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

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Crane Indiana

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

- 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
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

Test Pack: Eight 15 Ah LiNiO₂ cells in series

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)
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

32% DoD, 113 Min Orbit Period
40% DoD, 90 Min Orbit Period

32% DoD, 90 Min Orbit Period
80% DoD every 30 days

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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

Charge Temperature
Discharge Temperature

32% DoD, 113 Min Orbit Period
40% DoD, 90 Min Orbit Period

Charge Temperature

Cycle

0 3000 6000 9000 12000 15000 18000 21000 24000 27000 30000

15.0 16.0 17.0 18.0 19.0 20.0 21.0 22.0 23.0 24.0 25.0 26.0 27.0 28.0 29.0 30.0

26.0 25.0 24.0 23.0 22.0 21.0 20.0 19.0 18.0 17.0 16.0 15.0 14.0 13.0 12.0 11.0
QUALLION 15 Ah (G001QL)
Post Life Cycle Test Results

Comparison Capacity Test Results

<table>
<thead>
<tr>
<th>Test Case</th>
<th>Initial Evaluation</th>
<th>Post Life Cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>End LEO Life Test</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capacity 20°C</td>
<td>15.00</td>
<td>15.00</td>
</tr>
<tr>
<td>Charge Retention</td>
<td>14.00</td>
<td>14.00</td>
</tr>
<tr>
<td>Capacity 0°C</td>
<td>12.00</td>
<td>12.00</td>
</tr>
<tr>
<td>Capacity 20°C</td>
<td>10.00</td>
<td>10.00</td>
</tr>
<tr>
<td>Capacity 40°C</td>
<td>16.00</td>
<td>16.00</td>
</tr>
<tr>
<td>Capacity 20°C</td>
<td>15.00</td>
<td>15.00</td>
</tr>
</tbody>
</table>
QUALLION 15 Ah (G001QL) Post Life Cycle Test Results

Impedance Comparison

- SoD
- 60 Min into Discharge
- EoD

Initial Evaluation

Post Life Cycle
LITHION 50 AHR LITHIUM-ION CELLS
LEO LIFE CYCLE TEST
LITHION 50 Ahr Lithium-Ion Cells
Test Parameters

Test Pack: Four 50 Ah LiNiO$_2$ 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.


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

<table>
<thead>
<tr>
<th>Cell S/N</th>
<th>20°C Capacity (Ahr)</th>
<th>0°C Capacity (Ahr)</th>
<th>40°C Capacity (Ahr)</th>
<th>20°C Charge Retention (Ahr)</th>
<th>20°C Impedance (Ahr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>220</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>234</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>243</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>250</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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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

Cycle 7654 → Cycle 8290

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

### Cycle 8240

<table>
<thead>
<tr>
<th>Cell</th>
<th>End of Discharge Voltage</th>
<th>End of Charge Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell #1</td>
<td>3.48702</td>
<td>3.94228</td>
</tr>
<tr>
<td>Cell #2</td>
<td>3.49946</td>
<td>3.95135</td>
</tr>
<tr>
<td>Cell #3</td>
<td>3.50563</td>
<td>3.95135</td>
</tr>
<tr>
<td>Cell #4</td>
<td>3.53681</td>
<td>3.95472</td>
</tr>
<tr>
<td>Voltage Spread</td>
<td>0.04979</td>
<td>0.01244</td>
</tr>
</tbody>
</table>

### Cycle 8203

<table>
<thead>
<tr>
<th>Cell</th>
<th>End of Discharge Voltage</th>
<th>End of Charge Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell #1</td>
<td>3.34283</td>
<td>3.83635</td>
</tr>
<tr>
<td>Cell #2</td>
<td>3.71513</td>
<td>4.19647</td>
</tr>
<tr>
<td>Cell #3</td>
<td>3.61626</td>
<td>4.05788</td>
</tr>
<tr>
<td>Cell #4</td>
<td>3.36023</td>
<td>3.71006</td>
</tr>
<tr>
<td>Voltage Spread</td>
<td>0.37230</td>
<td>0.48641</td>
</tr>
</tbody>
</table>

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GSFC PACK: G002LL, 50AH Lithion 20°C, 40% DOD

Leo Life Cycling, 3.95V Clamp per cell (15.8V total) with cell balancing

DIS: 25.0A for 45 min  CHG: 22.0A to 15.8V total vol t trip then taper 60 minutes max.

Graph showing cell voltages for different cycles.

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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

Cycle 8290
Cycle 14826
Cycle 12520
Cycle 16493

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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

End of Charge Temperature
End of Discharge Temperature

Relocation of test pack
Ambient Temperature adjusted

Cycles
0 2000 4000 6000 8000 10000 12000 14000 16000 18000 20000 22000 24000

Charge Temperature
28.0
26.0
24.0
22.0
20.0
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0

Discharge Temperature
33.0
32.0
31.0
30.0
29.0
28.0
27.0
26.0
25.0
24.0
23.0
22.0
21.0
20.0
19.0
18.0

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

80% Capacity Comparison Test Pack G002LL
Charge 22 amps for 65 minutes, Discharge 15 amps for 160 minutes

- Cell #220
- Cell #234
- Cell #243
- Cell #250
- BTPACKCUR

Discharge Cycle Number

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LITHION 50 Ahr Lithium-Ion Cells
Post Cycle Test Summary

Impedance Test
Initial Evaluation vs Post Cycling

Impedance (milliohms)

- SoD
- Mid-Discharge
- EoD

Cell S/N

Initial Evaluation
220 234 243 250

Post Life Cycling
220 234 243 250
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
ABS 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

State of Charge VS End of Charge Voltage @ 20 Deg C

SOC Voltage
SOD Voltage

SOC

0% 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%

Voltage

27.00
28.00
29.00
30.00
31.00
32.00
33.00
34.00

SOC

ABSL 5 Ahr Lithium-Ion Battery

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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

SDO-GEO DISCHARGE TIMES
23-DAY ECLIPSE SEASON

Max Duration 72 Minutes

Min Duration 28 Minutes

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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 – 1st Eclipse Season
6 January to 4 June 2009 – 1st Solstice Season
5 June to 3 July 2009 – 2nd Eclipse Season
4 July to 4 December 2009 – 2nd Solstice Season
5 to 27 December 2009 - 3rd Eclipse Season
28 December 2009 to 27 May 2010 – 3rd Solstice Season
28 May to 22 June 2010 – 4th Eclipse Season
23 June to Present – 4th Solstice Season
ABSL 5 Ahr Lithium-Ion Battery
SDO-GEO Life Cycle Test

SDO-GEO Test 42NG01

Total Voltage

Eclipse #1 Cycle 1 to Eclipse #2 Cycle 174 to 196
Eclipse #3 Cycle 347 to 369
Eclipse #4 Cycle 520 to 542

Low voltage due to charge current too low (0.2) increased to 0.4 amp on Cycle 8.

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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

Eclipse #1
Cycle 13

Eclipse #2
Cycle 185

Eclipse #3
Cycle 360

Eclipse #4
Cycle 532

Cell Voltage

3.10 3.20 3.30 3.40 3.50 3.60 3.70 3.80 3.90 4.00 4.10 4.20

Time (minutes)

0 72 144 216 288

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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
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

80% DOD after de-rated to 4 Ahr

80% DOD -Failed

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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

V(t)olt  Curr

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Pack ABSL02
LRO-LLO Cycle 477 to 9693 09-23-2010
Trend-Plot End of Charge and End of Discharge (Monthly 80% DoD Capacity Test)
• Tvolt × Curr

- 80% DoD after de-rated to 4 Ahr
- 80% DoD -Failed
A123 40 AHR LITHIUM-ION BATTERY

GPM LIFE CYCLE TEST
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

Orbit period: 93 minutes

GPM Eclipse Duration

Eclipse duration (minutes)

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

66NL40 GPM Cycle
30 04-17-2009 to 5490 04-13-2010 every 15th Cycle - Graph 66NL40LC
Orbit Period 93 minutes - 15 Cycles per day - 365 Days = 5490 cycles

Battery Voltage

15th cycle of day shown

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A123 40 Ahr Lithium-Ion Battery
GPM Life Cycle Test

66NL40 GPM Cycle
30 04-17-2009 to 5490 04-13-2010 every 15th Cycle - Graph 66NL40LC
Orbit Period 93 minutes - 15 Cycles per day - 365 Days = 5490 cycles

- Temp 1
- Temp 2
- Temp 3
- Temp 4
- AmbT

Temperature

15th cycle of day shown

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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)

* Tvolt  * Curr

Battery Voltage

Battery Current

Cycles (93 minute orbit, 15 cycles per day)
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)

Temperature

Cycles (93 minute orbit, 15 cycles per day)
66NL40 GPM Cycle
Cycle 4965 03-09-2010 - 66NL40C
Day 330 93 Min Orbit

Time - 93 minute orbit

Battery Voltage

Current

0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100

25.0 30.0

25.0 -25.0

26.0 27.0 28.0 29.0 30.0

25.0 20.0 15.0 10.0 5.0 0.0

-5.0 -10.0 -15.0 -20.0 -25.0

-25.0 0.0 5.0 10.0 15.0 20.0 25.0

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66NL40 GPM Cycle
Cycle 4965 03-09-2010 - 66NL40C
Day 330  93 Min Orbit

Temp 1  Temp 2  Temp 3  Temp 4  AmbT

Temperature

Time - 93 minute orbit
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.
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

MMS Life Cycle

- Battery Voltage
- Battery Current

Calendar Day

Voltage

Current

FINAL – Distribution Approved NASA Goddard Space Flight Center
A123 40 Ahr Lithium-Ion Battery
MMS Life Cycle Test

MMS Life Cycle

Discharge Temperature

Charge Temperature

Calendar Day

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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.

T: volt  C: curr

Time (Minutes)
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.

Voltage

Temp 1 Temp 2 Temp 3 Temp 4

Time (Minutes)
## Performance Test Results:

<table>
<thead>
<tr>
<th>After 1 yr Test</th>
<th>GPM</th>
<th>MMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity Test 20°C –</td>
<td>37.5</td>
<td>38.2</td>
</tr>
<tr>
<td>Charge Retention 20°C –</td>
<td>36.6</td>
<td>37.3</td>
</tr>
<tr>
<td>Capacity Test 20°C –</td>
<td>37.9</td>
<td>38.2</td>
</tr>
</tbody>
</table>

**Loss**

- 4.3 Ahr
- 3.9 Ahr
- 4.0 Ahr
- 1.3 Ahr
- 1.0 Ahr
- 1.4 Ahr
## A123 40 Ahr Lithium-Ion Battery
### GPM & MMS Life Cycle Test

**Characterization tests: GPM**

<table>
<thead>
<tr>
<th>Test</th>
<th>Initial</th>
<th>Post Cycling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity Test 20°C −</td>
<td>41.8</td>
<td>37.5 Ahr</td>
</tr>
<tr>
<td>Capacity Retention Test 20°C −</td>
<td>40.5</td>
<td>36.6 Ahr</td>
</tr>
<tr>
<td>Capacity Test 0°C −</td>
<td>41.1</td>
<td>37.5 Ahr</td>
</tr>
<tr>
<td>Capacity Test 40°C −</td>
<td>41.8</td>
<td>38.3 Ahr</td>
</tr>
<tr>
<td>Capacity Test 20°C −</td>
<td>41.8</td>
<td>38.4 Ahr</td>
</tr>
</tbody>
</table>

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

**Characterization tests: MMS**

<table>
<thead>
<tr>
<th>Test</th>
<th>Initial</th>
<th>Post Cycling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity Test 20°C −</td>
<td>39.5</td>
<td>38.2 Ahr</td>
</tr>
<tr>
<td>Capacity Retention Test 20°C −</td>
<td>38.3</td>
<td>37.3 Ahr</td>
</tr>
<tr>
<td>Capacity Test 0°C −</td>
<td>38.5</td>
<td>38.0 Ahr</td>
</tr>
<tr>
<td>Capacity Test 40°C −</td>
<td>39.6</td>
<td>38.7 Ahr</td>
</tr>
<tr>
<td>Capacity Test 20°C −</td>
<td>39.6</td>
<td>39.0 Ahr</td>
</tr>
</tbody>
</table>

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