QUALLION




# Characteristics of Quallion's Battery for Aerospace Application

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**2011 NASA Aerospace Battery Workshop, 11/15-17/2011**

*Powering Life.*

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- **Tittle III Cell Manufacturing Line Status**
- **Quallion's chemistry evaluation**
  - LEO cycle (@ various DOD and charge voltage, R.T.)
  - Calendar life (@ 100% SOC, 4.1V, R.T.)
  - ZeroVolt™ + LEO cycle performance
  - Life prediction
- **Battery pack Characterization**
  - Test battery configuration
    - 1P-8S QL015KA
    - 1P-8S QL075KA
    - 2P-8S QL015KA
  - Test condition
    - LEO cycle @ 20% DOD, R.T. or 30°C
    - Accelerated HEO cycle @ 20°C

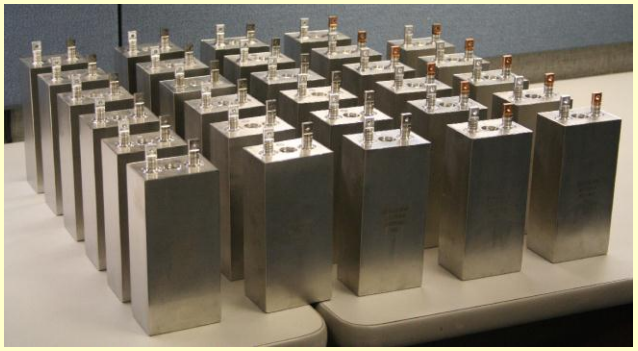
# Historical Overview and Quallion's Satellite Cell / Battery Development

- Quallion has been working on several cell / battery development projects over the past years to evaluate test batteries for life cycle to be used on future endeavors.
  - 2002
    - Chemistry evaluation
    - QL015KA cell development
  - 2005
    - QL075KA cell development
  - 2006
    - 8s-1p 15Ahr (ZeroVolt™) Test Battery (~51,000 cycles LEO)
      - The goal of the program was to assess current technology capabilities and understand thermal characteristics of battery pack. Several Characterization analysis was conducted to perform trade studies.
  - 2006
    - 12s-2p 75Ahr (Non-ZeroVolt) Test Battery (~5,000 cycles LEO)
      - Ultimate go forward design was using Quallion's existing chemistry due to performance
  - 2007
    - 8s-1p 75Ahr (Non-ZeroVolt) Test Battery (~27,000 cycles LEO)
      - The goal of the program was to evaluate Cu substrate in a larger cell/battery configuration.
  - 2009
    - 8s-2p 15Ahr (ZeroVolt™) Test Battery
      - The goal of the program was to evaluate battery under environmental and electrochemical tests for actual usage
  - 2011
    - 8s-2p 15Ahr (ZeroVolt™) Test Battery
      - Integrated in Tac-SAT4 and launched on 9/27/2011
      - On ground, the copied battery has been tested under the accelerated HEO cycle

# Quallion's Satellite Cell & Battery Design Support for Custom Cell and Battery

## Cell Design Support (Hardware, Chemistry)

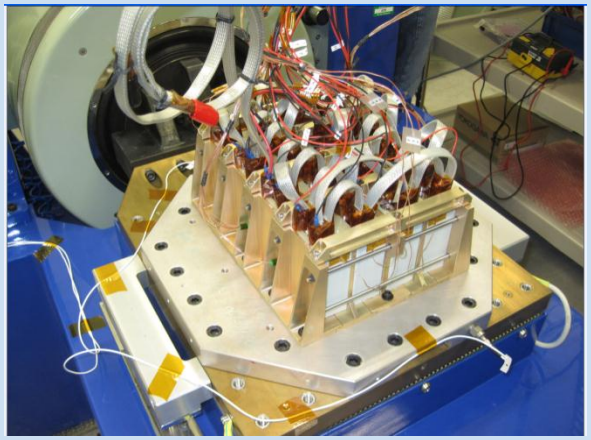
### QL075KA-SS



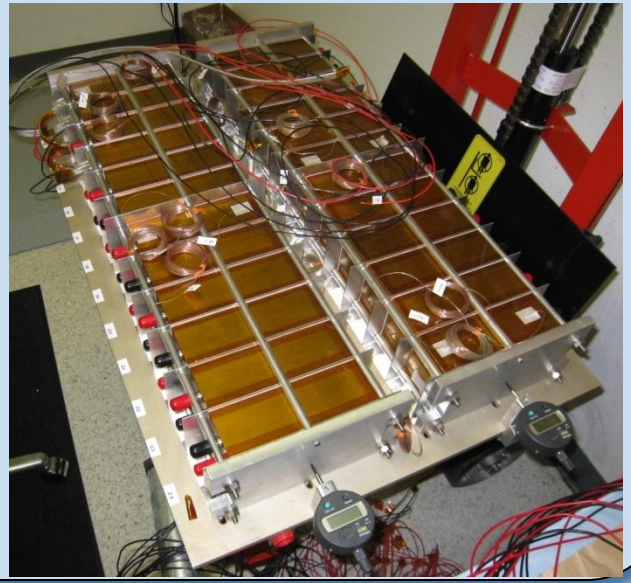
### QL015KA-SS

## Battery Design Support (Hardware, Electronics)

### QL015KA-SS, 8S-2P Battery



### QL075KA-SS, 12S-2P Battery



### QL015KA-SS, 8S-1P Battery

# SATELLITE CELLS MANUFACTURING SET UP STATUS (TITTLE III CELL LINE SET UP)



# Products from Tittle III Cell Line
# QL075KA / QL015KA

**QL075KA**

**QL015KA**

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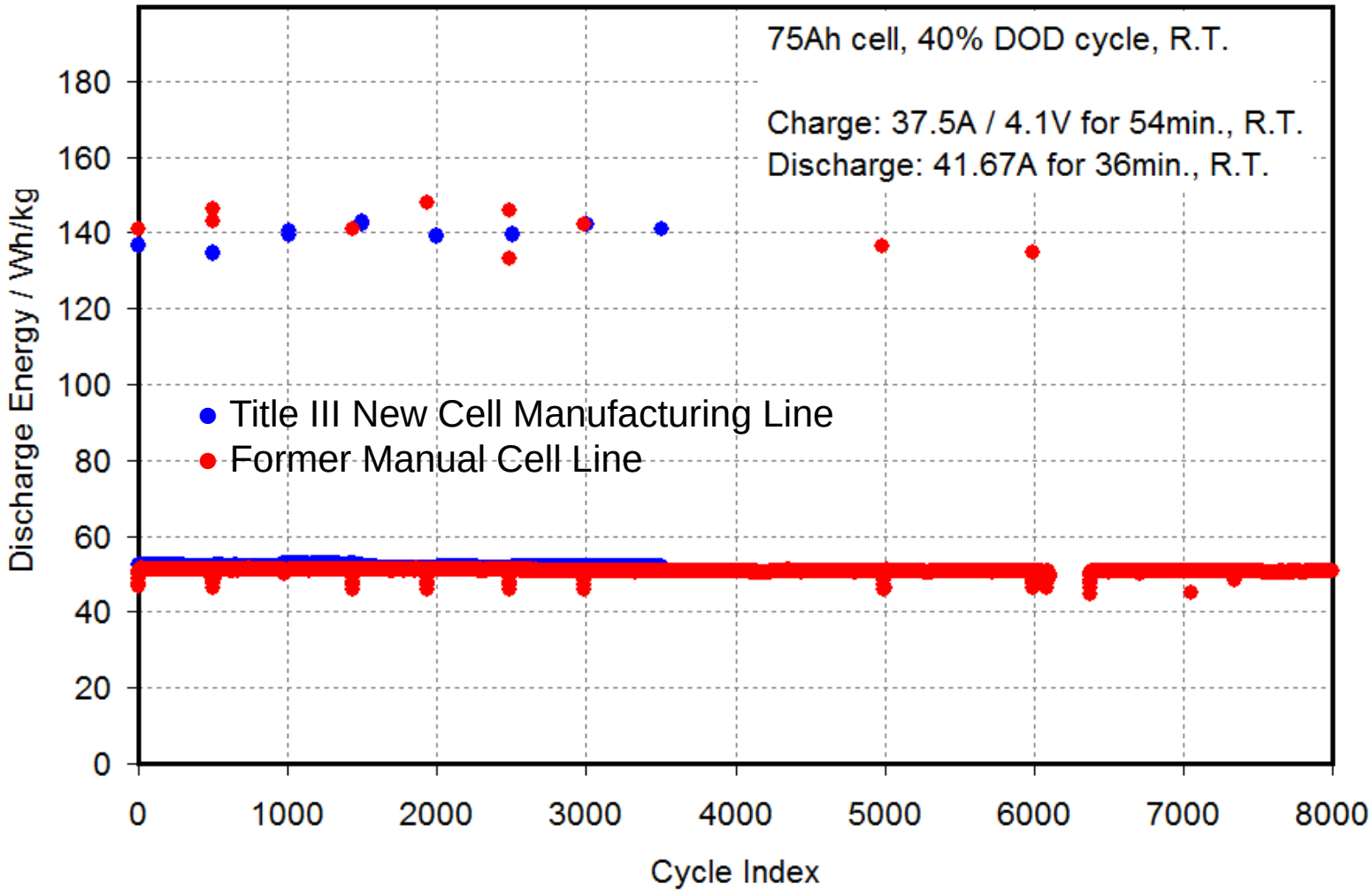
# QL075KA Cell Manufactured by Tittle III Cell Line LEO Cycle at Room Temperature

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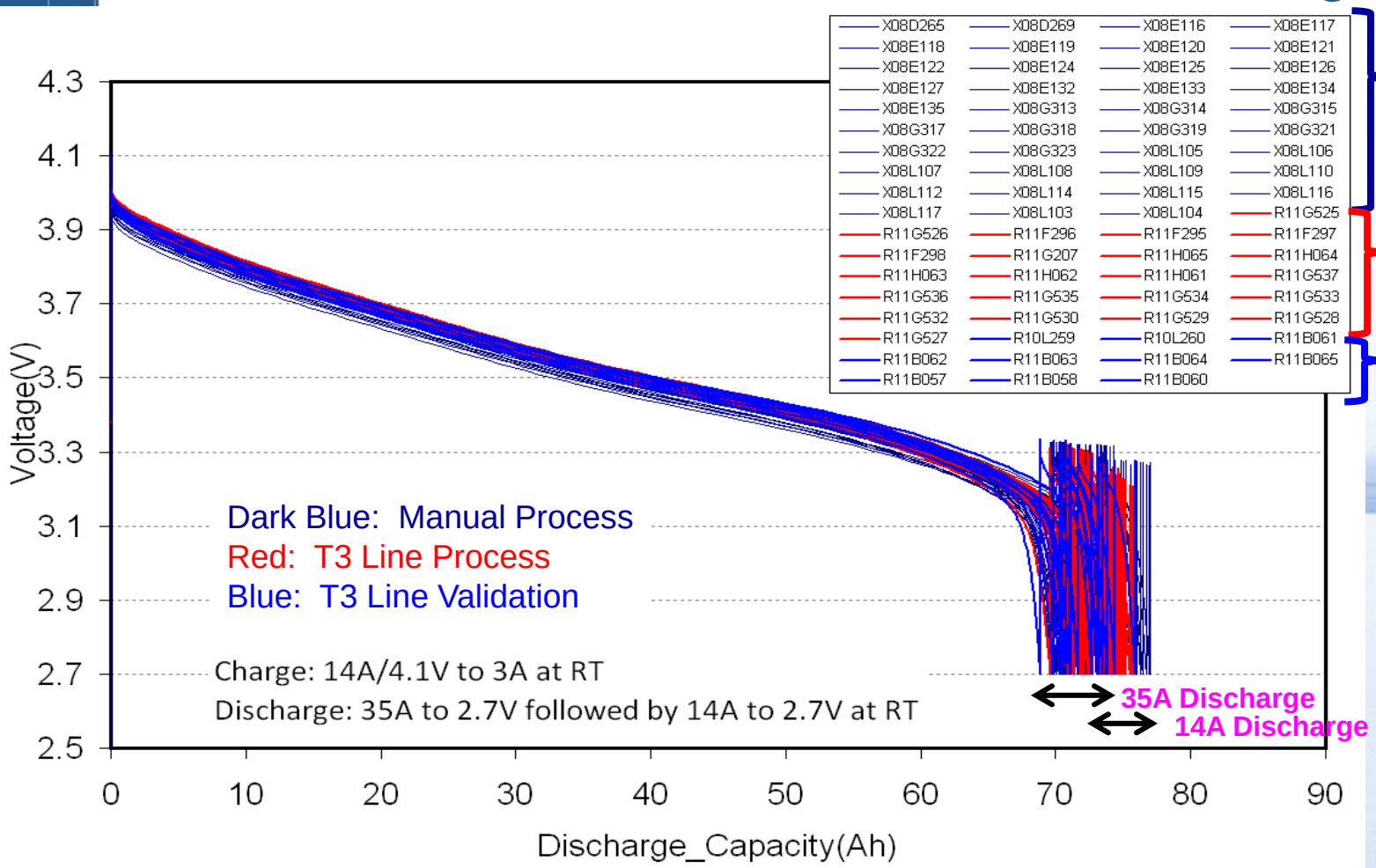
# QL075KA Cell Manufactured by Tittle III Cell Line Cell Discharge Curves

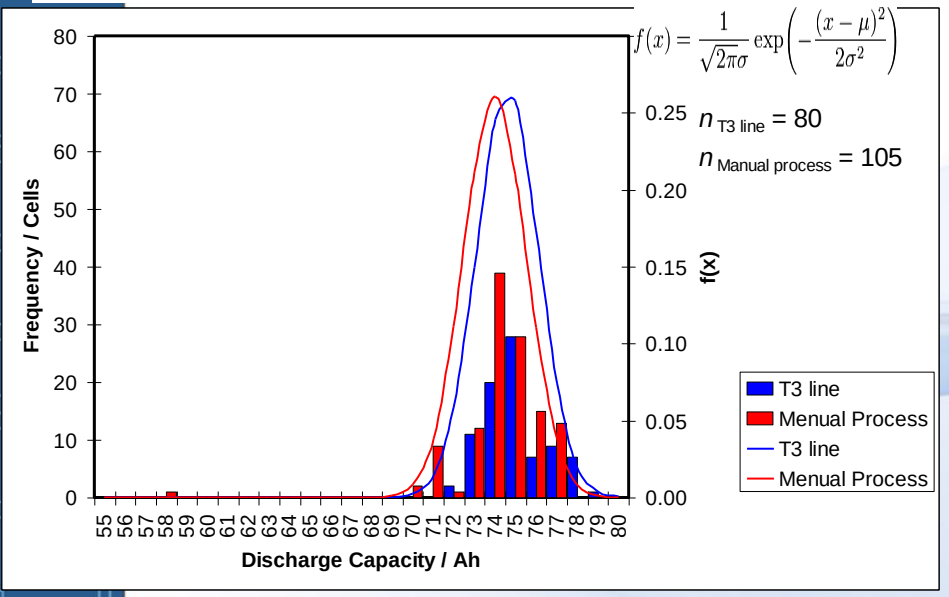



- T3 cells demonstrated less voltage difference.
- Characteristic of T3 cells are consistent to the results (red lines) from the former manual processed cells (dark blue line) and the validation tests (blue lines).

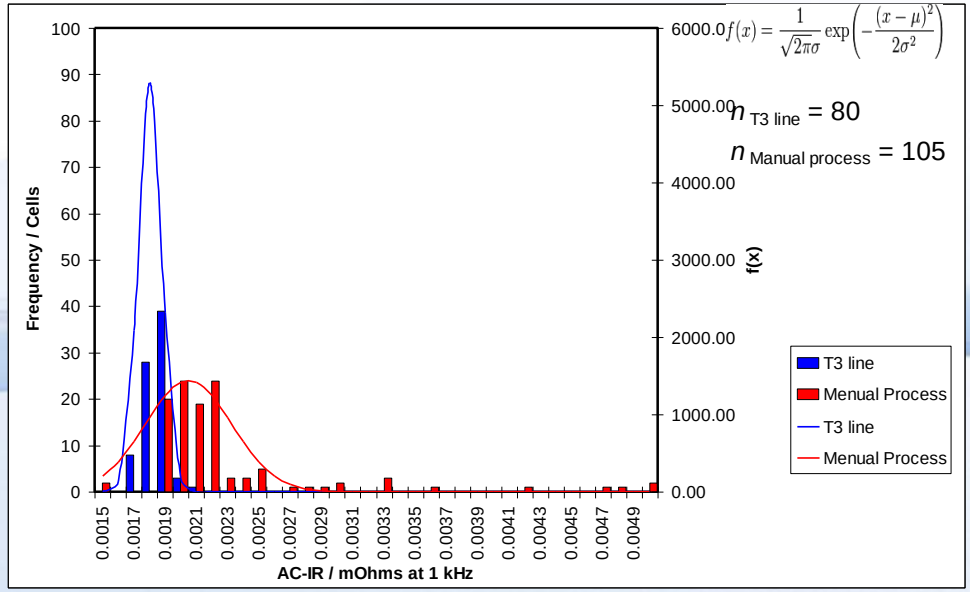
# QL075KA Cell Manufactured by Tittle III Cell Line
## Distribution of Cell Characteristics
### Tittle III Cell Line vs. Former Manual Process

Dark Blue: Manual Process
Red: T3 Line Process

## Discharge Capacity




## AC-IR (1 kHz)




- T3 cells demonstrated the same distribution of discharge capacity.
- T3 cells were in tighter range of AC-IR than the ones from former manual cell line, which provides the better cell matching for battery assembly.

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# Quallion's Chemistry Characteristics

- Cycle Performance
- Active Material Lot Viriance
- Calendar Life Perfomance
- ZeroVolt™ Technology

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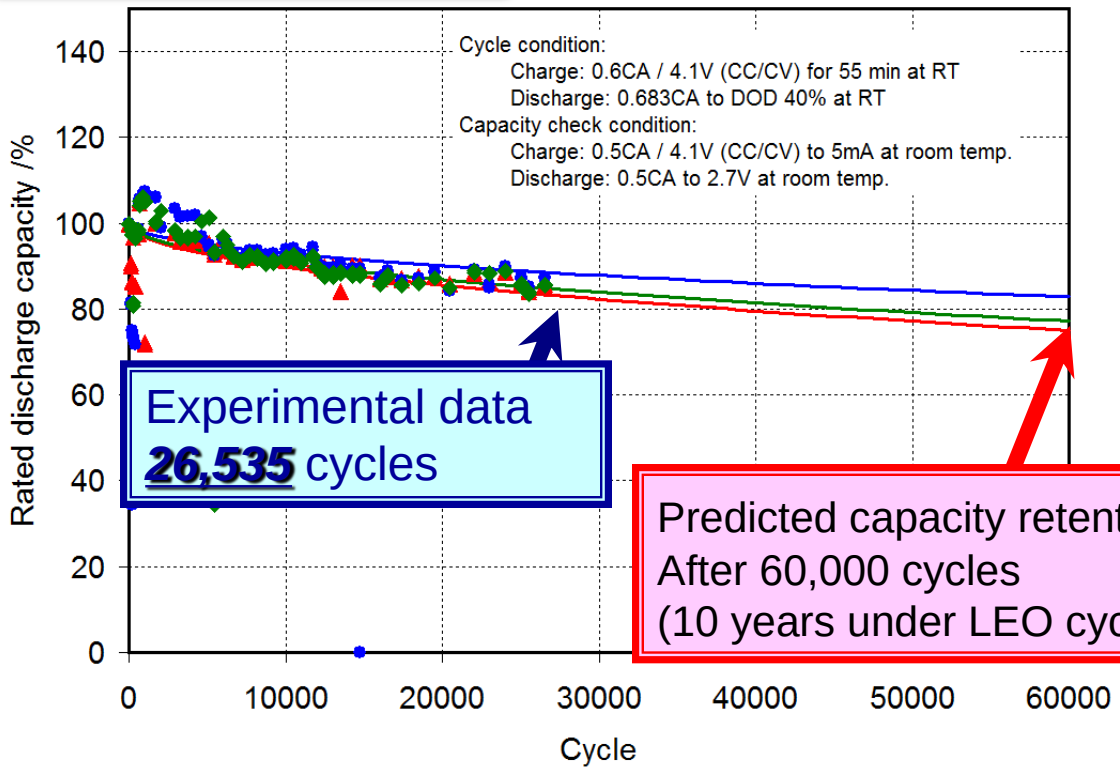
# Quallion Chemistry Evaluation
# 40% DOD LEO Cycle Performance
## (170mAh wound type model cell)

**Capacity retention equation** *)

$$\text{(Discharge capacity retention)} = 100 - k \times \sqrt{N_{cycle}}$$

*) ***k***: constant to determine capacity fading rate
$N_{cycle}$: charge and discharge cycle index

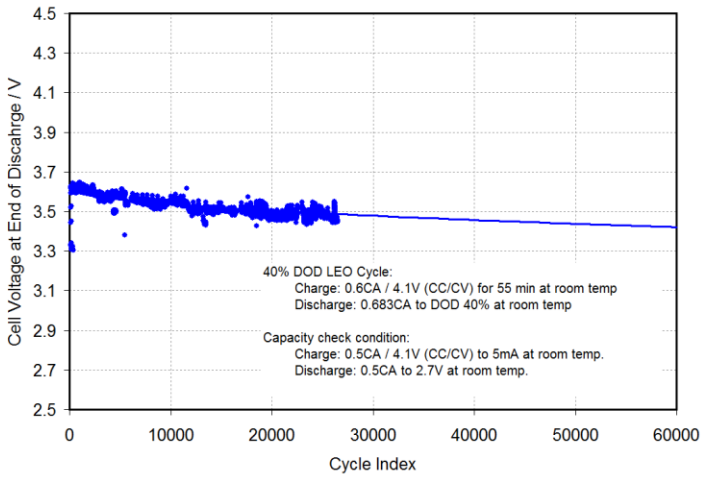
Discharge Capacity Retention




Experimental data
**26,535** cycles

Predicted capacity retention = **75-83%**
After 60,000 cycles
(10 years under LEO cycle condition)

Cell Voltage

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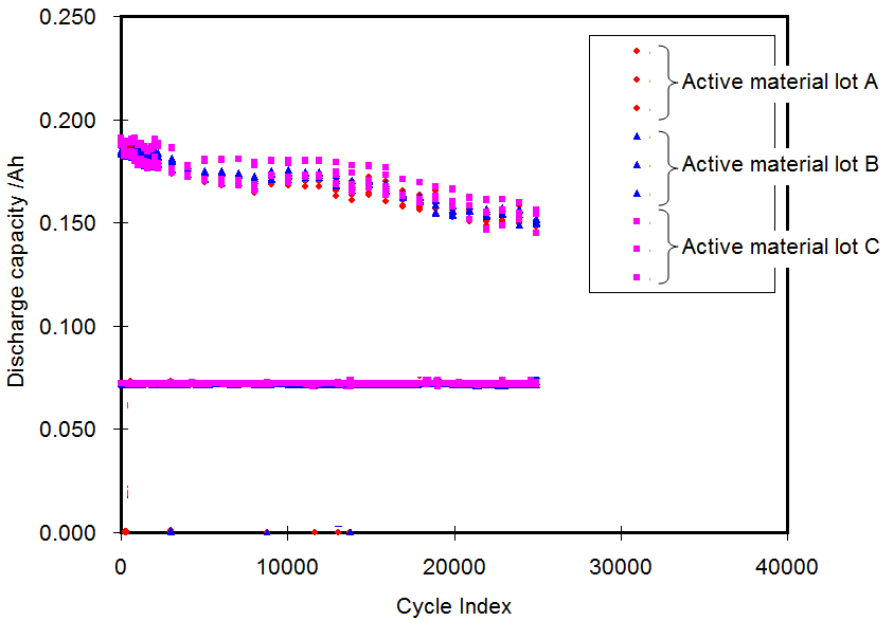
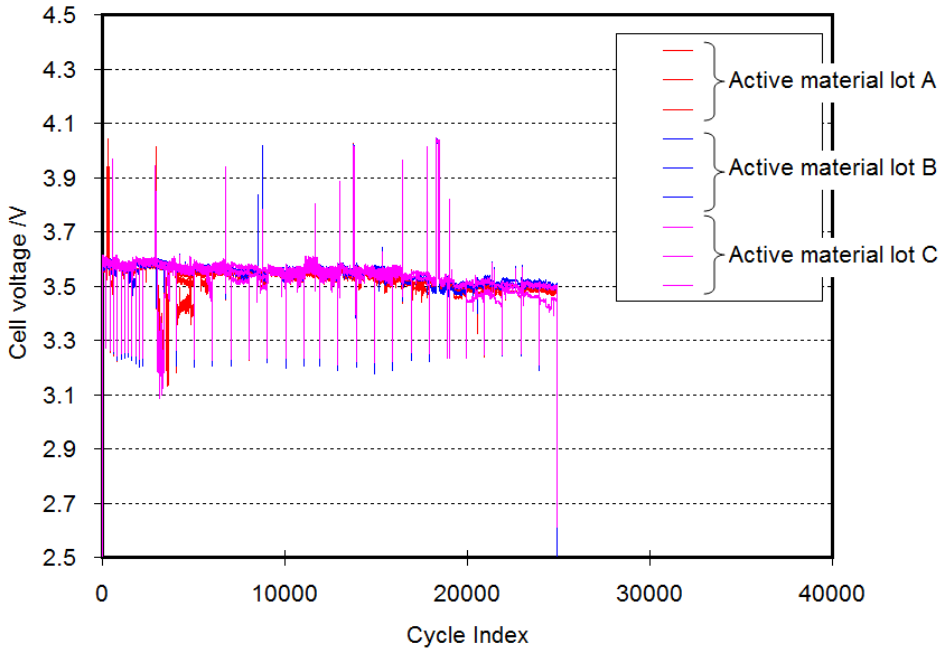
# Active Material Lot Difference in 40% DOD LEO Cycle (200mAh Wound Type Model Cell)

## Discharge Capacity




## Cell Voltage @ End of Discharge




No performance variance was observed among three active material lots.

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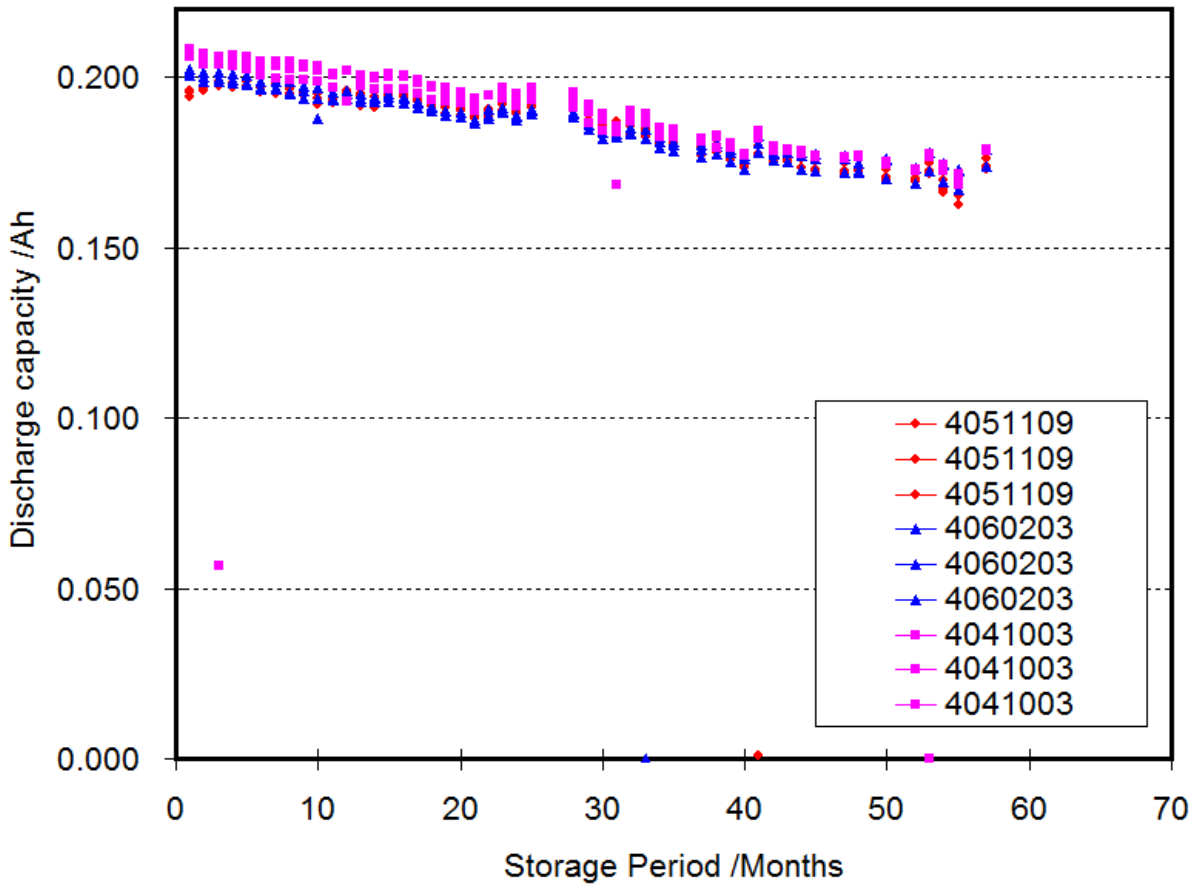
# Active Material Lot Difference in Calendar Life (200mAh Wound Type Model Cell)

## Discharge Capacity



# Quallion Chemistry Evaluation
# ZeroVolt™ Capability; Comparison with Conventional LIB Test Method

- **Test sample cell**
  - Quallion 18650 cell (Zero-Volt™ technology)
  - Sony 18650H2 cell (Hard carbon cell)

- **Test procedure**

1. Capacity check to determine baseline capacity (before storage)
   - The cells are cycled three times at room temperature according to the following standard procedures.
     - a) CC charge at C/2 rate to 4.2V
     - b) CV charge at 4.2V with a current cutoff of C/20
     - c) CC discharge at C/2 rate to 2.7V
2. **Simulate 0V state by short-circuiting the cell with a 20 ohm resistor.**
3. **Storage at room temperature for 3 days.**
4. Charge the cells at room temperature in two steps
   - CC charge at C/200 rate to 3.0V
   - CC charge at C/20 rate to 4.2V
5. Repeat the capacity check test from step 1 to determine the cell capacity after 0V storage.

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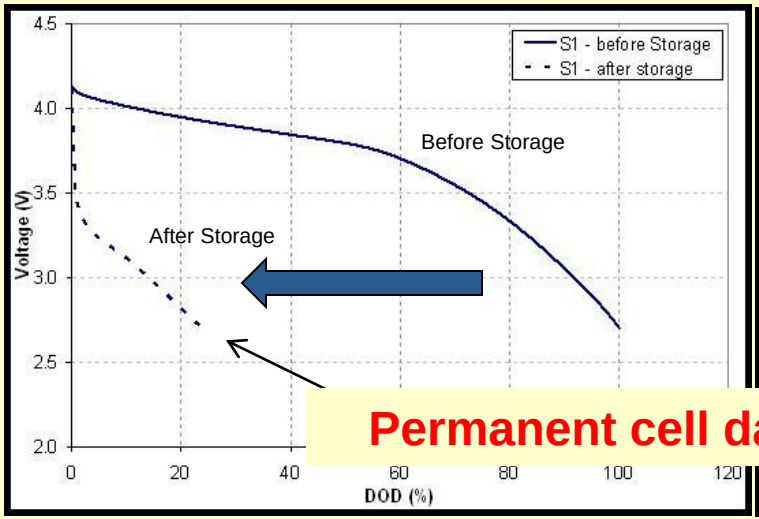
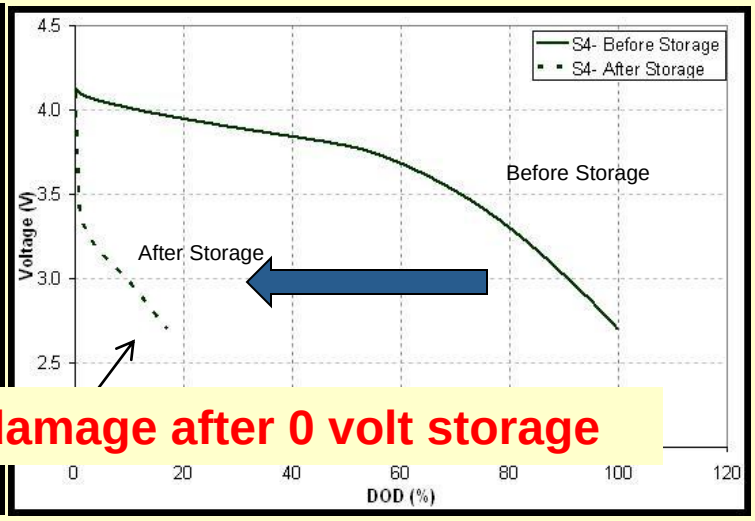
# Quallion Chemistry Evaluation
# Before and After 3-day Storage at Zero Volt

**SONY 18650**
**Cu substrate**

**Room temperature storage**



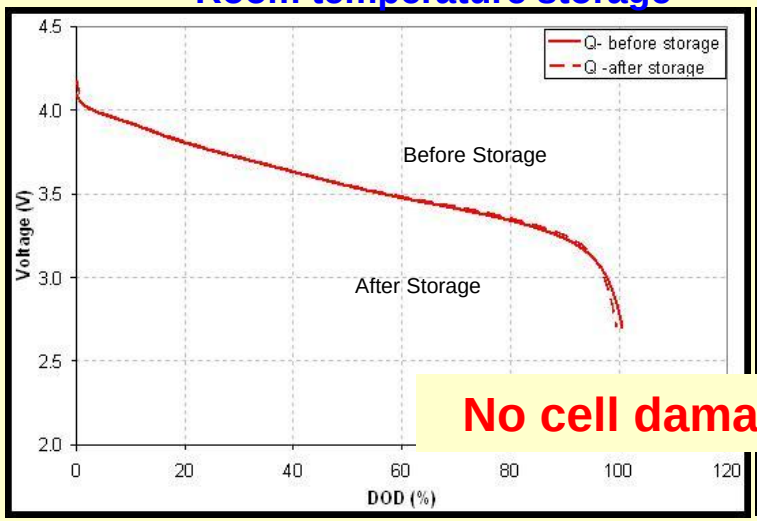

**40C storage**



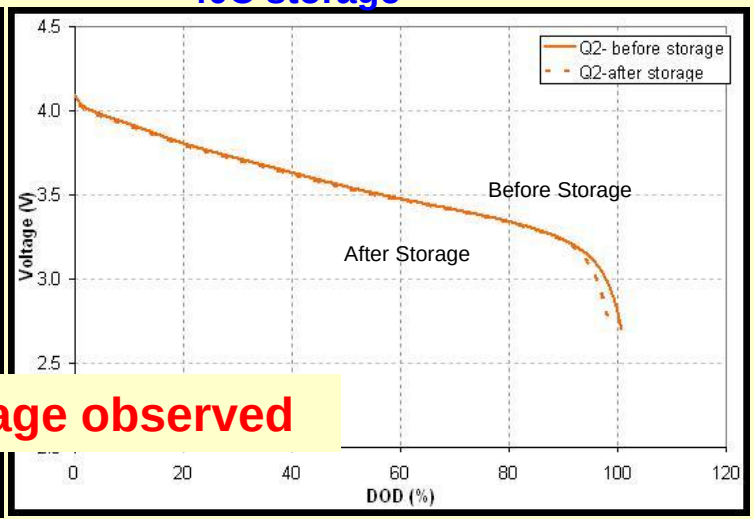

**Permanent cell damage after 0 volt storage**

**Quallion 5A-2**
**zero-volt**
**18650**
**Ti substrate**

**Room temperature storage**




**40C storage**




**No cell damage observed**

# Quallion Chemistry Evaluation

## Zero Volt™ Capability

## 40% DOD LEO Cycle Performance after 0V Storage (17 months)

## (200mAh wound type model cell)

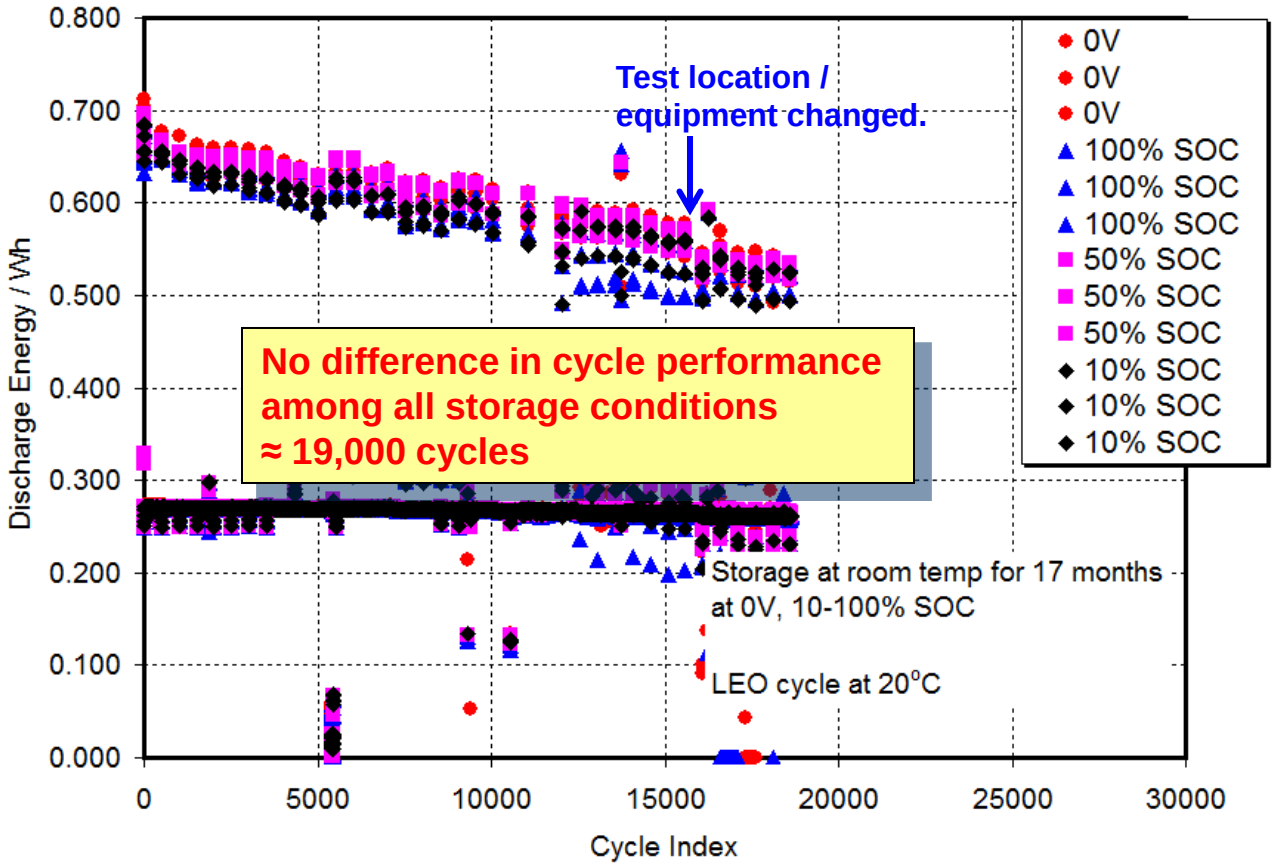
Storage Condition
For **17 months**,
- 100% SOC (3 cells)
- 50% SOC (3 cells)
- 10% SOC (3 cells)
- 0V (3 cells)

(at room temperature)

Cycle condition
- LEO cycle (40% DOD)

Capacity check
- 100% DOD
  at every 500 cycles

(at 20°C)

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# Quallion Chemistry Evaluation
# Zero Volt™ Capability
## 40% DOD LEO Cycle Performance after 0V Storage (29 months)
## (200mAh wound type model cell)

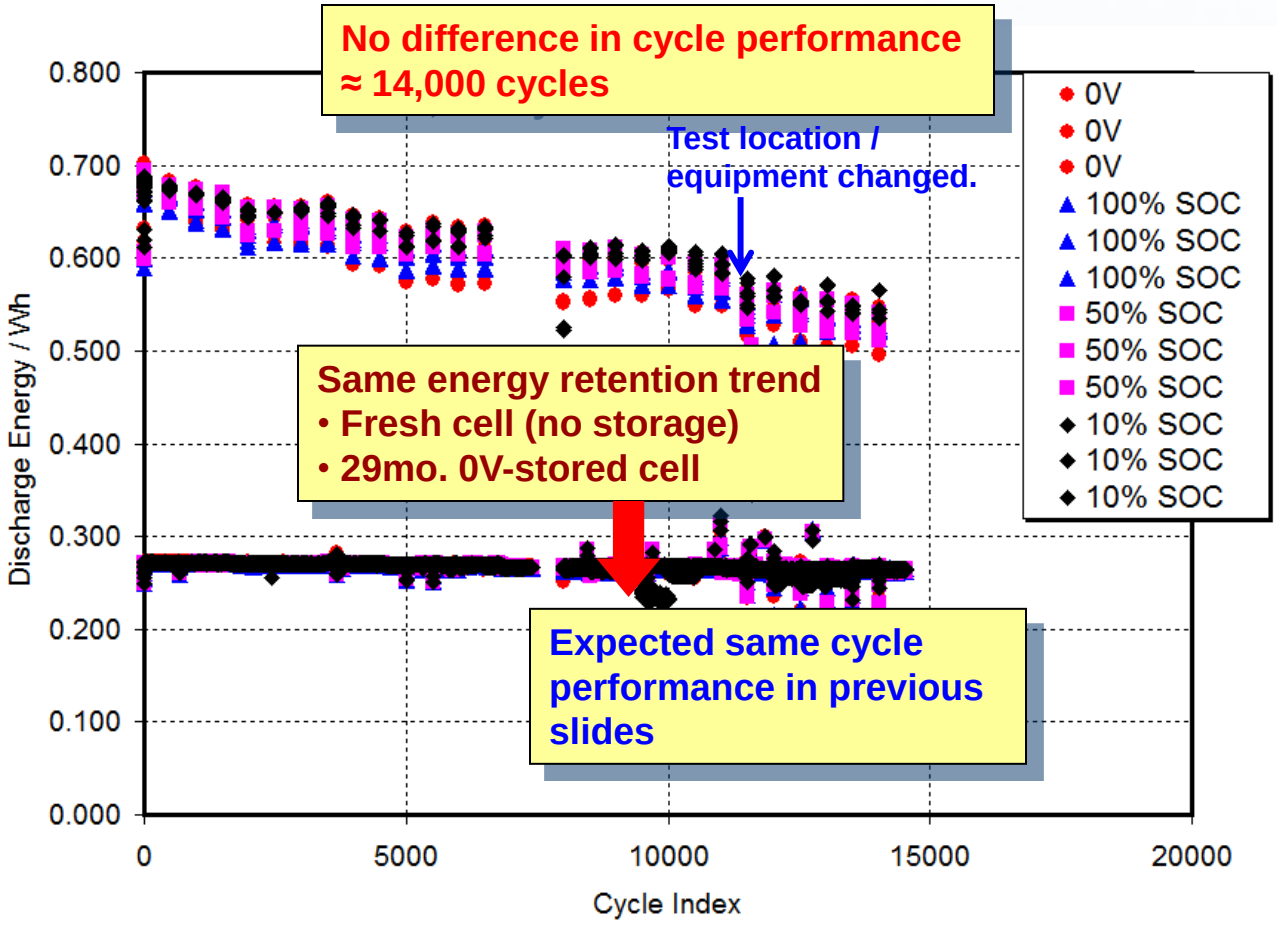
Storage Condition
For **29 months**,
- 100% SOC (3 cells)
- 50% SOC (3 cells)
- 10% SOC (3 cells)
- 0V (3 cells)

(at room temperature)

Cycle condition
- LEO cycle (40% DOD)

Capacity check
- 100% DOD
  at every 500 cycles

(at 20°C)

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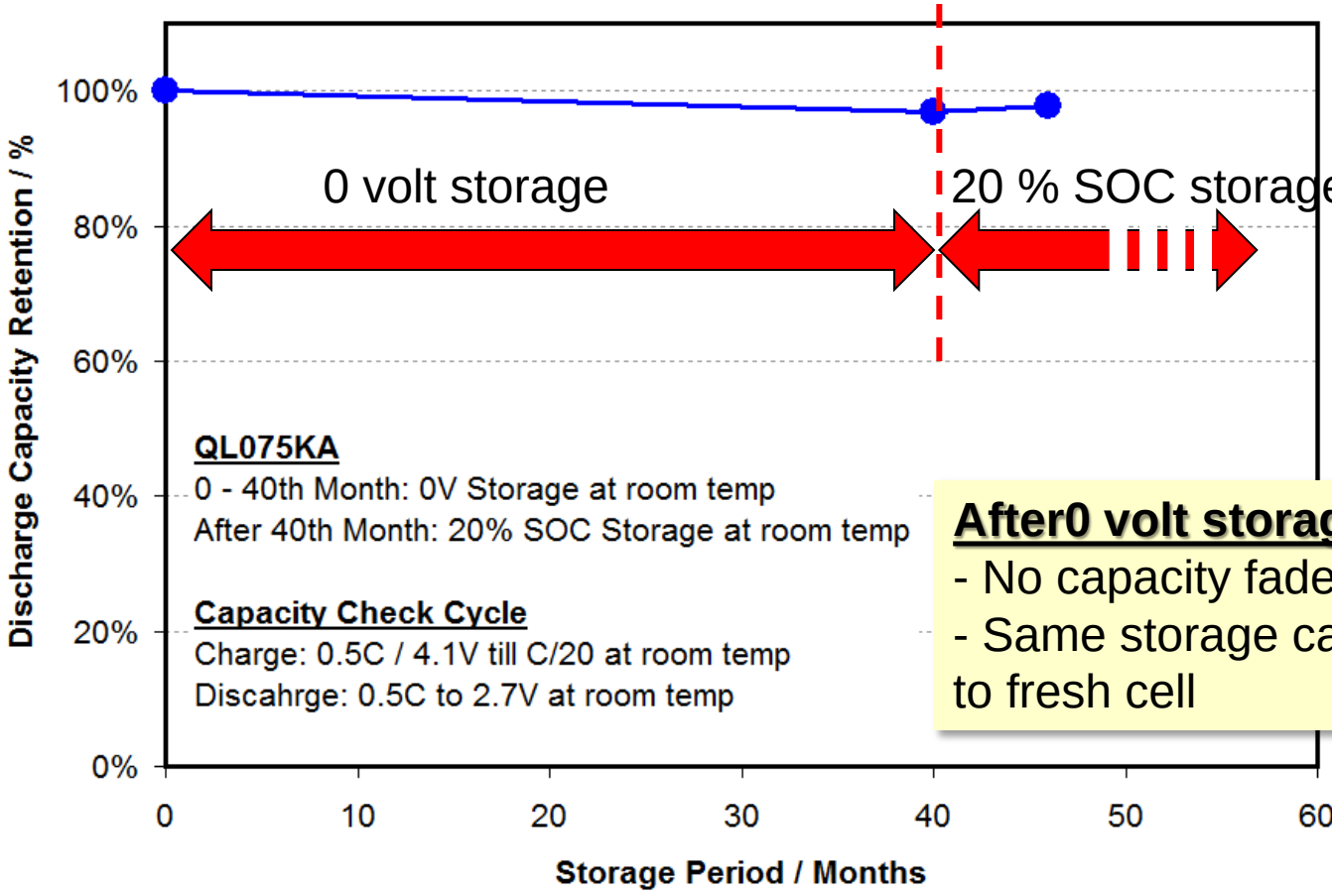
# Zero Volt™ Capability

## Capacity Retention after 0V Storage (40 months)
## (QL075KA cell, 20% SOC Storage Performance)




**After0 volt storage**

- No capacity fade
- Same storage capability to fresh cell

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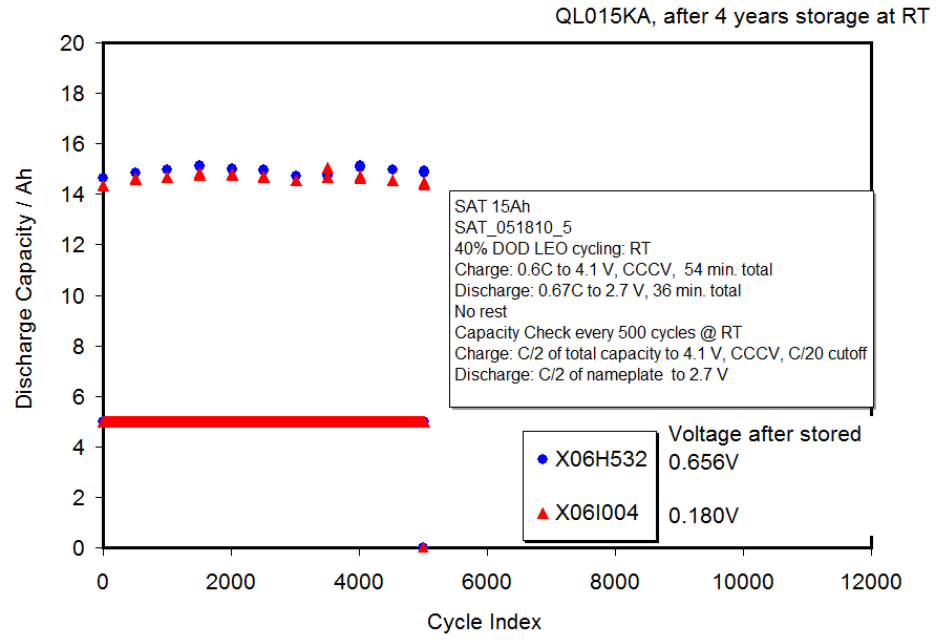
# Zero Volt™ Capability

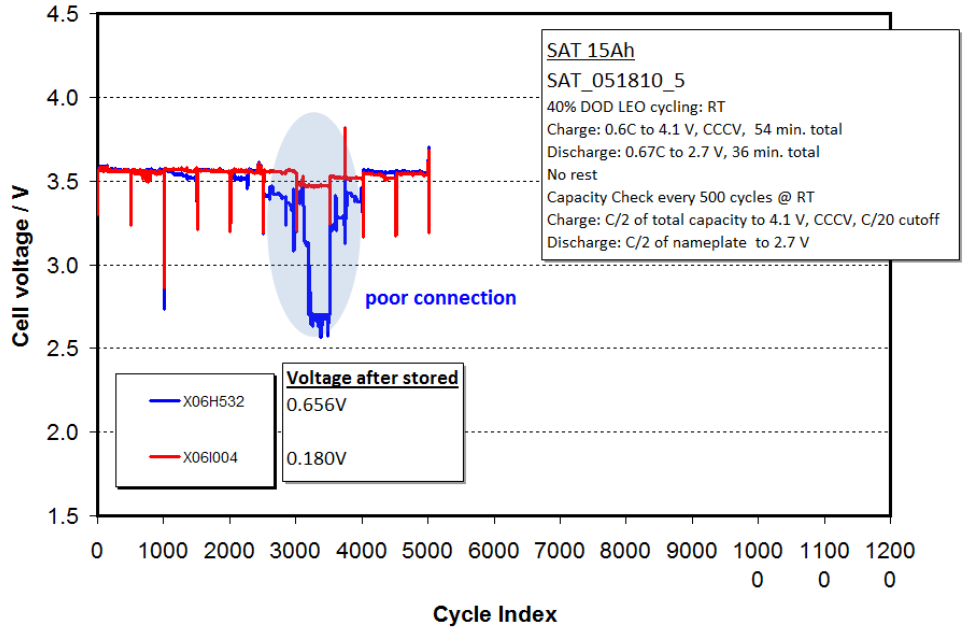
## Capacity Retention and Cell Voltage after 0V Storage (49 months) (QL015KA cell, 40% DOD LEO Cycle Performance)

| | Cell Voltage during Storage / Volts | Discharge Capacity / Ah | | |
|---|---|---|---|---|
| | | Before Storage | After Storage (49 months) | After 5000 cycles |
| X06H532 | 0.656 | 14.6 | 14.6 | 14.9 |
| X06I004 | 0.180 | 14.7 | 14.4 | 14.5 |

## Discharge Capacity




## Cell Voltage @ End of Discharge

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# Quallion's SAT Cell Characteristics QL015KA / QL075KA

- Cycle Performance
- Life Prediction

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# Cell characteristics
# QL015KA

**QL015KA-SS**

| | QL015KA | | | |
|---|---|---|---|---|
| | SS-STD | Al-STD | SS-HP | Al-HP |
| Application | Standard C-rate | | High C-rate | |
| Case material | SS | Al | SS | Al |
| Height / mm | 89 | | | |
| Width / mm | 54.5 | | | |
| Thickness / mm | 37.5 | | | |
| Weight / g | 470 | 385 | 510 | 425 |
| Operating voltage / V | 2.7 – 4.1 | | | |
| Discharge capacity / Ah* | 14.5 | | 12.4 | |
| Maximum continuous discharge rate capability | 1C | 1C | 3C | 3C |
| Pulse discharge rate capability | 3C | 3C | 10C | 10C |
| Weight energy density / Wh/kg | 111 | 136 | 88 | 105 |
| Volumetric energy density / Wh/l | 287 | | | |
| Zero-Volt™ technology | Applicable | | n/a | |

* Charge: 0.5C/4.1V to C/20, Discharge: C/2 to 2.7V at 25ºC

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# QL015KA Characterization

## LEO Cycle Test Conditions; Evaluation of Charge Voltage / DOD

- **Test cell**
  - QL015KA (nameplate capacity 12.5Ah)
  - SS case, ZeroVolt™
- **Test condition**
  - Room temperature
  - LEO cycle conditions (current based on nameplate capacity)
    - Charge: specified current / **4.0V** or **4.1V** for 54 minutes
    - Discharge: specified current for 36 minutes

| | Charge Rate (C) | Discharge Rate (C) |
|---|---|---|
| **20% DOD** cycle | 0.3 | 0.3 |
| **40% DOD** Cycle | 0.6 | 0.7 |
| **60% DOD** cycle | 0.9 | 1.0 |

  - Capacity check cycle
    - Charge: 0.5C / 4.1V with tapered current till C/20
    - Discharge: 0.5C to 2.7V
    - Every 500 cycles of LEO condition

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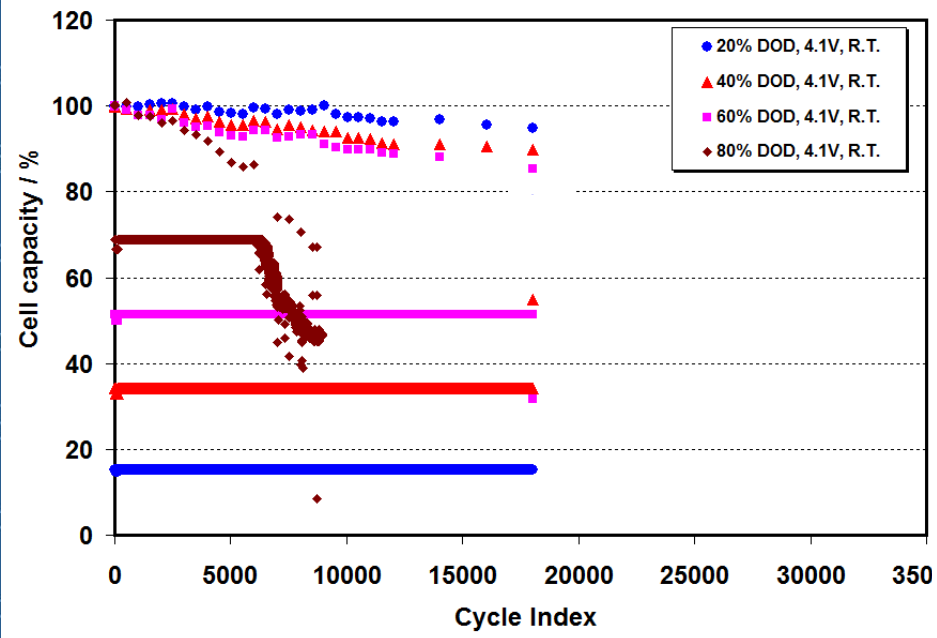
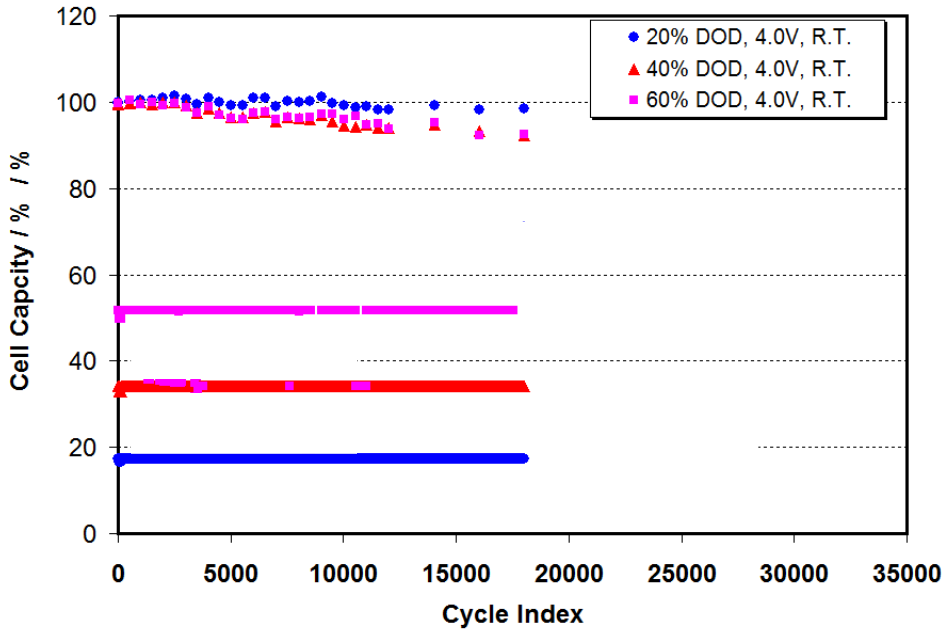
# QL015KA Cell Characterization
## Effect of Charge Voltage and DOD on LEO Cycle Performance (1)

### 4.1V Charge; Discharge Capacity




Charge: 54 min @ **4.1V**, R.T.
Discharge: 36 min to 20 - 80 % DOD @ R.T.

### 4.0V Charge; Discharge Capacity




Charge: 54 min @ **4.0V**, R.T.
Discharge: 36 min to 20 -60 % DOD @ R.T.

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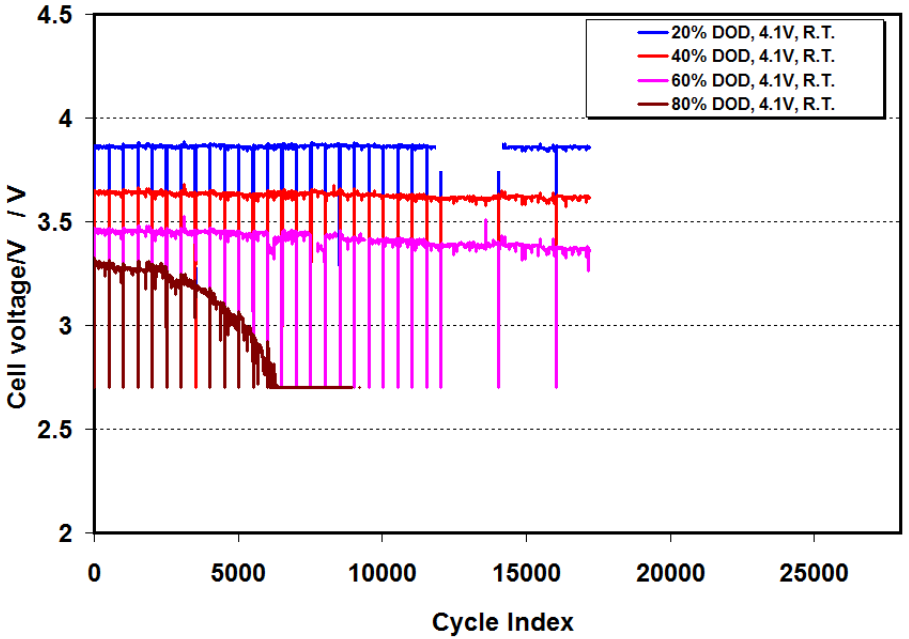
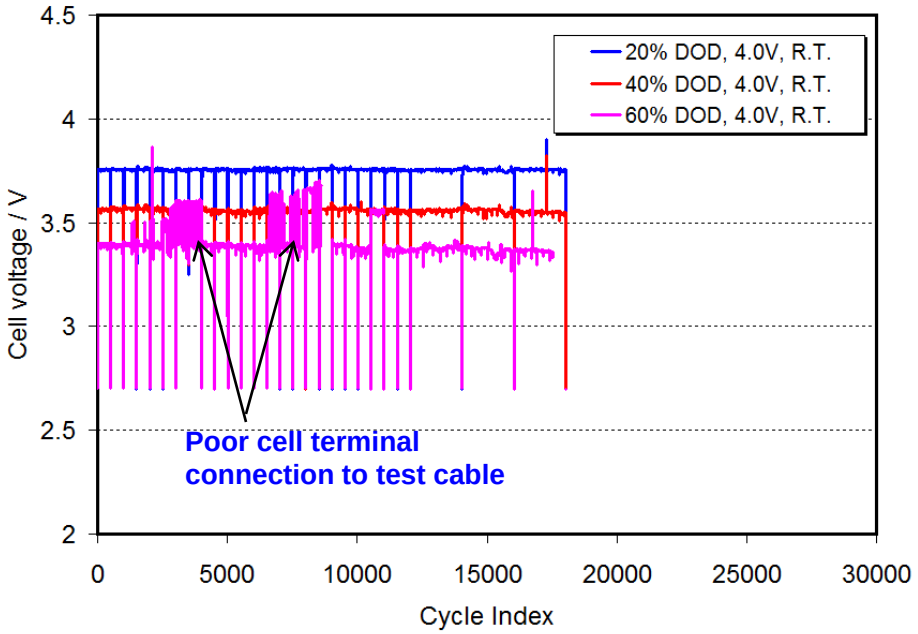
# QL015KA Cell Characterization
## Effect of Charge Voltage and DOD on LEO Cycle Performance (2)

### 4.1V Charge; Cell Voltage @ EOD




Charge: 54 min @ **4.1V**, R.T.
Discharge: 36 min to 20 -60 % DOD @ R.T.

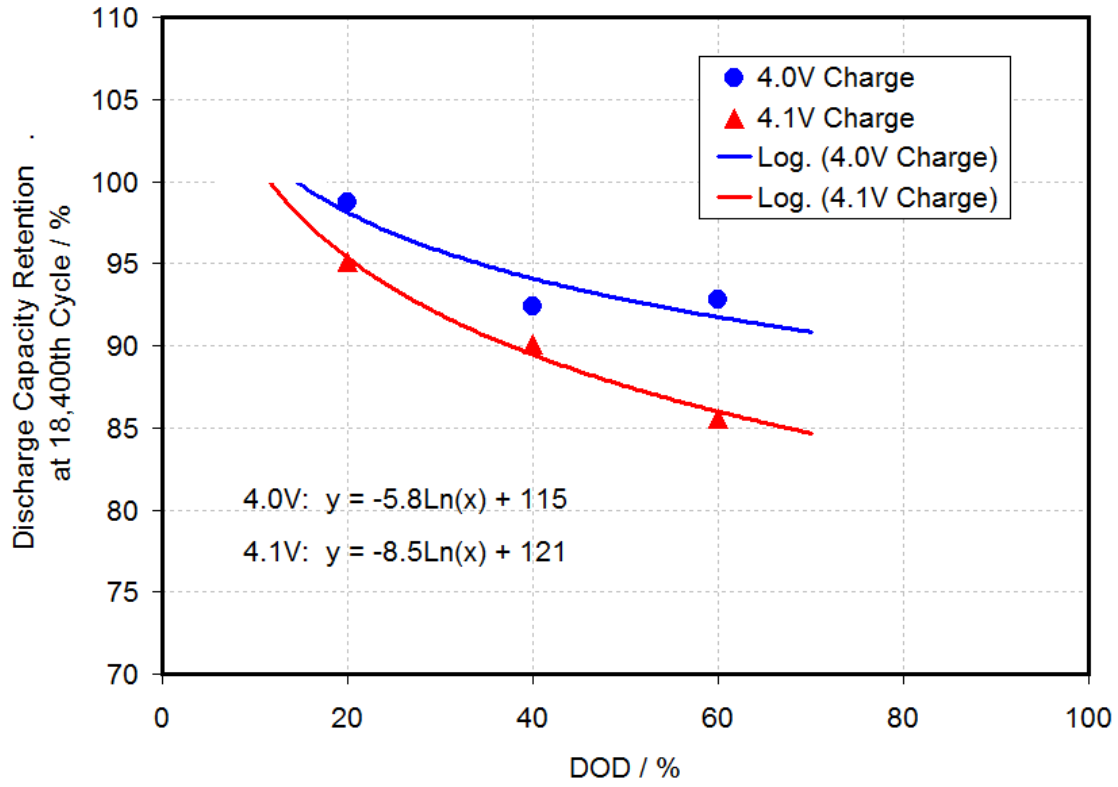
### 4.0V Charge; Cell Voltage @ EOD




Charge: 54 min @ **4.0V**, R.T.
Discharge: 36 min to 20 -60 % DOD @ R.T.

# QL015KA Characterization
## Effect of Charge Voltage and DOD on Capacity Retention (LEO Cycle Performance)

### Capacity Retention after 18,400 cycles




Data suggests that lower charge voltage / DOD makes cell life longer. At lower charge voltage, dependency of cycle life on DOD is less. (Need further cycle test and analysis.)

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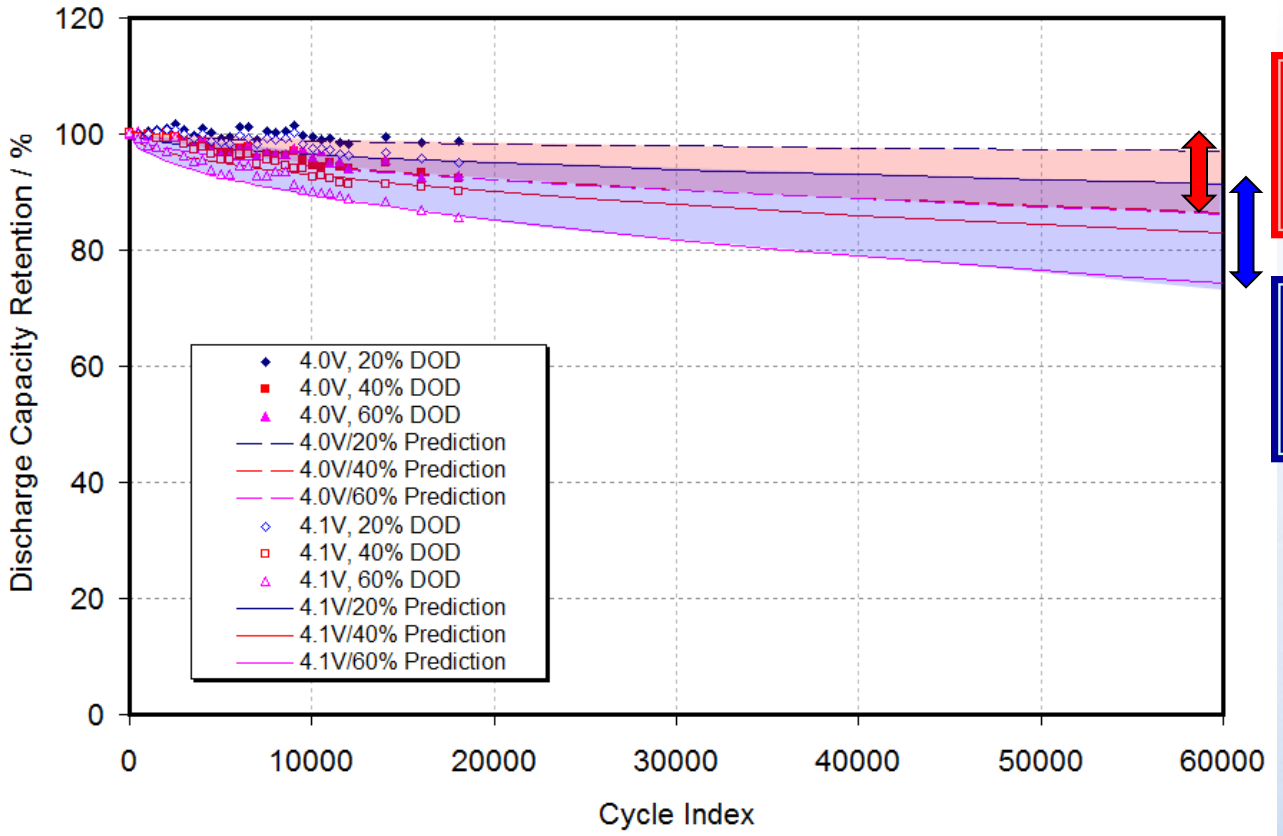
# QL015KA Performance Prediction
# LEO Cycle Performance: 20-60% DOD, 4.1V, R.T.

**Capacity retention equation** *)

$$\text{(Discharge capacity retention)} = 100 - k \times \sqrt{N_{cycle}}$$

*) $k$: constant to determine capacity fading rate
$N_{cycle}$: charge and discharge cycle index




***86 – 97 % @ 4.0V Charge @ 60,000th*** cycle, 10 years LEO operation

***74 – 91 % @ 4.1V Charge @ 60,000th*** cycle, 10 years LEO operation

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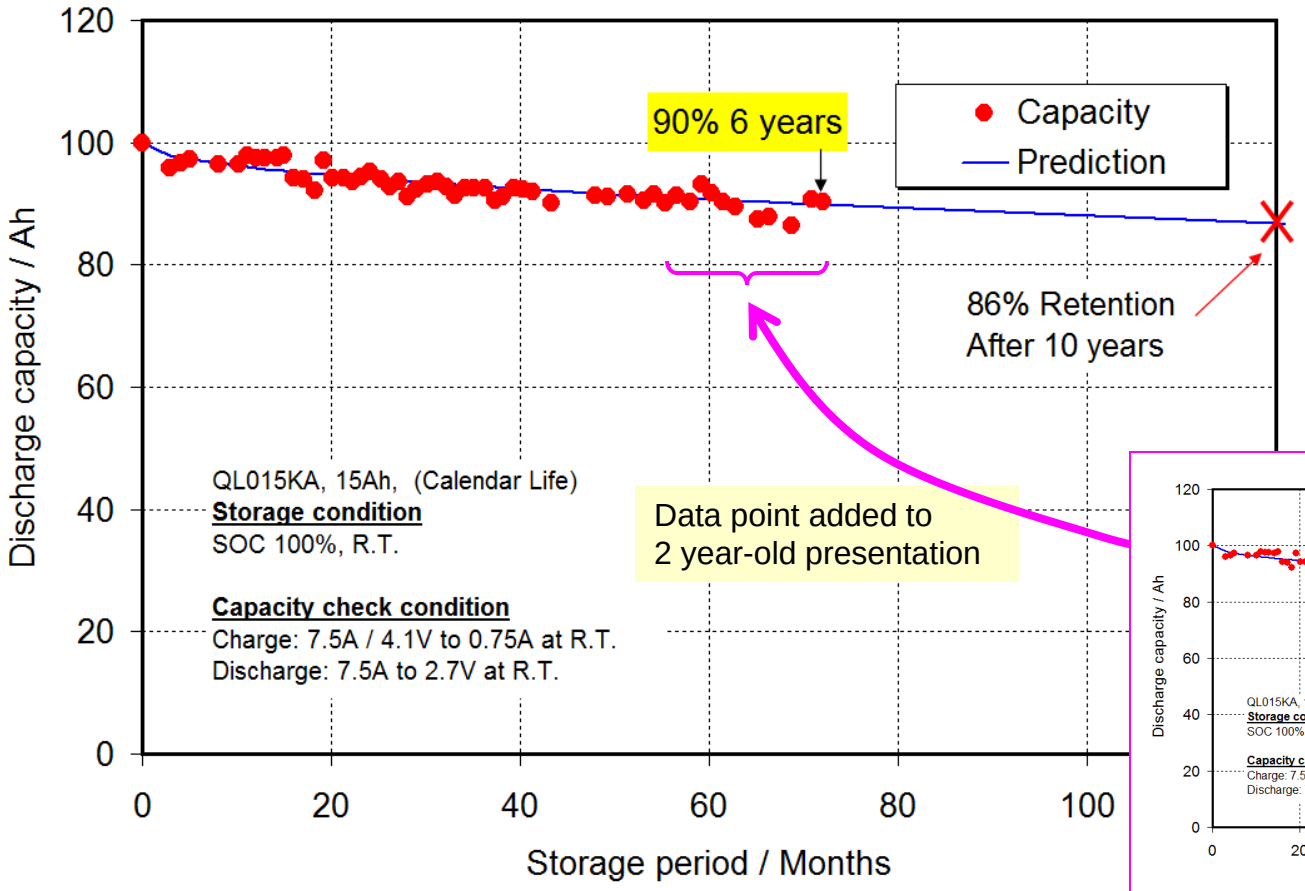
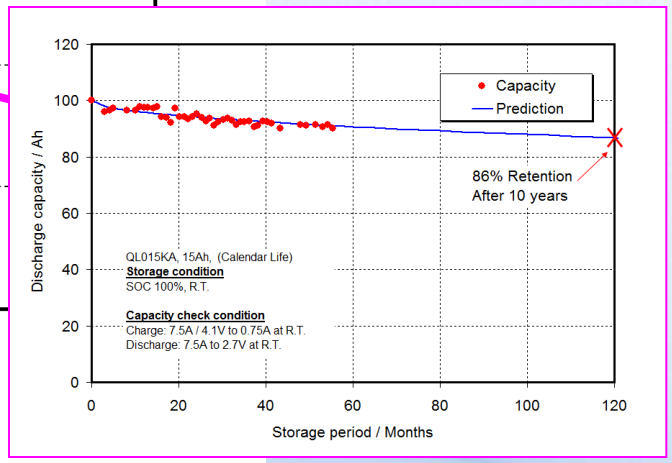
# QL015KA Characterization
# Calendar Life: 100% SOC, 4.1V, R.T. Storage

**Capacity retention equation** *)

(Discharge capacity retention) = 100 - $k \times \sqrt{Time}$

*) $k$: constant to determine capacity fading rate
$N_{cycle}$: charge and discharge cycle index

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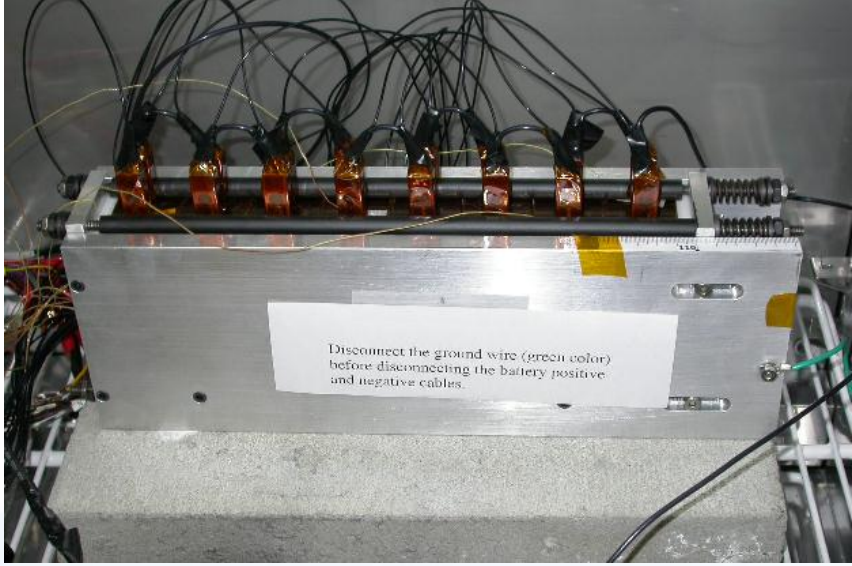


# 8S-1P QL015KA Battery
# (no Cell Balancing Circuit)

## Voltage / Temperature Profiles
## in LEO 20% DOD Cycling
## (Status up to 52,231 cycles; 60 months)

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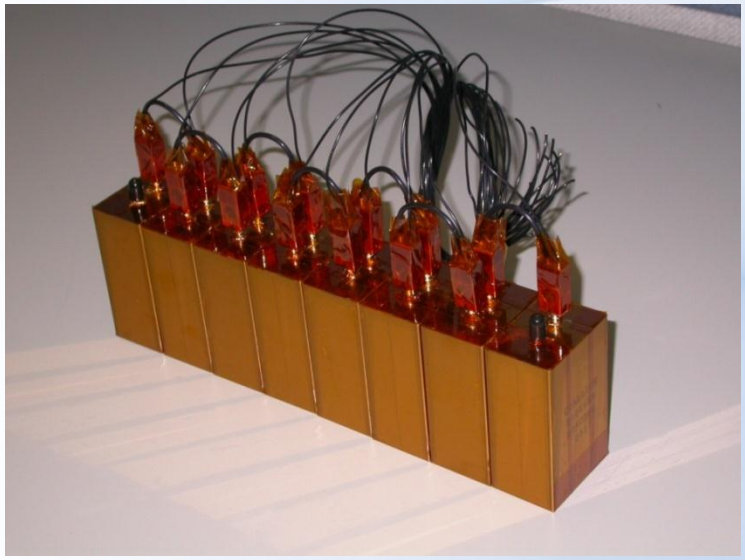
# 8S-1P QL015KA Battery

## Characteristics of QL015KA **8 cells in series** connection under **20% DOD** cycling at 30°C,

- Electrical characterization
  - Cell / battery voltage transition
    - Difference of cell voltages
- Thermal characterization
  - Temperature profile in cycling
  - Maximum temperature difference during cycling

| | |
|---|---|
| Cell type | QL015KA |
| Configuration | 8 cells in series |
| Capacity | 15 Ah |
| Voltage | 21.6 – 32.8 V |
| Dimension | 89 x 54.5 x 304 mm |



# 8S-1P QL015KA Battery
## Cycle test protocol

Charge:

CC Charge: Constant current at 9A until one individual cell reaches 4.1V

CV Charge: Constant voltage charge at the last battery voltage recorded when first individual cell hit 4.1V.

Total charge time of 27.5 minutes

Discharge:

CC discharge: Constant current at 10.3 A for 17.5 min (3 Ah = 20% DOD)

Total discharge time of 17.5 min

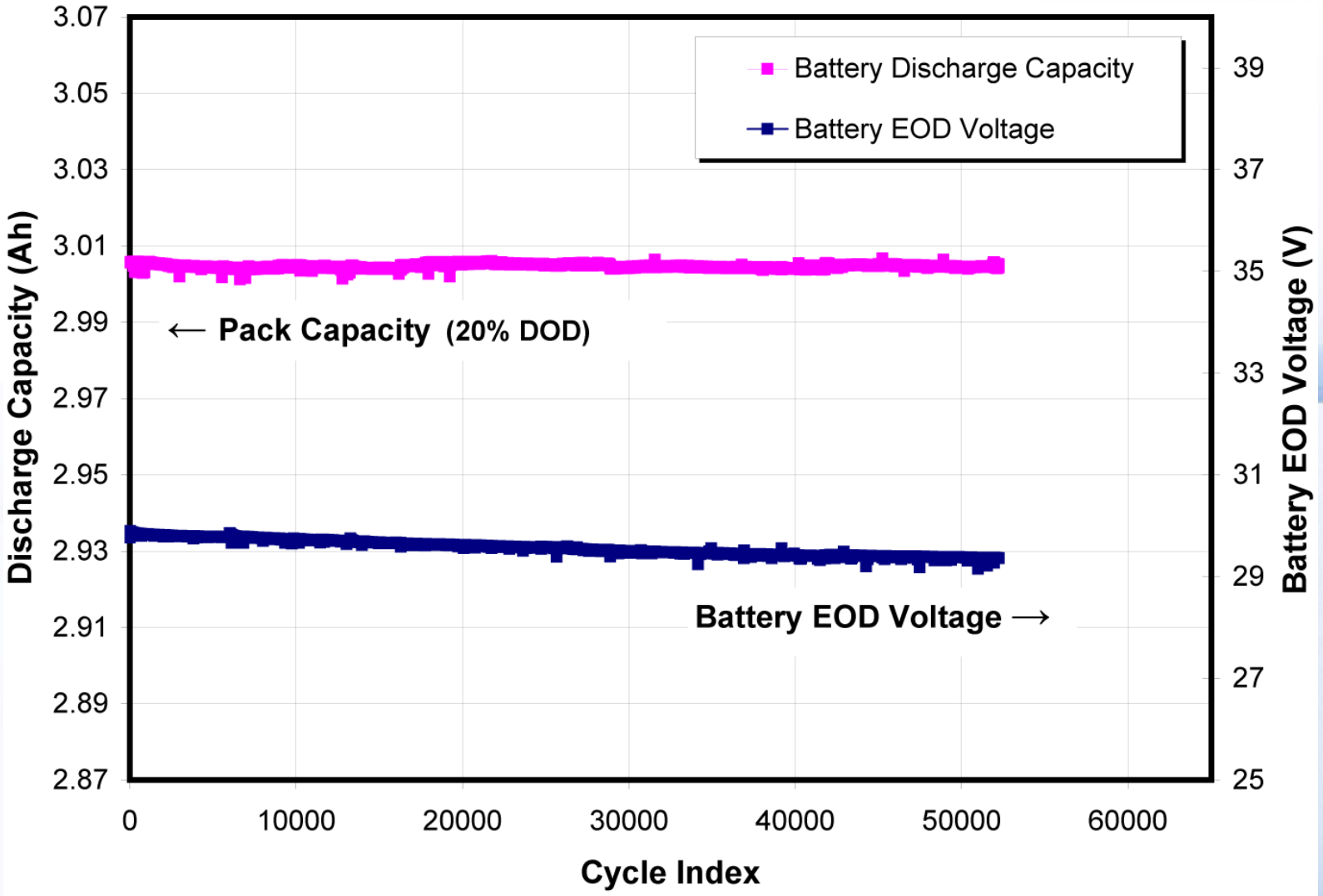
Temperature: 30$^{o}$C

- No rest between charge and discharge steps

- No cell balancing circuit

# Pack EOD Voltage and Battery Discharge Capacity (20% DOD)

Pack EOD voltage and discharge capacity through **52,231** cycles (**60** months duration)

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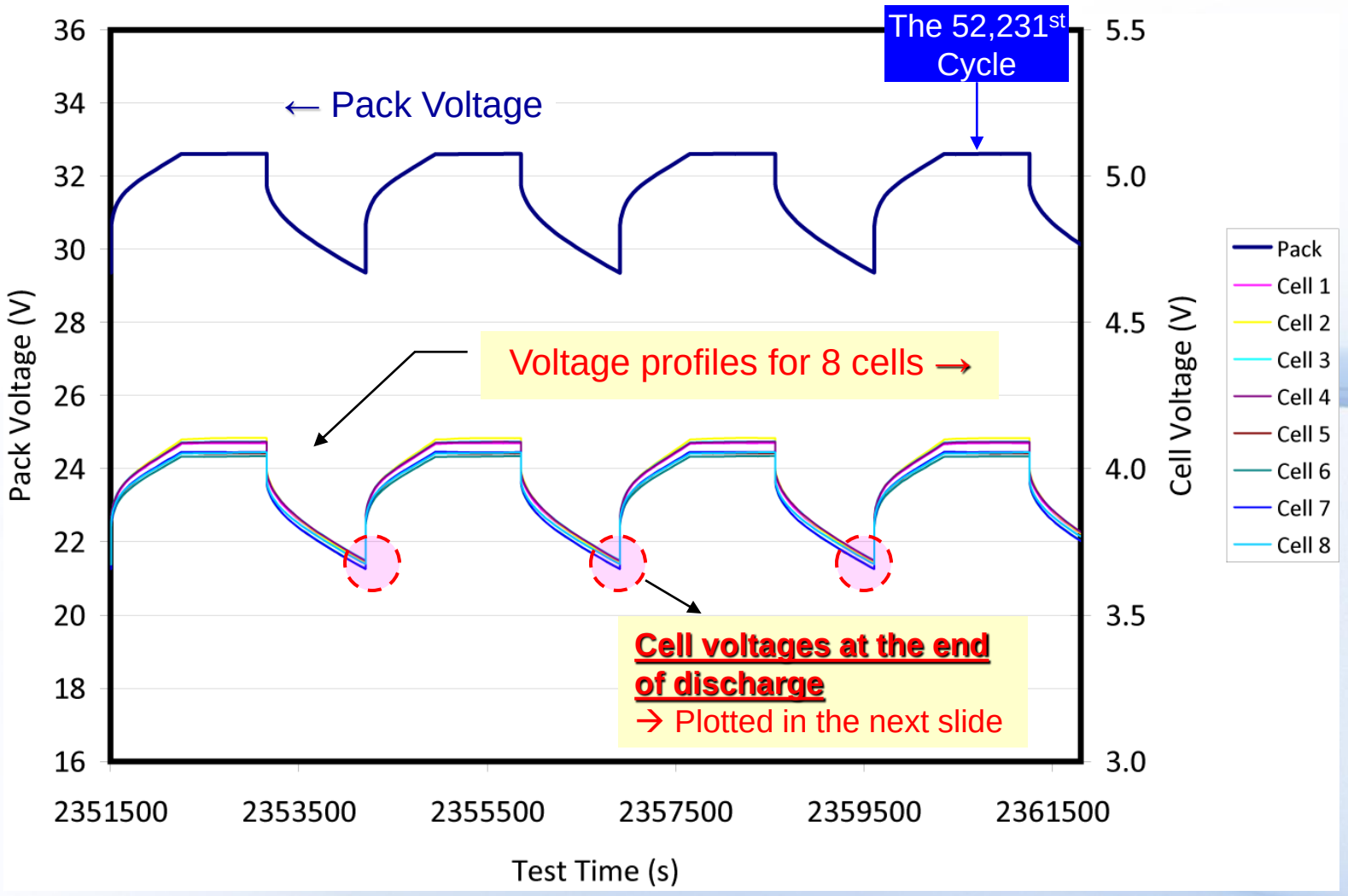
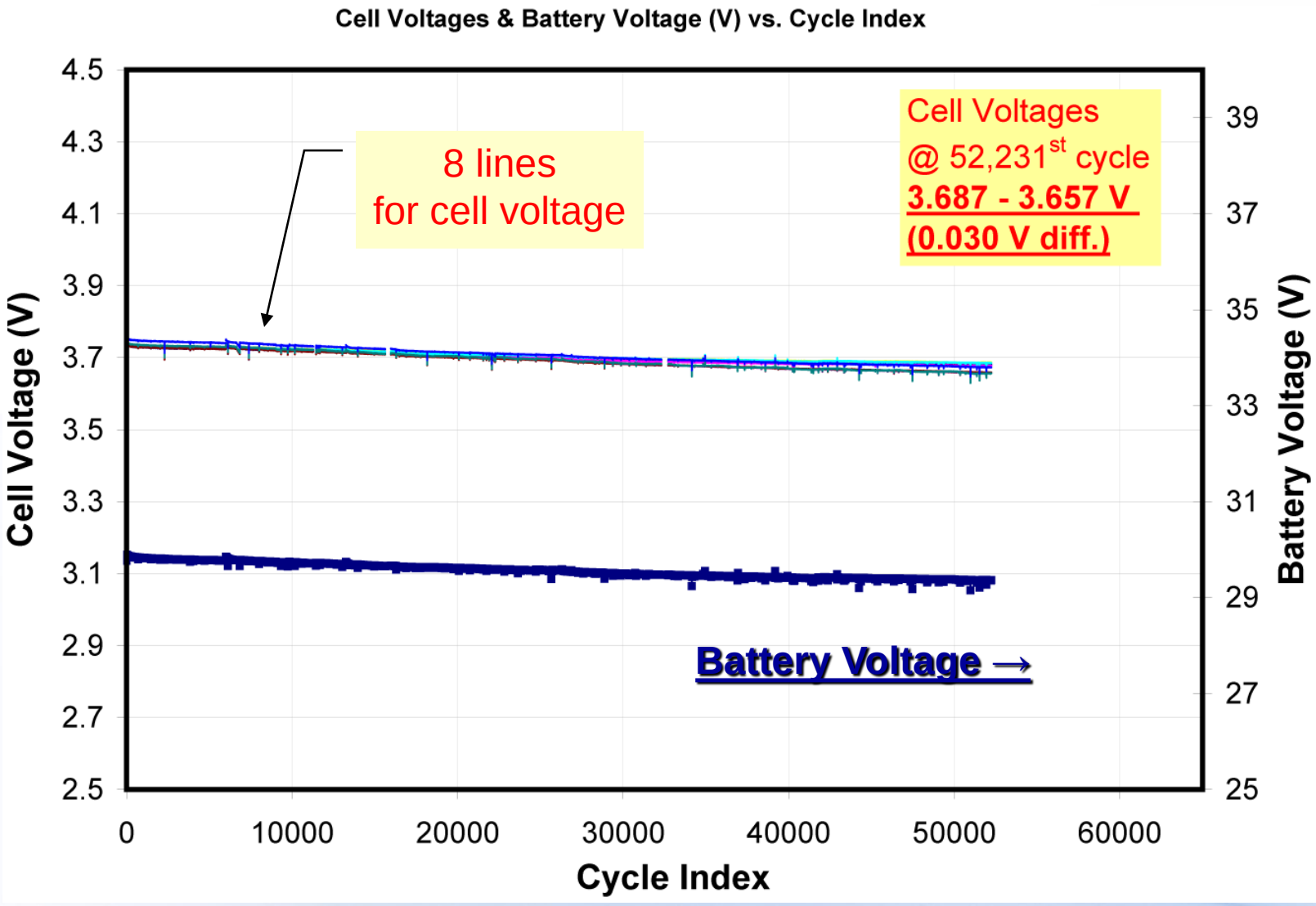
# Pack / Cell Voltage vs. Time (in cycling) for last few cycles



# Cell & Pack EOD voltages

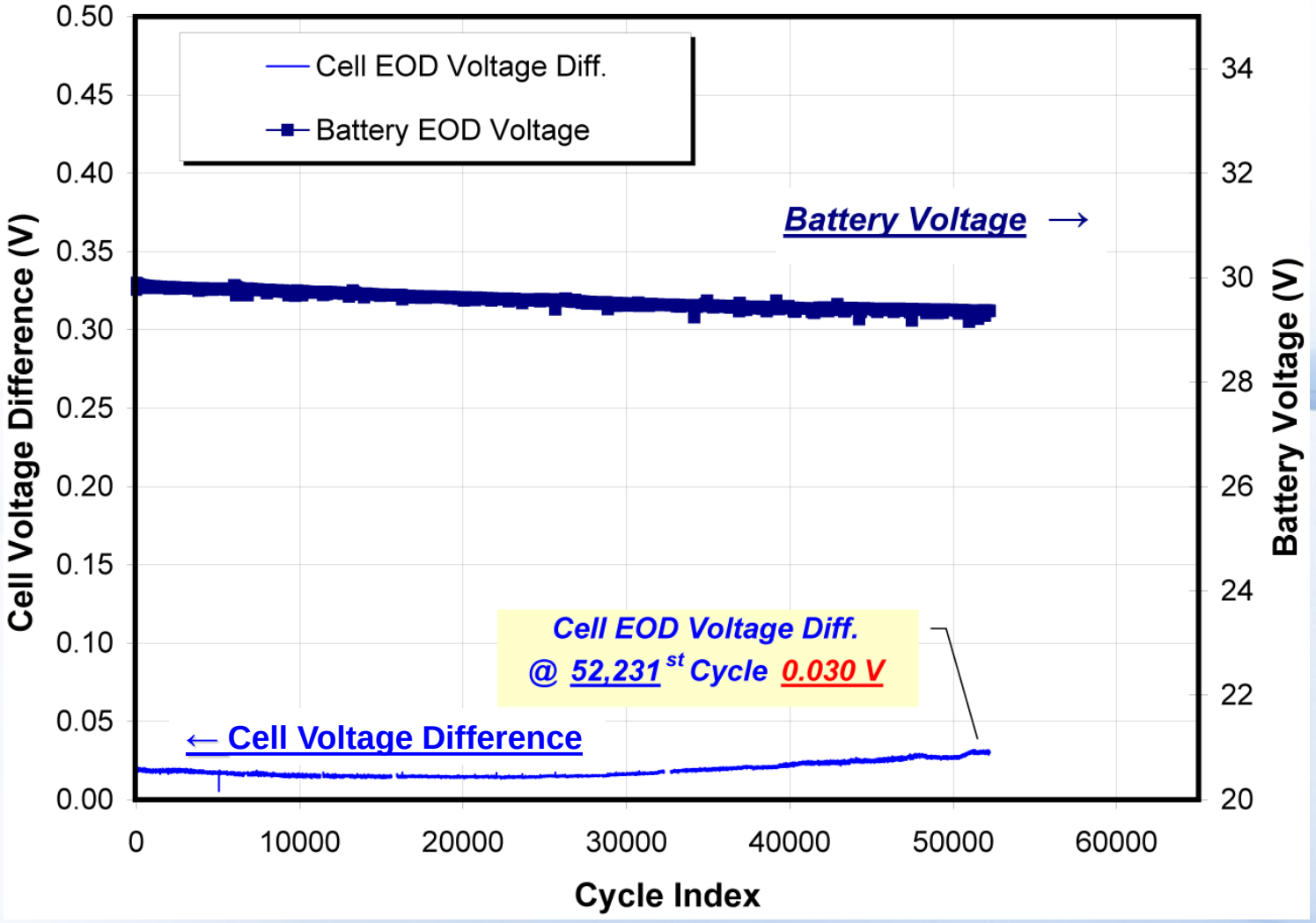
Consistent cell voltage through **52,231** cycles (for **60 months** duration)




Powering Life.

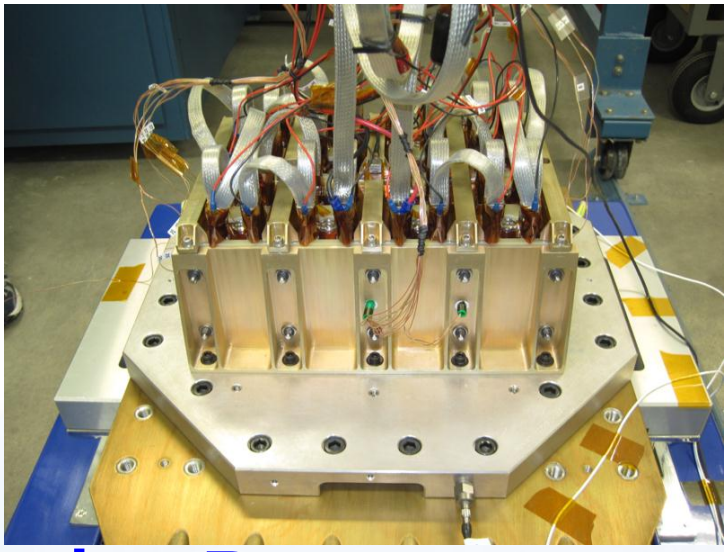
# Cell Voltage Difference (@ the end of discharge) & Battery Voltage (@ the end of discharge)

Cell voltage difference (@ the end of discharge) through **52,231** cycles




Powering Life.

QUALLION



# 2P-8S Tac-sat IV Configuration Battery

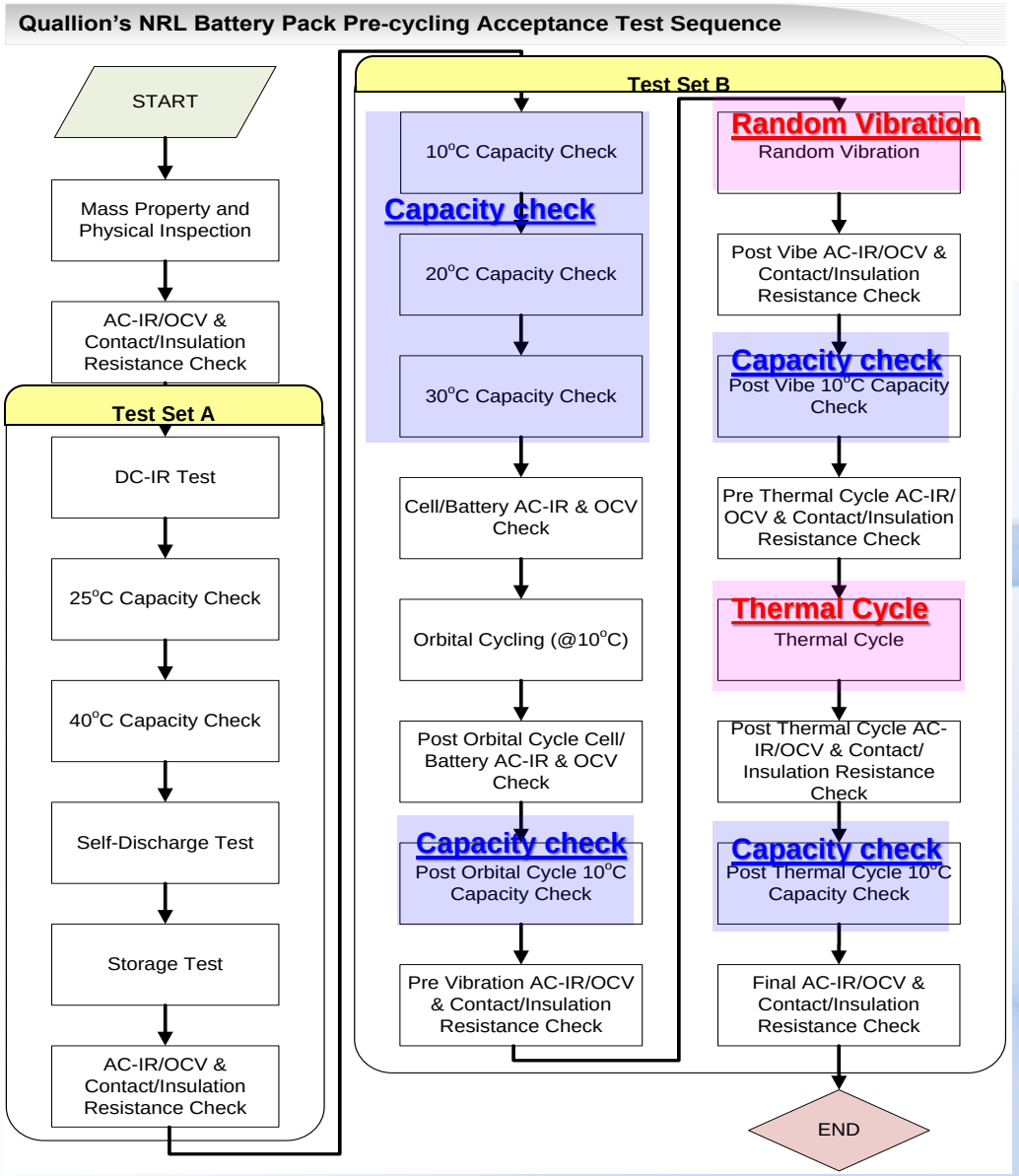
## (no Cell Balancing Circuit)

## Initial Characterization (Electrical, Environmental)

Tac-SAT4 was launched with Quallion's QL015KA on 9/27 from Kodiak, Alaska.
(Quallion has been cycling the copied battery system under the accelerated HEO test condition.)

Powering Life.

# 2P-8S Tac-sat IV Configuration Battery Initial Characterization Test Flow




1) Capacity check cycle at prescribed temperature
   - Charge: 0.2C / 4.1V till C/20
   - Discharge: 0.2C to 2.7V

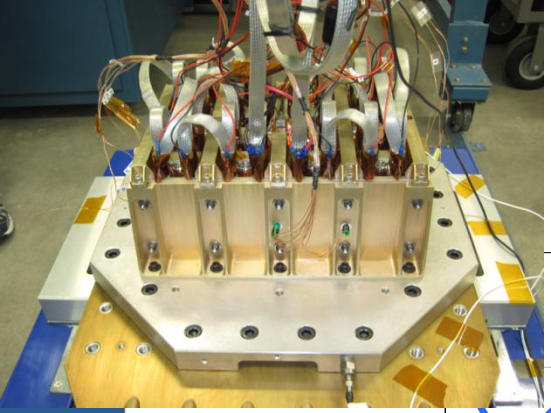
2) Random vibration condition

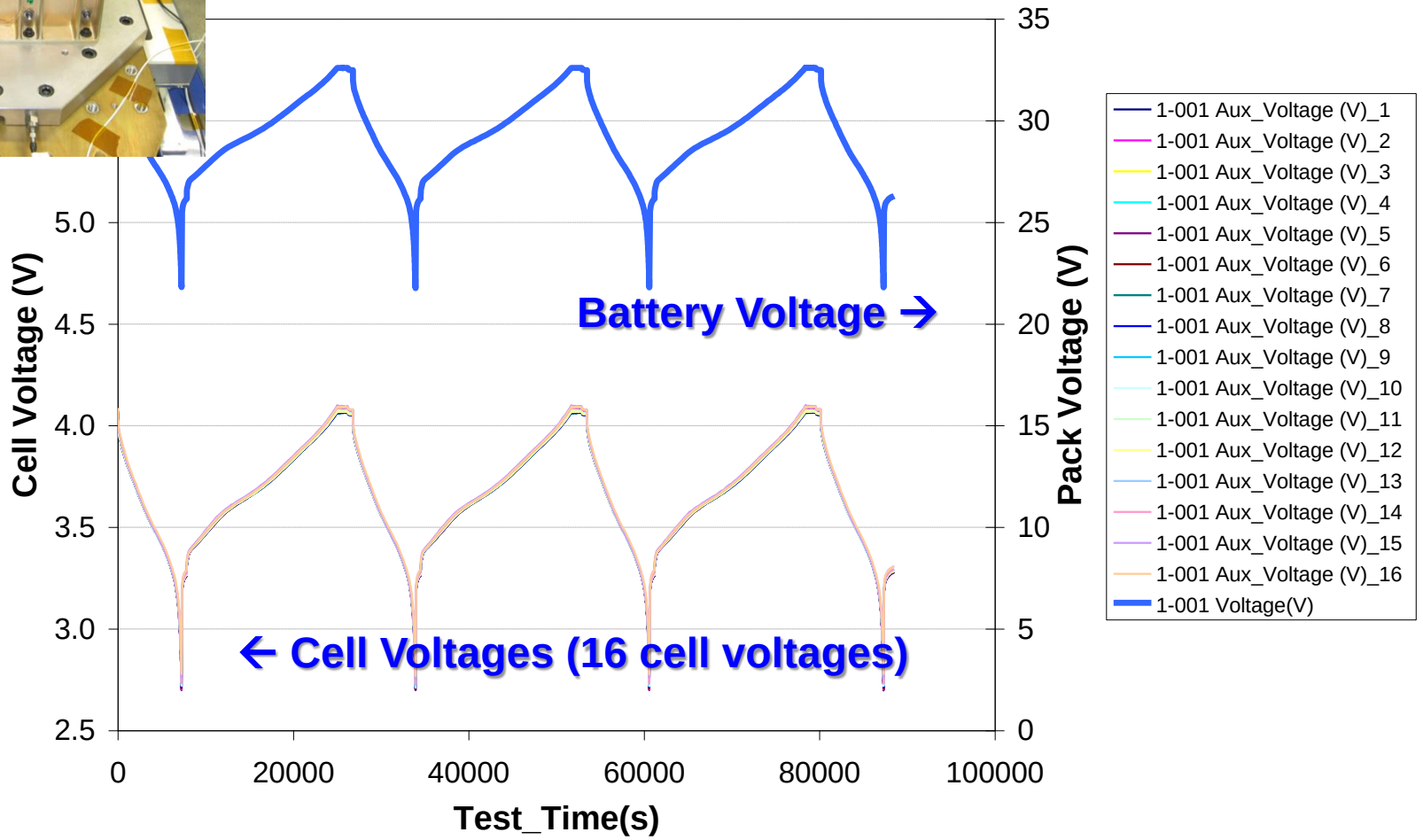
| Frequency (Hz) | PSD Level |
|---|---|
| 20 | 0.0263 $g^2$/Hz |
| 20-50 | +6 Db/Oct |
| 50-800 | 0.16 $g^2$/Hz |
| 800-2000 | -6.0 Db/Oct |
| 2000 | 0.026 $g^2$/Hz |
| Overall Amplitude = 14.1 Grms<br>Duration = 60 seconds | |

3) AC-IR: at 1 kHz

Powering Life.

# 2P-8S Tac-sat IV Configuration Battery
## Initial Characterization
## 100% DOD Charge / Discharge Curves (10°C)

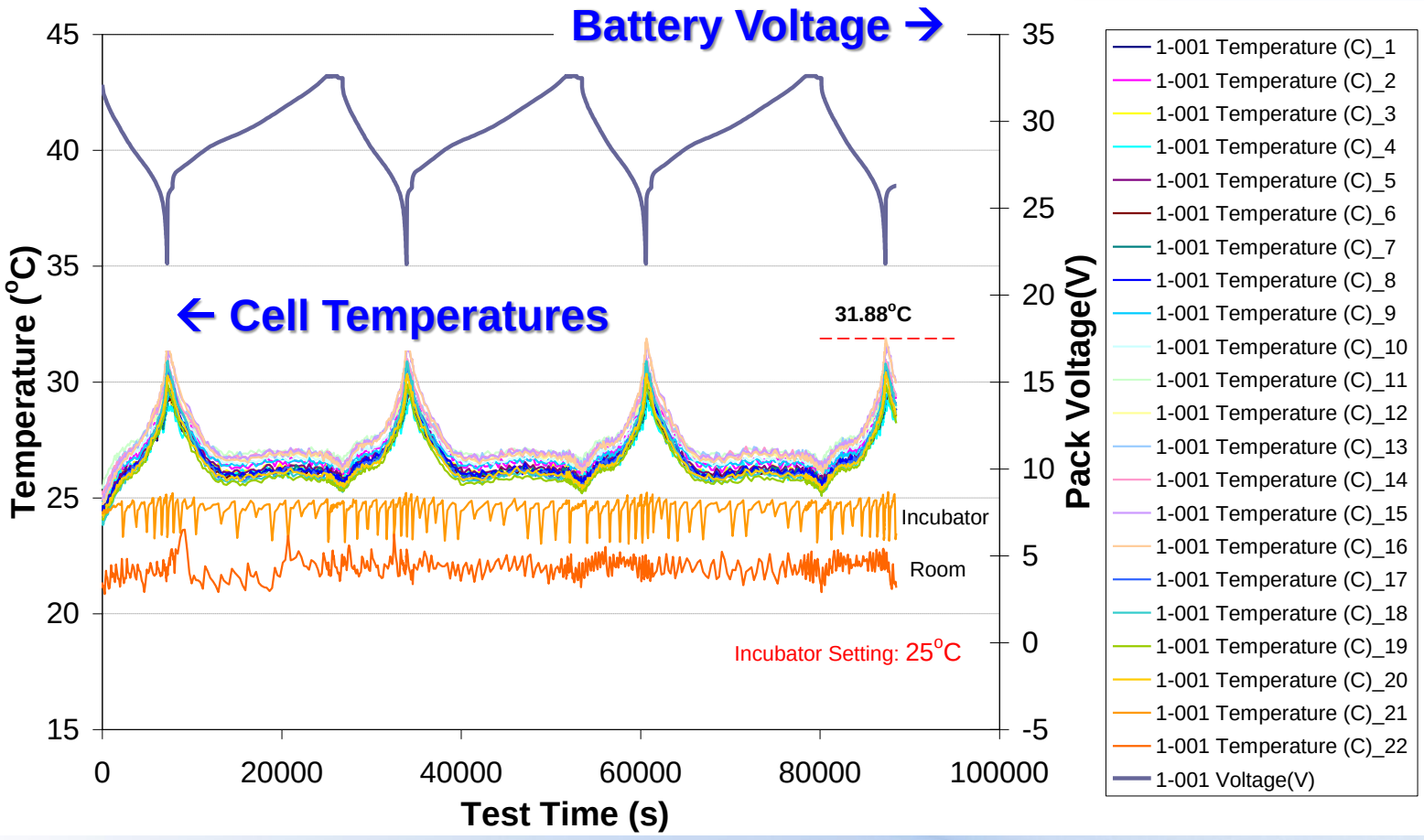





1. CC Charge pack at C/5 (6 A) to 32.8 V (4.1 V/cell) followed by CV charge until charge current reaches 0.6A;
2. Rest for 10 minutes;
3. CC Discharge at C/5 (-6 A) to 21.6 V (2.7 V/cell);
4. Discharge rest for 10 minutes.

Powering Life.

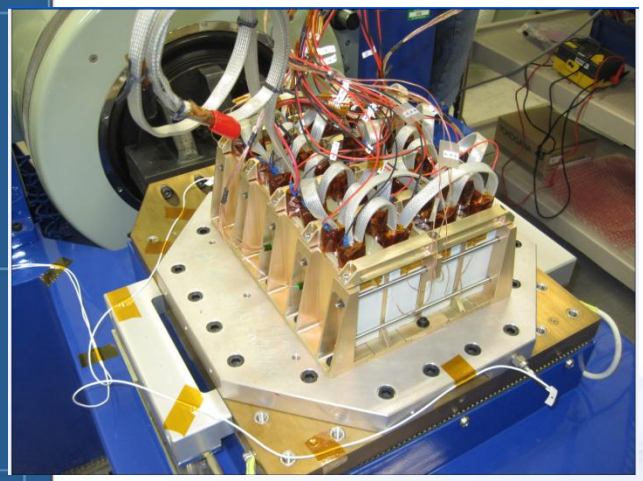
# 2P-8S Tac-sat IV Configuration Battery
## Initial Characterization Test
## 100% DOD Charge / Discharge Curves and Cell Temperatures



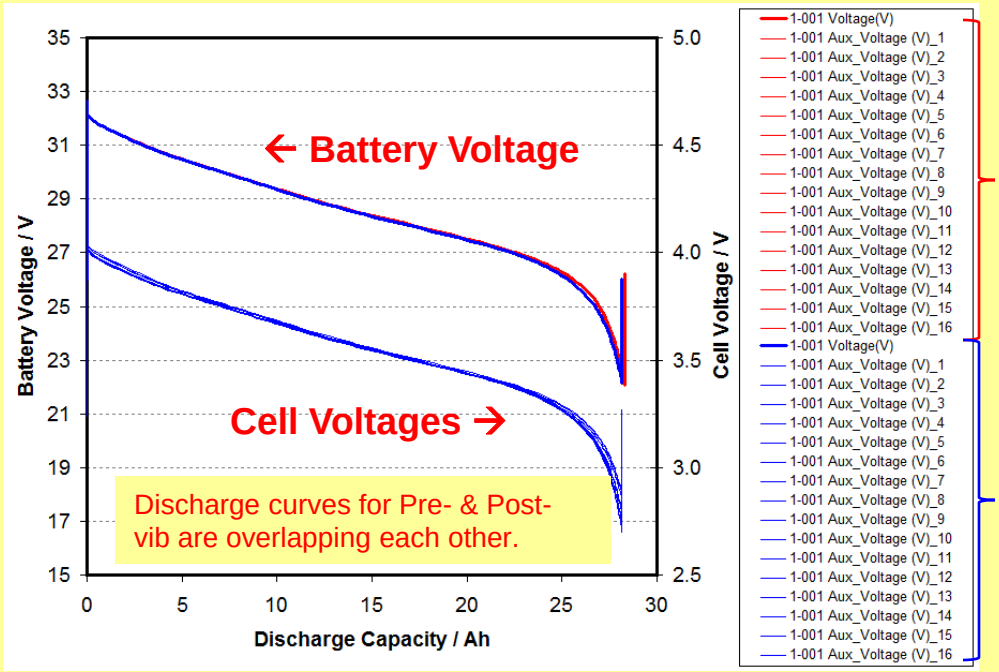

Powering Life.

# 2P-8S Tac-sat IV Configuration Battery
## Initial Characterization Test
## Pre- & Post- Vibration Test

### In-house Vibration Table



| | Pre-vib. | Post-vib. |
|---|---|---|
| Discharge Capacity @ 10°C | 1. 28.3 Ah<br>2. 28.3 Ah<br>3. 28.3 Ah | 1. 28.1 Ah<br>2. 28.2 Ah<br>3. 28.2 Ah |
| AC-IR (1kHz) | 19.5 mΩ | 19.6 mΩ |




Powering Life.

# 2P-8S Tac-sat IV Configuration Battery : ATP Test Results Summary

| Acceptance Test | Creitria | Test Result | Conclusion |
|---|---|---|---|
| 10 °C Capacity Check | Capacity on final dischage:≥ 25Ah | 28 Ah | Pass |
| 20 °C Capacity Check | Capacity on final dischage:≥ 27Ah | 30 Ah | Pass |
| 30 °C Capacity Check | Capacity on final dischage:≥ 29Ah | 31 Ah | Pass |
| Orbital Cycling (@10 °C) | End of discharge voltage: > +21.6Vdc | 26 V | Pass |
| Post Orbital cycle 10 °C Capacity Check | Capacity on final dischage:≥ 25Ah | 28 Ah | Pass |
| Random Vibration | No visual physical degradation | No | Pass |
| Post Vibe AC-IR/OCV & Contact /Insulation Resistance Check | No short circuit anomalies occurred | No | Pass |
| | Cell OCV fluctuates: < ±0.025V | Max: 0.003V | Pass |
| | Insulation resistance: >100 MΩ | OL* | Pass |
| Post Vibe 10 °C Capacity Check | Capacity on final dischage:≥ 25Ah | 28 Ah | Pass |
| Thermal Cycle | Performace test without erro | Performance test no error | Pass |
| Post Thermal Cycle AC-IR/OCV & Contact /Insulation Resistance Check | Power Connection Contact Resistance: <10 mΩ at AC 1 kHz. | Max: 1.6mΩ | Pass |
| | Voltage Sense Line Contact Resistance:<30 mΩ at AC 1 kHz | Max: 1.1mΩ | Pass |
| | Electrical Continuity between Cell Terminal and Battery Plates:≥ 100 MOhm at 50Vdc | OL* | Pass |
| | Electrical Continuity between Cell Cases and between Cell Case and Battery Plates≥ 100 MOhm at 50Vdc | OL* | Pass |
| Post Thermal Cycle 10 °C Capacity Check | Capacity on final dischage:≥ 25Ah | 28 Ah | Pass |
| Final AC-IR/OCV & Contact /Insulation Resistance Check | Power Connection Contact Resistance: <10 mΩ at AC 1 kHz. | Max: 1.3mΩ | Pass |
| | Voltage Sense Line Contact Resistance:<30 mΩ at AC 1 kHz | Max: 1.1mΩ | Pass |
| | Electrical Continuity between Cell Terminal and Battery Plates:≥ 100 MOhm at 50Vdc | OL* | Pass |
| | Electrical Continuity between Cell Cases and between Cell Case and Battery Plates≥ 100 MOhm at 50Vdc | OL* | Pass |

* "OL" means over-loaded or insulated

Powering Life.

# 2P-8S Tac-sat IV Configuration Battery Accelerated HEO Test Setup

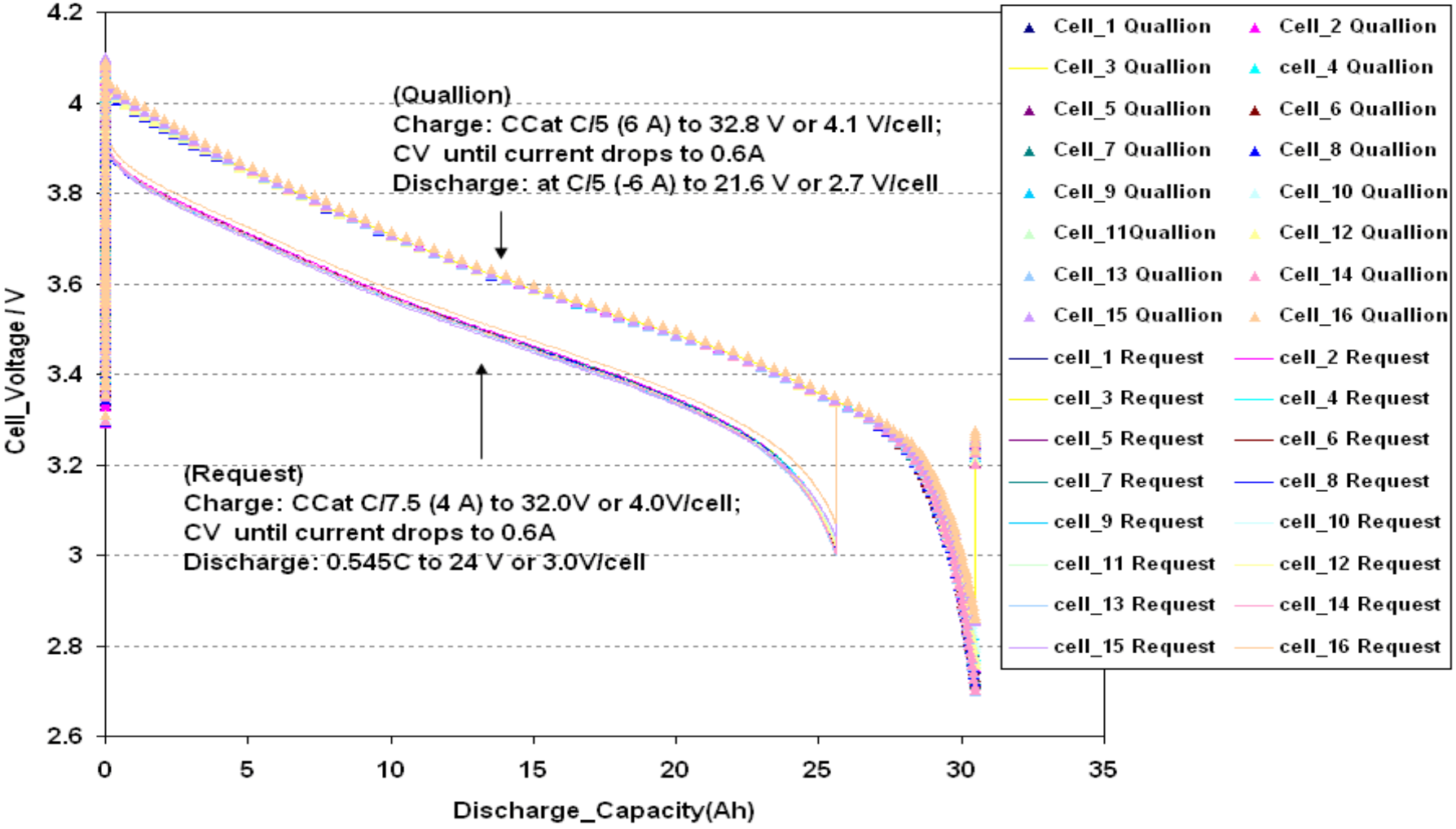

Powering Life.

# 2P-8S Tac-sat IV Configuration Battery : Accelerated HEO Cycle Characterization Test Protocol

- Capacity check (Quallion)
  - Purpose: Compare capacity results with ATP results ( 6months ago) to make sure the battery no change after 6months
  - Test Condition
    - Initial Discharge pack at -6 A (C/5) to a voltage limit of 21.6V or 2.7 V/cell
    - Rest 10minutes
    - Perform 3 charge/discharge cycles:
    - CC Charge pack at C/5 (6 A) to 32.8 V or 4.1 V/cell; CV charge until current drops to 0.6A
    - Rest 10minutes
    - CC Discharge at C/5 (-6 A) to 21.6 V or 2.7 V/cell
    - Rest 10minutes
- Capacity check and DC-IR test (In accelerated HEO Cycle)
  - Purpose: Compare DC-IR data using different test method and the capacity data by accelerated HEO capacity operation method as reference afterwards
  - Test Condition
    - CC Charge pack at C/7.5 (4 A) to 32V or 4.0 V/cell; CV charge until current drops to 0.6A
    - Rest 10 minutes
    - CC Discharge at 0.545C to 24 V or 3.0V/cell.
    - Rest 10 minutes
    - CC Charge pack at C/7.5 (4 A) to 32V or 4.0 V/cell; CV charge until current drops to 0.6A
    - Rest 10 minutes
    - CC Discharge at C/2 for 30minutes, C/10 for 10 second, C/2 to 24V or 3.0V/cell.

# 2P-8S Tac-sat IV Configuration Battery: Accelerated HEO Cycle Discharge Curves @20°C

## Quallion vs. HEO Characterization




Powering Life.

# 2P-8S Tac-sat IV Configuration Battery HEO Test sequence

- Eclipse Season cycling (192 cycle) @20$^{O}$C
  - CC Discharge at 0.545C for different time, as shown in Table.
  - CC charge at C/7.5 (4 A) to 4.0 V / cell; CV charge to  total cycle time (discharge and charge) 6 hours
- Solstice Season @20$^{O}$C
  - CC Charge at C/7.5 (4 A) to 4.0 V/ cell; hold for 19.5 days; Every other solstice season operate capacity and resistance measurement

Powering Life.

# 2P-8S Tac-sat IV Configuration Battery Accelerated HEO Test Condition Discharge Time (Planned and Accentual Test Time) (1st Eclipse Season)

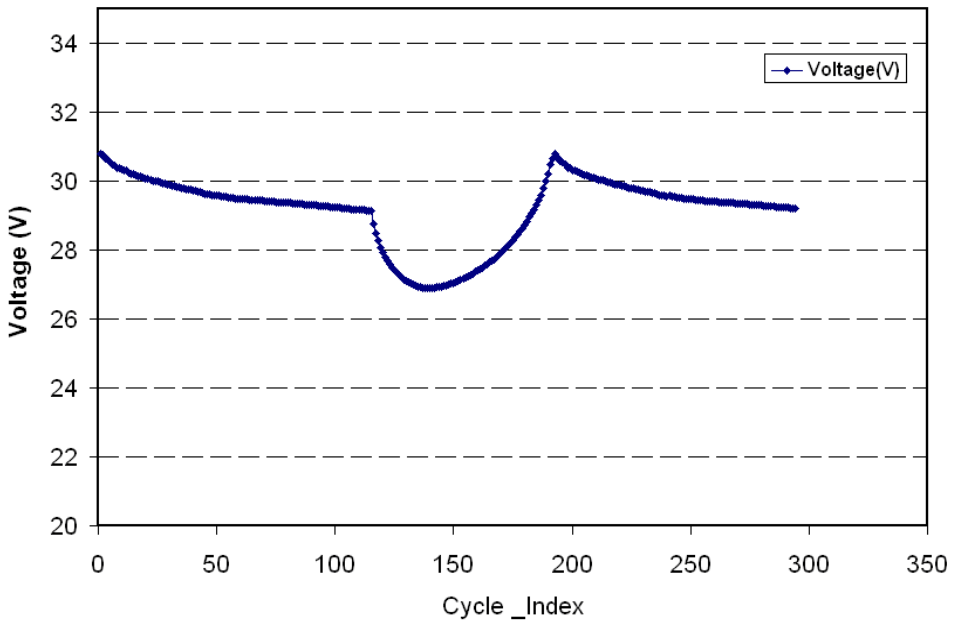
| Cycle | Disch. Time (sec) | Acture Disch. Time (sec) | Delta Disch. Time (sec) | Cycle | Disch. Time (sec) | Acture Disch. Time (sec) | Delta Disch. Time (sec) | Cycle | Disch. Time (sec) | Acture Disch. Time (sec) | Delta Disch. Time (sec) | Cycle | Disch. Time (sec) | Acture Disch. Time (sec) | Delta Disch. Time (sec) | Cycle | Disch. Time (sec) | Acture Disch. Time (sec) | Delta Disch. Time (sec) | Cycle | Disch. Time (sec) | Acture Disch. Time (sec) | Delta Disch. Time (sec) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 96 | 95.98 | -0.02 | 33 | 816 | 815.3 | -0.66 | 65 | 1175 | 1174 | -1.05 | 97 | 1362 | 1361 | -0.89 | 129 | 3686 | 3683 | -3.46 | 161 | 3316 | 3314 | -1.75 |
| 2 | 146 | 145.4 | -0.64 | 34 | 826 | 825.4 | -0.64 | 66 | 1181 | 1180 | -0.88 | 98 | 1368 | 1367 | -0.93 | 130 | 3742 | 3739 | -3.35 | 162 | 3266 | 3264 | -1.86 |
| 3 | 186 | 185.5 | -0.47 | 35 | 846 | 845.2 | -0.76 | 67 | 1187 | 1186 | -0.95 | 99 | 1374 | 1373 | -0.93 | 131 | 3782 | 3777 | -4.99 | 163 | 3196 | 3194 | -1.74 |
| 4 | 216 | 215.2 | -0.8 | 36 | 866 | 865 | -0.99 | 68 | 1193 | 1192 | -1.11 | 100 | 1381 | 1380 | -1.09 | 132 | 3835 | 3830 | -5.28 | 164 | 3136 | 3134 | -1.69 |
| 5 | 246 | 245.6 | -0.37 | 37 | 886 | 885.4 | -0.58 | 69 | 1199 | 1198 | -0.92 | 101 | 1387 | 1386 | -1.00 | 133 | 3868 | 3864 | -3.90 | 165 | 3076 | 3073 | -2.95 |
| 6 | 306 | 305.6 | -0.38 | 38 | 896 | 895.3 | -0.72 | 70 | 1205 | 1204 | -0.84 | 102 | 1393 | 1392 | -0.86 | 134 | 3898 | 3895 | -3.09 | 166 | 3016 | 3015 | -1.50 |
| 7 | 326 | 325.5 | -0.51 | 39 | 906 | 905.2 | -0.79 | 71 | 1211 | 1210 | -1 | 103 | 1400 | 1399 | -1.02 | 135 | 3928 | 3924 | -3.73 | 167 | 2946 | 2945 | -1.47 |
| 8 | 356 | 355.1 | -0.91 | 40 | 926 | 924.8 | -1.16 | 72 | 1217 | 1216 | -1.01 | 104 | 1406 | 1405 | -1.11 | 136 | 3948 | 3946 | -2.07 | 168 | 2876 | 2874 | -1.59 |
| 9 | 376 | 375.4 | -0.56 | 41 | 936 | 935.2 | -0.82 | 73 | 1223 | 1222 | -1.03 | 105 | 1413 | 1412 | -0.95 | 137 | 3968 | 3966 | -2.12 | 169 | 2806 | 2804 | -1.69 |
| 10 | 396 | 395.6 | -0.42 | 42 | 956 | 955.3 | -0.72 | 74 | 1229 | 1228 | -0.95 | 106 | 1419 | 1418 | -0.94 | 138 | 3968 | 3966 | -2.26 | 170 | 2726 | 2725 | -1.46 |
| 11 | 426 | 425.6 | -0.43 | 43 | 966 | 965.1 | -0.91 | 75 | 1234 | 1233 | -0.90 | 107 | 1426 | 1425 | -1.07 | 139 | 3978 | 3976 | -1.87 | 171 | 2656 | 2655 | -1.45 |
| 12 | 436 | 425 | -11 | 44 | 986 | 984.9 | -1.15 | 76 | 1240 | 1239 | -1.12 | 108 | 1433 | 1432 | -1.13 | 140 | 3988 | 3986 | -1.85 | 172 | 2576 | 2575 | -1.49 |
| 13 | 466 | 465.3 | -0.66 | 45 | 1006 | 1005 | -0.94 | 77 | 1245 | 1244 | -0.92 | 109 | 1439 | 1437 | -1.99 | 141 | 3978 | 3976 | -2.11 | 173 | 2496 | 2494 | -1.59 |
| 14 | 486 | 485.4 | -0.56 | 46 | 1016 | 1015 | -0.72 | 78 | 1250 | 1249 | -0.92 | 110 | 1446 | 1445 | -1.17 | 142 | 3968 | 3966 | -1.83 | 174 | 2416 | 2415 | -1.47 |
| 15 | 496 | 495.4 | -0.62 | 47 | 1036 | 1035 | -0.94 | 79 | 1256 | 1255 | -1.03 | 111 | 1452 | 1451 | -1.08 | 143 | 3958 | 3956 | -1.72 | 175 | 2336 | 2334 | -1.53 |
| 16 | 526 | 524.9 | -1.1 | 48 | 1046 | 1045 | -1.02 | 80 | 1261 | 1260 | -1.13 | 112 | 1459 | 1458 | -0.60 | 144 | 3948 | 3946 | -1.63 | 176 | 2246 | 2245 | -1.45 |
| 17 | 536 | 535.4 | -0.64 | 49 | 1053 | 1052 | -0.82 | 81 | 1267 | 1265 | -2.48 | 113 | 1466 | 1466 | -0.42 | 145 | 3938 | 3936 | -1.78 | 177 | 2156 | 2155 | -1.34 |
| 18 | 556 | 555.4 | -0.56 | 50 | 1059 | 1058 | -0.86 | 82 | 1272 | 1271 | -1.08 | 114 | 1472 | 1471 | -0.95 | 146 | 3918 | 3916 | -1.68 | 178 | 2066 | 2065 | -1.48 |
| 19 | 586 | 585.4 | -0.62 | 51 | 1065 | 1064 | -0.97 | 83 | 1277 | 1276 | -1.05 | 115 | 1500 | 1499 | -1.19 | 147 | 3908 | 3906 | -1.81 | 179 | 1976 | 1975 | -1.35 |
| 20 | 596 | 595.1 | -0.87 | 52 | 1074 | 1073 | -0.95 | 84 | 1283 | 1282 | -1.07 | 116 | 1834 | 1833 | -1.16 | 148 | 3878 | 3876 | -1.91 | 180 | 1876 | 1873 | -2.64 |
| 21 | 616 | 615.1 | -0.93 | 53 | 1081 | 1080 | -1.34 | 85 | 1288 | 1287 | -1.03 | 117 | 2124 | 2123 | -1.30 | 149 | 3848 | 3846 | -1.73 | 181 | 1776 | 1775 | -1.23 |
| 22 | 636 | 635.4 | -0.63 | 54 | 1105 | 1104 | -1.4 | 86 | 1294 | 1293 | -0.90 | 118 | 2354 | 2353 | -1.27 | 150 | 3818 | 3816 | -1.82 | 182 | 1666 | 1665 | -1.29 |
| 23 | 656 | 655.1 | -0.87 | 55 | 1112 | 1111 | -1.08 | 87 | 1300 | 1299 | -1.09 | 119 | 2564 | 2563 | -1.44 | 151 | 3778 | 3776 | -1.87 | 183 | 1556 | 1555 | -1.21 |
| 24 | 666 | 665.1 | -0.9 | 56 | 1118 | 1117 | -1.03 | 88 | 1306 | 1305 | -1.05 | 120 | 2744 | 2743 | -1.36 | 152 | 3752 | 3750 | -1.81 | 184 | 1436 | 1435 | -1.18 |
| 25 | 686 | 684.1 | -1.87 | 57 | 1125 | 1124 | -0.81 | 89 | 1312 | 1311 | -0.97 | 121 | 2904 | 2903 | -1.46 | 153 | 3712 | 3710 | -1.70 | 185 | 1316 | 1315 | -1.11 |
| 26 | 706 | 705.5 | -0.53 | 58 | 1132 | 1131 | -0.87 | 90 | 1318 | 1317 | -1.01 | 122 | 3044 | 3042 | -1.67 | 154 | 3662 | 3660 | -1.80 | 186 | 1176 | 1175 | -1.08 |
| 27 | 716 | 715.4 | -0.59 | 59 | 1138 | 1137 | -0.83 | 91 | 1324 | 1323 | -0.97 | 123 | 3164 | 3163 | -1.49 | 155 | 3622 | 3620 | -1.95 | 187 | 1036 | 1035 | -0.99 |
| 28 | 736 | 735.9 | -0.13 | 60 | 1145 | 1144 | -1.18 | 92 | 1330 | 1329 | -0.58 | 124 | 3274 | 3272 | -1.78 | 156 | 3576 | 3574 | -1.69 | 188 | 866 | 865 | -0.99 |
| 29 | 756 | 755.9 | -0.14 | 61 | 1151 | 1150 | -0.85 | 93 | 1337 | 1337 | -0.38 | 125 | 3380 | 3378 | -1.63 | 157 | 3526 | 3524 | -1.76 | 189 | 666 | 665 | -0.89 |
| 30 | 766 | 765.5 | -0.52 | 62 | 1157 | 1156 | -0.87 | 94 | 1343 | 1342 | -0.96 | 126 | 3470 | 3468 | -1.85 | 158 | 3476 | 3474 | -1.90 | 190 | 486 | 485 | -0.61 |
| 31 | 786 | 785.2 | -0.85 | 63 | 1163 | 1162 | -0.97 | 95 | 1349 | 1348 | -0.92 | 127 | 3550 | 3549 | -1.44 | 159 | 3426 | 3424 | -1.79 | 191 | 276 | 275 | -0.59 |
| 32 | 806 | 805 | -0.98 | 64 | 1169 | 1168 | -1.06 | 96 | 1355 | 1354 | -1.06 | 128 | 3616 | 3614 | -1.52 | 160 | 3376 | 3374 | -1.69 | 192 | 180 | 179 | -1.07 |

Actual discharge time is same as planned

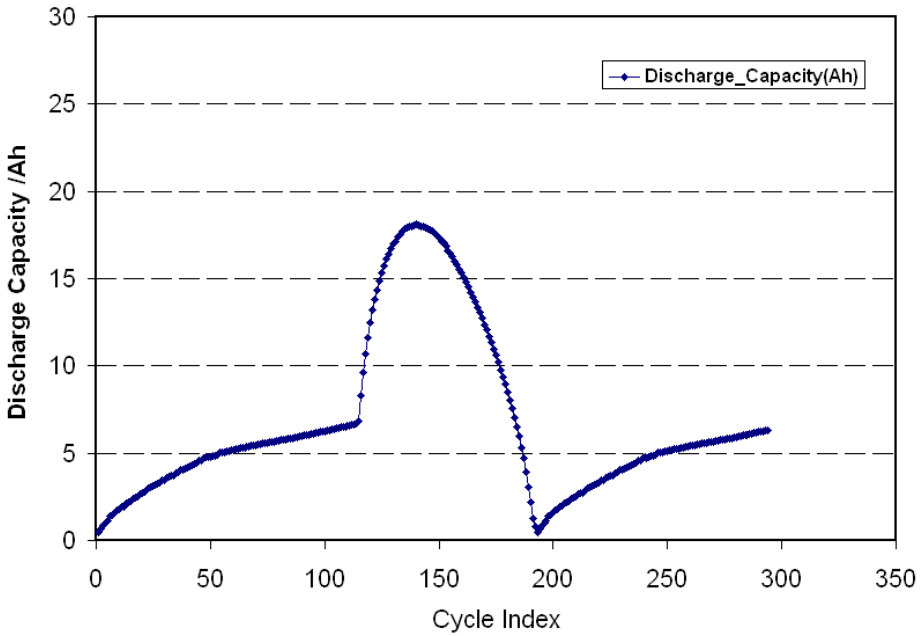
Powering Life.

# 2P-8S Tac-sat IV Configuration Battery : Accelerated HEO Test
# Battery Voltage (@ End of Discharge) and Discharge capacity

## Battery Voltage

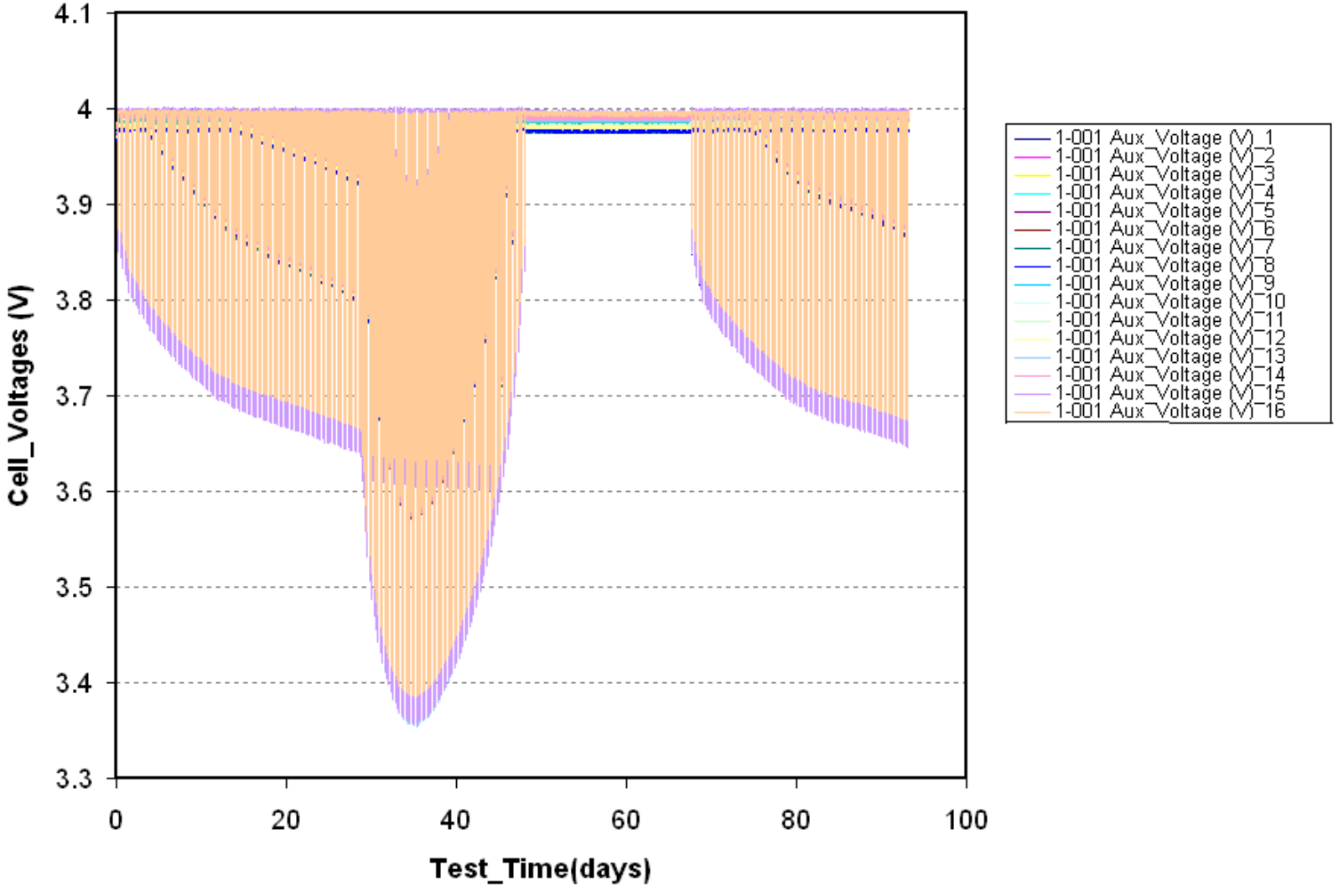



## Battery Capacity



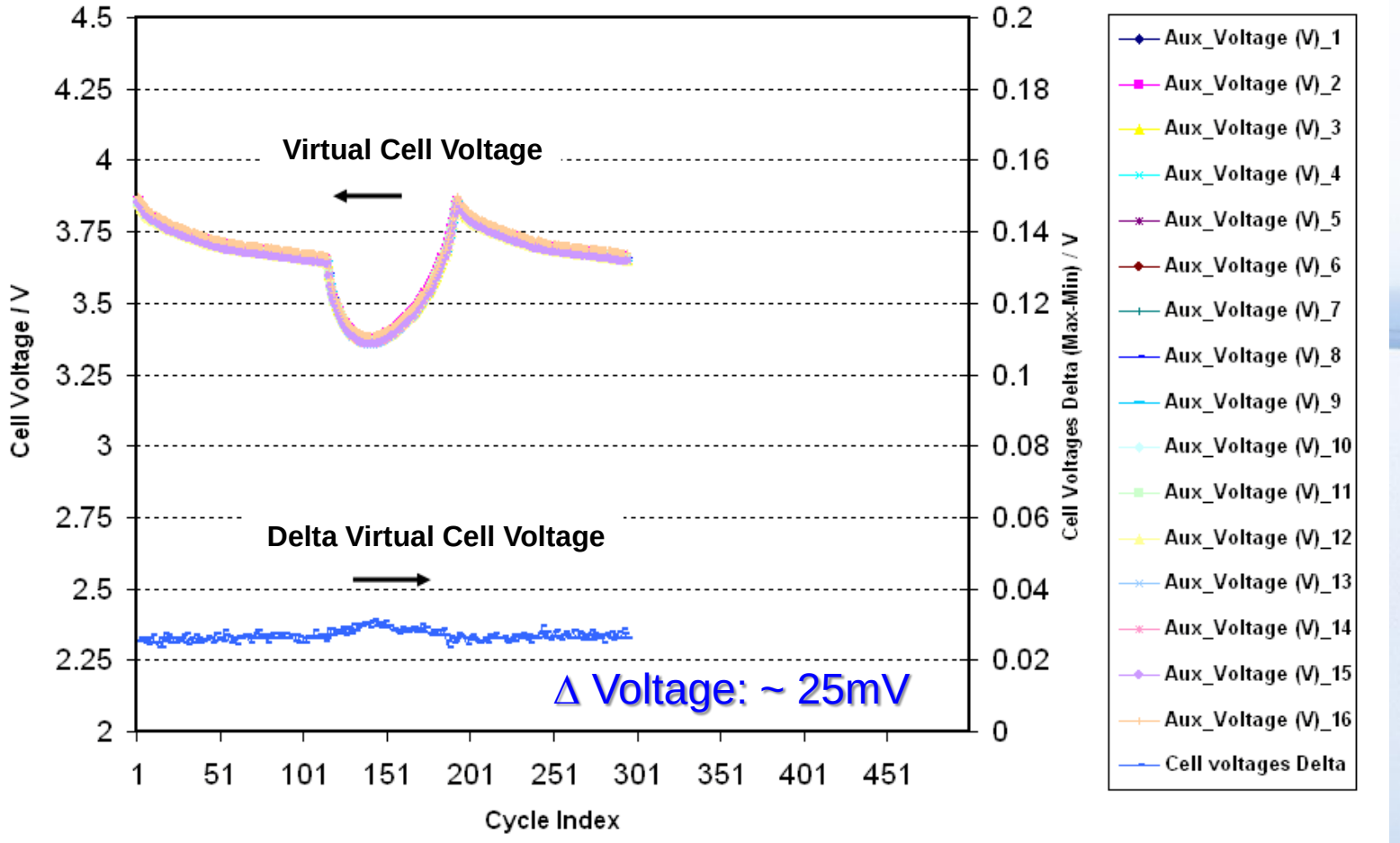

Powering Life.

# 2P-8S Tac-sat IV Configuration Battery: Accelerated HEO Test Cell Voltage vs. test time




Powering Life.

# 2P-8S Tac-sat IV Configuration Battery: Accelerated HEO Test Virtual Cell Voltages and Delta Cell Voltage @ end of discharge




Powering Life.

# Summary

- **Tittle III Cell Manufacturing Line**
  - Ramped up cell manufacturing volume
  - Duplicated cell performance with the new facility to the former manual process (LEO cycle, calendar life)

- **Chemistry**
  - By using semi-empirical requisition,
    - 5A-2$^{TM}$ Chemistry was expected to maintain 75 – 80% capacity under LEO cycle at 40% DOD, R.T. after 10 years
    - 5A-2$^{TM}$ Chemistry was expected to maintain 86% capacity under 100% SOC storage at R.T.
    - After 1.5 – 2.5 year-storage at 0V at R.T., ZeroVolt$^{TM}$ Technology was expected to maintain 80% capacity under LEO cycle at 40% DOD, R.T. after 10 years.

- **QL015KA / QL075KA cell characterization**
  - Cycle discharge capacity retention: predicted 74-91% @ 4.0V charge, 86-97% @ 4.1v charge (varied by DOD level) for 60,000 cycles
  - Calendar life discharge capacity retention: 86% retention @ 100% SOC, room temp.
  - 0V capability (upto 49 mo.): no impact to storage and LEO cycle performance (no capacity loss upto 5,000 cycles)

- **8S-1P QL015KA Battery**
  - The battery pack shows consistent performance through 52,231 cycles (in 60 months)
  - Each cell in the pack performs closely
  - The discharge energy fading rate is $3.23 \times 10^{-3}$%/ cycle
  - Cell voltage difference @ the end of 52,231$^{st}$ discharge is 30 mV

- **2P-8S Tac-sat IV Configuration Battery**
  - Battery and cell voltages, AC-IR discharge capacities measured pre- and post-vibration test were consistent (no change).
  - Initial battery characterization finished in Jan./2011, and accelerated HEO cycling test started. Currently in 2$^{nd}$ season, battery performance has been monitored closely.

Powering Life.