Thermal Runaway Propagation Assessment of the SAFER Astronaut Jetpack Battery

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*- NASA Glenn Research Center, # - The Boeing Co, & - Naval Surface Warfare Center - Crane, % - The Aerospace Corporation
Background

• The NASA Engineering Safety Center (NESC) Electrical Power Technical Discipline Team (TDT) has been conducting reviews of deployed batteries for human missions consisting of lithium-ion and lithium metal cell chemistries.

• Independent Review Teams (IRTs) were formed to assess the thermal runaway propagation hazard for these batteries.

• Simplified Aid for Extravehicular Activity Rescue (SAFER) battery assessment was requested by International Space Station (ISS) managers.

• The SAFER IRT was tasked to:
  1. Assess the battery design risk of thermal runaway (TR) and safety/hazard controls via analysis and test.
  2. Determine if design is robust enough to tolerate a catastrophic cell failure without propagating to neighboring cells.
  3. Identify issues, risks, and opportunities.
  4. Provide actionable technical recommendations to mitigate risk.

SAFER Battery Assessment Team

- **IRT Members**
  - Dr. Thomas P. Barrera, Lead, The Boeing Co.
  - Penni Dalton, Co-Lead, NASA-Glenn Research Center
  - Dr. Boyd C. Carter, The Aerospace Corporation
  - Dr. Dan Doughty, Battery Safety Consultants
  - Concha Reid, NASA-Glenn Research Center
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- **Technical Support**
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  - Ron Cook, NASA-Johnson Space Center
  - Dr. Eric Darcy, NASA – Johnson Space Center
  - Tamra George, NASA-Johnson Space Center
  - Jason Graika, NASA-Johnson Space Center
  - Dr. Judy Jeevarajan, NASA-Johnson Space Center (former consultant)
  - Samuel Russell, Member, NASA-Johnson Space Center
  - Yaramy Treviño/NASA-Johnson Space Center

- **Sponsor**
  - Dr. Chris Iannello, NESC Sponsor, NASA-Kennedy Space Center
SAFER Battery

- Provides power for the astronaut jetpack to allow astronaut to safely return to the ISS.
- Jetpack operation is for contingency use in case astronaut becomes untethered from the ISS.

SAFER jetpack

Location of SAFER battery
Battery Design

• 3.75 Ah, 40V (nominal) battery
  – 14S3P arrangement
  – Series strings consist of 4 and 10 cell bundles
• Duracell Ultra 123 primary LiMnO₂ cell*
  – COTS cell
  – Spiral wound, cylindrical design
• Cell contains a vent and a resettable positive temperature coefficient device (PTC)
• Polyswitches and diodes provide battery protection
• Battery electronics gauge board provides capacity, voltage and temperature measurement
• Communication with avionics system via RS 232
• 3-5 year orbital replacement unit – battery housing refurbished with new cells

*Used on SAFER since 2013
Approach

• Conduct credible worst-case SAFER battery safety tests to quantify the severity of a thermal runaway condition which may result in cell-to-cell propagation
  – External short circuit testing
  – Thermal runaway testing

• Tests conducted at the individual cell-level, at the 4-cell and 10-cell bundle level, and at the battery-level

• Test cells screened and matched using flight ATP protocols

• This paper will focus on TR evaluations
Thermal Runaway Trigger Cell Testing

<table>
<thead>
<tr>
<th>Heater Power (W)</th>
<th>Heater Location</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>Bottom</td>
<td>Ambient</td>
</tr>
<tr>
<td>15</td>
<td>Side</td>
<td>Ambient</td>
</tr>
<tr>
<td>10</td>
<td>Bottom</td>
<td>Ambient</td>
</tr>
<tr>
<td>10</td>
<td>Side</td>
<td>Ambient</td>
</tr>
<tr>
<td>20</td>
<td>Bottom</td>
<td>Ambient</td>
</tr>
<tr>
<td>20</td>
<td>Side</td>
<td>Ambient</td>
</tr>
<tr>
<td>25</td>
<td>Bottom</td>
<td>Ambient</td>
</tr>
<tr>
<td>25</td>
<td>Side</td>
<td>Ambient</td>
</tr>
<tr>
<td>15</td>
<td>Side</td>
<td>49°C</td>
</tr>
<tr>
<td>20</td>
<td>Side</td>
<td>49°C</td>
</tr>
<tr>
<td>25</td>
<td>Side</td>
<td>49°C</td>
</tr>
</tbody>
</table>

- Single cell tests in the above matrix were completed
- Additional tests performed as determined
Single Cell Results

- 20W heater located on the side of the cell chosen for battery level testing due to combination of highest consistent TR onset temperature and time to TR.

- Trial runs showed TR for 20W heater achieved after:
  - ~5.7-6.5 minutes for heaters on the side of cell (ambient)
  - ~8.5 minutes for heaters on the bottom of cell (ambient)

- TR onset temperature was not sensitive to the environment temperature (ambient or 49°C).
Single Cell Data for Trigger Cell with 20W Heater
(located on side, ambient temp)

- Jacket Temp
- Block Temp
- Clamp Temp
- Pos Term Temp
- Air Temp

All temps steady state @ ~ 30°C

06:34 - Thermal runaway @ 204°C cell jacket temp

03:58 - Vent with electrolyte @ 155°C cell jacket temp

Max cell jacket temp = ~ 684°C

Max positive terminal temp = ~ 532°C

Max clamp temp = ~ 178°C

Max air temp = ~ 38°C

Max block temp = 41°C
20W Heater Cell-Level Thermal Runaway Test

Before

During

After
Battery–Level TR Testing

- Two battery-level tests are complete
- Both tests at trigger cell position #1 (corner; 4S bundle)
  - Test #1: 20W heater – pathfinder test
- Flight–like configuration
  - Electrical and mechanical replication
  - No interface plate
  - PTC and diode safety devices installed
  - Ambient temperature and pressure

Gauge Board

Trigger cell position #1
Results of Test #1 – 20W Heater

SAFER Battery Thermal Runaway Test
Battery-Level Trigger Cell Test #1 (20W @ Ambient)

Elapsed Time (mm:ss.s)

Temperature, °C
Results of Test #1 – 20W Heater (zoomed in)
Results of Test #1 – 20W Heater

SAFER Battery Thermal Runaway Test
Battery-Level Trigger Cell Test #1 (20W @ Ambient)

Voltage (volts)

Temperature, °C

Elapsed Time (mm.ss.s)

4S1 bundle short @ 07:31

4S2/S3 bundle short @ 13:20
20W Heater Battery-Level Thermal Runaway Test

Before  

During

After
## 20W Heater Battery-Level Forensics

### Battery Test #1 – 20W

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Trigger Cell TR</th>
<th>4S Bundle(s) TR &amp; Propagation</th>
<th>Capacity Gauge Board</th>
<th>10S Bundle(s) TR &amp; Propagation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Yes</td>
<td>Yes</td>
<td>Melted/Burned</td>
<td>No</td>
</tr>
</tbody>
</table>

- 10S bundles discharged and shorted
20W Heater - Battery Results Summary

• Pathfinder test

• TR propagation in 4S bundles resulted from battery level test with 20W heater in trigger cell position #1

• Adjacent cells heated up significantly prior to trigger cell going into TR

• No propagation to 10S bundle side of battery
  – 10S bundles discharged and shorted, but no TR or propagation

• TR propagation results inconclusive since significant heating of adjacent cells may have biased test results
  – Occurrence of TR in these cells may have been due to a combination of their cell temperature and propagation, rather than due only to propagation,
  – This may be a legitimate failure mechanism, but is not the mechanism we were attempting to simulate

• Test plan adjusted to consider 30W heater
SAFER Battery Thermal Runaway Test

Single Cell Data for Trigger Cell with 30W Heater
(located on side, ambient temp)

- **Jacket Temp**
- **Clamp Temp**
- **Pos Term Temp**
- **Air Temp**

- Max cell jacket temp = ~ 659°C
- Max positive terminal temp = ~ 568°C
- Max clamp temp = ~ 178°C
- Max air temp = ~ 39°C

03:40 - Thermal runaway @ 164°C cell jacket temp
02:28 - Vent with electrolyte @ 122°C cell jacket temp

All temps steady state @ ~ 30°C
Battery–Level TR Testing

- Two battery-level tests complete
- Both at trigger cell position #1 (corner; 4S bundle)
  - Test #1: 20 W heater – pathfinder test
  - **Test #2: 30 W heater**
- Flight–like configuration
  - Electrical and mechanical replication
  - No interface plate
  - PTC and diode safety devices installed
  - Ambient temperature and pressure

Gauge Board
- TR Trigger Cell #1
- TC Location
- TC Location (outside the chassis)
Results of Test #2 – 30W Heater

SAFER Battery Thermal Runaway Test
Battery-Level Trigger Cell Test #2 (30W @ Ambient)
Results of Test #2 – 30W Heater (zoomed in)
Results of Test #2 – 30W Heater

SAFER Battery Thermal Runaway Test
Battery-Level Trigger Cell Test #2 (30W @ Ambient)

Voltage (V)

Temperature (°C)

Elapsed Time (min.ss.ss)

4S1 bundle discharge @ 2:50
4S1 bundle short @ 3:05
4S2/53 bundle short @ 6:25

Trigger Cell Top (Heater)
30W Heater Battery-Level Thermal Runaway Test

Before

During

After
### 30W Heater - Battery-Level Forensics

**Battery Test #2 – 30W**

![Image of battery test setup]

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Trigger Cell TR</th>
<th>4S Bundle(s) TR &amp; Propagation</th>
<th>Capacity Gauge Board</th>
<th>10S Bundle(s) TR &amp; Propagation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Yes</td>
<td>Yes</td>
<td>Melted/Burned</td>
<td>No</td>
</tr>
<tr>
<td>2</td>
<td>Yes</td>
<td>Yes</td>
<td>Melted/Burned</td>
<td>No</td>
</tr>
</tbody>
</table>
30W Heater Battery-Level Results Summary

• TR propagation in 4S bundles resulted from battery level test with 30W heater in trigger cell position #1

• Adjacent cells again heated up prior to trigger cell TR, but to a much lesser extent than for the 20W test
  – TR achieved ~04:50 (mm:ss) faster than 20W battery test

• No TR propagation to 10S bundle side of battery

• Go to 35W heater?
  • Physical/mechanical limits for heater size under investigation
  • 35W may be highest feasible heater power for patch heaters for this cell.
  • As needed, determine other options to obtain the desired data
Summary

• External short circuit and thermal runaway tests were conducted to assess risk of propagation of a catastrophic cell failure in the SAFER jetpack battery

• Thermal runaway tests resulted in propagation to neighboring cells, however this may have been an overtest or “false positive”

• Tests to be repeated with 35W heater to determine if a higher heater power will eliminate biasing of neighboring cells prior to TR in the trigger cell

• Interface plate for true flight configuration may be used to provide a more flight-like oxygen source test environment

• Mass simulators will be used in place of 10S bundles to conserve test assets

• Additional tests as required to be determined
Future Work

• Determine optimum heater power
  – Address heater size limitations. Conduct additional trigger cells tests on the single cell, bundle and battery level to complete TR characterization

• Add interface plate to better replicate flight-like configuration and determine effect of oxygen availability on TR severity

• Understand 4S bundle discharging event during TR. Significant?

• Thermal vacuum testing may be performed to reproduce worst-case operational environments

• Heat-to-vent testing to characterize thermal signature of cell using an accelerating rate calorimeter may be performed if additional data is required

• Summarize findings and report
Acknowledgements

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Thanks for your attention!