Charging Algorithms for Increasing Lead Acid Battery Cycle Life for Electric Vehicles

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Presentation Outline

- Purpose
- Background
- Module Cycle Life Test - Zero Delta Voltage (ZDV) Charging Technique
- Pack Cycle Life Test - Current Interrupt Technique

Purpose

- **Increase the cycle life of both modules and packs by focusing on the Oxygen Recombination Efficiency of a battery during overcharge. A Zero Delta Voltage (ZDV) charging technique was applied to a module whereas a Current Interrupt (CI) technique was used during overcharge for battery pack.**

Background

- Typical charging techniques for Valve Regulated Lead Acid (VRLA) batteries are a two step constant current (CC) technique or some combination of Constant Voltage (CV) and CC.
- Both VRLA and NiCd operate on oxygen-recombination to minimize water loss.
- The extreme depolarizing effect of the oxygen cycle must be taken into account.
- At the end of life, the oxygen recombination cycle consumes most or all of the overcharge current allowed by the charge.

Effective Charging Algorithm Includes…

- High inrush currents.
- No limitation on the percent overcharge.
- A modest-to-high rate of charging.
- High finishing currents.
- An effective charging termination point.

Optima Battery under ZDV Cycle Life Test

Cycling of 12 Volt/ 50 Ah Module

- The charge algorithm was as follows:
  - 50A to 70% charge return
  - 10A until Zero Delta Voltage
  - Overcharge: 5A for 3.0-10.0 Ah – Amount depends on cycle life number. [Cycles 0-295, 3 Ah; Cycles 296-340, 10.0 Ah; Cycles 341-356, 6-7Ah]
- Discharge is 25A until 10.5V (100% DOD)

Sensing ZDV – 10 Amps until…

30 Readings – 1 Reading/sec → Ave_0

30 Readings – 1 Reading/sec → Ave_1

$Diff_0 = Ave_1 - Ave_0$

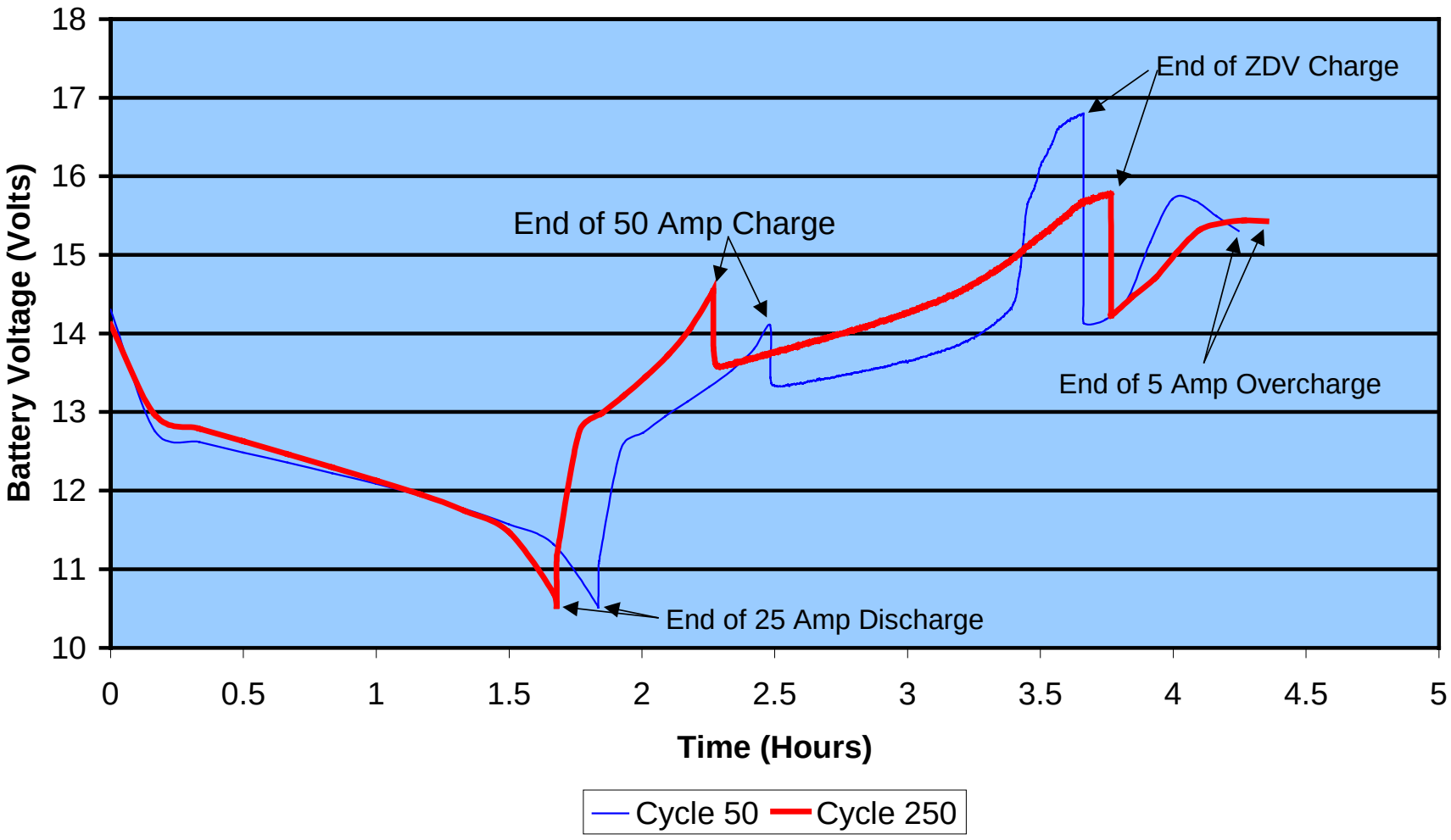
30 Readings – 1 Reading/sec → Ave_5

30 Readings – 1 Reading/sec → Ave_6

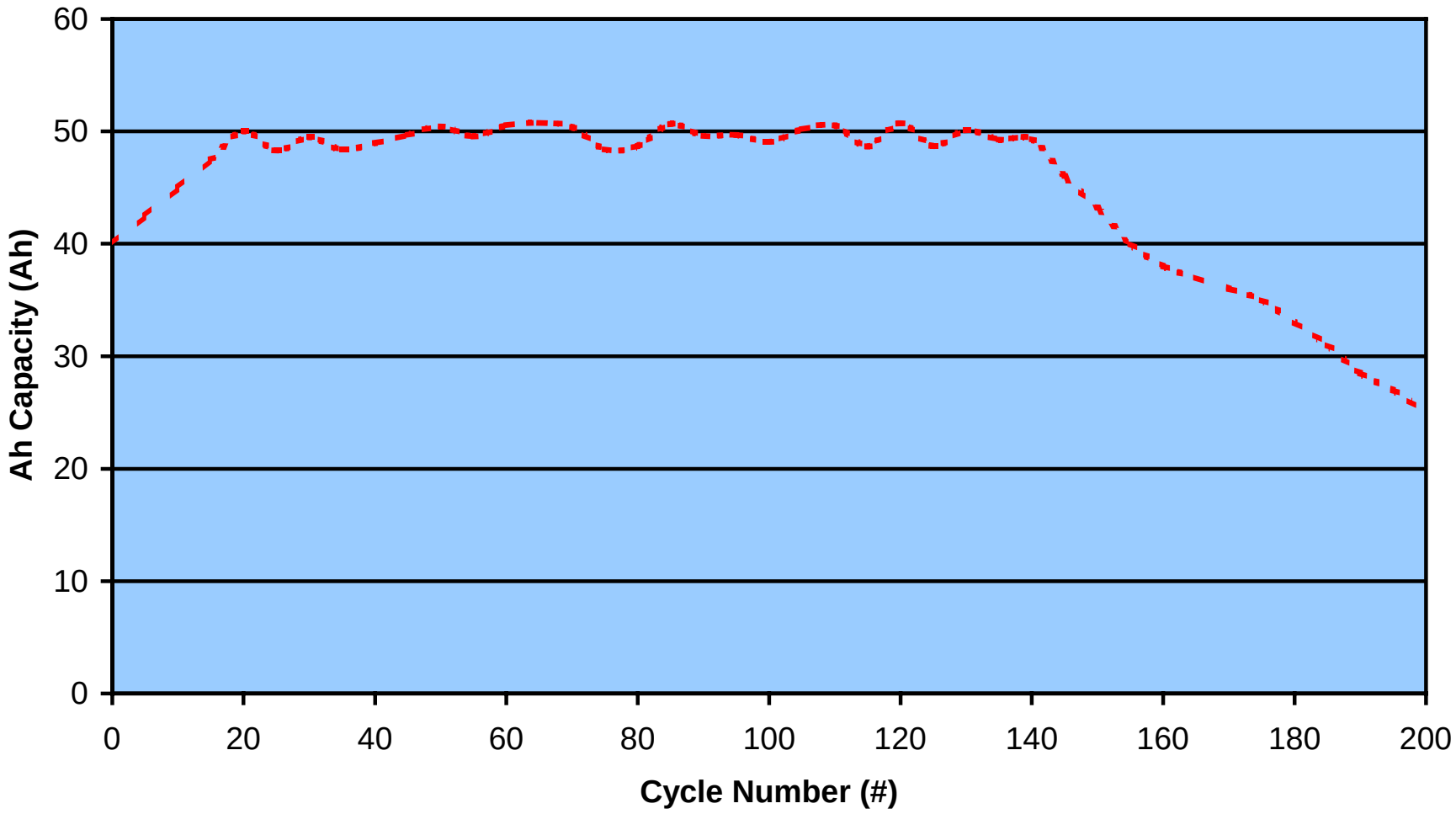
$Diff_4 = Ave_6 - Ave_5$

If 5 consecutive differences are less than a prescribed limit (0.015 Volts), then zero delta voltage has been sensed.

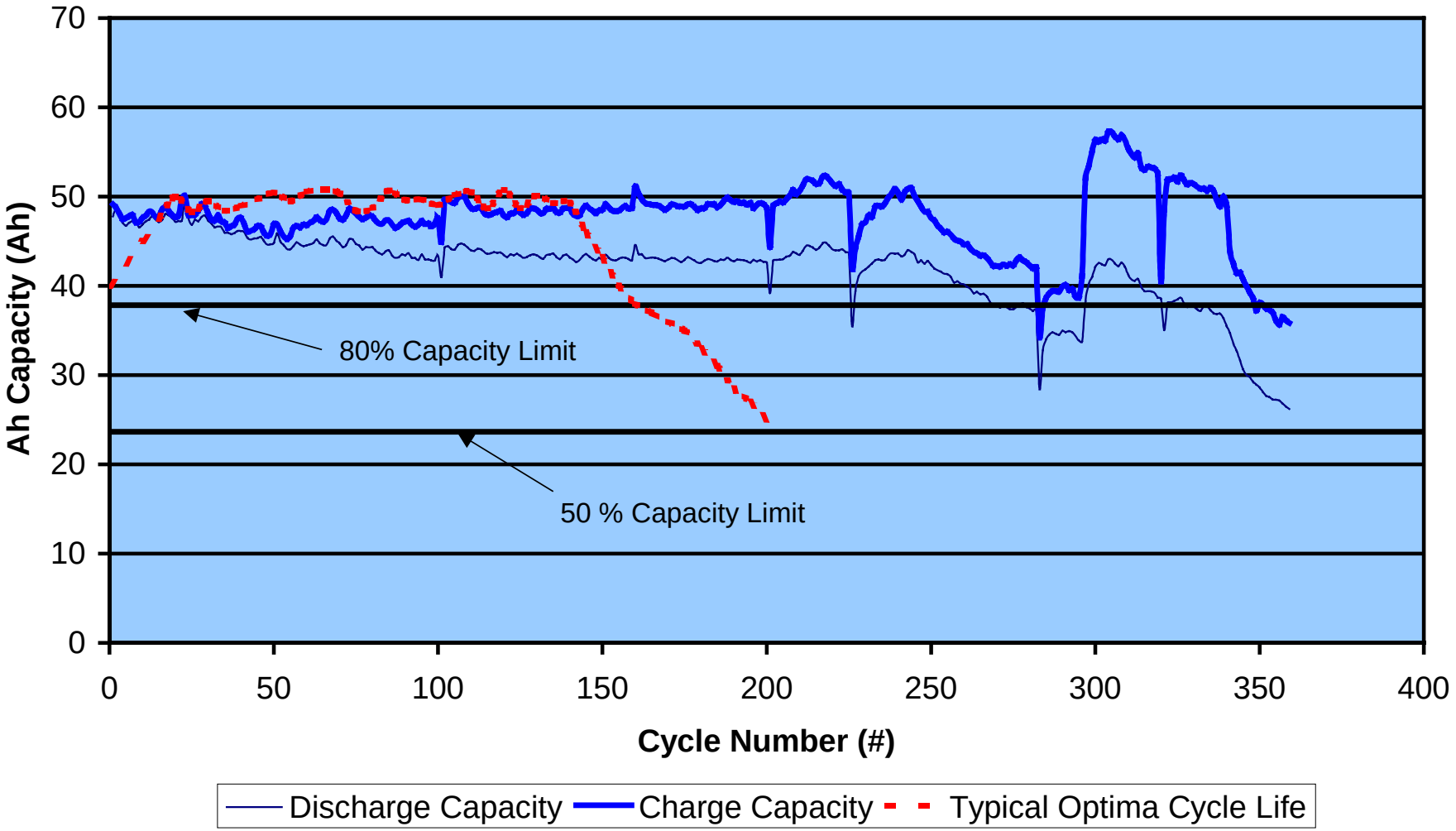
Cycle 50 and 250 of ZDV Cycling



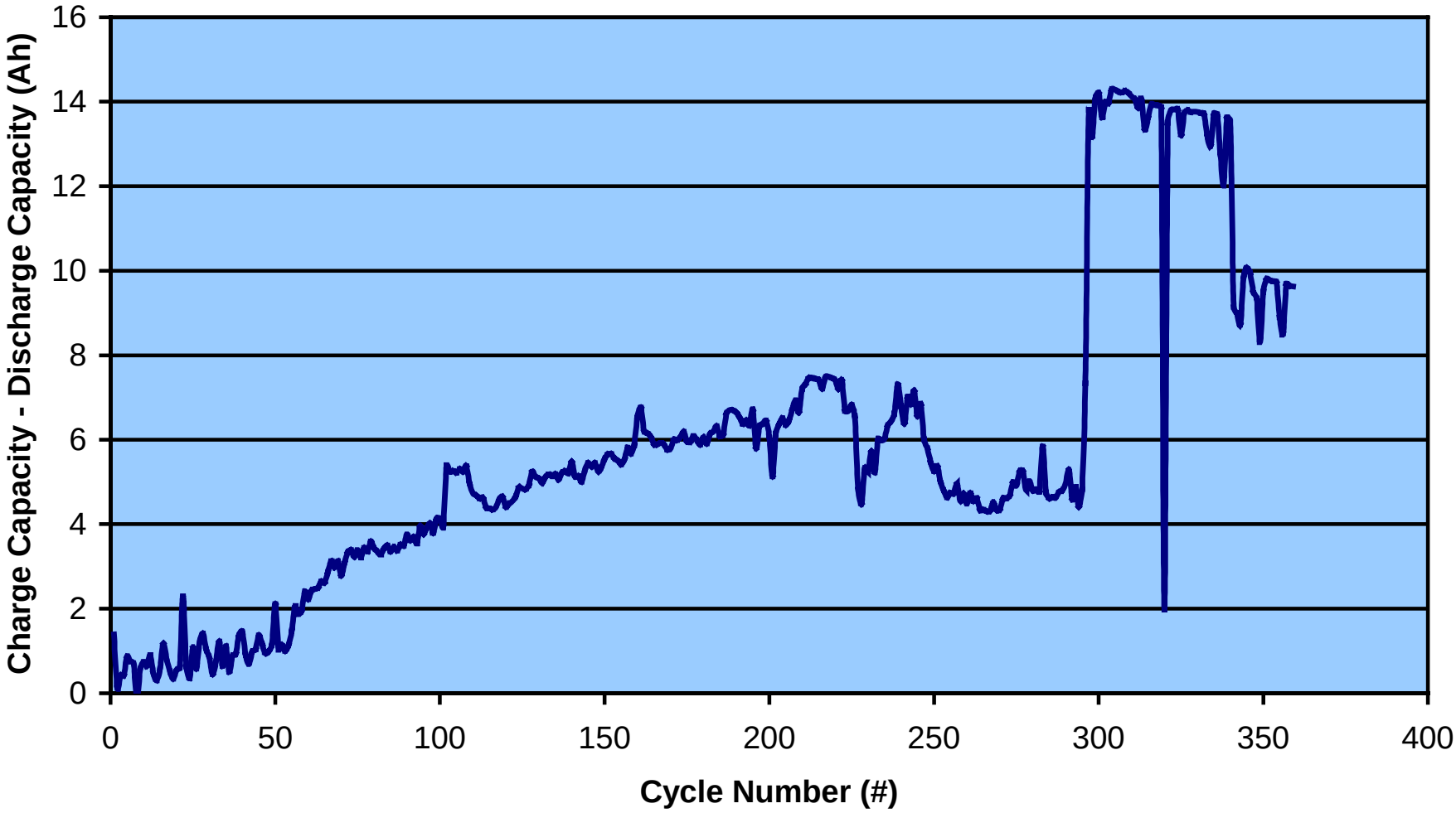
Typical Cycle Life Data for Optima 50 Ah Battery under CC/CV Charge



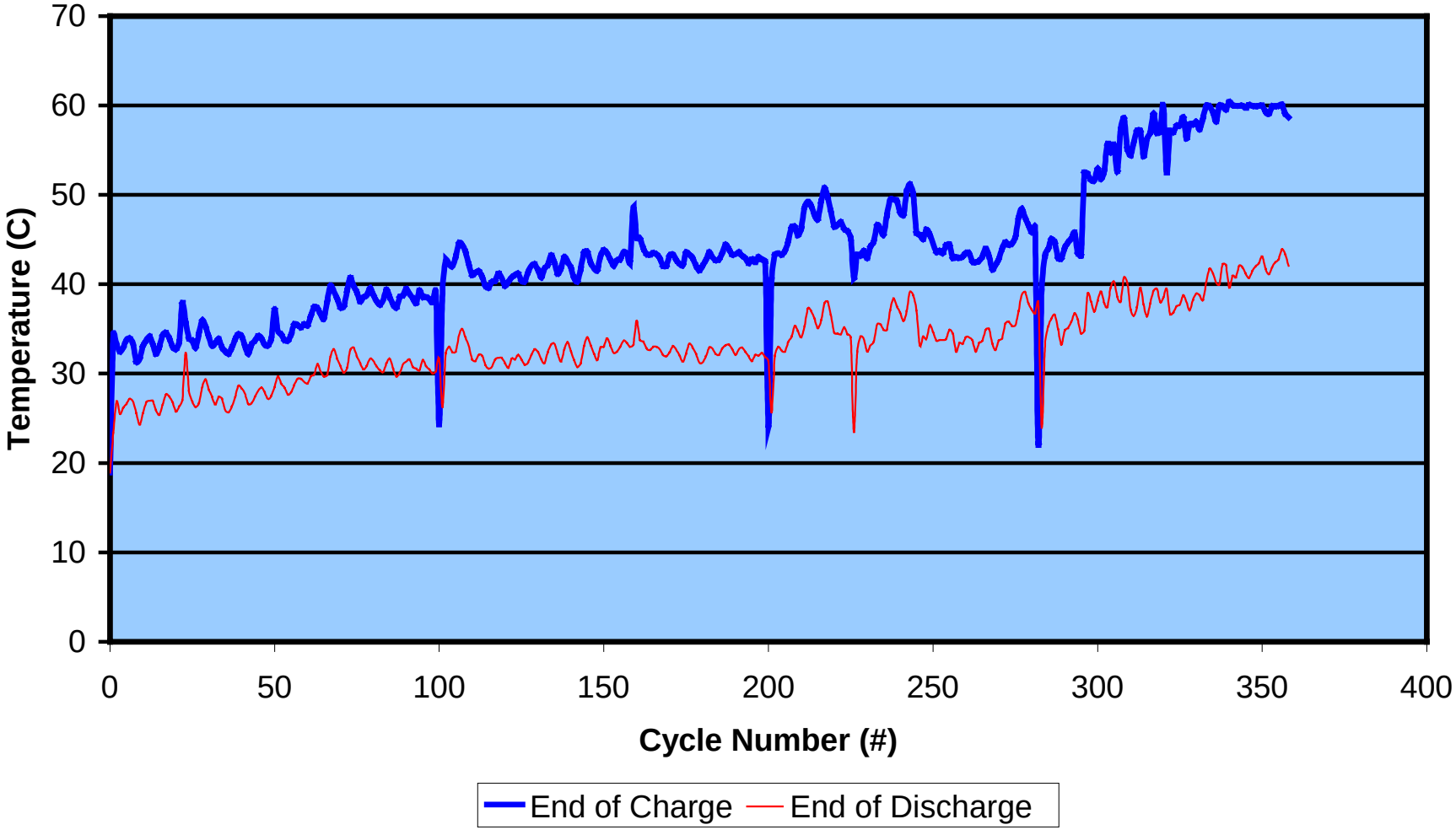
ZDV Cycle Life Test



Overcharge during ZDV Cycle Life Test



Maximum & Minimum Temperature Data for ZDV Test



Conclusions for ZDV Cycle Life Test

- **“Dry-out” was not a failure mode.**
- **Negative-plate sulfation was not severe.**
- **With a ZDV technique, we were able increase the cycle life of the Optima VRLA by a factor of 2.**
- **The charge/termination algorithm must be adjustable to respond to a batteries aging.**

288 Volt/ 24 Module Pack Cycling

Battery pack in an insulated box with air cooling

Why a CC charge and CI Technique?

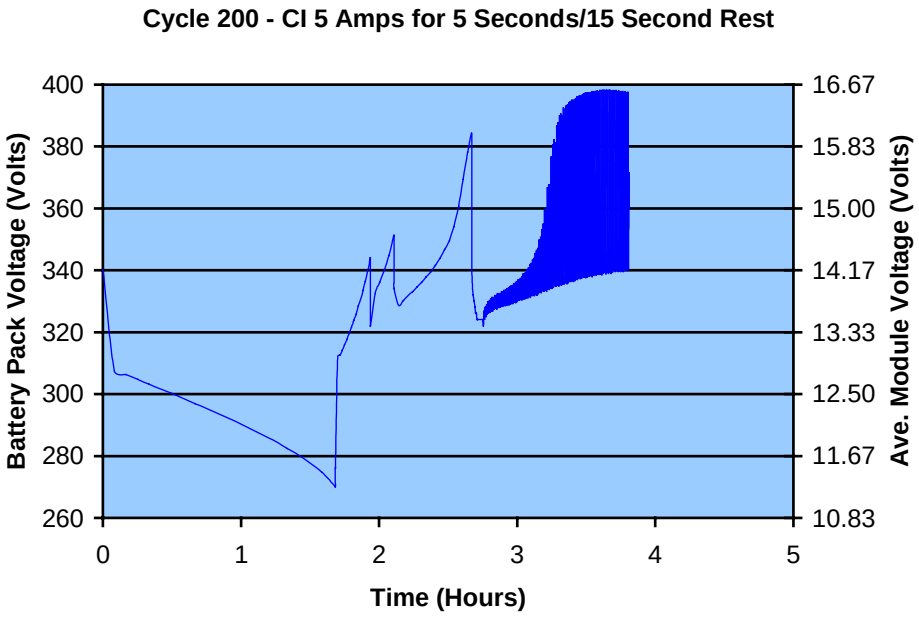
- A CC charge allows for fast recharge.
- Current interrupt allows use of high currents with rest periods to maximize recharge efficiency, minimize overcharge, and reduce overall pack temperature.
- The charge/rest rate and current for a multi-step CI must be optimized.

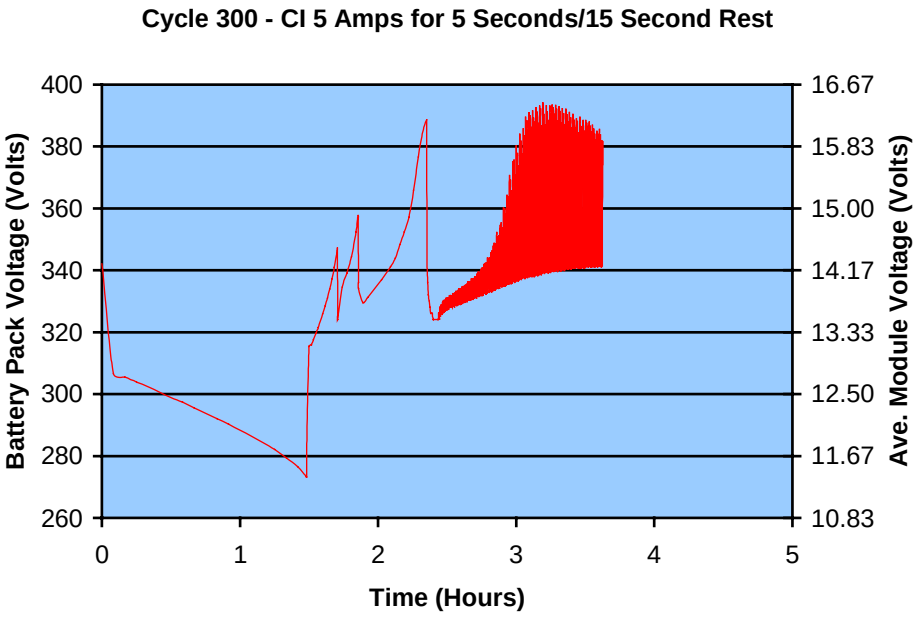
What is Current Interrupt (CI)?

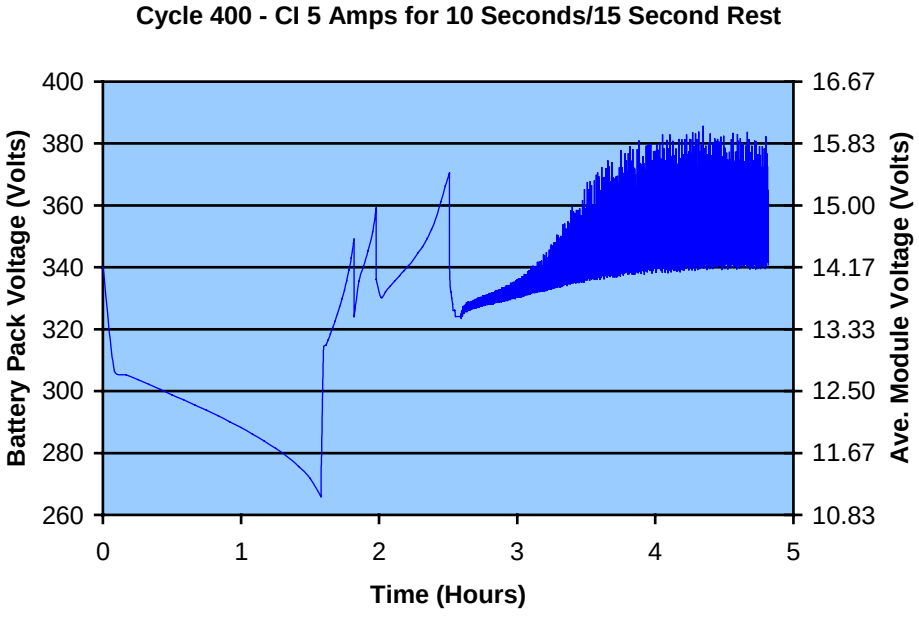
- A pulsed-charge technique with on-off times of 5-30 seconds.
- Used with thin plate batteries for the finishing charge step.
- No voltage limit during the charge steps.
- Polarization during charge and rest voltages below 14.0 volts are used as criteria to trigger an increase in the pulsed-current amplitude.
- Late in life, pulsed-current levels of 2C-4C may be necessary to achieve 100% recharge.

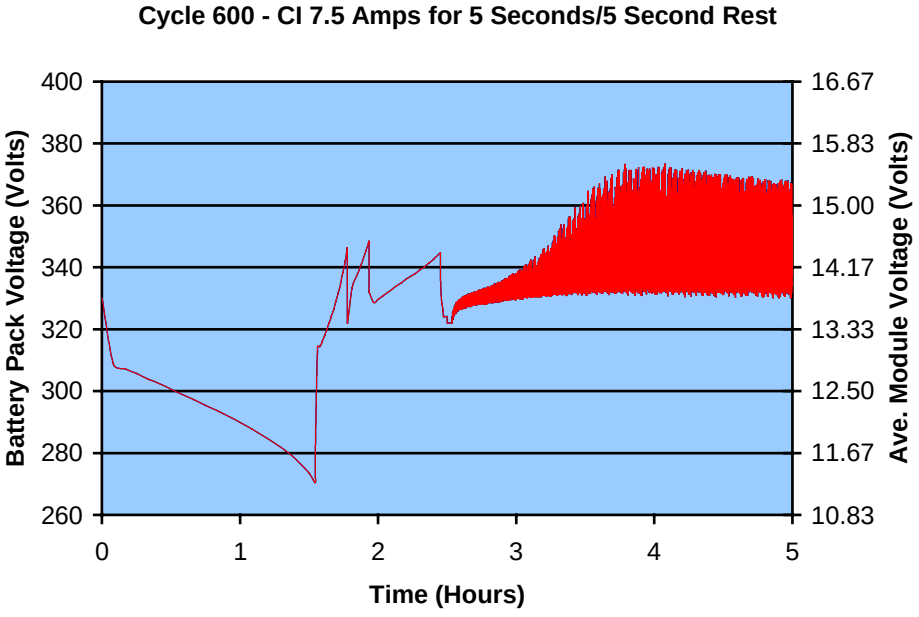
Cycling of 288V/50 Ah Pack

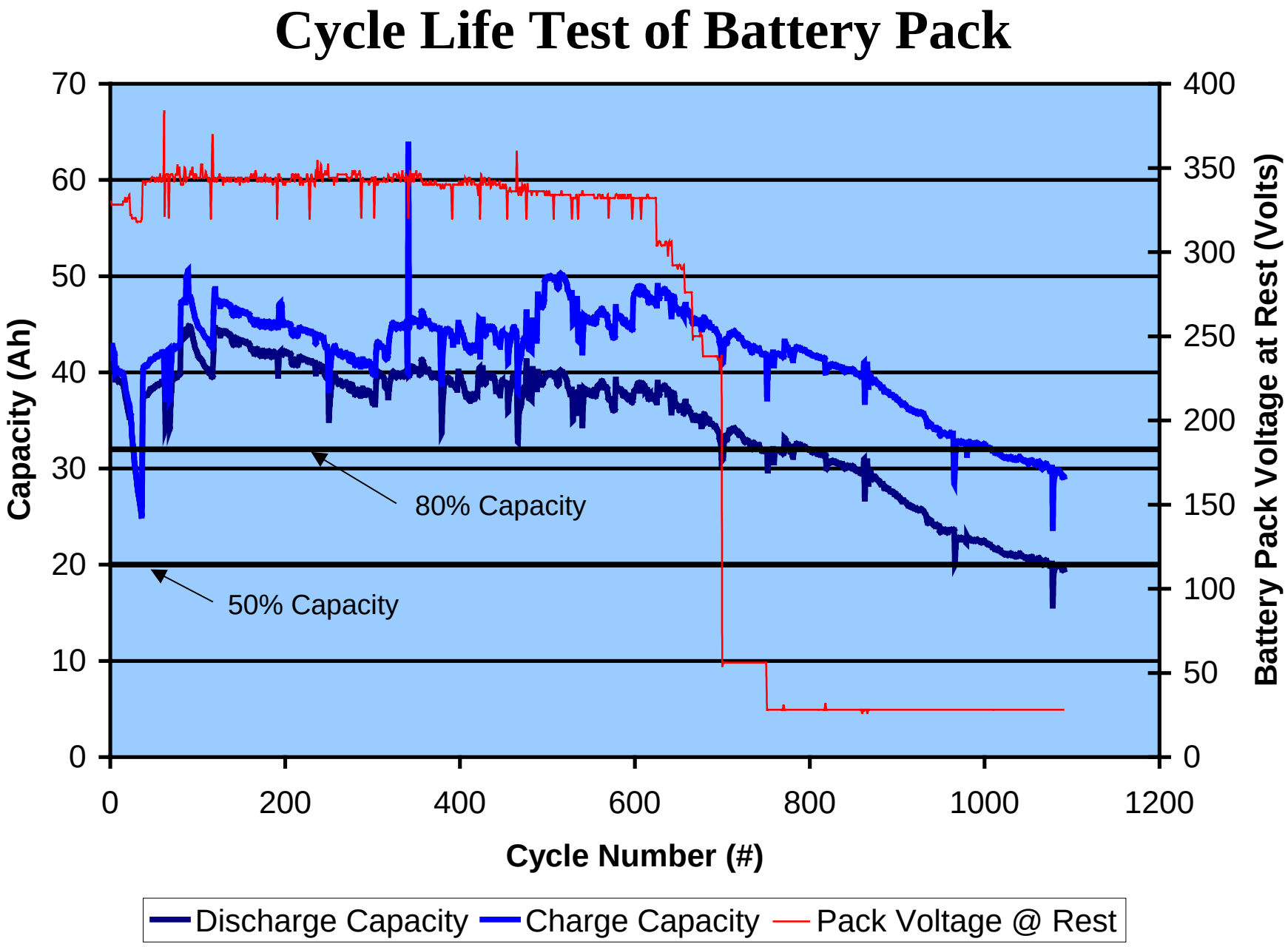
- The pack was composed of 24 12 V/50Ah Optima Yellow Top modules.
- The charge algorithm was a stepped - CC program with a CI finish:
  - 100A to 60% charge return
  - 50A to 80% charge return
  - 15A to 100% charge return
  - CI overcharge (7.5A/5sec on, 5 sec off)
- Discharge was 25A to the first module reaching 10.5V.
- Modules limiting performance (i.e., reaching 10.5V on discharge) were removed and replaced when necessary by new, conditioned modules.
- At ~ 600 cycles, modules were no longer replaced upon failure (but were bypassed), so the pack voltage was gradually stepped down.

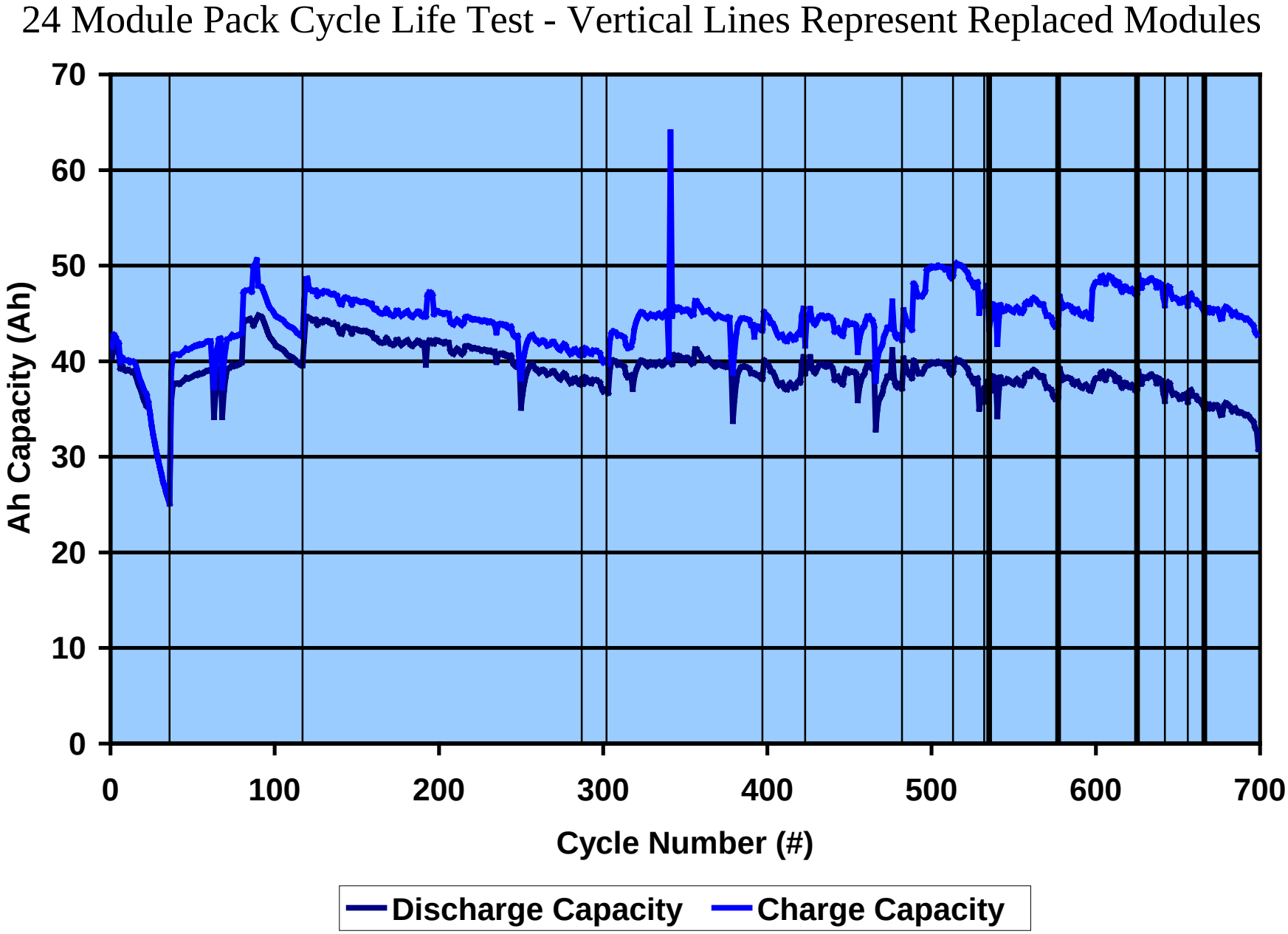

Cycle 200 - CI 5 Amps for 5 Seconds/15 Second Rest
Battery Pack Voltage (Volts)
Ave. Module Voltage (Volts)
Time (Hours)
400
380
360
340
320
300
280
260
16.67
15.83
15.00
14.17
13.33
12.50
11.67
10.83
0
1
2
3
4
5


Cycle 300 - CI 5 Amps for 5 Seconds/15 Second Rest
Battery Pack Voltage (Volts)
Ave. Module Voltage (Volts)
Time (Hours)
400
380
360
340
320
300
280
260
16.67
15.83
15.00
14.17
13.33
12.50
11.67
10.83
0
1
2
3
4
5

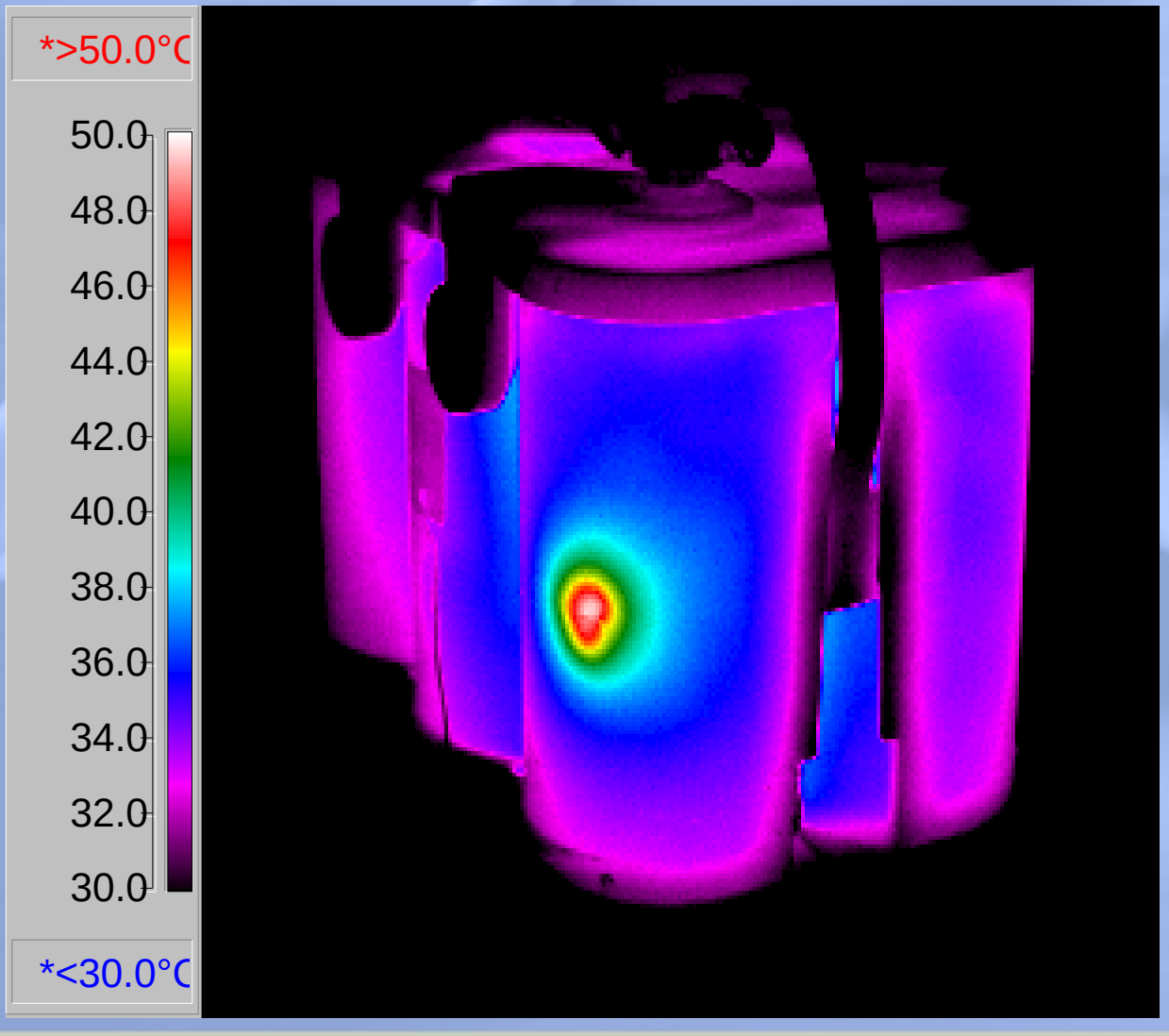

Cycle 400 - CI 5 Amps for 10 Seconds/15 Second Rest
Battery Pack Voltage (Volts)
Ave. Module Voltage (Volts)
Time (Hours)
400
380
360
340
320
300
280
260
16.67
15.83
15.00
14.17
13.33
12.50
11.67
10.83
0
1
2
3
4
5


Cycle 600 - CI 7.5 Amps for 5 Seconds/5 Second Rest
Battery Pack Voltage (Volts)
Ave. Module Voltage (Volts)
Time (Hours)
400
380
360
340
320
300
280
260
16.67
15.83
15.00
14.17
13.33
12.50
11.67
10.83
0
1
2
3
4
5

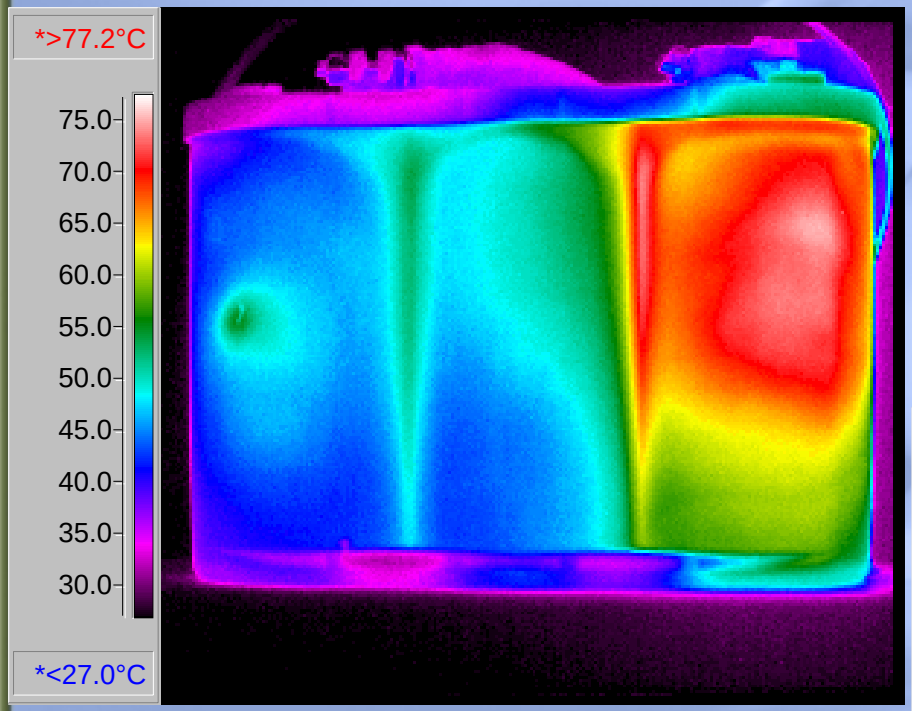

Cycle Life Test of Battery Pack
Capacity (Ah)
Battery Pack Voltage at Rest (Volts)
Cycle Number (#)
80% Capacity
50% Capacity
Discharge Capacity
Charge Capacity
Pack Voltage @ Rest
0
10
20
30
40
50
60
70
0
50
100
150
200
250
300
350
400
0
200
400
600
800
1000
1200


24 Module Pack Cycle Life Test - Vertical Lines Represent Replaced Modules
Ah Capacity (Ah)
70
60
50
40
30
20
10
0
0
100
200
300
400
500
600
700
Cycle Number (#)
Discharge Capacity
Charge Capacity

Thermal Image of Module with Shorted Layers

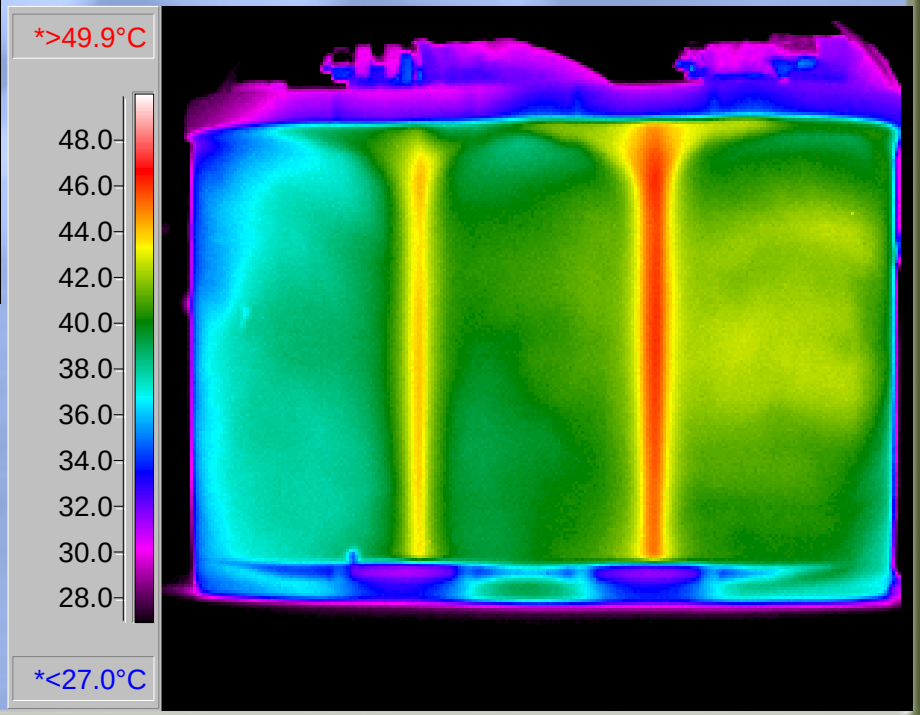


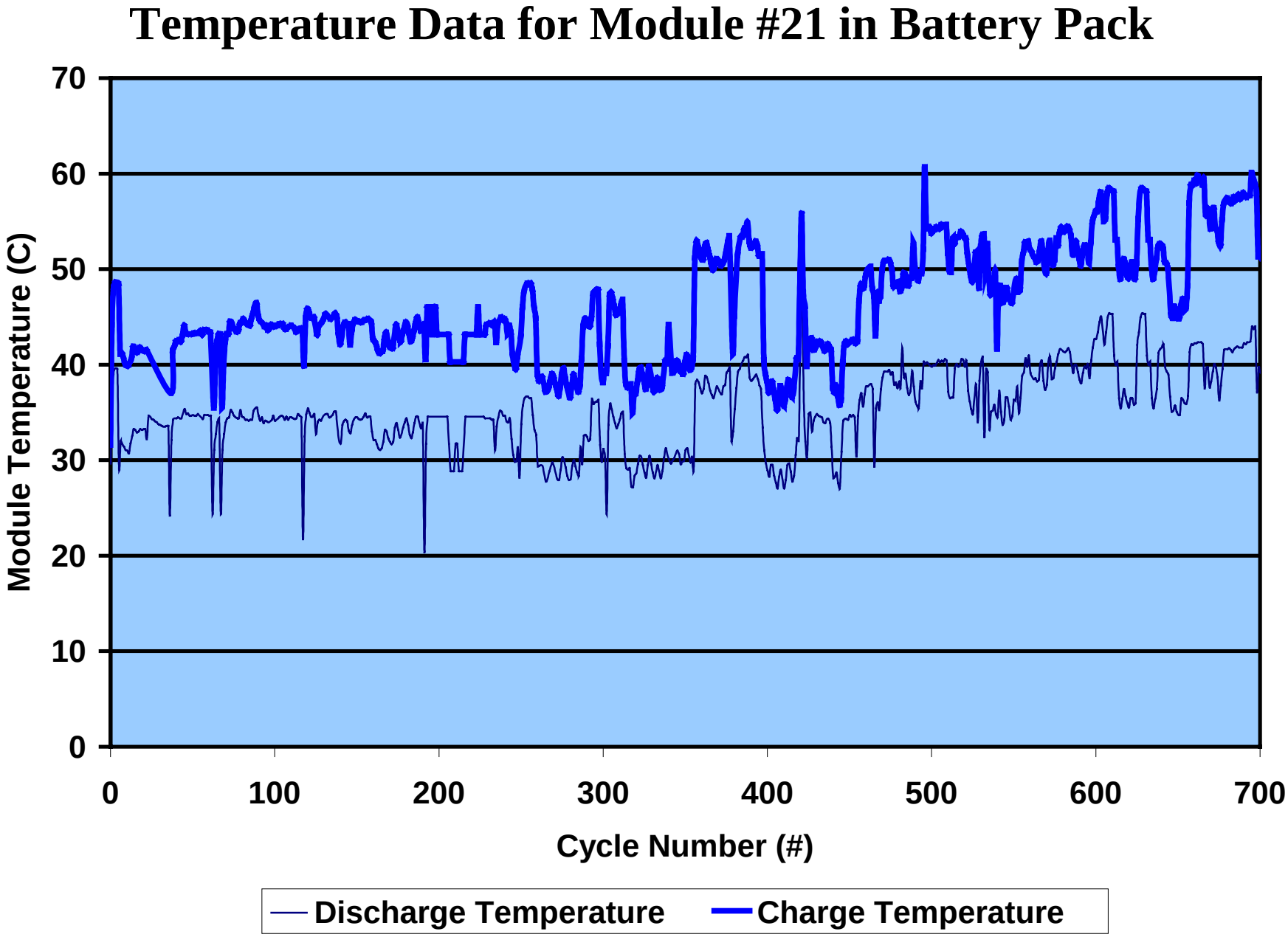
Module 22 – Cycle 751



Charge

Discharge



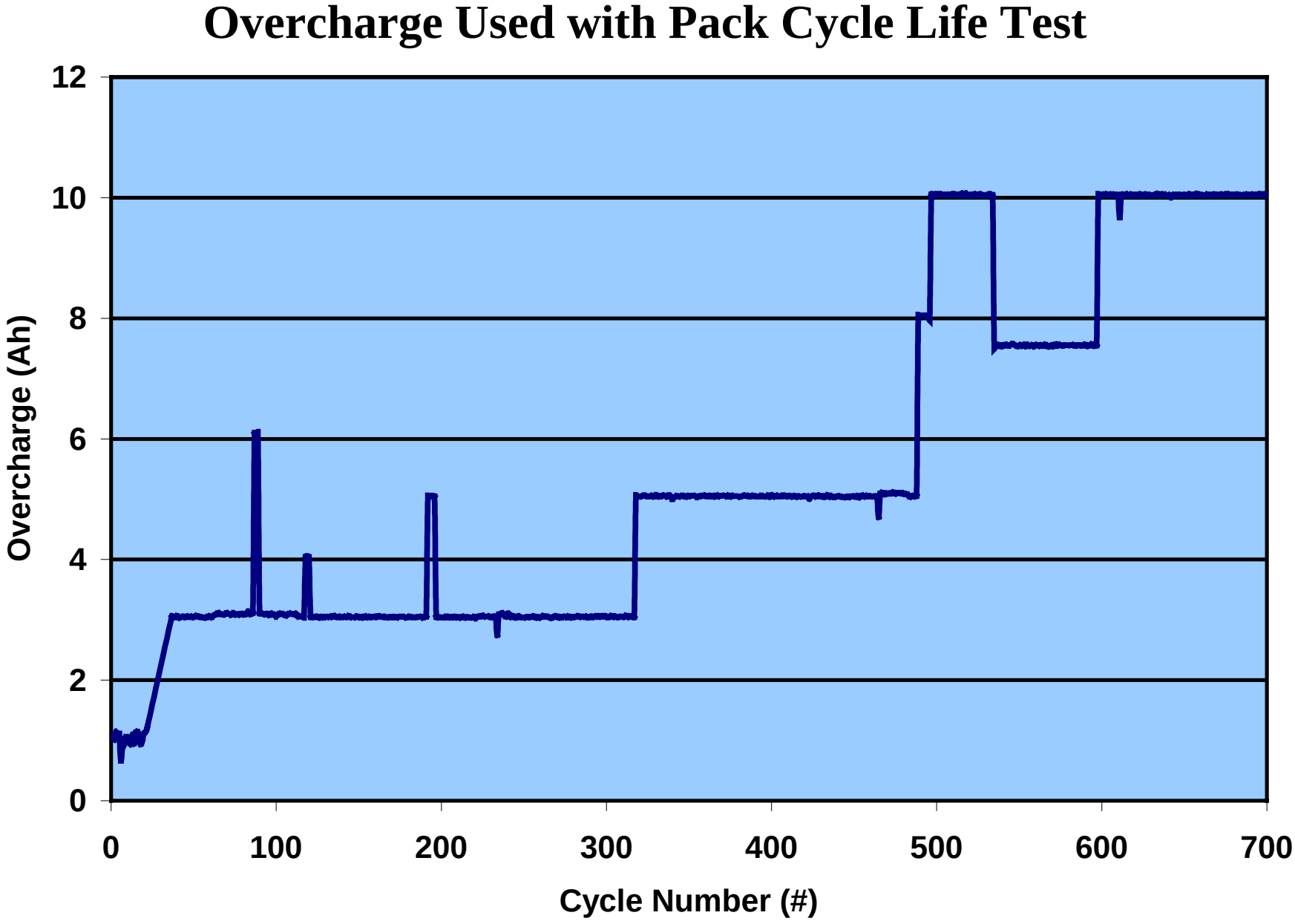

Temperature Data for Module #21 in Battery Pack
Module Temperature (C)
70
60
50
40
30
20
10
0
0
100
200
300
400
500
600
700
Cycle Number (#)
Discharge Temperature
Charge Temperature

Conclusions from the 288V Pack Cycling

- Application of the multi-step CC/CI charge algorithm *without battery management* results in excellent pack cycle lifetime for the Optima product.
- At times, insufficient recharge of individual 12V modules.
- “Dryout” is not a failure mode.
- Negative-plate sulfation is not severe.
- No clear correlation between operating temperature and failure.

Conclusions (cont'd)

- Increased the cycle life of the Optima pack from 150 cycles to approximately 700 cycles.
- This experiment equates to 3-4 years of service (700 cycles), with replacement of 12 of 24 original modules (21.6kWh total) due to electrochemical failure. Total Ah output in that time is ~28,000; total kWh output is ~8,100. Rate/mile is ~$0.10.


Overcharge Used with Pack Cycle Life Test
Overcharge (Ah)
12
10
8
6
4
2
0
0
100
200
300
400
500
600
700
Cycle Number (#)