Battery Safety Science Webinar Series

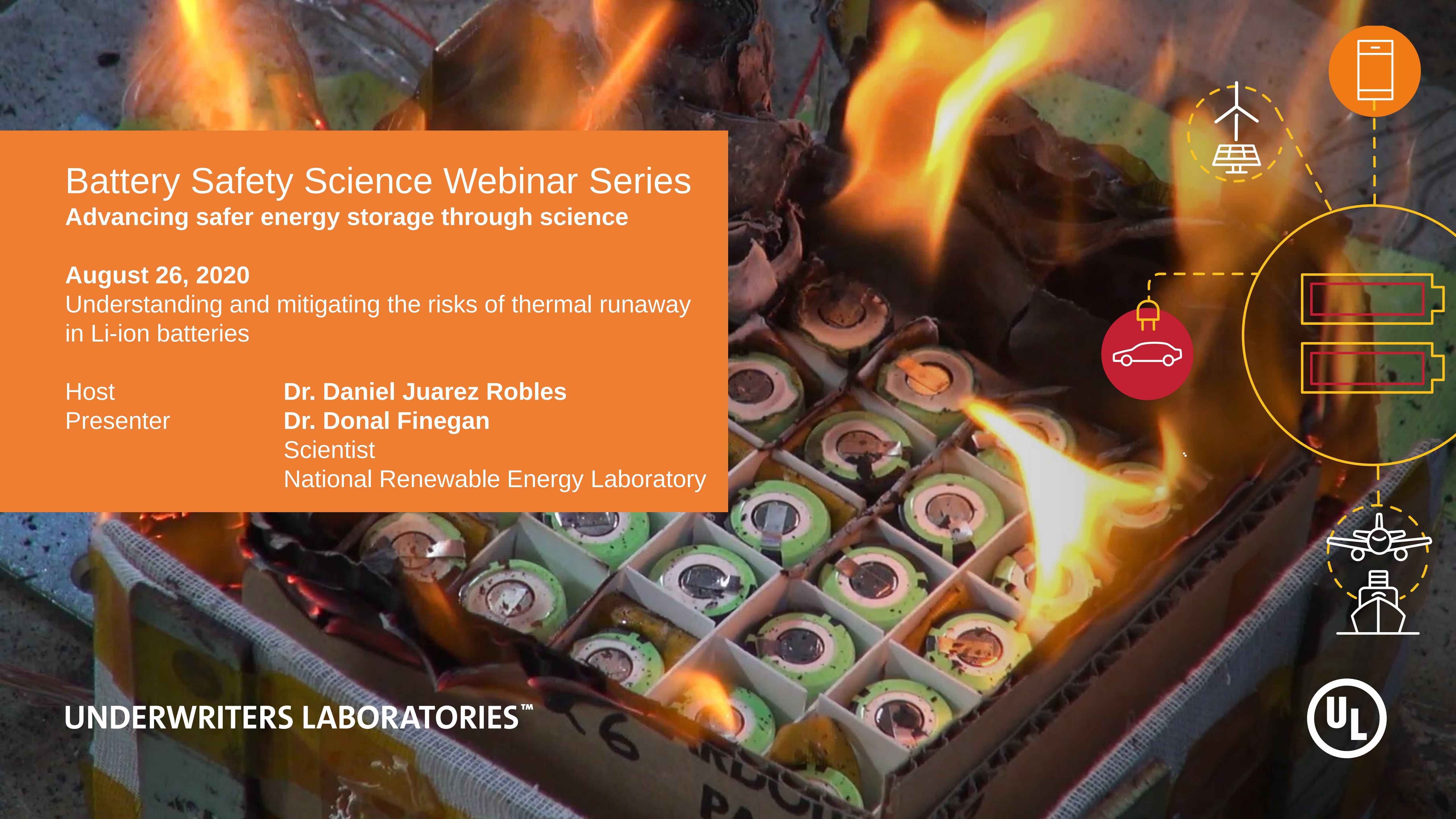
Advancing safer energy storage through science

August 26, 2020

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

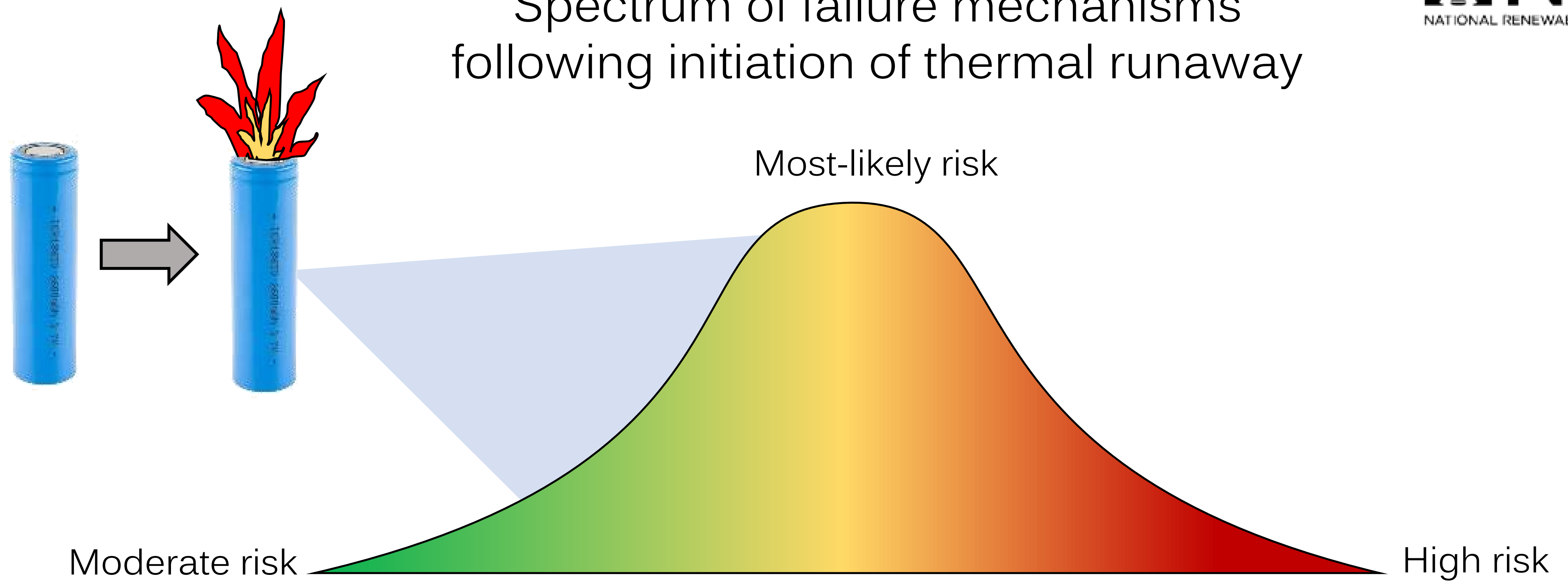
Host **Dr. Daniel Juarez Robles**

Presenter **Dr. Donal Finegan**
Scientist
National Renewable Energy Laboratory



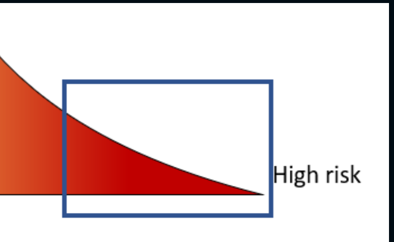
UNDERWRITERS LABORATORIES™

Spectrum of failure mechanisms following initiation of thermal runaway



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



18650 cells

High-risk failure mechanisms


Bursting: Top


Bursting: Bottom


Breach: Top


Breach: Top


Breach: Side


Breach: Side


Breach: Bot

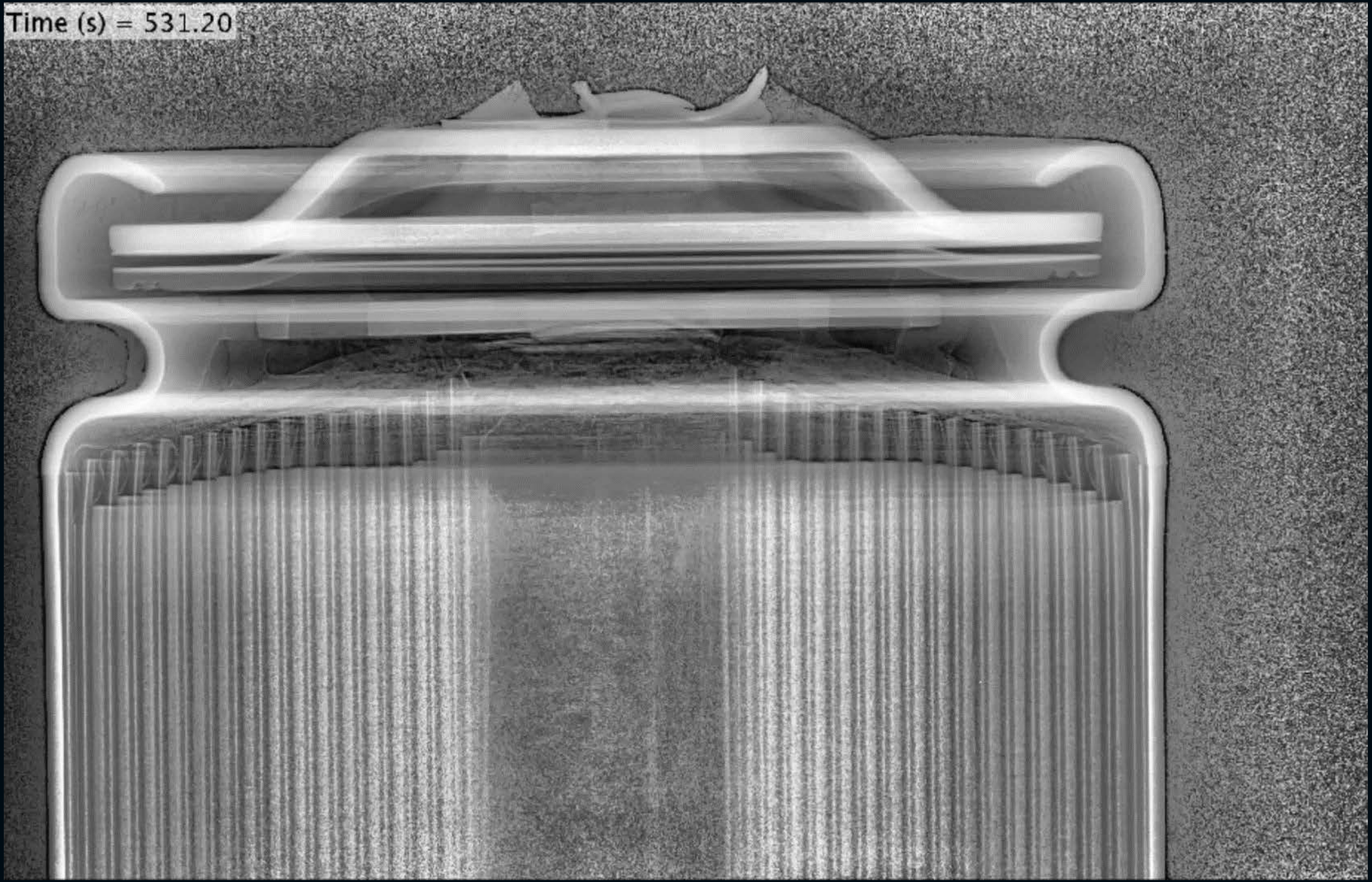

Breach: Bot

Hazardous flare stemming from breach


Image courtesy of E. Darcy (NASA)

Most challenging failure mechanism to handle

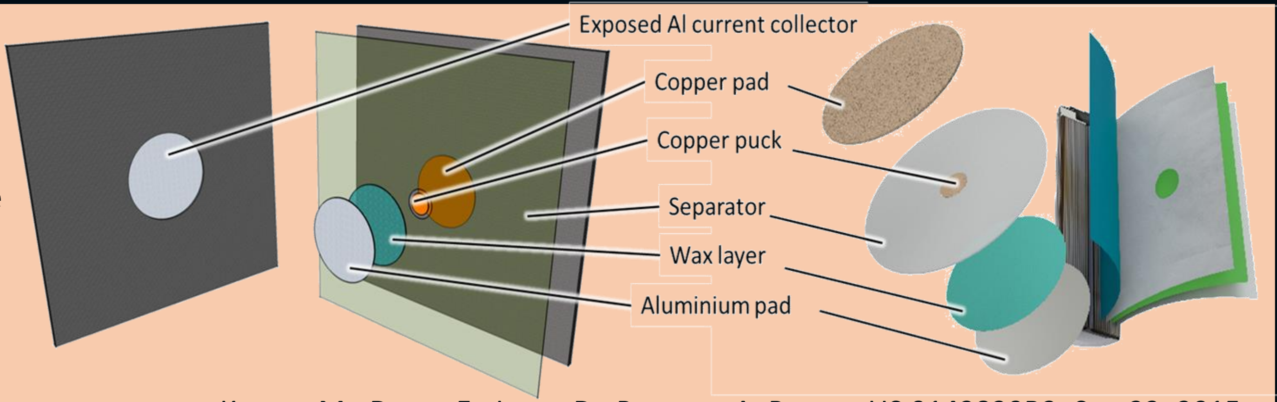
LG 18650-S3 imaged at 10 fps



VIDEO

Characterizing thermal runaway

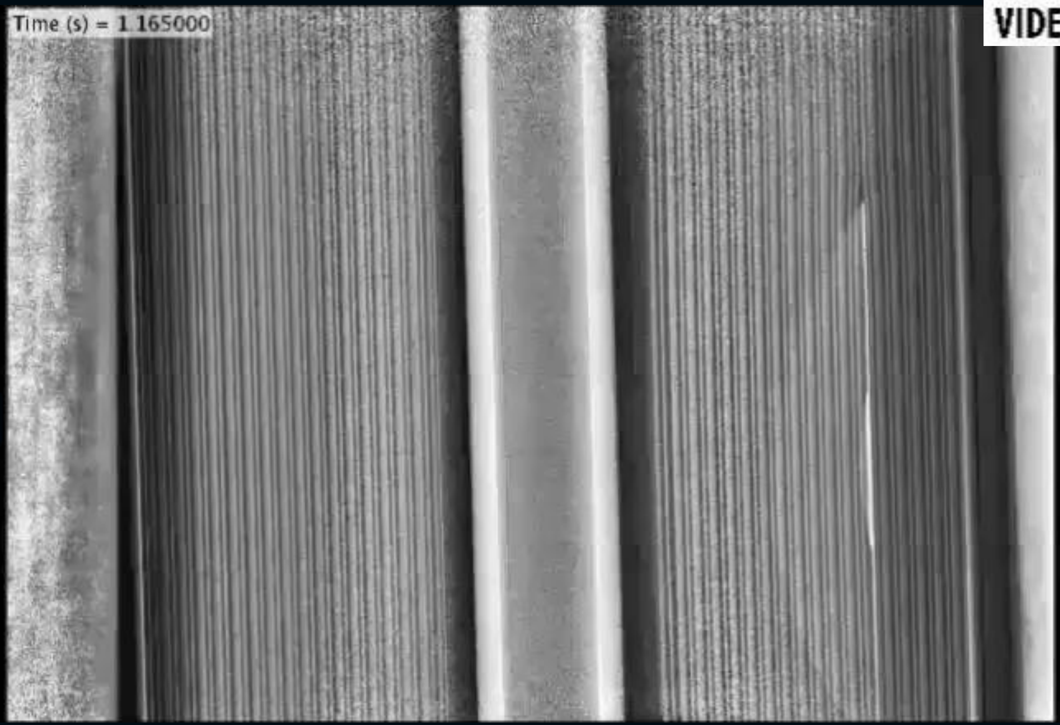
Using an internal short circuiting device to visualize initiation and propagation of thermal runaway



Keyser, M.; Darcy, E.; Long, D.; Pesaran, A. Patent, US 9142829B2, Sep 22, 2015

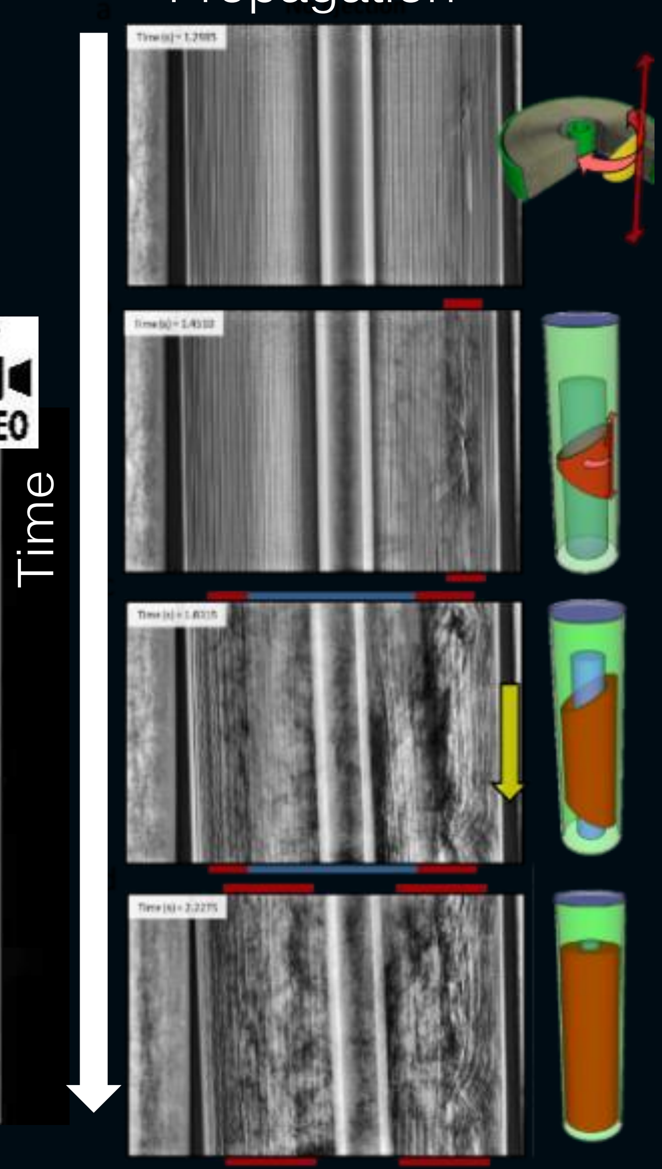
The European Synchrotron (ESRF), France

VIDEO



2000 fps

Propagation

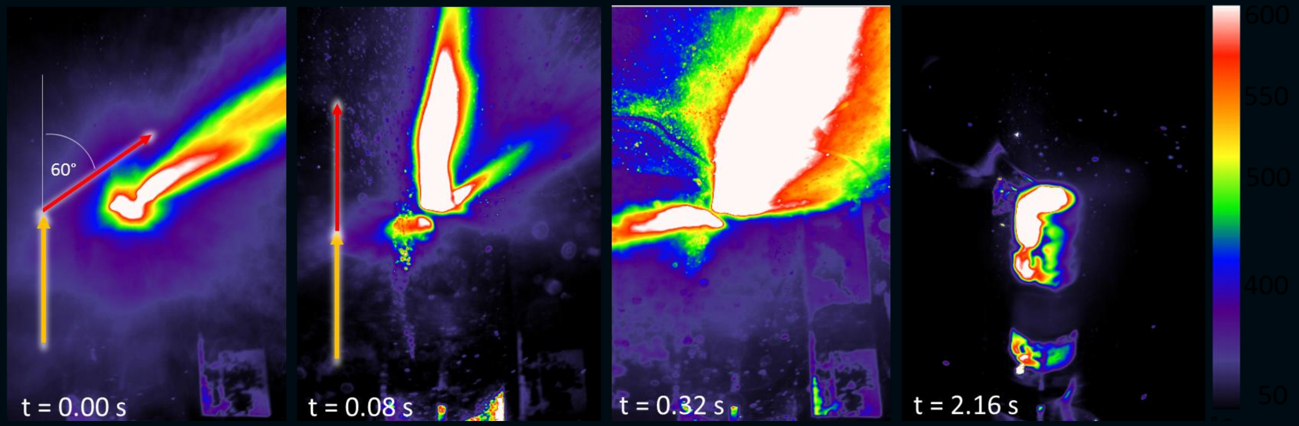


Key Insights:

- Thermal runaway spreads fastest in azimuthal and longitudinal direction
- Forms a cylindrical fluidized 'reaction zone'

Finegan et al., *Energy and Environ. Sci.* 2017, DOI: 10.1039/C7EE00385D

Characterizing breaching mechanism



Breach: Top

VIDEO

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

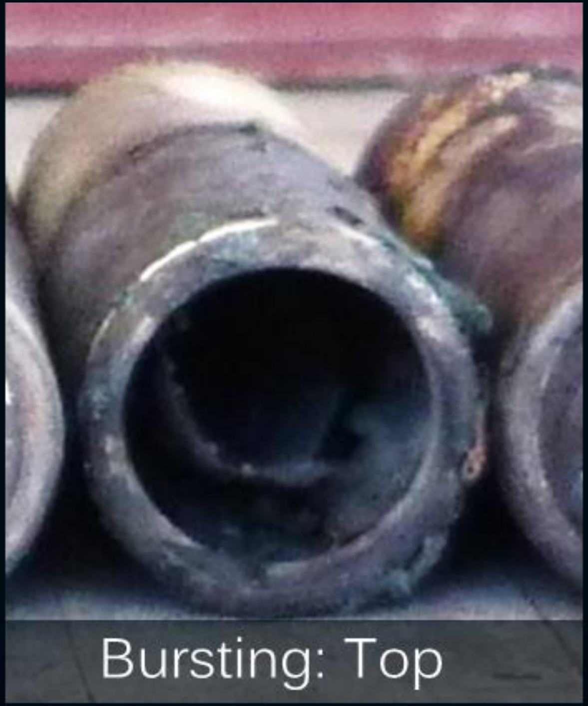
Location of FOV longitudinally: Top
Frame rate: 2000 Hz
Frame dimension (Hor x Ver): 1822 x 1140 pixels
Pixel size: 10 µm

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

Characterizing breaching mechanism

?

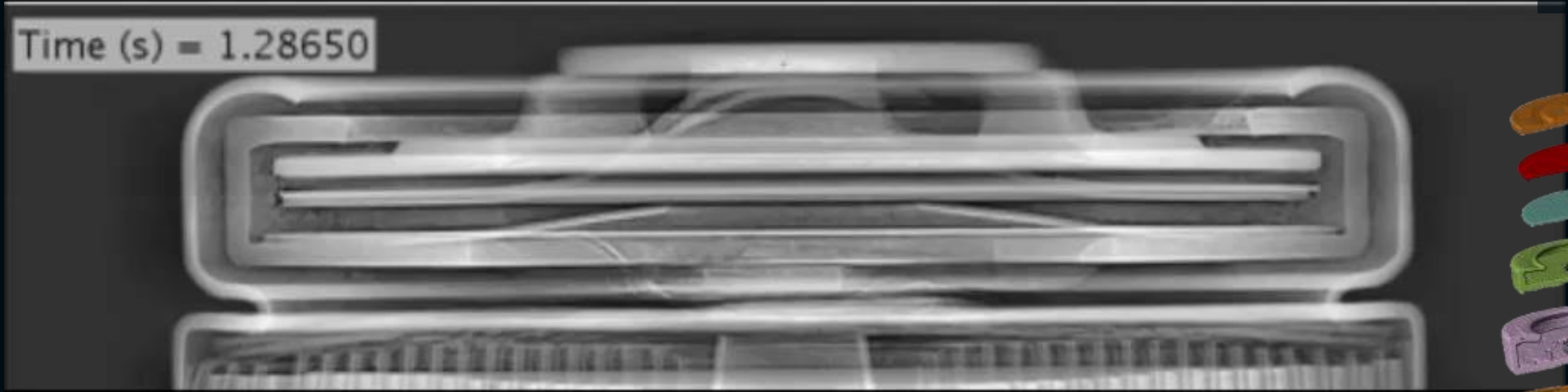


Characterizing bursting process

20,272 fps

VIDEO

Panasonic NCR18650B



Finegan *et al.* Advanced Science, 2017

- 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

Key Findings

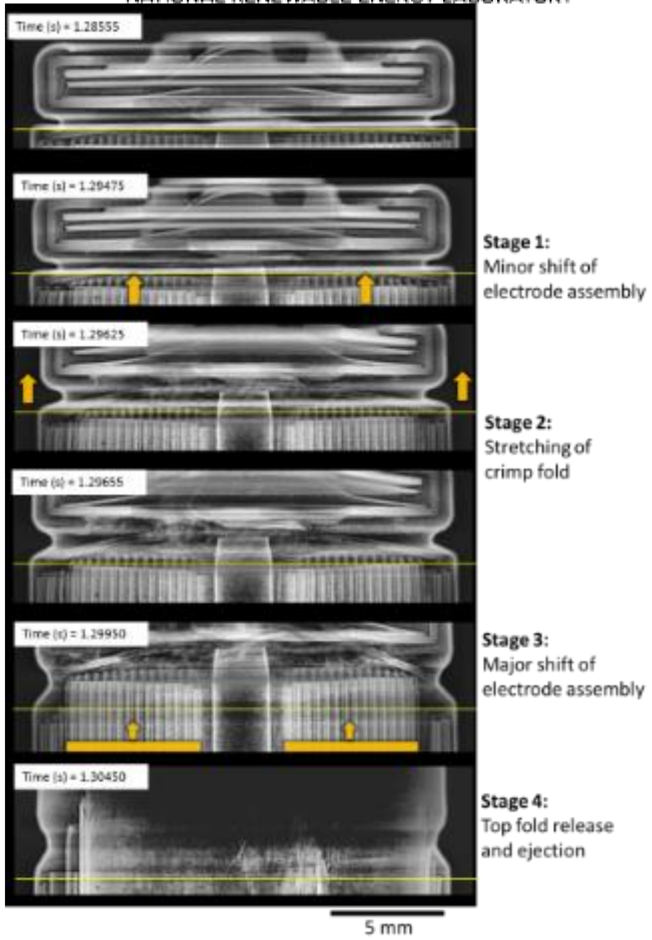
Bursting process occurred in four stages:

- **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



To help avoid bursting

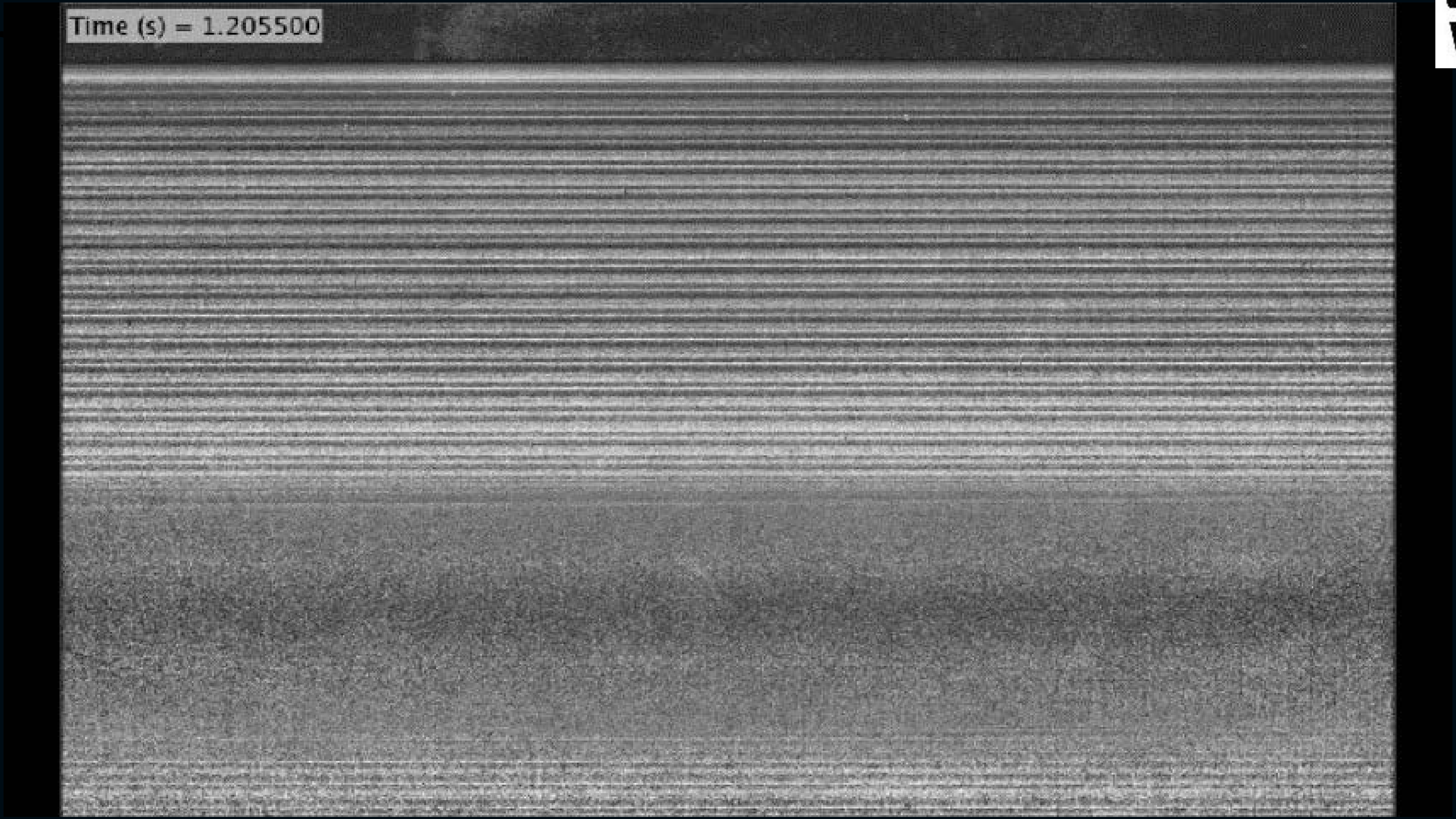
Alternative vent for pressure relief required to prevent Stage 3

To help avoid breach

Improve the heat dissipation or thermal resistance at vulnerable locations via e.g., different alloys or thicker casings

Finegan *et al.* Advanced Science, 2017,

Nail penetration

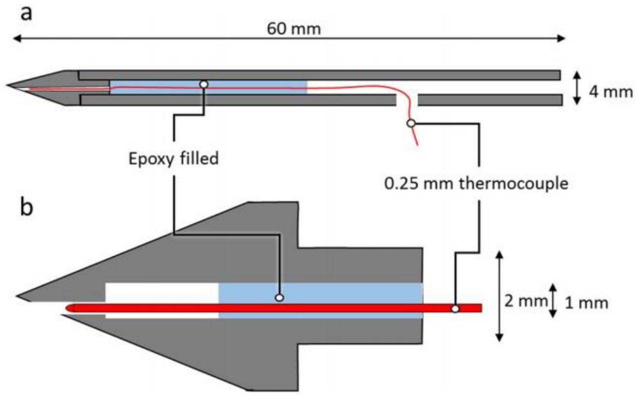


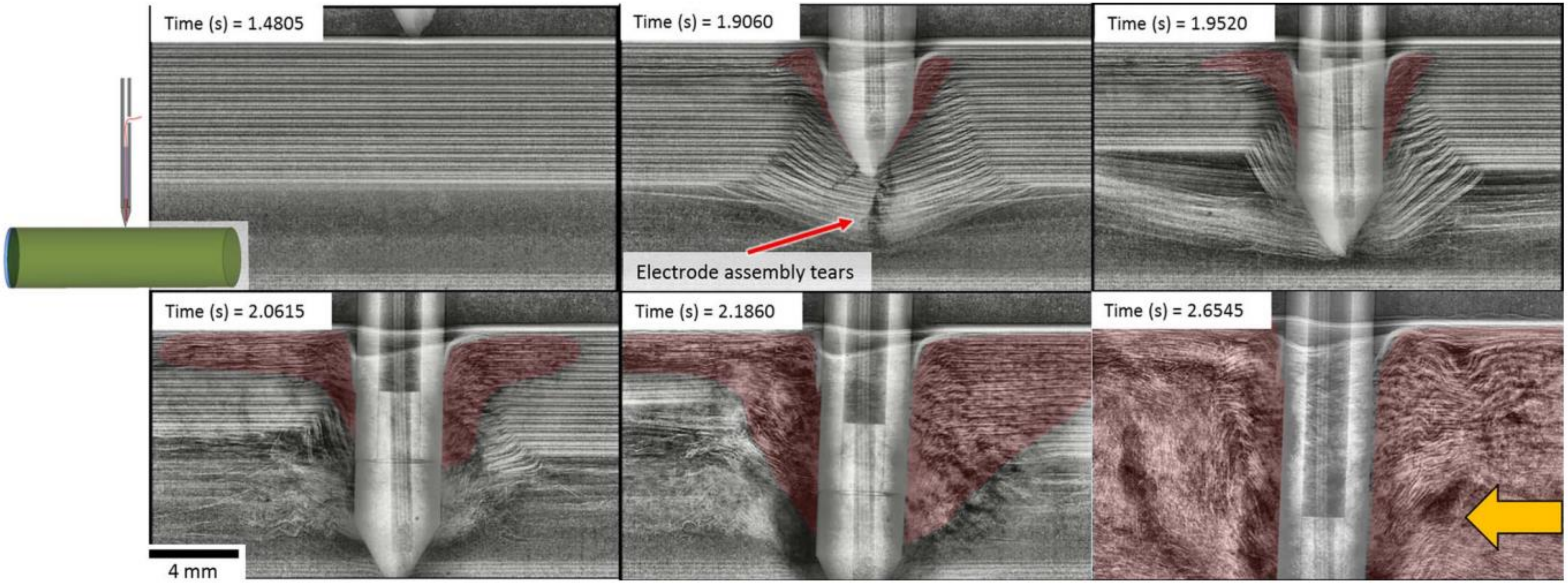
Mechanical abuse and thermal response

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





Finegan et al., Tracking Internal Temperature and Structural Dynamics during Nail Penetration of Lithium-Ion Cells. *Journal of The Electrochemical Society* **2017,** *164* (13), A3285-A3291.

Contents

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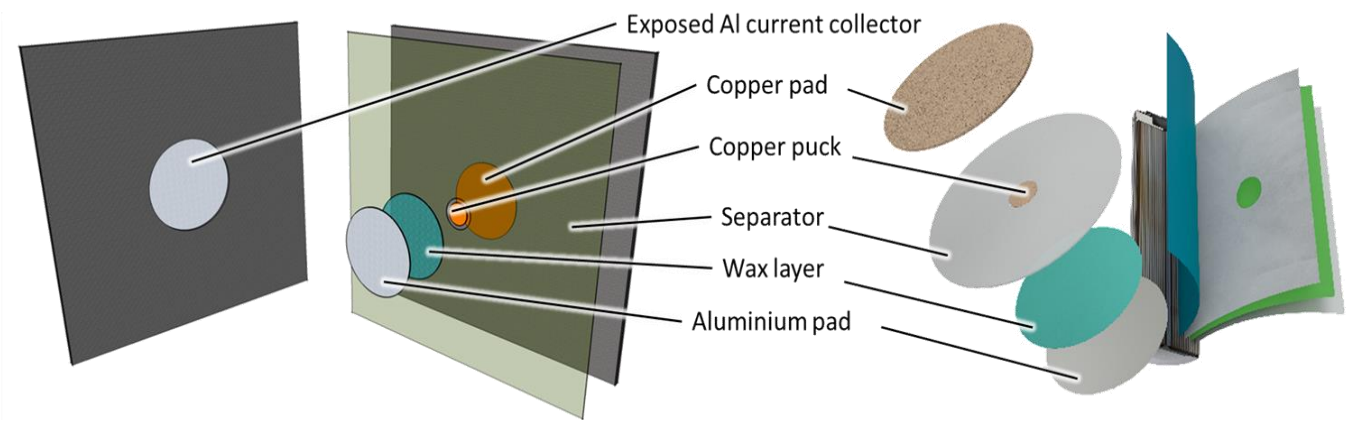
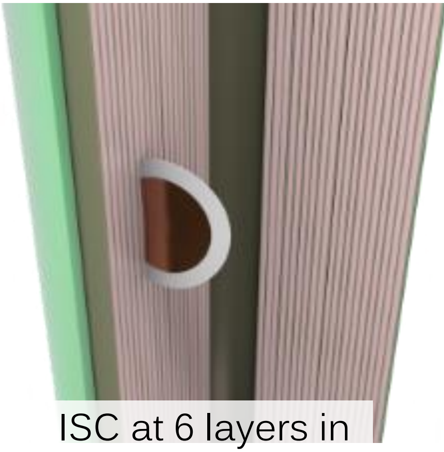
Selective Positioning of the ISC Device

Internal short-circuiting device

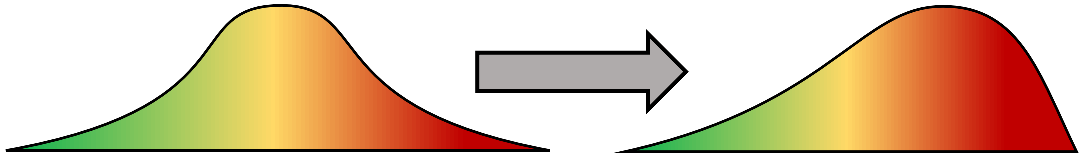
- 18650 cells were manufactured with the ISC device placed at **3 different longitudinal locations**



ISC at bottom ISC at top ISC at midway

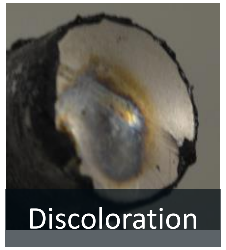


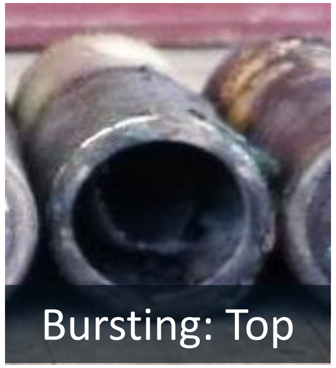
Risk map

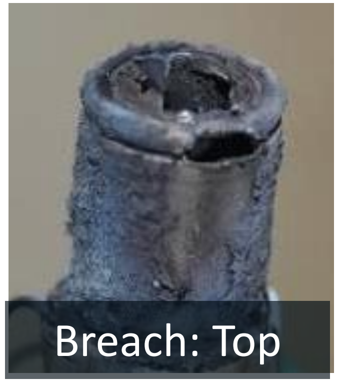


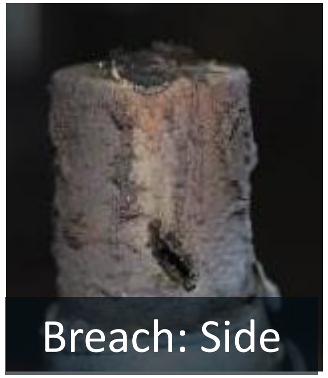
The number in each box represents the fraction of cells of that particular design, to undergo a particular failure mechanism

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

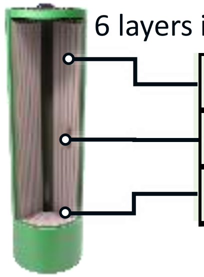


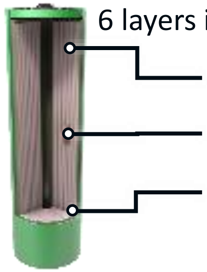






ISC Position	Design	Total	Bursting		Breach			Contained
			Top	Bot	Top	Side	Bot	
None	220 µm, BV	45	0.00	1.00	0.00	0.00	0.44	0.00
None	220 µm, NBV	46	0.02	0.00	0.07	0.02	0.16	0.98
None	250 µm, NBV	43	0.00	0.00	0.07	0.00	0.00	1.00
Top	220 µm, BV	11	0.09	0.27	0.64	0.00	0.27	0.64
Mid	220 µm, BV	13	0.08	0.54	0.08	0.00	0.62	0.38
Bot	220 µm, BV	12	0.00	1.00	0.00	0.17	1.00	0.00
Top	250 µm, NBV	9	0.00	0.00	0.56	0.00	0.00	1.00
Mid	250 µm, NBV	7	0.00	0.00	0.43	0.14	0.43	1.00
Bot	250 µm, NBV	8	0.00	0.00	0.38	0.13	0.25	1.00





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**

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.

Contents

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

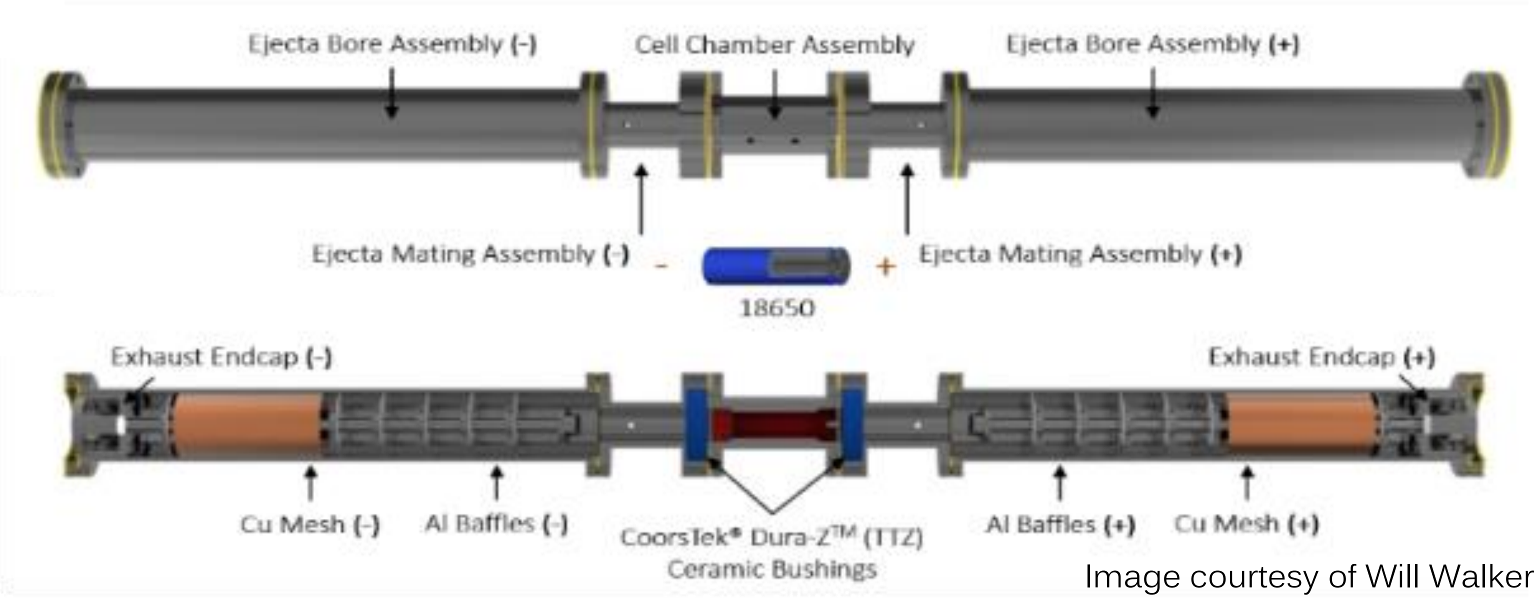
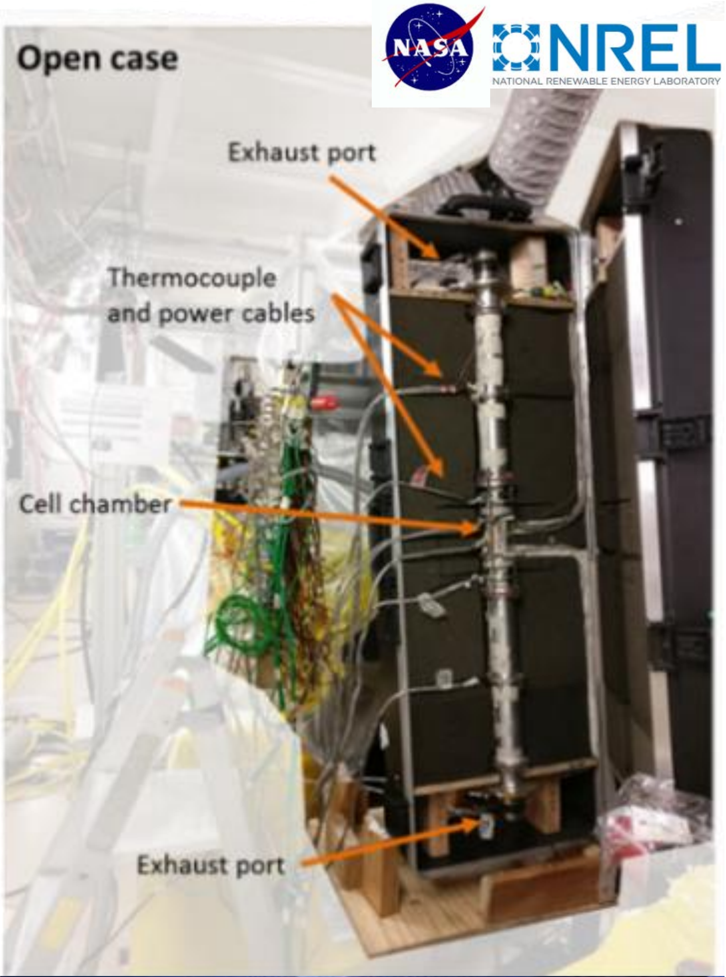


Image courtesy of Will Walker (NASA)



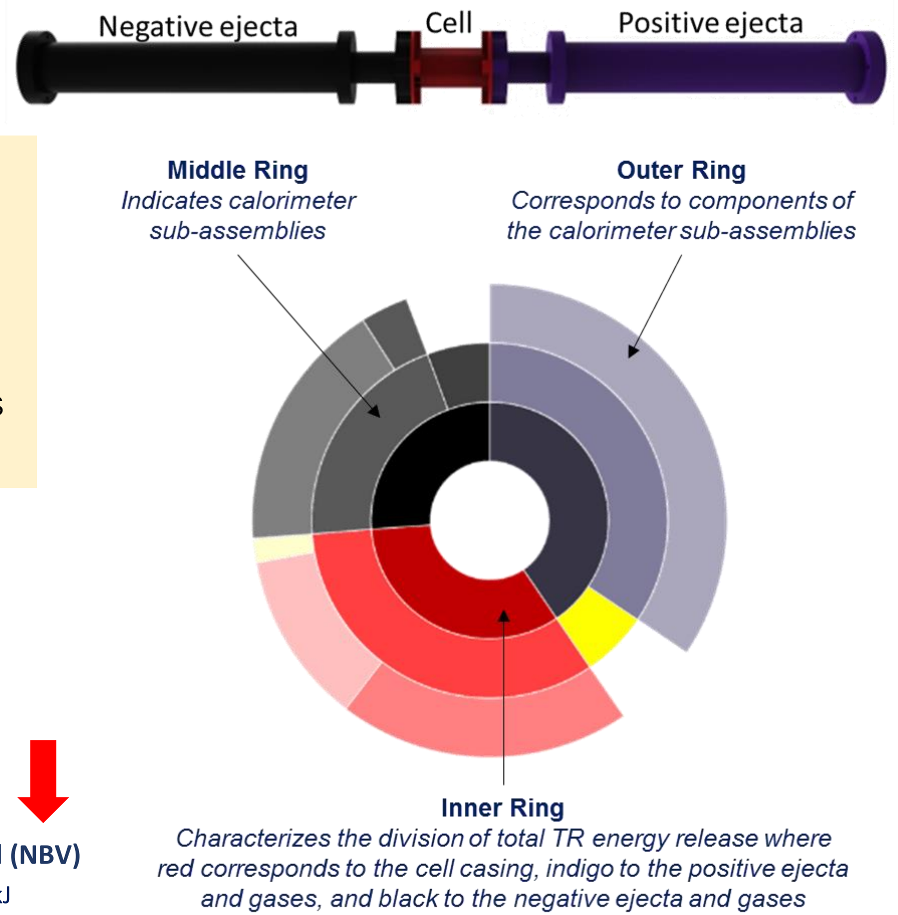
X-ray transparent calorimeter for high-speed X-ray imaging

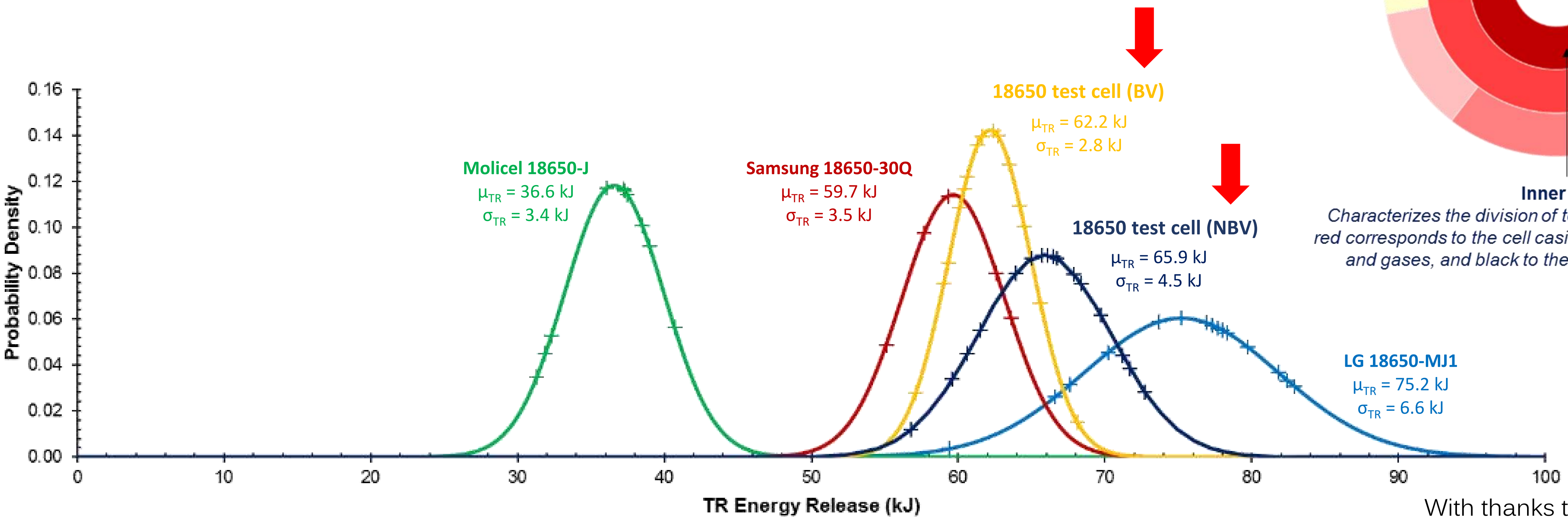
- Experiments took place at The European Synchrotron (ESRF), France.
- Simultaneous high-speed X-ray imaging and single cell calorimetry
  - **Link internal phenomenon with external risks**
  - Clarify the **merits of bottom vents and thicker casing** walls

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



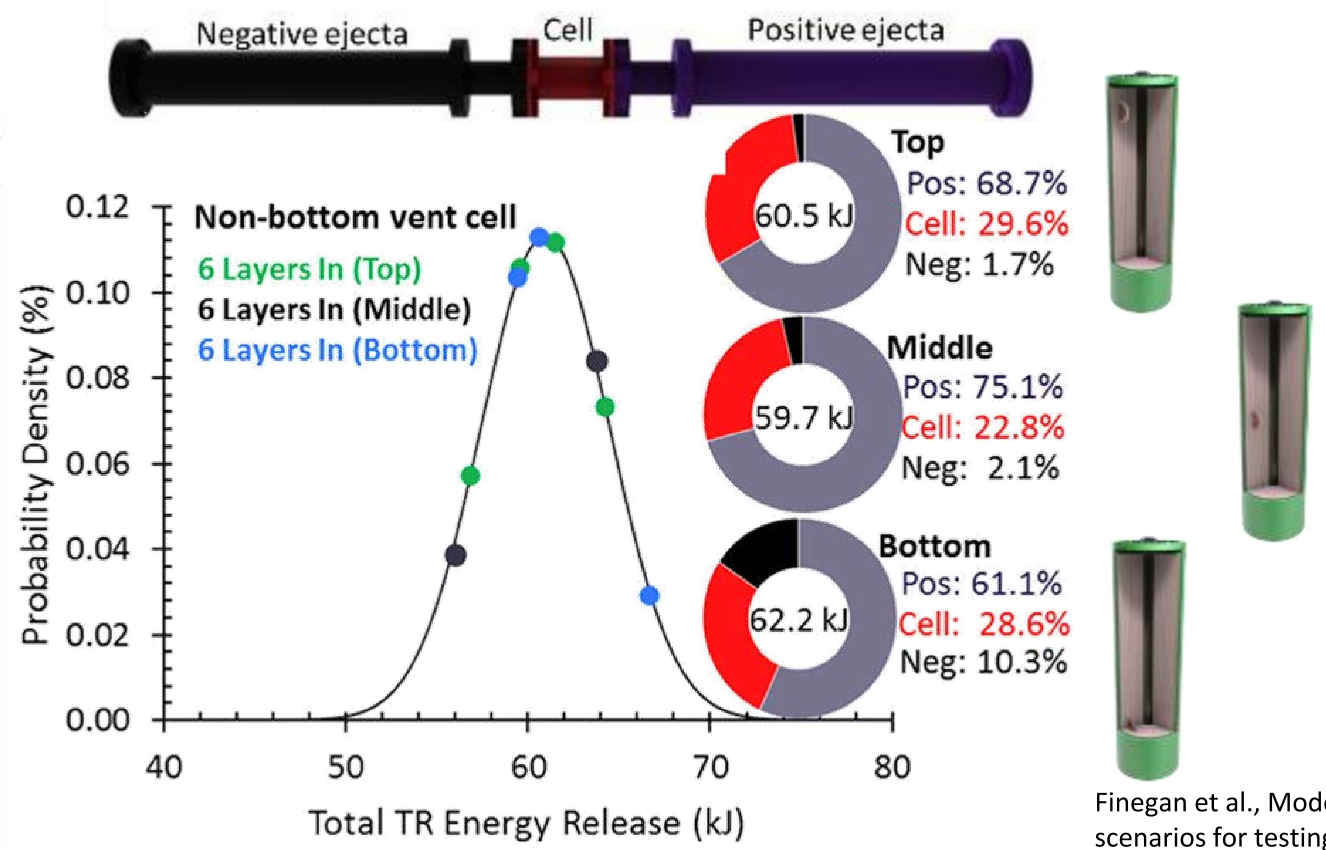


With thanks to William Walker (NASA)

Fractional thermal runaway calorimeter (FTRC)

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**

Contents

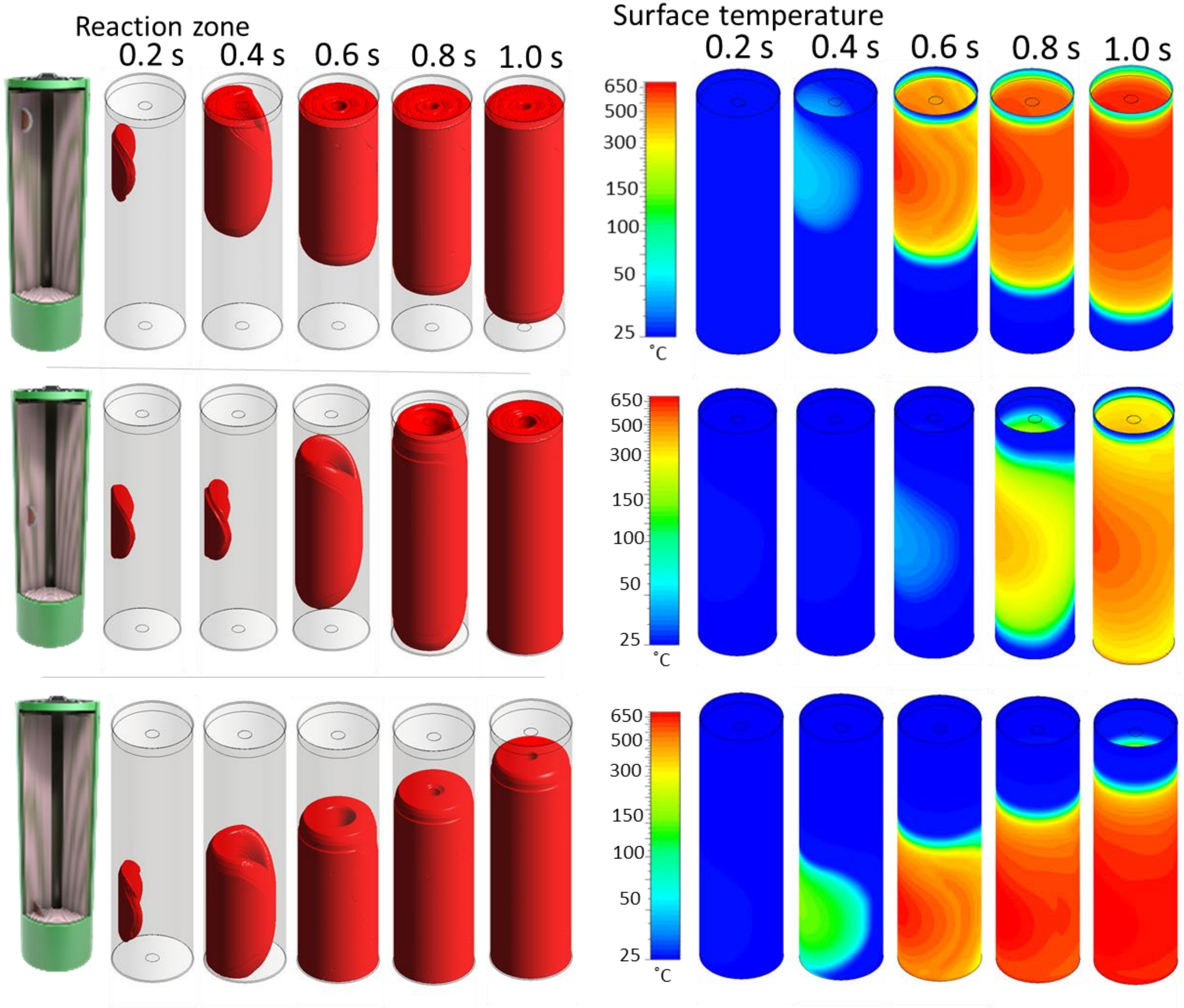
Modelling thermal runaway propagation and surface temperature

Modelling surface temperatures

- 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.



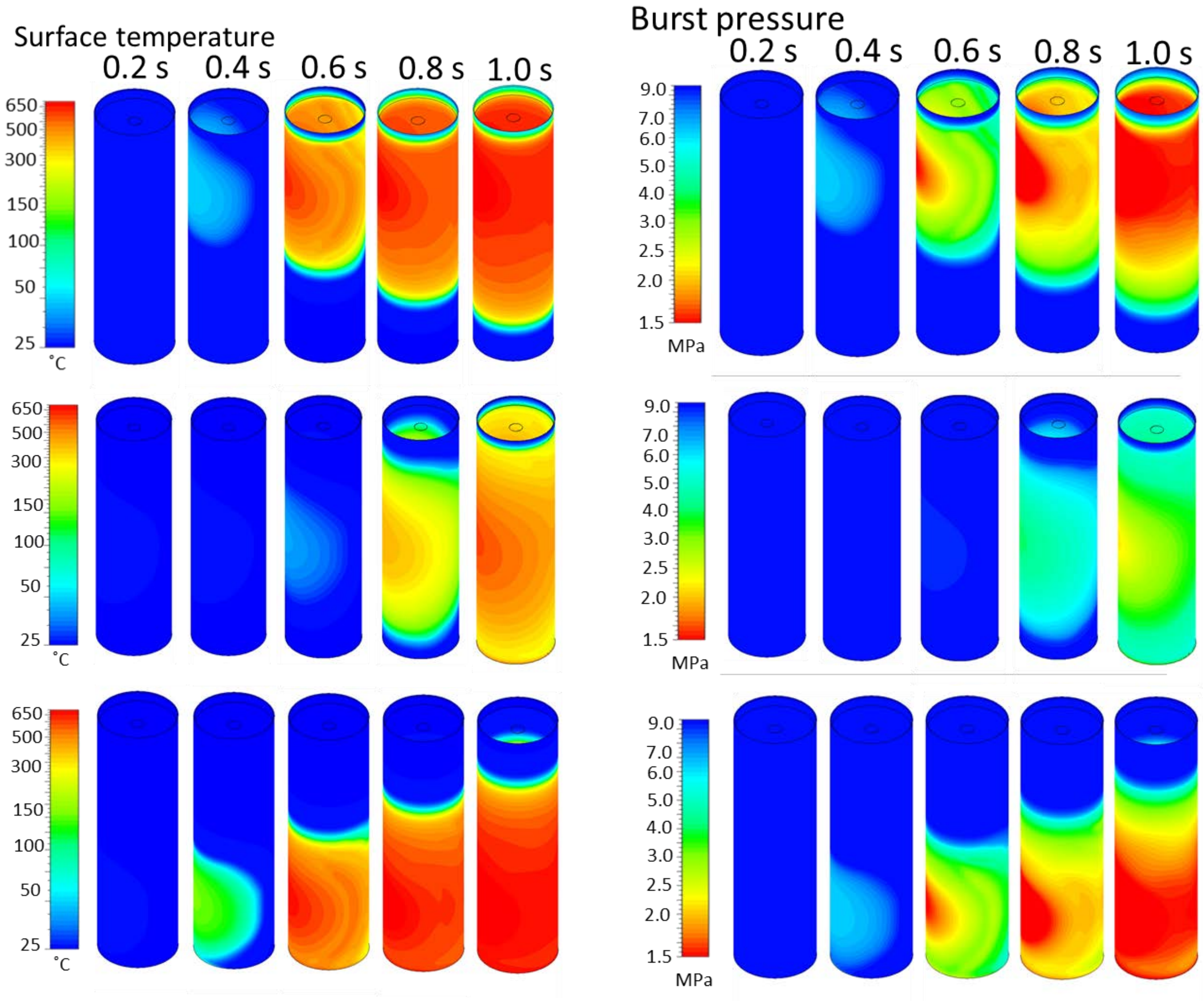
Finegan et al., Modelling and experiments to identify high-risk failure scenarios for testing the safety of lithium-ion cells, *J. of Power Sources*, **2019**

Thermal stress and bursting pressure

Surface temperature and burst pressure

- 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

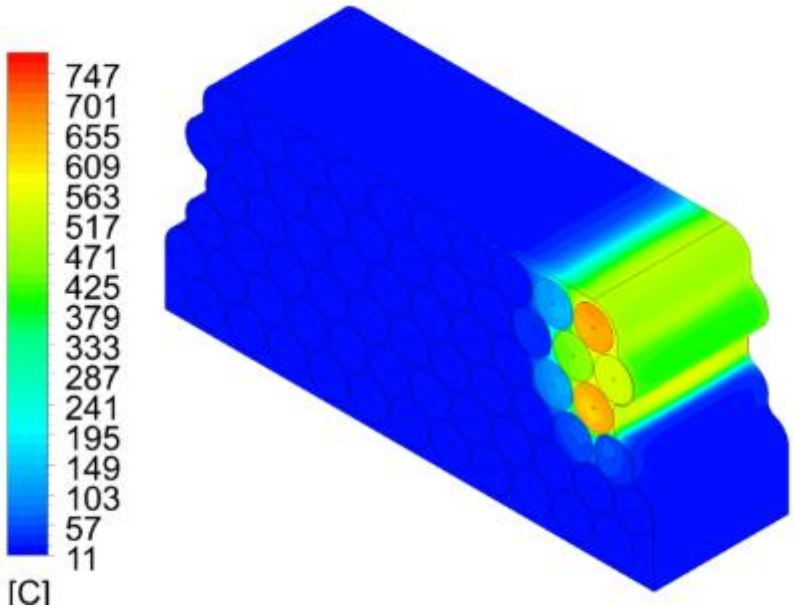


Based on tensile strength properties for S350GD mild steel

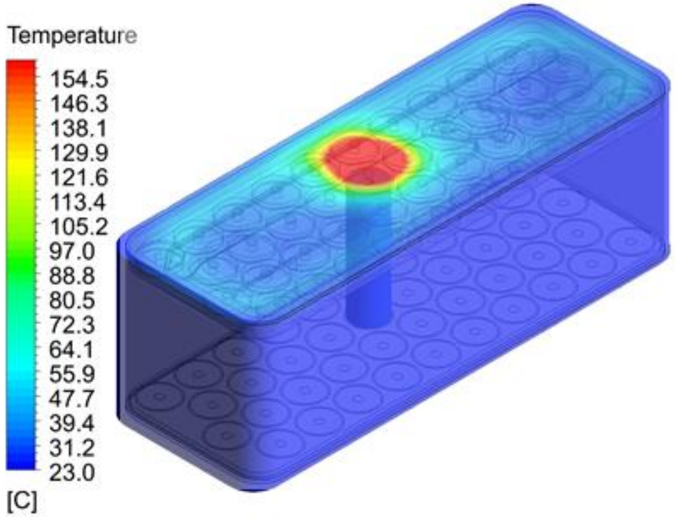
Results guiding safe battery designs

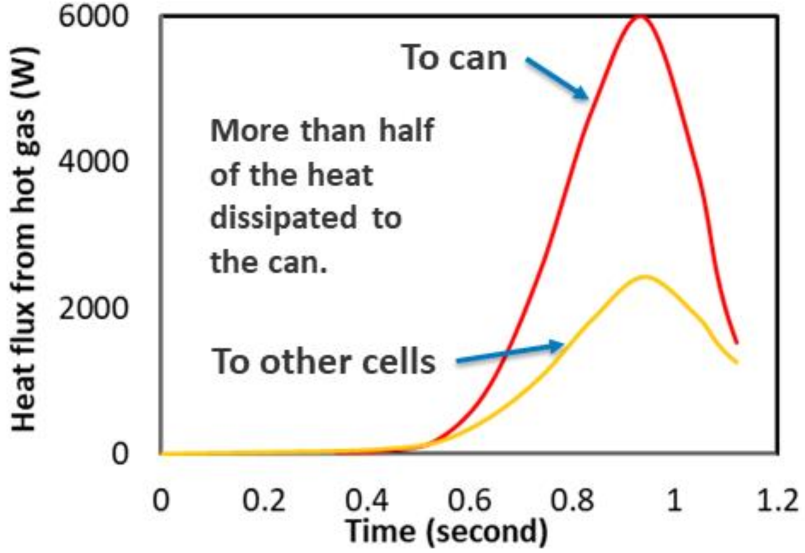
- **Single cell data applied to battery pack simulations**
  - Modelling sizing of heat sinks to avoid propagation
  - Estimating temperatures of pack enclosures when subject to ejected heat
  - Spatially quantifying the distribution of heat within an enclosure following cell failure

Heat sink sizing



Enclosure (can) subject to ejected heat





Work by Chuanbo Yang (NREL)

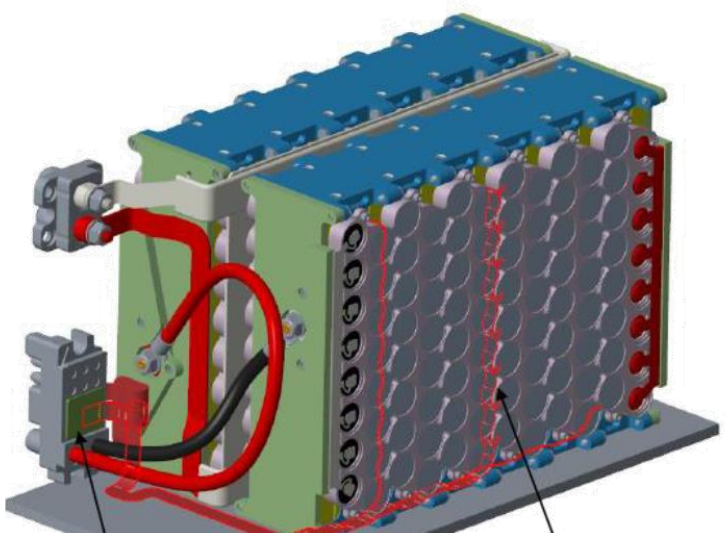
Results guiding safe battery designs

Space suit battery pack

NASA X57 electric aircraft

Eric Darcy and team at Johnson Space Center

Orion back up power module

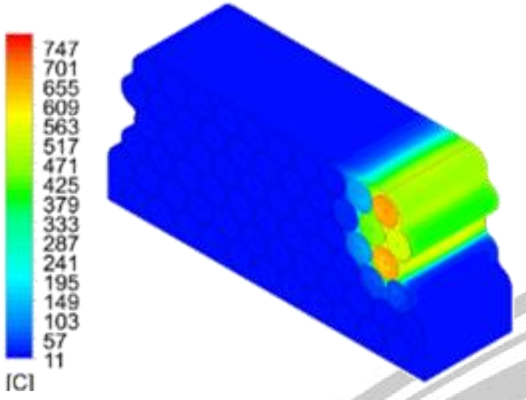


Contents

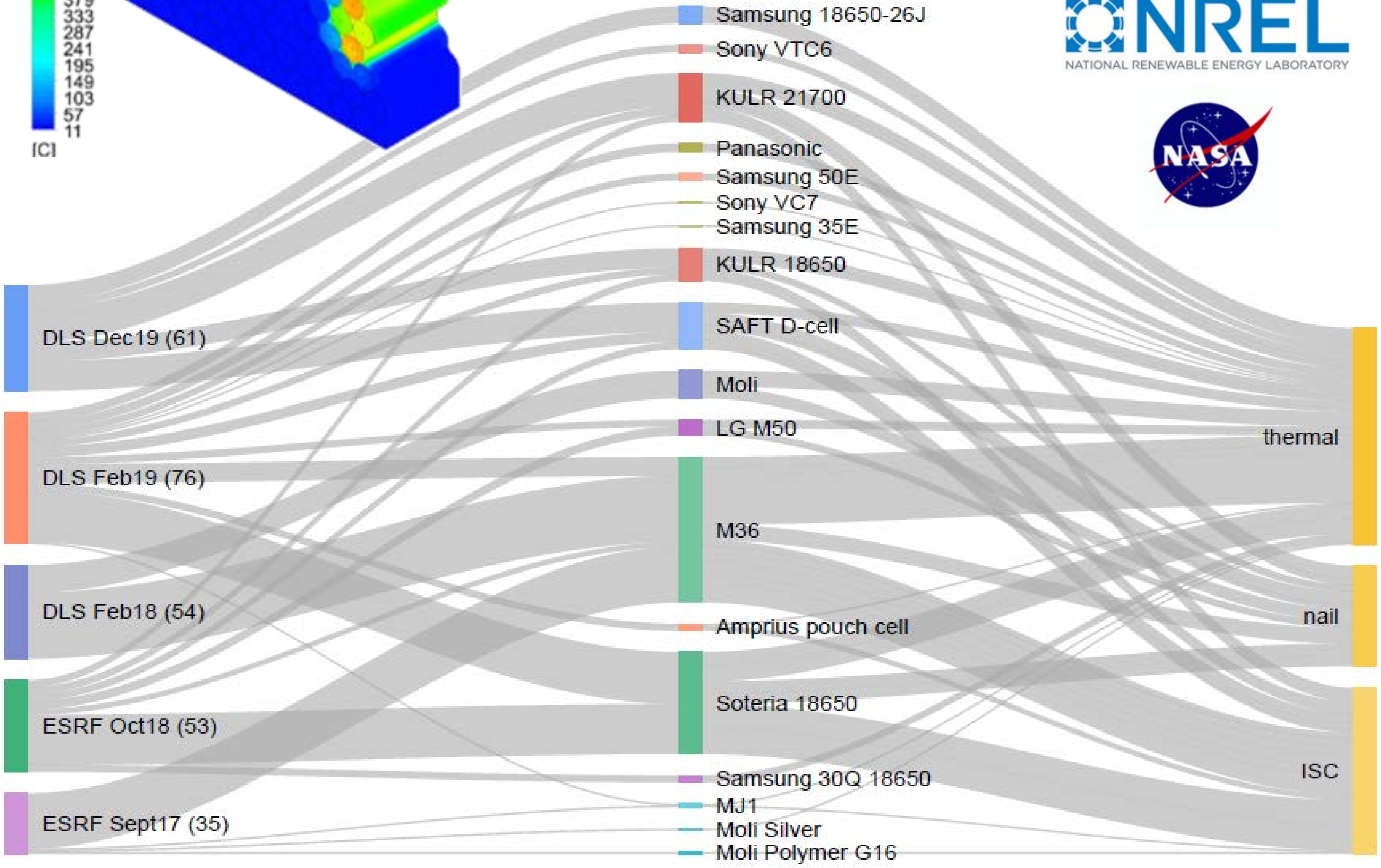
Battery failure databank

NATIONAL RENEWABLE ENERGY LABORATORY

- **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

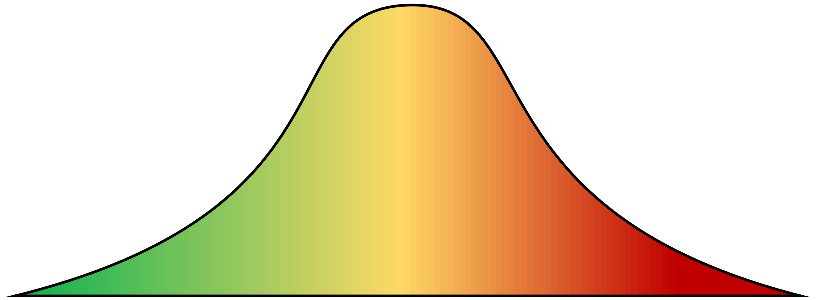


Mechanical abuse and thermal response

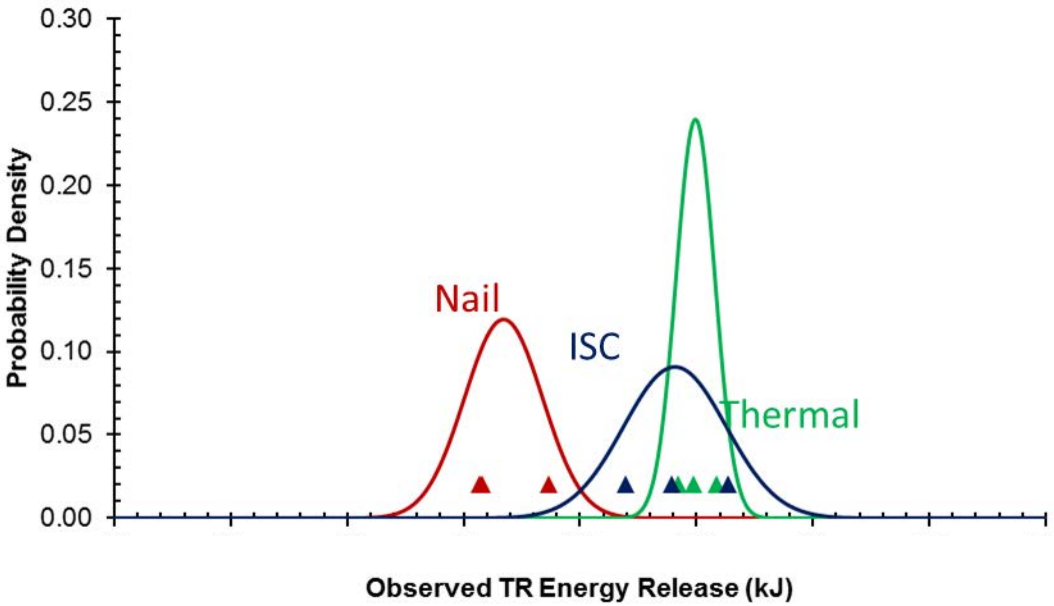
Nail penetration: How does it weigh-up when it comes to failure?

- 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?

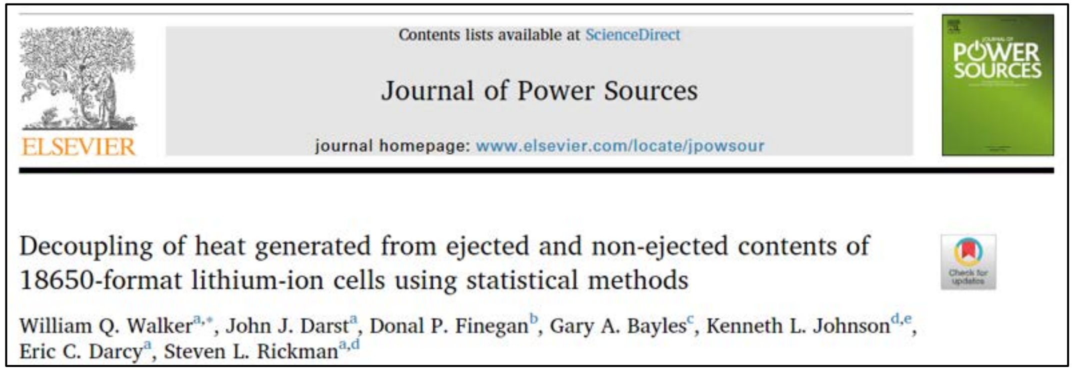
Different test methods produce different risk spectrums



Data gathered on 18650 cells of the same type



Battery failure databank


Contents lists available at ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

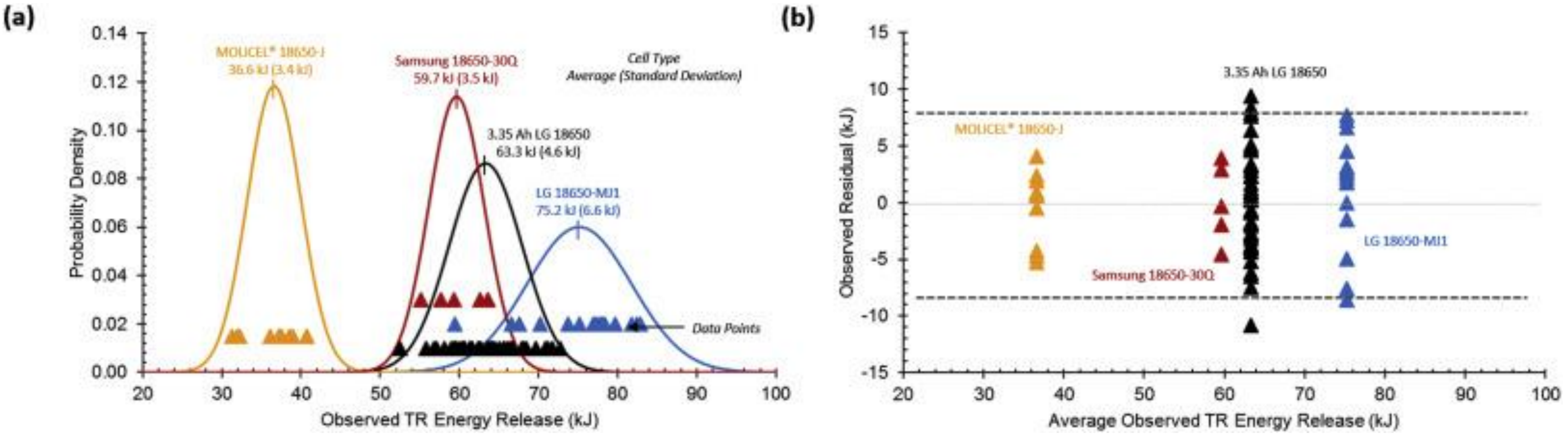
ELSEVIER

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

William Q. Walker[a,*], John J. Darst[a], Donal P. Finegan[b], Gary A. Bayles[c], Kenneth L. Johnson[d,e], Eric C. Darcy[a], Steven L. Rickman[a,d]

Heat output distributions of different cell types

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

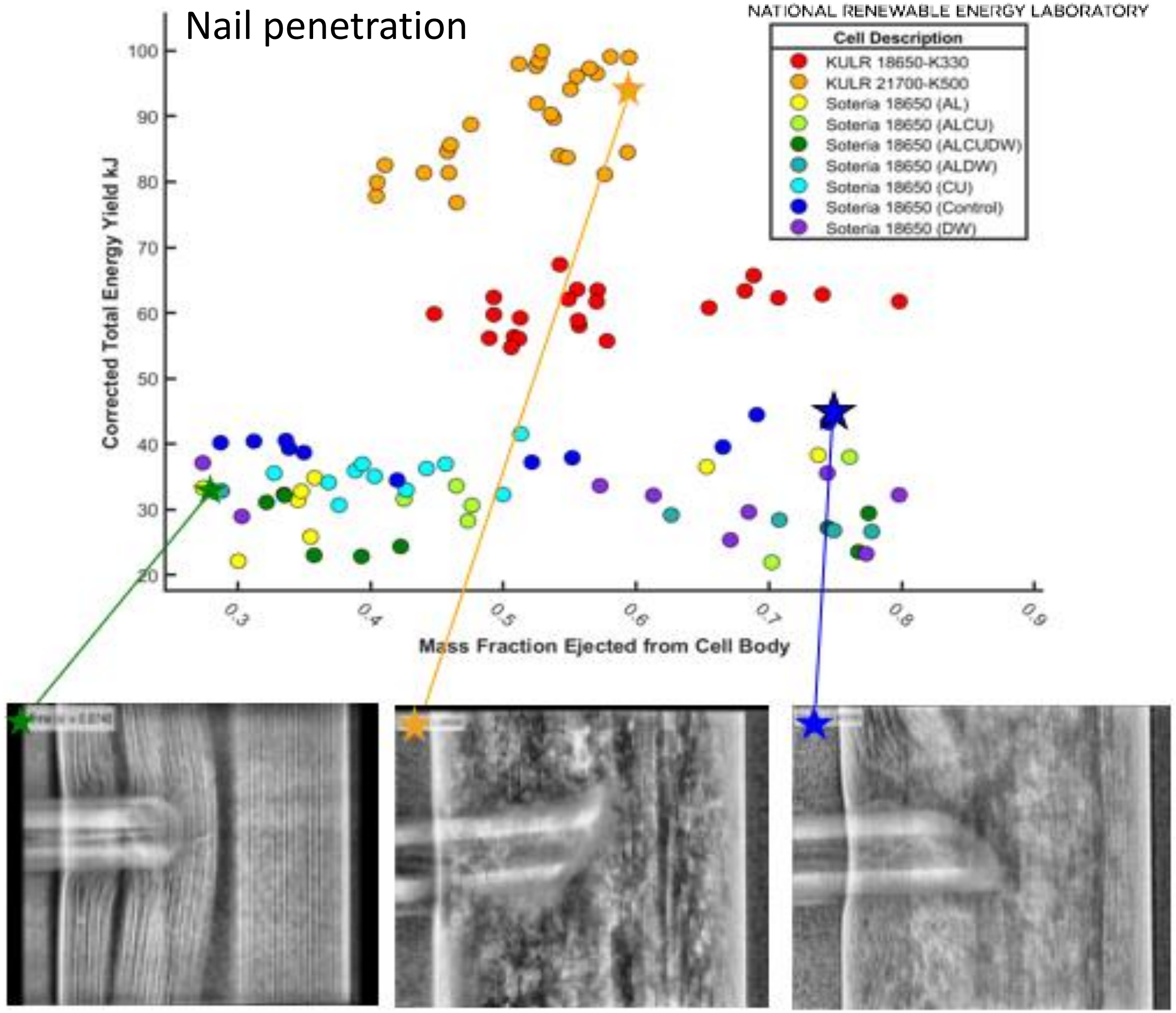


(a) the normal distribution curves based on the observed thermal runaway energy release and (b) the observed residuals of the thermal runaway energy release values vs. the observed average thermal runaway energy release.

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

Donal Finegan
donal.finegan@nrel.gov

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.
2. Finegan et al., Identifying the Cause of Rupture of Li-Ion Batteries during Thermal Runaway. *Advanced Science*, 1700369, **2017**.
3. Finegan et al., In-operando high-speed tomography of lithium-ion batteries during thermal runaway. *Nature Communications* **2015,** *6*.
4. Finegan et al., Tracking Internal Temperature and Structural Dynamics during Nail Penetration of Lithium-Ion Cells. *Journal of The Electrochemical Society* **2017,** *164* (13), A3285-A3291.
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

www.nrel.gov

NREL
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Thank you.