



# STRATEGIC MISSIONS



**DETER  
DEFEND  
DEFEAT**

# **Lithium Ion Testing at NSWC Crane in Support of NASA Goddard Space Flight Center**

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**CRANE DIVIDSON, NAVAL SURFACE WAREFARE CENTER  
Crane Indiana**

**NASA AEROSPACE BATTERY WORKSHOP – Nov 16-18, 2010  
Huntsville, Al**



- **QUALLION 15 Ahr Lithium-Ion Cells**
  - LEO Life Cycle Test
- **LITHION 50 Ahr Lithium-Ion Cells**
  - LEO Life Cycle Test
- **ABSL 5 Ahr Lithium-Ion Battery**
  - LRO-LLO Life Cycle Test
  - SDO-GEO Life Cycle Test
- **A123 40 Ahr Lithium-Ion Battery**
  - GPM Life Cycle Test
  - MMS Life Cycle Test



# QUALLION 15 Ahr Lithium-Ion Cells LEO Life Cycle Test



# QUALLION 15 Ah (G001QL) TEST PARAMETERS

**Test Pack: Eight 15 Ah LiNiO<sub>2</sub> cells in series**

**Manufacturer: QUALLION**

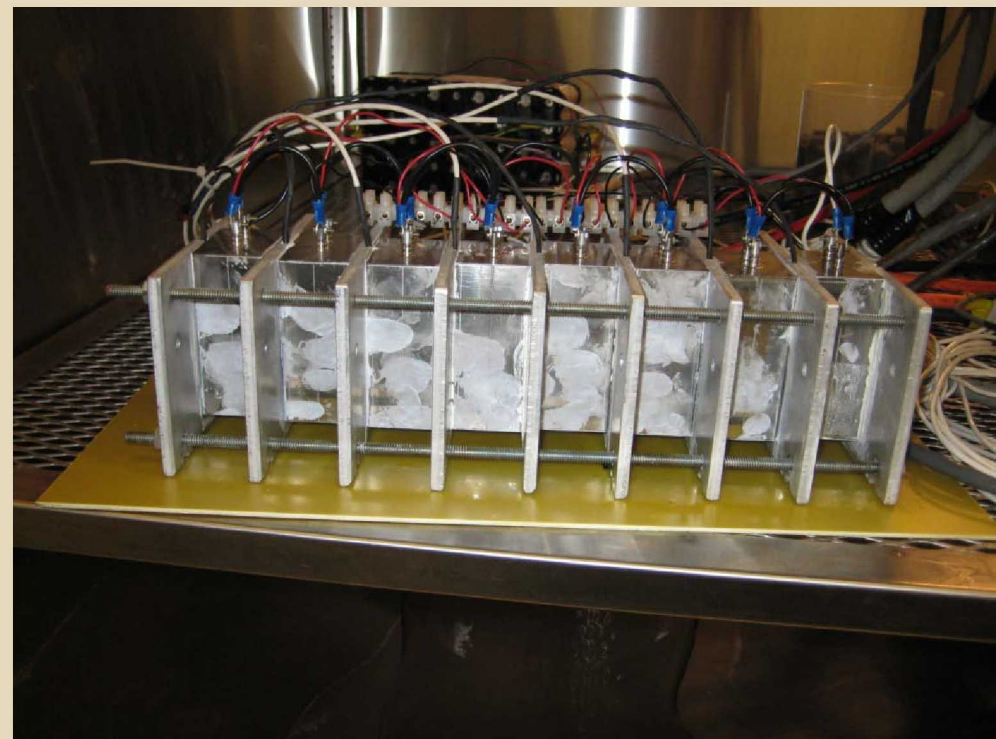
**Initial Evaluation:**

**Actual Capacity at 20°C = 14 Ahr,  
0°C = 12 Ahr,  
40°C = 15.6 Ahr**

**Initial Parameters:**

**Test Temperature 20°C**

**Pre-Life Cycle Charge:  
C/10 charge to 32.8V,  
taper to C/100**



**LEO Life Cycle: 6A discharge for 48 minutes (32% DOD)**

**7A charge to 31.6V, taper for 65 minute charge time**

**80% DOD Deep Discharge**

**Every 30 days: 7A charge to 32.8V, taper for 65 minute charge time**

**6A discharge for 120 minutes (80% DOD)**

**Return to LEO Life Cycle profile**

# QUALLION 15 Ah (G001QL) TEST HISTORY



**9 December 2004 – Began Initial Evaluation test**

**22 February 2005 – Began life cycling**

**6A discharge for 48 minutes (32% DOD)**

**7A charge to 31.6v, Taper for remainder of 65 minutes**

**9 May 2005 – Changed discharge rate for Deep Discharge to 4.5A for 160 minutes**

**8 June 2005 – Changed Life Cycling charge rate to 6A (Cycle 1217)**

**6 May 2008 – LEO Life Cycle profile changed to (Cycle 13,453):**

**9.6A discharge for 30 minutes (32% DOD)**

**6.5A charge to 31.6v, Taper for remainder of 60 minutes**

**20 May 2008 – LEO Life Cycle profile changed to (Cycle 13,677):**

**12.0A discharge for 30 minutes (40% DOD)**

**8.1A charge to 31.6v, Taper for remainder of 60 minutes**

**80% DOD Deep Discharge Cycle Eliminated**

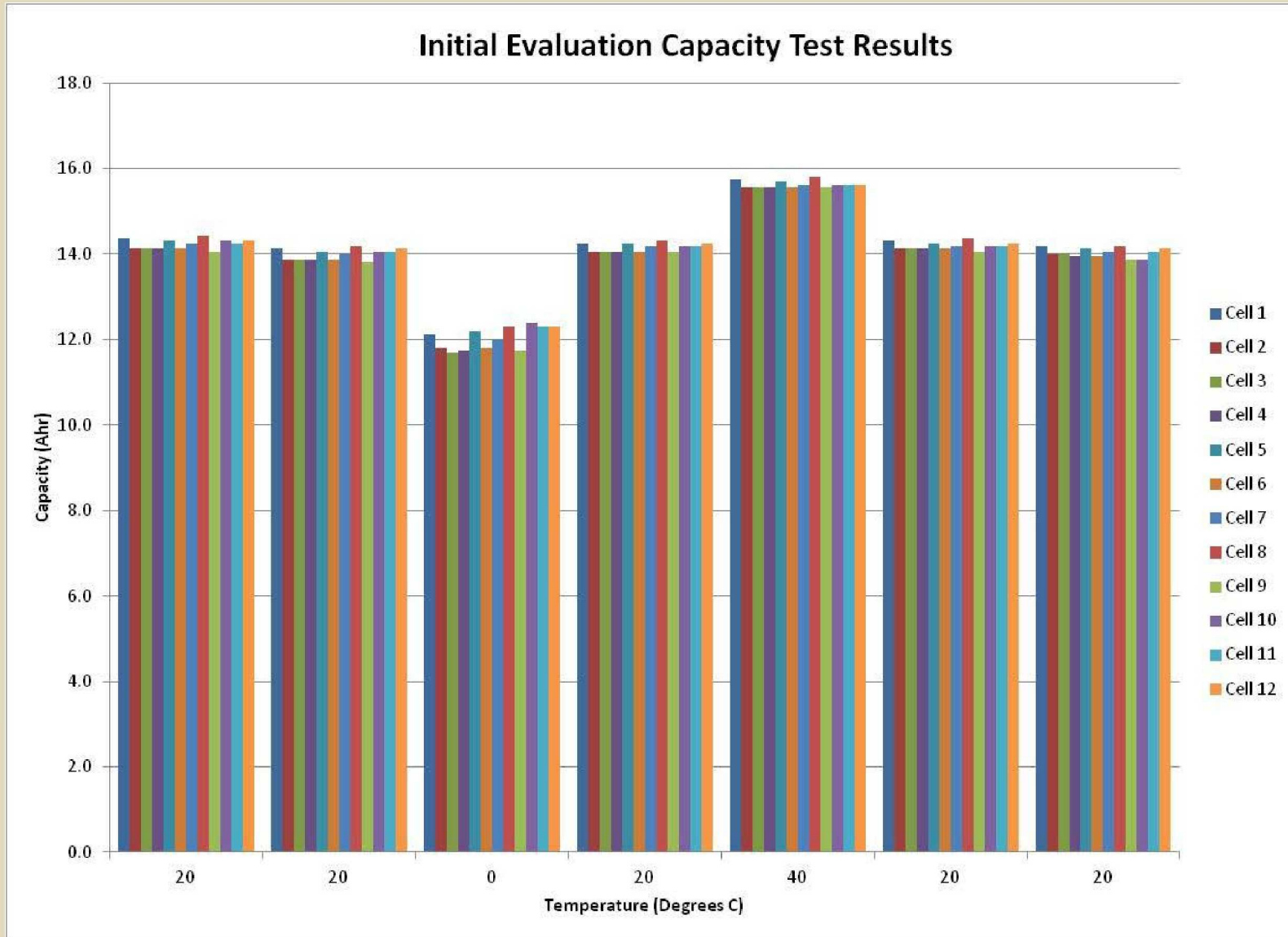
**8 September 2008 – Cycle 15,426. Test Pack was moved from its location in Building 3235 to a new test system in building 3287 due to renovation of the building 3235 area.**

**23 June 2010 – End LEO Life Test – 25,533 cycles 5 years, 4 months  
Performed Post Cycle Test**

**30 August 2010 – Report GDD GXS 10-093**



# QUALLION 15 Ah (G001QL) Initial Evaluation Results



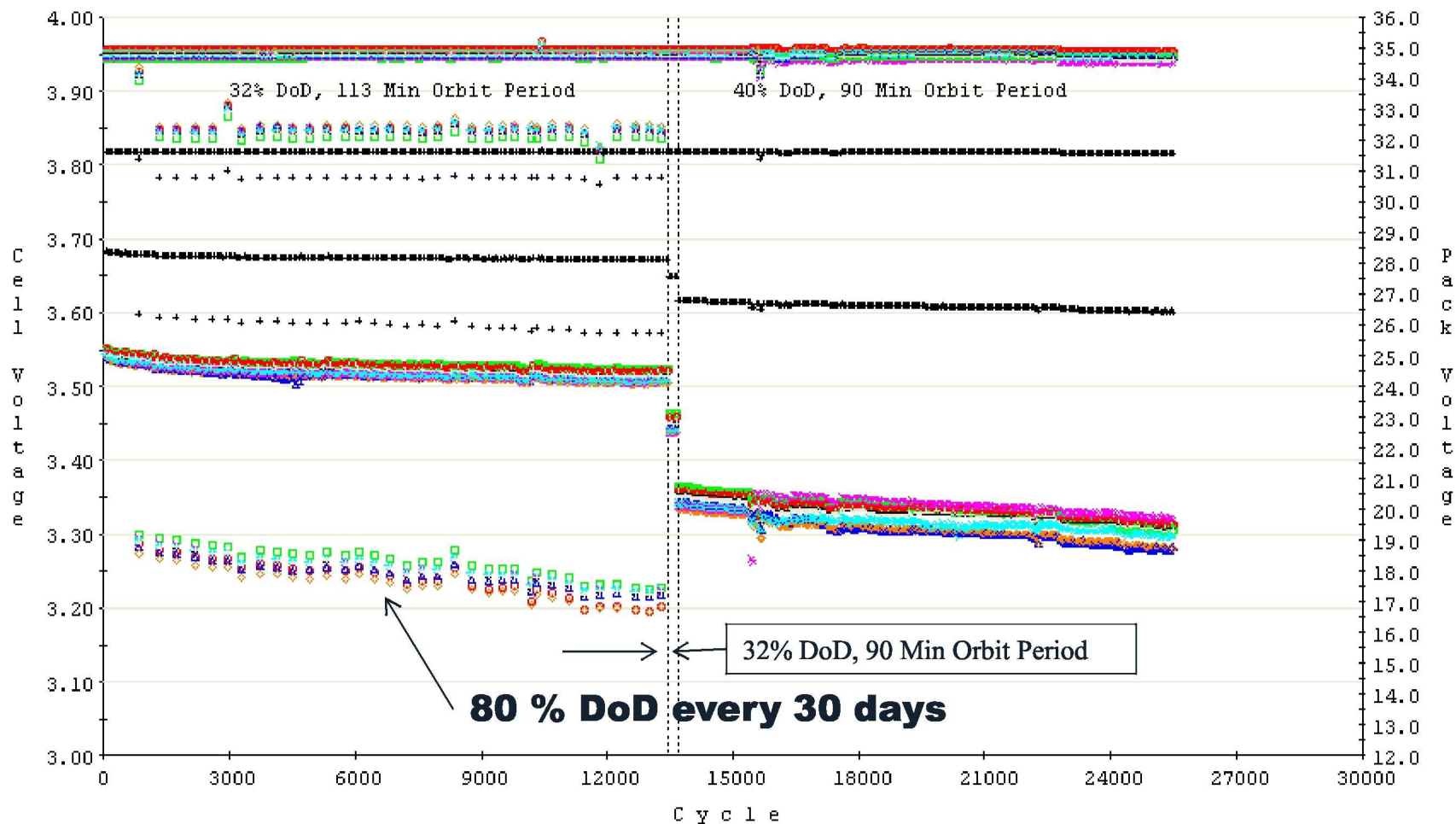


# QUALLION 15 Ah (G001QL) Life Cycle Test Results

## Life Cycle Test Results G001QL

Test Start 50 02-26-2005 To End 25500 06-21-2010 Every 50 cycles

■ Cell 1 
 ● Cell 2 
 ▲ Cell 3 
 ◆ Cell 4 
 ✱ Cell 5 
 ▶ Cell 6 
 - Cell 7 
 + Cell 8 
 + Tvolt

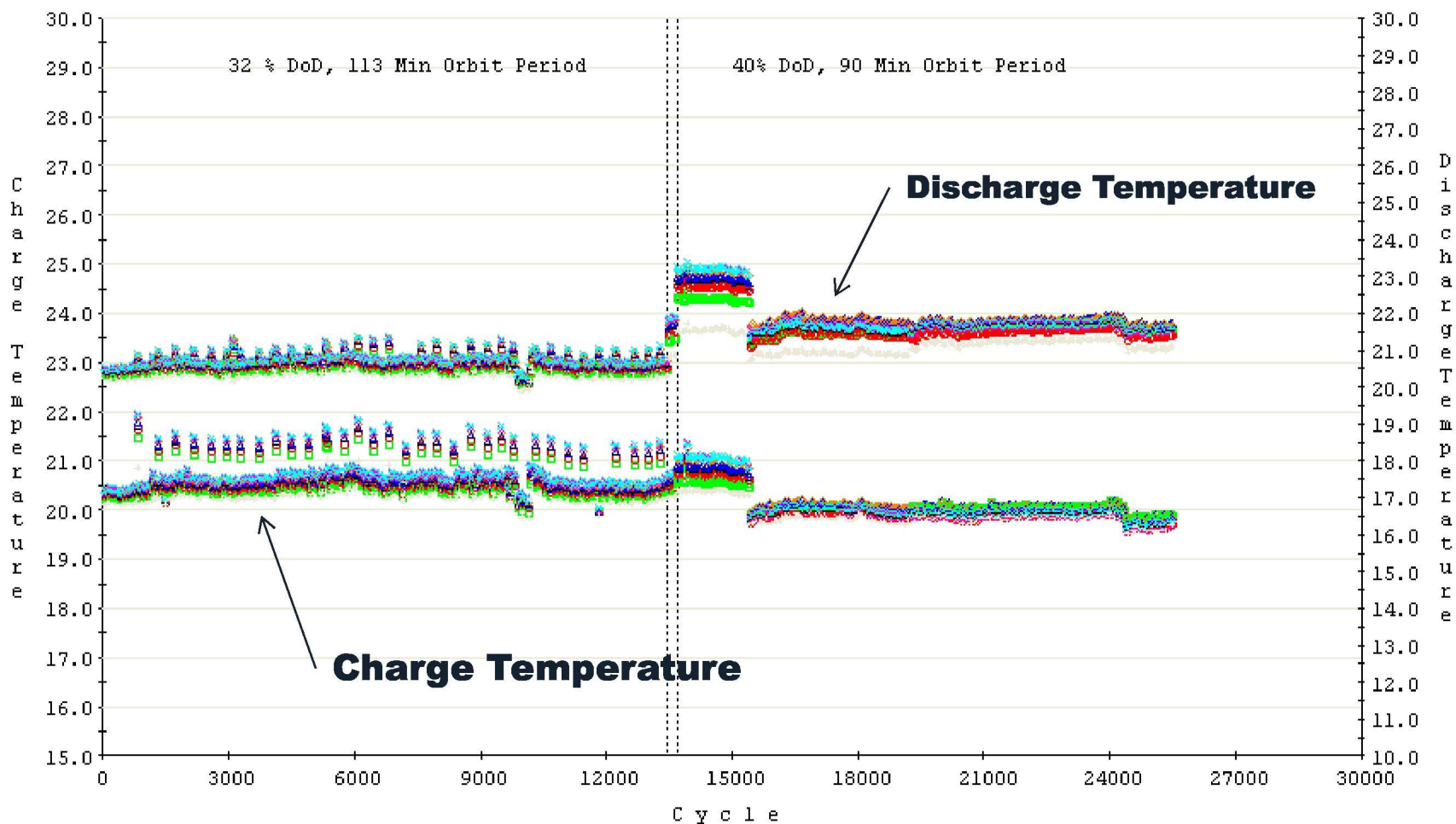


# QUALLION 15 Ah (G001QL) Life Cycle Test Results

## Life Cycle Test Results G001QL

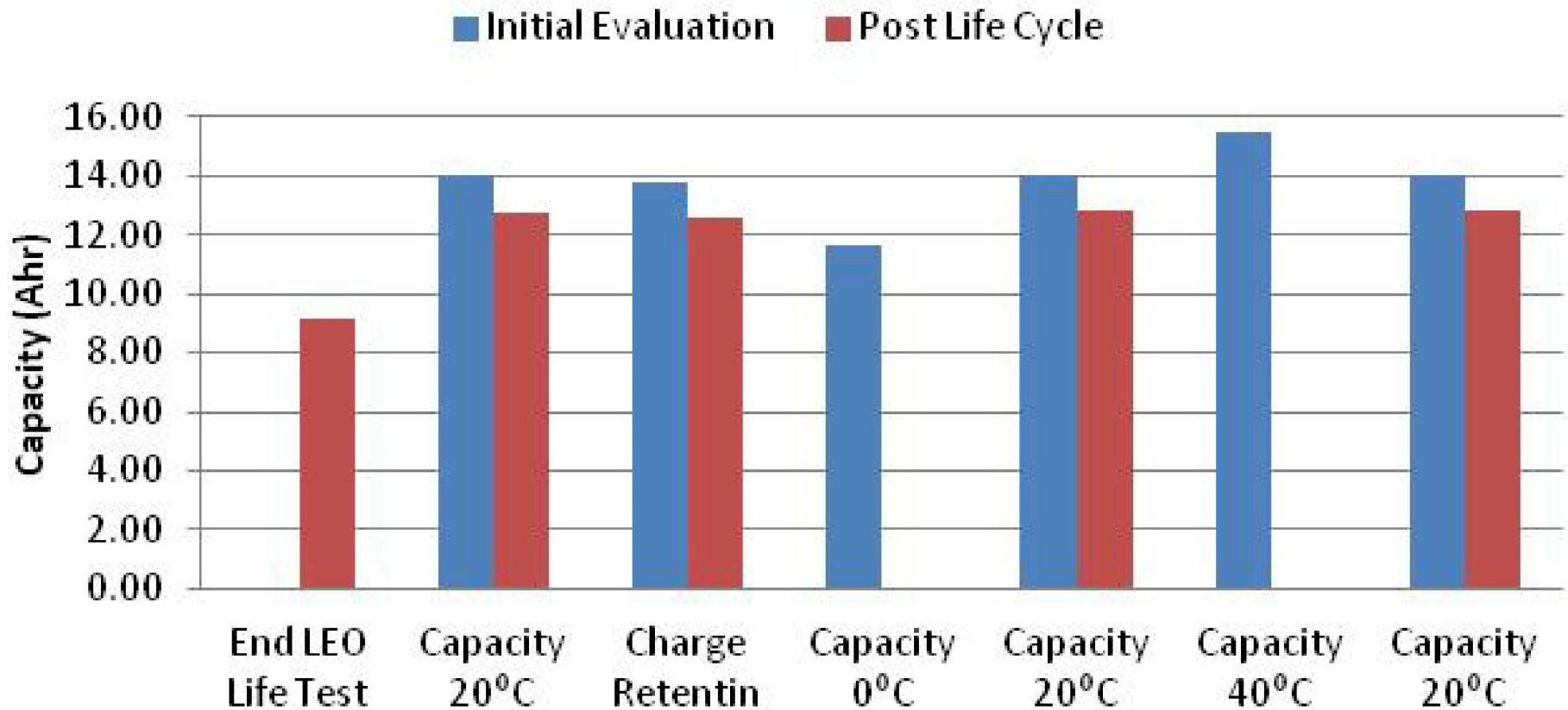
Test Start 50 02-26-2005 To End 25500 06-21-2010 Every 50 cycles

■ Cell 1 
 ■ Cell 2 
 ▲ Cell 3 
 ◆ Cell 4 
 ✖ Cell 5 
 ▶ Cell 6 
 - Cell 7 
 + Cell 8



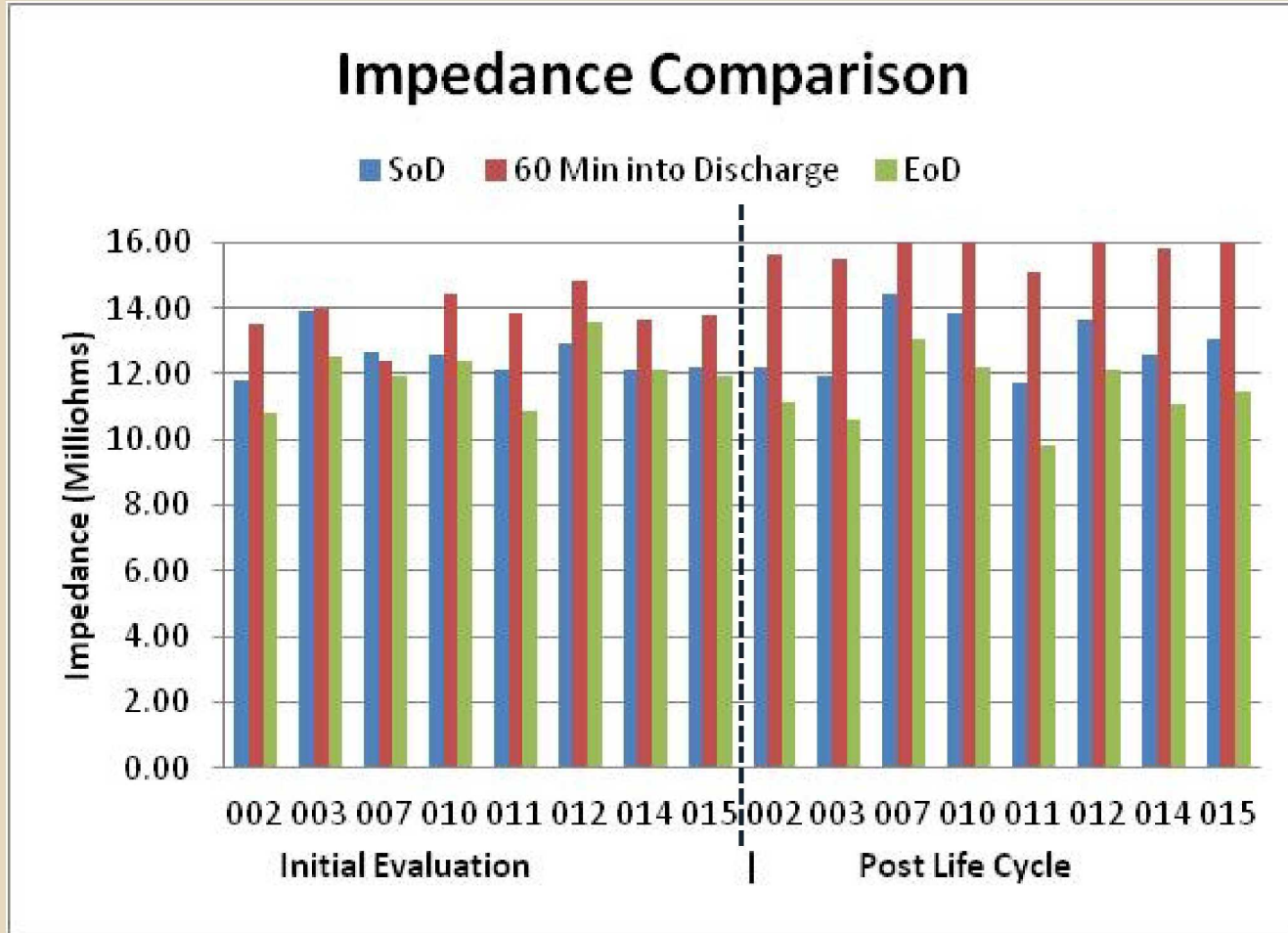
# QUALLION 15 Ah (G001QL) Post Life Cycle Test Results

## Comparison Capacity Test Results





# QUALLION 15 Ah (G001QL) Post Life Cycle Test Results





# LITHION 50 AHR LITHIUM-ION CELLS LEO LIFE CYCLE TEST



# LITHION 50 Ahr Lithium-Ion Cells Test Parameters



**Test Pack: Four 50 Ah LiNiO<sub>2</sub> cells in series**  
**Manufacturer: YARDNEY TECHNICAL PRODUCTS INC.**

**Initial Evaluation:**

**Actual Capacity at 20°C = 57.7 Ahr,**  
**0°C = 56.6 Ahr,**  
**40°C = 61.0 Ahr**

**Initial Parameters:**

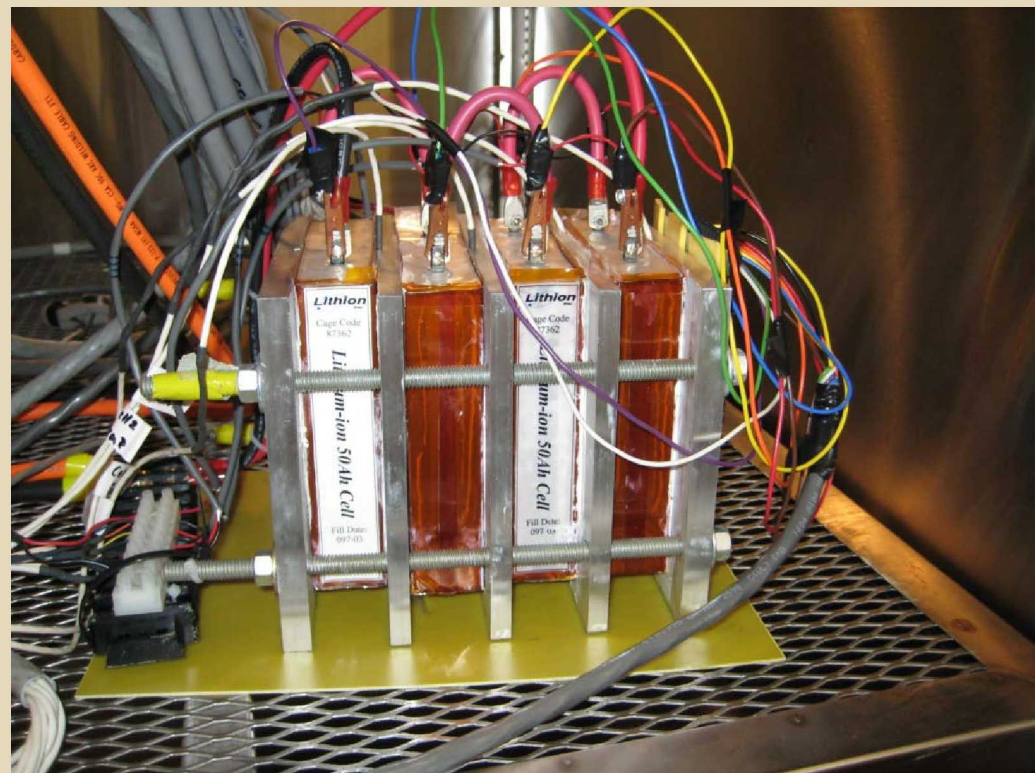
**Test Temperature 20°C**

**Pre-Life Cycle Charge:**  
**C/10 charge to 16.4V,**  
**then taper to C/100**

**Every 6 months:**

**22A Charge to 16.4V,**  
**taper for 65 minute charge time**  
**15A Discharge for 160 minutes (80% DOD)**  
**Return to LEO Life Cycle profile**

**LEO Life Cycle: 25A discharge for 48 minutes (40% DOD)**  
**22A charge to 15.8V, taper for 65 minute charge time**





# LITHION 50 Ahr Lithium-Ion Cells Test History



**24 March 2005 – Began Initial Evaluation**

**28 April 2005 – Began life cycling – The cells began diverging.**

**6 February 2007 – Cycle 7654. To decrease cell divergence, increased EOCV from 15.8V to 16.4V and EUVL from 4.2V to 4.3. Was not successful.**

**23 March 2007 – Cycle 8204. Attached Crane Developed Resistor Cell Balance Unit. The EOCV was lowered back to 15.8V and EUVL to 4.2**

**30 March 2007 – Cycle 8290. Removed Crane Developed Resistor Cell Balance Unit.**

**17 April 2008 – Cycle 12,520. Crane Developed Resistor Cell Balance Unit attached again because of increasing cell divergence. To be removed in 6 months.**

**4 September 2008 – Cycle 14,274. Test Pack was moved from its location in Building 3235 to a new test system in building 3287 due to renovation of the building 3235 area.**

**20 October 2008 – Cycle 14,845. Crane Developed Resistor Cell Balance Unit removed.**

**3 March 2009 – Cycle 16,493. Crane Developed Resistor Cell Balance Unit reinstalled on pack. Resistance Balance Circuit remained on for remainder of test,**

**23 June 2010 – Discontinued. Completed 22,461 cycles 5 years  
Performed Post Cycle test.**

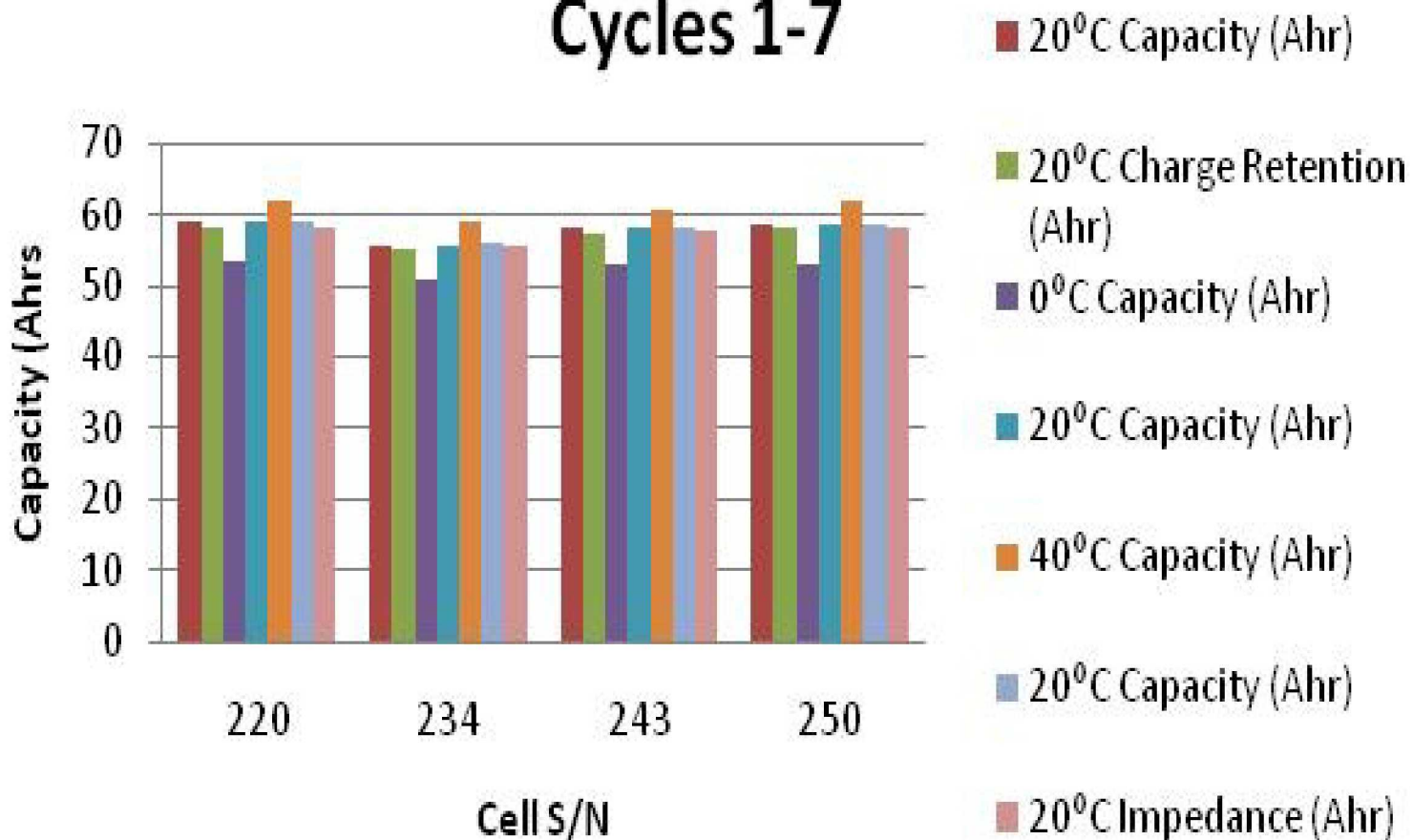
**24 September 2010 – Report GDD GXS 10-107**

# LITHION 50 Ahr Lithium-Ion Cells Initial Evaluation Summary

Capacity at 20°C = 57.7 Ahr,  
0°C = 56.6 Ahr,  
40°C = 61.0 Ahr

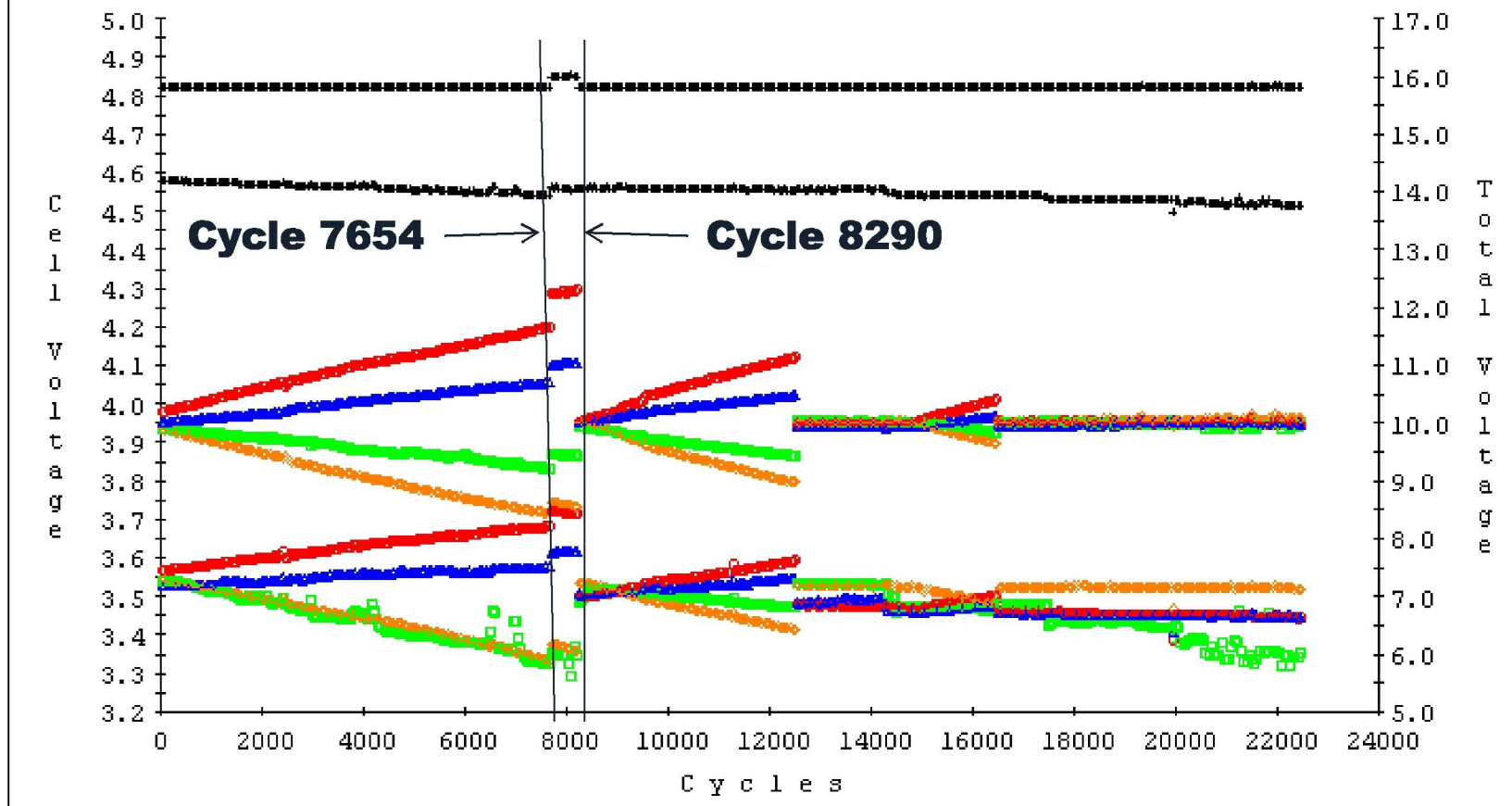
## Initial Evaluation Test Pack B001L

### Cycles 1-7



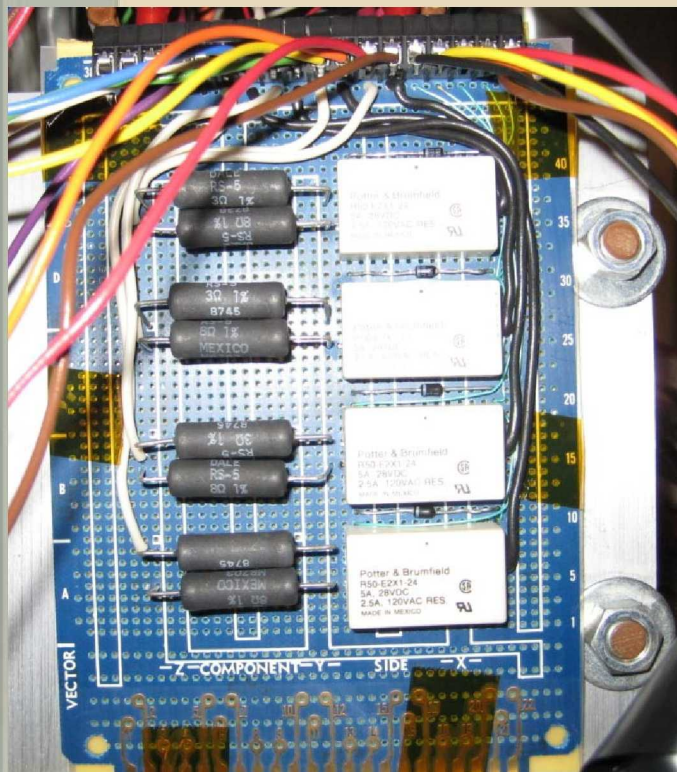
# LITHION 50 Ahr Lithium-Ion Cells Life Cycle Test Summary

Life Cycle Test Summary - Pack G002LL  
 Cycle 50 05-02-2005 to 22450 06-22-2010 - plotted every 50 cycles  
 LEO Cycling at 20 Deg C, Discharge 40% (25A for 48 Min.), Charge 22.0A to 15.8v, taper for remainder 65 min.  
 □ Cell 220 ○ Cell 234 ▲ Cell 243 ◆ Cell 250 + Tvolt

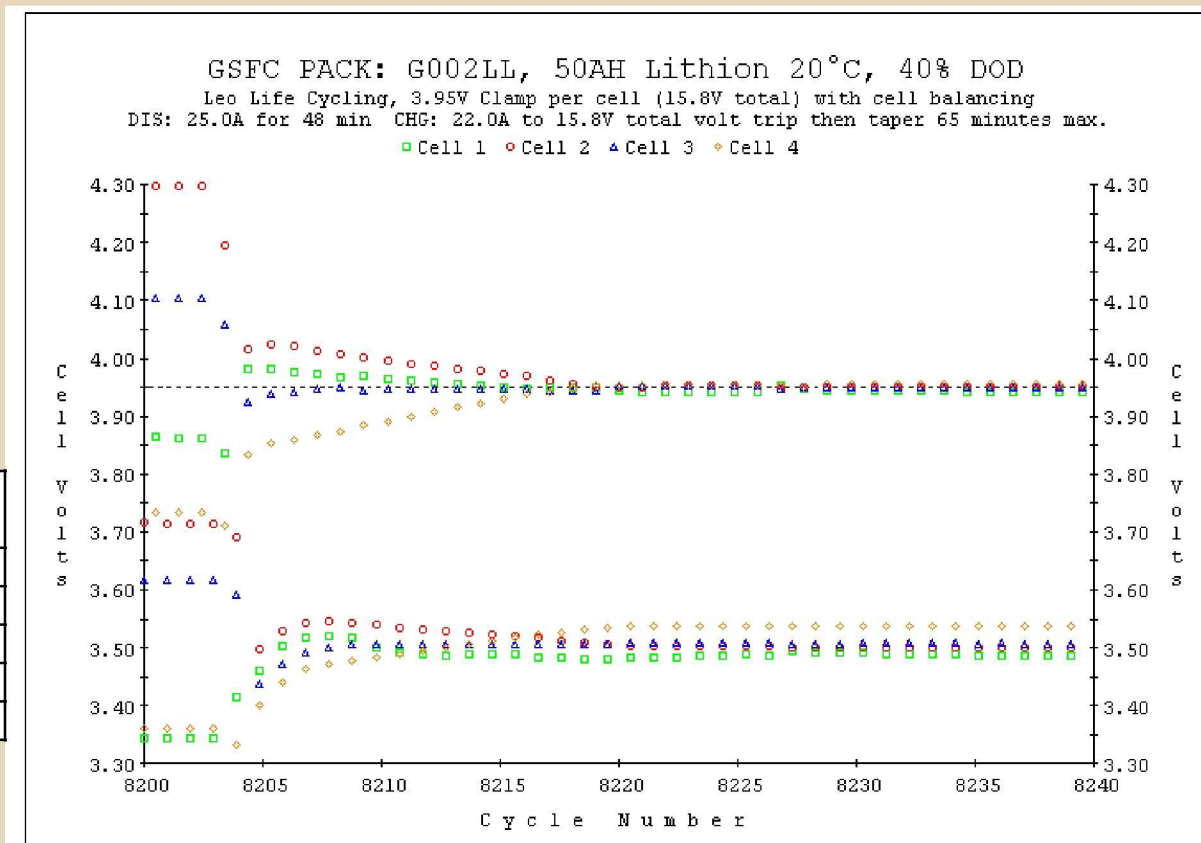




# LITHION 50 Ahr Lithium-Ion Cells LEO Life Cycle Test

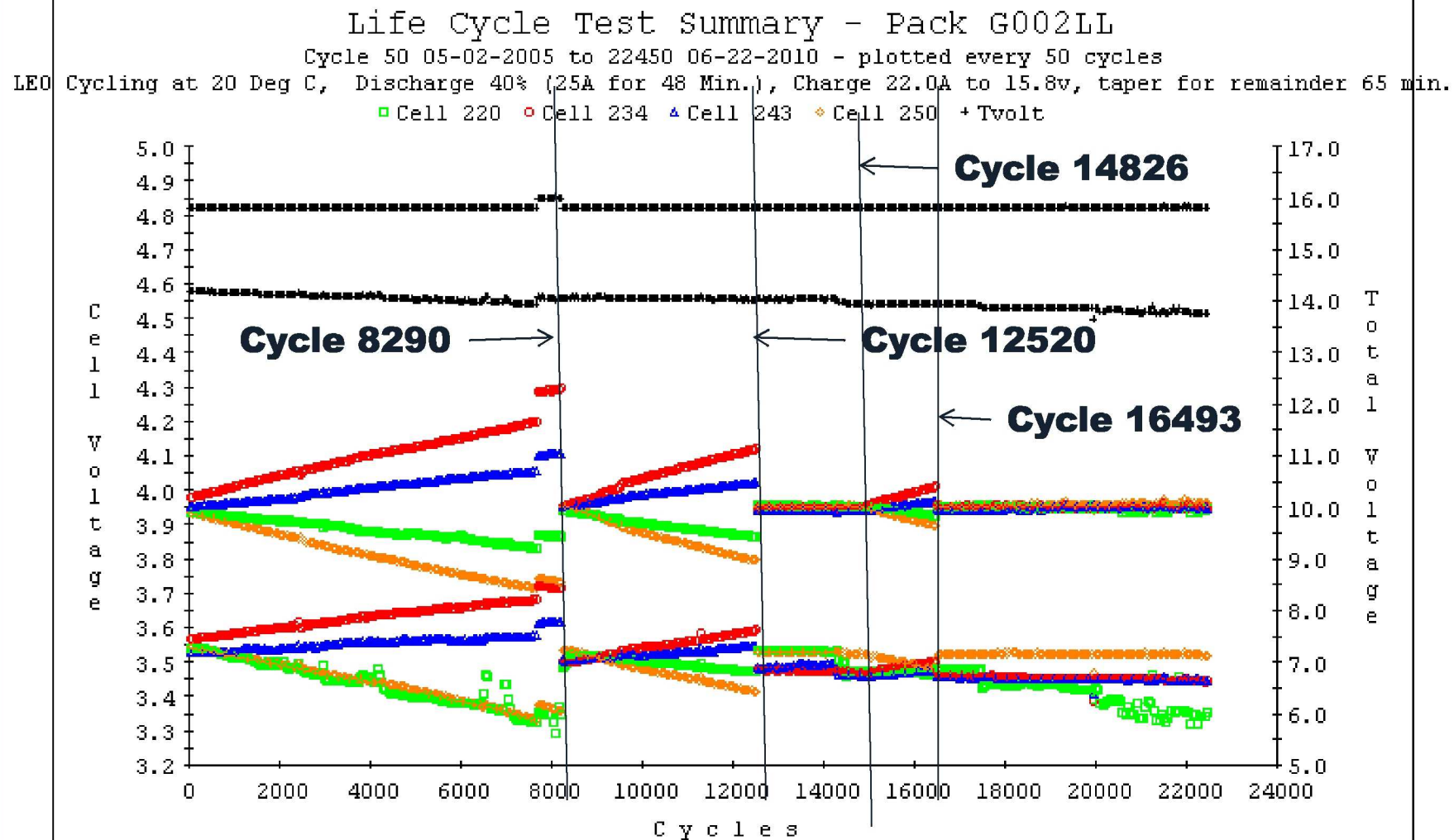


Cycle 8203	End of Discharge Voltage	End of Charge Voltage
Cell #1	3.34283	3.83635
Cell #2	3.71513	4.19647
Cell #3	3.61626	4.05788
Cell #4	3.36023	3.71006
<b>Voltage Spread</b>	<b>0.37230</b>	<b>0.48641</b>



Cycle 8240	End of Discharge Voltage	End of Charge Voltage
Cell #1	3.48702	3.94228
Cell #2	3.49946	3.95175
Cell #3	3.50563	3.95135
Cell #4	3.53681	3.95472
<b>Voltage Spread</b>	<b>0.04979</b>	<b>0.01244</b>

# LITHION 50 Ahr Lithium-Ion Cells Life Cycle Test Summary



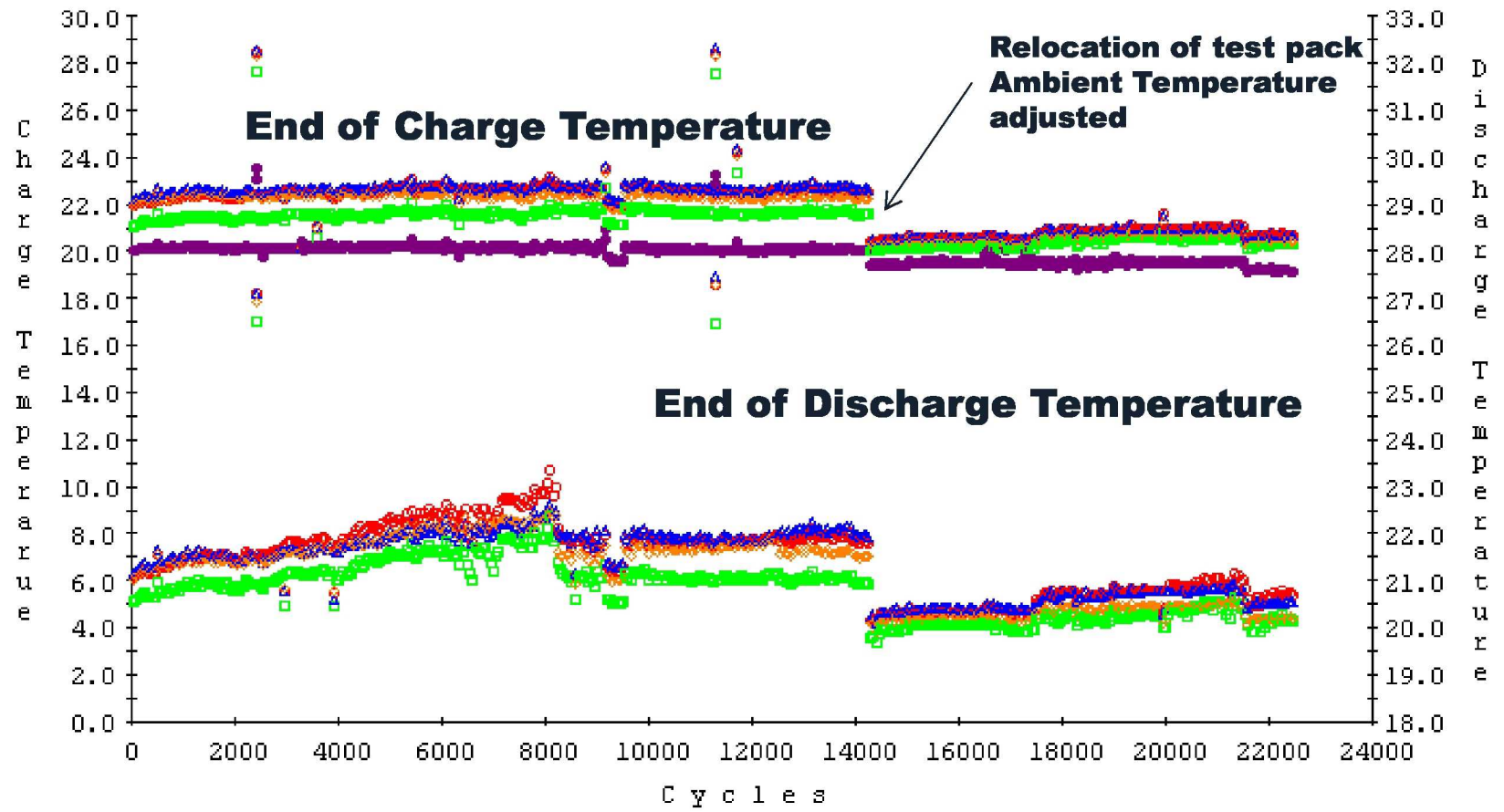
# LITHION 50 Ahr Lithium-Ion Cells Life Cycle Test Summary

## Life Cycle Test Summary - Pack G002LL

Cycle 50 05-02-2005 to 22450 06-22-2010 - plotted every 50 cycles

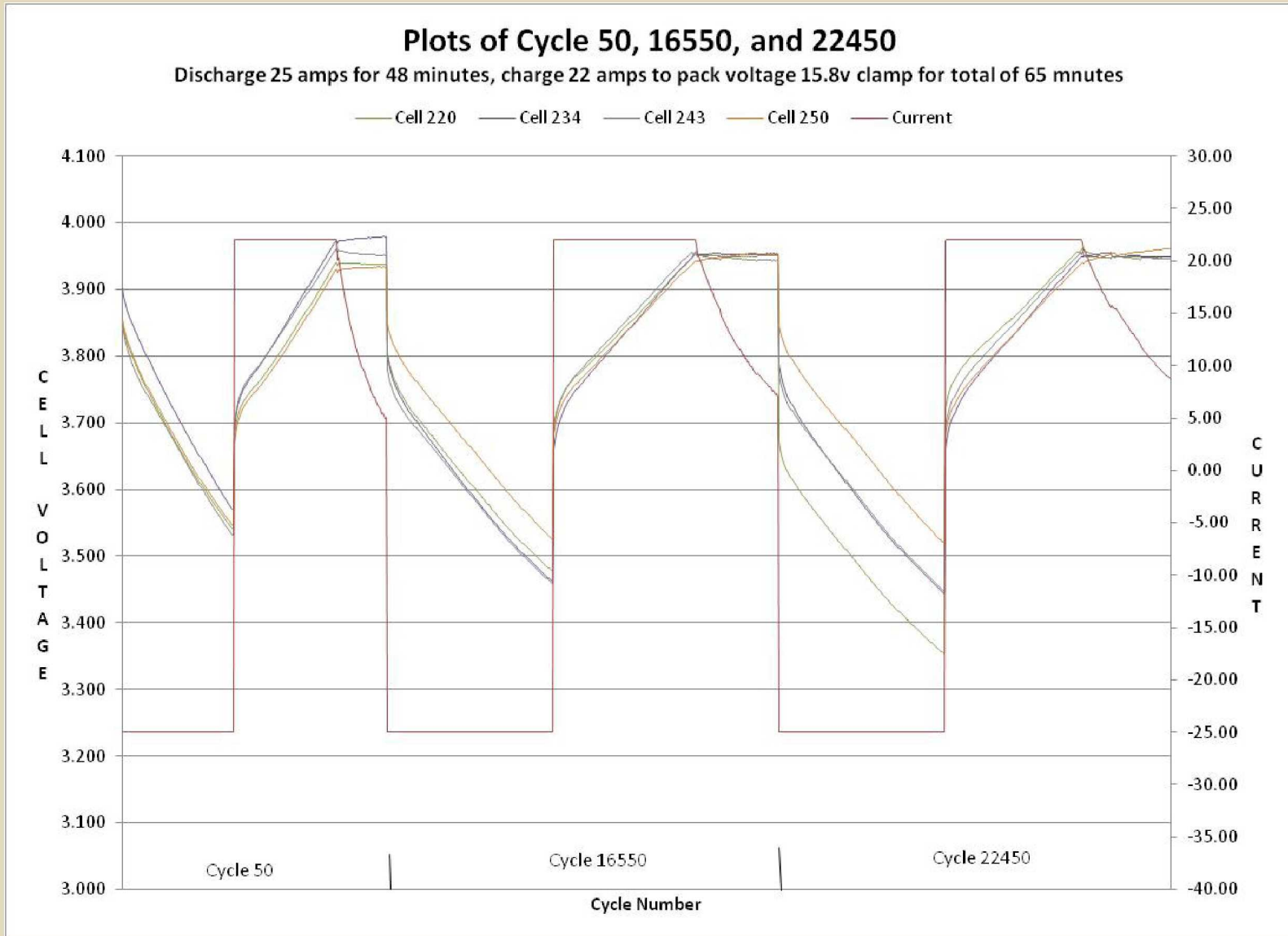
LEO Cycling at 20 Deg C, Discharge 40% (25A for 48 Min.), Charge 22.0A to 15.8v, taper for remainder 65 min.

■ Cell 220 ○ Cell 234 ▲ Cell 243 ◆ Cell 250 ● AmbT

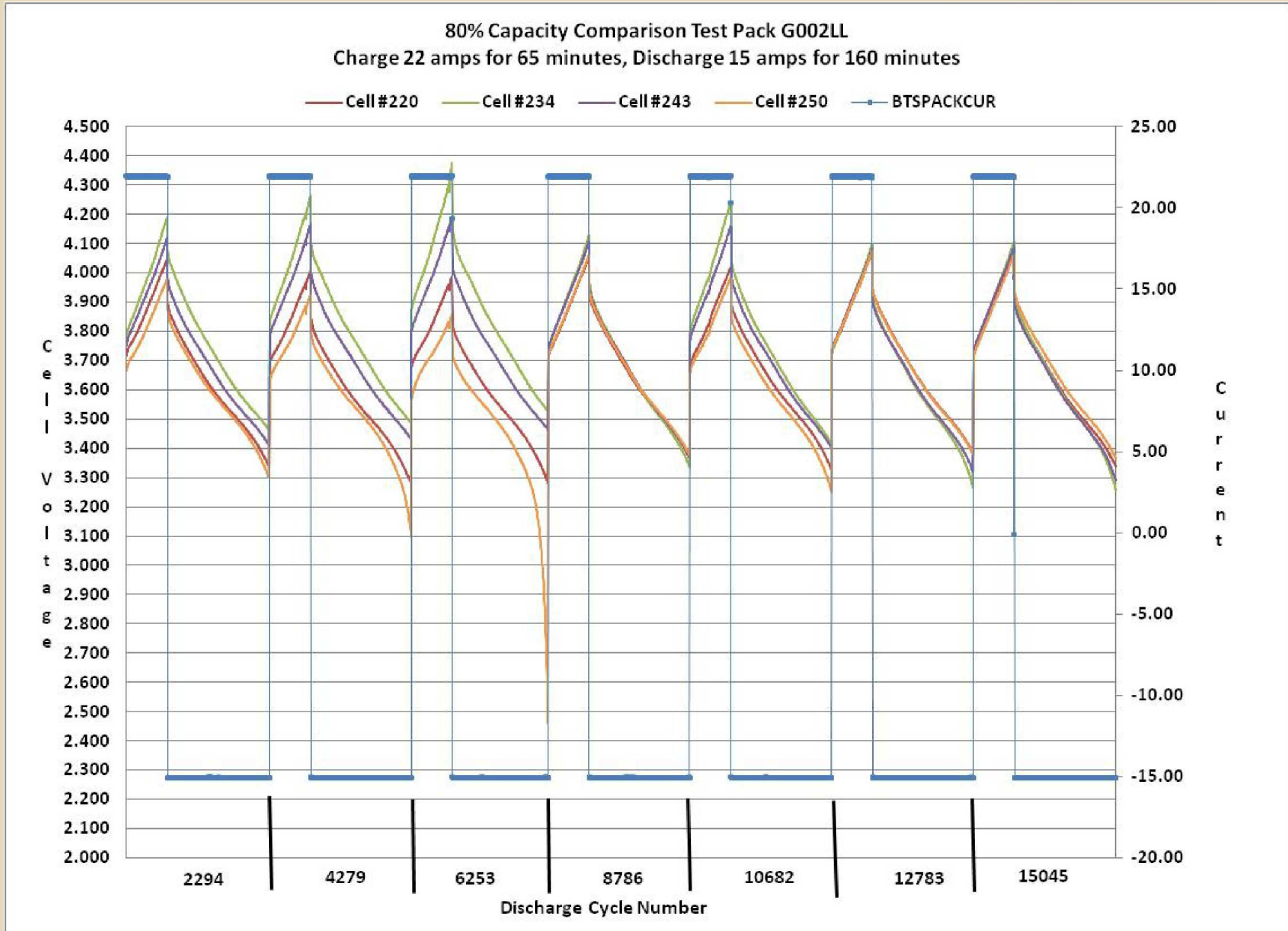




# LITHION 50 Ahr Lithium-Ion Cells Life Cycle Test Summary

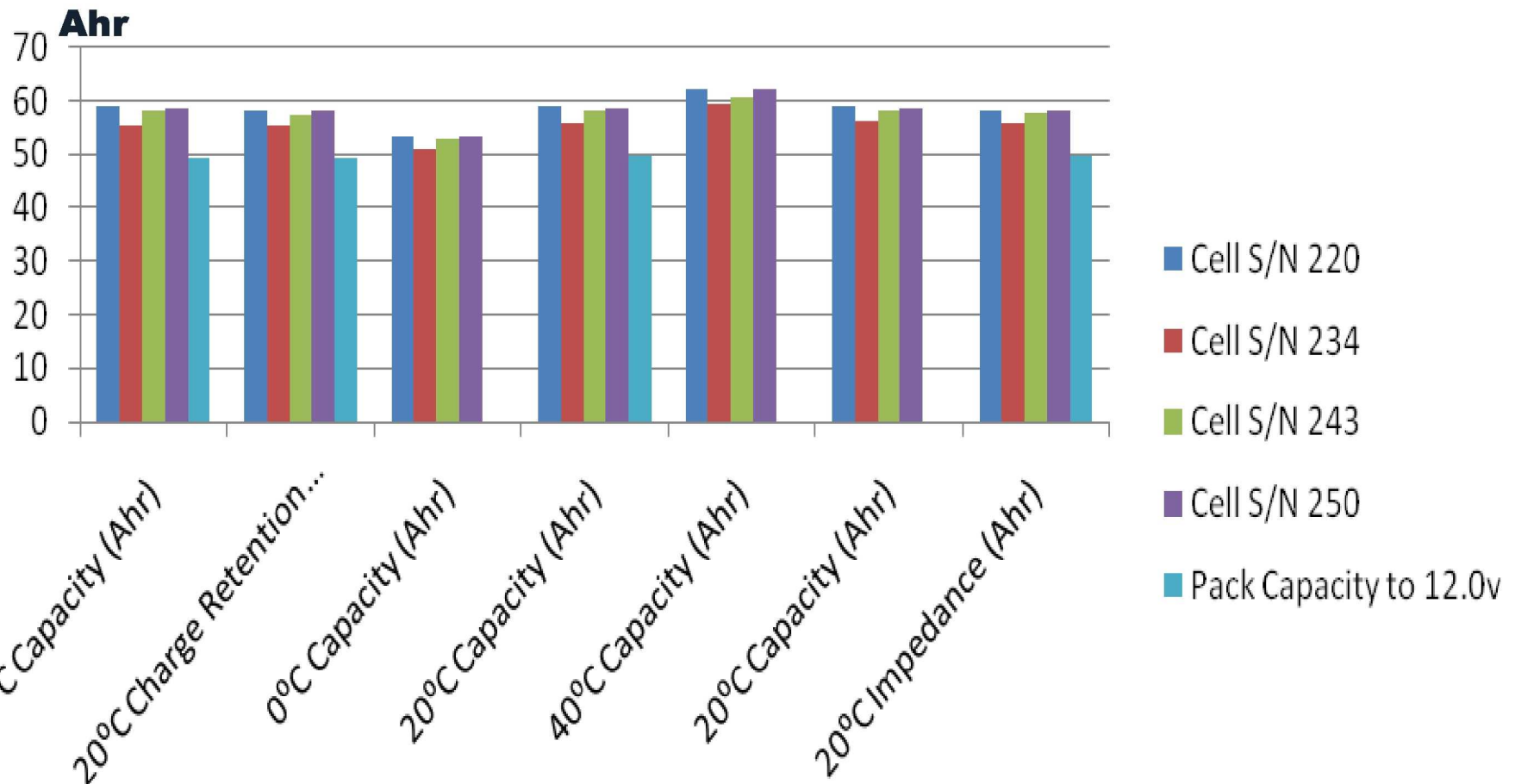


# LITHION 50 Ahr Lithium-Ion Cells Life Cycle Test Summary



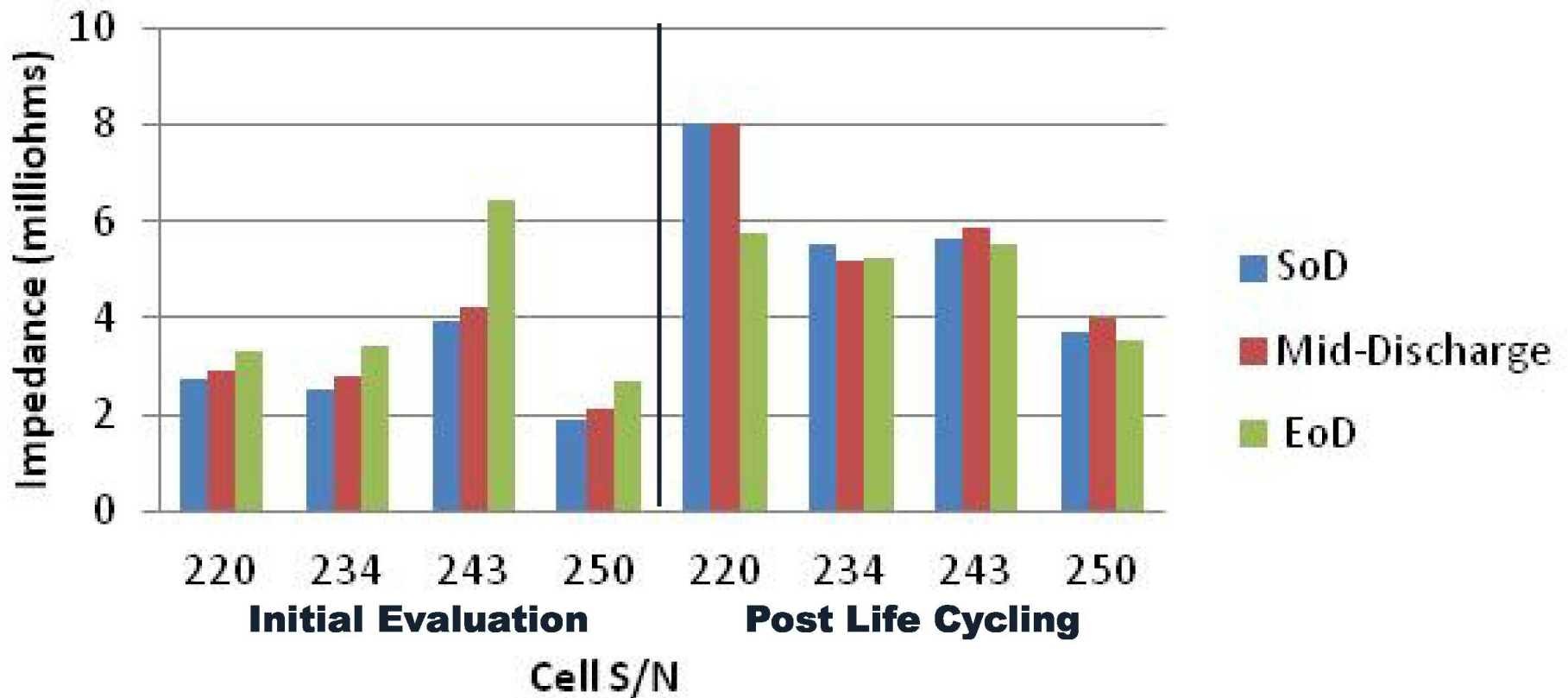
# LITHION 50 Ahr Lithium-Ion Cells Post Cycle Test Summary

## Comparison Initial Evaluation to Post Life Cycle





## Impedance Test Initial Evaluation vs Post Cycling





# **ABSL 5 AHR LITHIUM-ION BATTERY SDO-GEO LIFE CYCLE TEST LRO-LLO LIFE CYCLE TEST**



**Test Pack: AEA Battery Systems Limited (ABSL) 5 Ah Lithium Ion Battery consisting of 32 SONY 18650 cells in 4P/8S configuration**

**Rated Capacity = 5 Ahr**

**Prior to testing, battery de-rated to 4 Ahr**

**Battery was subjected to following tests:**

**Initial Evaluation – Capacity test at 20°C**

**State-Of-Charge Test to develop voltage hysteresis curve**

**SDO-GEO Life Cycle Test – Pack 42NG01**

**LRO-LLO Life Cycle Test – Pack ABSL02**



# ABSL 5 Ahr Lithium-Ion Battery State Of Charge



**SOC Tests performed at 20°C.**

## **Charge Curve.**

**Charge at C/10 for 1.0 hour. OC for 5 minutes.**

**Discharge at C/2 to 24.0V.**

**Increase charge increment by one hour and  
continue cycling to 33.6V.**

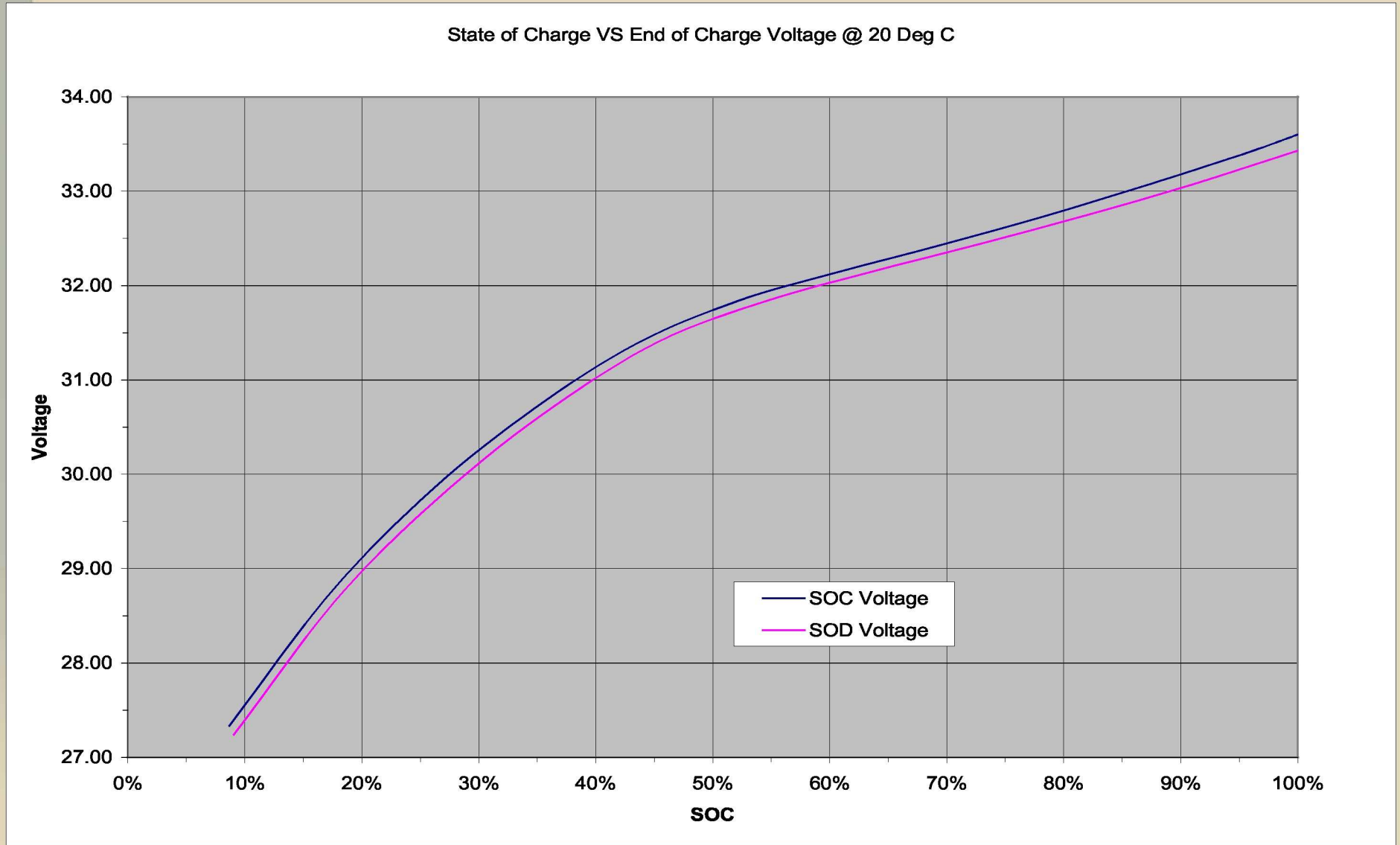
## **Discharge Curve.**

**Charge at C/10 to 33.6V. OC for 5 minutes.**

**Discharge at C/2 to 24.0V.**

**Decrease charge increment by one hour and  
continue cycling until  
minimum of one hour charge is completed.**

# ABSL 5 Ahr Lithium-Ion Battery State Of Charge Test



# **ABSL 5 Ahr Lithium-Ion Battery SDO-GEO Life Cycle Test**



## **Shadow Regime:**

**Eclipse Season = 23 Days**

**Test Cycle Duration = 24 hours**

**Temperature = 10°C**

**Discharge Rate = 0.6C**

**Discharge Time = Based on SDO-GEO Discharge Time Graph**

**Charge Rate = C/20 to 90% SOC based on SOC Curve.**

**Clamp and taper for remainder of Charge Time.**

**Charge Time = 24 hours minus Discharge Time**

**Apply sine wave pulses (~0.2 amps peak-to-peak) as follows:**

**83 Hz pulse during first 30 days of testing.**

**3 Hz pulse thereafter, increasing to 83 Hz for 1 day at start of every month.**

**Subsequent frequency changes to be provided by sponsor.**

## **Solstice Regime:**

**Solstice Season = 150 days.**

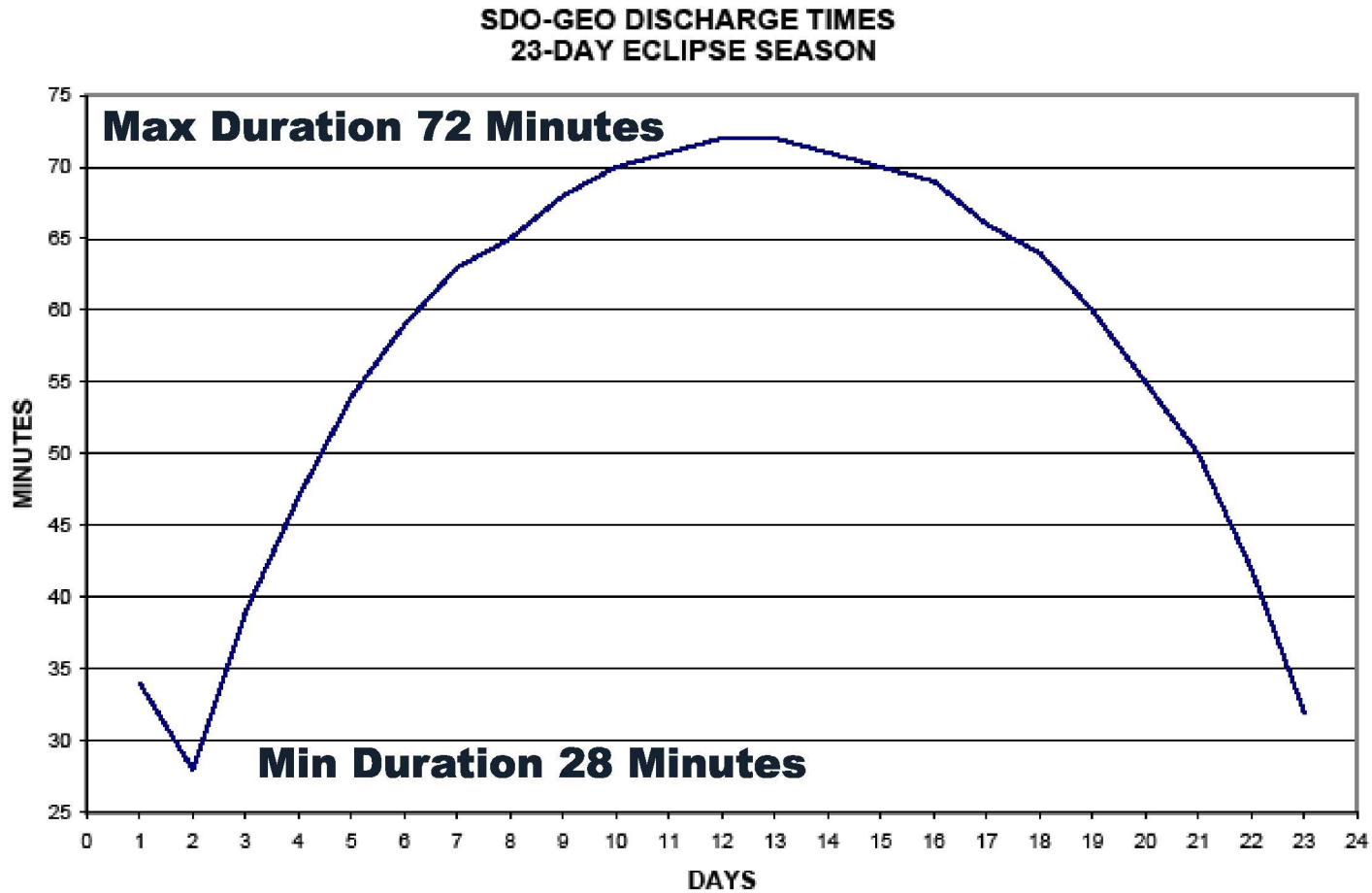
**Temperature = 10°C**

**Charge at C/20 to 50% SOC, clamp and taper for 149 days.**

**For Day 150, charge at C/20 to 90% SOC and taper for 1 day.**



# ABSL 5 Ahr Lithium-Ion Battery SDO-GEO Life Cycle Test



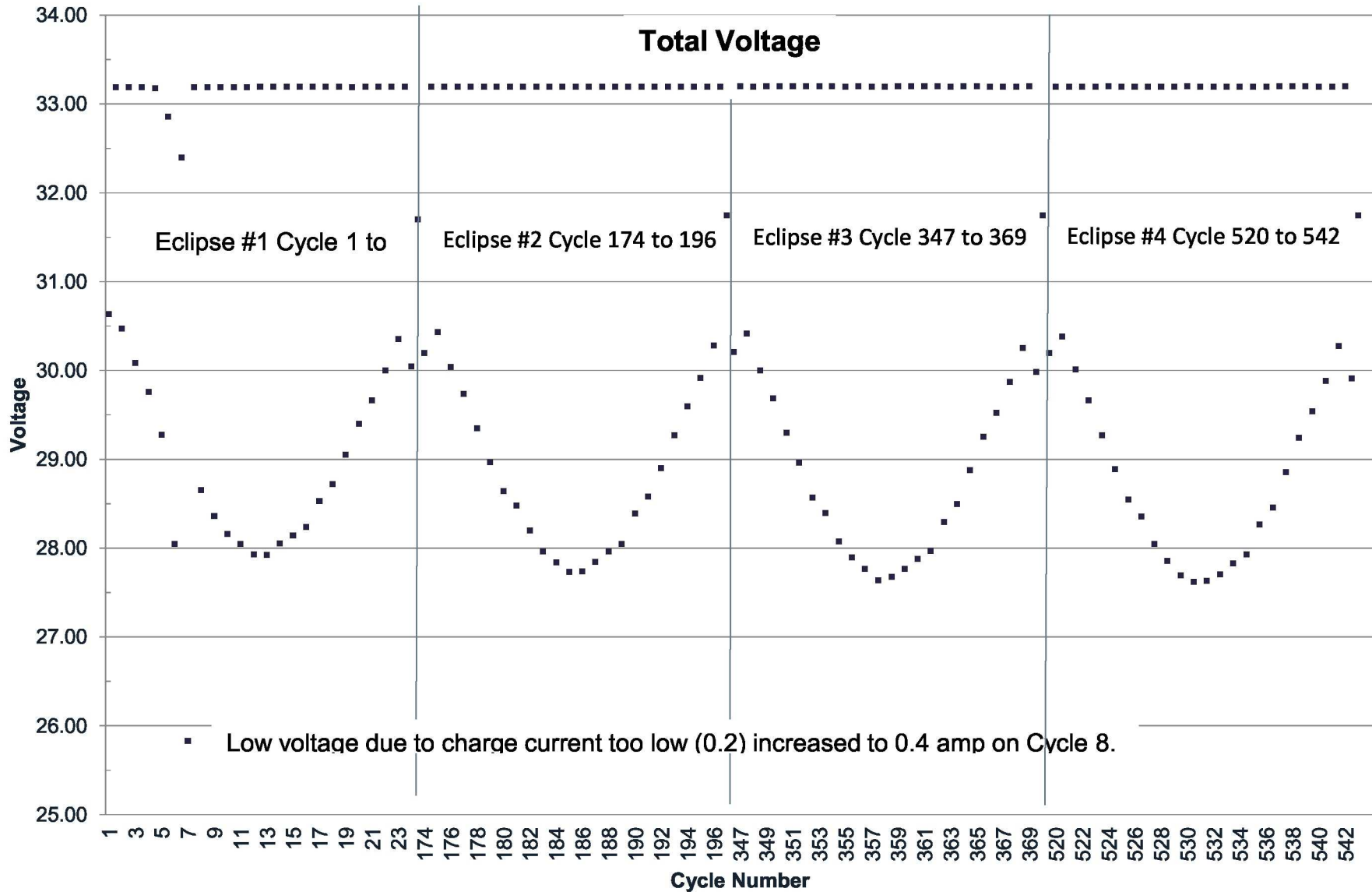
# **ABSL 5 Ahr Lithium-Ion Battery Test History – SDO-GEO Life Test**



- 
- 11 July 2008 Began Initial Evaluation**
  - 28 August 2008 – Began SOC Test**
  - 11 December 2008 - Began SDO-GEO Life Cycling**
  - 11 December 2008 to 5 January 2009 – 1<sup>st</sup> Eclipse Season**
  - 6 January to 4 June 2009 – 1<sup>st</sup> Solstice Season**
  - 5 June to 3 July 2009 – 2<sup>nd</sup> Eclipse Season**
  - 4 July to 4 December 2009 – 2<sup>nd</sup> Solstice Season**
  - 5 to 27 December 2009 - 3<sup>rd</sup> Eclipse Season**
  - 28 December 2009 to 27 May 2010 – 3<sup>rd</sup> Solstice Season**
  - 28 May to 22 June 2010 – 4<sup>th</sup> Eclipse Season**
  - 23 June to Present – 4<sup>th</sup> Solstice Season**

# ABSL 5 Ahr Lithium-Ion Battery SDO-GEO Life Cycle Test

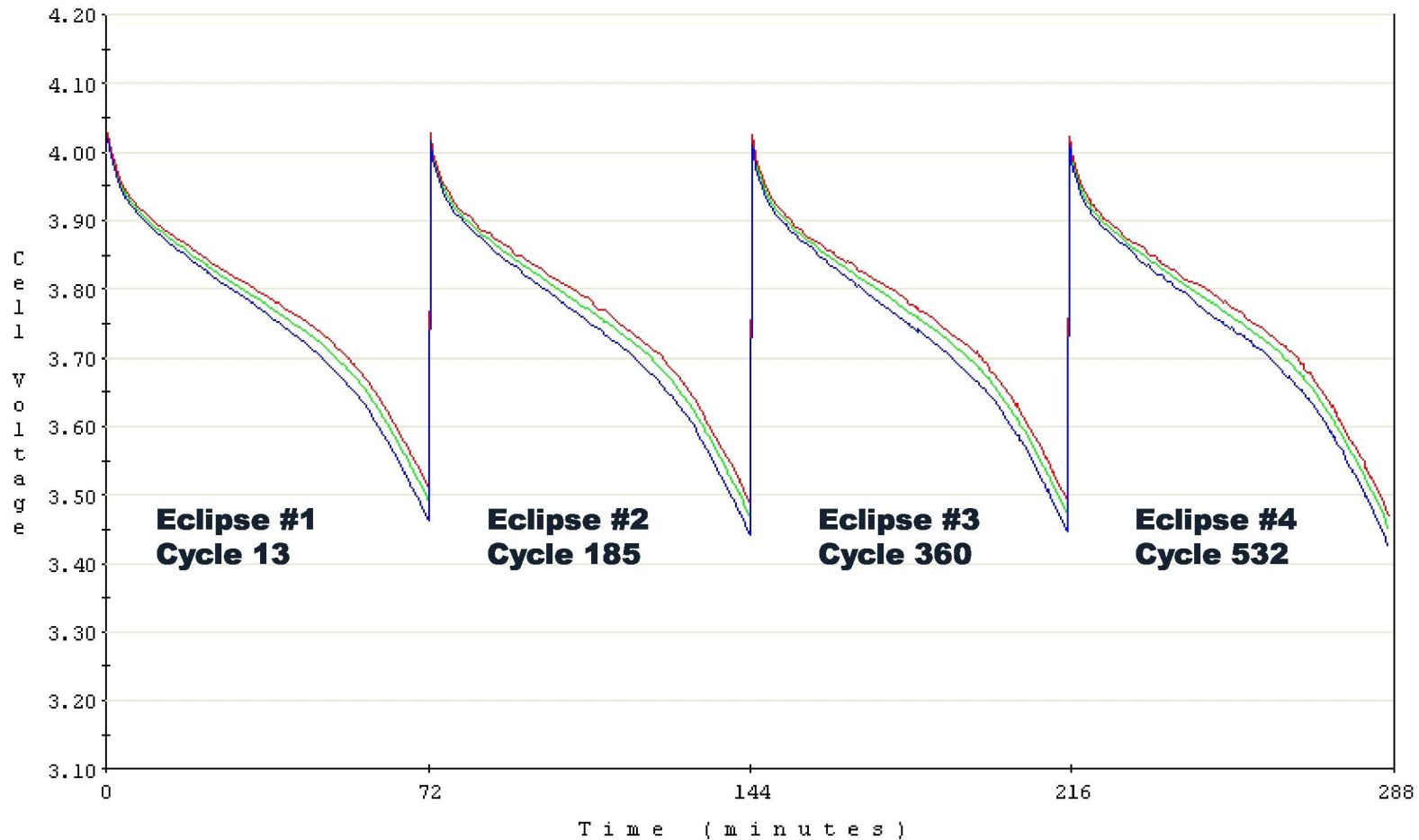
## SDO-GEO Test 42NG01





# ABSL 5 Ahr Lithium-Ion Battery SDO-GEO Life Cycle Test

SDO-GEO Test 42NG01  
 Cycle 13 12-23-2008 to 06-09-2010 (42NG01MID)  
 Mid-Point Discharge Each Eclipse #1- #4  
Vavg Vmax Vmin



# ABSL 5 Ahr Lithium-Ion Battery LRO-LLO Life Cycle Test



**LRO-LLO Life Cycle: 2.5A discharge for 48 minutes (40% DOD) 3A charge to 32V, taper for 65 minute charge time**

**Every 30 days: 3A Charge to 33.6V, taper for 65 minute charge time 1.5A Discharge for 160 minutes (80% DOD)  
Return to Life Cycle profile**

# **ABSL 5 Ahr Lithium-Ion Battery LRO-LLO Life Cycle Test**



## **Test History:**

**7 August 2008 – Began Life Cycling**

**16 September 2008 – Cycle 478. Cells down-rated to 4 Ah due to low cell voltage on 80% DOD deep discharge. Life Cycle profile changed to: 2A discharge for 48 minutes 2.4A charge to 32V, taper for 65 minutes charge time**

**31 October 2010 – Continue testing completed cycle 10,175**





# ABSL 5 Ahr Lithium-Ion Battery LRO-LLO Life Cycle Test



NSWC Crane

Pack ID ABSL02

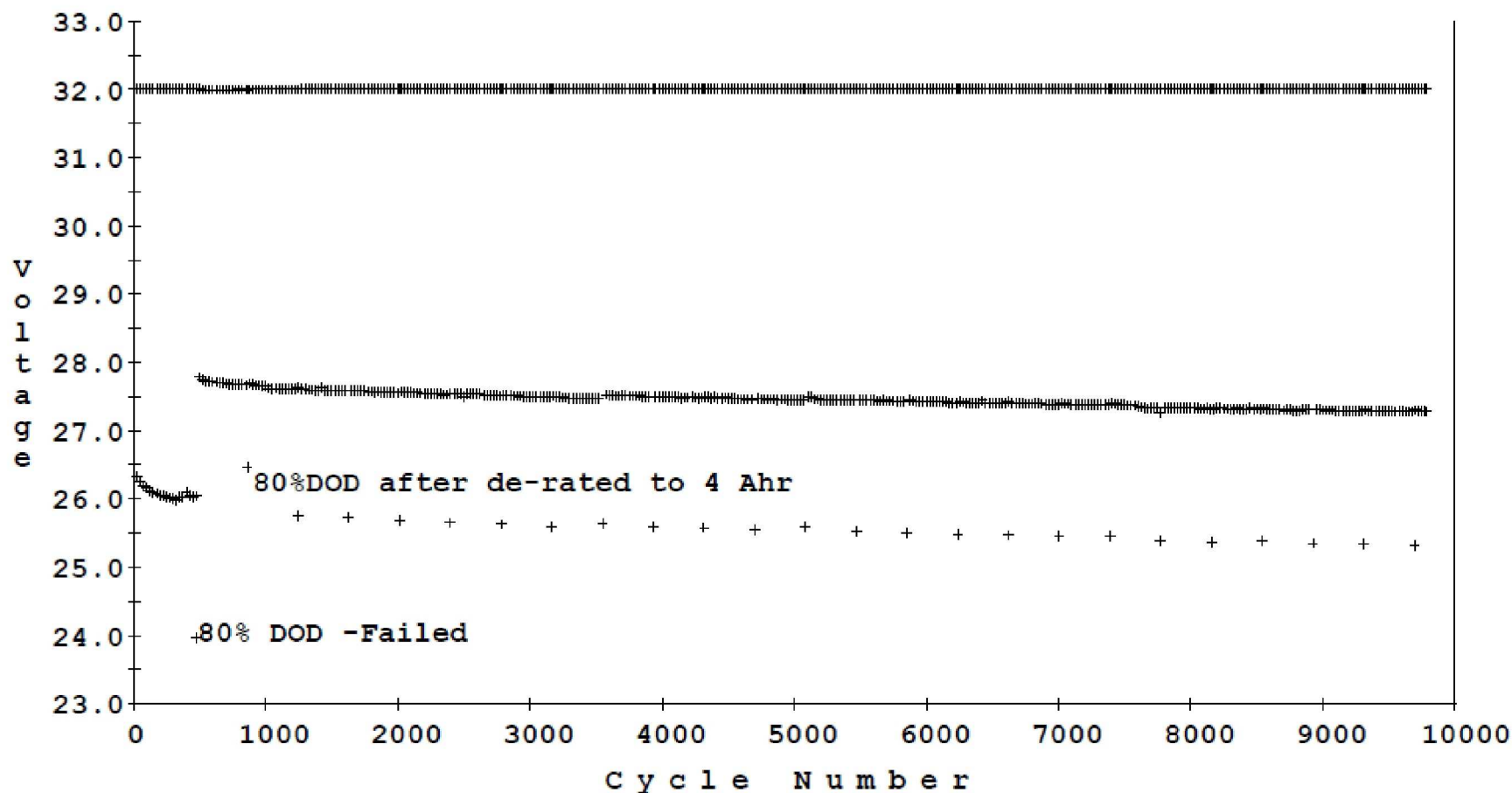
EOC/EOD Trend Plot (Monthly 80% DOD Capacity Test)

08-10-2008 - 10-01-2010

Down-rated to 4 AH

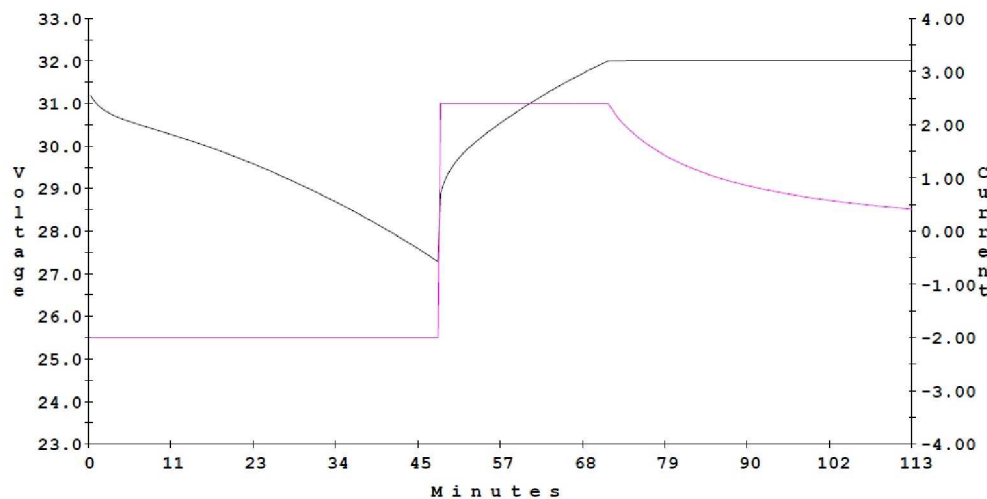
TEMP (C): 20

+ Tvolt

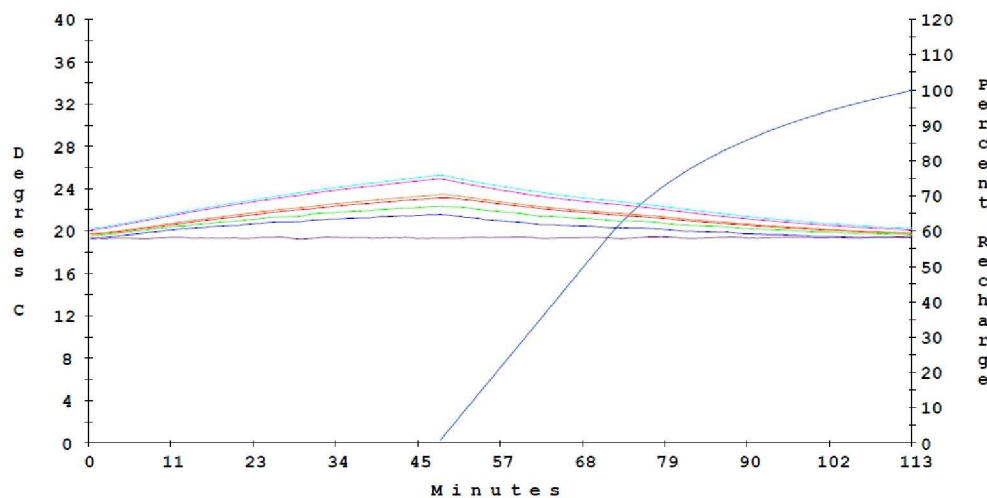


# ABSL 5 Ahr Lithium-Ion Battery LRO-LLO Life Cycle Test

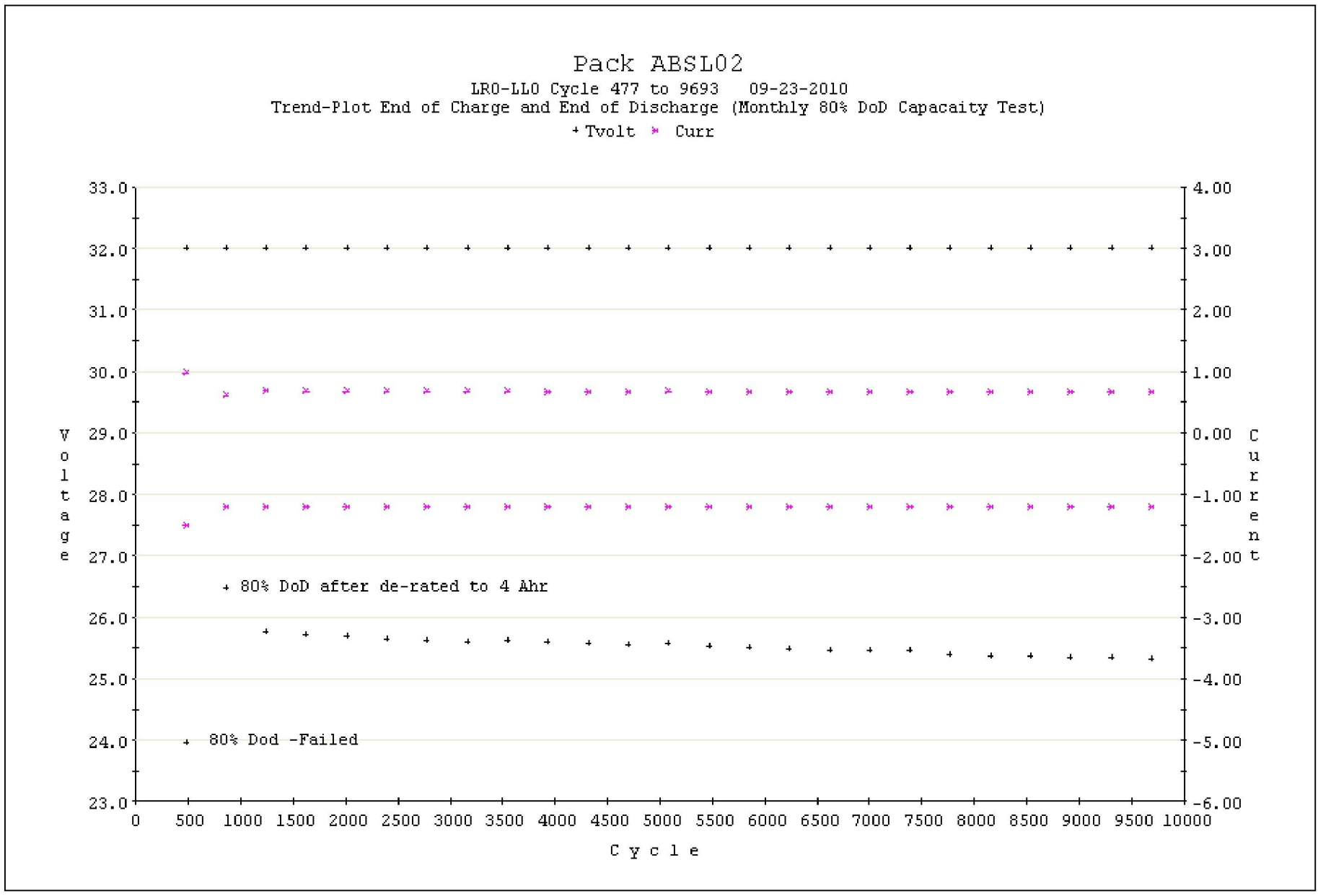
NSWC Crane Pack ID ABSL02  
 LRO-LLO Cycle Plot -- Cycle 9775 09-30-2010  
 Down-rated to 4 AH TEMP (C): 20 DOD (%): 40  
Tvolt Curr



%Rchg Top Bot Left Right STR2-C4 STR3-C5 AmbT



# ABSL 5 Ahr Lithium-Ion Battery LRO-LLO Life Cycle Test







# **A123 40 AHR LITHIUM-ION BATTERY**

**GPM LIFE CYCLE TEST**  
**MMS LIFE CYCLE TEST**

# **A123 40 Ahr Lithium-Ion Battery GPM & MMS Life Cycle Test**



## **Test parameters**

**Two batteries consisting of 160 cells each.**

**8 series strings of 20 cells in parallel.**

**Cell Type: ANR26650-M1, Capacity 2.3Ahr, Voltage 3.3V**

**Manufactured by A123 Systems**

**Capacity Rated 44 Ahr, De-rated to 40 Ahr**

**Battery Voltage – 28.8 volts**

**GPM test profile – Pack ID 66NL40**

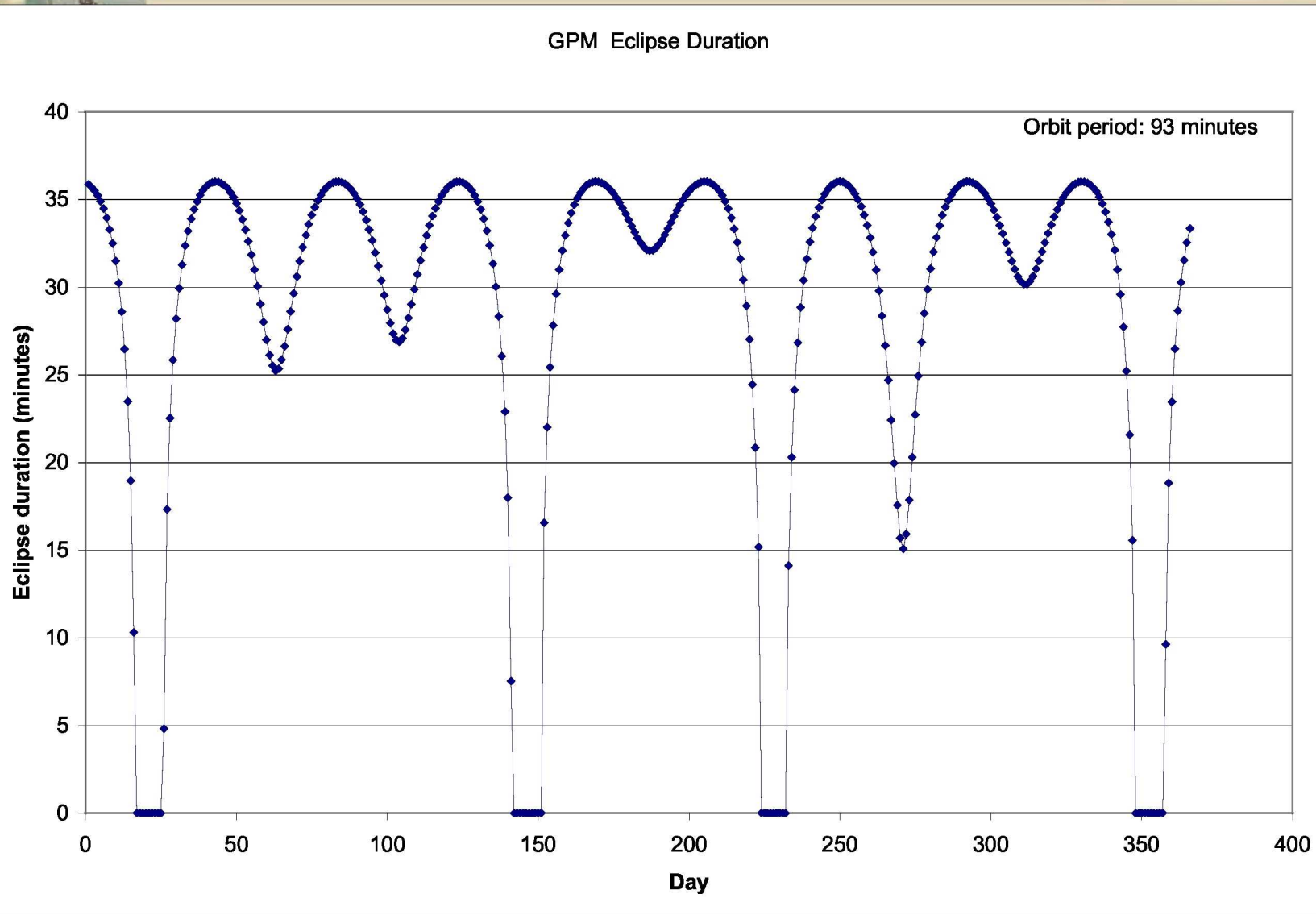
**Temperature = 20°C**

**Discharge at C/2 (20A) for specified time**

**Charge at C/2 (20A) charge with a voltage clamp of 28.8V for a remainder of 93 minute orbit.**

**15 orbits per day**

# A123 40 Ahr Lithium-Ion Battery GPM Life Cycle Test



**Temperature = 20°C**

**Discharge at C/2 (20A) for specified time**

**Charge at C/2 (20A) charge with a voltage clamp of 28.8V for a remainder of 93 minute orbit.**

**15 orbits per day**



# **A123 40 Ahr Lithium-Ion Battery GPM Life Cycle Test**



**Test History – GPM Life Cycle Test Pack 66NL40**

**Characterization tests:**

**Capacity Test 20°C – 41.8 Ahr**

**Capacity Retention Test 20°C – 40.5 Ahr**

**Capacity Test 0°C – 41.1 Ahr**

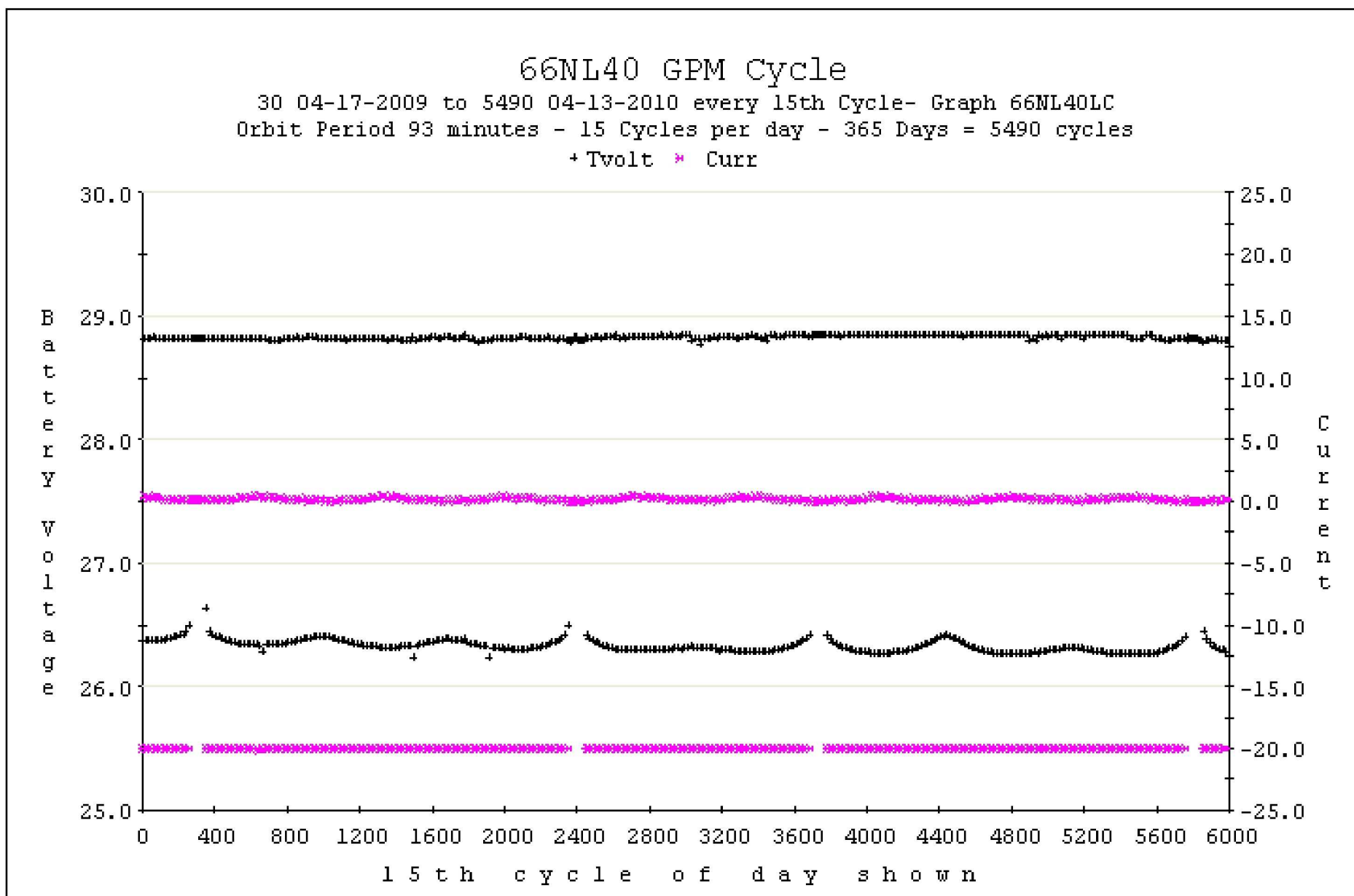
**Capacity Test 40°C – 41.8 Ahr**

**Capacity Test 20°C – 41.8 Ahr**

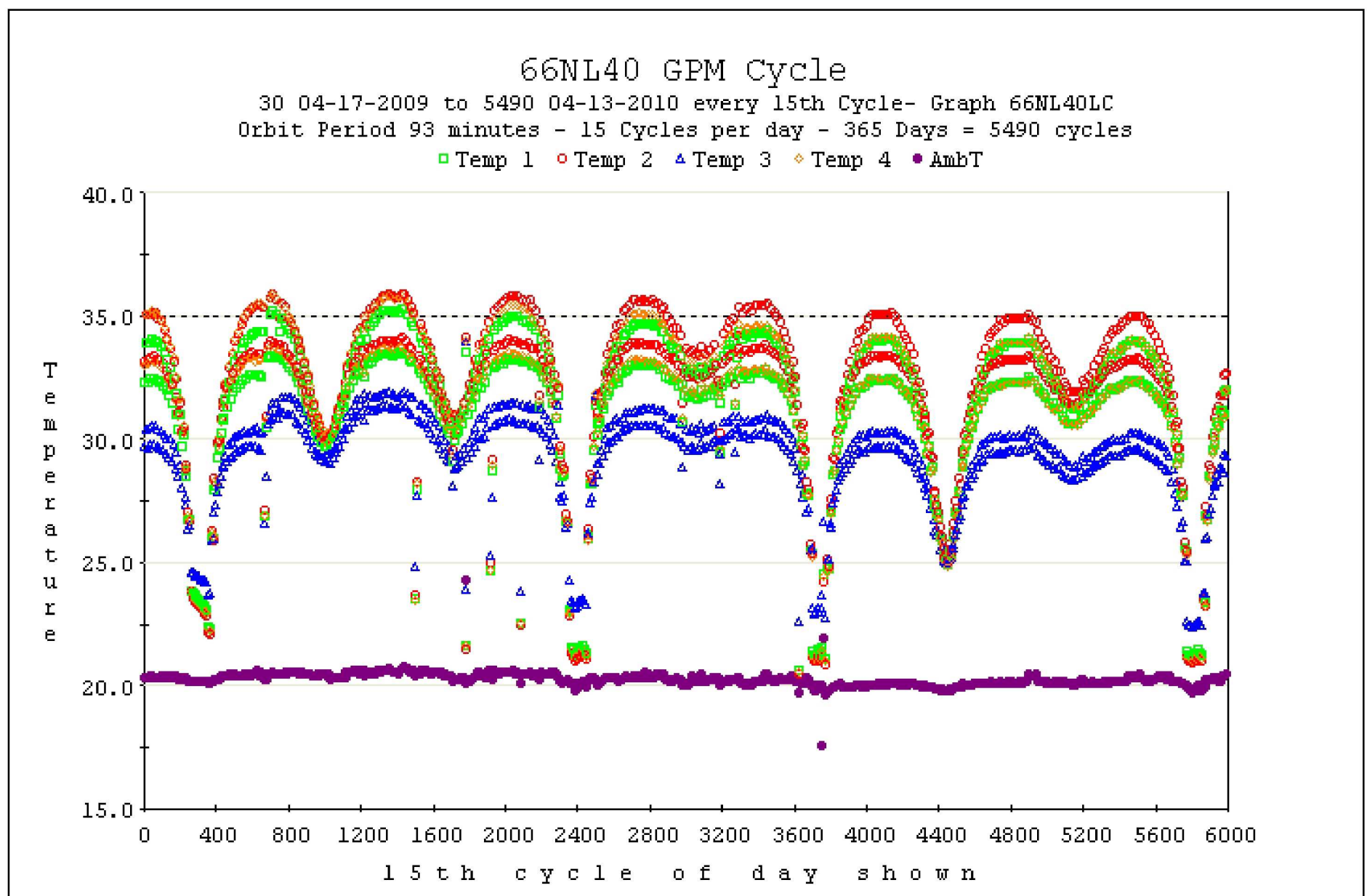
**Began Life Cycle Test – April 2009**

**Test Discontinued – 19 April 2010 Completed 365  
days of GPM profile -5494 Cycles**

# A123 40 Ahr Lithium-Ion Battery GPM Life Cycle Test

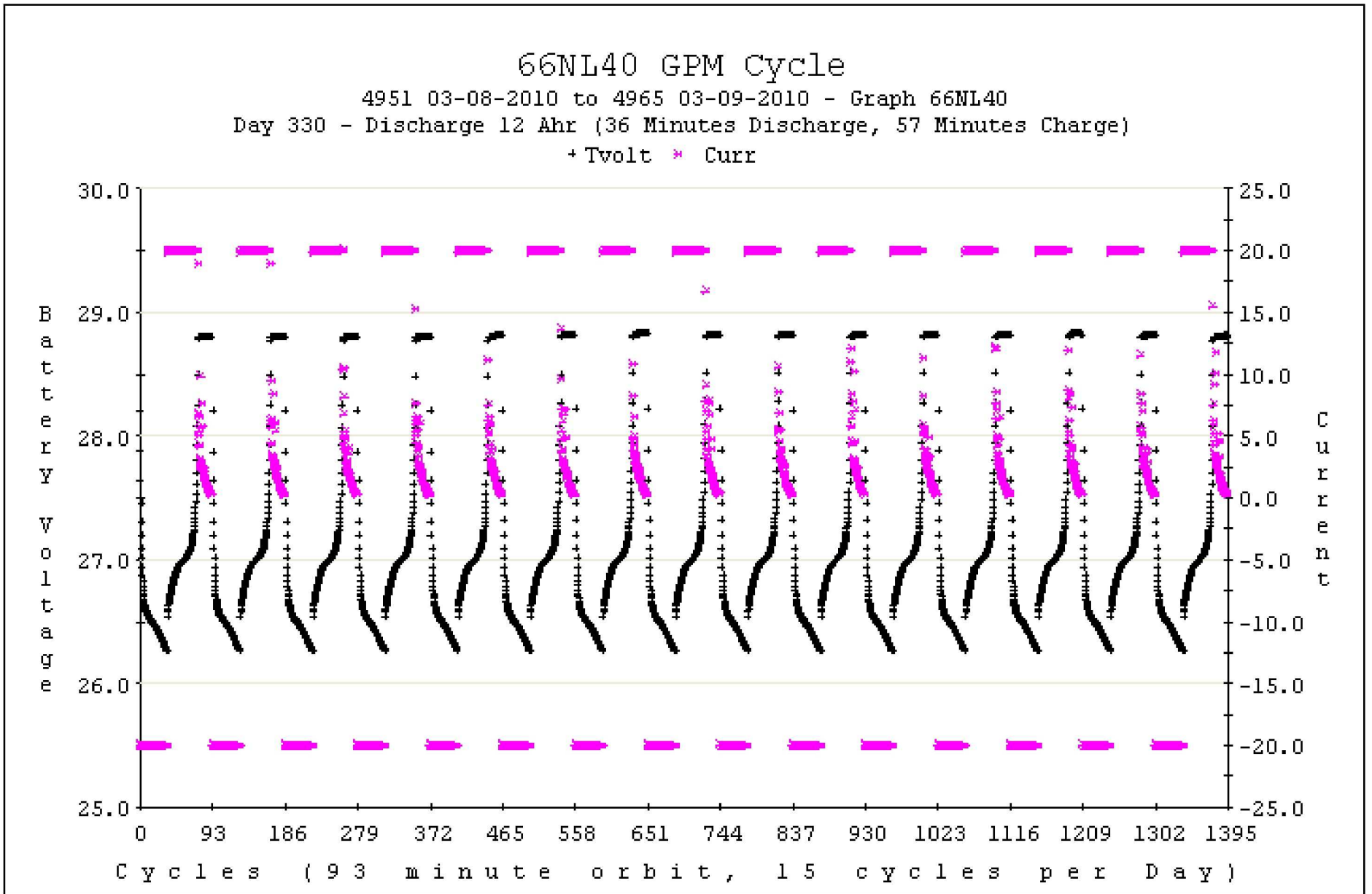


# A123 40 Ahr Lithium-Ion Battery GPM Life Cycle Test





# A123 40 Ahr Lithium-Ion Battery GPM Life Cycle Test



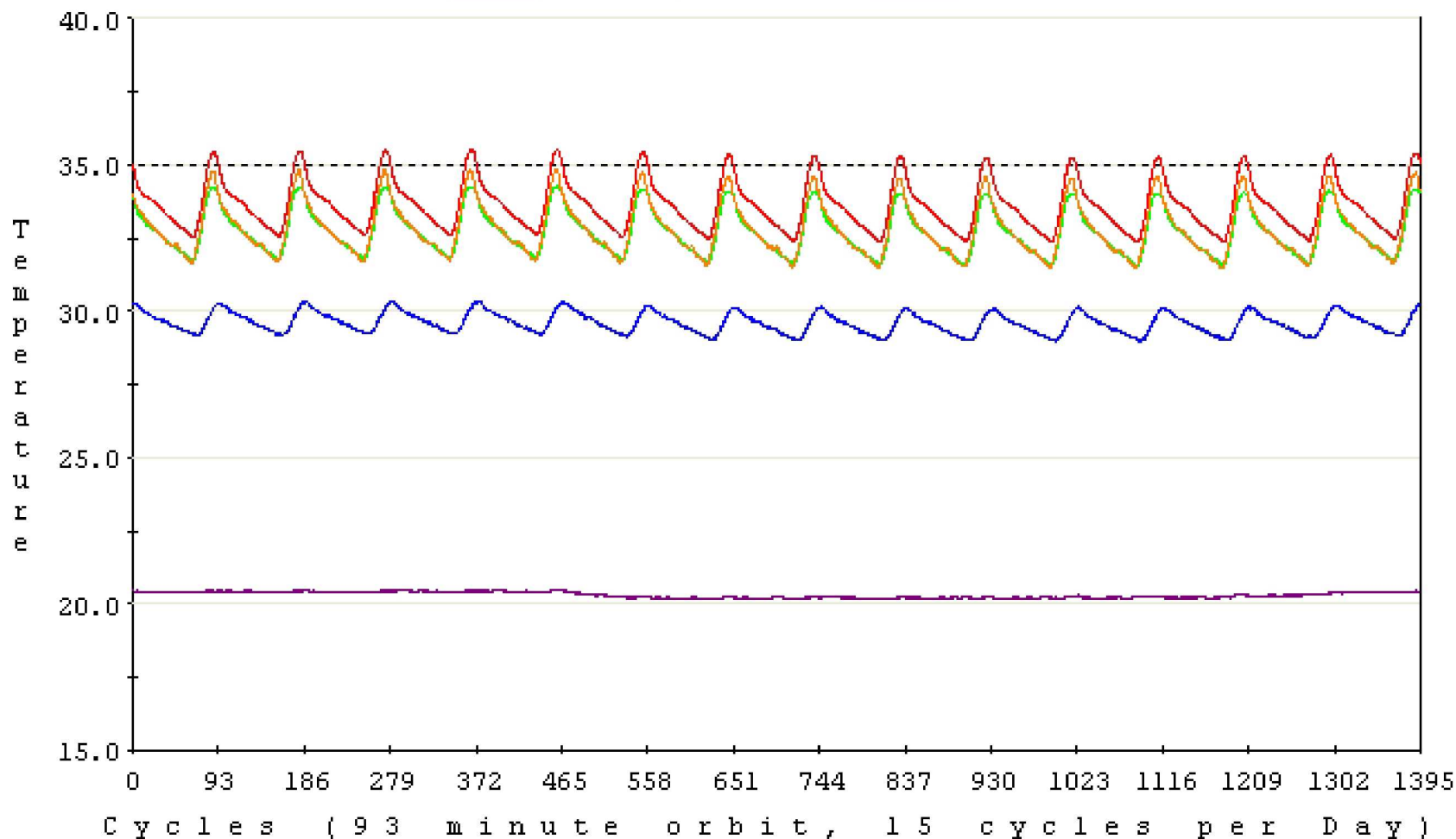
# A123 40 Ahr Lithium-Ion Battery GPM Life Cycle Test

## 66NL40 GPM Cycle

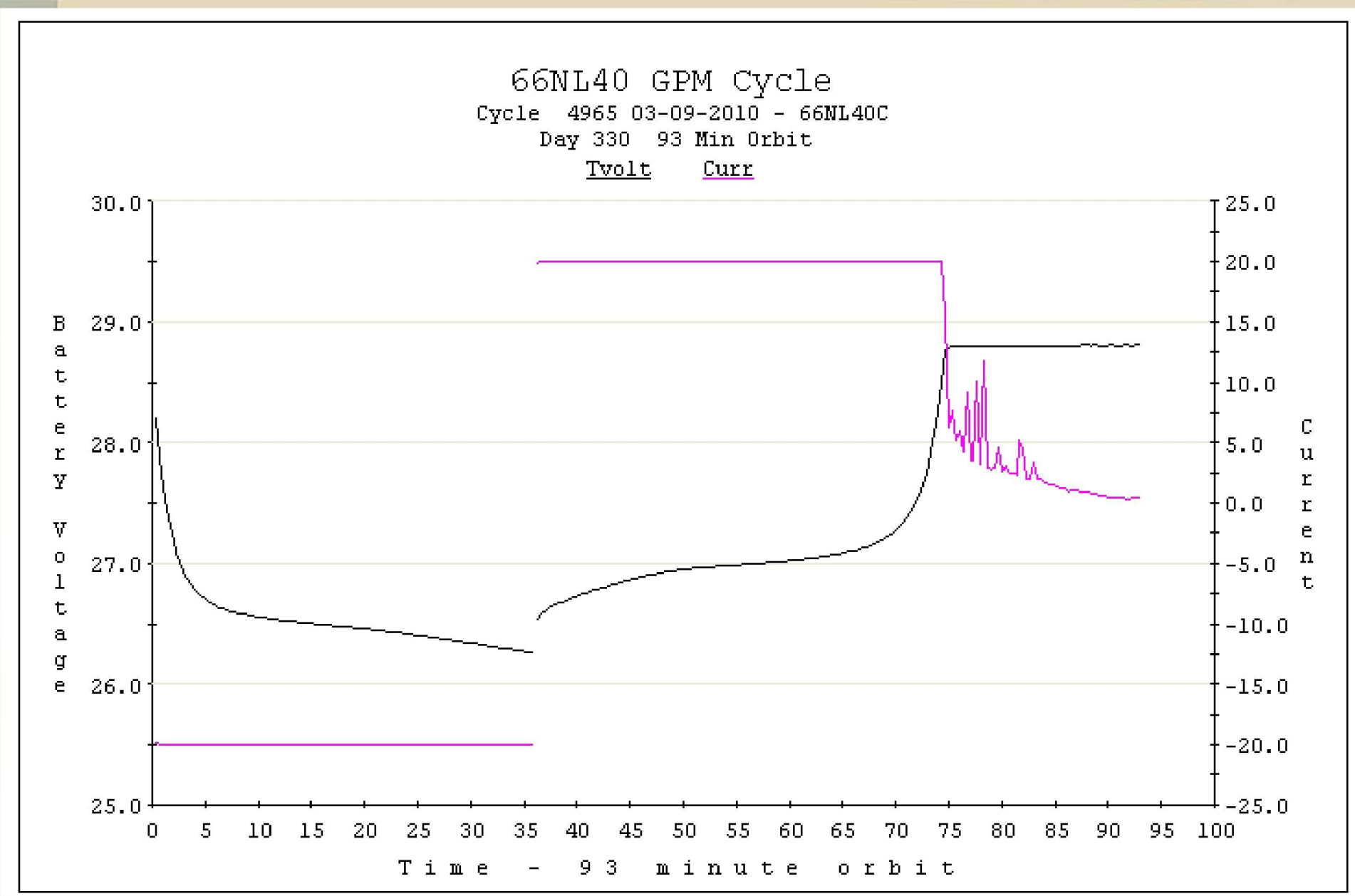
4951 03-08-2010 to 4965 03-09-2010 - Graph 66NL40

Day 330 - Discharge 12 Ahr (36 Minutes Discharge, 57 Minutes Charge)

Temp 1   Temp 2   Temp 3   Temp 4   AmbT

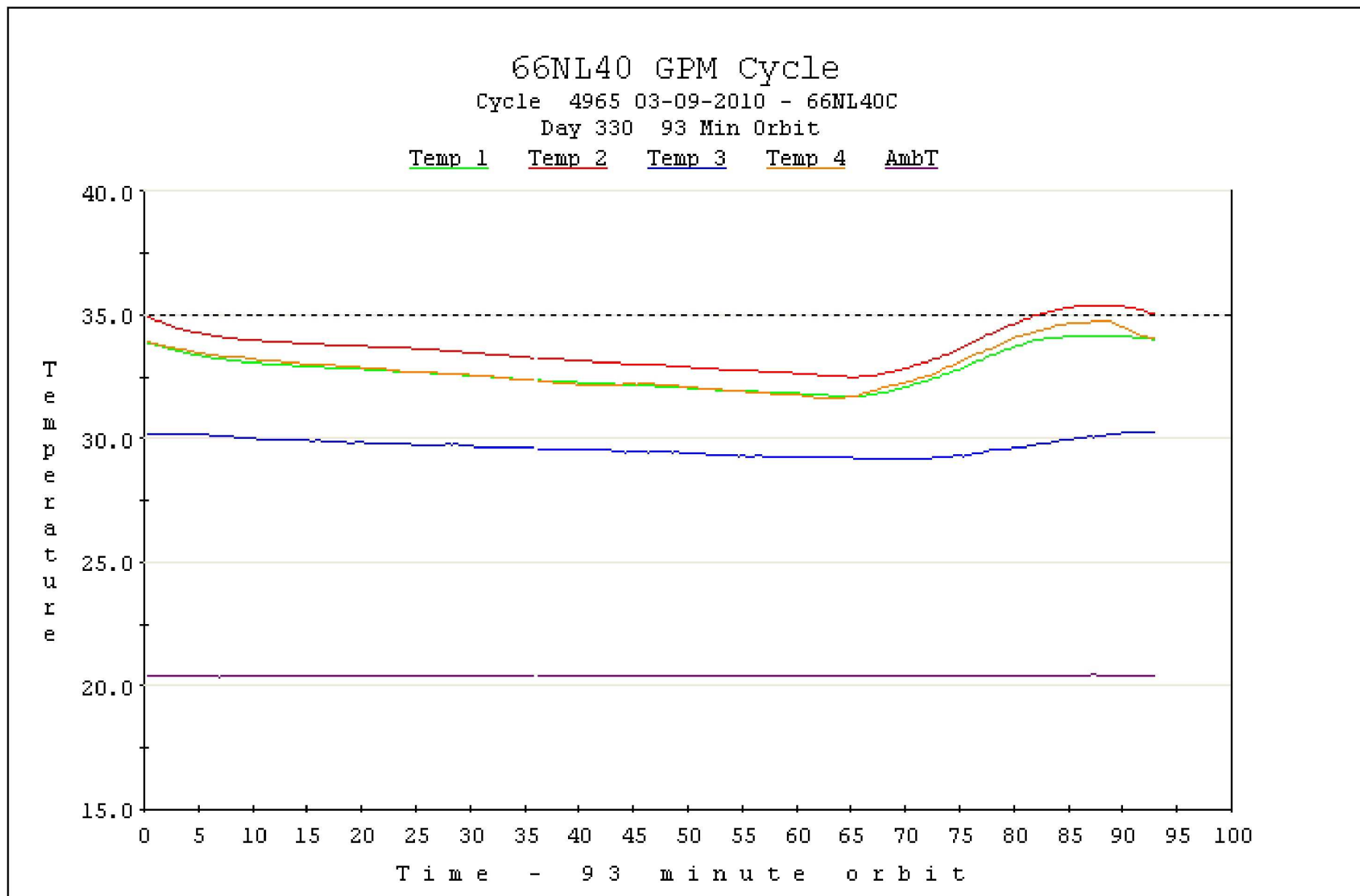


# A123 40 Ahr Lithium-Ion Battery GPM Life Cycle Test





# A123 40 Ahr Lithium-Ion Battery GPM Life Cycle Test



# A123 40 Ahr Lithium-Ion Battery MMS Life Cycle Test



## MMS test profile: Pack ID 67NL41

**Phase 1 – At 20°C, Discharge 50% DoD in 4 hrs (approx 5A), Charge for 20 hrs at 3.3A to 28.8v voltage clamp for 6 months.**

**Phase 2 – At 20°C, Discharge 50% DoD in 2 hrs (approx 10A), Charge for 22 hrs at 3.3A to 28.8v voltage clamp for 6 months.**

**Annually perform residual capacity and 20°C capacity and charge retention test.**

# A123 40 Ahr Lithium-Ion Battery MMS Life Cycle Test



## Test History:

### Characterization tests:

**Capacity Test 20°C – 39.5 Ahr**

**Capacity Retention Test 20°C – 38.3 Ahr**

**Capacity Test 0°C – 38.5 Ahr**

**Capacity Test 40°C – 39.6 Ahr**

**Capacity Test 20°C – 39.6 Ahr**

**Began Life Cycle Test – 23 April 2009**

## Test Status

**23 October 2009 - Completed 180 cycles at 50% DoD at 5 amp rate**

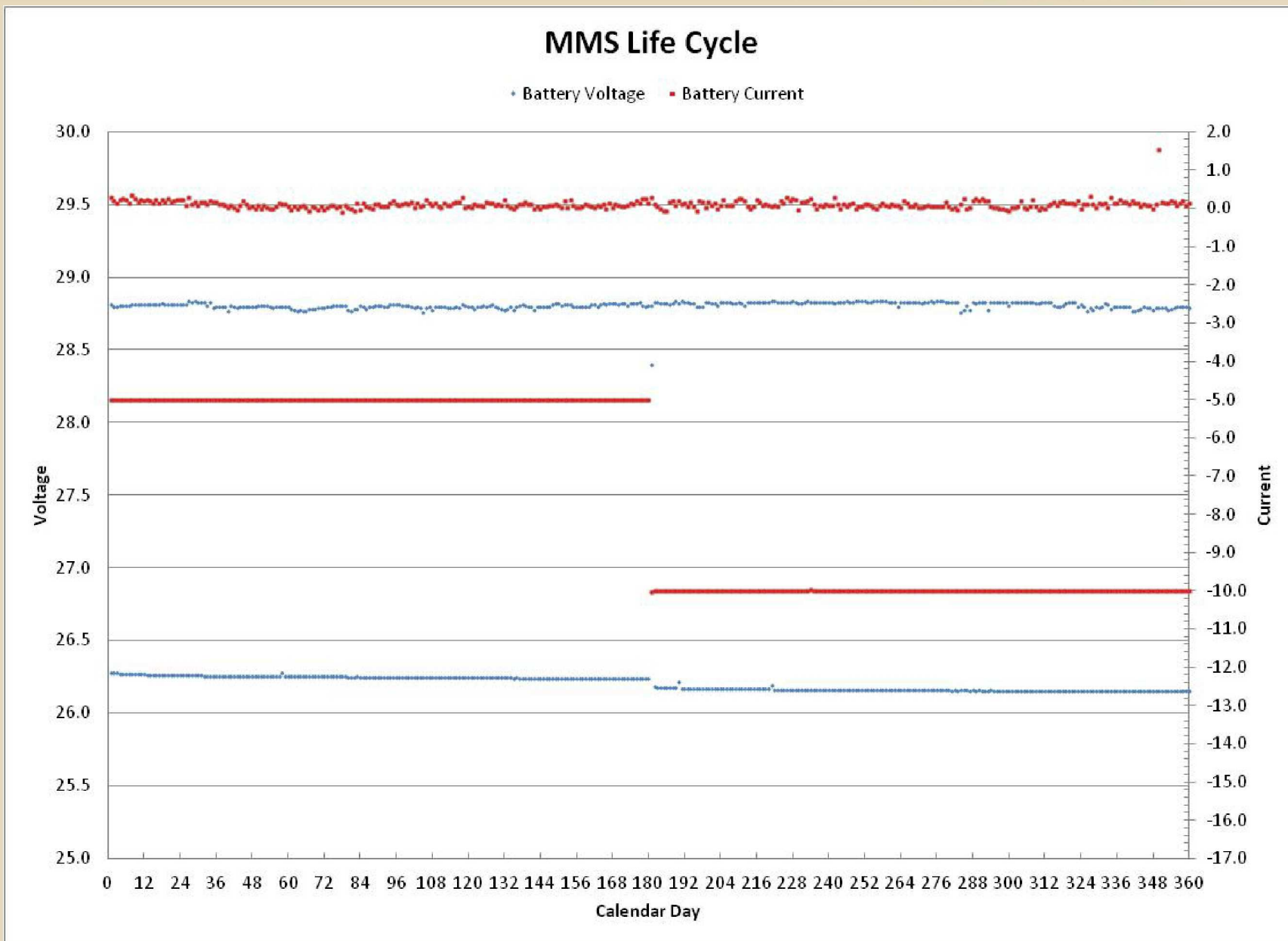
**23 April 2010 – Completed 180 cycles at 50% DoD at 10 amp rate**

**Test Discontinued 23 May 2010**

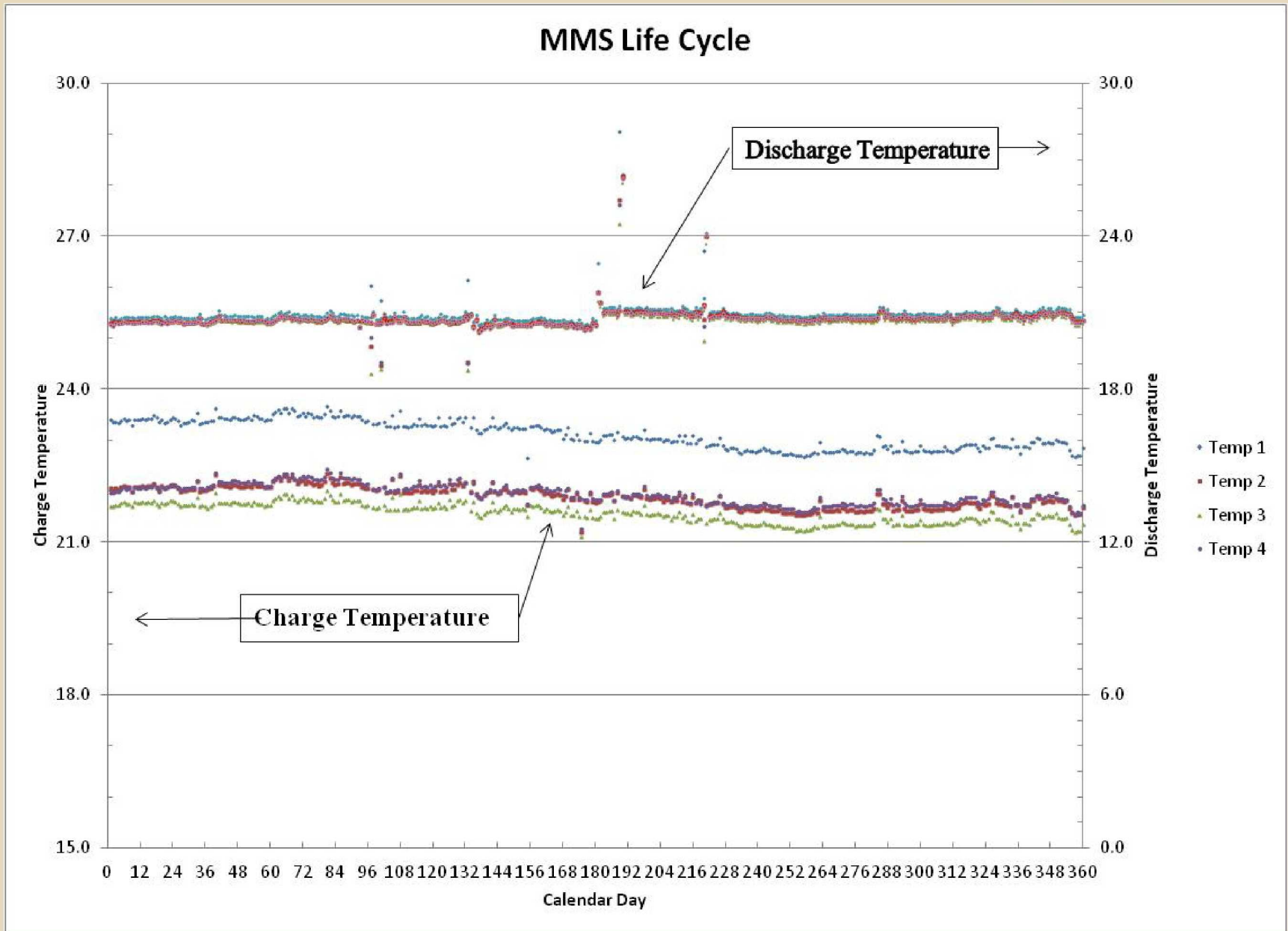
**Performed Annual Performance Tests – Complete 11 June 2010**



# A123 40 Ahr Lithium-Ion Battery MMS Life Cycle Test



# A123 40 Ahr Lithium-Ion Battery MMS Life Cycle Test

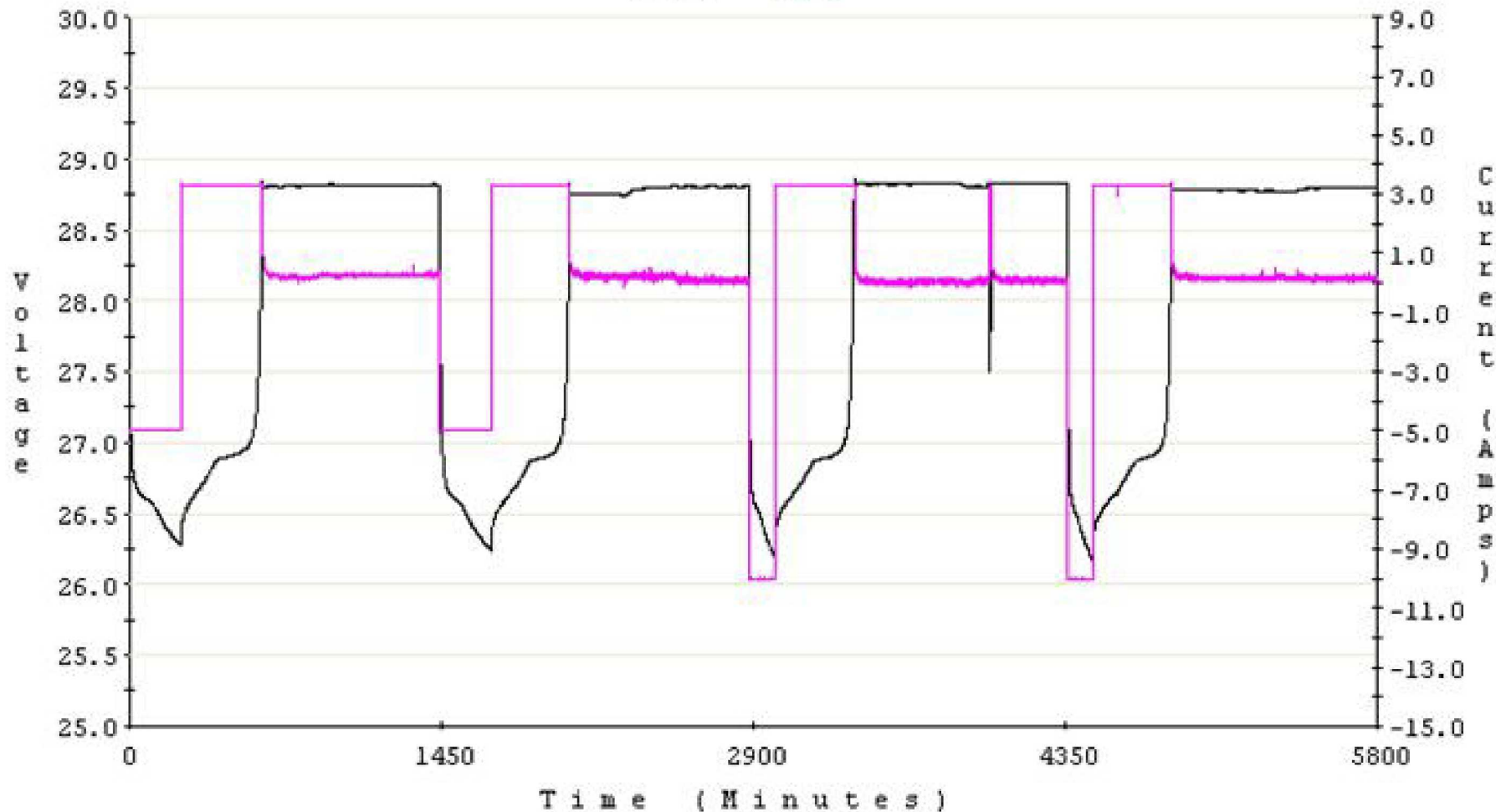


# A123 40 Ahr Lithium-Ion Battery MMS Life Cycle Test

## Test Pack 67NL41

Cycle 6 & 185 - Discharge C/5 for 2 hrs, Charge C/2 to 28.8 V voltage clamp for 22 hrs. [67NL41FC]  
 Cycle 370 & 549 - Discharge C/4 for 2 hrs, Charge C/2 to 28.8 V voltage clamp for 22 hrs.

Tvolt    Curr





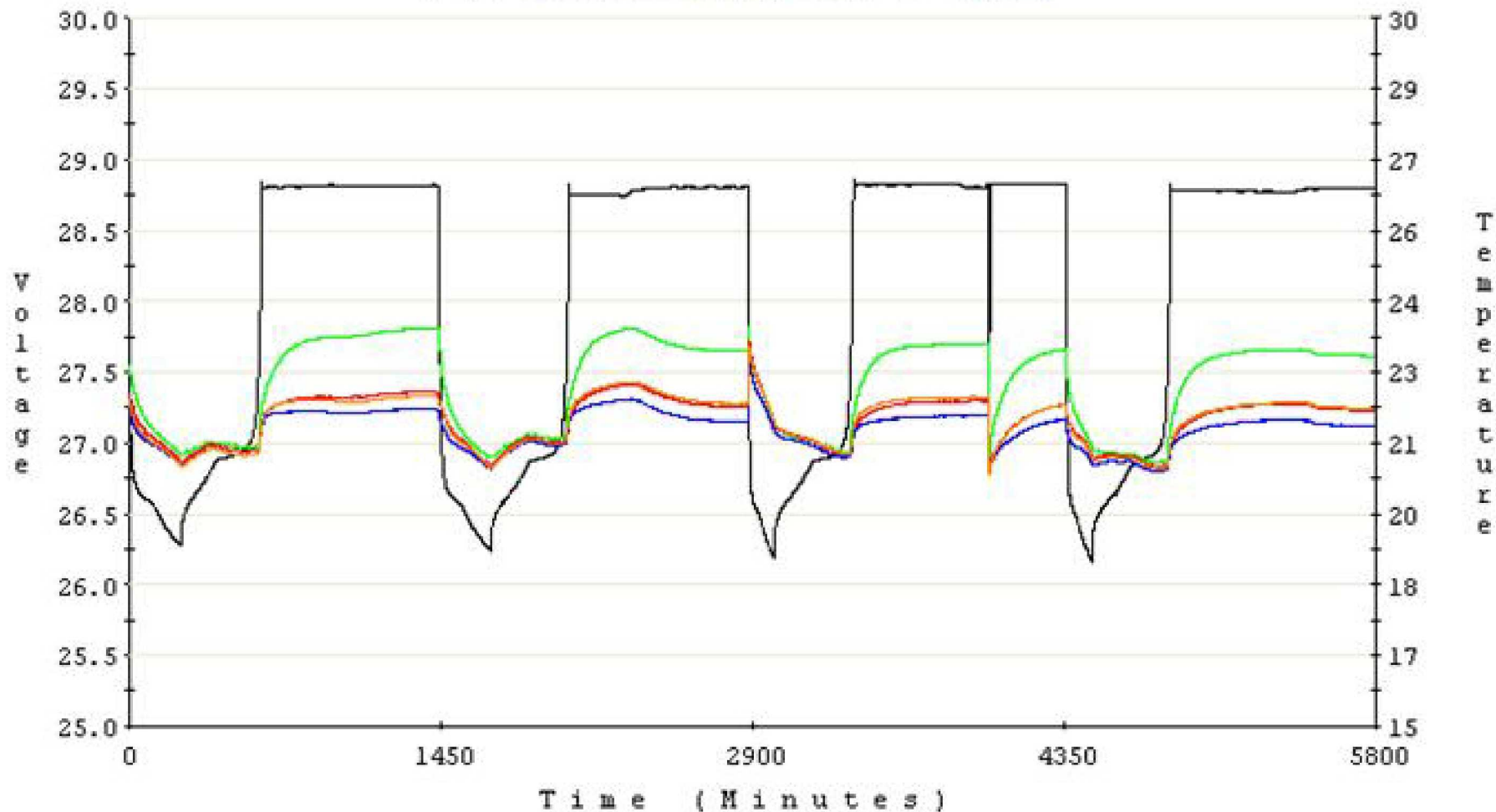
# A123 40 Ahr Lithium-Ion Battery MMS Life Cycle Test

## Test Pack 67NL41

Cycle 6 & 185 - Discharge C/5 for 2 hrs, Charge C/2 to 28.8 V voltage clamp for 22 hrs. [67NL41FC]

Cycle 370 & 549 - Discharge C/4 for 2 hrs, Charge C/2 to 28.8 V voltage clamp for 22 hrs.

Volt   Temp 1   Temp 2   Temp 3   Temp 4



# A123 40 Ahr Lithium-Ion Battery GPM & MMS Life Cycle Test



## Performance Test Results:

After 1 yr Test	GPM	Loss
Capacity Test 20°C –	37.5	4.3 Ahr
Charge Retention 20°C –	36.6	3.9 Ahr
Capacity Test 20°C –	37.9	4.0 Ahr
	MMS	
Capacity Test 20°C –	38.2	1.3 Ahr
Charge Retention 20°C –	37.3	1.0 Ahr
Capacity Test 20°C –	38.2	1.4 Ahr





# A123 40 Ahr Lithium-Ion Battery GPM & MMS Life Cycle Test



<b>Characterization tests: GPM</b>	<b>Initial</b>	<b>Post Cycling</b>
<b>Capacity Test 20°C –</b>	<b>41.8</b>	<b>37.5 Ahr</b>
<b>Capacity Retention Test 20°C –</b>	<b>40.5</b>	<b>36.6 Ahr</b>
<b>Capacity Test 0°C –</b>	<b>41.1</b>	<b>37.5 Ahr</b>
<b>Capacity Test 40°C –</b>	<b>41.8</b>	<b>38.3 Ahr</b>
<b>Capacity Test 20°C –</b>	<b>41.8</b>	<b>38.4 Ahr</b>

**Loss of 3-4 Ahr after 1 year**

## **Characterization tests: MMS**

<b>Capacity Test 20°C –</b>	<b>39.5</b>	<b>38.2 Ahr</b>
<b>Capacity Retention Test 20°C –</b>	<b>38.3</b>	<b>37.3 Ahr</b>
<b>Capacity Test 0°C –</b>	<b>38.5</b>	<b>38.0 Ahr</b>
<b>Capacity Test 40°C –</b>	<b>39.6</b>	<b>38.7 Ahr</b>
<b>Capacity Test 20°C –</b>	<b>39.6</b>	<b>39.0 Ahr</b>

**Loss of .4 to 1 Ahr after 1 year**