Panasonic Small Cell Testing For AHPS

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Contents

- Background
  - AHPS Battery
  - Motivation
- Test Overview
- Conclusions
AHPS Battery System Overview

- AEA selected in May 2004 to develop the Lithium-ion battery system for the NASA Space Shuttle Advanced Hydraulic Propulsion (System)
- AEA received contract from NASA JSC in Dec 03 to test the Panasonic CGR18650C cell for the AHPS application
- Battery system to provide high voltage electrical power to the Electro-hydraulic Unit (EHDU)
- Battery system: 3 Battery Assemblies
- Battery Assemblies: 2 Battery Modules (series connected)
AHPS Battery Requirements

- Output Voltage: 360V – 230V
- Discharge Capacity: 28 kWh
- Maximum Load: 130kW (565A @ min V)
- Low cycle life
- High pulse load

**DRIVERS**
- Safety and reliability
- Mass
- Cost
- Increase hydraulic flow
- Increase redundancy

**MODULE CONFIGURATION**
- 43s92p – SONY 18650HC
- Assembly 2s modules
**Background: AHPS Battery Challenges**

- Large range in battery interface temperature
  - Cold temperature <10°C
  - Hot temperature ~60°C
- Cold temperature
  - Increased internal resistance
  - Low EOD voltage for same load
- Hot temperature
  - Internal protection device (PTC) operates ~70°C
  - PTC operation dependent in temperature and cell load
  - Upon PTC operation, cell internal resistance rises significantly
- Battery electrical design driven by understanding both cases
AEA employs Panasonic cell in terrestrial packs

- Test program completed recently
- Test report submitted to NASA
- Main drivers for program
  - Increased performance suggested by capacity
  - Understand Hot case, seen as driving SONY cell battery size
Initial Inspection

Receiving inspection & test (232 cells)
- Mass, volume
- PTC cold resistance
- Stabilisation Cycling

![Graph showing Mass (g) vs. Cell Number]

- TEST 1: Receiving Inspection and Test
- TEST 2: Capacity and Resistance Performance
- TEST 3,4: Cell PTC Trip Time against Temp and Current
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- TEST 8: Hot Temperature PTC Trip for Battery Sizing
- TEST 9: Cell PTC withstanding Voltage
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- TEST 13: Cell Internal Short Circuit
- TEST 14: Cell Destructive Parts Analysis
Capacity under Cycling

- 22°C cycle repeated 30 times
  - 2.59W discharge, 20W pulses (3s/6min)
  - 2.5V voltage limit
  - 1 less pulse cycle 26 onwards

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Cycling Comparison

- AEA Internal tests
- 100% DOD
- Ambient temperature
PTC Trip Temperature Evaluation

- Mission profile test – 86s50p
  - 3 cells tested
  - 24°C, 70°C

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PTC: Predicting Hot Performance

- PTC characterisation
  - Trip time measured
  - 22 and 70°C
  - PTC trip time is function of current and temperature

![Graph showing PTC trip time against current at 70°C and 22°C](image)

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AHPS Performance Prediction: SONY

- Success modelling SONY 18650HC for AHPS profile
- Key factor for AHPS selection
- Iterative tests to find minimum configuration with Panasonic cell
  - Time consuming tests finding minimum configuration PTC trips
- AEA attempted to modify basic BEAST algorithm for Panasonic cell
Panasonic measured electrical parameters entered into model

Performance predictions indicated cold case would drive battery sizing
Mission Profile Tests: Hot Case

- Scaled 86s50p mission tests performed:
  - 75°C, 80°C, 85°C, 90°C
- All tests performed on 3 cells
- PTC only begins to activate at 90°C, way above expected AHPS max temp

Heating power of PTC measured using voltage and current measurement

Activation

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Mission Profile Tests: Cold Case

- **20degC test**
  - 86s: 50p, 54p, 58p, 60p
- Confirmed 54p limit at cold temperature

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- **HOT CASE:** 86s 50p, 90degC limit
- **COLD CASE:** 86s 54p, 20degC limit

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COLD CASE IS DRIVER
PTC Withstanding Voltage

- Attempt to measure robustness of PTC to failure under high voltage
- 22degC, placed in series with 15A DC supply
- Results indicated maximum voltage was around 38V – similar to SONY cell
- More representative testing performed at string level on SONY 18650HC
  - Thermal effects from other cells
## Self Discharge and Leakage Test

<table>
<thead>
<tr>
<th>Temp (°C)</th>
<th>100% SOC</th>
<th>80% SOC</th>
<th>40% SOC</th>
<th>10% SOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°C</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>NP 097, 98, 99</td>
</tr>
<tr>
<td>22°C</td>
<td>NP085</td>
<td>NP088</td>
<td>NP089</td>
<td>NP090</td>
</tr>
<tr>
<td>40°C</td>
<td>NP086</td>
<td>NP091</td>
<td>NP092</td>
<td>NP093</td>
</tr>
<tr>
<td>70°C</td>
<td>NP087</td>
<td>NP094</td>
<td>NP095</td>
<td>NP096</td>
</tr>
</tbody>
</table>

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Note: Thermal cycle + Vibration
- Cell NP087 damaged during removal from vibe jig
- Thought leakage in NP085 and 086 could be due to similar problem
- High temp mass loss thought to be due from chemical dissociation and gas release

**Self Discharge and Leakage Test**

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**Storage in days**

<table>
<thead>
<tr>
<th>Storage in days</th>
<th>Decrease in mass (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NP085 100% SoC, 22 deg C &amp; vibed</td>
<td>-0.01</td>
</tr>
<tr>
<td>NP090 10% SoC 22deg C</td>
<td>0</td>
</tr>
<tr>
<td>NP092 40% SoC at 40 deg C</td>
<td>0.01</td>
</tr>
<tr>
<td>NP094 80% SoC at 70 deg C</td>
<td>0.02</td>
</tr>
<tr>
<td>NP097 at 10% SoC at 0 deg C</td>
<td>0.03</td>
</tr>
<tr>
<td>NP088 80% SoC, 22 deg C</td>
<td>0.04</td>
</tr>
<tr>
<td>NP088 100% SoC at 40 deg C &amp; vibed</td>
<td>0.05</td>
</tr>
<tr>
<td>NP093 10% SoC at 40 deg C</td>
<td>0.06</td>
</tr>
<tr>
<td>NP095 40% SoC at 70 deg C</td>
<td>0.07</td>
</tr>
<tr>
<td>NP098 at 10% SoC at 0 deg C</td>
<td>0.08</td>
</tr>
</tbody>
</table>
**Self Discharge and Leakage Test**

- Low voltage drop due to self-discharge
- Self discharge increase with temperature evident in 10%SOC plot
- Test error meant capacity loss from self-discharge could not be differentiated from irreversible capacity loss

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<thead>
<tr>
<th>No.of.days on Test</th>
<th>Voltage (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>4.0</td>
</tr>
<tr>
<td>5</td>
<td>3.9</td>
</tr>
<tr>
<td>10</td>
<td>3.8</td>
</tr>
<tr>
<td>15</td>
<td>3.7</td>
</tr>
<tr>
<td>20</td>
<td>3.6</td>
</tr>
<tr>
<td>25</td>
<td>3.5</td>
</tr>
<tr>
<td>30</td>
<td>3.4</td>
</tr>
<tr>
<td>35</td>
<td>3.3</td>
</tr>
<tr>
<td>40</td>
<td>3.2</td>
</tr>
<tr>
<td>45</td>
<td>3.1</td>
</tr>
<tr>
<td>50</td>
<td>3.0</td>
</tr>
<tr>
<td>55</td>
<td>2.9</td>
</tr>
<tr>
<td>60</td>
<td>2.8</td>
</tr>
<tr>
<td>65</td>
<td>2.7</td>
</tr>
<tr>
<td>70</td>
<td>2.6</td>
</tr>
<tr>
<td>75</td>
<td>2.5</td>
</tr>
<tr>
<td>80</td>
<td>2.4</td>
</tr>
<tr>
<td>85</td>
<td>2.3</td>
</tr>
<tr>
<td>90</td>
<td>2.2</td>
</tr>
<tr>
<td>95</td>
<td>2.1</td>
</tr>
</tbody>
</table>

- **NP085** 100%(22°C) vibed
- **NP086** 100%(40°C) vibed
- **NP087** 100%(70°C)
- **NP088** 80%(22°C)
- **NP089** 80%(40°C)
- **NP090** 80%(70°C)
- **NP091** 40%(22°C)
- **NP092** 40%(40°C)
- **NP093** 40%(70°C)
- **NP094** 10%(22°C)
- **NP095** 10%(40°C)
- **NP096** 10%(70°C)
- **NP097** 10%(0°C)
- **NP098** 10%(0°C)
Cell Overcharge

- Charged to 12V, fixed currents
  - 0.6A, 1.2A, 4.8A
- All 6 cells disconnect close to 5V
- Matched other dedicated testing at 1.2A

### TEST 11: Cell Overcharge

![Graph showing cell overcharge behavior with different capacities and voltages.](image)
Cell Overdischarge

- Fully charged cells discharged
  - to 2.5V held for 60mins (@XAmps)
  - to 2.0V held for 60mins (@XAmps)
  - to 1.0V held for 60mins (@XAmps)
  - Charged back to 4.2V (@0.43A)
  - Discharged to 2.8V (@0.43A)
  - Discharged to 0V (@XAmps)
  - Discharged at 1.2A to 150% of 1C
- 3 cells each at X=1.2A, 2.4A, 4.8A
- At negative voltages, all cells soft short and act as resistors

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Cell Internal Short Circuit

- 3 fully charged cells
- 25°C±5°C
- Non-metallic crush rod through cell centre
- Voltage, temperature monitored

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Cell Internal Short Circuit

- All 3 cells caught fire as cells cleave in 2
- Screw action test may leave soft short

No temperature data over 500°C
Cell DPA

- 2 cells disassembled, chemical composition analysed
- Electrolyte extracted with anhydrous methanol
  - Organic analysis
  - Inorganic analysis
  - Karl Fischer test (water content)
- SEM and EDAX examination
  - Anode
  - Cathode
- Separator analysis
  - IR spectroscopy
- Cell Construction inspection
  - Similar to all other 18650s encountered
- Cell burst and vent pressure measured
  - Burst ~47bar max Vent ~18bar max
  - Above 2.5 safety ratio

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Conclusions

- AEA selection and successful Interim Design Review for AHPS proves maturity of small cell approach for very large batteries.
- Cells show excellent opportunity for battery mass reduction for AHPS and other low cycle applications.
- Lack of cycle and extended calendar life make EOL battery performance difficult (AHPS 8 year mission).
- Preliminary design, AEA retained SONY 18650HC cell as baseline:
  - Well characterised performance
  - Wealth of safety test data