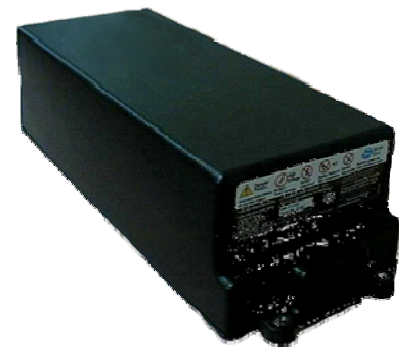


## Summary

This paper investigates the cell balancing and equalization requirements for very long life lithium ion battery pack systems. Two EnerDel 65 Volt 13 Ampere-Hour battery packs cycled continuously to more than 50% depth of discharge for 5.6MWh and 3.6MWh cumulative energy throughput. The effect of cell equalization was measured. It was determined that as the packs aged, 375mA/Ah of equalization current resulted in rapid equalization cycles and good performance.

## Test Configuration

- Two EnerDel 65V15 lithium battery packs
  - EnerDel EP-Series 4.44 Amp-hour cells (3 in parallel by 18 in series)
  - Capacity: 13.3Ah or 875Wh
  - Maximum pack voltage: 73.8V (4.10V/cell by 18 cells)
  - Minimum voltage under load: 50.0V (2.77V/cell)



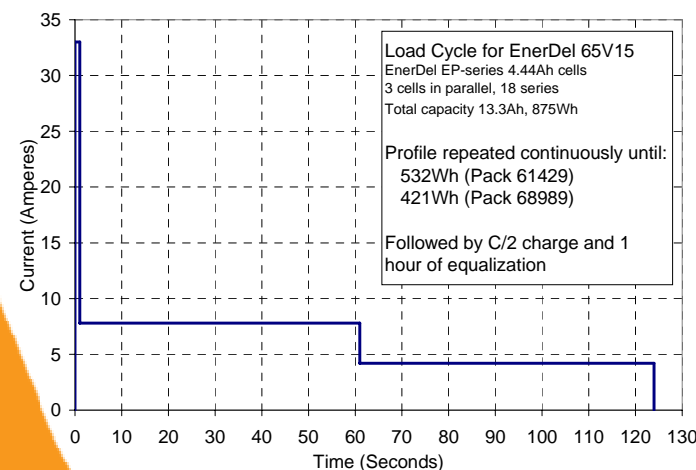
EnerDel 65V15 Battery Pack System



EnerDel EP4.4 Cell

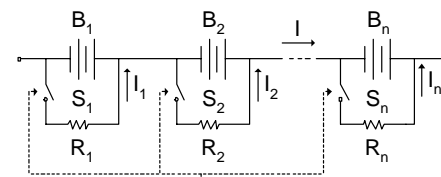
### Load Profile

- Average C/2 rate with 2C pulses
- Run continuously for either 526Wh (Pack 61429) or 431Wh (Pack 68989)
- DOD approximately 60% (Pack 61429) and 50% (Pack 68989).
- Charging at the C/2 rate until the maximum cell voltage was 4.10V
- After charging, equalization was restricted to a maximum of one hour
- C/5 reference cycle with full equalization performed every 100 cycles



## Equalization Hardware

- Resistive dissipation method
  - Restricted equalization to 1 hour after recharging
  - 50mA equalization current (375 mA/Ah)
  - Equalized 50mAh per hour, which is 0.375% SOC per hour

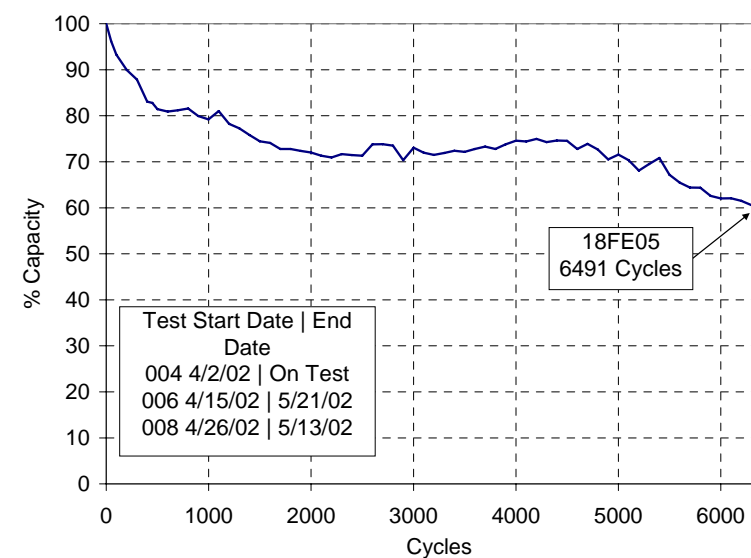


Simplified Equalization Hardware

- Test performed at 23°C
- Cycling on AeroVironment MT-30 battery testing machines

## Cycle Results

- Pack 68989 ran for 6491 cycles
- Chart shows the capacity as measured by the C/5 reference cycles
- Cumulative throughput (charge and discharge) is approximately 5.6 MWh
- Failure occurred on cycle 6491 when one cell dropped below 2.77V under load:

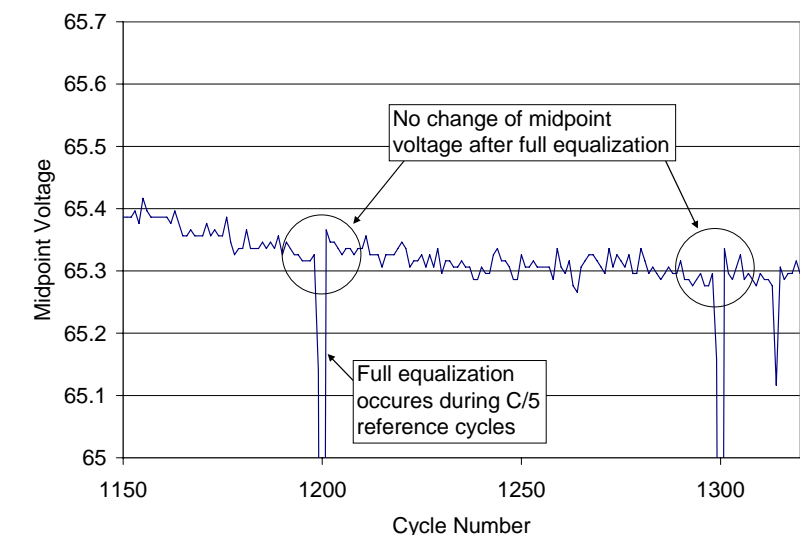


Pack 68989 Cycle Life

- Pack 61429 ran for 3370 cycles
- Cumulative throughput (charge and discharge) is approximately 3.6 MWh
- See full paper for cycle life graph for Pack 61429

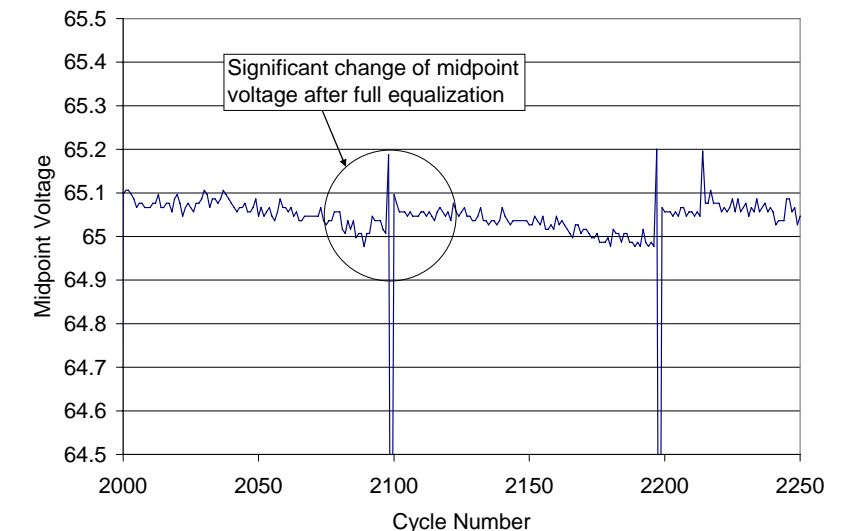
## Equalization Results

- Pack equalization determined by midpoint voltage of each cycle
  - Each cycle, the pack receives 1 hour of equalization at 375mA/Ah
  - Each C/5 reference cycle, the pack receives full equalization
  - Midpoint voltage does not drift before and after reference cycles
  - 1 hour equalization at 375mA/Ah works up to 1.6MWh cumulative throughput (1500 cycles)



Pack 68989 Midpoint Voltage for Cycles 1150-1350

- For 2MWh+ throughput (2000+ cycles), more balancing is needed
  - Midpoint voltage drifts down 50-100mV over 100 cycles, indicating accumulation of imbalance
  - Midpoint voltage recovers during reference cycle
  - To extend useful pack life, more balancing is required as the cell age
  - Either equalization time or rate can be increased



Pack 68989 Midpoint Voltage for Cycles 2000-2250