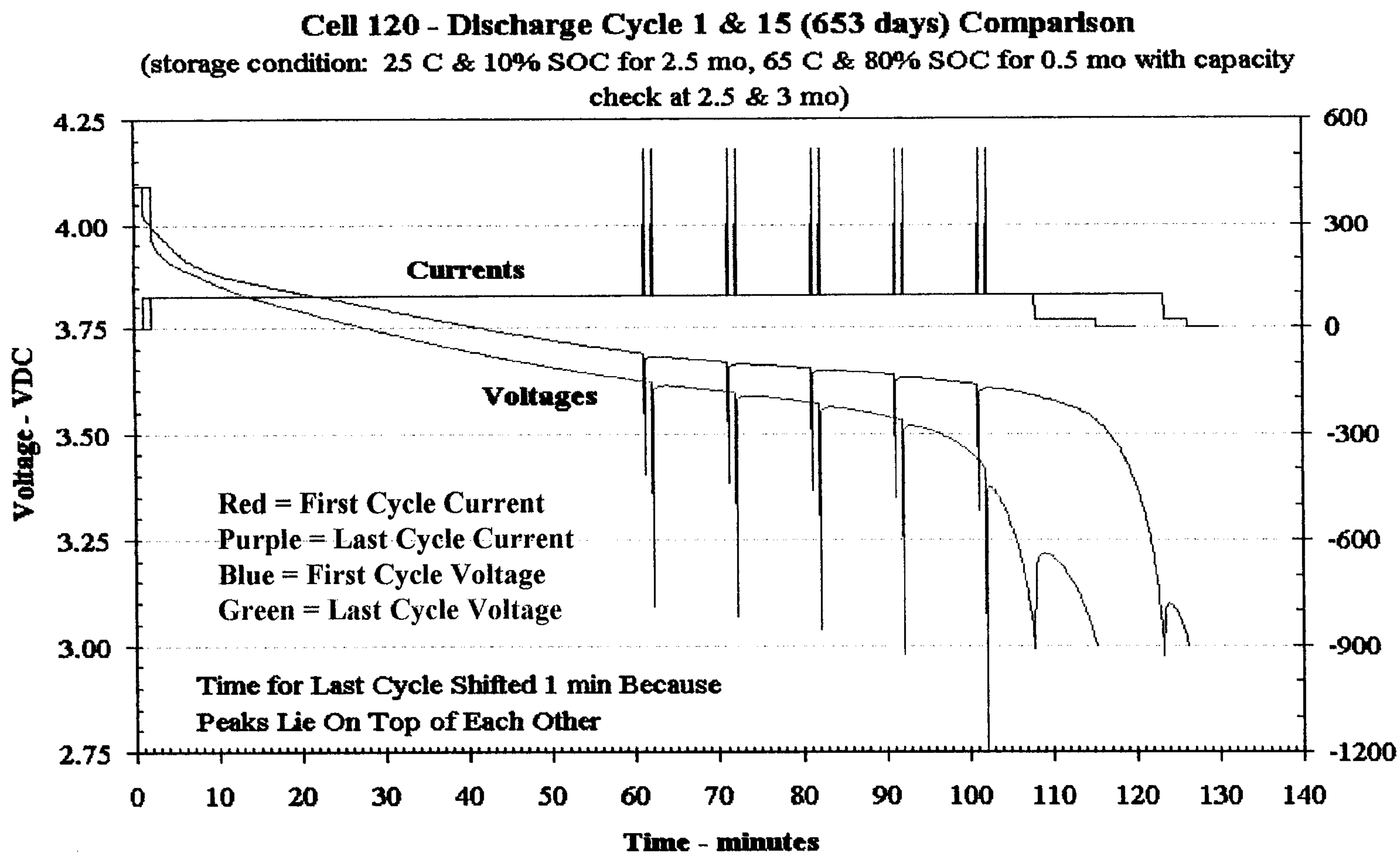
Comparison of Discharges Under Conditions of On-Orbit at 25 °C/40 °C & 10%/80% SOC

Cell 118 - Discharge Cycle 1 & 15 (653 days) Comparison
(storage condition: 25 C & 10% SOC for 2.5 mo, 40 C & 80% SOC for 0.5 mo with capacity check at 2.5 & 3 mo)



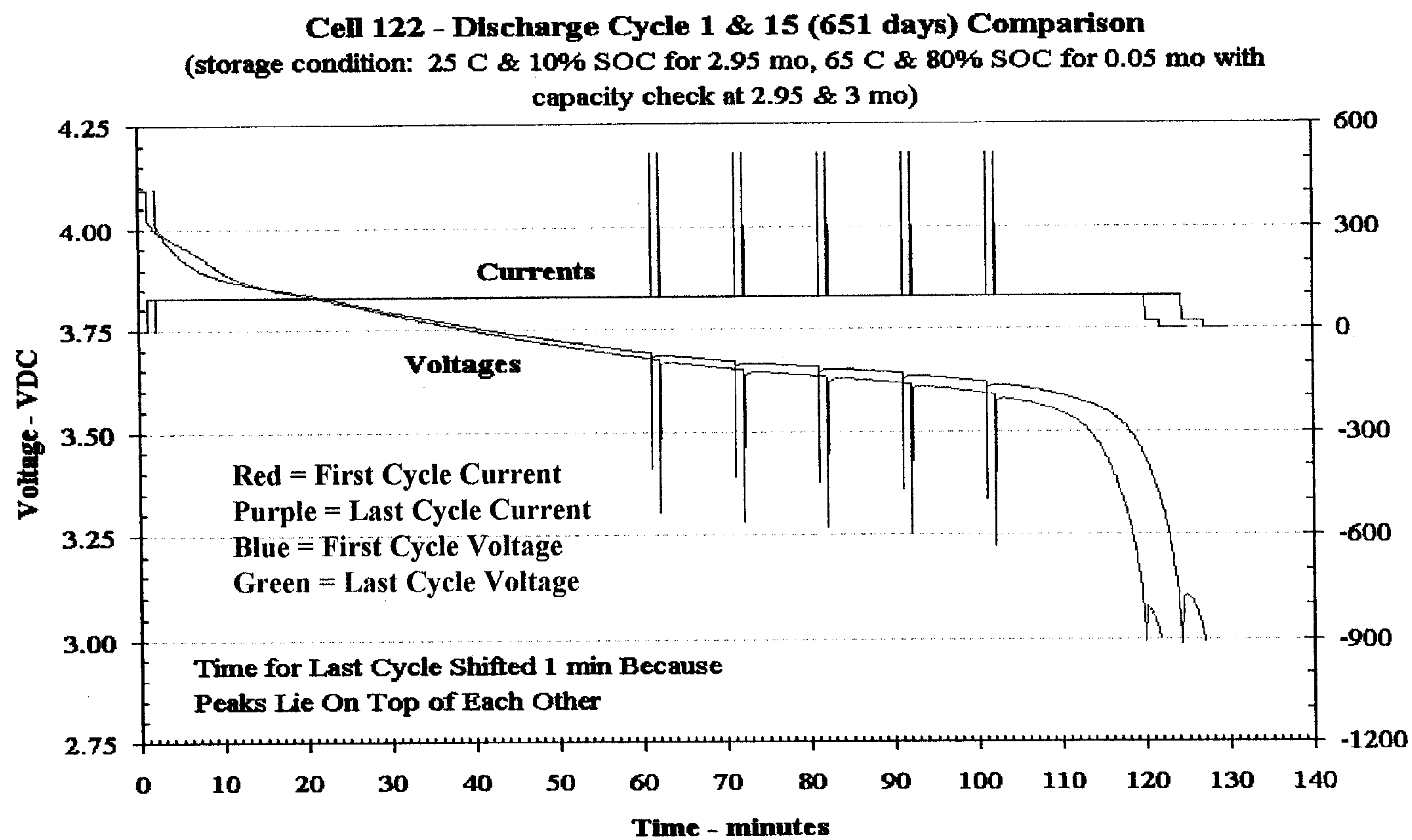
Judith Jeevarajan/NASA-JSC

Comparison of Discharges Under Conditions of On-Orbit at 25 °C/65 °C & 10%/80% SOC



Judith Jeevarajan/NASA-JSC

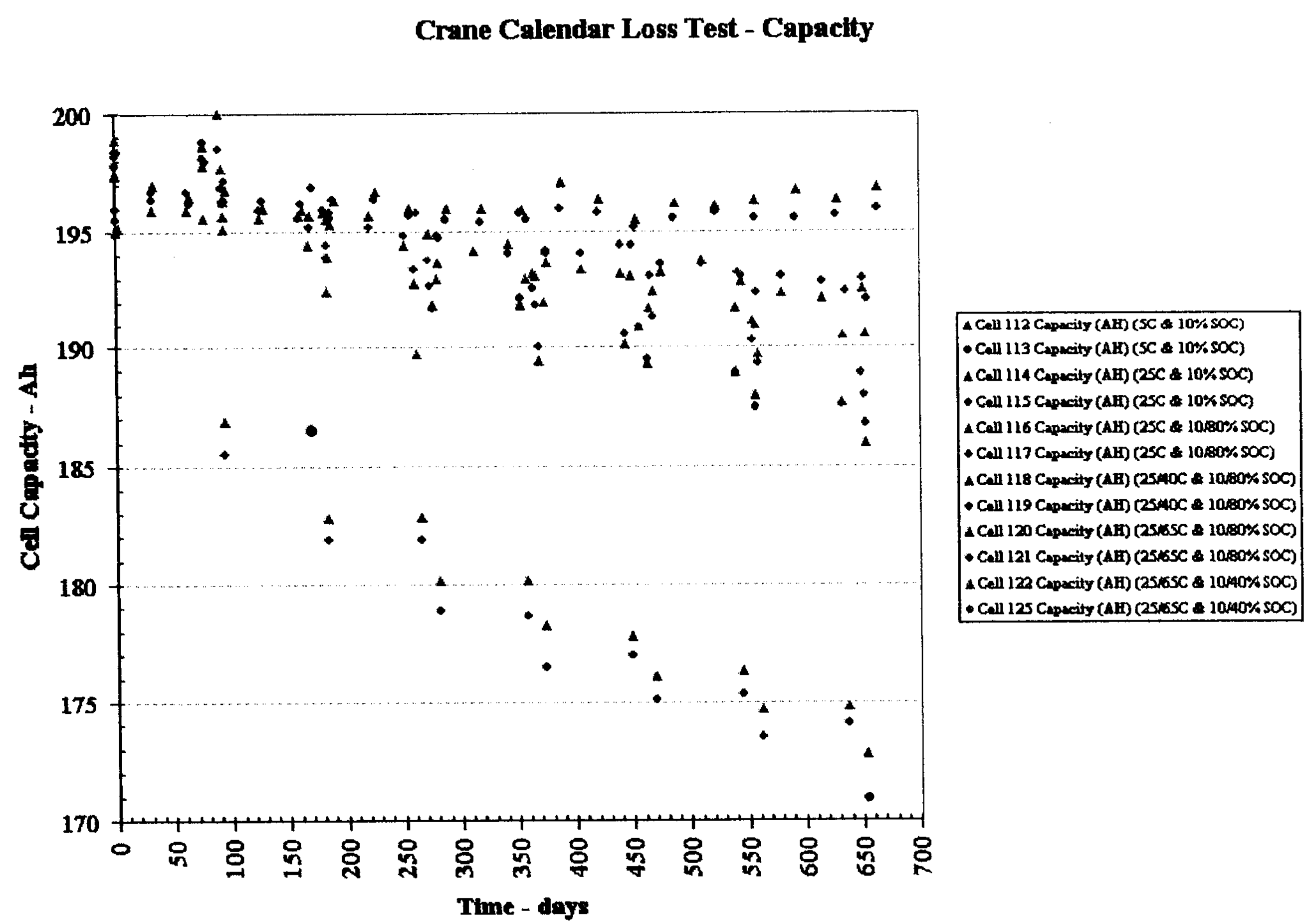
Comparison of Discharges Under Conditions of Post Landing at 25 °C/65 °C & 10%/80% SOC



Judith Jeevarajan/NASA-JSC

Capacity Loss Data

Quantity of Data Points & Differing Starting Points Make These Results for <u>Absolute Capacity</u> Difficult to Interpret

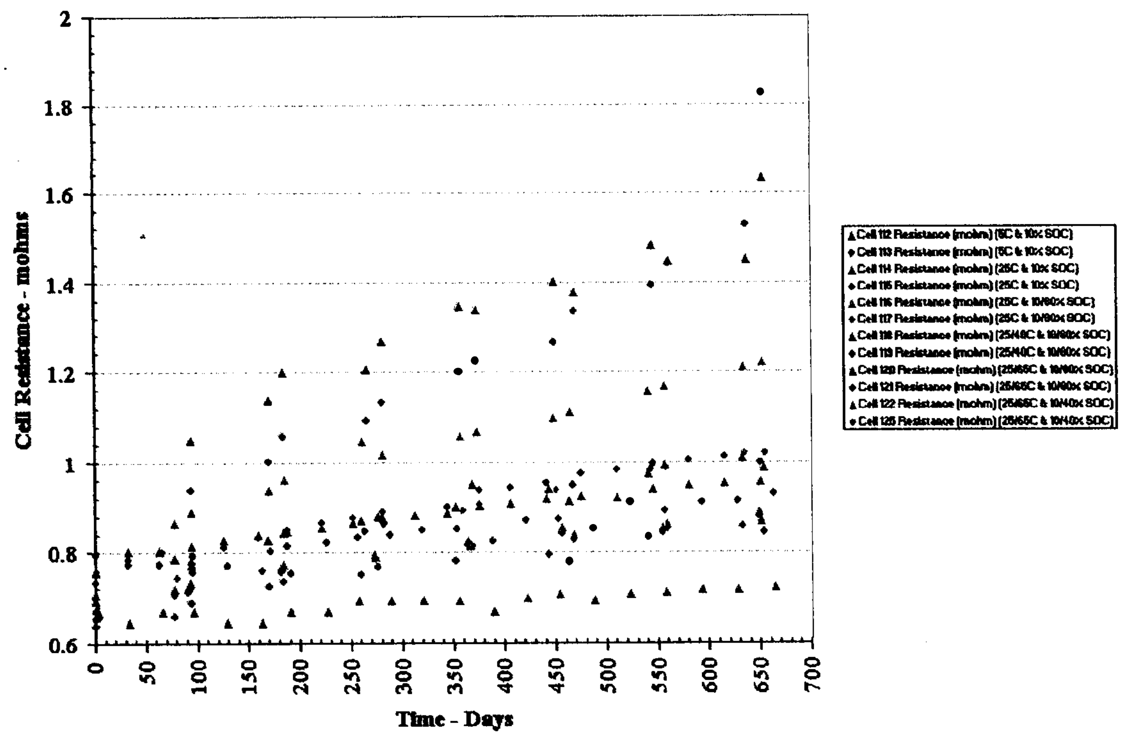


Judith Jeevarajan/NASA-JSC

Resistance Growth

Quantity of Data Points & Differing Starting Points Make These Results for <u>Absolute Resistance</u> Difficult to Interpret

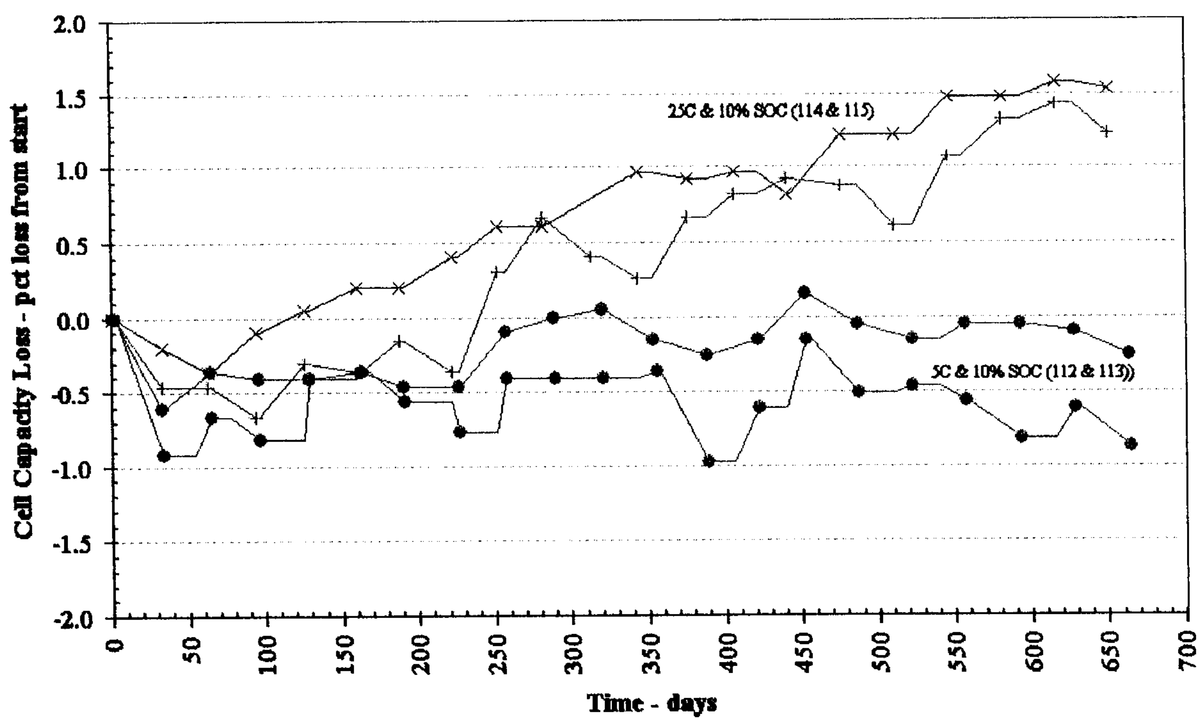
Crane Calendar Loss Test - Resistance



Judith Jeevarajan/NASA-JSC

Capacity Loss – Ground Storage Conditions

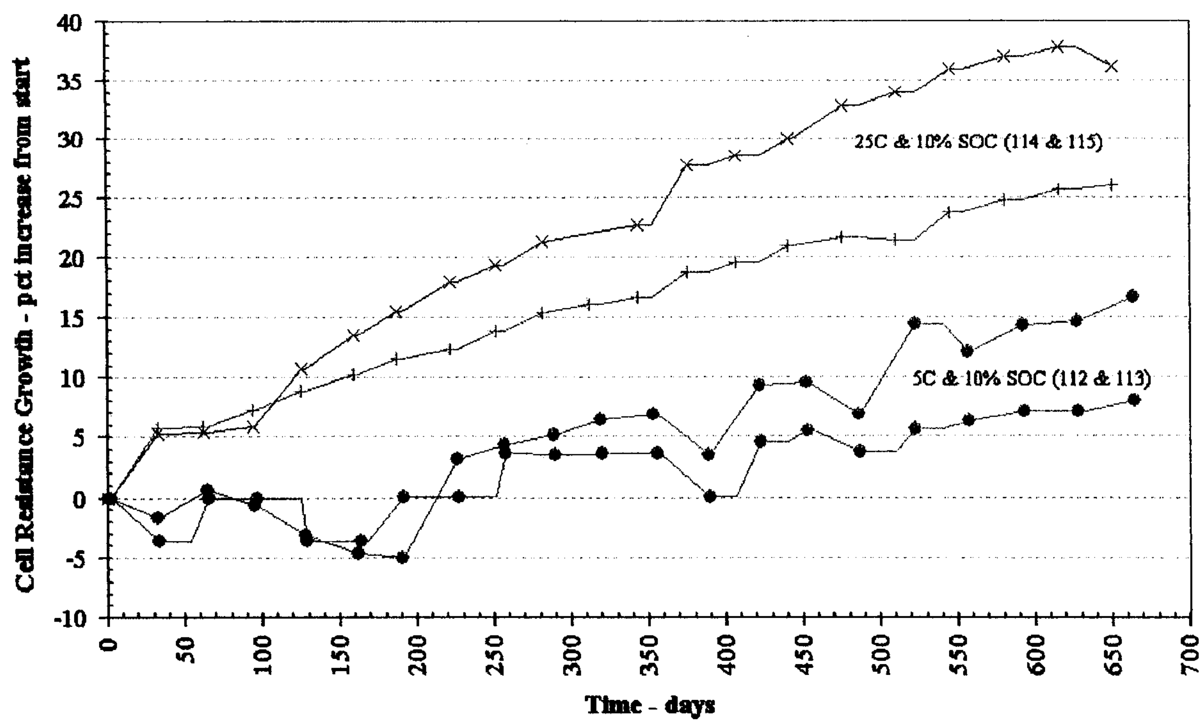
Melco 190 Ah Cell Long Term Capacity Loss (Ground)



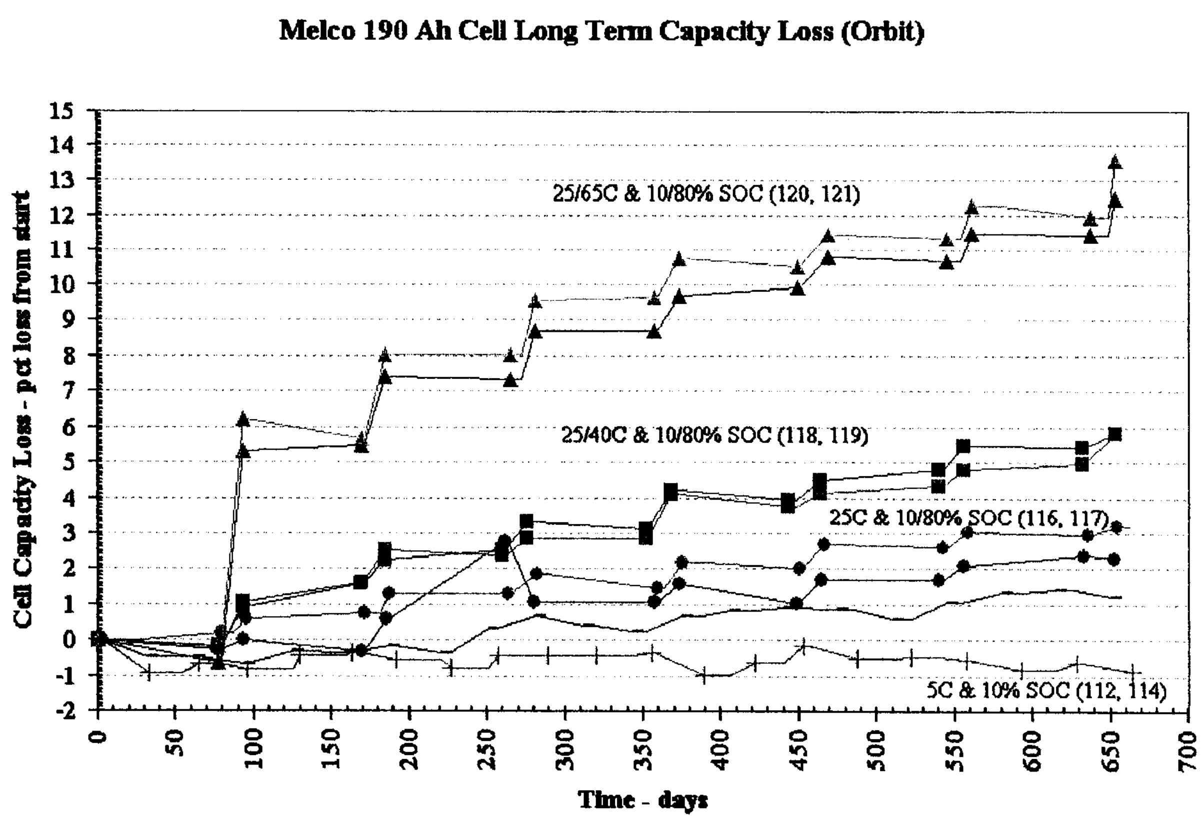
Judith Jeevarajan/NASA-JSC

Resistance Growth – Ground Storage Conditions

Melco 190 Ah Cell Long Term Resistance Growth (Ground)



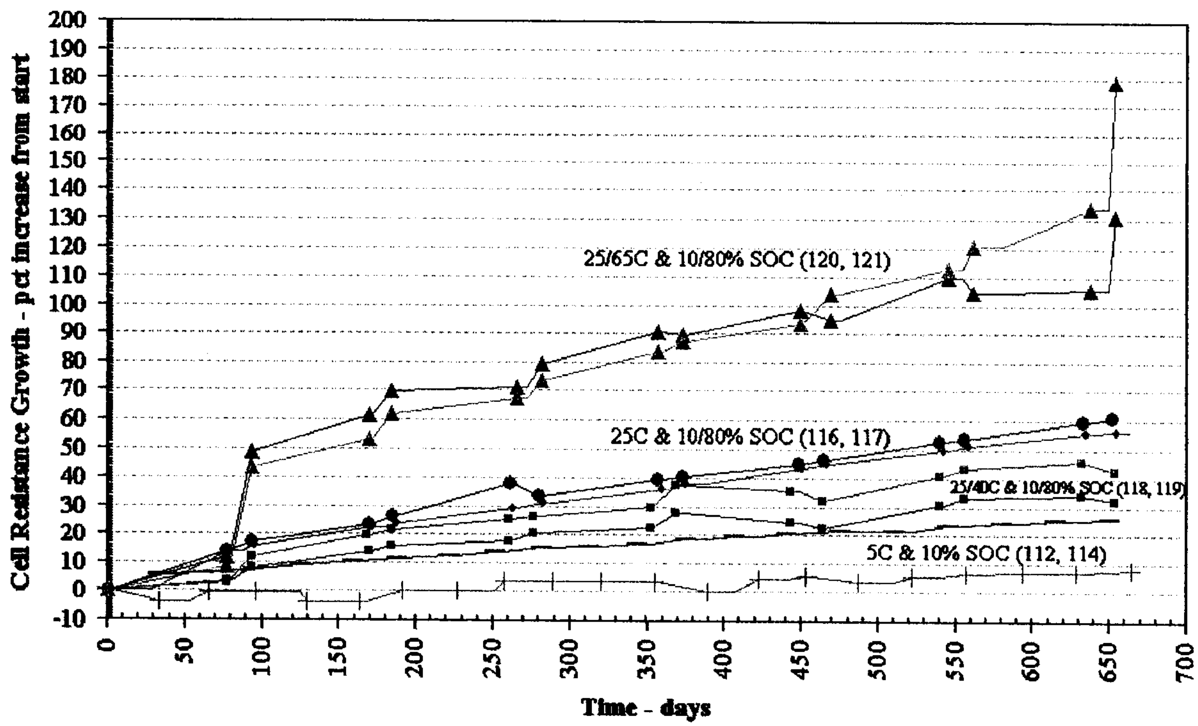
Capacity Loss – On-Orbit Storage Conditions



Judith Jeevarajan/NASA-JSC

Resistance Growth – On-Orbit Storage Conditions

Melco 190 Ah Cell Long Term Resistance Growth (Orbit)



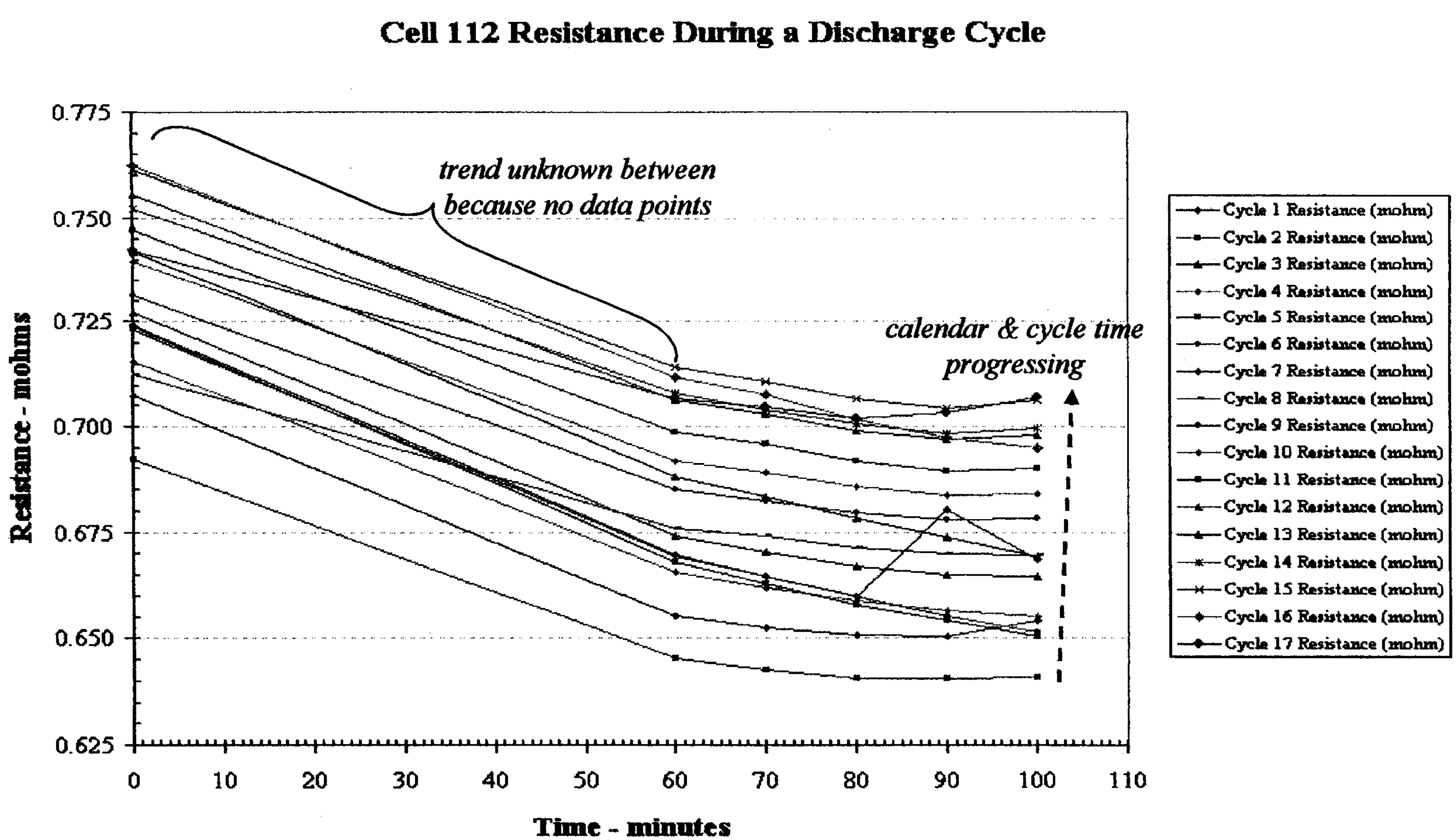
Judith Jeevarajan/NASA-JSC

Resistance During Standard Capacity Cycle Profile

(cells with most benign and most extreme storage conditions)

Mission Resistance – Ground Cold Storage

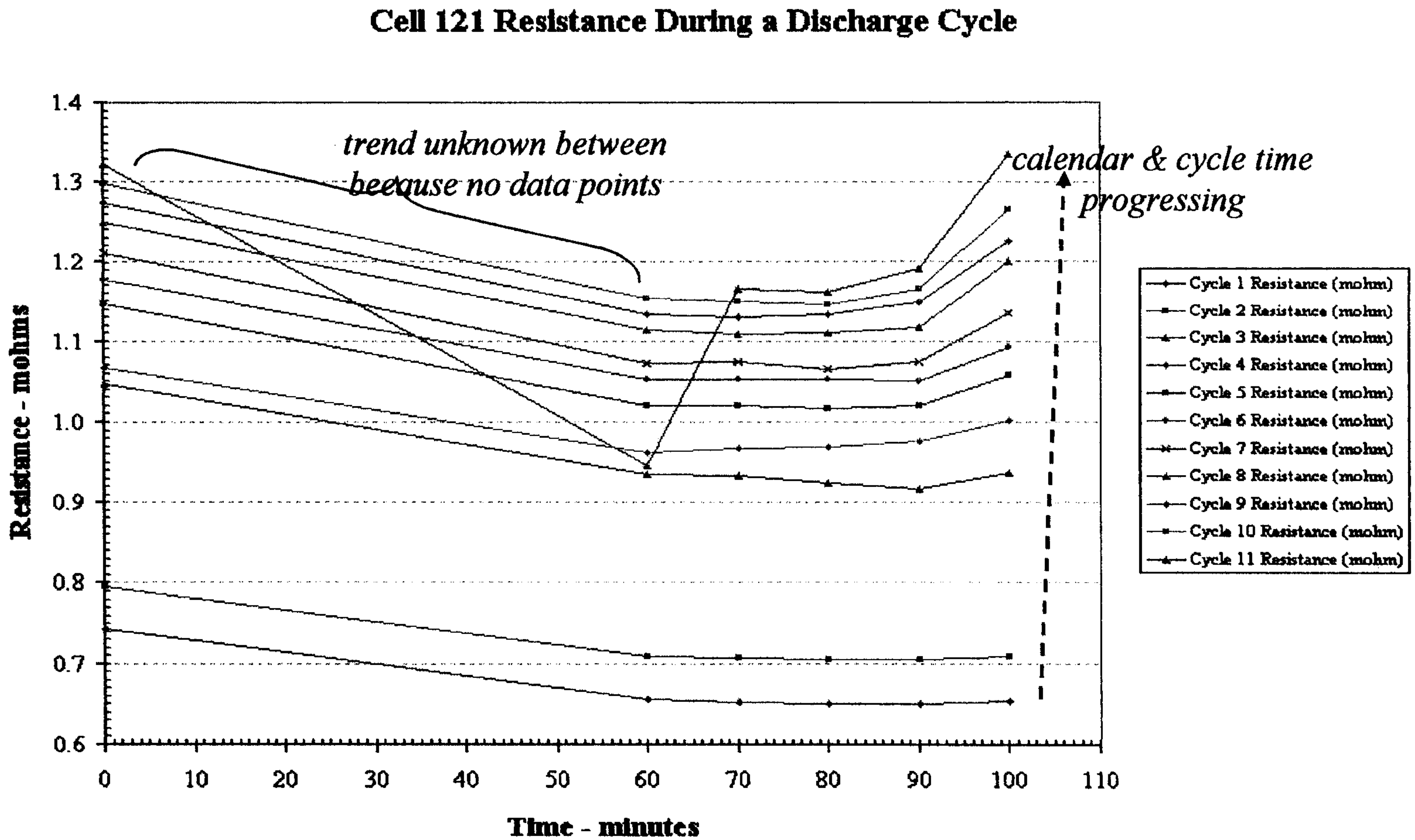
Cell With Most Benign Storage Condition Shows Upward Shifting Curves



Judith Jeevarajan/NASA-JSC

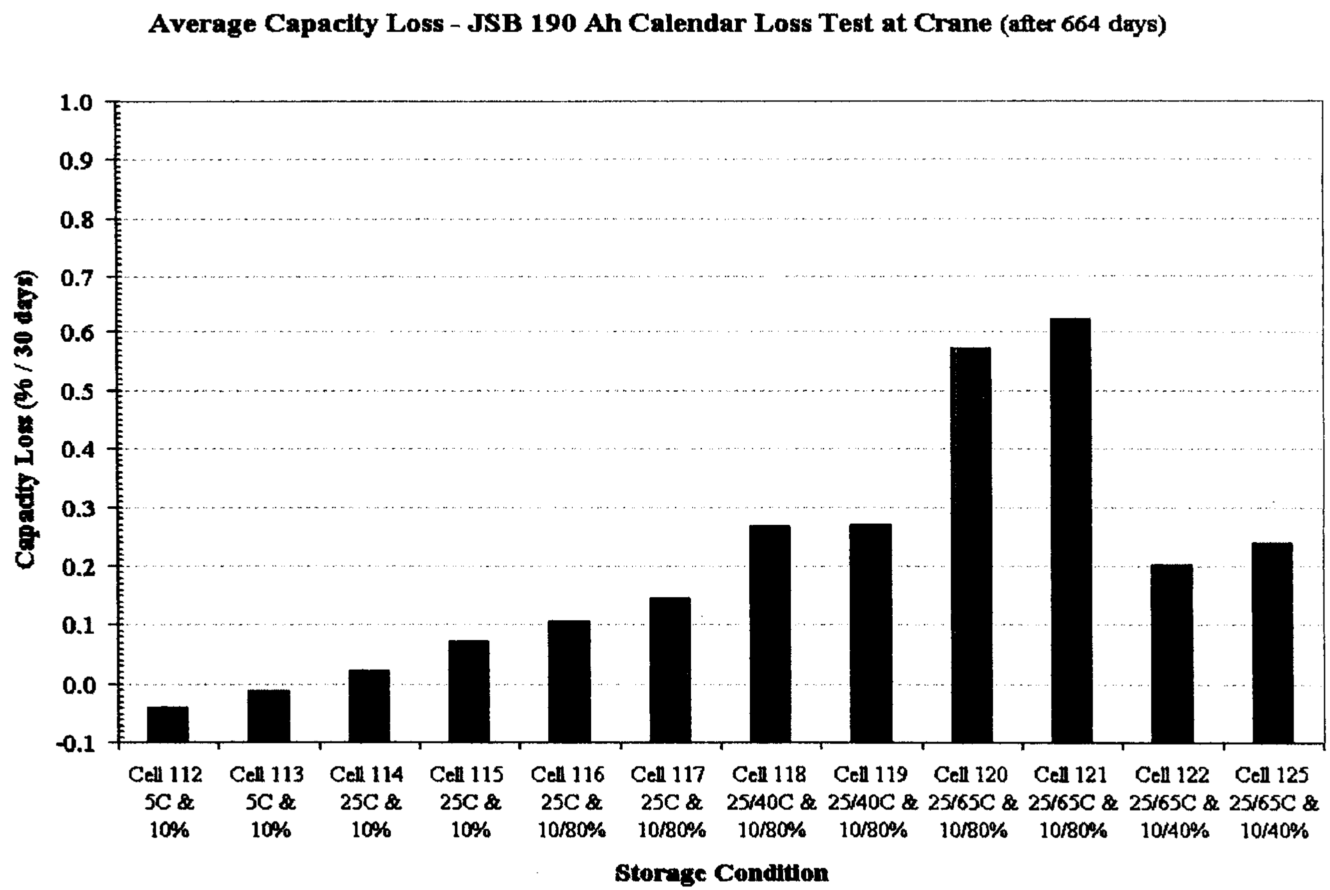
Mission Resistance – Orbit Hot Storage

Cell With Most Extreme Storage Condition Shows Upward Shifting Curves and Rise at End



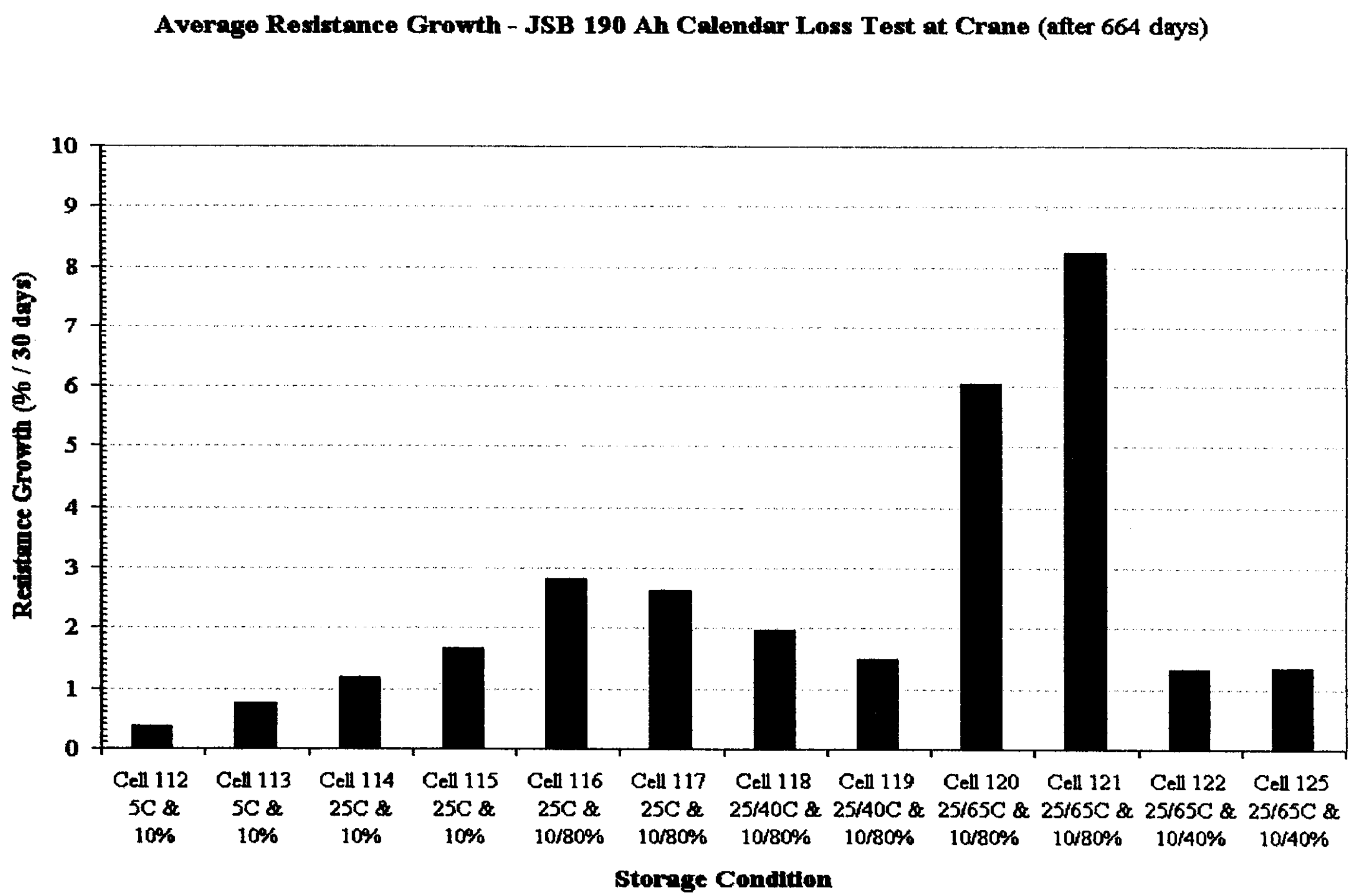
Judith Jeevarajan/NASA-JSC

Summary of Average Capacity Loss



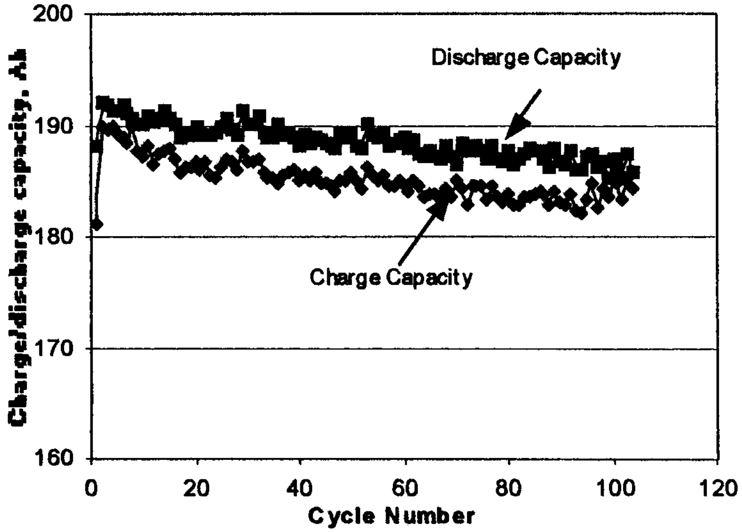
Judith Jeevarajan/NASA-JSC

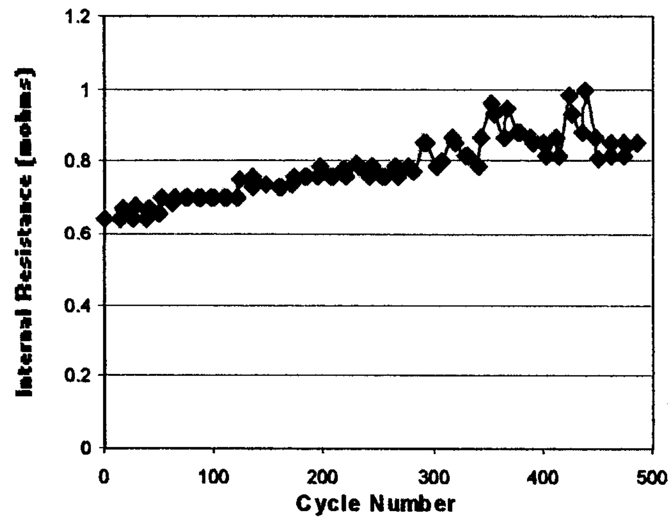
Summary of Average Resistance Growth

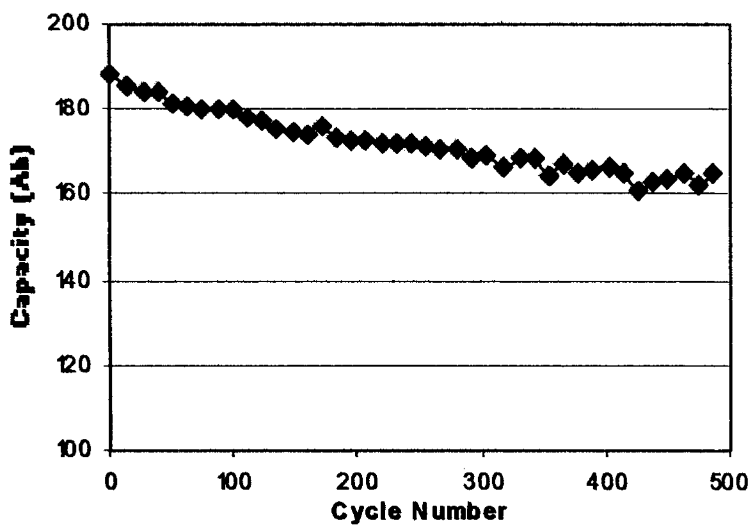


Judith Jeevarajan/NASA-JSC

Results for 190 Ah Cycle Test Conducted at Schlumberger in Rosharon, TX







Judith Jeevarajan/NASA-JSC

Summary of Results

- **Results Excellent for the Orbiter AHPS Application**
- **Mostly Expected Trends with Temperature and State of Charge**
  - Higher Temp and/or Higher SOC Produce More Cell Degradation
- **Cell Capacity Loss Characteristics are Excellent**
- **Cell Resistance Growth Is Greater Than Capacity Loss (% change)**
  - However, Apparent Growth is ~~Results are Really~~ Magnified Because of the ~~Incredibly~~ Low Initial Cell Resistances
- **Comparison with Sizing Model Used to Reduce Needed Cell Size for AHPS Application from 190 Ah to 120 Ah**
  - Measured Capacity Loss is Less Than Model
  - Measured Resistance Growth is More than Model
  - Overall, 120 Ah Sizing Provides Adequate Margin for the AHPS Application 8 Mission, 30 Cycle, 3 year Requirement

Acknowledgment

NSWC in Crane, IN.