Battery Safety Science Webinar Series
Advancing safer energy storage through science

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Understanding and mitigating the risks of thermal runaway in Li-ion batteries

Host
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Contents

1. Understand what causes the spectrum of risks
2. Design testing conditions to intentionally induce the 'high-risk' failures
3. Quantify the risks
4. Modelling and pack design
5. An open source database
High-risk failure mechanisms

Bursting: Top
Bursting: Bottom

Breach: Top
Breach: Side
Breach: Bot

Hazardous flare stemming from breach

Most challenging failure mechanism to handle

Image courtesy of E. Darcy (NASA)

18650 cells
LG 18650-S3 imaged at 10 fps
Characterizing thermal runaway

Using an internal short circuiting device to visualize initiation and propagation of thermal runaway

Key Insights:
- Thermal runaway spreads fastest in azimuthal and longitudinal direction
- Forms a cylindrical fluidized ‘reaction zone’

2000 fps

Characterizing breaching mechanism

**Cause of breach**

- Reacting material fluidizes and flows towards the top vent
- Material deflects off the spin-groove, causing thermal stress
- The spin-groove melts leading to a breach and escape of hot material

**Cell type:** Li-ion 18650  
**Capacity:** 3.4 Ah  
**State of Charge:** 100% (4.2 V)  
**Bottom vent:** Yes  
**Wall thickness:** 220 μm  
**Orientation of cell:** Positive end up  
**Location of ISCD radially:** 6 winds in  
**Location of ISCD longitudinally:** Top  
**Side of ISCD in image:** Right  

**Location of FOV longitudinally:** Top  
**Frame rate:** 2000 Hz  
**Frame dimension (Hor x Ver):** 1822 x 1140 pixels  
**Pixel size:** 10 μm
Characterizing breaching mechanism

Bursting: Top
20,272 fps

• Rupture and ejection caused by vent clogging
• Cell required minimum of 2 mm to extend and eject – pressure-induced breach may otherwise occur
• Bottom vent is expected to help eliminate the major shift of electrode assembly

Panasonic NCR18650B

Bursting: Top

Cap
PTC
Bursting disk
CID & support

Finegan et al. Advanced Science, 2017
Bursting process occurred in four stages:

- **Stage 1** involved a minor shift of the electrode assembly towards the vent.
- **Stage 2** involved the spin groove straightening out. This stage appeared to result from the build-up of gas beneath the crimp components.
- **Stage 3** involved a major shift the electrode assembly and cylindrical mandrel towards the vent, thereafter exerting force on the crimp components.
- **Stage 4** involved the final step of the top fold straightening out as a result of the force exerted by the electrode assembly, releasing the cell header.

The bursting process of LG and Sanyo cells followed the same four stages.

**Breaching process stages:**

- **Stage 1** reacting material fluidizes and deflects off obstacles upon ejection
- **Stage 2** The obstacles incur high thermal stress and a breach starts to form
- **Stage 3** The flow of ejecting material then passes through the breach

**Key Findings**

To help avoid bursting

- Alternative vent for pressure relief required to prevent Stage 3

To help avoid breach

- Improve the heat dissipation or thermal resistance at vulnerable locations via e.g., different alloys or thicker casings
Nail penetration
Nail penetration: Internal dynamics and propagation of thermal runaway

Key findings:
- Propagation is slower than other types of failure – possibly due to softer shorting mechanisms
- The nail pins the electrode assembly reducing the risk of clogging and the cell bursting
- The nail introduces a heat sink to the shorting region and provides an additional escape path

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Selective Positioning of the ISC Device

- 18650 cells were manufactured with the ISC device placed at 3 different longitudinal locations

Internal short-circuiting device

- Exposed Al current collector
- Copper pad
- Copper puck
- Separator
- Wax layer
- Aluminium pad

ISC at bottom
ISC at top
ISC at midway
ISC at 6 layers in
**Risk map**

From a study of 200 cells, the propensity of cell to undergo certain failure mechanisms, under certain conditions, was mapped.

<table>
<thead>
<tr>
<th>ISC Position</th>
<th>Design</th>
<th>Total</th>
<th>Bursting</th>
<th>Breach</th>
<th>Contained</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Top</td>
<td>Bot</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Top</td>
<td>Side</td>
<td>Bot</td>
</tr>
<tr>
<td>Top</td>
<td>220 µm, BV</td>
<td>45</td>
<td>0.00</td>
<td>1.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Mid</td>
<td>220 µm, BV</td>
<td>46</td>
<td>0.02</td>
<td>0.00</td>
<td>0.07</td>
</tr>
<tr>
<td>Bot</td>
<td>250 µm, NBV</td>
<td>43</td>
<td>0.00</td>
<td>0.00</td>
<td>0.07</td>
</tr>
</tbody>
</table>

The number in each box represents the fraction of cells of that particular design, to undergo a particular failure mechanism.

Key findings:

1. Proximity of the ISC device to either end increases the risk of breach/bursting at that end.
2. Thicker casings reduce the risk of bursting but have a similar risk of breaching.
3. Bottom vents reduce the risk of breaching overall, but increase the risk of bottom breaching.

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**Finegan et al., Modelling and experiments to identify high-risk failure scenarios for testing the safety of lithium-ion cells, *J. of Power Sources*, 2019**
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Fractional thermal runaway calorimeter (FTRC)

Calorimeter: Allows comparative analysis of risks between failure mechanisms
- Highlight risks associated with the spread of heat sources when cells rupture and compare to when they remain intact
- Calculate total heat output and determine the fractions of heat released through the cell casing vs. through the ejected material

Experiments took place at The European Synchrotron (ESRF), France.
- Simultaneous high-speed X-ray imaging and single cell calorimetry
  - Link internal phenomenon with external risks
  - Clarify the merits of bottom vents and thicker casing walls

X-ray transparent calorimeter for high-speed X-ray imaging
- Image courtesy of Will Walker (NASA)
Fractional thermal runaway calorimeter (FTRC)

Statistical assessment of thermal behavior

- Thermal runaway results:
  - Total heat output during thermal runaway
  - Heat release fractions (see image on right)
  - Remaining cell mass post-thermal runaway

- Observations from total heat output measurements:
  - Cells with a bottom vent (BV) produce less heat than non-bottom vent (NBV) cells
  - The standard deviation for BV cells is less than NBV cells

- Total heat output during thermal runaway
- Heat release fractions (see image on right)
- Remaining cell mass post-thermal runaway

**Molicel 18650-J**
- $\mu_{TR} = 36.6\ kJ$
- $\sigma_{TR} = 3.4\ kJ$

**Samsung 18650-30Q**
- $\mu_{TR} = 59.7\ kJ$
- $\sigma_{TR} = 3.5\ kJ$

**LG 18650-M36 (BV)**
- $\mu_{TR} = 62.2\ kJ$
- $\sigma_{TR} = 2.8\ kJ$

**LG 18650-MJ1**
- $\mu_{TR} = 75.2\ kJ$
- $\sigma_{TR} = 6.6\ kJ$

With thanks to William Walker (NASA)
Ejected and non-ejected heat output

- 3.6 Ah 18650 cells
- Location of thermal runaway initiation does not have significant impact on total heat output, but does influence the fraction of heat ejected
- Around 70% of heat is ejected, mostly through the positive vent
- Initiation near the bottom increases risk of bottom breach and heat from the bottom

Finegan et al., Modelling and experiments to identify high-risk failure scenarios for testing the safety of lithium-ion cells, *J. of Power Sources*, 2019
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The rate of propagation was determined from high-speed X-ray imaging videos of thermal runaway initiation.

The highest external temperatures were observed for when initiation occurred near the ends of the cells.

Explanation:
- Heat dissipation was highest for the middle position.
- This affected the rate at which the reaction zone spread initially.

Finegan et al., Modelling and experiments to identify high-risk failure scenarios for testing the safety of lithium-ion cells, *J. of Power Sources*, 2019
The highest risk scenarios for pressure-induced breaches are when initiation of thermal runaway occurs near either end of the 18650 cell.

- Bust pressures can reach < 1.5 MPa for temperatures > 650 °C.
- If a cell produces 6 L of gas, and is clogged, the internal pressure could reach 30 MPa.

Explains increased risk of breaching occurring, but not the consistent location at spin groove.
Results guiding safe battery designs

- Single cell data applied to battery pack simulations
  - Modelling sizing of heat sinks to avoid propagation
  - Estimating temperatures of pack enclosures when subject to ejected heat
  - Spatially quantifying the distribution of heat within an enclosure following cell failure

Heat sink sizing

Enclosure (can) subject to ejected heat

Work by Chuanbo Yang (NREL)
Results guiding safe battery designs

- Space suit battery pack
- NASA X57 electric aircraft
- Orion back up power module

Eric Darcy and team at Johnson Space Center
1. Understand what causes the spectrum of risks
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Battery failure databank

- Radiography and thermal data from over 300 tests of commercial cells
  - Providing engineers and researchers with data to inform models
- Link internal phenomena with external risks
- Compare heat output and mass ejection from different abuse mechanicals
  - Nail penetration
  - Thermal abuse
  - Internal short circuiting
- Compare different models of cells
  - Power cells
  - Energy cells

DLS – Diamond Light Source
ESRF – European Synchrotron Radiation Facility
Mechanical abuse and thermal response

**Nail penetration:** How does it weigh-up when it comes to failure?

- Nail penetration-induced failures may not generate as much heat as other types of failures.
- How do internal structural dynamics compare to other types of failure?

Data gathered on 18650 cells of the same type

Different test methods produce different risk spectrums
Heat output distributions of different cell types

- Draw comparisons between commercial cells
- Understand the distribution of heat output from different cell types

(a) the normal distribution curves based on the observed thermal runaway energy release and (b) the observed residuals of the thermal runaway energy release values vs. the observed average thermal runaway energy release.

Decoupling of heat generated from ejected and non-ejected contents of 18650-format lithium-ion cells using statistical methods

William Q. Walker*1, John J. Darst2, Donal P. Finegan3, Gary A. Bayler4, Kenneth L. Johnson5, Eric C. Darcy6, Steven L. Rickman7,8
Battery failure databank

Link internal events to external risks

- Leverage the simultaneous radiography data to explain why some cells release less heat than others
  - e.g. preliminary data indicates a correlation between the amount of ejected materials and the total heat output

Radiography of three samples showing the characterization of the distribution of mass fraction ejected
Conclusions

- High-speed X-ray imaging useful for **guiding and validating thermal runaway models** for identifying internal and external hotspots.

- Highest surface temperatures and **lowest burst pressures were achieved when initiation occurred near either ends of the cell**, due to relatively poor heat dissipation.

- Each cell type has a different response during thermal runaway (heat output, ejected mass, likelihood to breach).

- The likelihood high-risk failure scenarios can be increased by **selectively locating** the point of thermal runaway initiation within a cell.

- Thermal data from the fractional thermal runaway calorimeter (FTRC) is useful for accurately modelling efficacy of heat sinks and enclosures for withstanding thermal runaway.

- An open source database of radiography and thermal data to be released over coming months.
Thank you for listening

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List of relevant publications:
1. Finegan et al., Characterising thermal runaway within lithium-ion cells by inducing and monitoring internal short circuits. *Energy & Environmental Science* 2017, 10 (6), 1377-1388.
3. Finegan et al., In-operando high-speed tomography of lithium-ion batteries during thermal runaway. *Nature Communications* 2015, 6.
5. Finegan et al., Modelling and experiments to identify high-risk failure scenarios for testing the safety of lithium-ion cells, *J. of Power Sources*, 2019
6. Walker et al. Decoupling of heat generated from ejected and non-ejected contents of 18650-format lithium-ion cells using statistical methods, *J. Power Sources*, 2019

Videos presented and more at:
https://www.youtube.com/c/DonalFinegan
Thank you.