

Low Temperature Life-Cycle Testing of a Lithium-Ion Battery for Low-Earth-Orbiting Spacecraft

Concha Reid*

2004 NASA Aerospace Battery Workshop

Marriott - Huntsville

Huntsville, AL

November 16-18, 2004

Abstract

A flight-qualified, lithium-ion (Li-ion) battery developed for the Mars Surveyor Program 2001 Lander is undergoing life-testing at low temperature under a low-Earth-orbit (LEO) profile to assess its capability to provide long term energy storage for aerospace missions. NASA has embarked upon an ambitious course to return humans to the moon by 2015-2020 in preparation for robotic and human exploration of Mars and robotic exploration of the moons of outer planets. Li-ion batteries are excellent candidates to provide power and energy storage for multiple aspects of these missions due to their high specific energy, high energy density, and excellent low temperature performance. Laboratory testing of Li-ion technology is necessary in order to assess lifetime, characterize multi-cell battery-level performance under aerospace conditions, and to gauge safety aspects of the technology. Life-cycle testing provides an opportunity to examine battery-level performance and the dynamics of individual cells in the stack over the entire life of the battery. Data generated through this testing will be critical to establish confidence in the technology for its widespread use in manned and unmanned missions. (Cont.)

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Abstract (cont.)

This paper discusses the performance of the 28 volt, 25 ampere-hour battery through 6000 LEO cycles, which corresponds to one year on LEO orbit. Testing is being performed at 0 °C and 40% depth-of-discharge. Individual cell behaviors and their effect on the performance of the battery are described. Capacity, impedance, energy efficiency and end-of-discharge voltage at 1000 cycle intervals are reported. Results from this life-testing will help contribute to the database on battery-level performance of aerospace Li-ion batteries and low temperature cycling under LEO conditions.

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Background

- Life cycle data of lithium-ion cell chemistry is critical to continue to establish life and validate technology for flight programs
- Battery level testing is required in addition to individual cell level testing
- The current NASA goal for lithium-ion technology for low-Earth-orbit (LEO) is 30,000 cycles, the equivalent of about five years on orbit
- The test battery was designed, built and flight-qualified for the Mars 2001 Surveyor Program Lander
- 5 flight-qualified batteries became available for testing after the cancellation of the flight program
- Provided a unique opportunity to perform laboratory life-cycle testing on flight hardware



Battery Characteristics

- Vendor: Yardney Technical Products
- Lithium-ion liquid electrolyte chemistry
- Prismatic cell design
- 25 ampere-hours
- 28 Volts
- 8 series-connected cells



2001 Mars Surveyor Program Lander Batteries.

Two 8-cell battery stacks and connectors are shown. The unusual orientation of the stacks in this battery assembly was driven by the volume constraints of the Lander.

Coordinated Testing Effort of the Five Batteries among Multiple Organizations

- Four test organizations
 - NASA Glenn Research Center
 - LEO testing at 0 °C
 - NASA Jet Propulsion Lab (JPL)
 - LEO testing at 20 °C (first battery)
 - Mission Simulation testing (second battery)
 - Air Force Research Lab (AFRL)
 - LEO testing at 23 °C
 - Naval Research Lab (NRL)
 - Geosynchronous-Earth-orbit (GEO) testing

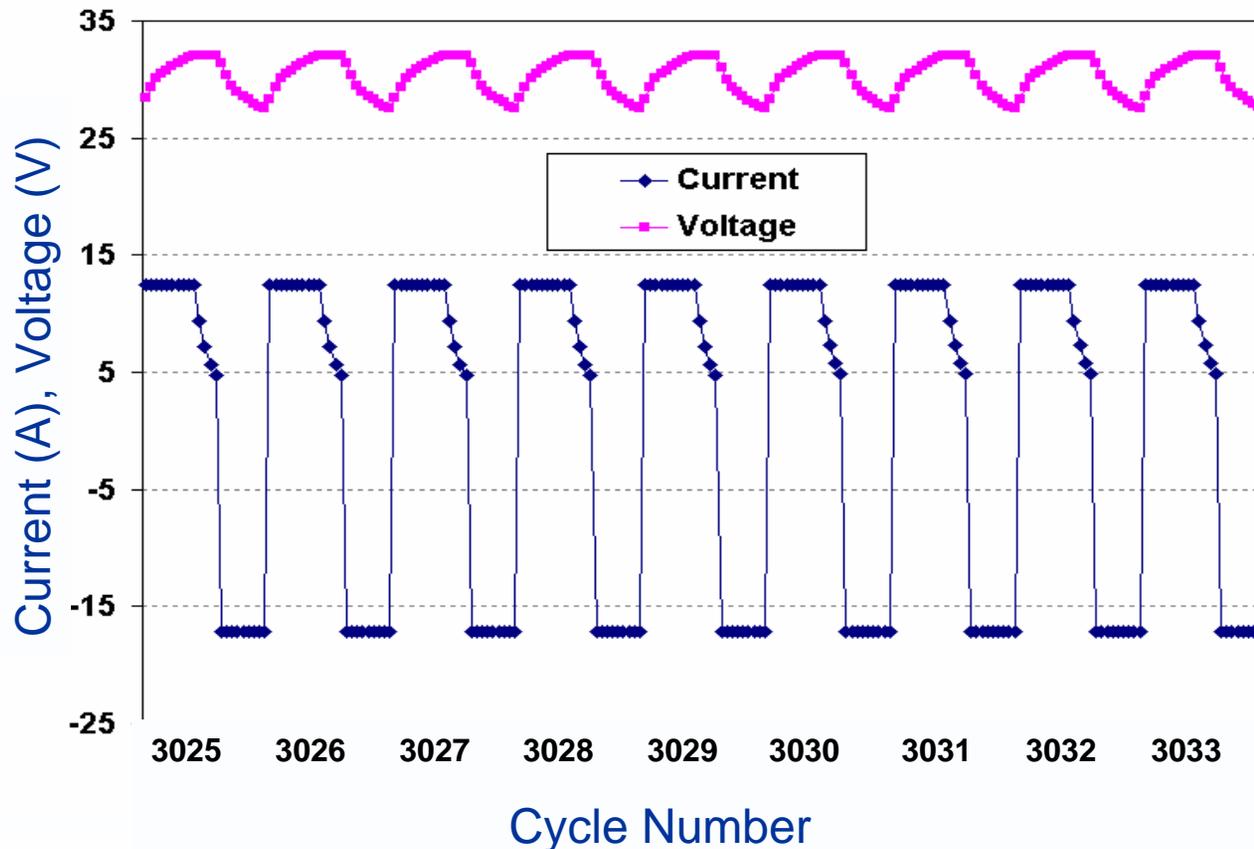
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LEO Cycling at 0 °C

Charge at C/2 (12.5 A) to 32 V battery voltage or 4.05 V on any cell.
Taper for the remainder of the 55 minute charge period.
Discharge at 17.14 A (40% DOD) for 35 minutes or 2.5 V on any cell.



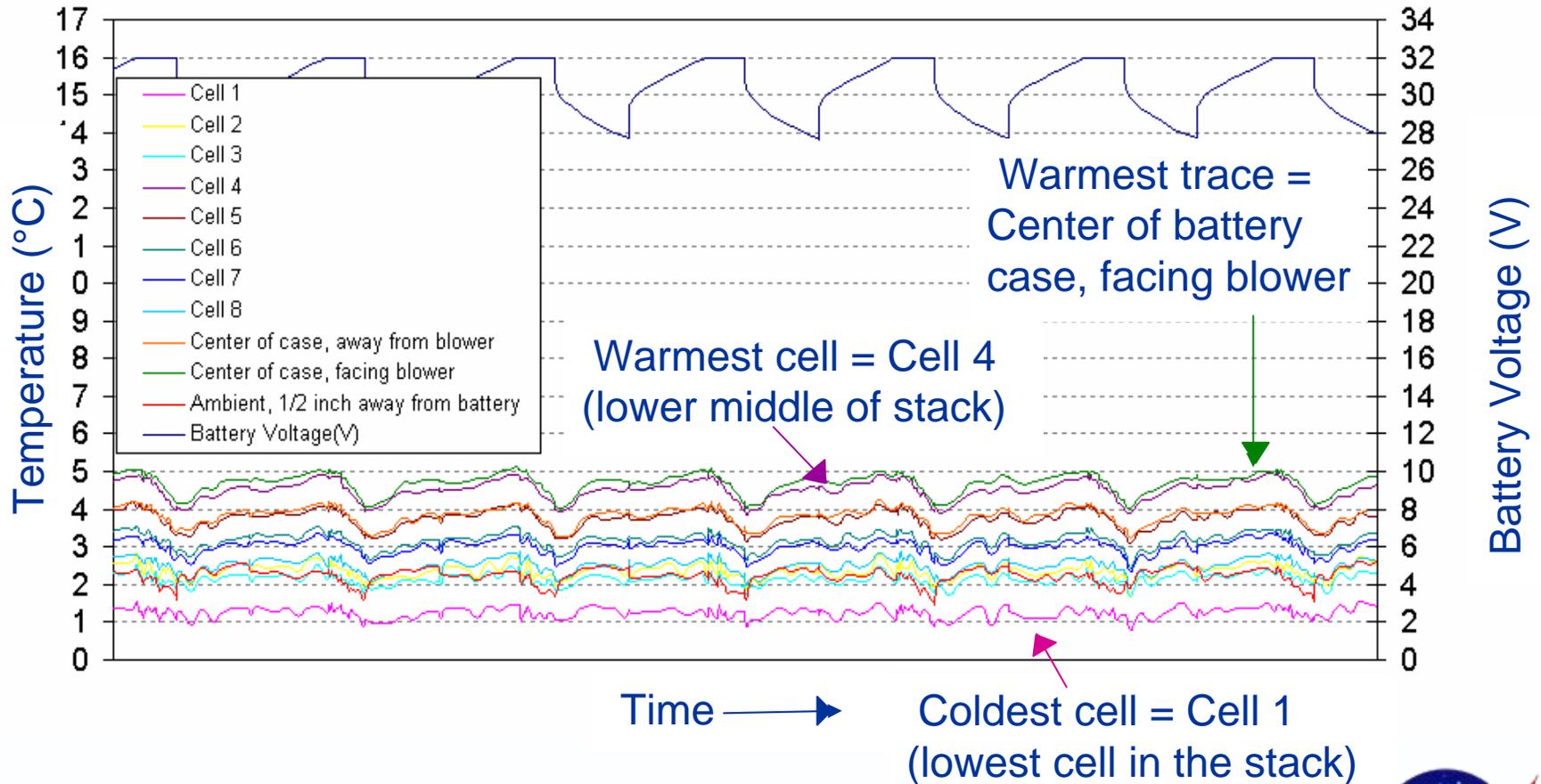
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Temperature Profile during LEO Cycling

Environmental chamber is set at 0 °C

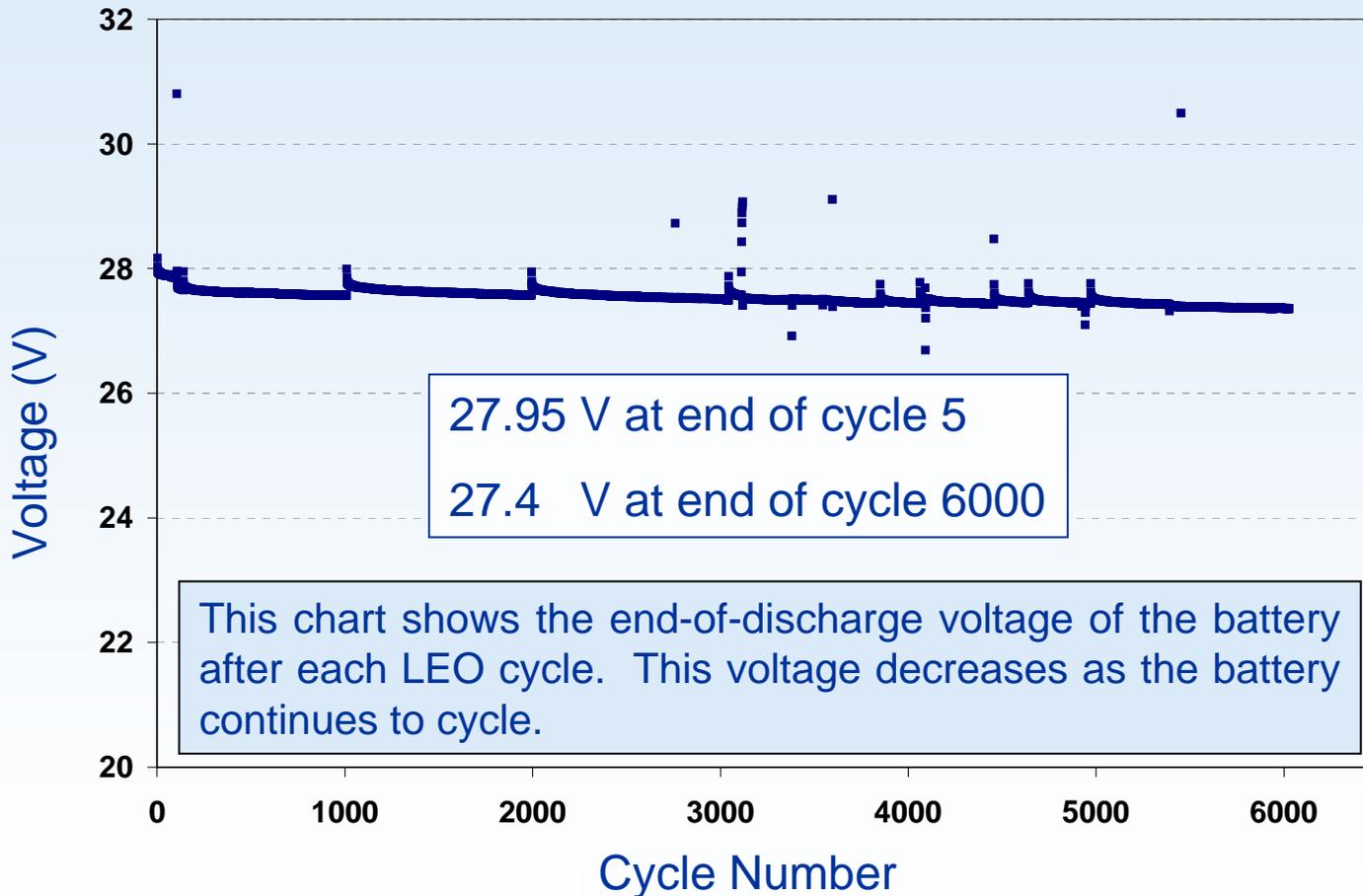


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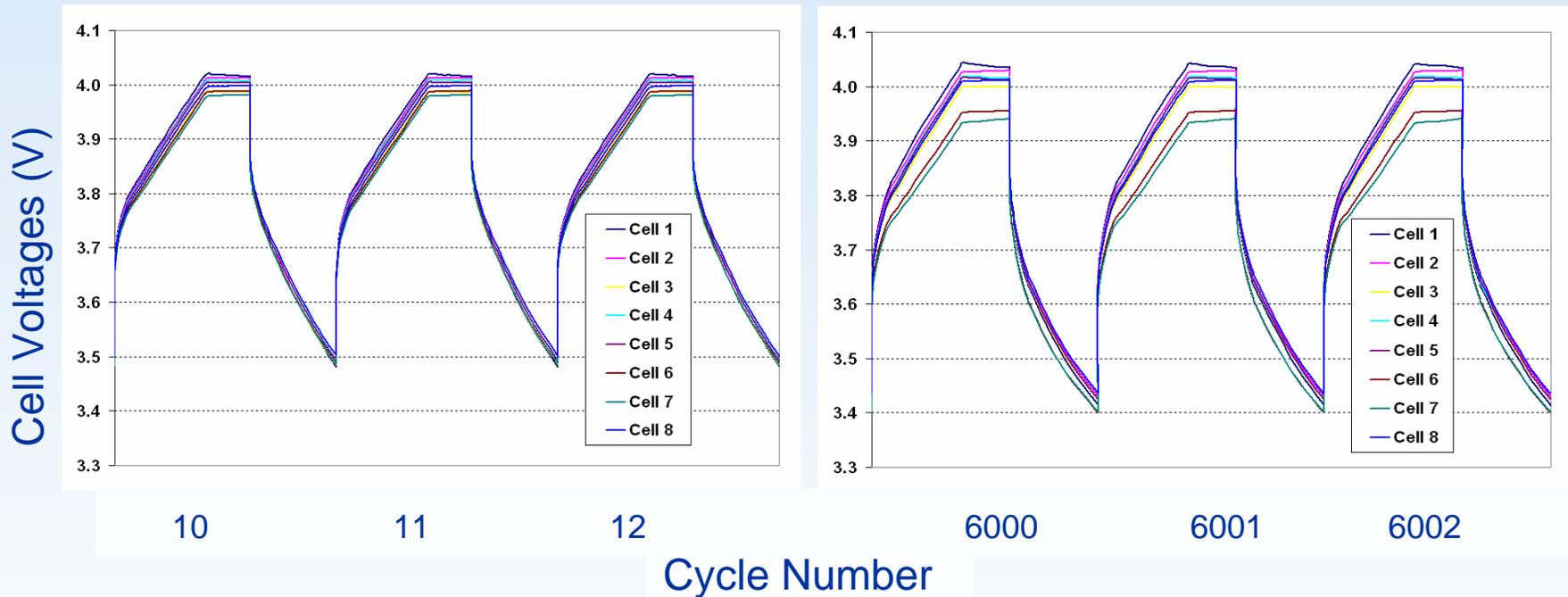
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End-of-Discharge Voltage



Cell Voltages During LEO Cycling



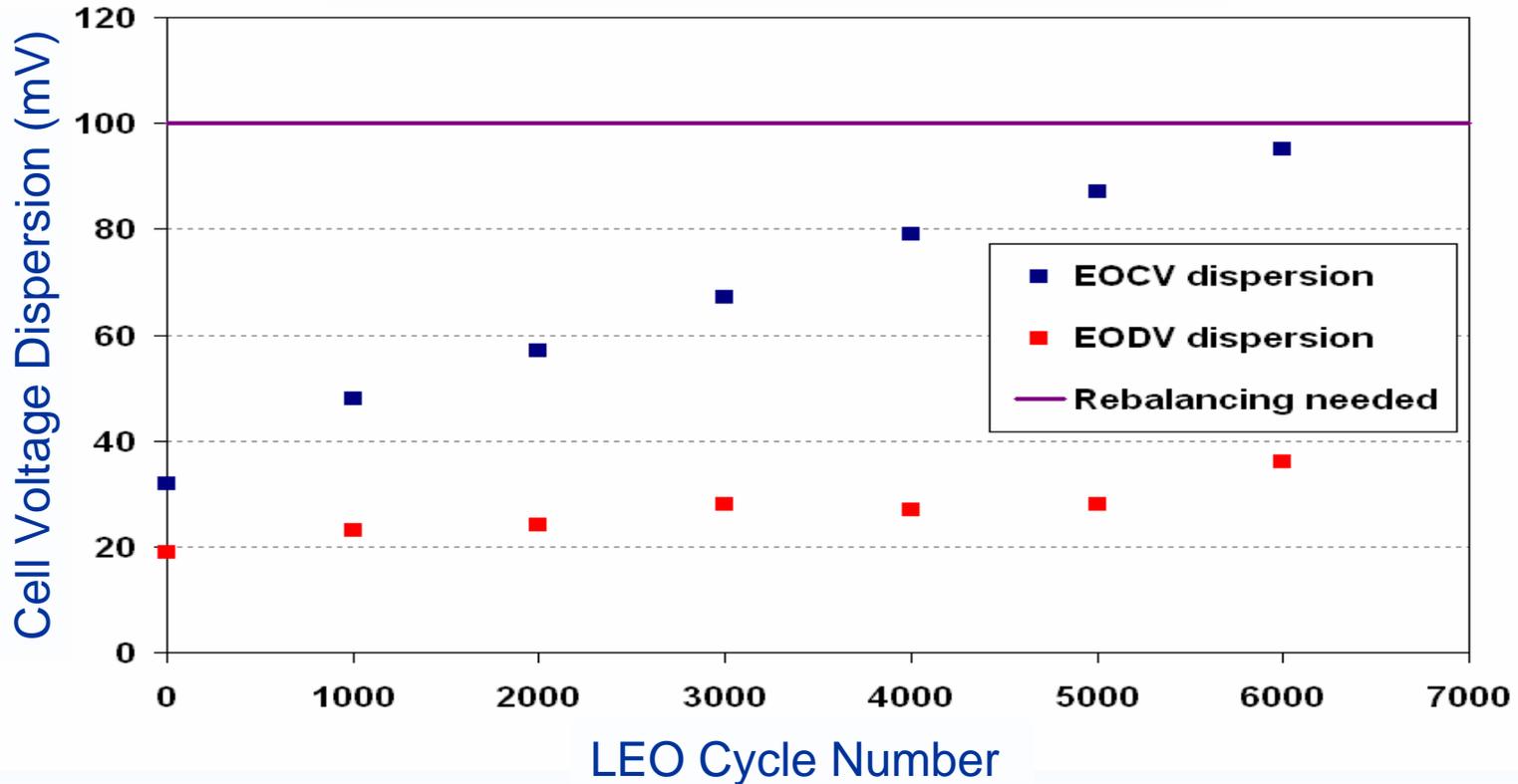
This chart shows the individual cell voltages versus time during LEO cycling near the beginning of life and at 6000 cycles. At the beginning of life, the cell voltages are operating tightly together and average 3.5 V at the end of discharge. After 6000 cycles without cell balancing, the cell voltages are separating, with cells 6 and 7 never achieving full charge. However, the battery voltage is still driving the length of the constant current charge period. The end-of-discharge cell voltages average 3.42 V at 6000 cycles.

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Cell Voltage Dispersion Trends

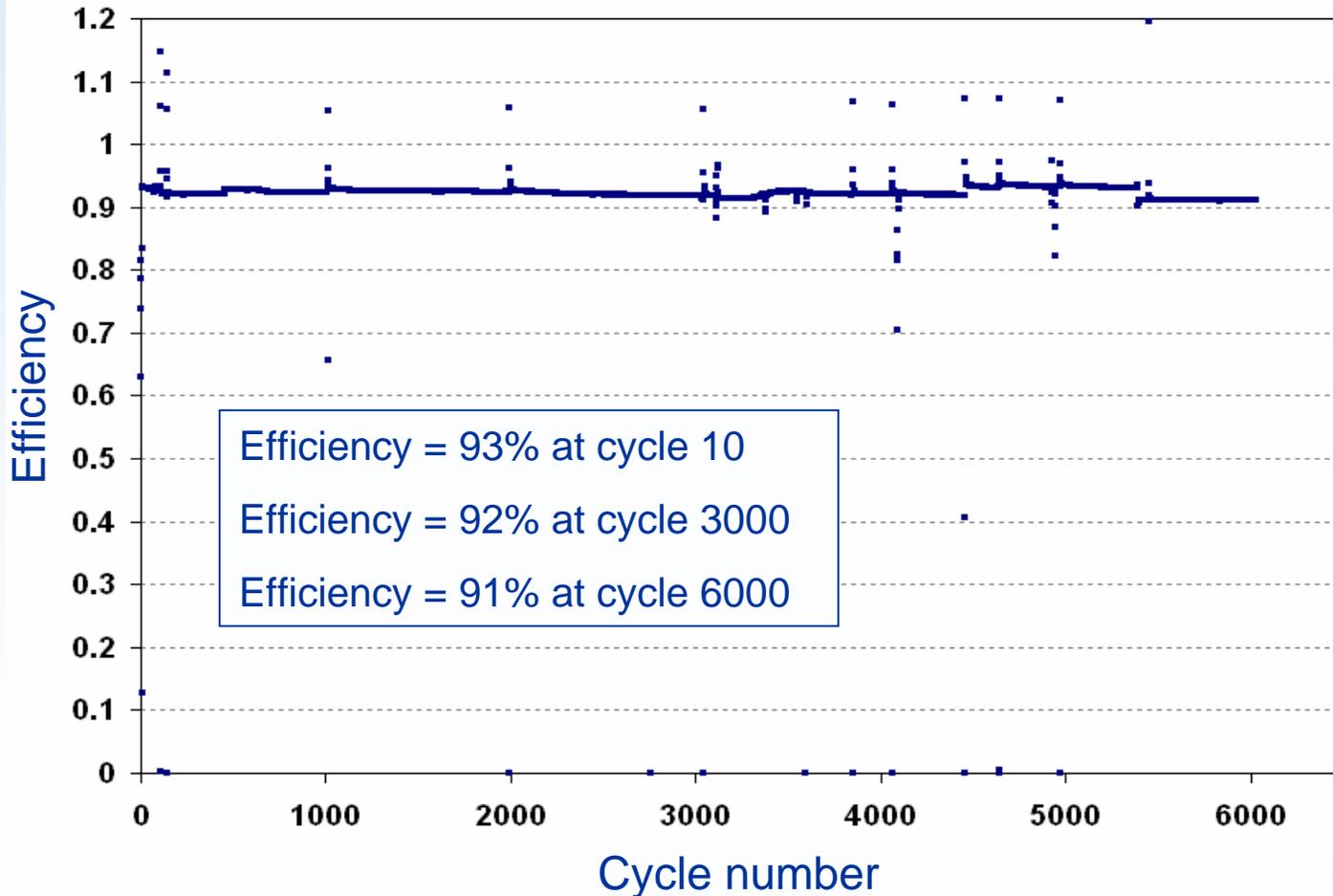


The end-of-charge (EOCV) and end-of-discharge (EODV) cell voltage dispersions are 95 mV and 36 mV, respectively, at the end of 6000 cycles. Rebalancing will be performed when EOCV voltage dispersion is 100 mV or EODV voltage dispersion is 80 mV.

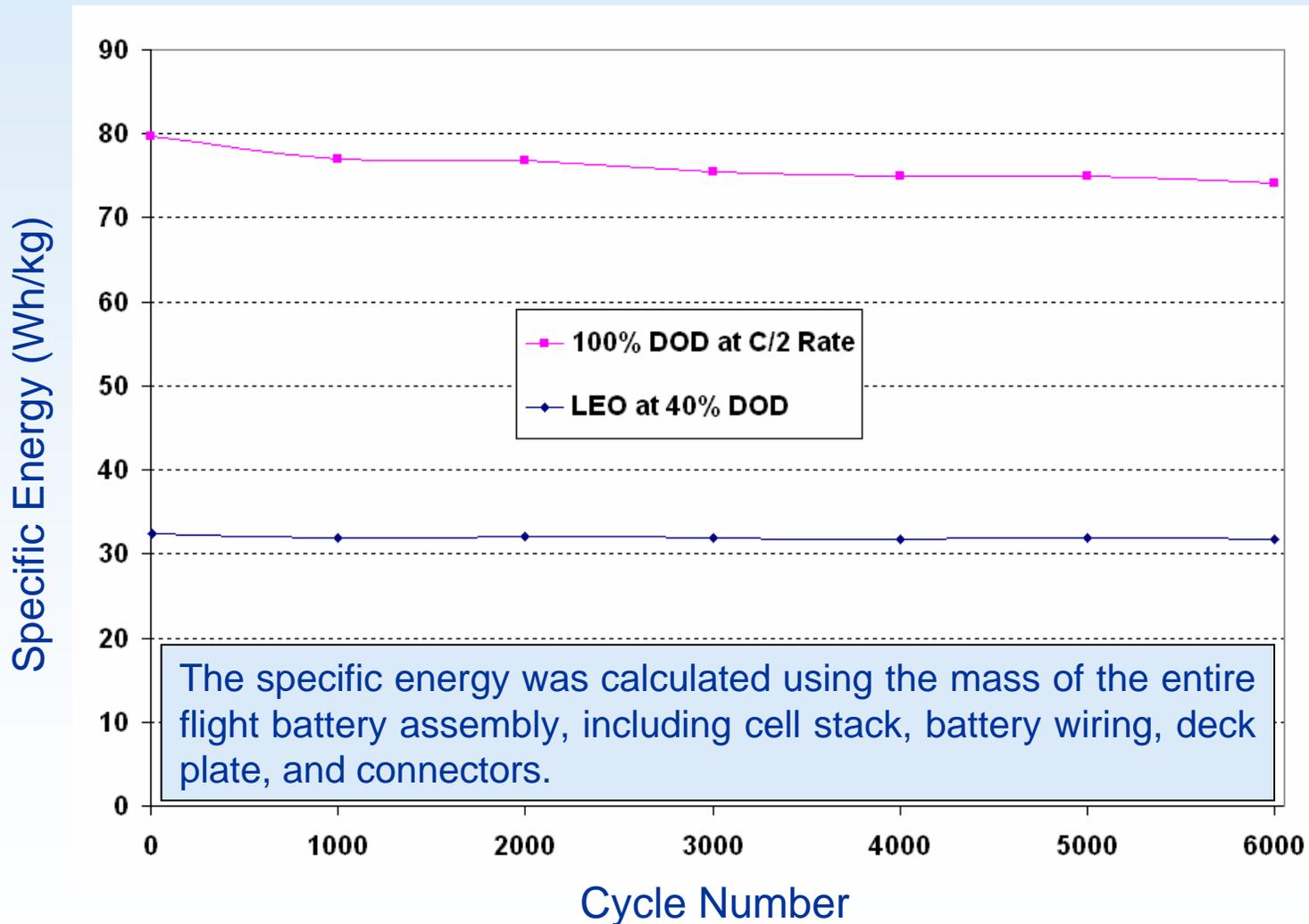


Energy Efficiency

(during LEO cycling at 40% DOD)



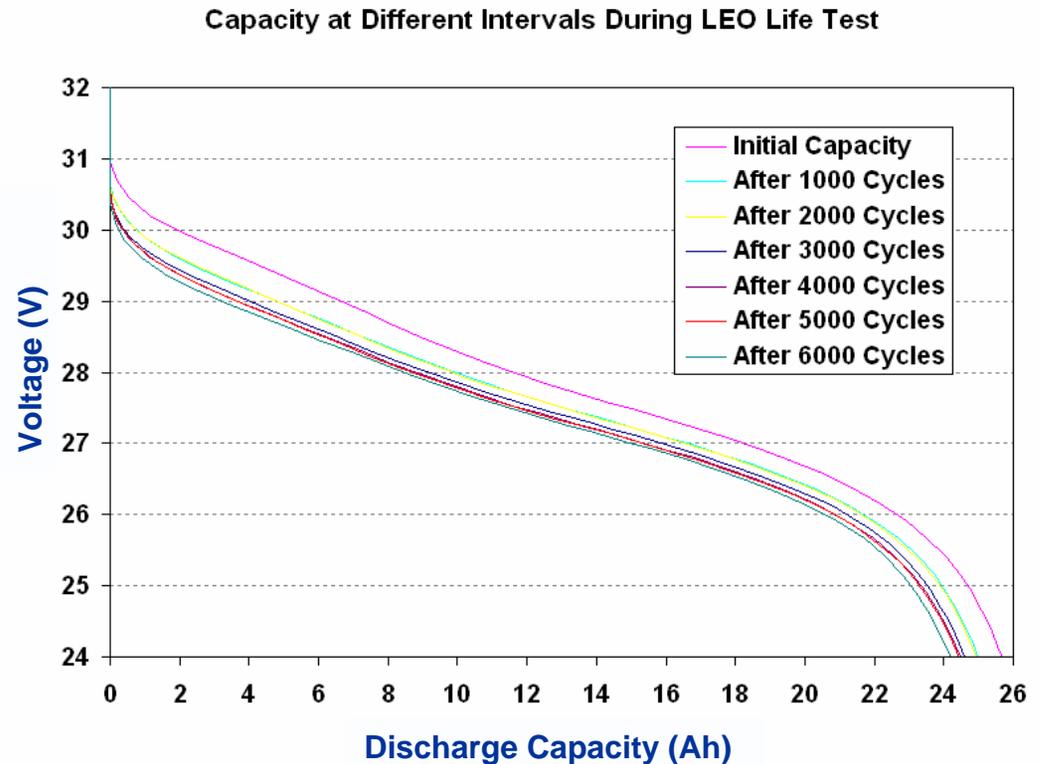
Specific Energy at 40% and 100% DOD



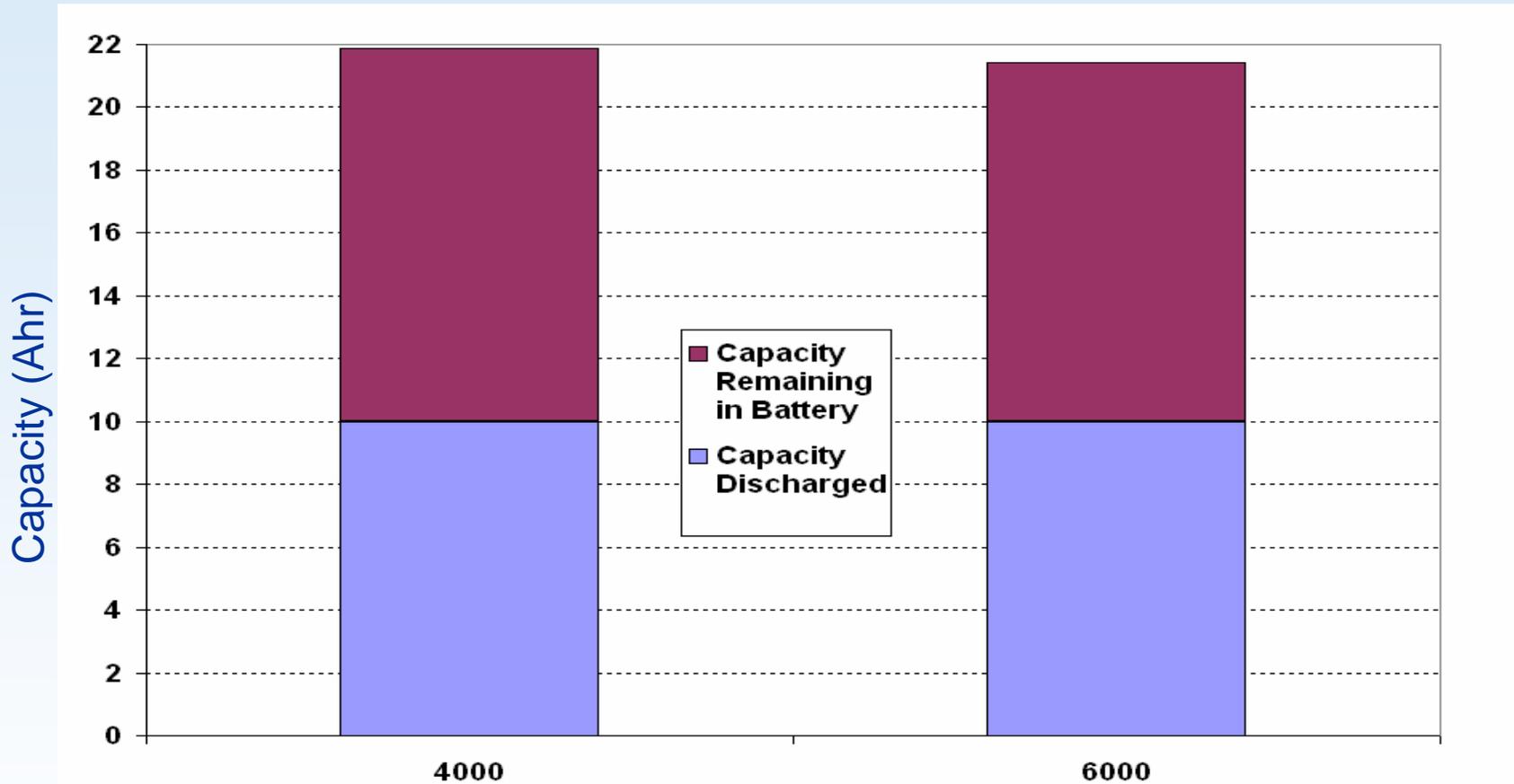
100% DOD Capacity Test Results at 0 °C

- Charge at C/2 to 32 V or until the first cell reaches 4.05 V, allow current to taper to C/50
- Discharge at 0.7C (40% DOD rate) to 24.0 V or until the 1st cell reaches 2.5 V

Interval (after X cycles)	Capacity (AH)	% of Initial Capacity
Initial	25.7	100
1000	25.0	97
2000	24.9	97
3000	24.6	96
4000	24.5	95
5000	24.5	95
6000	24.2	94



Capacity Remaining in Battery after LEO Cycling



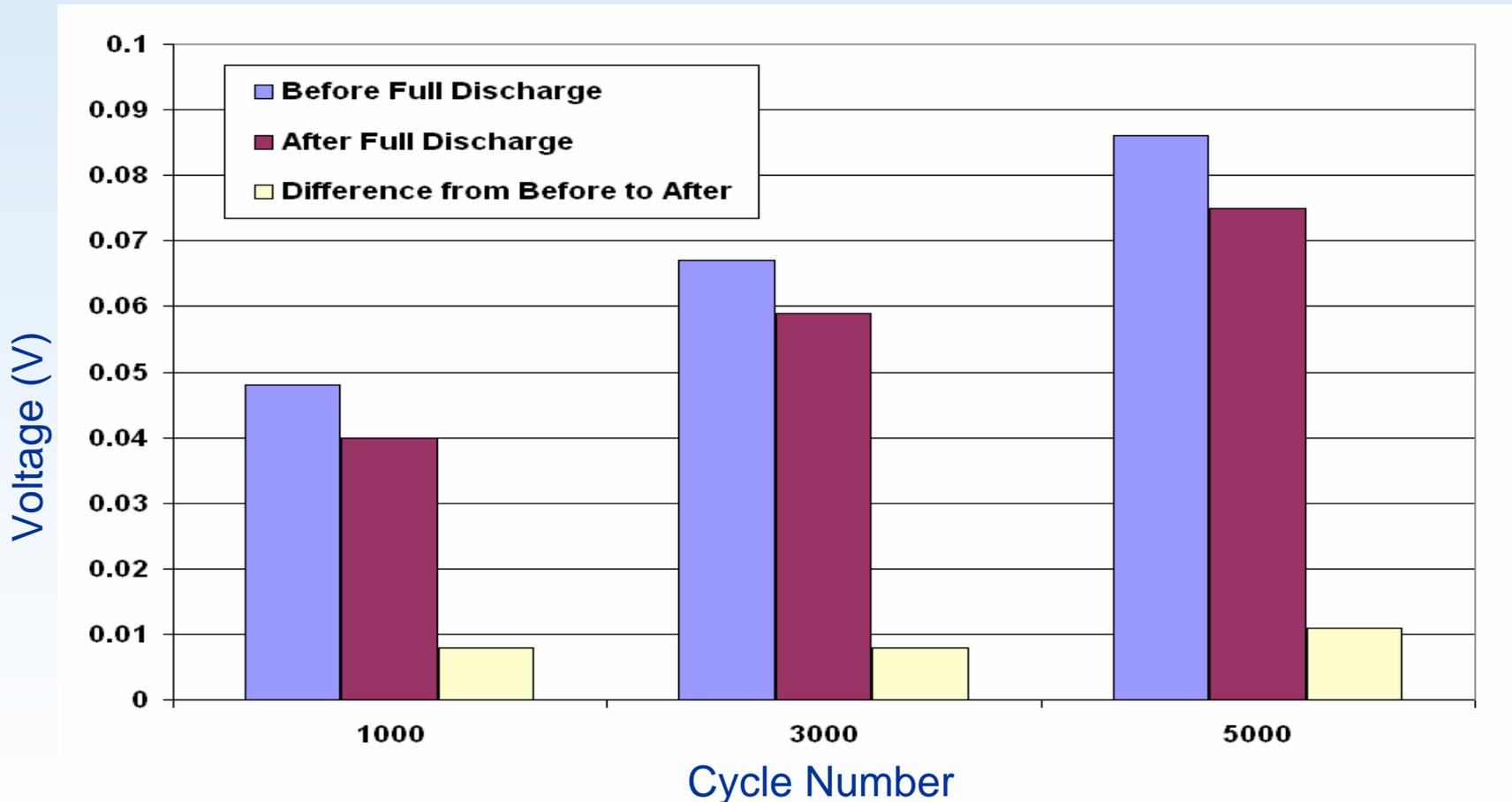
For this test program, 10 Ahrs are removed from the battery with each LEO discharge cycle. At 1000 cycle intervals, after the typical 10 Ahrs have been removed, the battery is allowed to continue discharging at the same rate until the battery voltage reaches 24 volts. 11.9 additional Ahrs were removed at 4000 cycles; 11.4 Ahrs were removed at 6000 cycles.

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Effect of Capacity Checks on Cell Voltage Dispersion on Charge



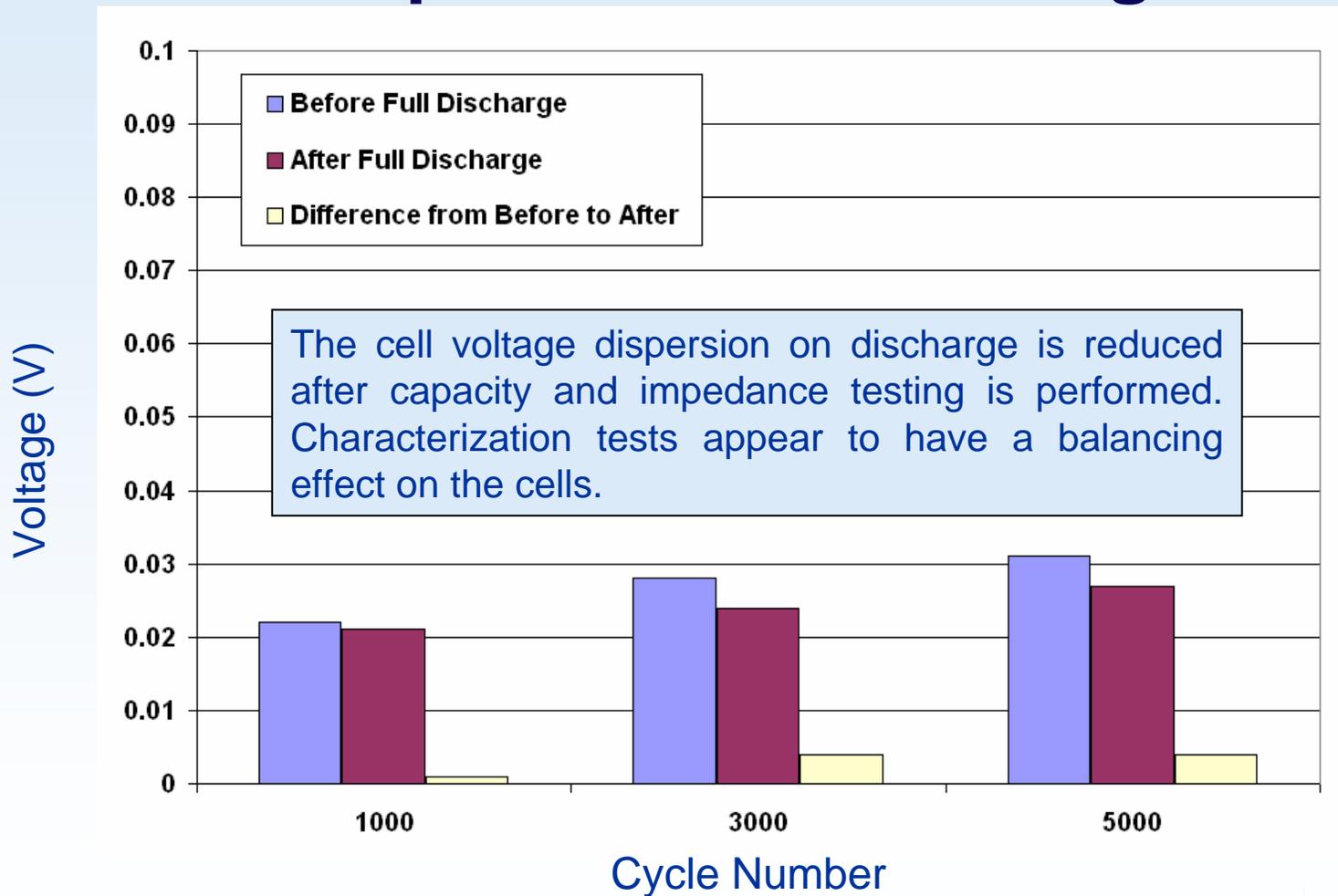
The cell voltage dispersion on charge is reduced after capacity and impedance testing is performed. Characterization tests appear to have a balancing effect on the cells.

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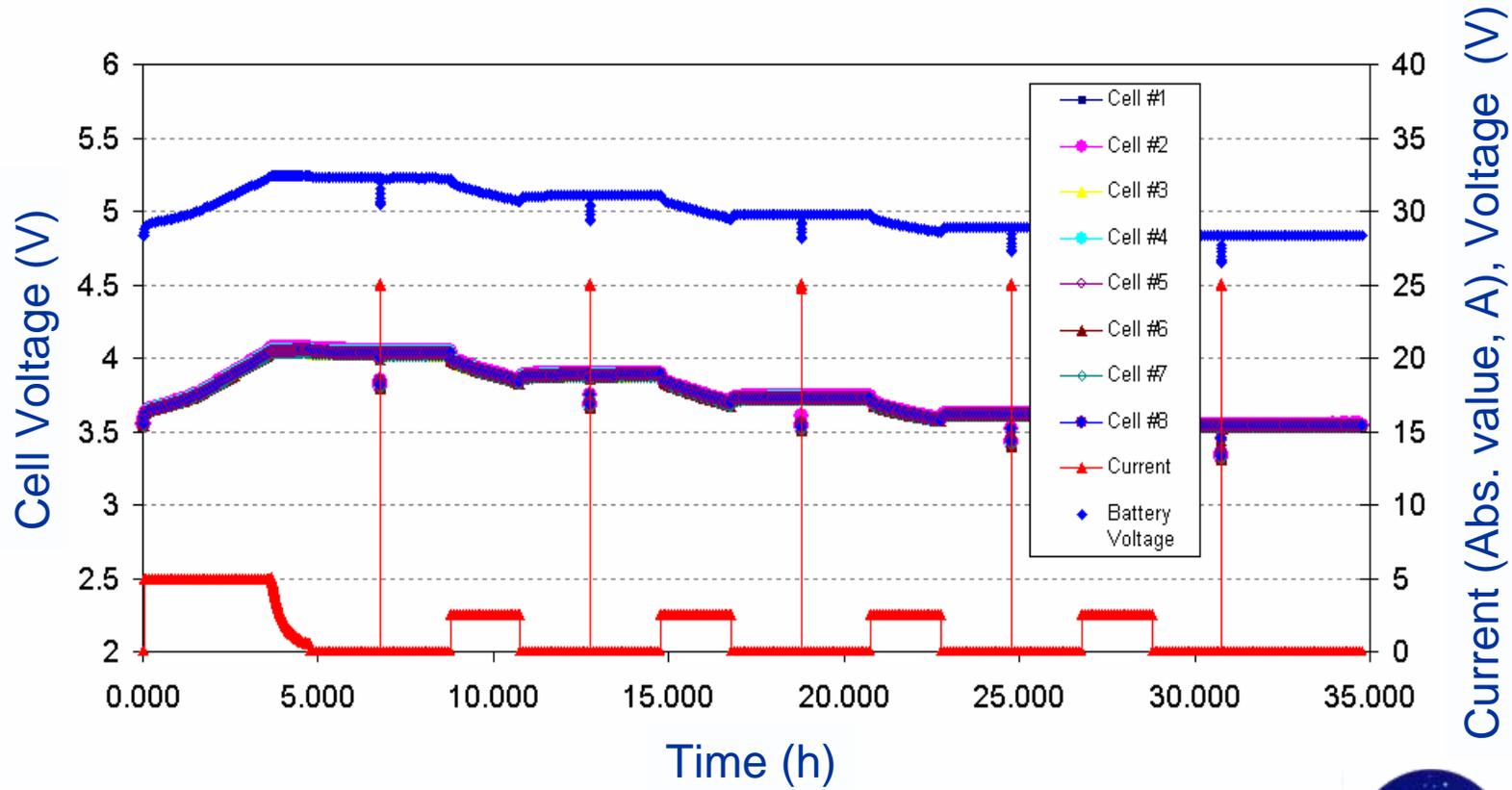


Effect of Capacity Checks on Cell Voltage Dispersion on Discharge

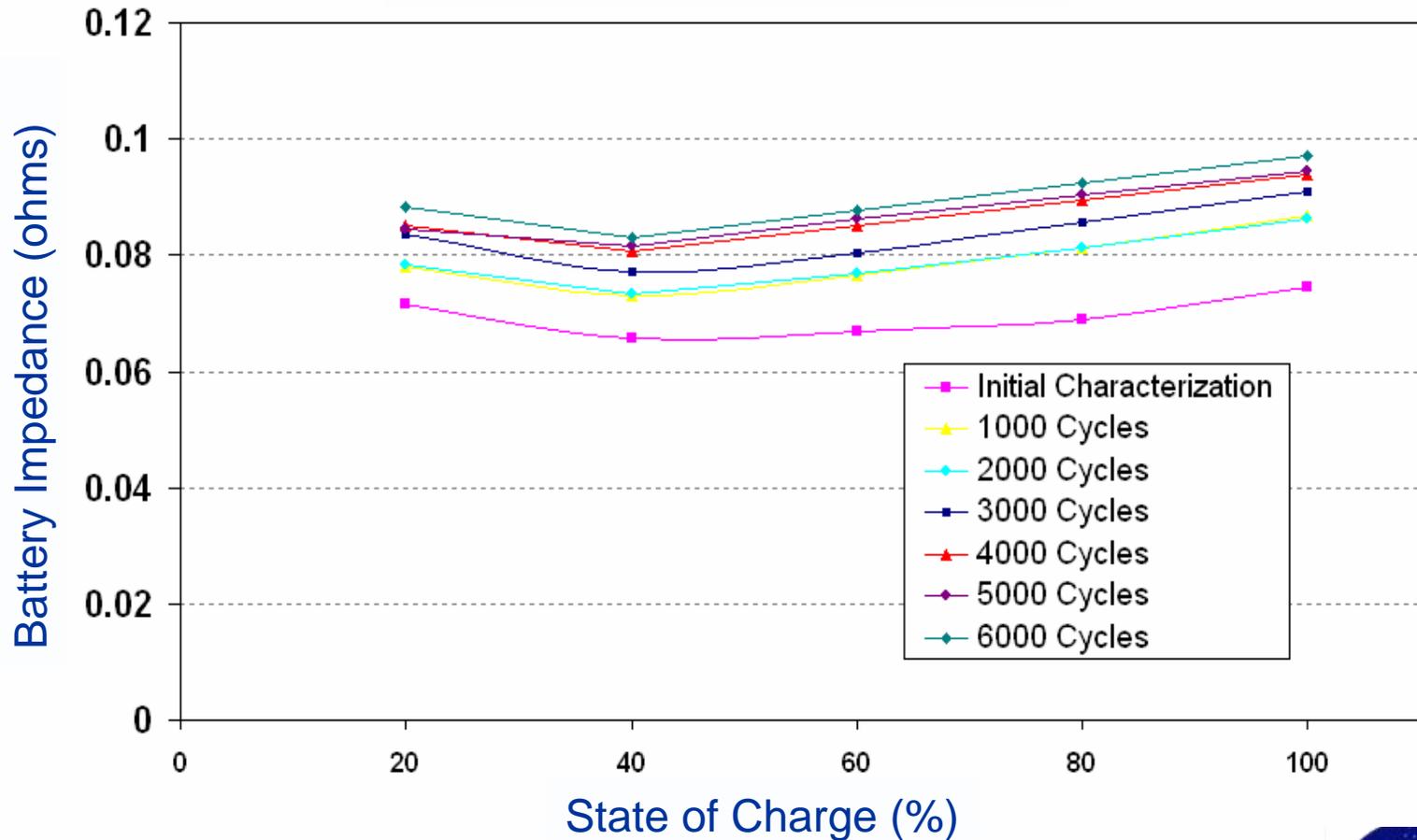


Current-Interrupt Impedance Test at 0 °C

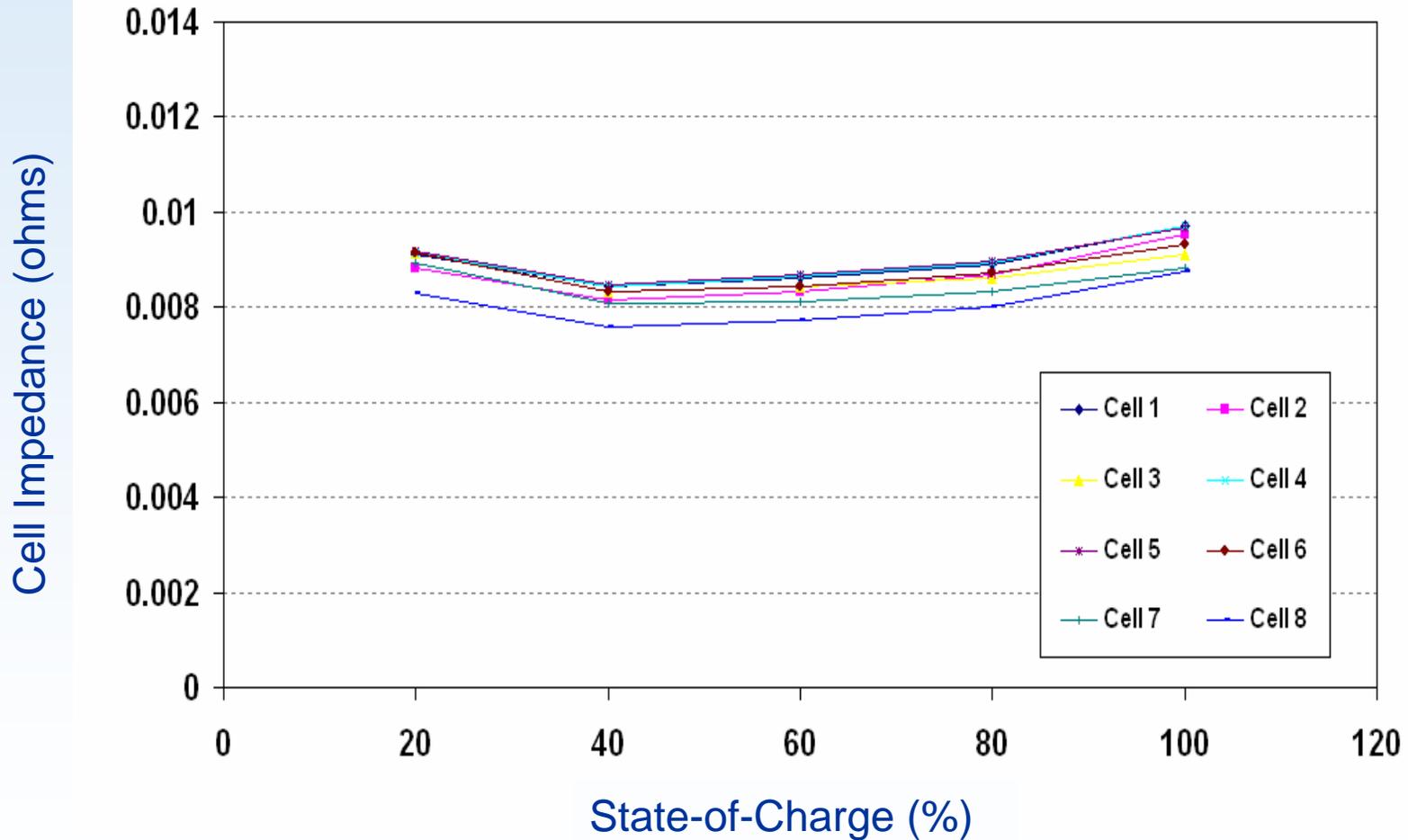
Charged at 5 A (C/5) to 32.4 V, Discharged at 25 A for 10 seconds
Rested 2 hours before and after each pulse
Discharged at 2.5 A for 2 hours (removed 5 Ah) between pulses



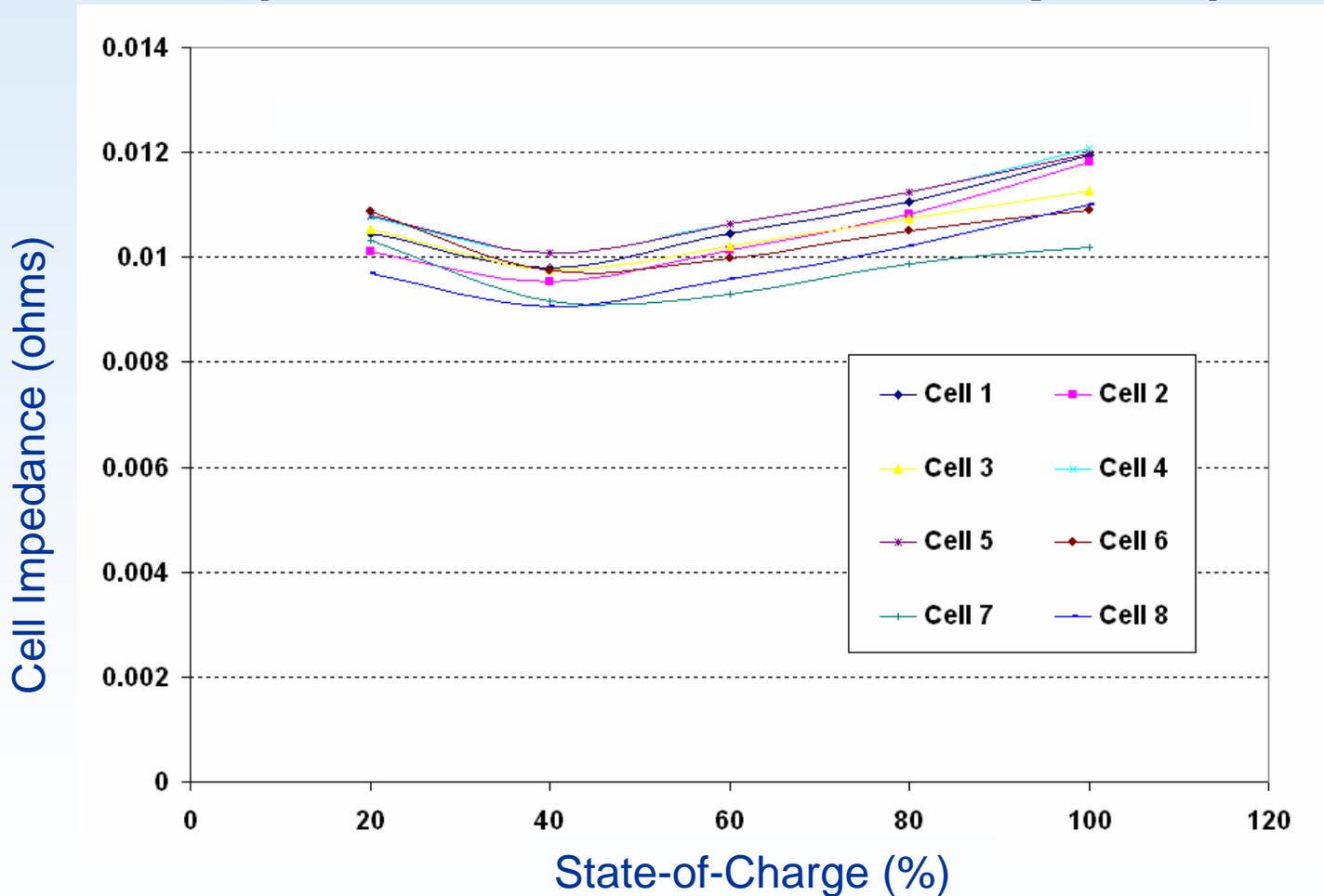
Battery Impedance at 0 °C at Different Intervals (calculated 1 hour after pulse)



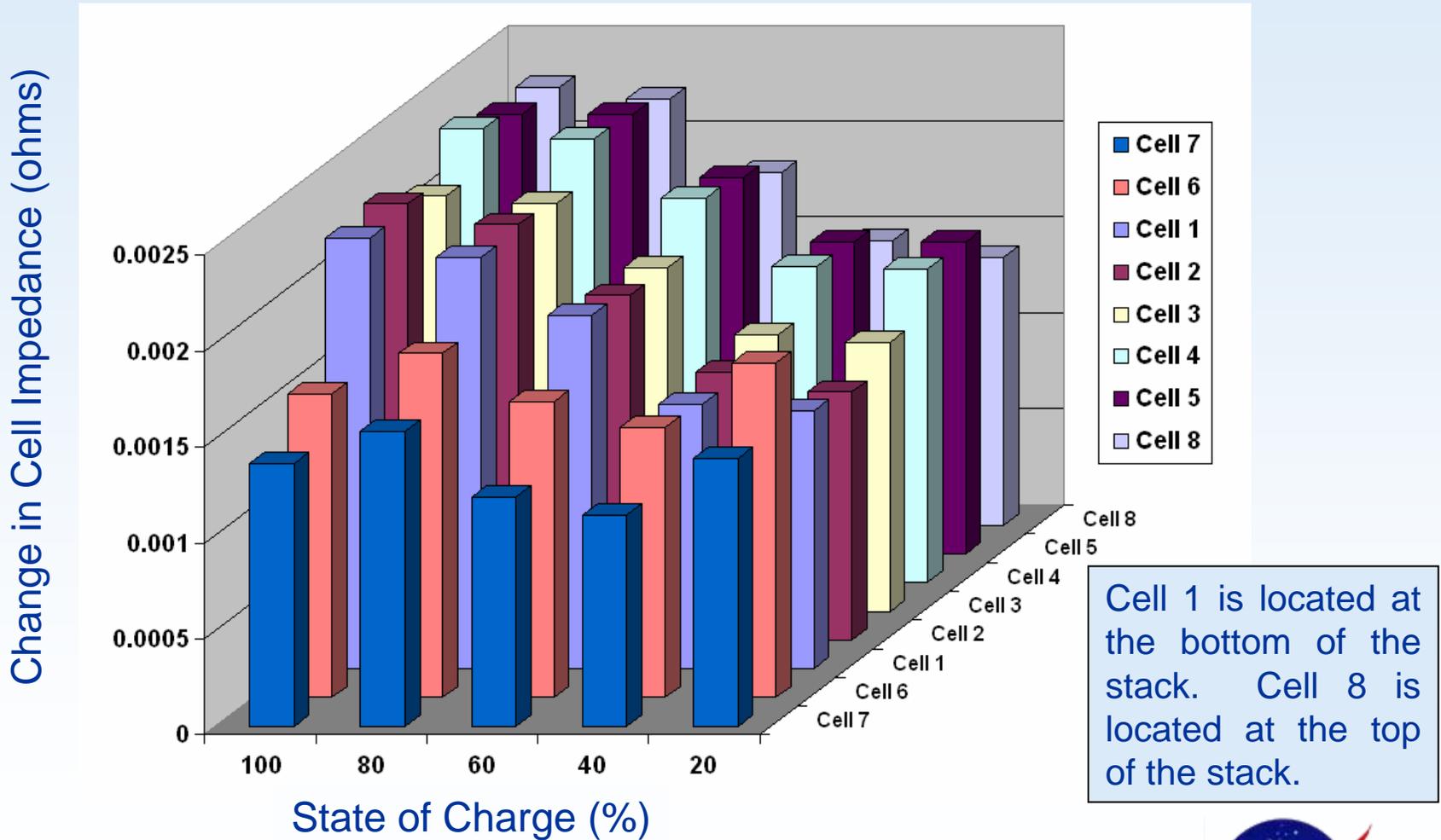
Initial Cell Impedances at 0 °C (calculated 1 hour after pulse)



Cell Impedances at 0 °C after 6000 Cycles (calculated 1 hour after pulse)



Change in Cell Impedances from Initial Characterization to 6000 Cycles



Conclusions

- Battery has delivered greater than 6000 cycles (equivalent to over 1 year in low-Earth-orbit).
- Battery delivered 94% of the initial capacity after 6000 cycles (measured using 100% DOD at 0 °C).
- Through 6000 cycles, cell voltage dispersion measured 95 mV on charge and 36 mV on discharge. Cell balancing is projected to be necessary after 7000 cycles.
- The battery end-of-discharge voltage decreased 550 mV over 6000 cycles.



Future Testing and Analysis

- The effect of characterization tests on cell balancing will be further examined.
- The possible correlation between the voltage and temperature of individual cells and their impedance will be investigated.
- Current-interrupt impedance tests at 0 °C will be repeated every 1000 cycles. Changes in impedances as a function of cycle life will be observed.
- Cells will be rebalanced when cell voltage dispersion exceeds 100 mV on charge and 80 mV on discharge.



Acknowledgements

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