Serial Charging Test On High Capacity Li-ion Cells for the Orbiter Advanced Hydraulic Power System

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Introduction

- Objective and Test Description
- Test Data
- General Observations and Conclusions

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Objective: Confirm That Charging a Series String of JSB 190 Ah Cells Is Feasible and Results in Acceptable Cell to Cell Voltage Differences

- Intent was to accelerate cell aging to see if cell to cell differences impact useful capacity

Description: Test conducted from April - August 2004 with a module consisting of six cells in series

Test plan sequence included 30 cycles performed over 6 months:

Start:	12 Charge / Discharge Cycles (Back to Back Cycles)	
1 Month:	1 Charge / Discharge Cycle	40 °C & 80% SOC Storage Between Cycles (changed to 30 °C after month 2)
2 Months:	1 Charge / Discharge Cycle	
3 Months:	1 Charge / Discharge Cycle	
4 Months:	1 Charge / Discharge Cycle	
5 Months:	1 Charge / Discharge Cycle	
6 Months:	1 Charge / Discharge Cycle	
6 Months:	12 Charge / Discharge Cycles (Back to Back Cycles)	

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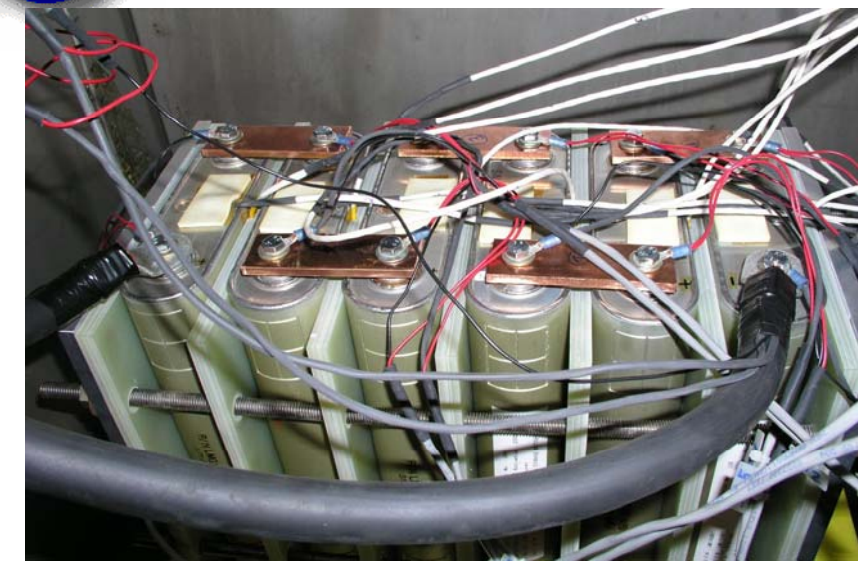
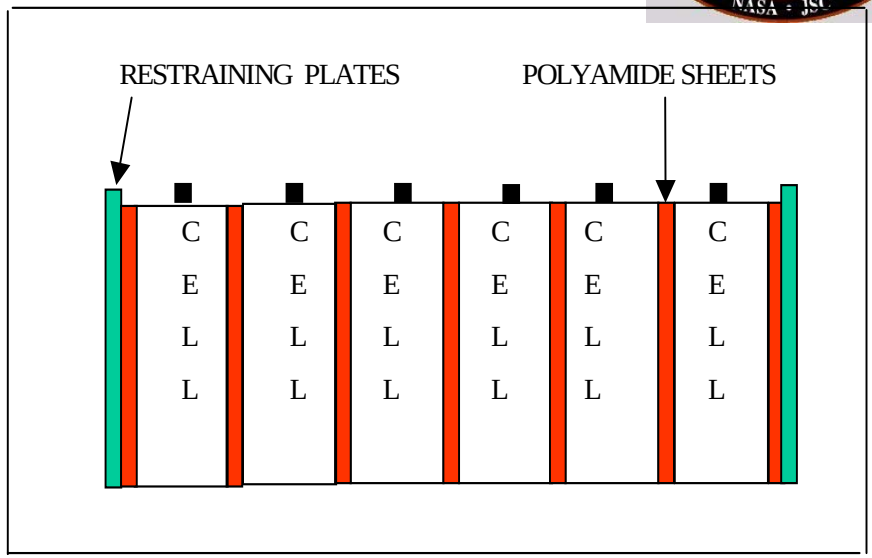
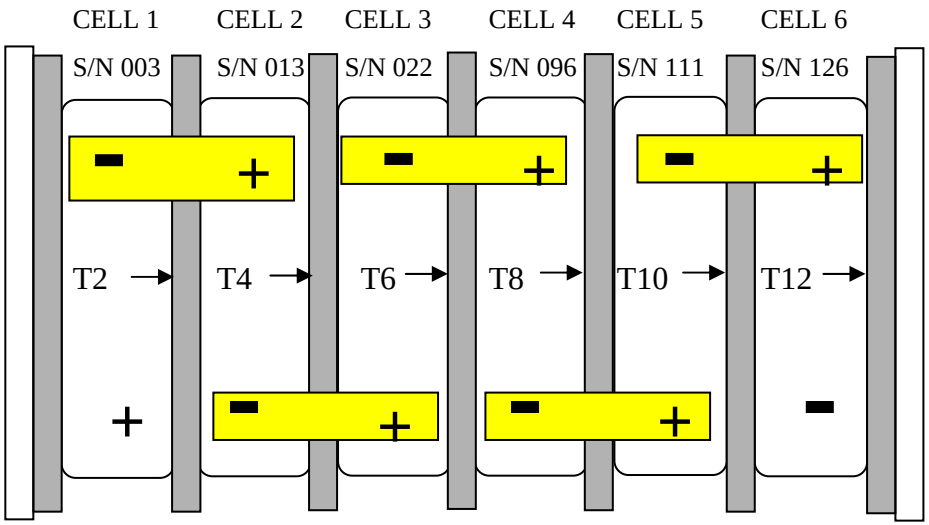
Module Configuration







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Cell History

Cell Position	Cell S/N	Cell Previous Testing	Capacity Cell Cycle Tests Performed Prior to Serial Charging Test (Ah at C/10 from 4.1 to 3.0 VDC)
1	003	3 month, 30 deg C Capacity Loss 8/01	199.3, 199.2, 199.3
2	013	None	190.4, 190.6, 190.6
3	022	None	195.8, 195.9, 195.8
4	096	None	193.6, 193.9, 193.8
5	111	Discharge vs Temp 2/02 (1 cycle each at 0ºC, 5ºC, 10ºC, 15ºC, 25ºC, 40ºC and 65ºC)	201.7, 201.6, 201.4
6	126	None	196.3, 196.1, 195.8

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Charge /Discharge Protocol

Placed in Chamber at 20 °C for Charge or Discharge

Charge:

- C/5 (38 A) to 24.6 V (4.1 V per cell)
- Constant voltage until current decreases to C/100 (1.9 A) or any one cell reaches 4.15 V

Discharge:

- C/2 (95 A) from 24.6 to 18.0 V (4.1 to 3.0 V per cell) or any one cell reaches 2.80 V with 5 second, 2.7 C (513 A) pulses at 15, 20, 50, 70, 85, 90 minutes
- C/10 (19 A) to 18.0 V or any one cell reaches 2.80 V

Partial Charge (only for storage between the 6 monthly cycles):

- C/5 (38 A) to 80% SOC

Placed in Chamber at 40 °C and 80% SOC for 1 Month Storage Between Cycles

- Changed to 30 °C after cycle 14

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Cutoff Points for Each Cycle

Cycle	CC Charge Stop	CV Charge Stop	C/2 Discharge Stop	C/10 Discharge Stop
1	24.6 V	1.9 A	18 V	2.8 V (6)
2	24.6 V	1.9 A	18 V	2.8 V (6)
3	24.6 V	1.9 A	18 V	2.8 V (4)
4	24.6 V	1.9 A	18 V	2.8 V (4)
5	24.6 V	1.9 A	18 V	2.8 V (4)
6	24.6 V	1.9 A	18 V & 2.8 V(4)	2.8 V (4)
7	24.6 V	1.9 A	18 V & 2.8 V(4)	2.8 V (4)
8	24.6 V	1.9 A	18 V & 2.8 V(4)	2.8 V (4)
9	24.6 V	1.9 A	18 V & 2.8 V(4)	2.8 V (3)
10	24.6 V	1.9 A	18 V	2.8 V (6)
11	24.6 V	1.9 A	18 V	2.8 V (6)
12	24.6 V	1.9 A	18 V	2.8 V (4)
13	24.6 V	1.9 A	2.8 V (3)	2.8 V (3)
14	24.6 V	1.9 A	2.8 V (3)	2.8 V (3)
15	24.6 V	1.9 A	2.8 V (3)	2.8 V (3)

Cycle	CC Charge Stop	CV Charge Stop	C/2 Discharge Stop	C/10 Discharge Stop
16	24.6 V	1.9 A	2.8 V (3)	2.8 V (3)
17	24.6 V	1.9 A	2.8 V (3)	2.8 V (3)
18	24.6 V	1.9 A	2.8 V (3)	2.8 V (3)
19	24.6 V	1.9 A	2.8 V (3)	2.8 V (3)
20	24.6 V	1.9 A	2.8 V (3)	2.8 V (3)
21	24.6 V	1.9 A	2.8 V (3)	2.8 V (3)
22	24.6 V	1.9 A	2.8 V (3)	2.8 V (3)
23	24.6 V	1.9 A	2.8 V (3)	2.8 V (3)
24	24.6 V	1.9 A	2.8 V (3)	2.8 V (3)
25	24.6 V	1.9 A	2.8 V (3)	2.8 V (3)
26	24.6 V	1.9 A	2.8 V (3)	2.8 V (3)
27	24.6 V	1.9 A	2.8 V (3)	2.8 V (3)
28	24.6 V	1.9 A	2.8 V (3)	2.8 V (3)
29	24.6 V	1.9 A	2.8 V (3)	2.8 V (3)
30	24.6 V	1.9 A	2.8 V (3)	2.8 V (3)

Note: numbers in parenthesis (x) indicate the cell which caused cutoff

Cutoff Points	**CC Charge Stop**	Module = 24.6 V	or	1st Cell = 4.15 V
	CV Charge Stop	Current = 1.9 A	or	1st Cell = 4.15 V
	C/2 Discharge Stop	Module = 18.0 V	or	1st Cell = 2.8 V
	C/10 Discharge Stop	Module = 18.0 V	or	1st Cell = 2.8 V

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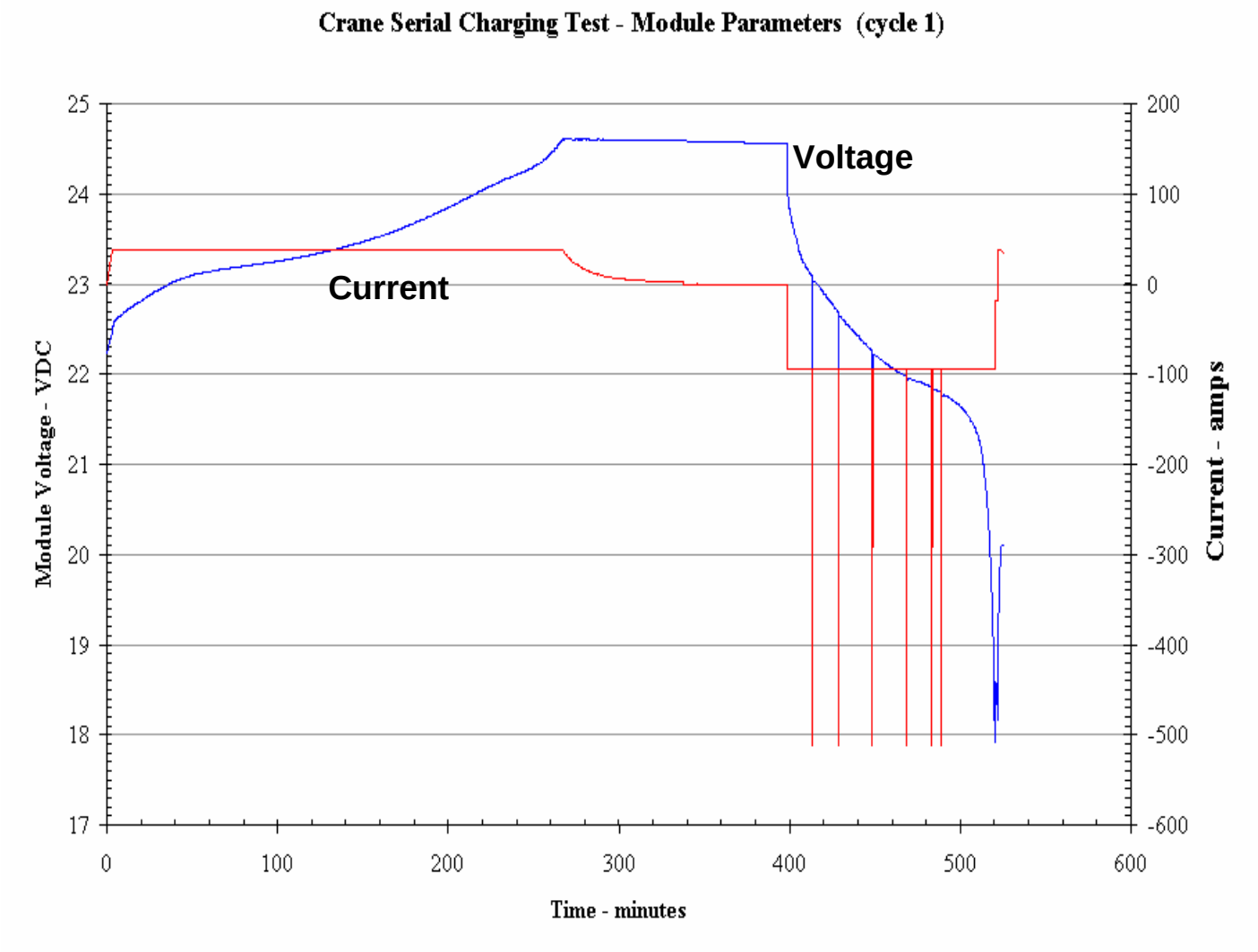
Typical Module Level Performance for One Cycle (cycle 1)



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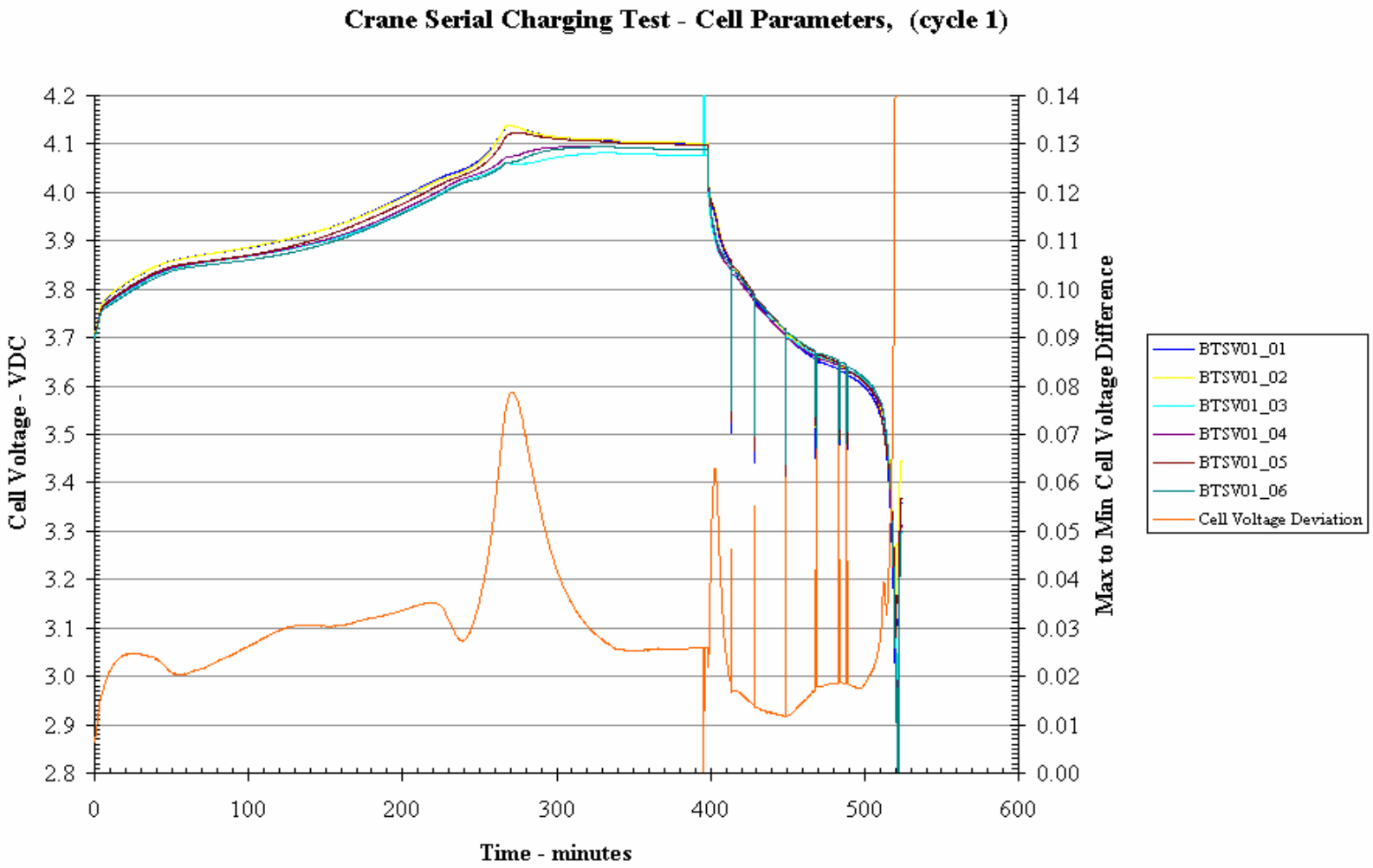
Typical Cell Level Performance for One Cycle (cycle 1)



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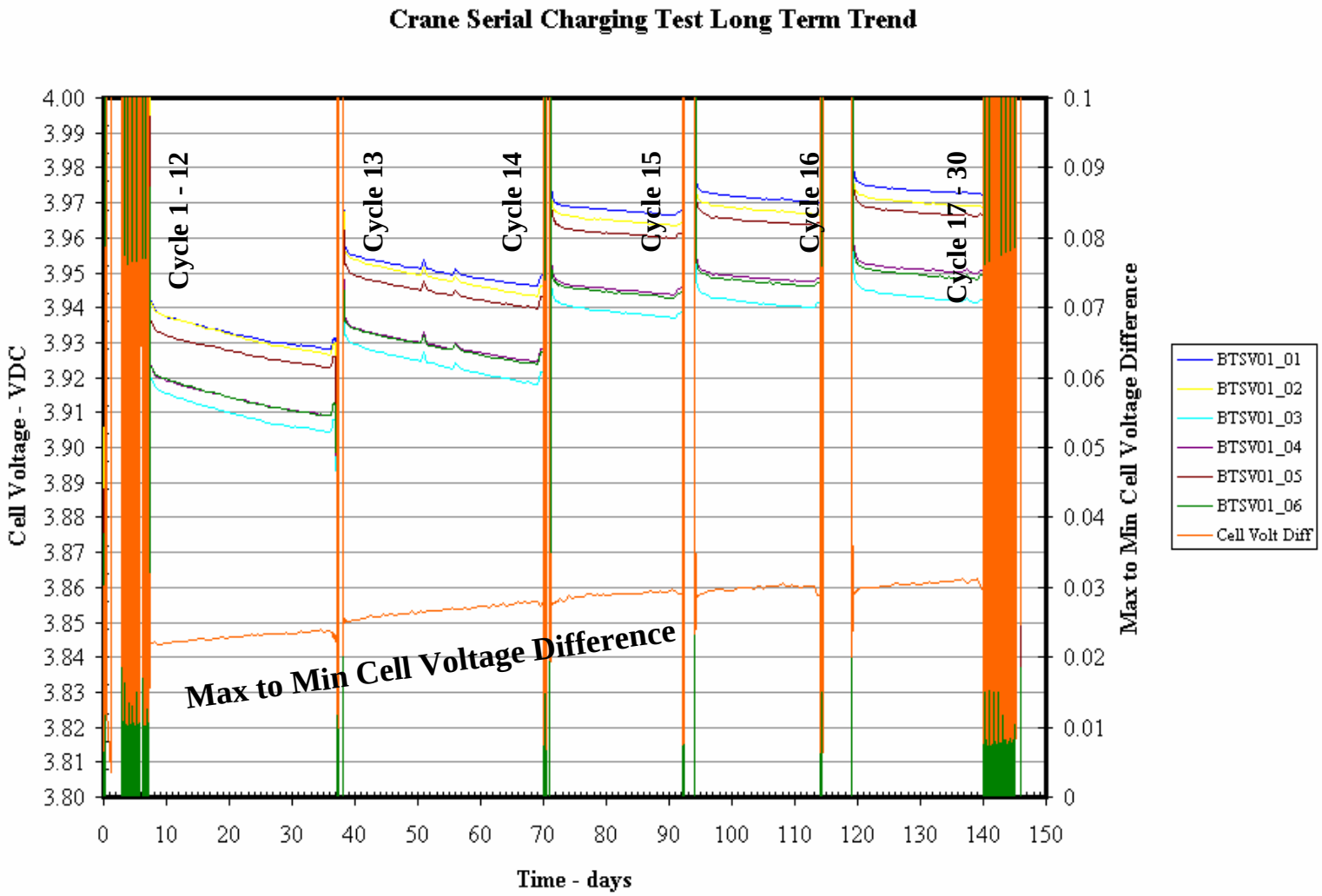
Cell Voltage Long Term Trends



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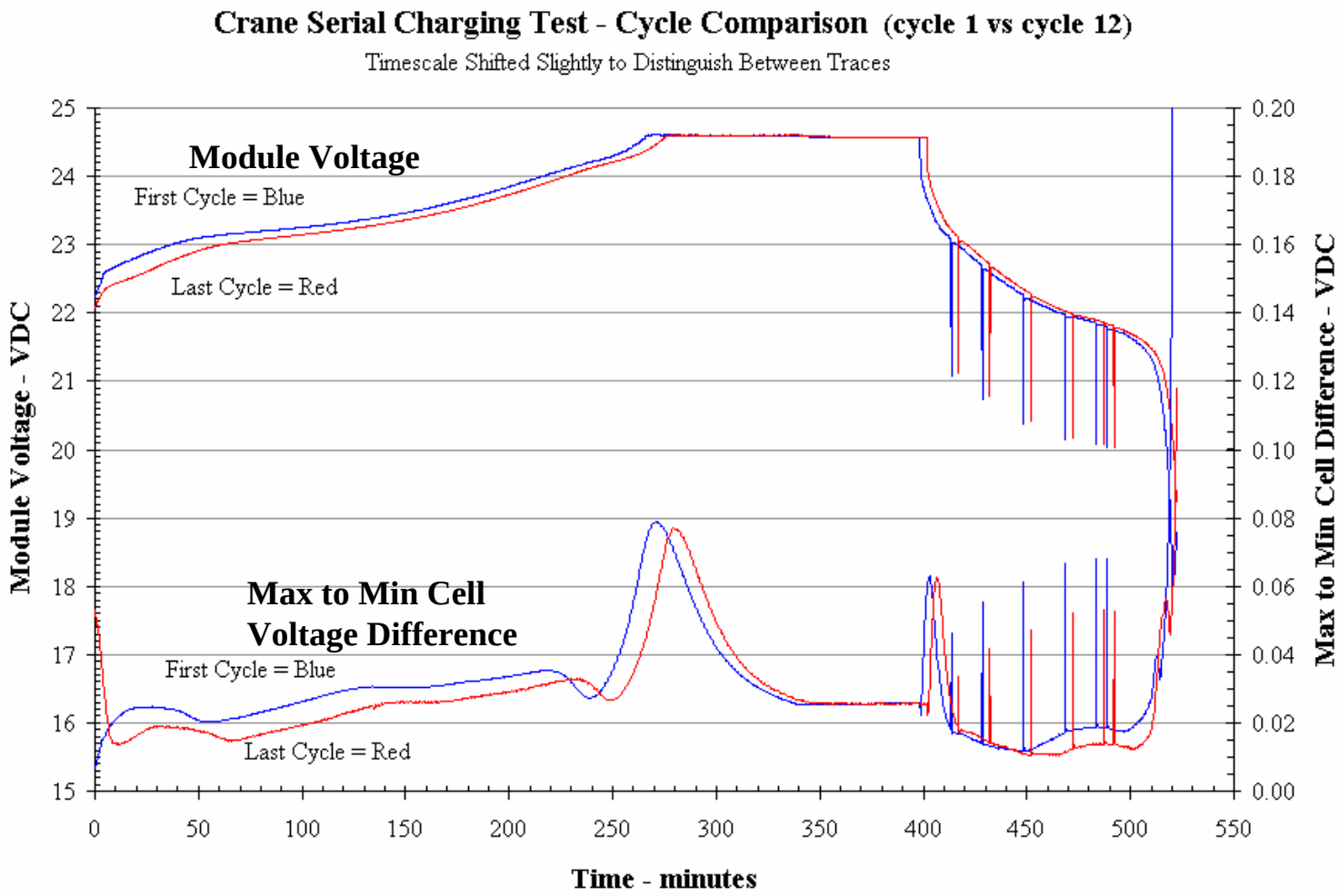
Module Level Performance Changes



Little Change in Initial 12 Back to Back Cycles

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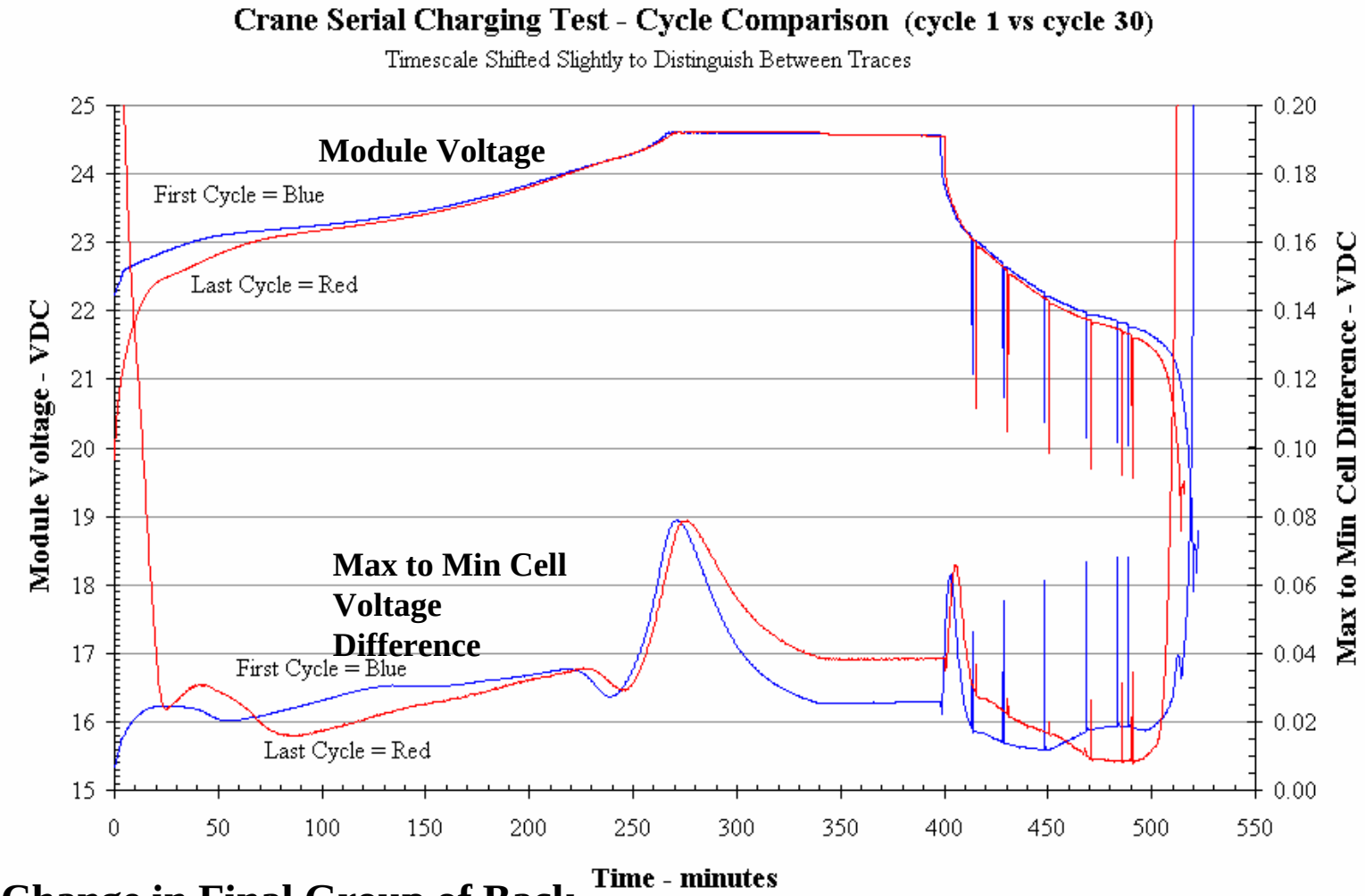
Module Level Performance Changes



Little Change in Final Group of Back to Back Cycles

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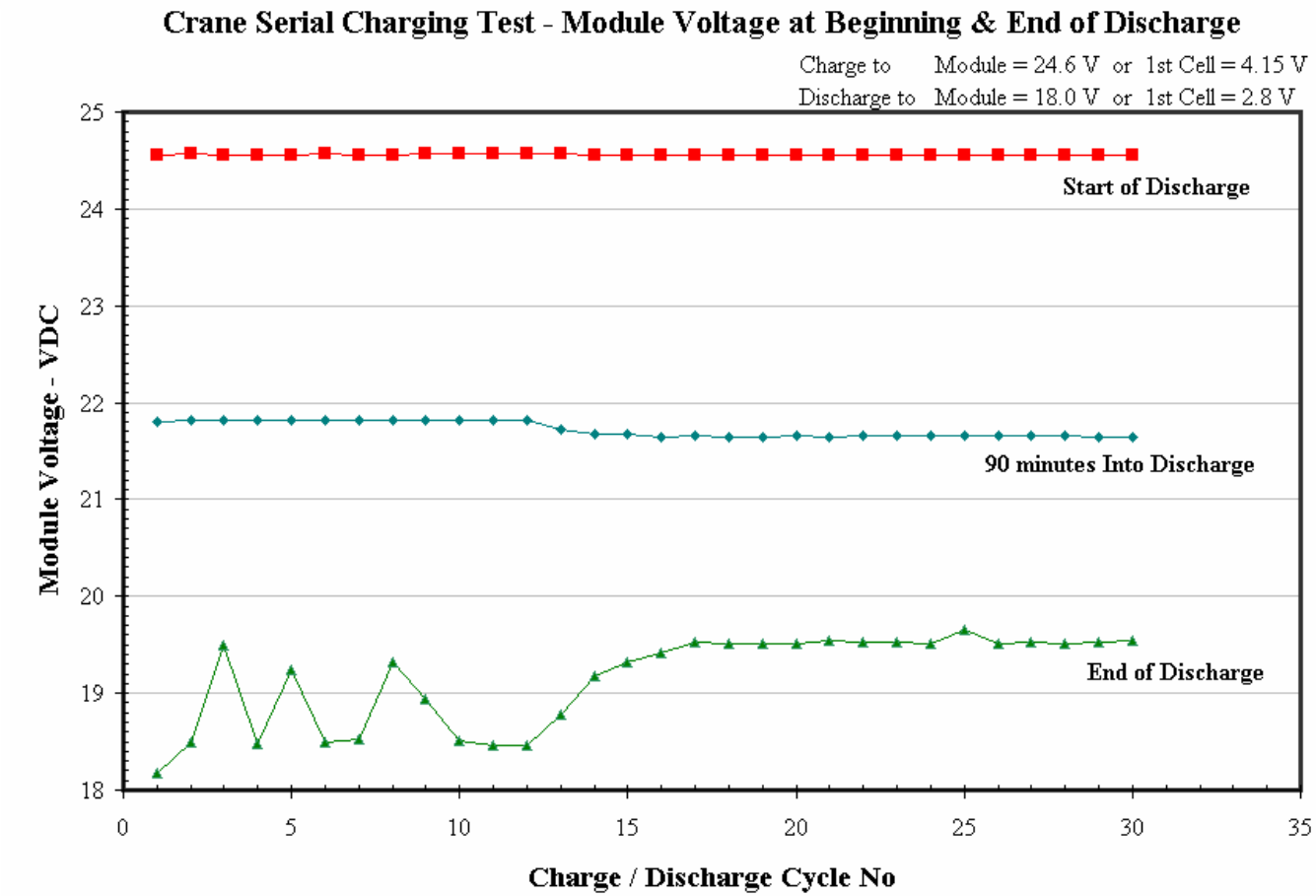
Module Level Voltage Trends



Increase In End of Discharge Voltage as Cells Age Because Discharge Cutoff Point Has Changed from Module Level to Cell Level

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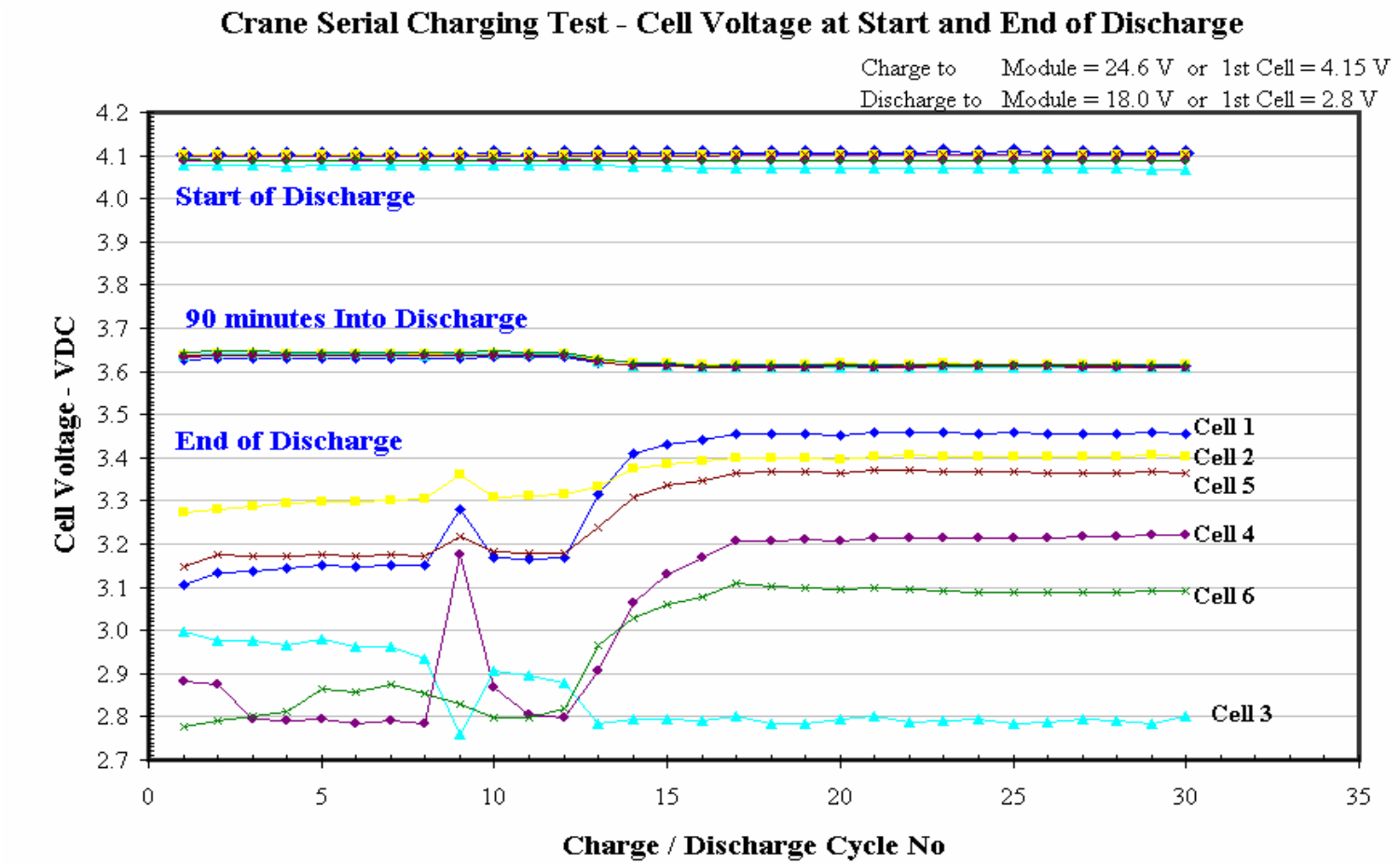
Cell Level Voltage Trends



Cell 3 Becomes the Driver for the Discharge Cutoff Point (compared to other cells, this cell has lowest initial resistance and mid range initial capacity)

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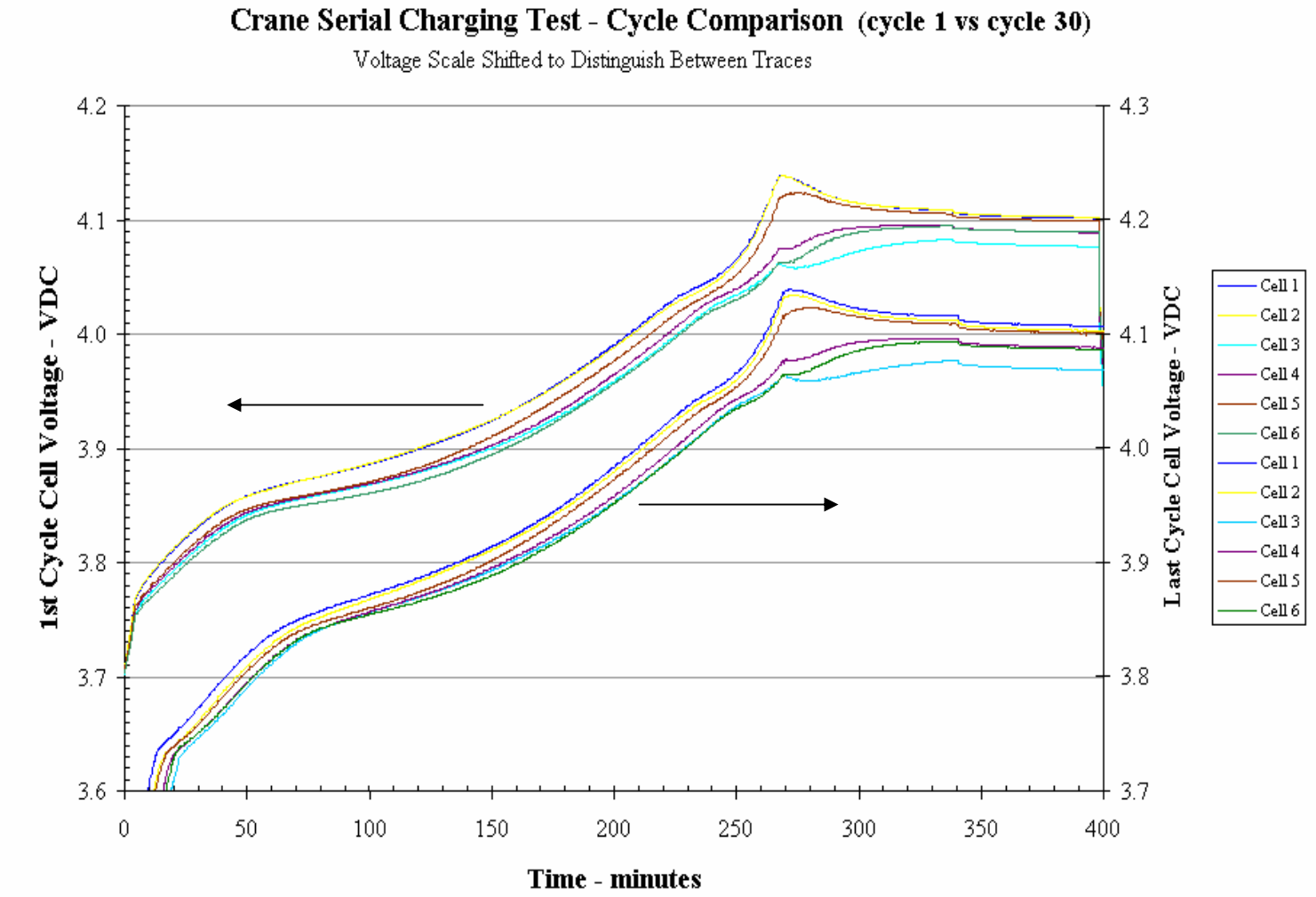
Cell-to-Cell Comparison During Charge



Little Change in Charge Performance or Order of Cell Voltage
(cell with highest voltage to cell with lowest voltage)

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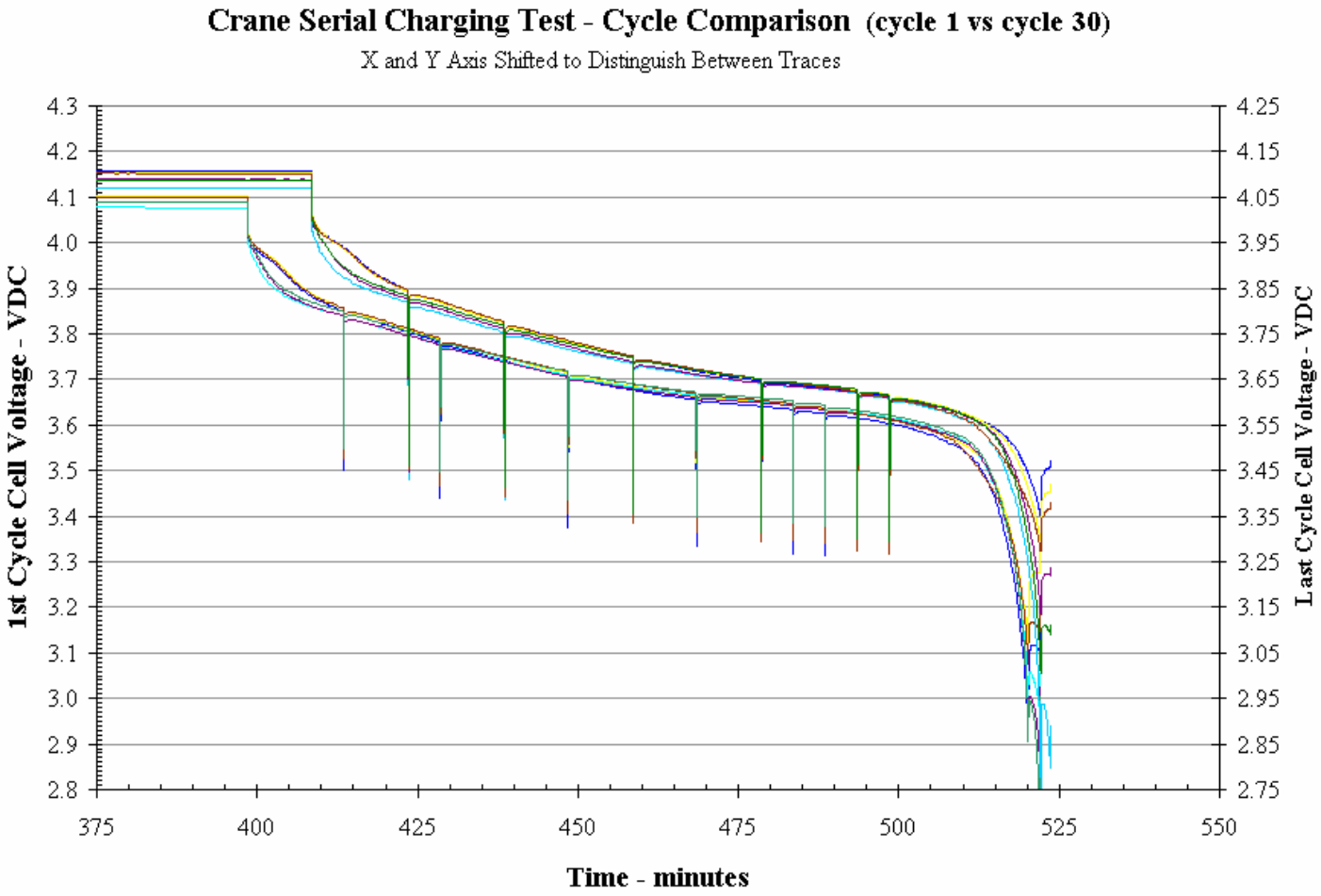
Cell-to-Cell Comparison During Discharge



Little Change in Order of Cell Voltage, But Discharge Duration Has Decreased

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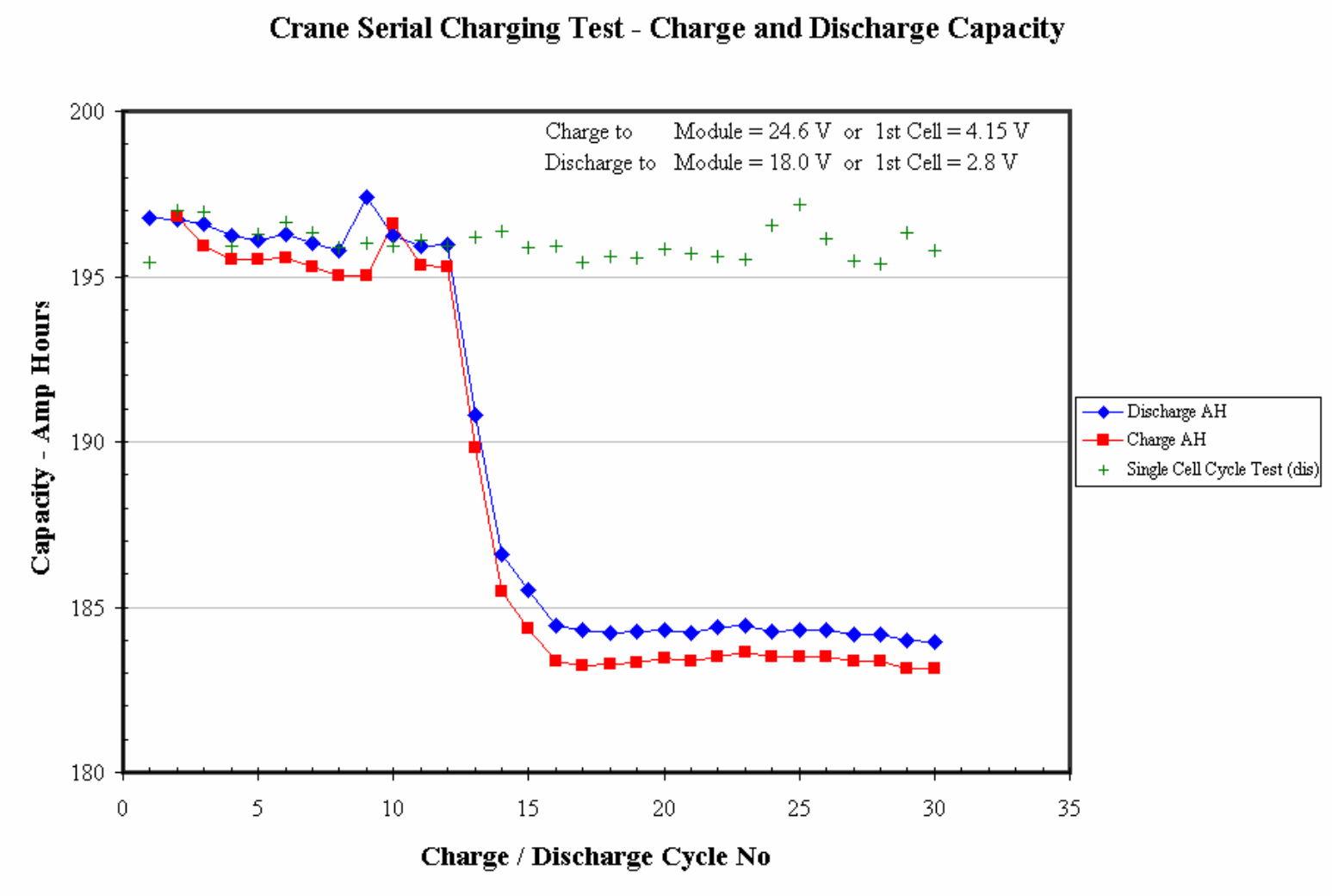
Module Capacity Long Term Trends



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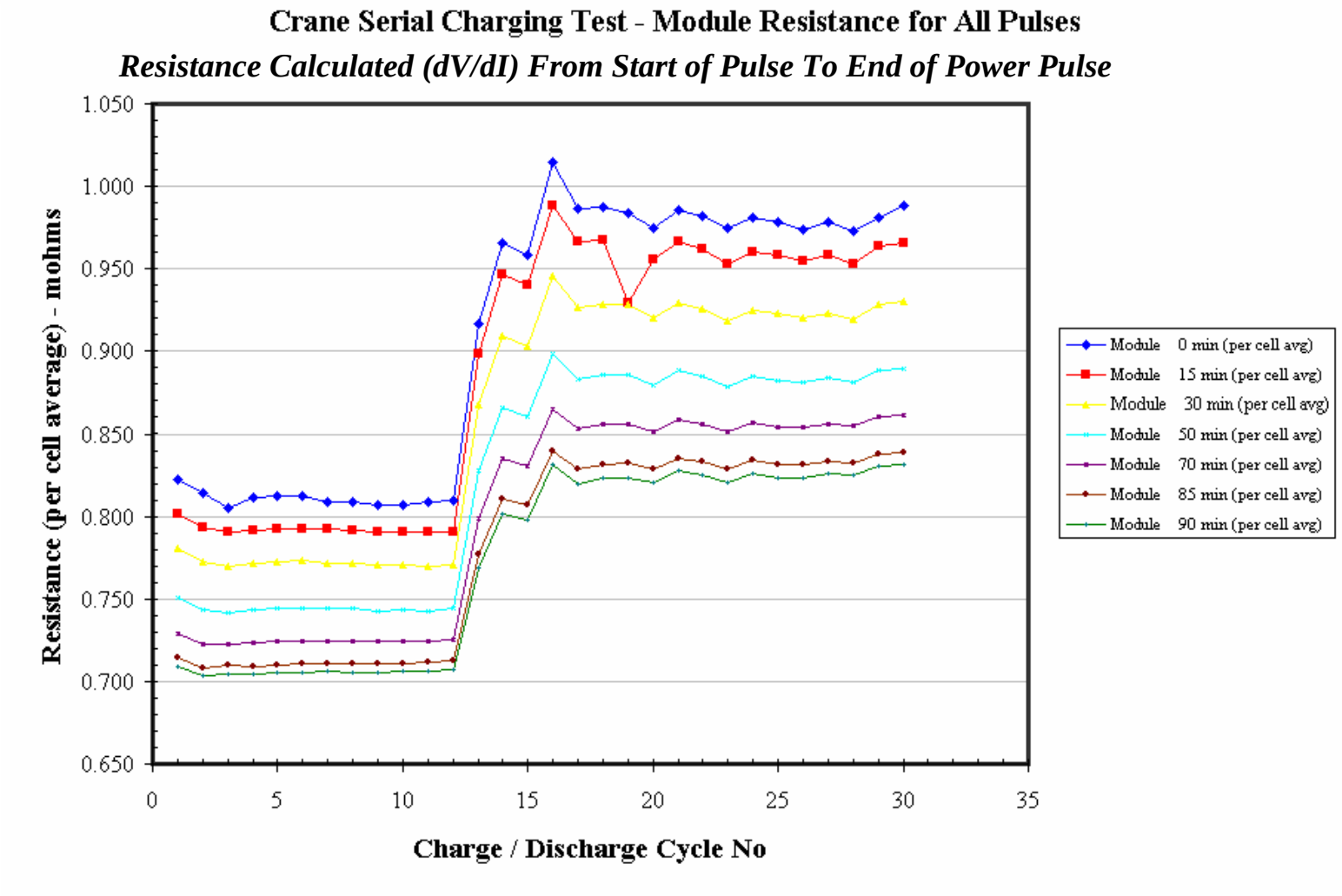
Module Resistance Trends



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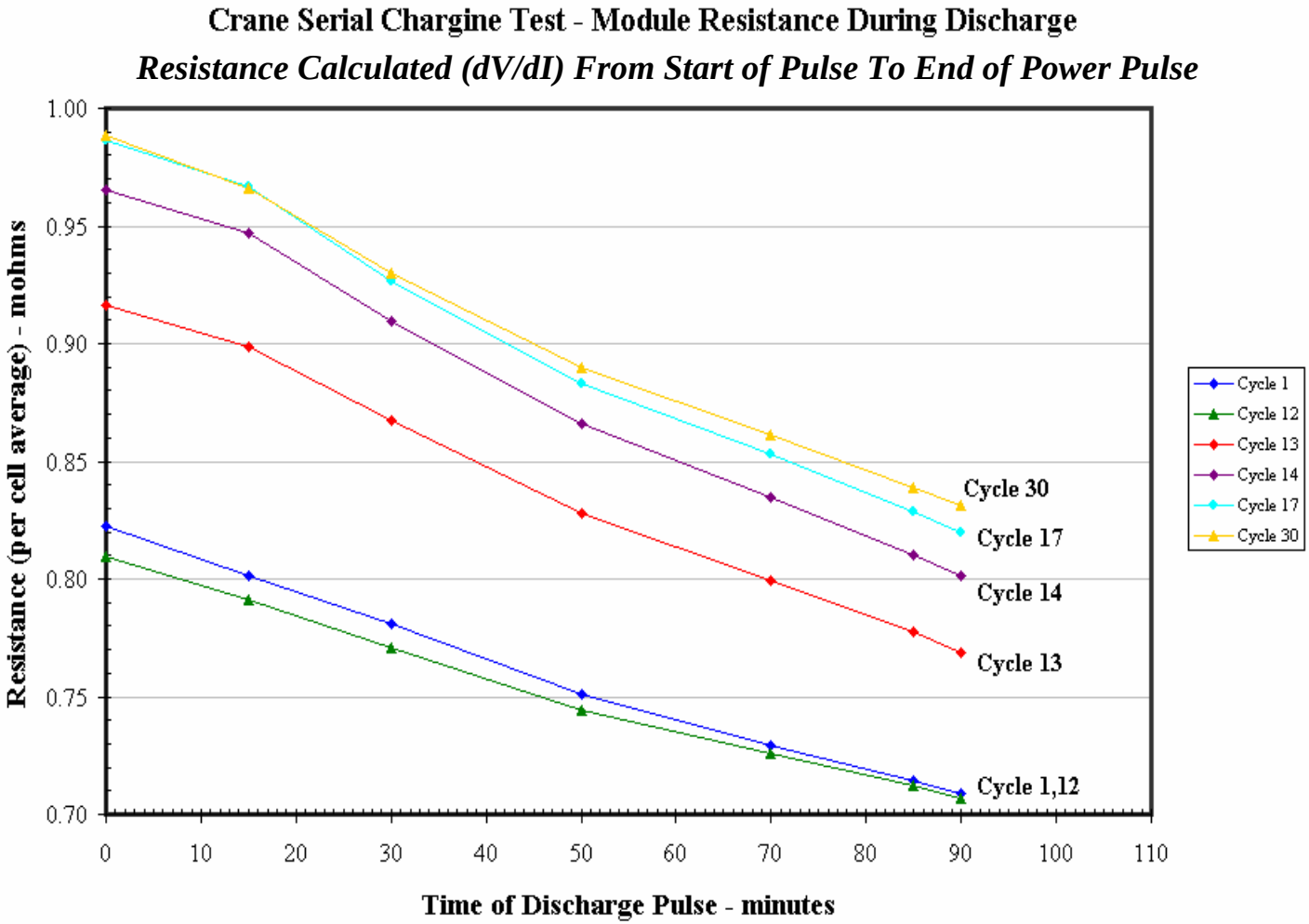
Module Resistance Trends



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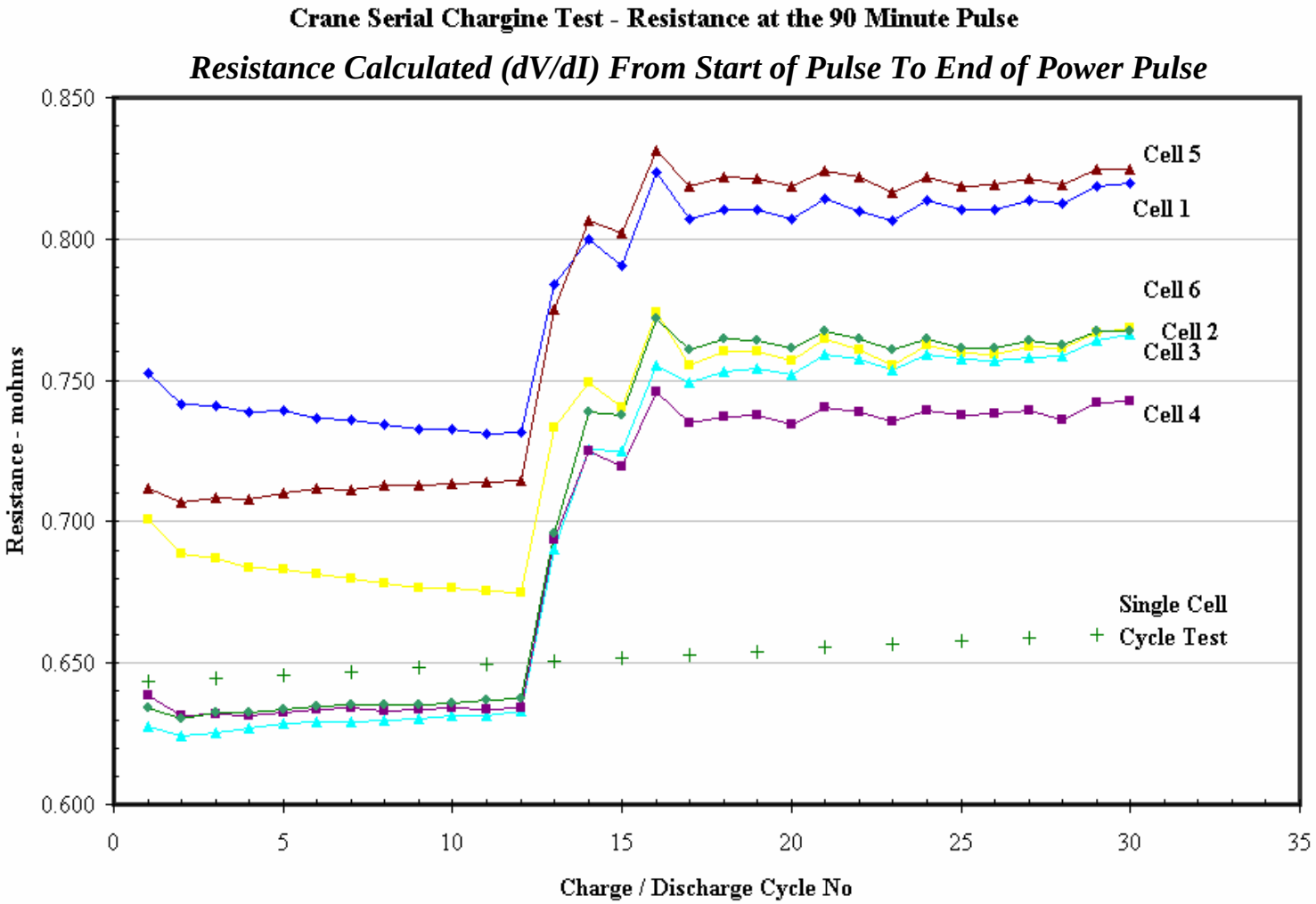

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Cell to Cell Ranking

Highest

Lowest

Cycle 1

Internal Resistance	Voltage - Charge	Voltage - Early in Discharge	Voltage - Late in Discharge
1	1	2	2
5	2	5	5
2	5	1	1
6	4	6	3
4	6	4	4
3	3	3	(6)

Cycle 12

Internal Resistance	Voltage - Charge	Voltage - Early in Discharge	Voltage - Late in Discharge
1	1	2	2
5	2	5	5
2	5	1	1
6	4	6	3
4	3	4	6
3	6	3	(4)

Highest

Lowest

Cycle 17

Internal Resistance	Voltage - Charge	Voltage - Early in Discharge	Voltage - Late in Discharge
5	1	1	1
1	2	5	2
6	5	2	5
2	4	6	4
3	3	4	6
4	6	3	(3)

Cycle 30

Internal Resistance	Voltage - Charge	Voltage - Early in Discharge	Voltage - Late in Discharge
5	1	1	1
1	2	5	2
6	5	2	5
2	4	6	4
3	3	4	6
4	6	3	(3)

- ***The Relative Order is Generally Consistent***

( ) = Cell Causing Discharge Cutoff

- ***Cells With Higher Internal Resistance Have Higher Voltage Throughout Charge/Discharge Cycle***
- ***Cells With Lower Internal Resistance Cause the Discharge Cutoff***

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Individual Cell Capacity Cycles

Cells Subjected to Capacity Cycles Before and After Serial Charging Test

- Pretest (3 cycles) 4.1 to 3.0 VDC at 19 amps
- Post Test (1 cycle) 4.1 to 3.0 VDC at 95 amps Followed By 19 amps to 3.0 VDC

Parameter	Cell 1 (s/n 003)	Cell 2 (s/n 013)	Cell 3 (s/n 022)	Cell 4 (s/n 096)	Cell 5 (s/n 111)	Cell 6 (s/n 126)
Ah Pretest Cycle 1	199.30	190.43	195.76	193.60	201.72	196.28
Ah Pretest Cycle 2	199.19	190.63	195.91	193.85	201.56	196.07
Ah Pretest Cycle 3	199.35	190.58	195.75	193.80	201.35	195.81
Ah Post Test	187.47	184.84	189.40	188.86	183.98	188.04
Decrease During Serial Charging Test	6.0%	3.0%	3.2%	2.5%	8.6%	4.0%

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General Observations

Although it looks like module level voltage drives the cutoff for charge, the actual cutoff is due to unbalanced cell voltages that drive the module voltage up.

Individual cell voltage drives the cutoff for discharge

Low resistance cells are the first to reach the low-voltage cutoff

Cell-to-Cell voltage differences are generally small and show similar trends for each cycle

Increase for a distinct window during charge and at the end of discharge
Increase in max to min cell voltage difference with time / cycles
Decrease in max to min cell voltage difference during high current pulses with time / cycles

Individual cell voltage trends (with respect to other cells) are very repeatable from cycle to cycle, although voltage slowly degrades with time / cycles (resistance growth)

Much more difference observed near end of discharge
Little change in order of cell voltage (cell with highest voltage to cell with lowest voltage)

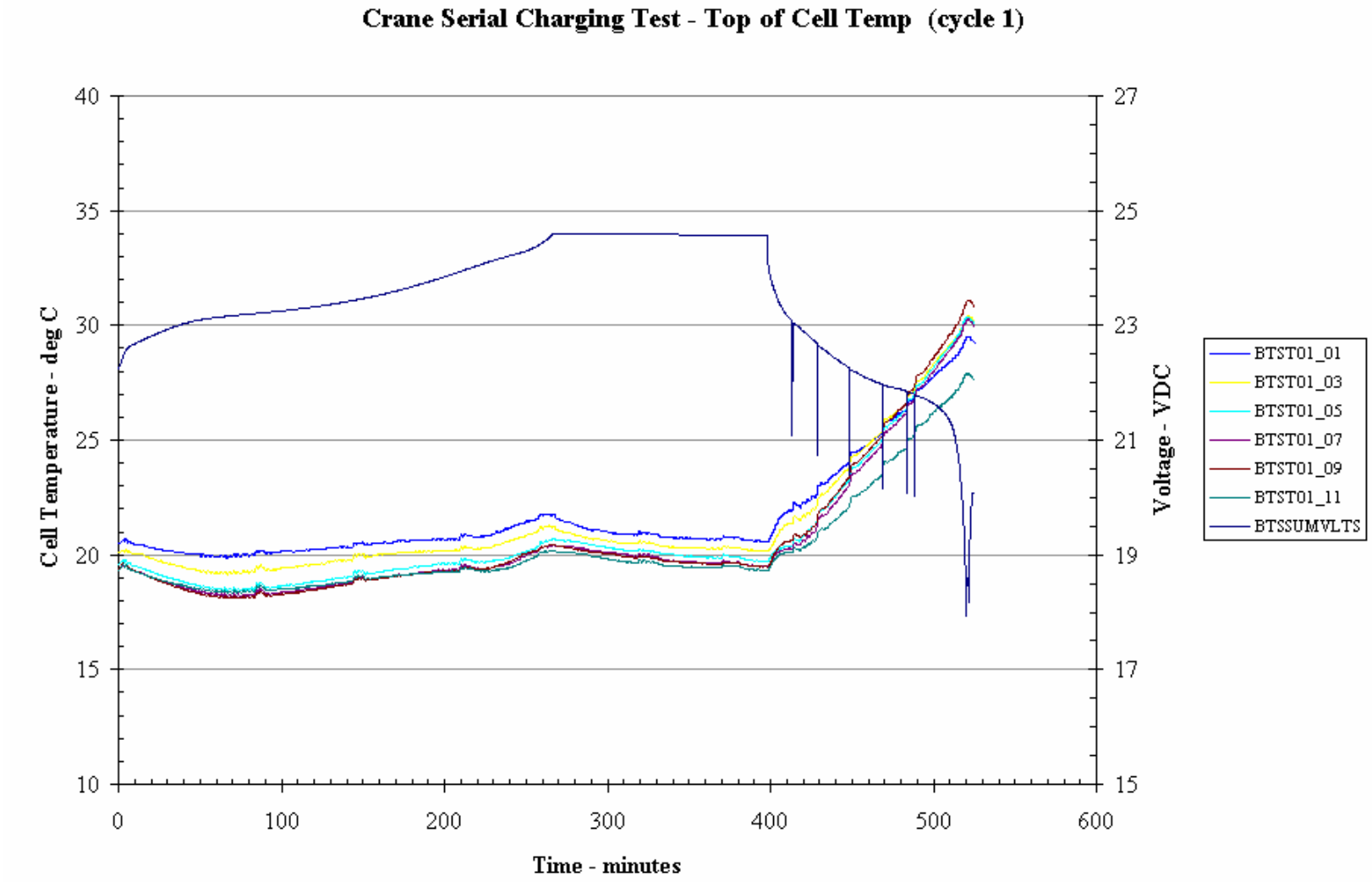
Temp sensor on the side of cell (between 2 cells) shows much greater rise during discharge than for single cell tests (18 °C vs 5 °C)

Conclusion: Serial Charging of this string of cells is feasible as it has only a minor impact on useful capacity

Acknowledgment

NSWC – Crane, Indiana for performing the tests.

Cell Level Temperatures - Discharge (cycle 1)



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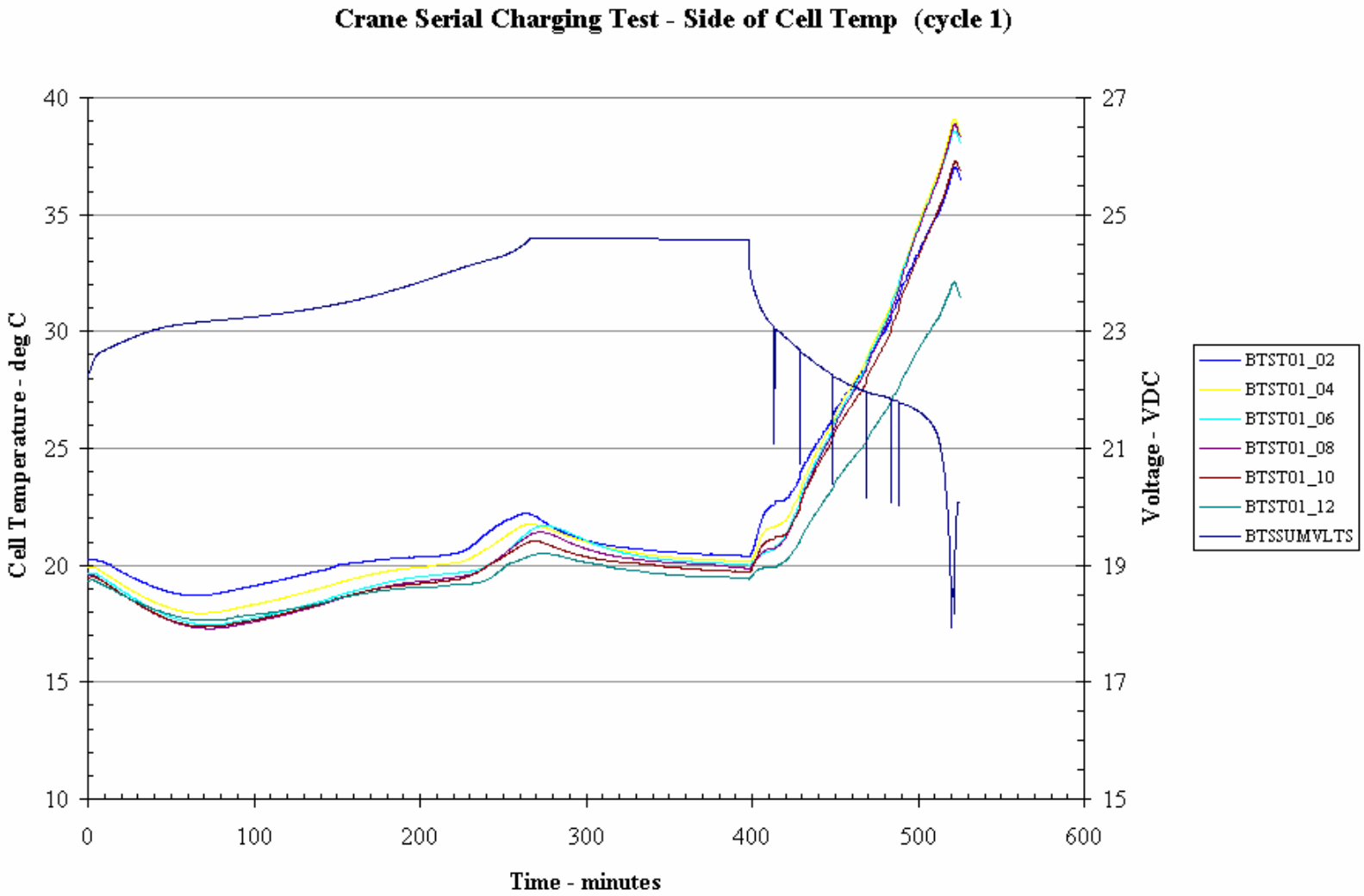

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