787 Dreamliner Li-Ion Battery Investigation:

Electrical and Thermal Characterization Results

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APU battery
(located in an equipment bay beneath main cabin)

Battery removed from here
787 Battery Configuration
Eight cell cases electrically isolated in aluminum box

- Bus bars link 8 cells in series
- Temperature sensor (1 of 2) on bus bar
- Plastic spacers surround each cell
- Cell vents oriented outward
  Original design vented into case
  Revised design vents out of case
- Battery monitoring unit (BMU)
  Four levels of overcharge protection

(Original “901” design shown above: current design used is “902”)
General Design and Construction - Cells
The Nail Penetration Test
Test Plan and Rationale

- Nail is inserted into the center-top of Cell 6
  - This cell was suspected as the location of first cell failure in Boston incident
  - Monitor temperature and voltage to understand propagation behavior during test

- Investigate cell-to-cell propagation failure under different test conditions:
  - Battery Temperature (70°C versus 15°C)
  - State of Grounding (grounded or ungrounded)

- Disassemble cells after test to better understand failure behavior

- Unfortunately, a full DOE could not be conducted due to limited number of battery systems available
Nail Penetration Apparatus

- Hydraulic-pneumatic ram, controlled remotely
- Ram pressure controlled for better consistency
- Framing for battery placement and alignment
- Nail contains thermocouple

<table>
<thead>
<tr>
<th>L (mm)</th>
<th>r (mm)</th>
<th>θ</th>
<th>D (mm)</th>
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<tbody>
<tr>
<td>126</td>
<td>90</td>
<td>60°</td>
<td>5</td>
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Thermocouple and Lead Placement (70°C)
Thermocouple and Lead Placement (15°C)
Thermal and Electrical Behavior

70°C Ungrounded Test
Nail Penetration Summary (70°C)

- All cells failed
- Propagation started at Cell 6, moved outward as heat energy transferred to adjacent cells

More details on Cells 6, 7, and 4 in this presentation.
70°C Test – Cell 6

Temps shown max temp at moment cell drops to 0V

1st sub-cell fails

Rest of cells fail

Short cleared, recovery

Cell 6 location
70°C Test – Cell 7

Temps shown max temp at moment cell drops to 0V

Incoming heat down busbar triggers Cell 7
Cell 4 is shorted to itself after Cells 5 and 3 vent, expand, and short to the case. Failure likely due to the shorting.

Heat to Cell 4 received from case due to shorting, as well as from vented Cells 5 and 3.
Details on Cell 4 Shorting

1. Voltage across Cell 4 drops significantly due to short circuit created when Cell 3 vents and shorts to case.

2. Discharge from Cell 4 at maximum immediately after failure of Cell 3. Heating on Cell 4 terminal increases.


4. Transient in Cell 3 voltage when cell 2 expands; disappears after Cell 2 vents and drops to zero volts.

5. Failure of Cell 2 re-establishes shorting path for Cell 4 and high-current discharge resumes. Heating on terminals resumes.

6. Sub-cells of Cell 4 fail and trigger venting event.

7. Cell 3 voltage returns to zero once Cell 4 vents and removes reverse biasing.
After the Test - Exterior
After the Test - Interior
Proposed Cell Failure Mechanism

Phase I: W2 and W3 to charge W1 to balance cell voltage

Phase II: ISC triggered at W1

Phase III: W1 fuse open due to large charge current from W2 and W3

Phase IV: W3 to charge W2 to balance cell voltage

Overheating propagates from W1 to cause separator melting and ISC at W2

Overheating propagates from W2 to W3 to cause thermal runaway
Another View of Cell Propagation

- Proposed failure mechanism suggests opened cell was first to fail.
- In many cells, aluminum anodes closest to heat source break open.
- Cells fused open tend to point towards heat source; can be used to reconstruct propagation path.
Thermal and Electrical Behavior

15°C Grounded Test
15°C Test – Cell 6

Thermal Behavior

Maximum temps for whole test listed

Cell 6 location
15°C Test – Cell 6
Grounding Behavior

- Cell 6 expands at time of venting, creates electrical short to case.
- Ground cable current at 150 mA at moment of nail penetration
- Case GND is raised to 20V, since Cells 1-5 are now shorted to case through Cell 6.
- Large current flow through ground connection, limited only by ground cable and internal battery resistance (629A measured)
- Ground cable overheats and fuses open
- Case GND remains at 20V since short through Cell 6 remains
High-Current Event Overview (15°C)

Voltage potentials shown referenced to system ground

20V potential across ground wire: current limited only by cable resistance and internal battery resistance

Cell 6 carbonized; shorts internally

Cell 6 expands during venting, creates short to case

Cells 7, 8 remain at open circuit during fault

Fuse open

SYSTEM GROUND

>600A

20V

20V

20V

20V
15°C Test – Cell 5

- Maximum temps for whole test listed; most probable flow direction shown with arrows.
- Busbar connected to Cell 6
- Face towards Cell 6
- Voltage drop due to high-current short

Graph:
- Temperature (°C) vs. Elapsed Test Time (s)
- Cell Voltage (V)
- Line colors and labels:
  - 211 <5101>
  - 302 <5201>
  - 303 <5301>
  - 304 <5501> (C)
  - 305 <5502> (C)
  - 205 <Cell 5> (VDC)

Cell 5 location:
15°C Test – Cell 7

Exposure to venting gases from Cell 6

Thermal effect only during short

Side nearest Cell 6

Maximum temps for whole test listed; most probable flow direction shown with arrows.
15°C Test – Other Cells

- Cells 1-4, 8 did not exceed 60-70°C during any part of the test.
- Any heating shown early in run is thermal transfer from Cell 6.
- Temperature rise late in test is due to entire battery approaching thermal equilibrium.
Frequency Spectrum Measurements
Spectral Noise Measurement (1)

- Coaxial leads to Cell 6 terminals
  - Cable sheathed in fiberglass braid for thermal protection
  - Terminated with ring crimp for enhanced contact integrity, attached to busbars using existing screws

- Time-Domain Characterization:
  - Constant “snap shots” taken of spectra throughout test
  - Resolution: 10 MS/s (10^7 samples per second) at 18 bits per sample
  - Duration: 100 ms per “snap shot” (1 million samples each)
  - Number of “snap shots”: 740 for 70°C test, 1999 for 15°C test
  - Total data size: >100 GB per test
Spectral Noise Measurement (2)

- FFT transformation and filtering
  - 500 kS/s spectra process:
    - Digital lowpass Butterworth filter, 10th order, −3dB @ 250 kHz
    - Decimated data by factor of 20 (1MS → 50kS)
    - Hanning filtered; result is 10Hz resolution to max 250 kHz
  - 10 MS/s spectra process:
    - Divide each spectra into 20 x 5 ms segments
    - Hanning filter and FFT on each
    - Average 20 resulting spectra to give one low-noise spectrum
    - Result is 200 Hz resolution to max 5 MHz

- Data Post-Processing
  - Developed custom software to auto-analyze data files and compile summary information
  - Maximum, minimum, and average magnitude at each frequency component, indexed to file number
Example Spectral Event, 15°C

At Moment of Cell 6 failure

Suspected Arcing to Case
Does the Spectrum Suggest Arcing?

- Data show $1/f^\alpha$ “pink noise” relationship
- Spectra are consistent with arcing; visual inspection of cell cases show evidence of arcing damage
Arcing Detection Method, 70°C

**Approach**

- Detect arcing by identifying files that contain many frequency maxima
- Since arcing is wideband, many frequency components will rise above background level during arcing

**Results**

- 9 out of 740 files show probable significant arcing events for 70°C dataset; more files also suggest arcing occurring

Each point on the graph locates the file number where the maximum amplitude at each frequency was detected. Large numbers of maxima in a single file suggest arcing occurring in that moment of time.
Arcing Detection – Interpretation 70°C

- Superimposing frequency data on top of cell voltage data assists in interpretation of events.
- Spectral events observed during venting of Cells 6, 7, 5, 3, and 4; possible arcing from cell case at moment of cell expansion due to metal-metal contact.
- Significant number of events observed while Cell 4 in suspected high-discharge state, suggests arcing to case during discharge.

Each point on the graph locates the file number where the maximum amplitude at each frequency was detected. Large numbers of maxima in a single file suggest arcing occurring in that moment of time.
Conclusions

- Initial cell and battery temperature has significant effect on cell propagation. (However, this may have not been a key factor in the actual incidents.)

- Grounding of battery can result in high-current discharge during cell venting event. Causes additional heating due to battery self-discharging.

- Though battery is dc, wideband spectral noise can be generated during arcing events. Effect on avionics is currently unclear but noted by NTSB as potential concern.
THANK YOU.