Battery Design Implications on Thermal Runaway Severity: NASA ISS SAFER Battery Safety Assessment

Jason Graika\textsuperscript{a}, Thomas Barrera\textsuperscript{b}, Concha Reid\textsuperscript{c}, Dan Doughty\textsuperscript{d}, Penni Dalton\textsuperscript{c}, and Samuel Stuart\textsuperscript{e}

2\textsuperscript{nd} International Battery Safety Workshop
Sandia National Laboratories
Albuquerque, New Mexico
May 8-10, 2017

(a). NASA-Johnson Space Center (Houston, TX, USA);
(b). LIB-X Consulting (Long Beach, CA, USA);
(c) NASA-Glenn Research Center (Cleveland, OH, USA);
(d). Battery Safety Consulting, Inc. (Albuquerque, NM, USA);
(e). Naval Surface Warfare Center (Crane, IN, USA).
Agenda

- Background
  - Battery Design
- Test Approach and Results
  - Single-Cell Trigger
  - SAFER Battery TR
- Summary
Background

- 2013 Commercial Aviation Li-Battery Incidents
  - Three (3) rechargeable lithium-ion battery (LIB)\(^1\)
  - **One (1) non-rechargeable lithium battery** \(^2\)

- Industry Impacts – Risk Mitigation
  - Severity of Thermal Runaway (TR) Event
    - Energetic cell internal short
    - Other causes
  - Consequences of TR Event
    - Effects of cell-to-cell propagation

- Standards and Legislation - Ongoing
  - Revisions to industry LIB safety standards
  - New test protocols and compliance methods

Ref:
1. Bauer, M., Swain, R., Jeevarajan, J., "Findings and Lessons Learned from The Boeing 787 Investigations", 2015 Space Power Workshop, May 11-14, Manhattan Beach, CA, USA.
Impacts To NASA Programs

- **Goals & Objectives**
  - Implementation of NASA Engineering Safety Center (NESC)-sponsored risk assessments
  - Independent reviews of deployed and new lithium batteries
    - ISS Main LIB Orbital Replacement Unit (ORU)
    - *Extravehicular Mobility Unit (EMU)*

- **Approach**
  - Critical independent reviews of TR hazards
  - Perceptive relevant testing to determine TR hazards risk
  - Risk $\alpha$ [Severity $\times$ Consequences]
  - Implementation of new design solutions to reduce safety risk, if necessary

---

*NASA/ISS Transition from Ni-H$_2$ to LIB ORU*

- Long Life Li-Ion Battery (LLB)
- Li-Ion Rechargeable EVA Battery (LREBA)
- Simplified Aid For EVA Rescue (SAFER)
- Battery – Non-rechargeable Li Battery
- Li-Ion Pistol Grip Tool (LPGT)
Objective
- Assess the severity of a TR event in the SAFER non-rechargeable lithium battery

Approach
- Conduct credible worst-case SAFER battery safety tests designed to quantify the severity of a TR condition which may result in cell-to-cell propagation
  - Utilize relevant flight configuration
  - Employ relevant flight environment

Conservative assumption that likelihood of single-cell TR event is non-zero
ISS EMU SAFER System Unit: Brief Intro

- **Purpose**
  - Self-contained, 24-jet free flyer “jet pack” system that provides capability for EVA crewmember self-rescue
    - SAFER Battery provides all SAFER system unit power
  - Jetpack operation is for contingency use in case astronaut becomes un-tethered from ISS
  - Worn by USA astronauts on EVA since 1994

![ISS SAFER System Unit](image1)

![USA Astronaut on EVA with SAFER attached to EMU](image2)
ISS EMU SAFER System Integration
Battery and COTS Cell Design

- **Battery Design**
  - **Non-rechargeable**
  - ORU refurb schedule = Every 3.5-yr.
  - 14S-3P topology \((4S+10S=14S)\)
  - Mass = 1.99kg
  - Nominal Voltage = 40V
  - Nominal Capacity = 3.75Ah
  - Operating Temp = \(-20^\circ\text{C}\) to \(+58^\circ\text{C}\)
  - Duracell® Ultra CR123 (2/3A size; Li-MnO\(_2\))

- **Safety Devices**
  - Individual cell Schottky bypass diodes
  - Bundle-level PTC’s

- **Cell Design**
  - **Non-rechargeable**
  - Mass = 17g
  - Nominal Voltage = 3.00V
  - Nominal Capacity = 1.5Ah
  - Operating Temp = \(-20^\circ\text{C}\) to \(+75^\circ\text{C}\)

- **Safety Devices**
  - Internal PTC
  - External Vent

*Ref: Duracell® Lithium Technical Bulletin (www.duracell.com)*

Cross-sectional view of Duracell® Ultra 123 Li/MnO\(_2\) spiral-wound cell.
ISS SAFER 4S/10S Battery: Bundle Electrical Design

10-Cell (10S) Bundle PTC (Positive Temperature Coefficient)

Schematic Diagram
10-Cell (10S) Bundles

Schottky Diode

Schematic Diagram
4-Cell (4S) Bundles

Schottky Diode

4-Cell (4S) Bundle PTC
ISS SAFER Battery: 4S/10S-Cell Bundle Safety Devices

Schottky Diodes

Bundle PTC

10-Cell (10S) Bundle

Schottky Diodes

Bundle PTC

4-Cell (4S) Bundle
Single-Cell TR Trigger Testing
## Single-Cell TR Trigger Test Matrix Results

<table>
<thead>
<tr>
<th>Trial Run</th>
<th>Cell ID</th>
<th>Heater Power (W)</th>
<th>Heater Location</th>
<th>Cell Temp (°C)</th>
<th>Time to TR (min)</th>
<th>Cell Jacket Temp at Start of TR (°C)</th>
<th>Max Cell Jacket Temp (°C)</th>
<th>Max Positive Terminal Probe Temp (°C)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>53</td>
<td>15</td>
<td>Bottom</td>
<td>Ambient</td>
<td>-</td>
<td>-</td>
<td>-161</td>
<td>N/A</td>
<td>No thermal runaway after 44 min</td>
</tr>
<tr>
<td>1</td>
<td>70</td>
<td>15</td>
<td>Bottom</td>
<td>Ambient</td>
<td>~22</td>
<td>~199</td>
<td>~575</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>44</td>
<td>15</td>
<td>Side</td>
<td>Ambient</td>
<td>~11</td>
<td>~180</td>
<td>~733</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>50</td>
<td>15</td>
<td>Side</td>
<td>Ambient</td>
<td>~9</td>
<td>~158</td>
<td>~518</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>119</td>
<td>10</td>
<td>Bottom</td>
<td>Ambient</td>
<td>-</td>
<td>-</td>
<td>~120</td>
<td>-</td>
<td>No thermal runaway after 1 hr</td>
</tr>
<tr>
<td>3</td>
<td>129</td>
<td>10</td>
<td>Side</td>
<td>Ambient</td>
<td>-</td>
<td>-</td>
<td>~119</td>
<td>-</td>
<td>No thermal runaway after 1 hr</td>
</tr>
<tr>
<td>3</td>
<td>133</td>
<td>10</td>
<td>Side</td>
<td>Ambient</td>
<td>-</td>
<td>-</td>
<td>~162</td>
<td>-</td>
<td>No thermal runaway after 1 hr</td>
</tr>
<tr>
<td>5</td>
<td>142</td>
<td>20</td>
<td>Bottom</td>
<td>Ambient</td>
<td>~8.5</td>
<td>~175</td>
<td>~621</td>
<td>~632</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>167</td>
<td>20</td>
<td>Bottom</td>
<td>Ambient</td>
<td>~8.3</td>
<td>~172</td>
<td>~645</td>
<td>~882</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>169</td>
<td>20</td>
<td>Side</td>
<td>Ambient</td>
<td>~5.7</td>
<td>~209</td>
<td>~734</td>
<td>~409</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>175</td>
<td>20</td>
<td>Side</td>
<td>Ambient</td>
<td>~6.5</td>
<td>~204</td>
<td>~684</td>
<td>~532</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>406</td>
<td>25</td>
<td>Bottom</td>
<td>Ambient</td>
<td>~7</td>
<td>~155</td>
<td>~661</td>
<td>~275</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>419</td>
<td>25</td>
<td>Bottom</td>
<td>Ambient</td>
<td>~6.3</td>
<td>~177</td>
<td>~649</td>
<td>~1158</td>
<td>Heater power unstable</td>
</tr>
<tr>
<td>8</td>
<td>208</td>
<td>25</td>
<td>Side</td>
<td>Ambient</td>
<td>~4.7</td>
<td>~182</td>
<td>~582</td>
<td>~340</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>402</td>
<td>25</td>
<td>Side</td>
<td>Ambient</td>
<td>~5</td>
<td>~176</td>
<td>~608</td>
<td>~437</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>216</td>
<td>15</td>
<td>Side</td>
<td>49</td>
<td>~9:31</td>
<td>~250</td>
<td>~746</td>
<td>~690</td>
<td>False start @ &lt; 00:00; Heater not connected</td>
</tr>
<tr>
<td>12</td>
<td>246</td>
<td>15</td>
<td>Side</td>
<td>49</td>
<td>~7:19</td>
<td>~198</td>
<td>~569</td>
<td>~430</td>
<td>Clamp TC faulty</td>
</tr>
<tr>
<td>16</td>
<td>252</td>
<td>20</td>
<td>Side</td>
<td>49</td>
<td>~5:23</td>
<td>~178</td>
<td>~735</td>
<td>~562</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>308</td>
<td>20</td>
<td>Side</td>
<td>49</td>
<td>~6:10</td>
<td>~178</td>
<td>~585</td>
<td>~652</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>312</td>
<td>25</td>
<td>Side</td>
<td>49</td>
<td>~4:16</td>
<td>~170</td>
<td>~577</td>
<td>~502</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>319</td>
<td>25</td>
<td>Side</td>
<td>49</td>
<td>~3:51</td>
<td>~228</td>
<td>~717</td>
<td>~552</td>
<td>False start @ &lt; 00:00; Heater not connected</td>
</tr>
<tr>
<td>22a</td>
<td>251</td>
<td>35</td>
<td>Side</td>
<td>49</td>
<td>~2:46</td>
<td>~173</td>
<td>N/A</td>
<td>N/A</td>
<td>Heater appears to have shorted</td>
</tr>
<tr>
<td>22a</td>
<td>522</td>
<td>35</td>
<td>Side</td>
<td>49</td>
<td>~2:45</td>
<td>~173</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>23a</td>
<td>579</td>
<td>40</td>
<td>Side</td>
<td>49</td>
<td>~2:22</td>
<td>~216</td>
<td>N/A</td>
<td>N/A</td>
<td>Lost jacket temp after ~ 230°C</td>
</tr>
<tr>
<td>23a</td>
<td>839</td>
<td>40</td>
<td>Side</td>
<td>49</td>
<td>~1:54</td>
<td>~170</td>
<td>~730</td>
<td>N/A</td>
<td>Heater appears to have shorted</td>
</tr>
<tr>
<td>S12</td>
<td>17</td>
<td>35</td>
<td>Side</td>
<td>Ambient</td>
<td>~2:18</td>
<td>~134.8</td>
<td>~851</td>
<td>N/A</td>
<td>Spare cell; Ceramic heater (6.526 Ω DMM, 6.8 Ω data); TC on cell jacket</td>
</tr>
<tr>
<td>S13</td>
<td>135</td>
<td>35</td>
<td>Side</td>
<td>Ambient</td>
<td>~2:14</td>
<td>~170.2</td>
<td>~694</td>
<td>N/A</td>
<td>Spare cell; Ceramic heater (6.417 Ω DMM, 6.5 Ω data); TC on cell jacket</td>
</tr>
<tr>
<td>S14</td>
<td>25</td>
<td>35</td>
<td>Side</td>
<td>Ambient</td>
<td>~3:10</td>
<td>~155</td>
<td>~668</td>
<td>N/A</td>
<td>Spare cell; Ceramic heater (12.47 Ω DMM, 7.2 Ω data); TC on cell can; Op Error</td>
</tr>
<tr>
<td>S15</td>
<td>78</td>
<td>35</td>
<td>Side</td>
<td>Ambient</td>
<td>~2:48</td>
<td>~146.9</td>
<td>~569</td>
<td>N/A</td>
<td>Spare cell; Ceramic heater (7.49 Ω DMM, 7.2 Ω data); TC on cell can</td>
</tr>
<tr>
<td>22b</td>
<td>128</td>
<td>35</td>
<td>Side</td>
<td>Ambient</td>
<td>~2:11</td>
<td>~146.9</td>
<td>~492</td>
<td>N/A</td>
<td>Ceramic heater (6.56 Ω DMM, 6.4 Ω data); TC on cell can; Cell can TC too close to heater</td>
</tr>
<tr>
<td>22b</td>
<td>315</td>
<td>35</td>
<td>Side</td>
<td>Ambient</td>
<td>~2:08</td>
<td>~169</td>
<td>~1280</td>
<td>N/A</td>
<td>Ceramic heater (6.713 Ω DMM, 6.6 Ω data); TC on cell can</td>
</tr>
<tr>
<td>23b</td>
<td>381</td>
<td>40</td>
<td>Side</td>
<td>Ambient</td>
<td>~2:07</td>
<td>~130</td>
<td>~622</td>
<td>N/A</td>
<td>Ceramic heater (6.88 Ω DMM, 6.8 Ω data); TC on cell can</td>
</tr>
<tr>
<td>23b</td>
<td>706</td>
<td>40</td>
<td>Side</td>
<td>Ambient</td>
<td>~2:07</td>
<td>~175</td>
<td>~827</td>
<td>N/A</td>
<td>Ceramic heater (9.89 Ω DMM, 7.0 Ω data); TC on cell can</td>
</tr>
<tr>
<td>22c</td>
<td>26</td>
<td>35</td>
<td>Side</td>
<td>Ambient</td>
<td>~2:27</td>
<td>~173</td>
<td>~655</td>
<td>~375</td>
<td>Ceramic heater (7.1 Ω DMM, 6.9 Ω data); TC on cell can</td>
</tr>
<tr>
<td>22c</td>
<td>266</td>
<td>35</td>
<td>Side</td>
<td>Ambient</td>
<td>~2:18</td>
<td>~125</td>
<td>~551</td>
<td>~619</td>
<td>Ceramic heater (6.8 Ω DMM, 6.9 Ω data); TC on cell can</td>
</tr>
<tr>
<td>23c</td>
<td>486</td>
<td>40</td>
<td>Side</td>
<td>Ambient</td>
<td>~2:08</td>
<td>~163</td>
<td>~700</td>
<td>~216</td>
<td>Ceramic heater (6.9 Ω DMM, 6.9 Ω data); TC on cell can</td>
</tr>
<tr>
<td>23c</td>
<td>740</td>
<td>40</td>
<td>Side</td>
<td>Ambient</td>
<td>~1:40</td>
<td>~110</td>
<td>~213</td>
<td>~605</td>
<td>Ceramic heater (7.2 Ω DMM, 7.0 Ω data); TC on cell can; Cell OCV 3.02 V (low); Heater Current = ~ 5A startup then ~ 2.3A</td>
</tr>
</tbody>
</table>

35W heater power chosen for battery-level TR testing
Ceramic Patch Heater: Design & Installation

SAFER Cell

Twist insulated copper wires onto Nichrome wire ends.

Apply putty directly on cell.

Install heater, wire-side up, on putty-coated side of cell. Apply new coat of putty to fill in any cracks.

Cover heater with the slightly larger piece of mica paper.

Wrap cell with mica tape and secure with Kapton tape. Allow to dry for 12 hrs. for total of 24 hrs.
Internal Short Circuit Simulation - Single Cell Heater Trigger Test – Sequence of Events (Trial Run @ 35W)

- Time = 0 sec.  
  Cell Temp = 29°C

- Test Start

- Time = 2:40 min  
  Cell Temp = 360°C

- Cell TR - Sparks

- Time = 1:54 min  
  Cell Temp = 97°C

- Cell Venting - Smoke

- Time = 2:36 min  
  Cell Temp = 170°C

- Cell TR – Onset w/Sparks

- Time > 4 min  
  Cell Temp = Decreasing

- Cell TR – Onset w/Sparks/Flames

- Post-Test
Effect of Heater Power on Time-To-Cell TR

Cell Jacket Temperature, °C

Time, mm:ss

Decreasing Heater Power

- 10W Cell ID129
- 10W Cell ID133
- 15W Cell ID044
- 15W Cell ID050
- 20W Cell ID169
- 20W Cell ID175
- 25W Cell ID208
- 25W Cell ID402
- 30W Cell ID841
- 30W Cell ID013
- 35W Cell ID315
- 35W Cell ID266
- 35W Cell ID026
- 40W Cell ID381
- 40W Cell ID486
- 40W Cell ID706
Effect of Heater Power on Cell TR Temperature

Melting pt. of Li (m)
T_m = 180°C

Patch Heater

Ceramic Heater
Battery-Level TR Testing
“Flight Like” SAFER Battery Test Article: Build Quality Details

- Gauge Board Insert
- Non-rechargeable COTS Lithium cells (42 cells per battery)
- 4S Cell Bundle (3 per battery) w/Htr Harness
- Test Instrumentation Harness
- 10S Cell Bundles (3 per battery)
- SAFER Battery Chassis
- Gauge Board
- Gauge Board Cover
- SAFER Unit Mass Simulator
- Flight-Like SAFER Battery Test Article
SAFER Battery Heater Trigger TR Test – Worst-Case Trigger Cell Location Map

Trigger Cell “Worst-Case” Location Selection Rationale:

1. Choose trigger cells in both 4S and 10S sides of battery.
2. Choose trigger cell(s) with fewest adjacent cells (Positions #1, #2, #3, & #4).
3. Positions #3 and #4 are nearest to gauge board.
4. Choose 1 trigger cell location closest to heritage temp sensor location (Position #5).

Fewer adjacent cell(s) reduces likelihood of thermal biasing (over-test) test condition
SAFER Battery Heater Trigger TR Test: 35W; Pos. #2
SAFER Battery Heater Trigger TR Test: 35W; Pos. #2

Temperature, °C

Elapsed Time, min

Trigger Cell TR
SAFER Battery TR: Cell-To-Cell Propagation IR Images
Battery 4S & 10S-Side TR Test Results: Post-Test Forensics

Test #3
(35W; Pos. #1)

Test #4
(35W; Pos. #2)

Video

Cell-to-cell propagation
Project Summary

- **Experimental Results**
  - Worst-case single-cell TR results in catastrophic cell-to-cell TR propagation
    - Heritage cell bundle packaging design facilitates TR propagation
    - Gauge board “spacing” mitigates TR across entire SAFER battery pack
    - Ambient oxygen sources increases severity of SAFER battery TR consequences.

- **Flight Status**
  - Near-term continued use for ISS EVA’s is acceptable
    - Likelihood of catastrophic TR event deemed to be low

- **Next Steps**
  - Project currently evaluating options for SAFER battery re-design
    - Battery chassis vent capability
    - Cell packaging
    - Other
Acknowledgements

- **NESC Langley Research Center – Hampton, VA, USA**
  - Dr. Chris Iannello (NASA/Kennedy Space Center)

- **NASA/JSC Energy Systems Test Area (ESTA) – Houston, TX, USA**
  - Mr. Oscar Huerta, Mr. Adan Garza, Mr. Tony Parish, Mr. Pete Sanchez, Mr. Pablo Salazar and Mr. Dereck Lenoir.

- **NASA/JSC EVA Program Office and SR&QA**
  - Ms. Tamra George and Mr. Ron Cook

- **NASA/JSC Propulsion and Power Division – Houston, TX, USA**
  - Dr. Eric Darcy

- **The Boeing Co. Satellite Development Ctr – El Segundo, CA, USA**
  - Ms. Amalia Aviles

- **The Aerospace Corporation – El Segundo, CA, USA**
  - Dr. Boyd Carter
Thanks for your attention!