International Space Station
Lithium-Ion Main Battery
Thermal Runaway Propagation Test

NASA Battery Workshop
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Background & Overview

• NASA Engineering and Safety Center (NESC) funded a task to evaluate thermal runaway (TR) propagation of Li-Ion batteries on the International Space Station (ISS)
  • Response to Boeing 787 Li-Ion thermal runaway (TR) events of 2013
• ISS Main EPS Li-Ion battery used analysis to show that the design would not propagate beyond battery to damage ISS
  • Requirement to verify this via test not levied on the project
  • NESC assessment of ISS Analysis indicated conservative approach
• NESC funded TR test with intent to verify the analysis results
  • Test Article ORU build February – August 2016
  • Trigger method testing in March - July 2016
    • Space Power Workshop, 4/27/17, “ISS Main Battery Large Cell Thermal Runaway Propagation Testing”, Jason Graika
• White Sand Test Bed Integration September – October 2016
• White Sands Battery Propagation Test in October 2016
• Post Test analysis in November - December 2016
Outline

• Battery ORU and Safety Features
• Battery ORU Test Article
• Battery TR Propagation Test Bed
• Battery TR Propagation Test
• Results and Findings
ISS Li-Ion ORU

- 30 GS Yuasa LSE134-101 cells in series
  - Arranged in three “10 packs”
- 3.95 V/cell End of Charge Voltage
- ~15 Kwh
- Low Earth Orbit ~35 min discharge & 55 min charge
- 10 year (60,000 cycles) life

GS Yuasa 134 A-hr cell
ORU Safety Features
MMOD Shielding

Note: Existing Ni-H₂ batteries do not have MMOD (Micro-Meteoroid Orbital Debris) protection
ORU Safety Features
Flame Trap Pressure Relief Assemblies

- Allows ORU vent gas pressure relief
- Prevent Flames from escaping the ORU
- Baffles made of 300 series CRES (Stainless Steel)
- Directs vent effluent away from EVA crew member during Installation
- Once installed on ISS, vent ports face structure or adjacent ORUs, thus limiting effluent flow to EVA accessible areas

Note: Cell vents face up toward MMOD shielding – away from cold plate, adjacent cells, and IEA hardware
ORU Safety Features
Radiant Heat Barriers & Cell Spacing

- ORU Layout – three Cell “10-Packs” and 12 Radiant Barriers

Radiant Heat Barrier (12 per ORU)
- Higher margin against thermal runaway propagation
- One barrier between each cell pair
- Reflects 787 reach-back safety additions

Cell 10-Pack
~3.5” Spacing between 10-Packs
~2” ~1” Spacing between Cells

Spacing
ISS Li-Ion ORU Test Article

- As Flight Like as possible within cost and schedule constraints
  - Finned baseplate, enclosure, MMOD shield, flame trap vent assemblies, cell holding fixtures, thermal gaskets, radiant barriers, insulation, etc.
- Six live cells, 24 cell mass simulators
  - Live cells at and adjacent to initiating TR cell locations.
- Battery Interface Unit mass simulator
- Cable runs similar to flight configuration
- Additional Thermal Couple Instrumentation
- Enclosure modified to accommodate drill penetration apparatus

First two rows of cells on baseplate

Six live cells, 24 cell simulators
Trigger Method

• Patch Heater Method
  – Developmental tests on cells and mass simulators
  – Tested 800W heaters on a ISS cell
  – 1.2 MJ over 20 minutes to achieve TR
  – Resulted in TR with JR ejection
  – Too large of an initial temperature bias on battery and adjacent cells for implement on ORU TR test

• Drill Penetration Method
  – All resulted in TR within seconds with JR ejection
  – No temperature bias on adjacent cells, but requires breach of cell can prior to TR

• Drill Penetration Method selected for ORU TR test

• For further details reference
  • Space Power Workshop, 4/27/17, “ISS Main Battery Large Cell Thermal Runaway Propagation Testing”, Jason Graika
ISS Li-Ion ORU TR Propagation Test Bed

White Sands Thermal Runaway Propagation Test Bed

• Flight-like finned active cooling loop from ORU manufacturer, painted black over anodized gold coating for proper emissivity
• Affinity chiller selected for circulation of cooling fluid
  • Dynalene HC-10 fluid, on-orbit uses ammonia
  • Thermal analysis determined that differences were acceptable
• Two cameras, one inside test article, one inside chamber
• Drill Penetration Apparatus installed
ISS Li-Ion ORU TR Propagation Test

• ORU TR Test Execution – October 26, 2016
  • Cells charged to 3.95 V at C/6 prior to test start (on-orbit EOCV)
  • Chamber <1 torr
  • Chiller temp ~40 deg F and average cell temp 75 deg F
  • Heaters turned off, cameras began recording, drill actuated
  • TR initiated in Cell 1, lower area of the curved side
    • Drill stopped when sparks & electrolyte release were observed
    • Drill re-started after 14 seconds, run until full TR observed (see video)
  • Chamber camera captured cell venting (see video)
  • Continued monitoring temperatures & voltages post-TR
  • No propagation of TR to adjacent cells
  • 5 intact live cells discharged at C/6 prior to opening chamber
  • Test article shipped to JSC for destructive physical analysis
ISS Li-Ion ORU TR Propagation Test Videos

USB Camera inside Test Article

USB Camera outside Test Article
ISS Li-Ion ORU TR Propagation Test

• Test Summary – Cell Voltages
ISS Li-Ion ORU TR Propagation Test

• Test Summary – Cell 1 and Cell 10 Temperatures

Note: TC 1 failure, erratic readings on TC6 due to intermittent contact with the cell case
ISS Li-Ion ORU TR Propagation Test

- Test Summary – Baseplate Corner Temperatures

Note: Erratic readings on TC21 due to intermittent contact with the cell case
ISS Li-Ion ORU TR Propagation Test

- Test Summary – Baseplate Corner near jelly roll winding final location
ISS Li-Ion ORU TR Propagation Test

- Post-test Destructive Physical Analysis at JSC – Minimal Enclosure or MMOD shield damage
ISS Li-Ion ORU TR Propagation Test

- Post-test Destructive Physical Analysis at JSC

<table>
<thead>
<tr>
<th>Location</th>
<th>Mass (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell Winding</td>
<td>470</td>
</tr>
<tr>
<td>Cell #1 remains</td>
<td>328</td>
</tr>
<tr>
<td>Front corner near cell 1</td>
<td>165</td>
</tr>
<tr>
<td>Front corner near cell 5</td>
<td>157</td>
</tr>
<tr>
<td>Cell Header</td>
<td>157</td>
</tr>
<tr>
<td>Baseplate cell 30 row</td>
<td>128</td>
</tr>
<tr>
<td>Top of live cells</td>
<td>86</td>
</tr>
<tr>
<td>Current collector</td>
<td>44</td>
</tr>
<tr>
<td>Top of mass simulator plus doghouse</td>
<td>31</td>
</tr>
<tr>
<td>In Flame Trap near cell 1</td>
<td>30</td>
</tr>
<tr>
<td>Between Cell Rows 1-2</td>
<td>28</td>
</tr>
<tr>
<td>Between Cell Rows 2-3</td>
<td>18</td>
</tr>
<tr>
<td>Cell Core</td>
<td>16</td>
</tr>
<tr>
<td>Cell 5 and 6 area</td>
<td>10</td>
</tr>
<tr>
<td>Outside ORU under doghouse</td>
<td>3</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>1671</strong></td>
</tr>
</tbody>
</table>

Pretest Mass 3526

Missing Mass 1855
ISS Li-Ion ORU TR Propagation Test

- Post-test Destructive Physical Analysis at JSC – Flame Trap, Cell 1, and Header
ISS Li-Ion ORU TR Propagation Test

• Test Results
  • Trigger cell vented, achieved TR, followed by cell winding ejection
  • Battery enclosure contained TR products, including flames
    • Minimal damage to enclosure, MMOD shield, or radiant barriers
    • Gases vented and exited from enclosure
  • No propagation to neighboring cells
    • All 5 live cells maintained their pre-test Open Circuit Voltages

• Test Findings
  • Full-scale test did not propagate or damage adjacent cells
    • Cell winding ejection resulted in a suspected under-test condition
      • Limited ability to fully verify thermal model results
  • Battery design precluded effective use of patch heaters for TR trigger
    • Recommend development of TR trigger method that limits thermal bias

• Forward Work
  • NESC is pursuing further work on trigger method
    • Once developed, consider repeat the full-scale test
    • Use results to further assess thermal model predictions
Acknowledgements

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