BATTERY SAFETY UK 2025

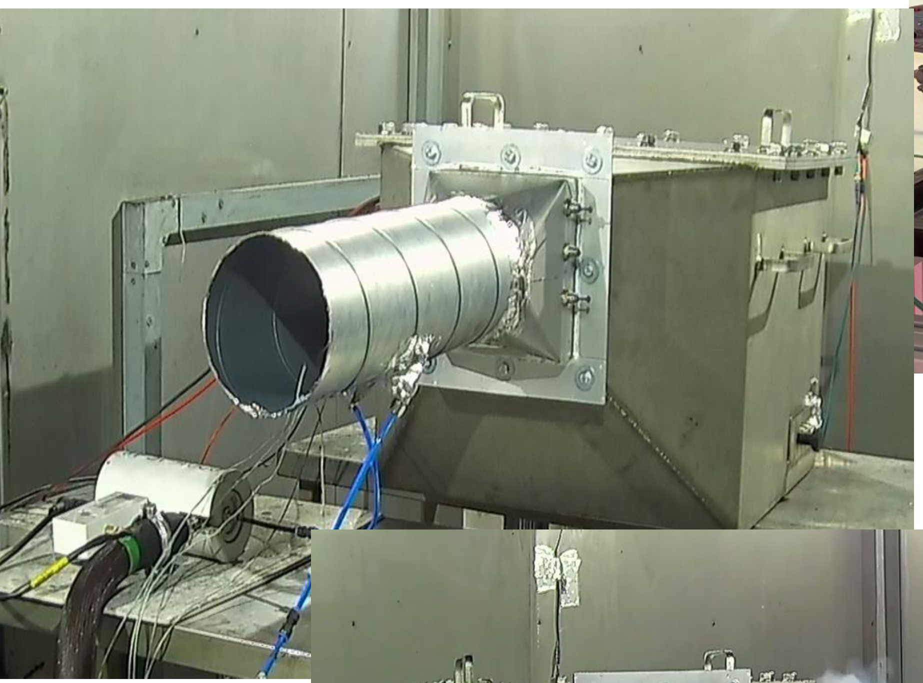
WMG, UNIVERSITY OF WARWICK

Thursday 10th April 2025

Safety Across a Battery's Lifecycle

Jonathan Buston

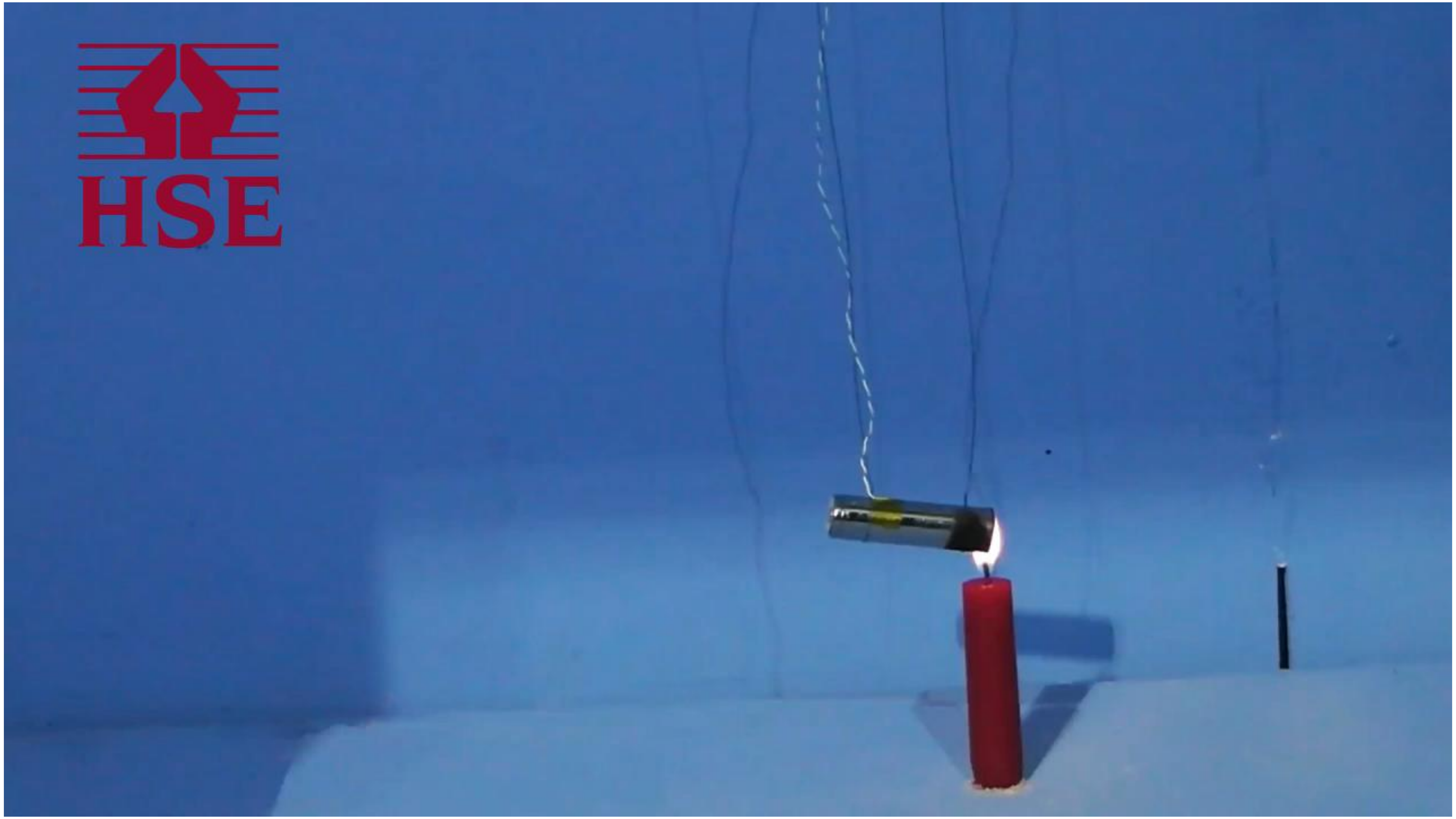
Where I come from…







That lurking concern…



Cells DON'T Explode..

…according to the manufacturers

But they might

Rapidly disassemble

or

Vent with flame

A Simplified Lifecycle

Design & Testing	Cell/Battery Manufacture	Item Manufacture	Logistics	Use	Disposal

Users

Workforce

Regulators

First Responders

Bystanders

What do we mean by “safe”?

What causes a Lithium-Ion cell to fail?

Accidental

Impact

Heat or Fire

Cell Fault

Electrical

Deliberate

So What Keeps a Battery System Safe…?

Design

Fire Detection Suppression	Thermal Management	Battery Control System	Electrical Safeguards (eg Fuses)

Implementation & Maintenance

And Just in Case…?

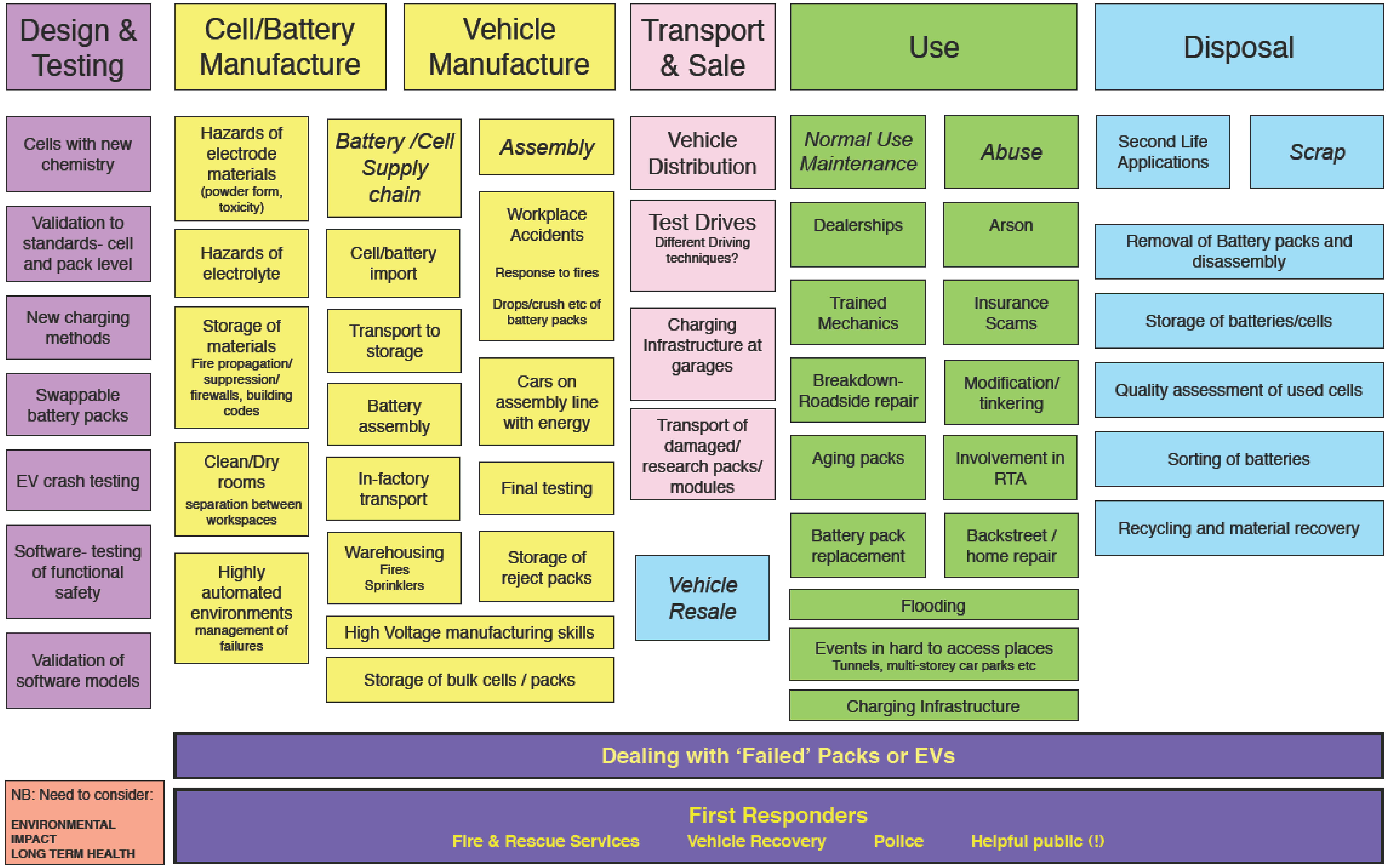
Is 100% safety tenable?

Suitable location? (Planning)	Emergency Response Plan	Environmental Protection	Cyber security

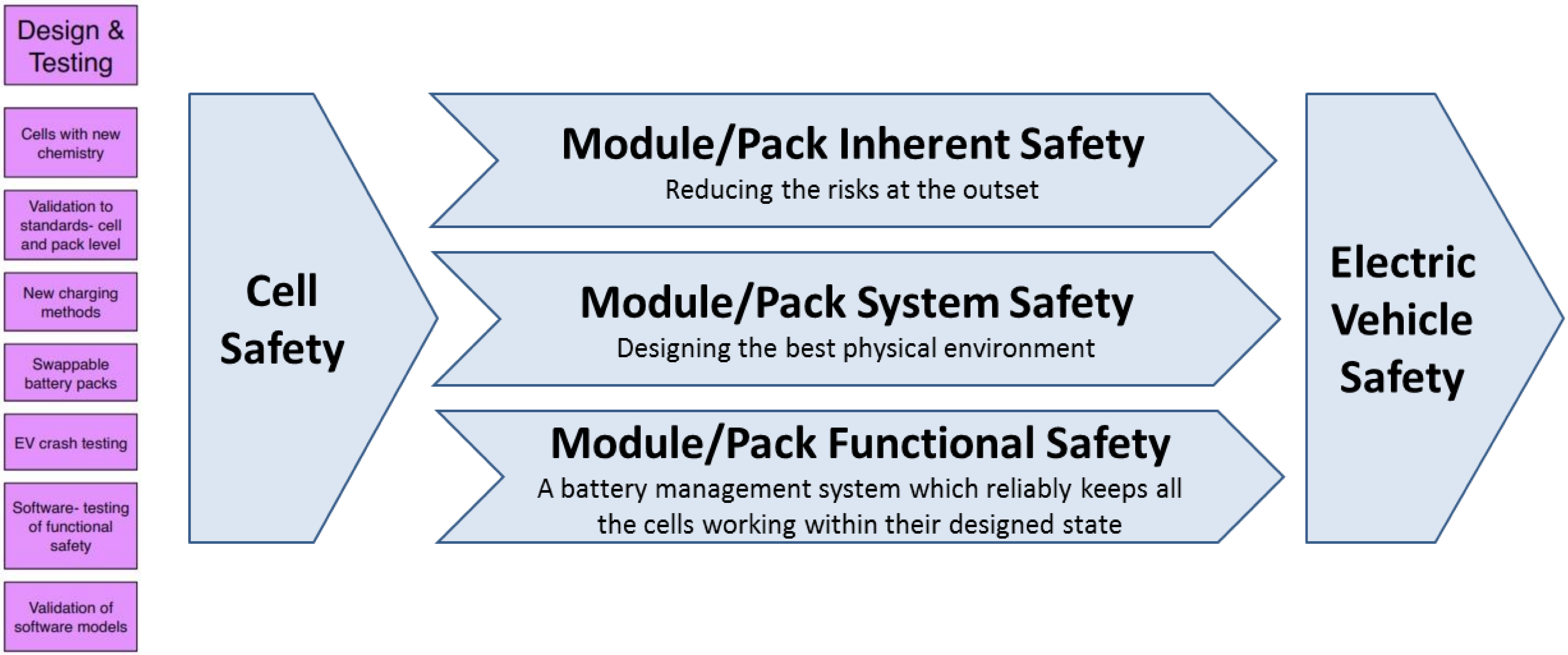
Is 100% security tenable?

PROTECTING PEOPLE AND PLACES HSE

EV Life Cycle: New or Changed Safety Scenarios



Design and Testing



Design and Testing

- Design & Testing
- Cells with new chemistry
- Validation to standards- cell and pack level
- New charging methods
- Swappable battery packs
- EV crash testing
- Software- testing of functional safety
- Validation of software models

Building on a sound evidence base

Understand

Thermal Runaway

Fire Growth

Component & Smoke Toxicity

Modelling the impact of catastrophic failure

Safety as an emergent property

Design & Use

Product development & testing

Location & Layout of manufacturing/recycling facilities

Safe warehousing & transport

Safe protocols for first responders and restoration

Informed discussion on risk tolerance

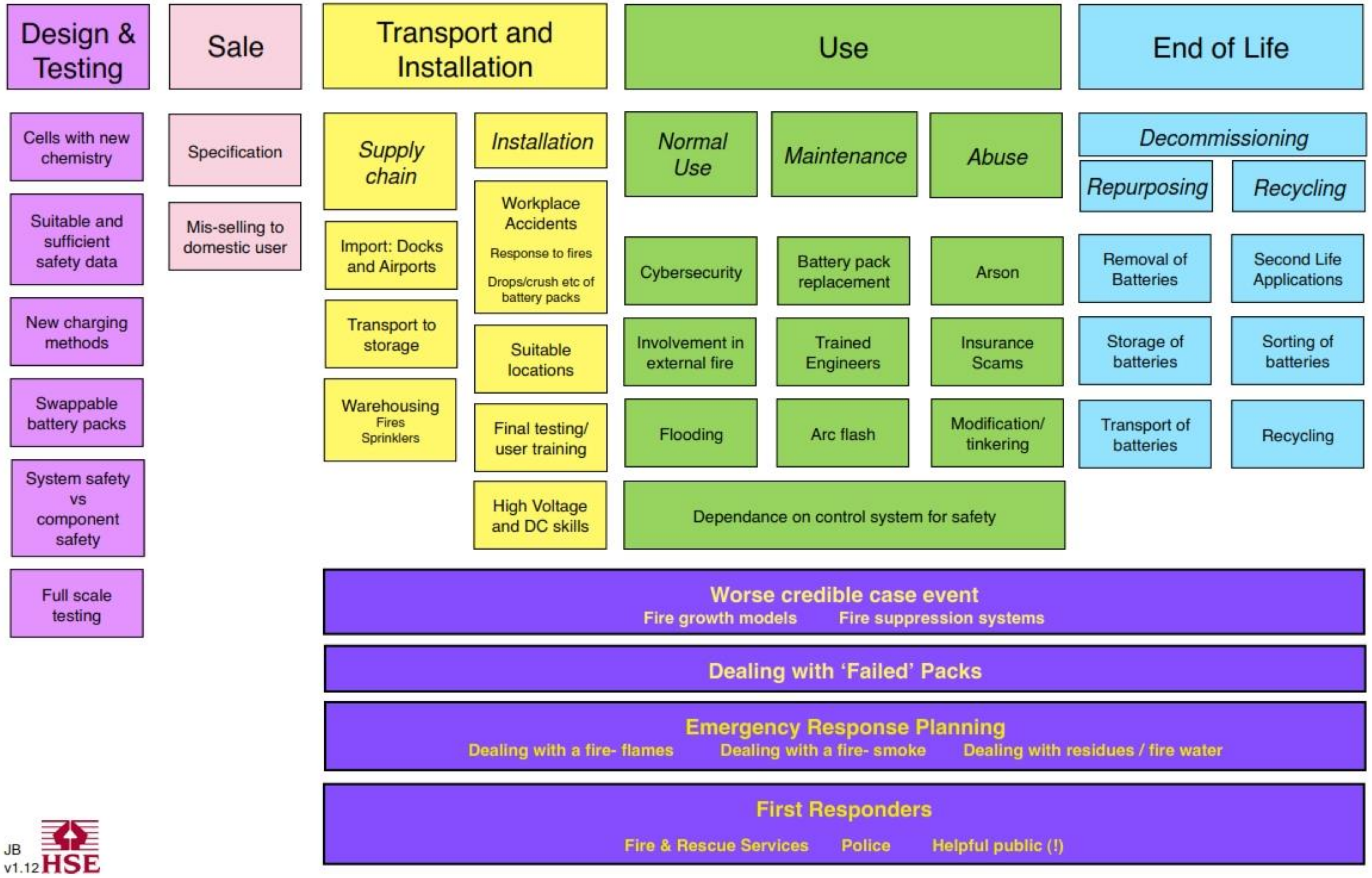
Manage

Regulation

Guidance

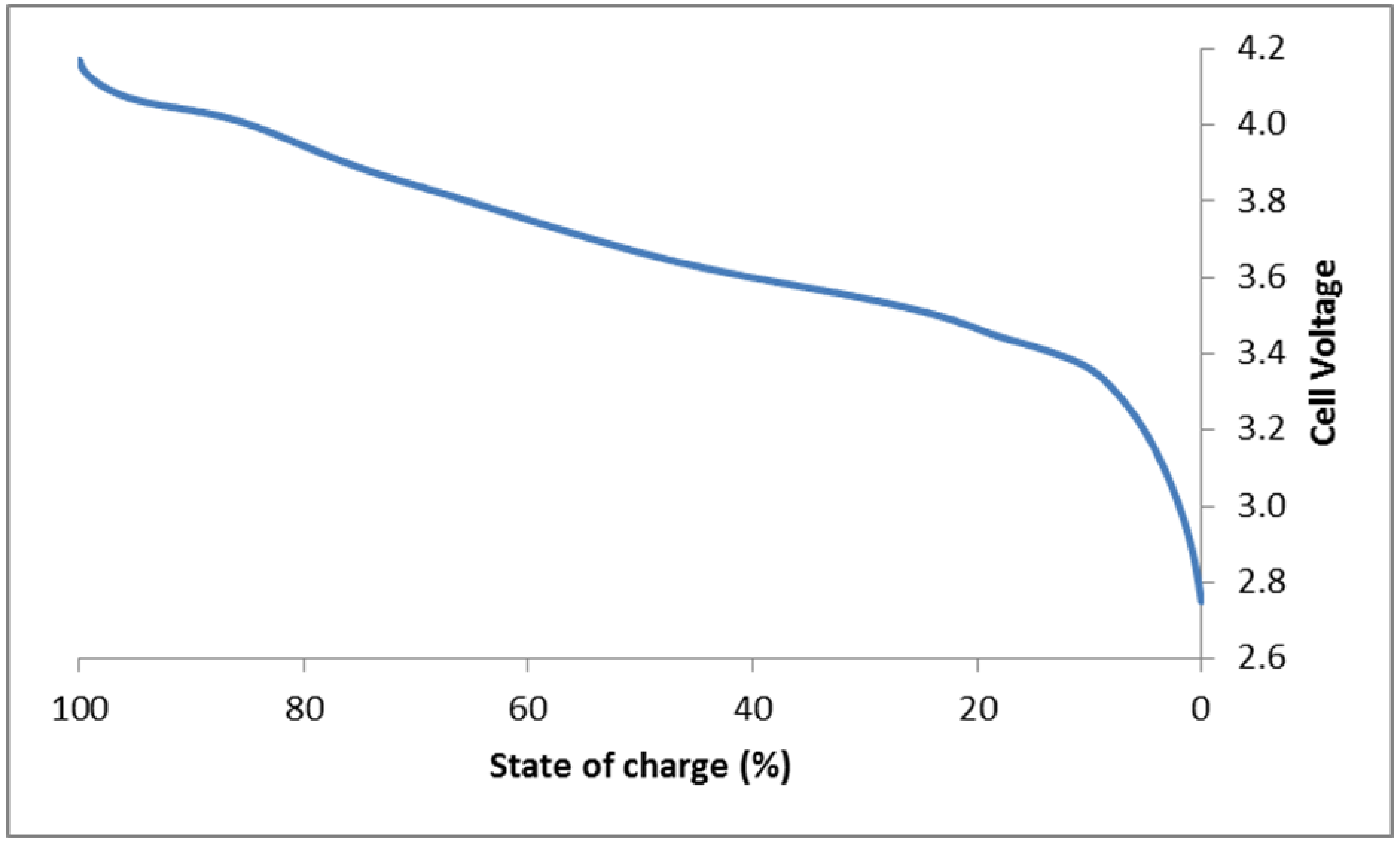
Standards

BESS: New or Changed Safety Scenarios



Potential Safety Issues to consider:

- Voltage (400-800 V DC for an EV)



Typical Single Cell

V_{max} 4.2 V
$V_{nominal}$ 3.7 V
V_{min} 2.75 V

Potential Safety Issues to consider:

- Unknown / variable outcome of events
- Fire growth?
- An event may not be over once flames defeated
    - Re-ignition if not cooled
    - How do you know?

Potential Safety Issues to consider:

- Flammable gas produced?
- Toxic gas produced?
- Nature of the smoke?
- Any projectiles?
- Is the residue toxic?

Potential Safety Issues to consider:

- Firewater?
- Decontamination of PPE/kit
- Decontamination of site

Observations

- Know what you don't **KNOW**

Observations

- Find the right technical specialist

Observations

- People are innovative

Observations

- We use batteries all the time…

- Don’t be scared!

jonathan.buston@hse.gov.uk


VERTICAL

Regulatory Landscape for eVTOL Battery

Dr Chris Lyness- Head of Battery

Vertical Aerospace April ‘25

- Electric Vertical and Take off Aircraft
- +300 Staff
- 4 sites in South West, UK
- 2nd Demonstrator Aircraft flight test underway

Battery Facility

- In-house Design
- In-house Test
- In-house Manufacturing

15,000sq ft based in the Bristol area

Purpose built facility for our battery pack manufacture

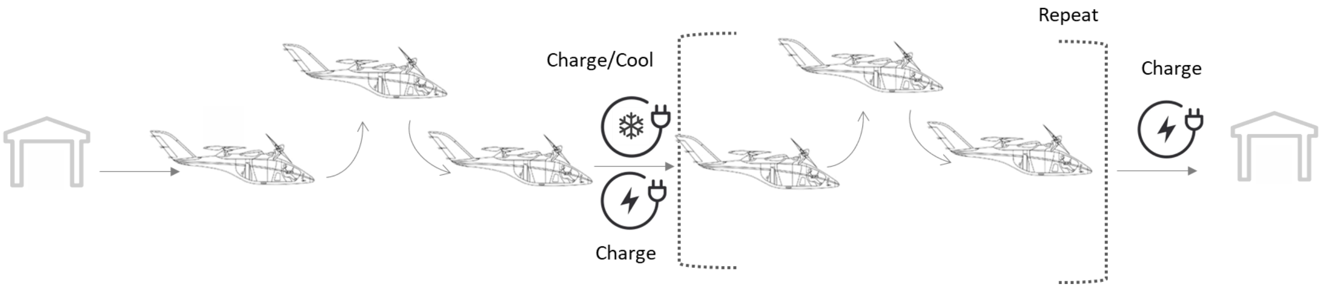
Testing our battery cells currently being produced from our partner, Molicel

Enables accelerated development testing

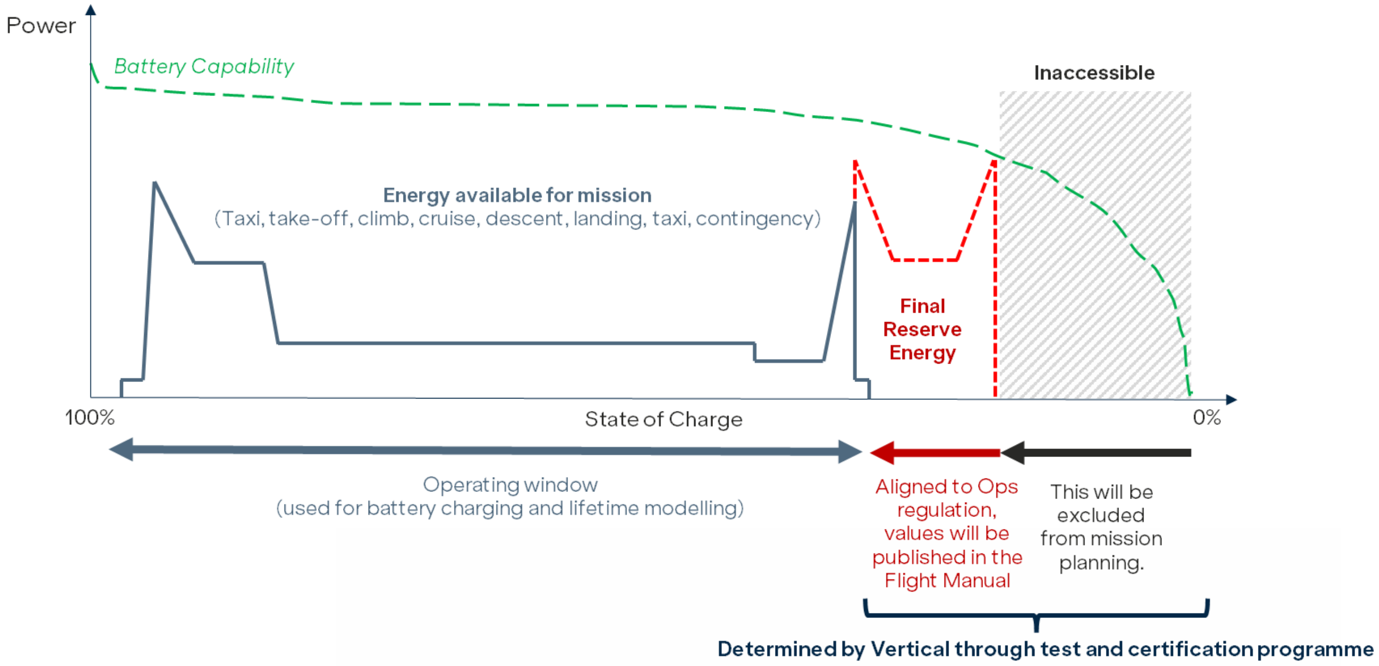
Preparations for low volume production

Gen 2 Battery design underway

Usage case

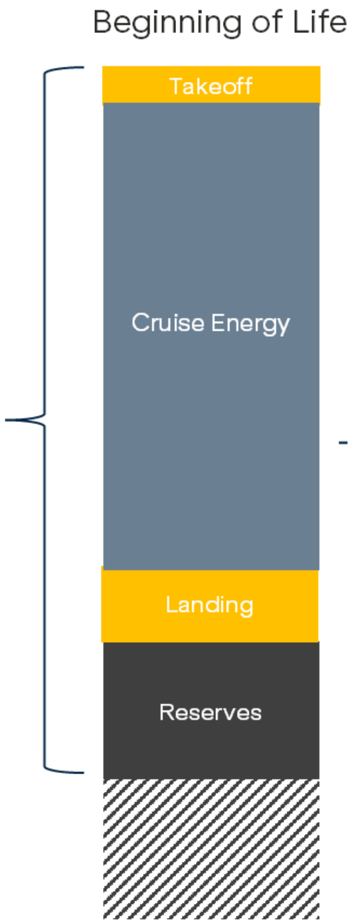


Charge/Cool
Charge
Repeat
Charge



Power
Battery Capability
Inaccessible
Energy available for mission
(Taxi, take-off, climb, cruise, descent, landing, taxi, contingency)
Final Reserve Energy
100%
State of Charge
0%
Operating window
(used for battery charging and lifetime modelling)
Aligned to Ops regulation, values will be published in the Flight Manual
This will be excluded from mission planning.
Determined by Vertical through test and certification programme

Usable Energy



Beginning of Life
Takeoff
Cruise Energy
Landing
Reserves

Who Determines the Regulations?

FEDERAL AVIATION ADMINISTRATION

EASA
European Aviation Safety Agency

UK Civil Aviation Authority

JCAB

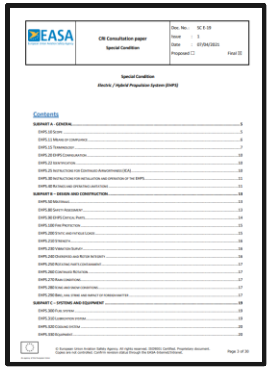
Transport Canada

ANAC

+ Global NAA

SCVTOL

SC-E19



Robust and proven framework for designing a safe aircraft now applyied to electrified power units

Examples of unique Battery safety requirements in Aviation

Unique Aircraft Batt Cert Requirements

- Aircraft Test Standards (DO-160)
- Runaway containment
- Redundancy
- 15.2m Drop
- DAL-A BMS
- Supply Chain control
- SOF Prediction

MOC.3.VTOL-2440
Propulsion batteries thermal runaway for VTOL category Enhanced

System demonstrate
- Single Cell Non-propagation

&

- Containment of thermal runaway with 20% of cells triggered within ~60s

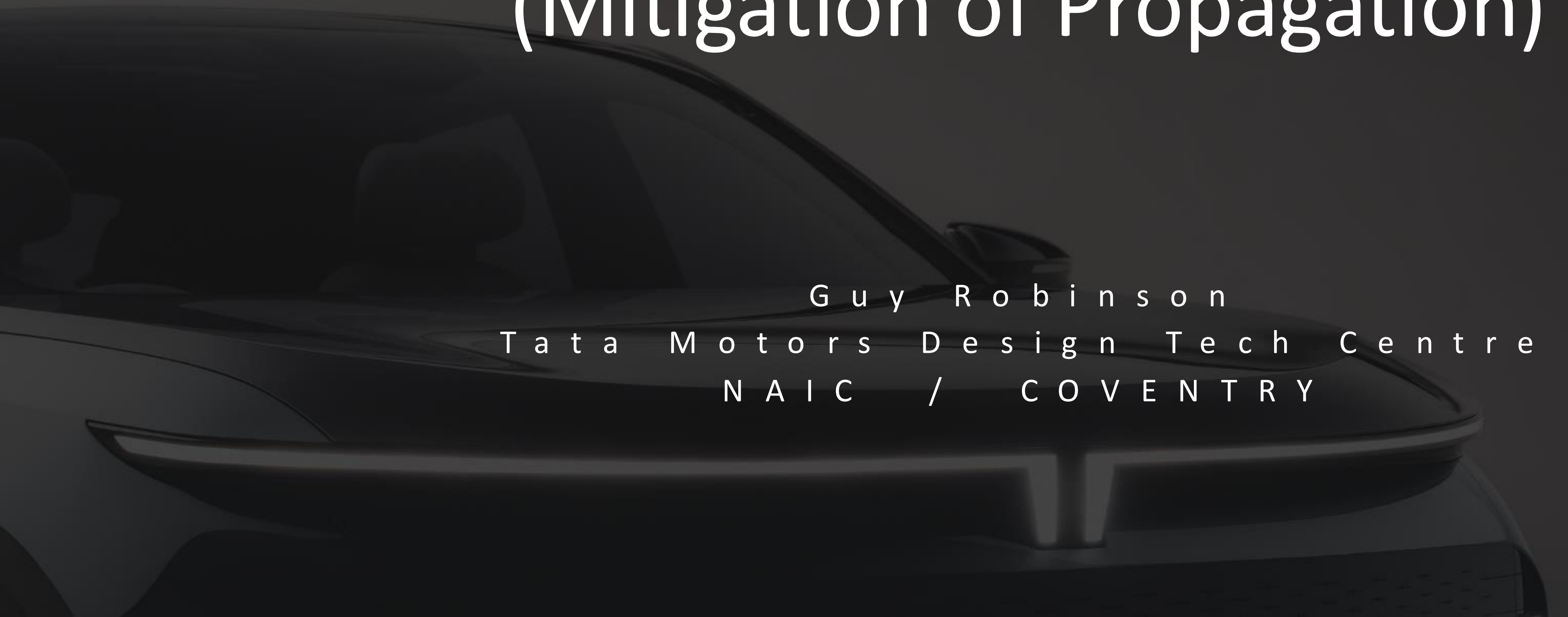
MOC.1.VTOL-2325
Fire protection- Energy storage Crash resistance

System demonstrate robustness to
- 15.2m/50ft Drop
- No hazardous energy release for 15minute

Application of robust and proven aerospace framework is generating unique challenges for battery safety engineering

A Battery Zonal Risk Assessment Approach

(Mitigation of Propagation)



Guy Robinson
Tata Motors Design Tech Centre
NAIC / COVENTRY

Our Story

The Beginning

Tata Motors Design Tech Centre (TMDTC), founded in 2005, is a UK hub for **automotive design**, **engineering** and **innovation**, driving **advanced technology** for Tata Motors and industry partners.

TMDTC continues to lead in **EV innovation**, **autonomous technology** and **future-ready EVs** while advancing **vehicle architecture**, **ADAS** and **connectivity**.

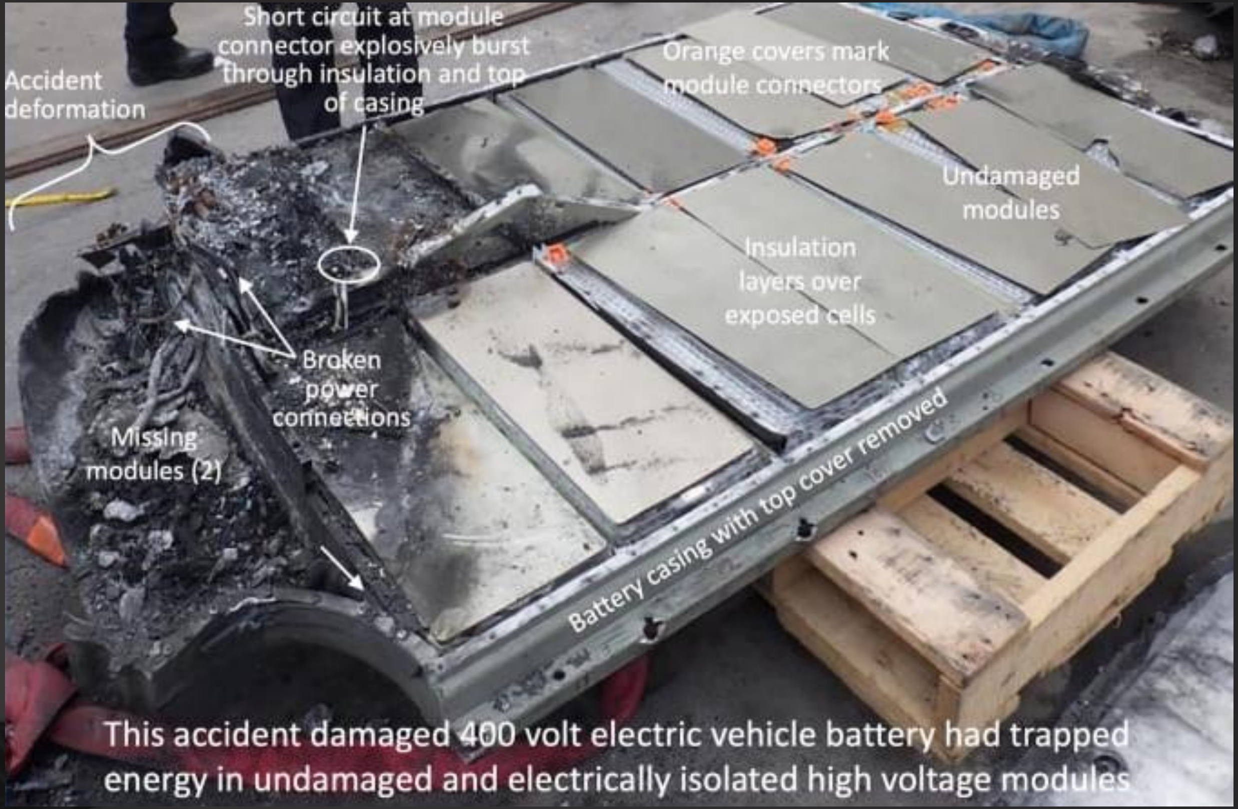
Introduction

Presentation intends to cover:

1) Context Battery Fire risks and mechanisms

2) A Zonal process to identify design risks and improvements

3) Share example design mitigations



https://blogs.sw.siemens.com/simcenter/making-sure-your-ev-battery-survives-rough-roads/

Battery Fire Overview

Battery Fires attract disproportionate news headlines

Severe fires occur when:

- Multiple cells suffer thermal runaway – domino effect
- Sufficient heat is created to ignite materials surrounding a battery

Importance of domino effect is time:

- Rapid or accelerating – Occupant risks
- Longer term and steady - Safer event, but bad PR

Ideally, a Cell Thermal Runaway does not propagate

- Single cells may vent and damage is isolated
- Limited impact on battery system

https://www.carexpert.com.au/car-news/firefighters-still-struggle-to-defeat-ev-fires-effectively

Propagation Modes

Cell conduction heat transfer normally considered by design

Additional mechanisms can include

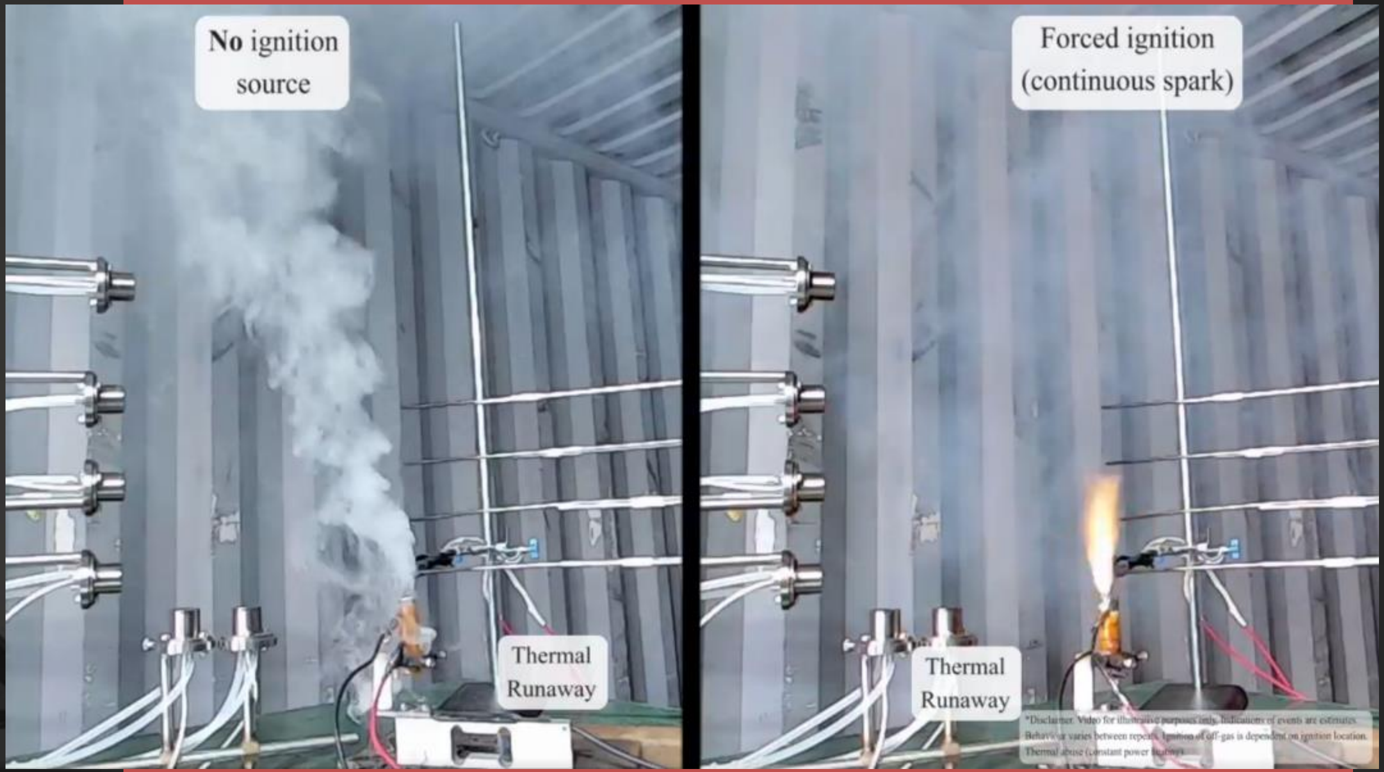
- Secondary Material fires
- Impinging vent gas/debris
- Gas Ignition LFP / Auto-Ignition NMC
- Arcing and subsequent Metal Ablation
- Short Circuit – Cell Overstress

Can these risks be foreseen?

Potentially - with some thought

Brave battery designs may propagate even with LFP cells

Effect of Ignition Sources on LFP vent gas



www.linkedin.com University of Sheffield Peter-Bugryniec

Propagation Modelling

Complexities in Modelling A Domino Effect

Multi-physics problem including:

- Thermodynamics
- Fluid dynamics
- Arcing
- Combustion
- Electrically conductive debris sprays
- Hot, Ionised Gas dispersion
- Cell expansion / bursting deformation
- Secondary Material Melting / Deformation

50

Creepage and Clearance standards may be adequate in normal operation

Arc Welding Comparison

50V DC and Above offer Good Arc characteristics

65V DC and above offer “Excellent” arc characteristics

https://www.weldclass.com.au/blog/34-mma-stick-welding-what-is-open-circuit-voltage-ocv-

What can we do?
Zonal Safety Analysis – Aerospace Inspiration

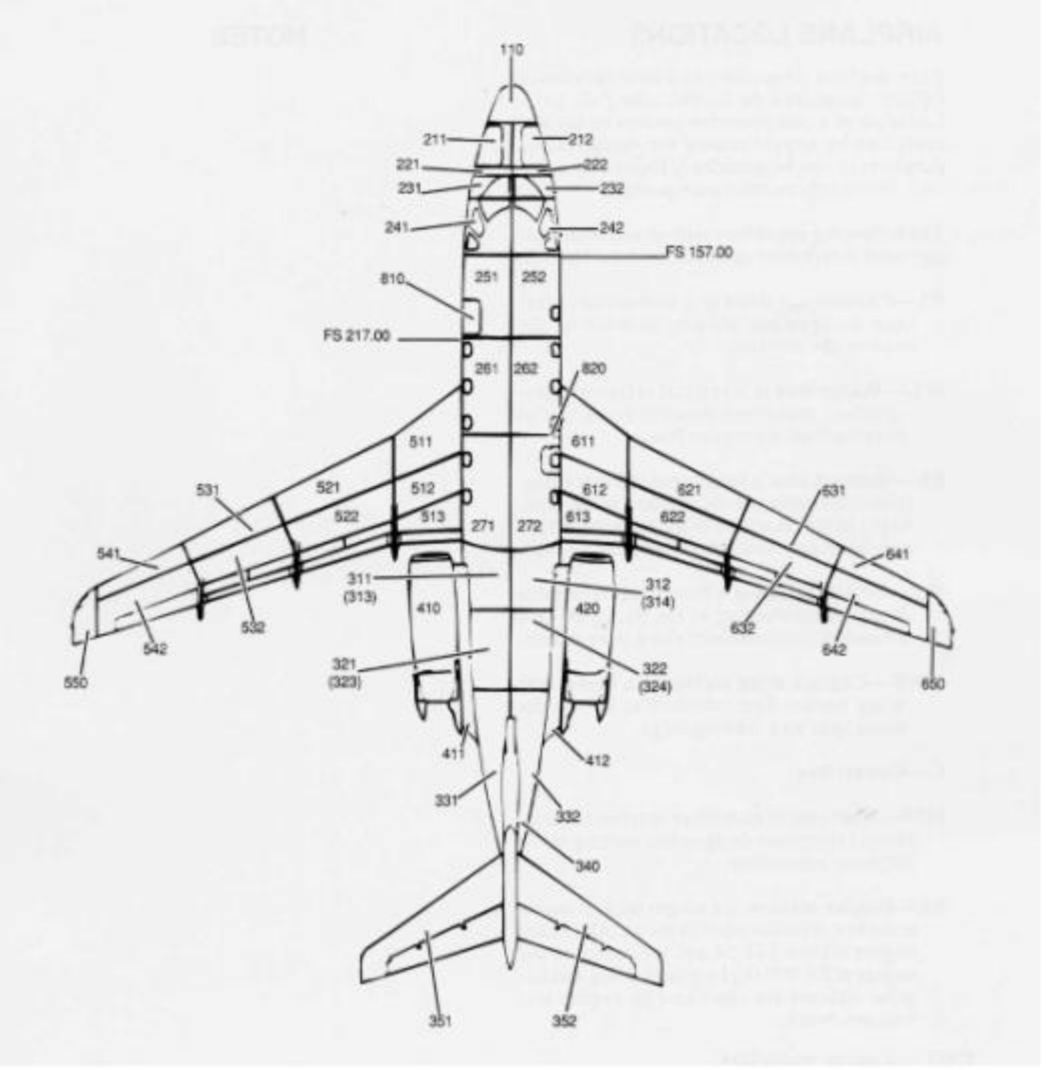
SAE ARP4761 defines a process for spatial assessment of equipment interference following an initial failure e.g.

- Engine Rotor Failure
- Accumulator burst
- Fluid leakage
- Etc

1) The aircraft is split into zones to facilitate analysis

2) Equipment located in close proximity is assessed for potential failure interactions

If not already applicable, we can take inspiration from this process



Battery Zonal Risk Analysis

Objectives

Enable focussed assessment of battery design for failure cascades

- OEM capability to hold designers to account

Reduce design risks of immensely complex interactions without compromising timing

Limit complexity of modelling

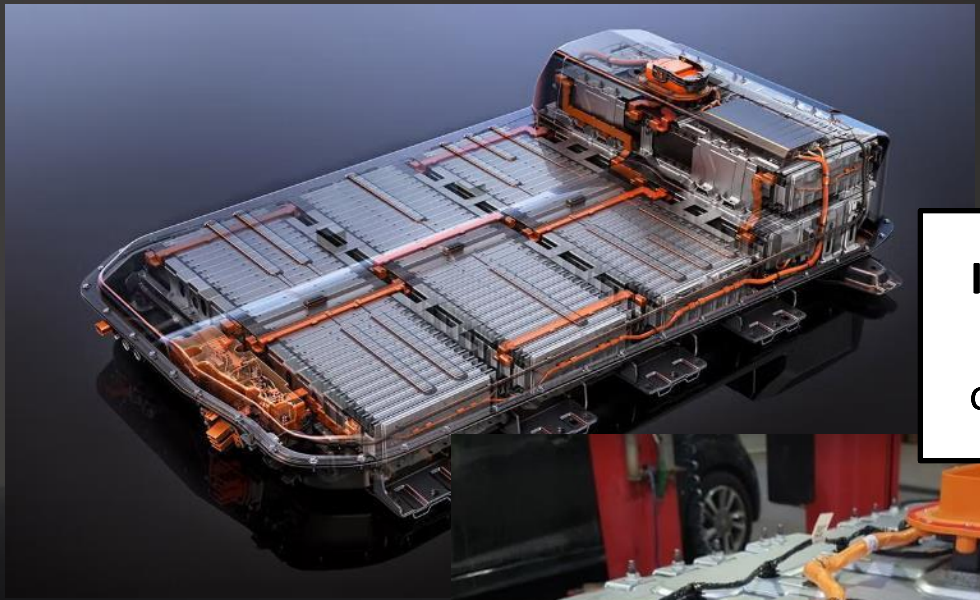
- Enable focussed modelling
- Identify efficient solutions

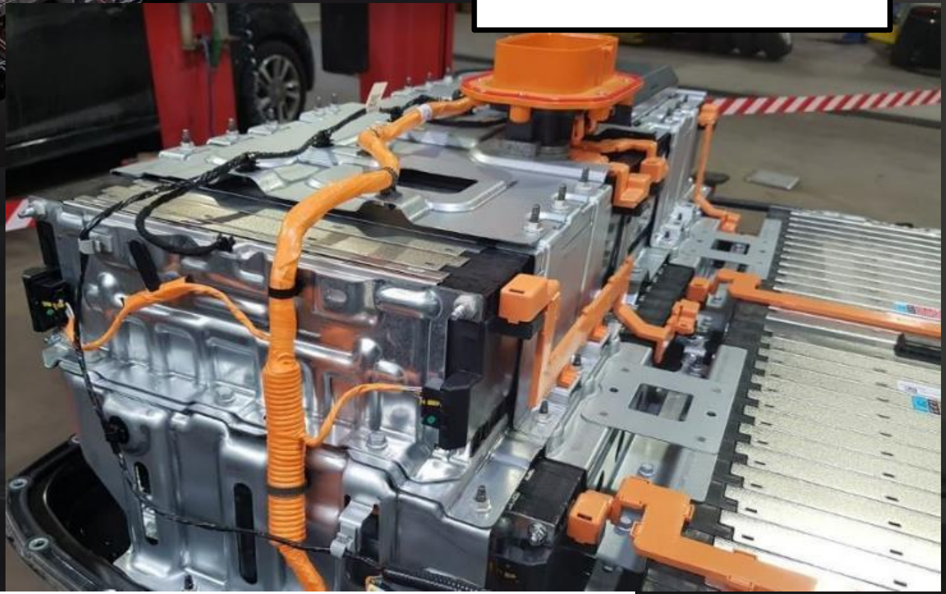
Support validation and field failure investigations

–> From this

-> To this

Process Flow – Spatial Assessment





https://www.caranddriver.com/news/a15345397/battery-taxonomy-the-differences-between-hybrid-and-ev-batteries/

Inputs Required
Detailed CAD
or physical parts

1) 3D Design Input

2) Identify Zones in Battery

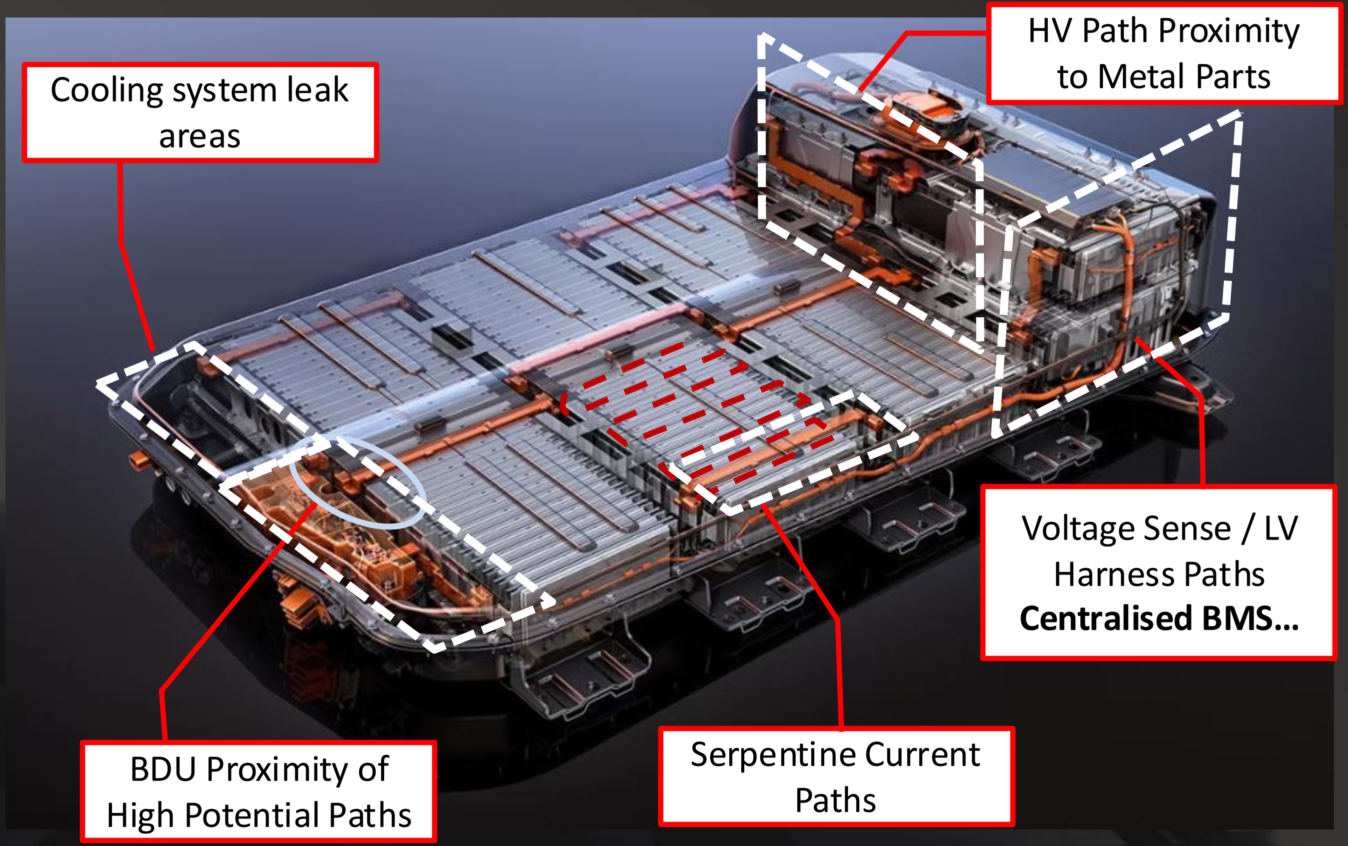
3) Complete detailed Zonal Review

4) Identify improvement options

5) Assess and Select updates

6) Update design and DFMEA

Process Flow



Chevrolet Bolt EV

https://www.caranddriver.com/news/a15345397/battery-taxonomy-the-differences-between-hybrid-and-ev-batteries/

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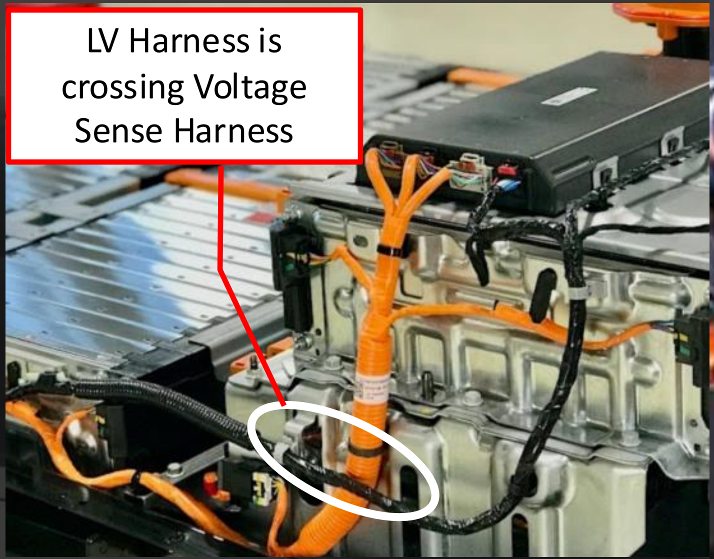
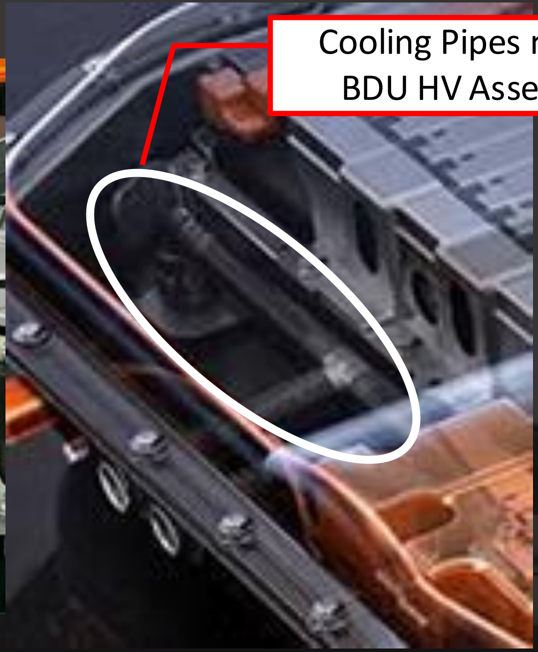
Process Flow – Detail Review

Busbar/Cells proximity to metal

LV Harness is crossing Voltage Sense Harness





Cooling Pipes next to BDU HV Assembly

1) 3D Design Input

2) Identify Zones in Battery

3) Complete detailed Zonal Reviews

Material types, Clearances, Cell Swelling

Debris Ejection, Harness Voltages, Affected Functions, Harness Fusing,

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https://www.caranddriver.com/news/a15345397/battery-taxonomy-the-differences-between-hybrid-and-ev-batteries/
https://www.linkedin.com/pulse/chevy-bolt-high-voltage-battery-yves-racette/

Process Flow – Detail Review

Example Review Table

ID	Subsectic	HV Zonal Risk Analysis	Overview	Example	Reviewed	Clearances	Material Data	Acceptable	Improvement Actions
Zone 4		**HV Positive/Negative Path Risks**	paths through pack						
	4.1	Proximity to metal parts / brackets		HV Busbar to Metal'!A1					
	4.2	Cell insulation abrasion/piercing risk to metal interfaces							
	4.3	Cell insulation piercing risk to other cells or metal interfaces with cell swelling							
Zone 5		**Contactor and HV Busbar Routing**	[illegible] /BMS area and identify risks around the cables and busbars around the contactors, main BMS harness and pack connectors						
	5.1	Local cross points		HV Cross'!A1					
	5.2	HV Contactor clearances							
	5.3	HV Sense harness routing bundle max potential and connector							
	5.4	HV Sense harness connectors max potential and pin segregation							
Detail 6		**Voltage sense Insulation temperature rating**	Determine if insulation could break down and lead to internal harness short or with nearby electrical parts						
	6.1	Material [illegible]							
	6.2	Temperature rating							
	6.3	Fire Rating							
	[illegible]	[illegible]	Determine [illegible] insulation could break down and lead to internal harness short						

Identify Zones and Contents

Review risks zone by zone considering detail of materials, clearances, harnesses and the cell groups included in a short circuit

Develop this process with your own design, experience of failure modes and battery project targets

1) 3D Design Input

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Material types, Clearances, Cell Swelling

Debris Ejection, Harness Voltages, Affected Functions, Harness Fusing,

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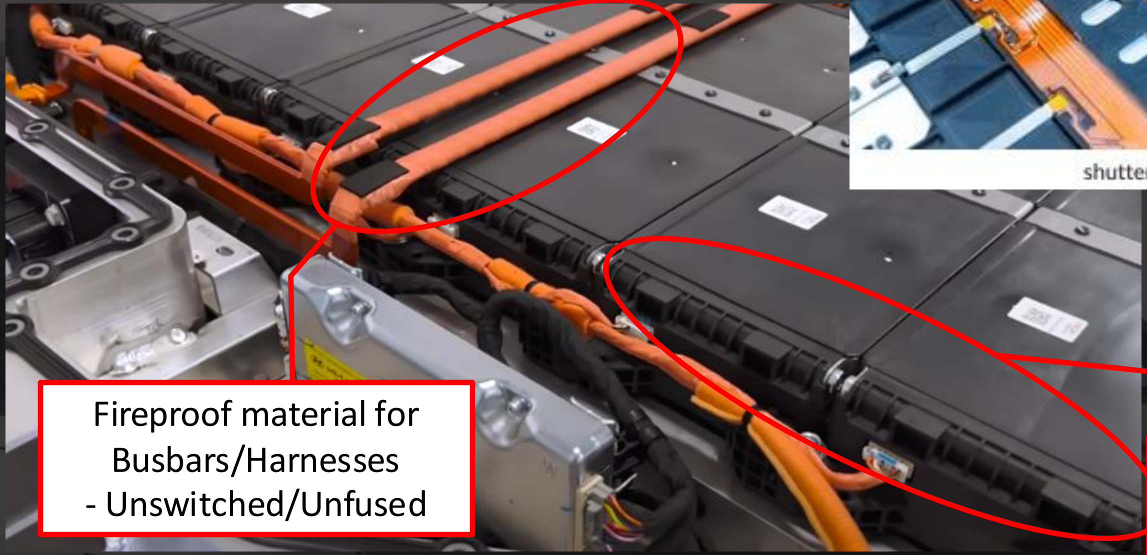
Process Flow – Improvement Options

Multiple Fusible Links – Break short circuits (Kia/Tesla)

Protect U-Shape paths from arcing
2x 15s Stacks (75-120v)



Fireproof material for Busbars/Harnesses
- Unswitched/Unfused

Module plastic parts lowers Pack arcing risk

- But creates melting/combustion risks

https://www.youtube.com/@MunroLive

1) 3D Design Input

2) Identify Zones in Battery

3) Complete detailed Zonal Review

4) Identify improvement options

Improve segregation, fire resistance, current paths (U-shapes)

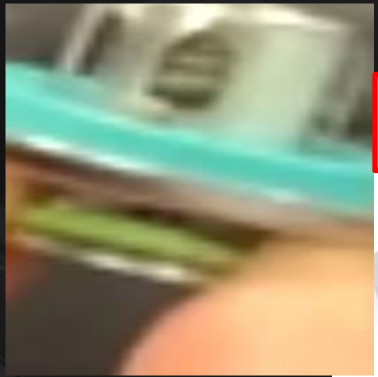
5) Assess and Select updates

6) Update design and DFMEA

Process Flow – Improvement Options

Tactical fireproof insulation on metallic parts – (BYD)

Segregate Cooling / Electrical Zones / Use of Low Conductivity Coolant



Manage fluid leakage / ingress (Tesla/Mercedes)

https://www.youtube.com/@MunroLive

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4) Identify improvement options

Fireproof insulation – Tactical use of Mica/Phenolic composites, segregation of fluids

5) Assess and Select updates

6) Update design and DFMEA

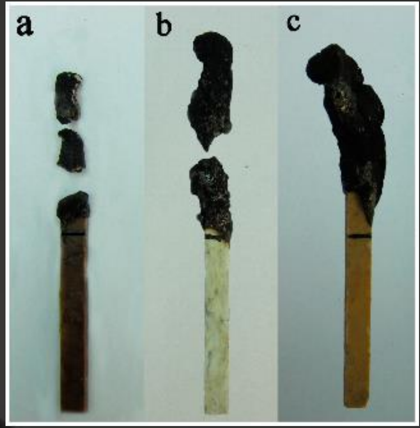
Process Flow – Improvement Options

Validation of Options

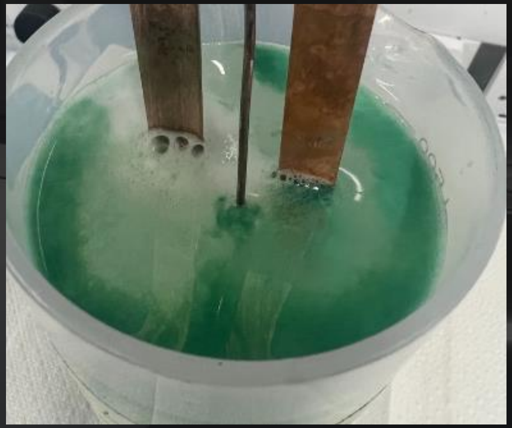
Identify Test Requirements for material tests, components and sub-systems

Example Validation Requirements

- Vent Gas Electrical characteristics
- Plastic Melting Behaviour/Carbonisation
- CTI changes with temperature and vent gas contamination
- New/Aged/Polluted Coolant conductivity
    - 50/50 Glycol or Dielectric Oil systems
- Centralised or Distributed Fusing Performance



https://doi.org/10.3390/polym11111851



https://www.ul.com/services/comparative-tracking-index-cti-iec-60112

1) 3D Design Input

2) Identify Zones in Battery

3) Complete detailed Zonal Review

4) Identify improvement options

Identify validation requirements

5) Assess and Select updates

6) Update design and DFMEA

Select Mitigation Improvements

Application objectives vary from sector to sector and project to project:

- Ultimate safety level
- Energy Density
- Cost
- Damage Tolerance / Survivability
- Weight
- Additional Complexities
  - Interactions of Loadcases – crash conditions
  - Immersion Cooling – effective, but heavy
  - Modularity and redundancy requirements

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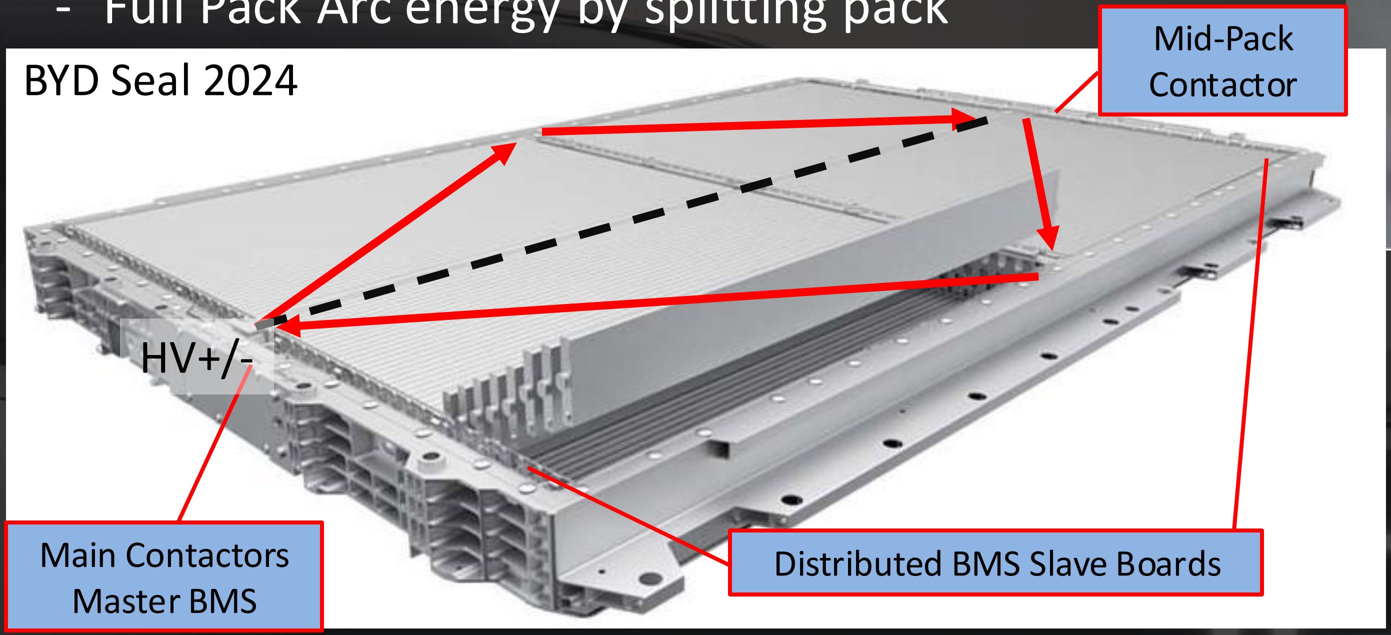
Example - BYD Yuan / BYD Seal

BYD batteries show rapid evolution

BYD 2018 -> 2024 – ePlatform 3.0

Latest variants include learning to mitigate:

- Cell to Cell Arc energy
- Arcing through BMS Harnesses
- Full Pack Arc energy by splitting pack



BYD Yuan - https://cnevpost.com/2022/06/28/chinese-analyst-team-dismantles-yuan-ev-for-their-research-on-byd/

Learning

BYD Seal - https://www.byd.com/eu/technology/byd-blade-battery

Update Battery Design and Capture Learning

Act during development phase or as a running change

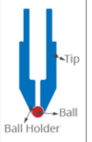
- Validate changes and review effectiveness
- Capture learning in DFMEA
- Hold Battery designers to account
- Record design rules for 2nd – 3rd – 4th generation batteries

Product Number: PT34325-4053 | Market: Japan | Team: Alex Drinal, Peter Loombard, Katie Samdras, Lin Woodlord

Product Name/Description: Ball Point Pen | Design Engineer Leader: Lin Woodlord | Document Number: DF325-12 | Orginal Date: Feb 10, 2019

Model: HandFree-P6 | Year: 2019 | Approved by: Mike Handson | Revision No.: 002 | Revision Date: May 14, 2019

Item / Function	Requirements	Potential Failure Mode	Potential Effect(s) of Failure	Severity	Classification	Potential Causes(s) of Failure	Current Design Controls Prevention	Occurrence	Current Design Controls Detection	Detection	RPN	Recommended Action(s)	Responsibility & Target Completion Date	Action Results: Actions Taken & Effective Date	Action Results: Severity	Action Results: Occurrence	Action Results: Detection	Action Results: RPN
Pen tip / disperses ink onto paper smoothly	Delivery proper ink amount onto paper	Not enough ink	Pen skip or Required heavy pressure while writing	7	A	Ball diameter is too big	Study tolerance of ball diameter and line weight and color	6	Writing test to detect if problem occurs	3	126							
						Narrow pen angle when writing	Study common range of writing angle	4		10	280	Writing Test with varying pen angles of the pen	Katie Nov, 24		7	3	2	42
						Not enough presure on the pen	Study the minimum presure of users and make sure ink can be dispnersed with minium presure	4	Writing test with minum presure on the paper	2	56							
		Too much ink	Globs or drip left behind the letters	7	A	Ball diameter is too small	Study tolerance of ball diameter and its effects to line weith and color	3	Writing test to detect if problem occurs	3	63							
						Pressure of user on the pen too much	Study user's pressure range	3	Writing test with high presure	3	63							
	The ball runs smoothly	Smoothly	Inconsistent line Skip or Glob left behind	8		Inproper selection of dimenson of the ball and ball socket	Study the tolerance of ball and ball socket and select the correct range	4	Writing test with miniumum presure on the paper	2	64							
						Improper selection of the ball roughness tolerance	Select surface roughness base on the standard	2	Check the prototype capability of ball surface	3	48							



https://www.iqasystem.com/news/dfmea-complete-guide/

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Conclusion

Safe and Reliable Batteries are more than chemistry

NMC can be safer than LFP with appropriate / inappropriate design

Learning needs to be rapid

Building Batteries and investigating failures delivers this learning…

With this approach, we can produce more cost-effective safe pack designs

https://koreajoongangdaily.joins.com/news/2024-08-05/business/industry/Exploded-Mercedes-EV-had-battery-from-Chinas-Farasis-Energy-govt-says/2106280

Thanks for listening

Tata Motors Design Tech Centre
NAIC / COVENTRY

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Rhodri Jervis and Xiaoxia Guo

UCL Department of Chemical Engineering and Faraday Institution

UCL

How does degradation affect safety: do polycrystalline materials behave differently to single crystal materials?

Rhodri Jervis

Battery Safety UK, Warwick, April 2025

electrochemical innovation lab

eil

THE FARADAY INSTITUTION

SCIENCE OF BATTERY SAFETY

SafeBatt

100

UCL Chemical Engineering since 1923

Thermo Fisher SCIENTIFIC

Enhancing safety and process control in battery manufacturing through vapor and gas analysis

Prasanna Kadirvelayutham
Senior Market Development Manager
Clean Energy
Analytical Instruments
April 2025

The world leader in serving science

Agenda

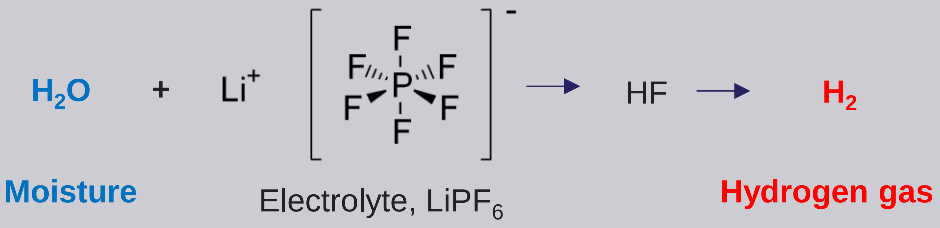
1 Monitoring moisture & NMP for enhanced quality and safe electrode production

2 Battery abuse and thermal runaway

1 Monitoring moisture & NMP for enhanced quality and safe battery production

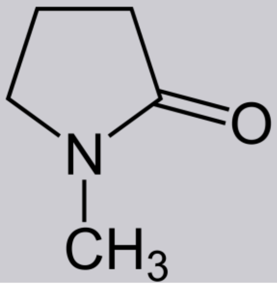
Why moisture monitoring is crucial for safety

Moisture



- **Generated HF can affect the quality of the battery and can degrade**
  - Current collectors (Al/Cu)
  - SEI layer on anode – compromising cell stability
  - Separator – cause to short circuit
- **Hydrogen gas generation and swelling**
  - Moisture can cause side reactions inside the cell leading to gas formation.
  - Swollen cells pose risks of pouch rupture, electrolyte leakage, or even explosions.
- **Accelerated thermal runaway**
  - HF generation increases internal resistance and localized heating.
  - Elevated heat can trigger thermal runaway - a chain reaction that causes battery fire or explosion.

Why NMP monitoring is crucial for safety

NMP		
	Chemical formula	C_5H_9NO
	Molar mass	99.133 g·mol−1
	Density	1.028 g/cm3
	Melting point	−24 °C

- **Toxic and flammable solvent**
  - Extended worker exposure to NMP vapor can cause respiratory issues, skin irritation, and reproductive toxicity.
  - Flammable at high temperatures - Inadequate removal of NMP during drying increases fire hazards in downstream processes.
- **Cost and regulatory risks**
  - Recovering and refining waste NMP for reuse is cost-effective.
  - Regulatory bodies strictly limit workplace exposure.
- **Adhesion and delamination risk**
  - Residual NMP can weaken binder adhesion (i.e., PVDF to Al foil).
  - This can lead to electrode delamination during cycling - risk of short circuit and internal arcing.

Where moisture and NMP matter most during electrode production

Monitoring moisture in anodes and NMP in cathodes is essential to prevent safety hazards, maintain electrode integrity, and ensure regulatory compliance.

Cathode electrode production – NMP and moisture monitoring

- Raw Materials
- Slurry Mixing
- Coating & Drying
- Post-Drying
- NMP Recovery
- Dry Room & Assembly

Moisture monitoring | Moisture and NMP monitoring

Anode electrode production – Moisture monitoring

- Raw Materials
- Slurry Mixing
- Coating & Drying
- Post-Drying
- Slitting & Storage
- Dry Room & Assembly

Benefits of gas monitoring from drying process

Process optimization

1. **Real-time monitoring**: Monitoring exhaust gases from the dryer allows real-time tracking of solvent removal efficiency.
2. **Optimized drying time**: Identifying the exact point when solvent removal is complete prevents unnecessary over-drying.
3. **Consistent product quality**: Prevents drying inconsistencies, minimizing variations in electrode quality.

Cost Reduction

1. **Energy savings**: Shorter drying times and reduced excessive heating lower electricity and gas consumption.
2. **Reduced material waste**: Prevents defects caused by over-drying, such as binder degradation or electrode cracking, reducing raw material loss.

Real-Time monitoring of moisture and NMP

Thermo Fisher SCIENTIFIC

Portable cart system

MAX-iR™ FTIR Gas Analyzer

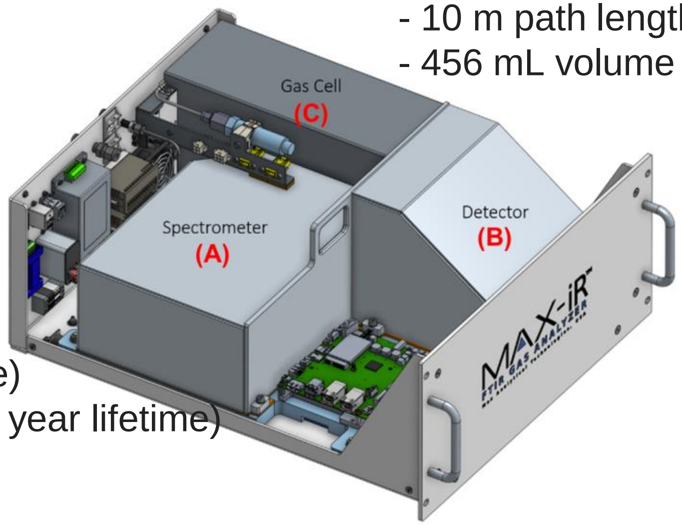
- Engineered for in-line process, environmental, and gas purity applications
- Small, rugged, high throughput interferometer
- DTGS detector
- 10m high throughput multipass gas cell

Gas cell (C)

- Ni coated Al
- 10 m path length
- 456 mL volume

Analyzer Dimension

- 19-Inch Rack Mount Case (5U) (48.26 x 60.96 x 22.225 cm)
- weight ~ 34 kg



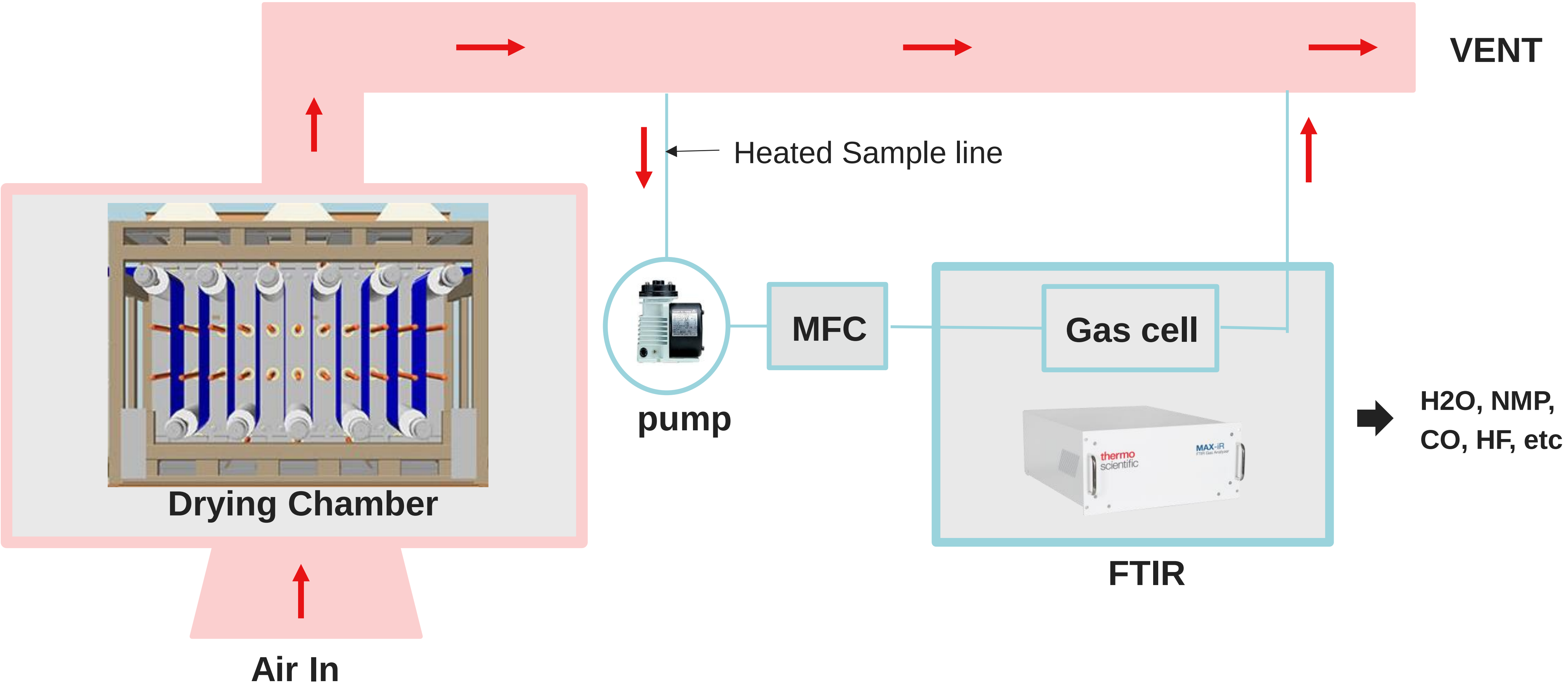
Spectrometer (A)

- SiC IR source (10-year lifetime)
- VCSEL reference laser (10-year lifetime)
- 1 - 32cm^{-1} resolution spectrometer (20+ year lifetime)
- ZnSe beam splitter

High Sensitivity Detectors (B)

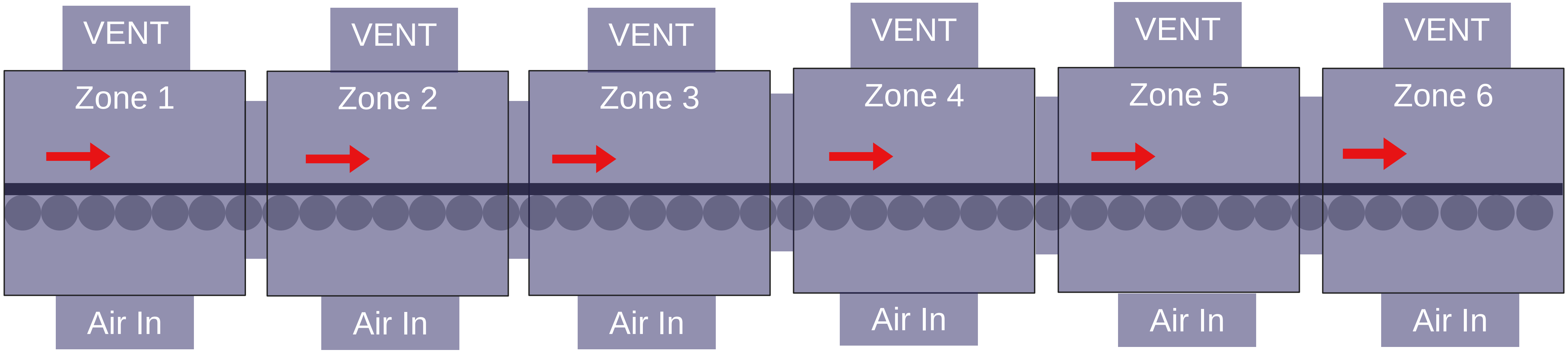
- DTGS (500 – 5000 cm^{-1})
- MCT with StarBoost (1800 – 3400 cm^{-1})

Drying process moisture & NMP monitoring



- During the Drying process Dry Air is introduced to Drying chamber and absorbs Moisture and NMP
- The air vented through the hood is flowed into the analyzer using a pump for gas analysis.
- After the analysis, the sample is reconnected to the hood and vented out
- It is also possible to measure both the inlet and outlet to monitor the amount of NMP and moisture generation

Drying process MAX-iR demo

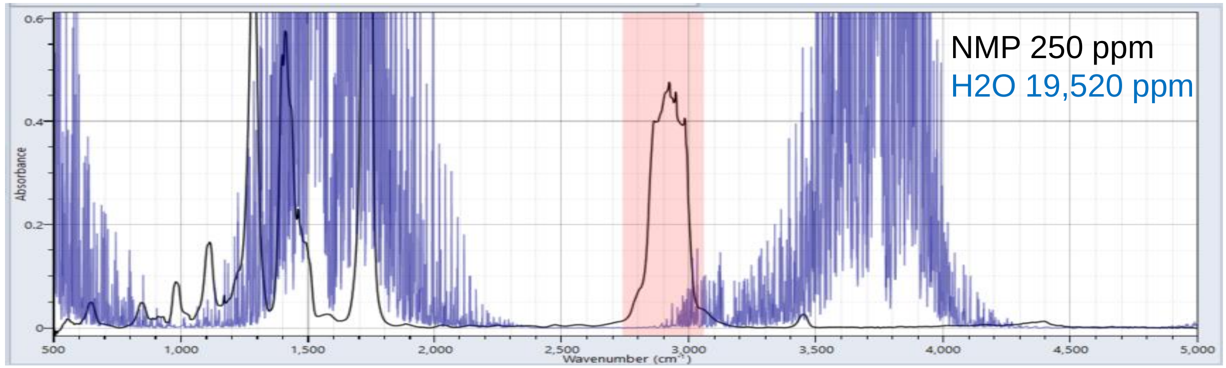


Cathode drying process TEST

- **Heated line was connected to the port at the vent hood and the gas inside the drying chamber was taken by pump.**
- **NMP, moisture, and CO2 were detected, but no other gases were detected.**
- **Concentration level of NMP was increased to Zone 5 and decreased at Zone 6 Moisture concentration level was similar by each zone and with the ambient level**
- **NMP is used as solvent when manufacturing cathode, so the NMP was a major concern in cathode manufacturing and moisture is used as solvent when manufacturing Anode**

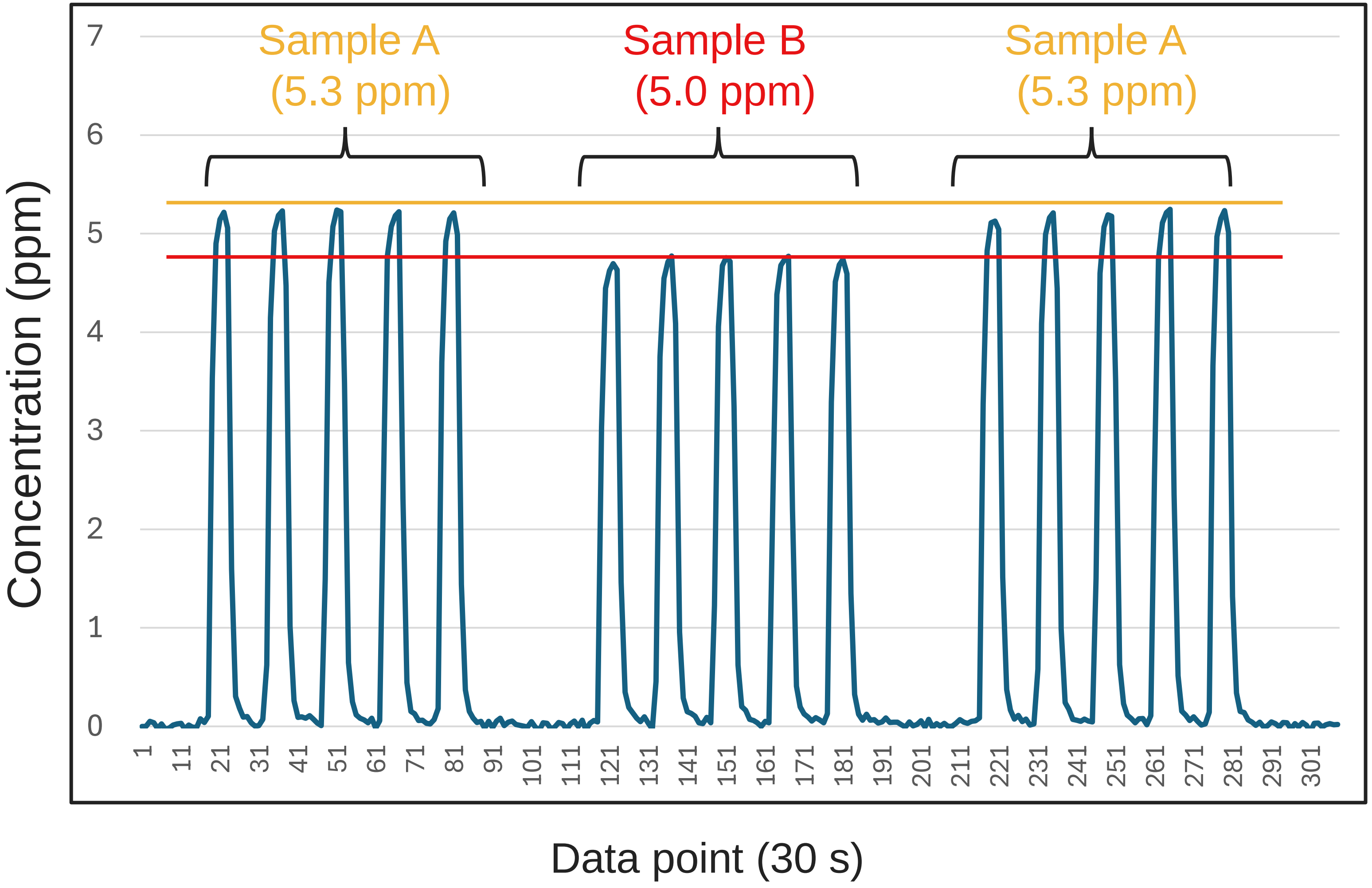
	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6
NMP	600	2200	2400	2800	2850	1900
Moisture	8000	12000	12000	12000	12000	12000

* Ambient : NMP 0 ppm, moisture 12000 ppm



MAX-iR DTGS moisture analysis performance test

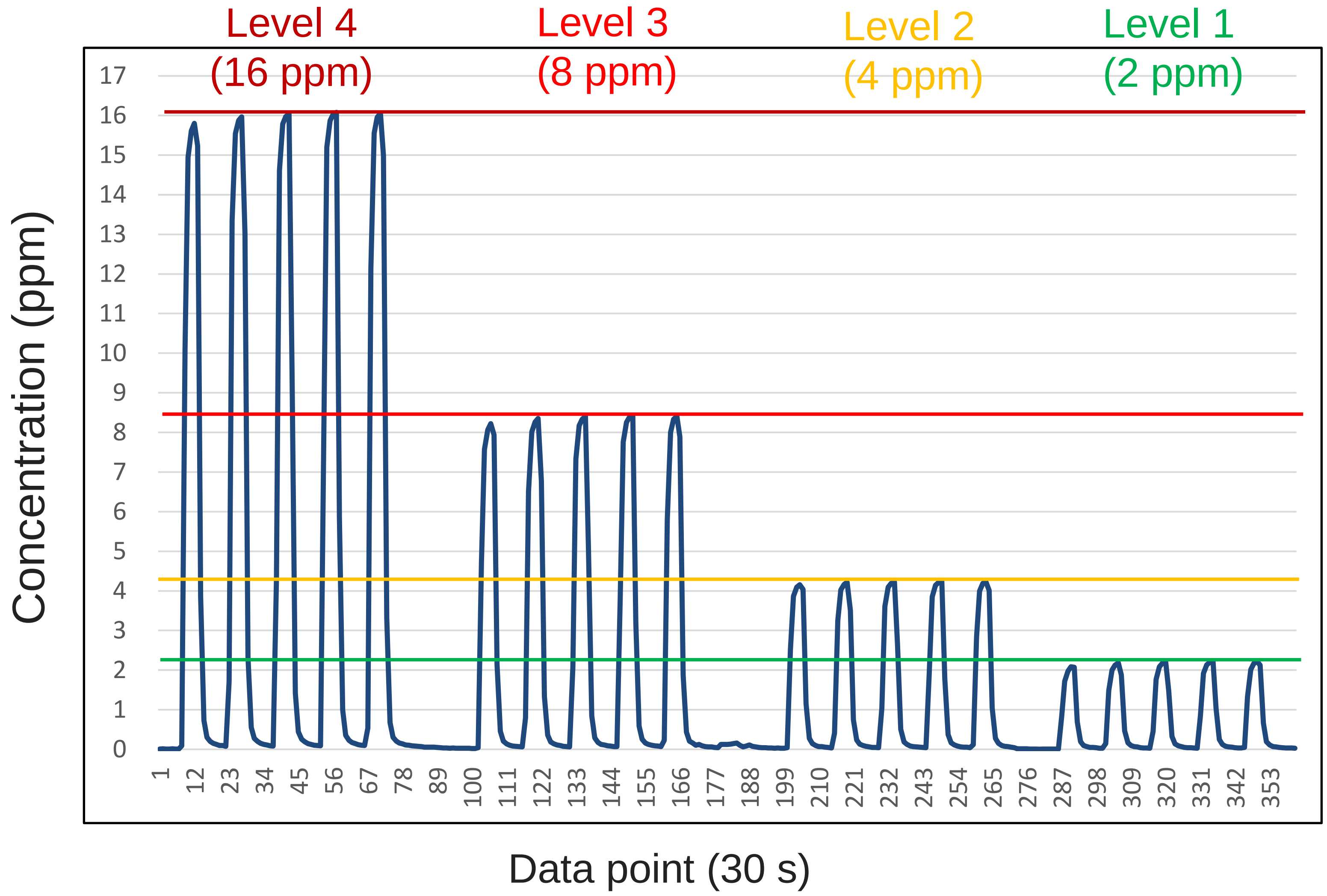
- 5 ppm, 5.3 ppm H_2O in Bulk N2



Repeatability Study Results			
	A	B	A
1	5.272	4.814	5.262
2	5.292	4.818	5.233
3	5.301	4.854	5.267
4	5.272	4.836	5.263
5	5.284	4.802	5.290
Average	5.284	4.825	5.263
STDEV	0.013	0.020	0.020
RSD (%)	0.24	0.43	0.38

MAX-iR DTGS HF analysis performance test

- 16 ppm, 8 ppm, 4 ppm, 2 ppm HF in N2



Repeatability Study Results				
	Level 4	Level 3	Level 2	Level 1
1	15.802	8.015	4.211	2.072
2	15.968	8.220	4.163	2.129
3	16.035	8.355	4.156	2.172
4	16.080	8.406	4.251	2.196
5	16.054	8.389	4.187	2.167
Average	15.988	8.277	4.194	2.147
STDEV	0.112	0.164	0.039	0.048
RSD (%)	0.701	1.976	0.927	2.249

MAX-iR™ FTIR gas analyzer

Thermo Fisher SCIENTIFIC

Reinvent how you solve your most demanding process and environmental gas analysis needs

Value

- ppb-ppt sensitivity while maintaining all the benefits of real-time FTIR
- Simultaneous analysis of many gases
- Always online

Positioning

- Eliminate the need for costly GC analyzers
- Replace multiple single-component analyzers (TDLAS, ND-IR, CRDS)

Benefits

- Minimum maintenance, low cost of ownership
- 24/7 unmanned operation with out need for calibration
- Compact size 5U – 19inch Standard rack

2 Battery abuse and thermal runaway

Undesirable properties

Use and abuse of the cells can lead to catastrophic failures

- Overcharging
- Impact/puncture
- Internal shorts
- Heat accumulation

- Thermal runaway
- Highly reactive raw materials
- Fires difficult to extinguish
- Toxic vapors generated on failure

Image from the Fire Safety Research Institute

The chemistry of LiB Failure

Failure leads to a cascade of complex reactions

- Overcharging

$$CH_3OCO_2CH_3 + 2e^- + 2Li^+ \rightarrow 2CH_3OLi + CO$$

$$CH_3OCO_2CH_3 + 2e^- + 2Li^+ + H_2 \rightarrow Li_2CO_3 + 2CH_4$$

$$CH_3OCO_2CH_3 + e^- + Li^+ + 0.5H_2 \rightarrow CH_3OCO_2Li + CH_4$$

- Thermal runaway

$$(CH_2OCO_2Li)_2 \rightarrow Li_2CO_3 + C_2H_4 + CO_2 + 0.5O_2$$

$$2Li + C_3H_4O_3 \rightarrow Li_2CO_3 + C_2H_4$$

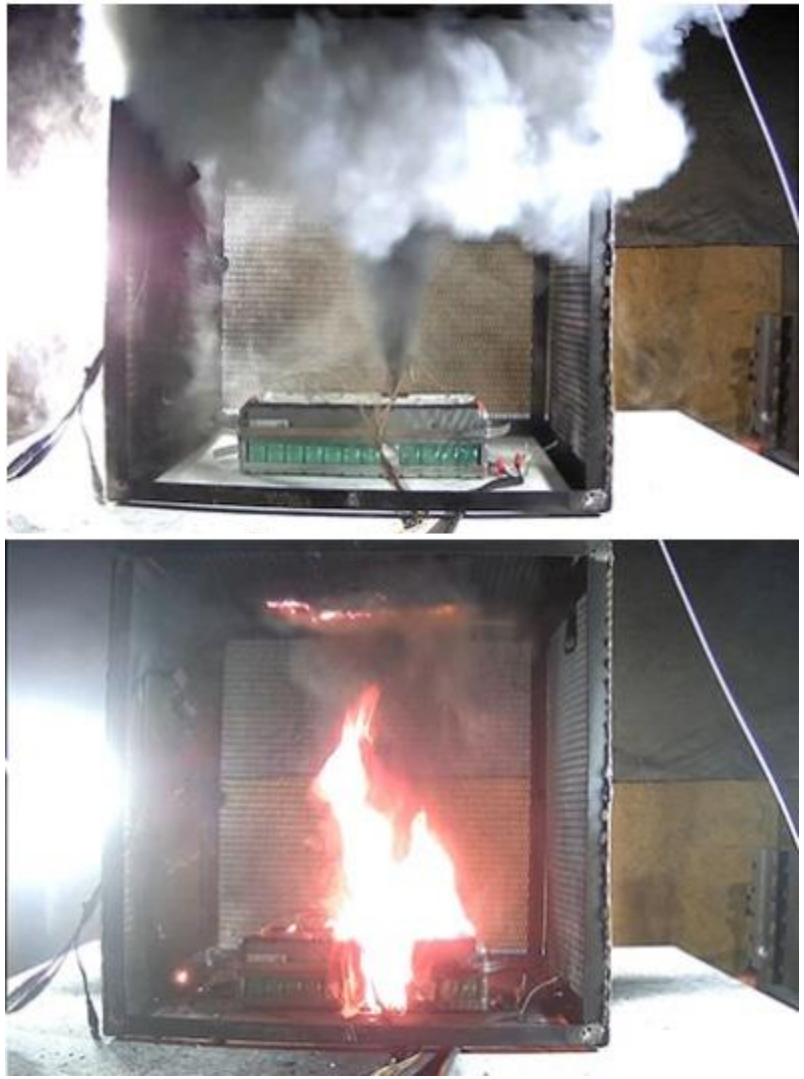
$$2Li + C_4H_6O_3 \rightarrow Li_2CO_3 + C_3H_6$$

$$2Li + C_3H_6O_3 \rightarrow Li_2CO_3 + C_2H_6$$

$$LiPF_6 \rightarrow LiF + PF_5$$

$$PF_5 + H_2O \rightarrow POF_3 + 2HF$$

$$LiPF_6 + H_2O \rightarrow LiF + POF_3 + 2HF$$



Images from Physics World/UL Research Institute Webinar “Characterization of Li-ion battery thermal runaway in ESS’s and EV’s”

Real – Time smoke analysis

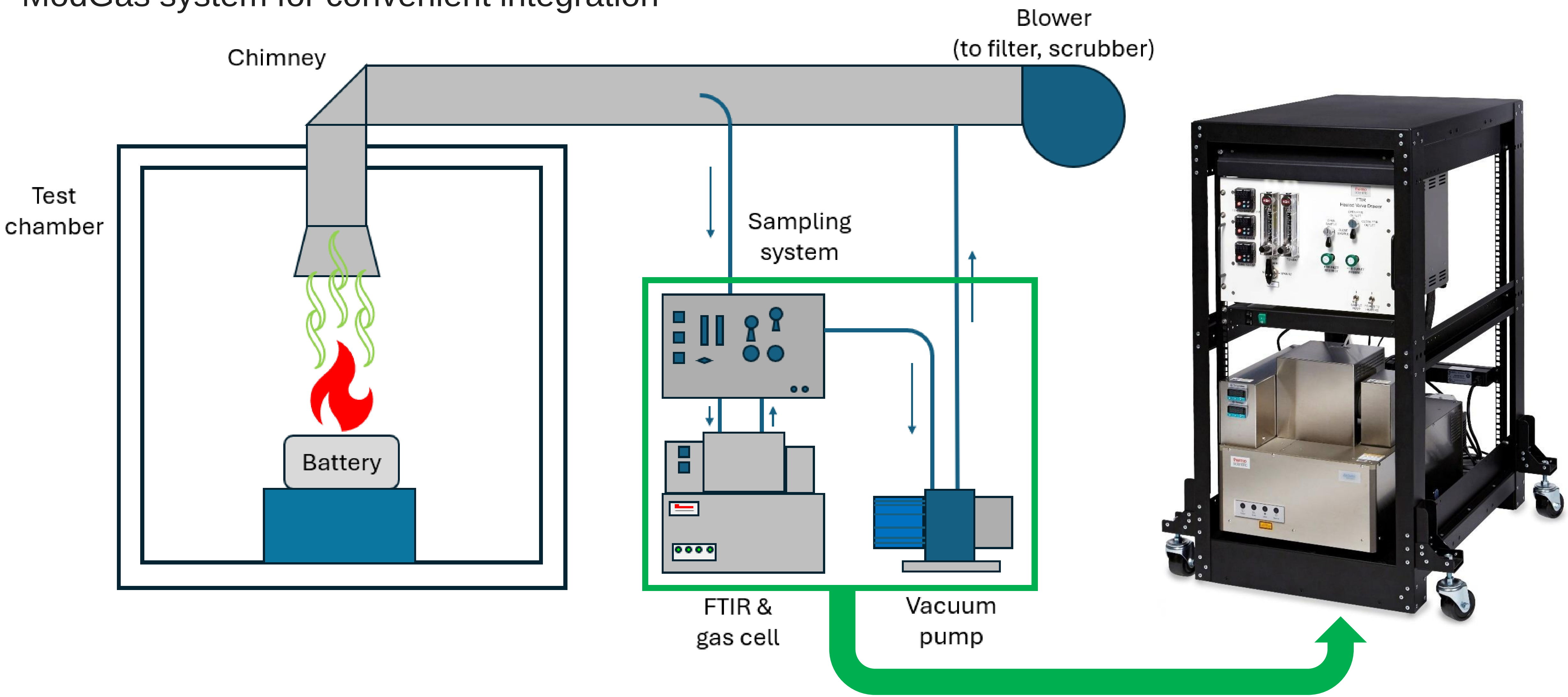
Thermo Fisher's Antaris IGS Solution for LiB Smoke Testing

- Capabilities
  - Real-time analysis of multiple gases
  - Quantitation across several orders of magnitude (ppm to %)
  - Collected data can be re-analyzed
    - Identify unknown vapors
    - Augment quantitative methods to include new species
  - Approved technique for EN/ISO smoke toxicity testing

- Possibilities
  - Understanding battery failure mechanisms
  - Evaluating smoke toxicity
  - Supporting development of new LiB materials, flame retardants

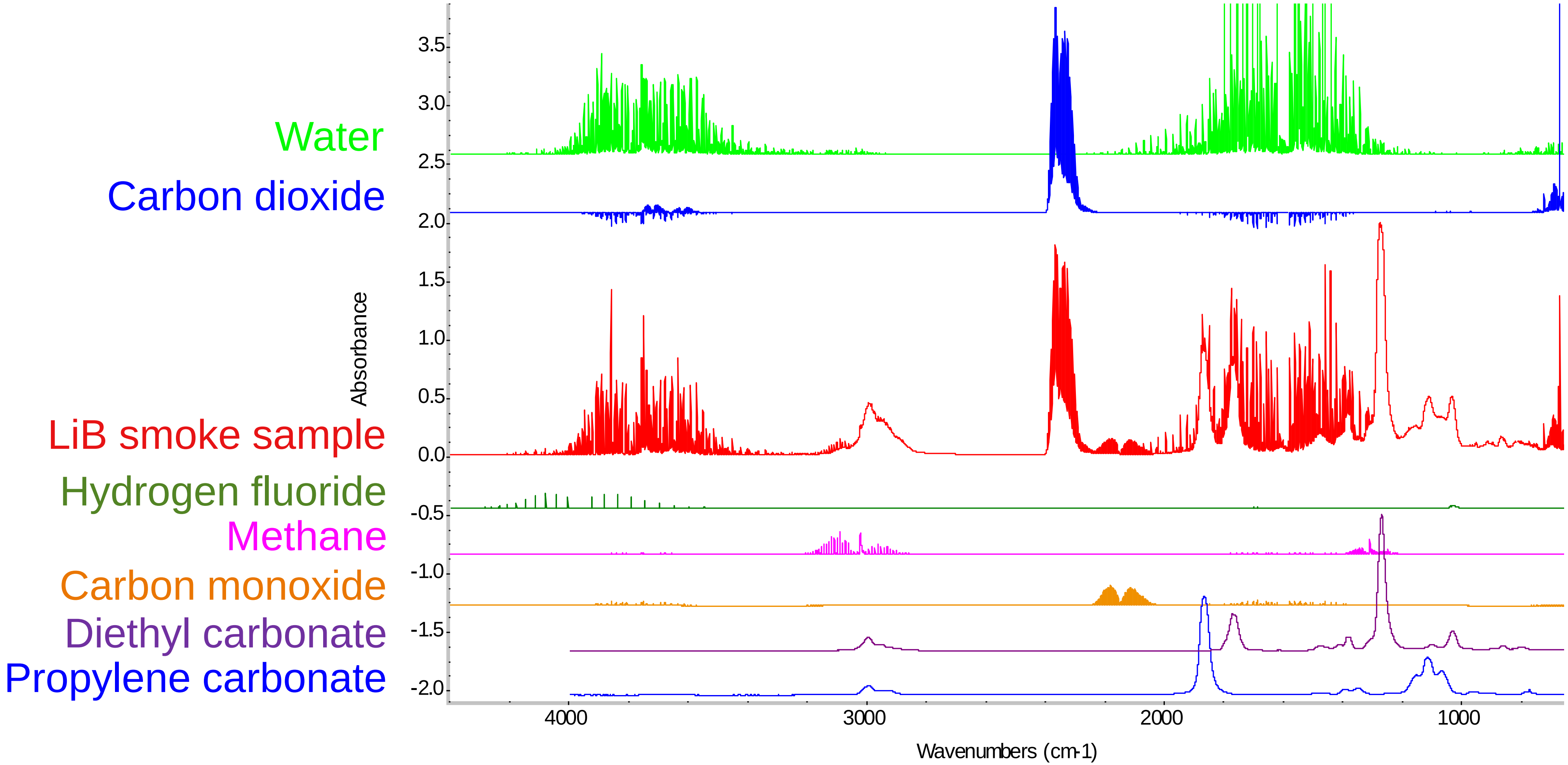
Typical test configuration

ModGas system for convenient integration



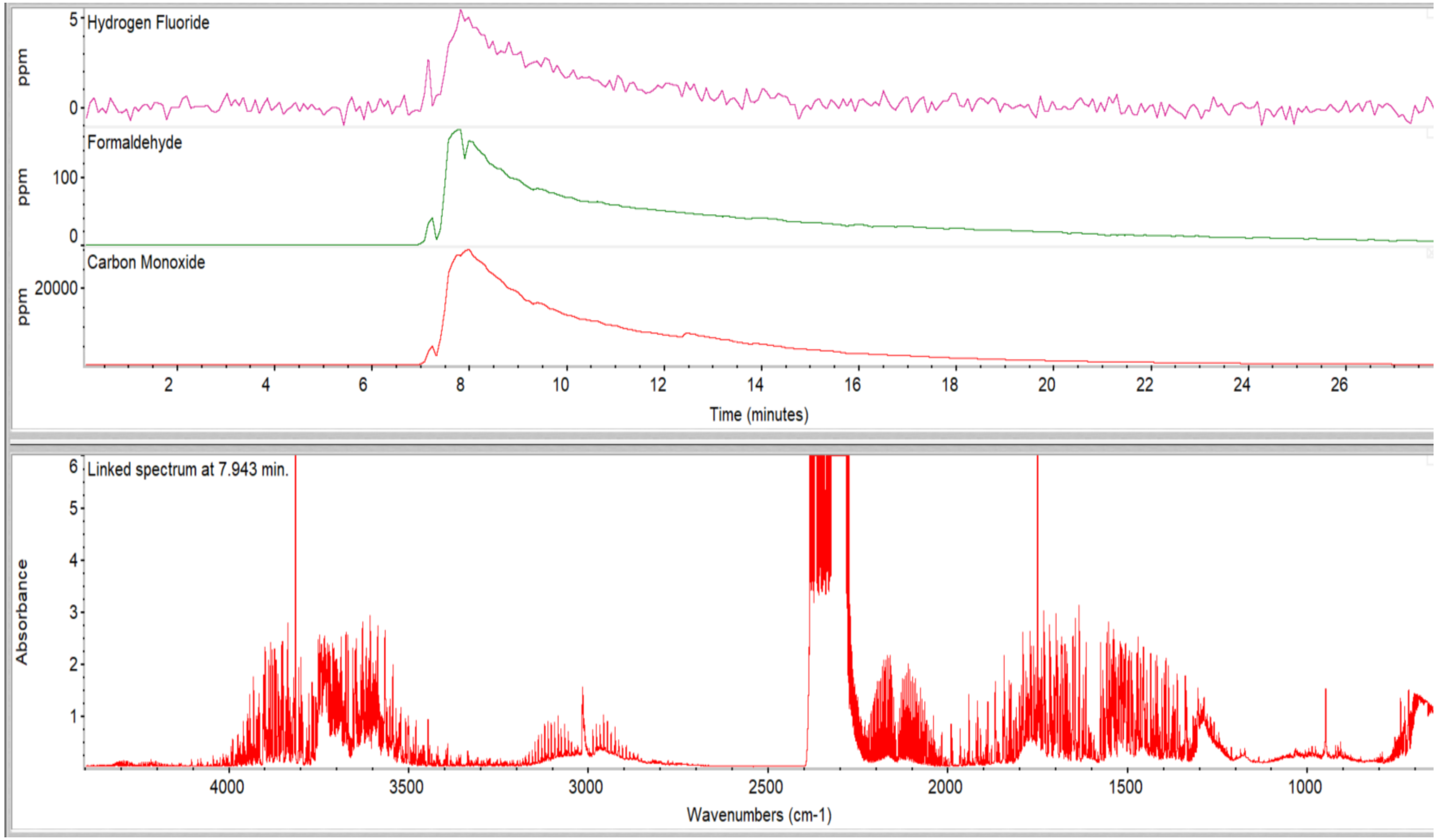
Example spectrum, thermal abuse of cells

Complex mixture of species



Real-Time analysis

Data-rich experiments enabled by purpose-built systems

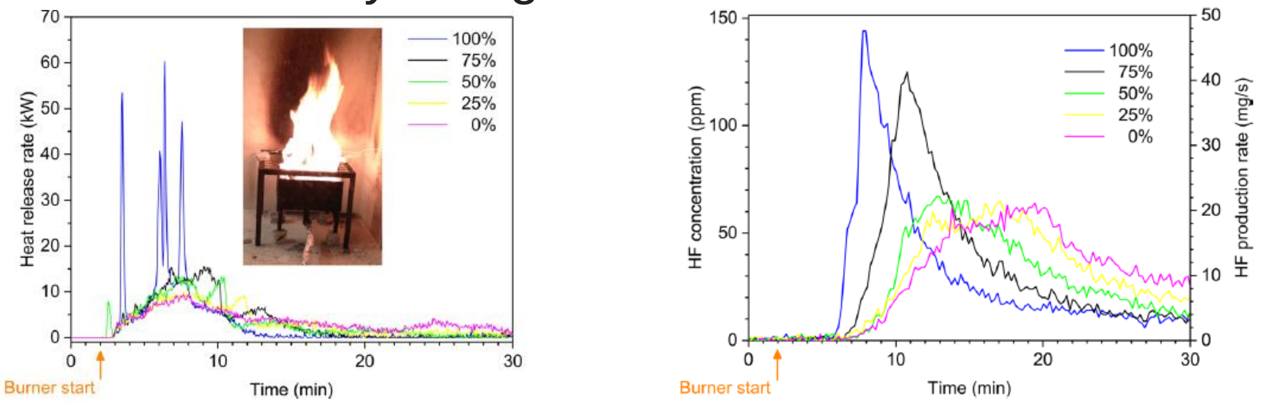


- Sampling rate up to 1 spectrum per second
  - MCT detector
  - Concentration charted during measurement
  - Real-time measurement of 25+ species
  - Real-time P and T correction

“Toxic fluoride gas emissions from lithium-ion battery fires”

Analyzing HF emitted by burning cells (Chalmers University of Technology, Safety and Transport RISE Research Institutes)

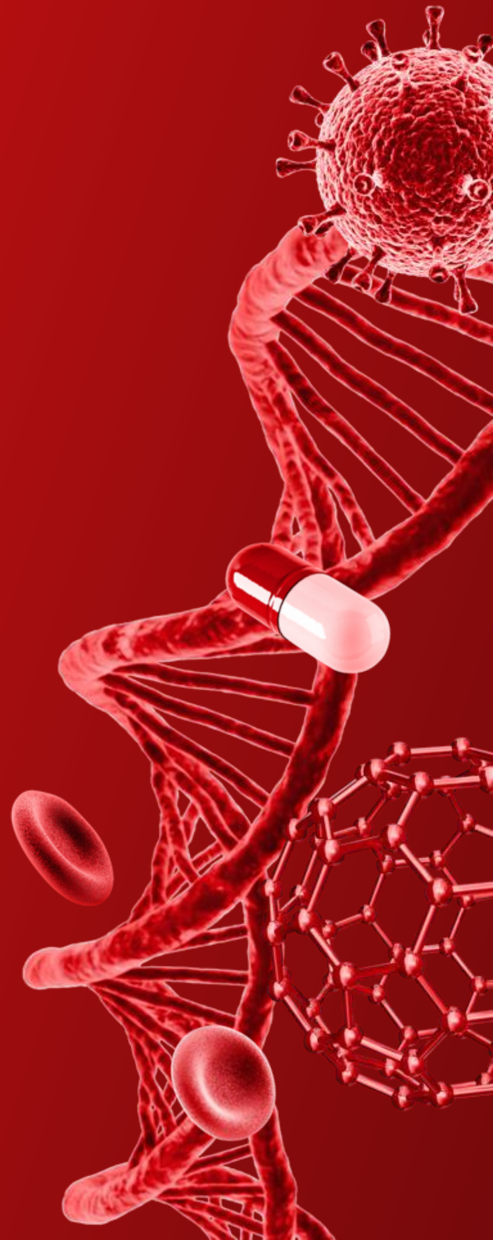
- HF emissions tested
  - Battery type
  - Orientation
  - Charge state
- Testing revealed correlation between Heat Release Rate (HRR) and HF concentration
- Rate of HF emission is affected by charge state



Fredrik Larsson et al., “Toxic Fluoride Gas Emissions From Lithium-ion Battery Fires,” *Scientific Reports* 7, no. 1 (August 24, 2017), https://doi.org/10.1038/s41598-017-09784-z.

Thank you

Questions?



The Future of Battery Safety at WMG

Dr Simon Jones
Chief Engineer –Energy Innovation Centre

10th April 2025

WMG
THE UNIVERSITY OF WARWICK

The Future of Battery Safety at WMG

WMG
THE UNIVERSITY OF WARWICK

Roadmap

- **Current State**
- Safety Needs
- Future State

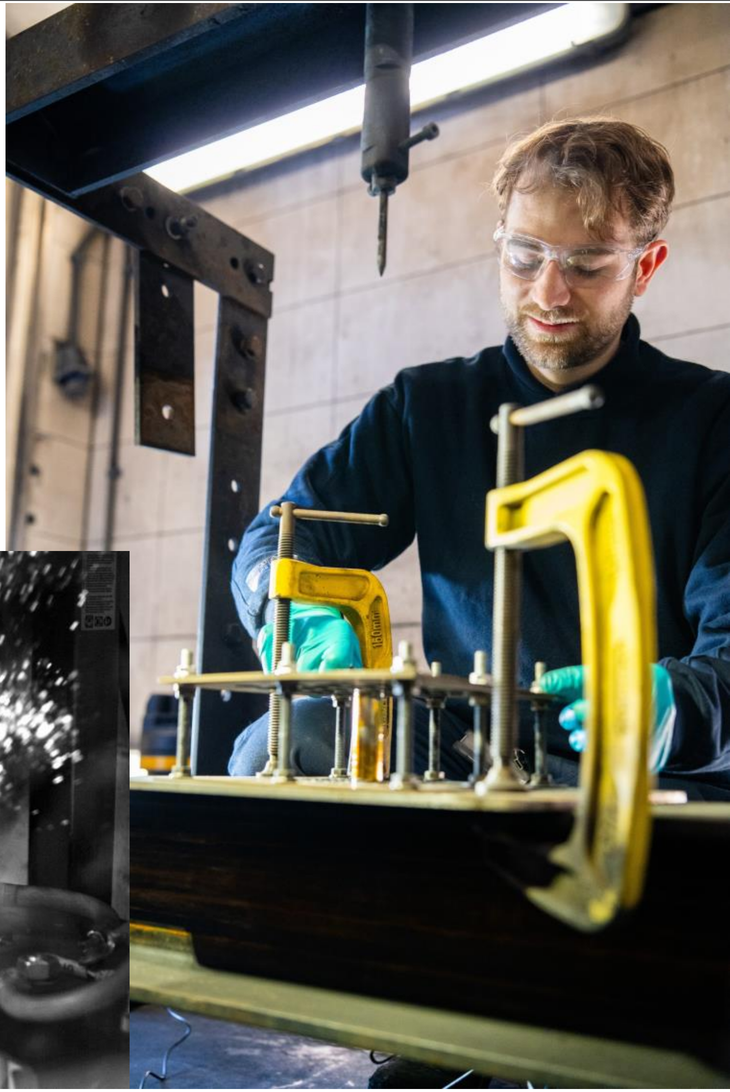
Current Facilities

- 7 abuse chambers
  - Fire rated with over-pressure protection
  - Gas detection and sprinklers
  - Vent gasses are wet scrubbed
  - Temperature controlled
- Measurement of
  - Temperature
  - Gasses/smoke/vapour (MS/FTIR)
  - Chamber pressure
  - High speed cameras
  - Thermal imaging
- Accelerating rate calorimeter (ARC) testing
- Cyclers for electrical abuse conditions

Expertise

WMG
THE UNIVERSITY OF WARWICK

- Focus on high quality science, not certification
- Unparalleled experience over 15 years operations
- Advanced test methodology development
- In cell sensing of temperature and pressure, before and during failure
- Multi-sector involvement including automotive, aerospace and micro-mobility
- Cell and system scale analysis, including mitigation methods against propagation
- Investigation of failure through simulation and modelling
- Providing specific, hands-on training in battery abuse methodology.



Typical test

Progressive failure of 4 x 80 Ah pouch cells with fire barrier

Current Limitations

- Central Campus Location
- Hazards:
  - Over-pressure
  - Conflagration of vapour clouds
  - Potential for fragmentation of Large Format Cells
  - Smoke
- Mitigations:
  - Stringent safety limit for "size" of any single event
  - Our wet scrubbers are effective at making the emissions safe
- However, people are sensitive to visible smoke and odour
- Lack of space for support facilities

The Future of Battery Safety at WMG

WMG
THE UNIVERSITY OF WARWICK

Roadmap

- Current State
- **Safety Needs**
- Future State

UK Industry Needs

- WMG has unique capabilities, differentiated versus
  - industrial providers through research focus
  - universities through abuse chambers capability and capacity
- However, industry needs are evolving rapidly
  - Large format cells are now typical
  - So cell cluster tests require a minimum ≈300 Ah capability
  - Module or pack testing requires space and freedom to operate
- Large scale Capability
  - Some OEMs now have at least medium scale capability
  - Test house capabilities are also significant
  - Also, HSE Buxton and University of Sheffield
- UK National Capability
  - FBC Battery Safety Project study
  - Currently unmet demand for "specialised safety infrastructure"
  - Compare with the RISE facility in Sweden

Blast / Overpressure

Problem

- Vapour cloud explosion, or deflagration
  - "only" a couple of hundred mbar over-pressure
  - destroy masonry walls
  - deform shipping containers
  - if uncontained then flying debris is a risk

Fire

Problem

- Energy release from kWh of cells
  - fireball/burning smoke layer/flame jets
  - flames may reach 1200°C, but typically 800°C
  - durations up to 30 minutes
  - additional fuel from module components

Emissions

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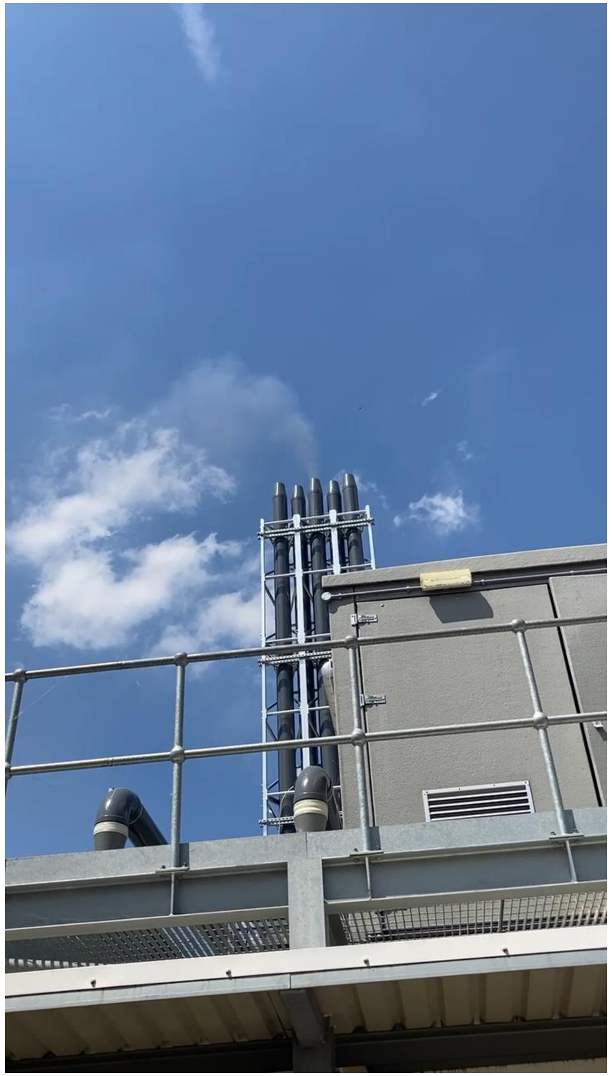
Problem

- Smoke and hot gasses
    - sooty particulates (visible as black smoke)
    - odour, largely from burning polymers
    - toxic gasses, including HF
- Nuisance is very weather dependant
- People are very sensitive to odours



The Future of Battery Safety at WMG

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Roadmap

- Current State
- Safety Needs
- **Future State**

New WMG Battery Safety Centre

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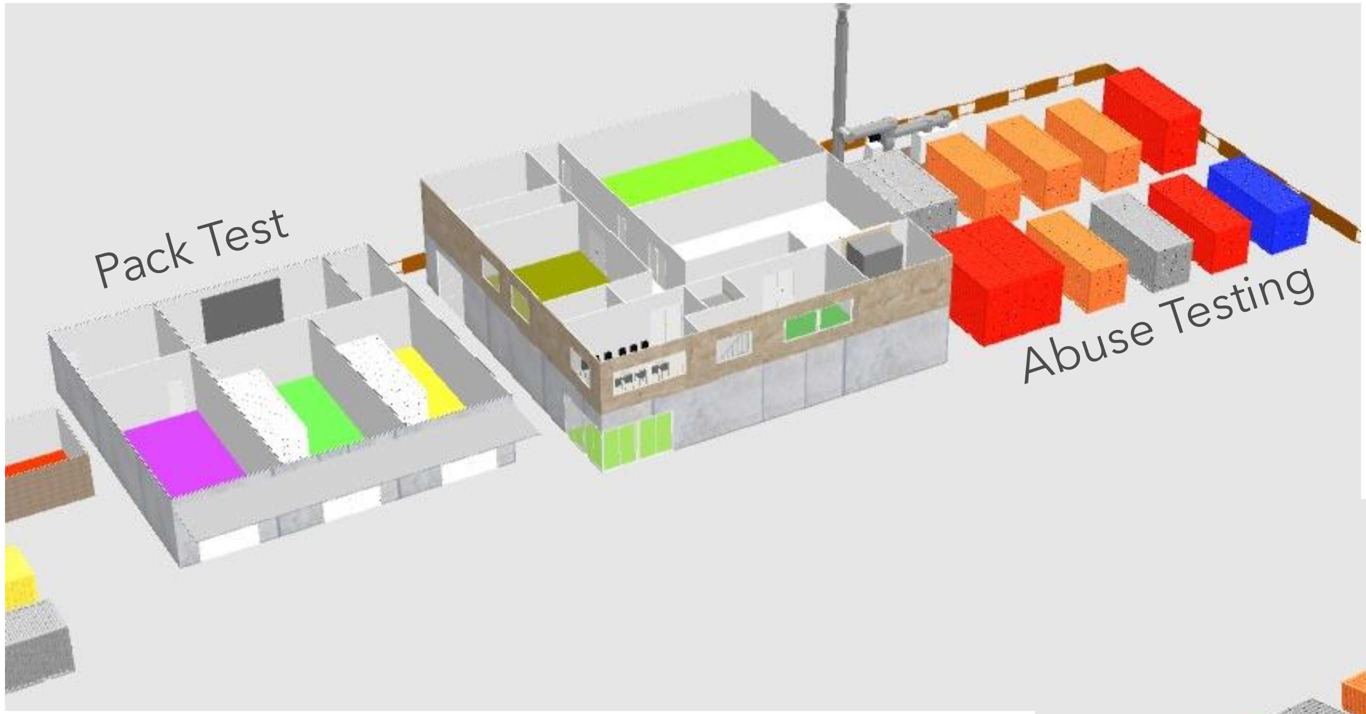
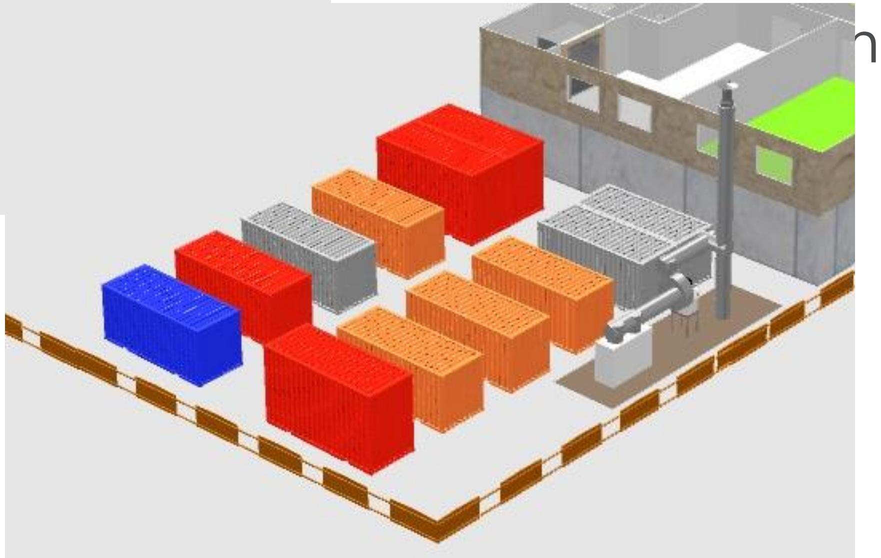


Investment for the future

- New campus site for battery testing
- Phase one: New Safety Centre
ng Summer 2026



CATAPULT
High Value Manufacturing

New WMG Battery Safety Centre

WMG
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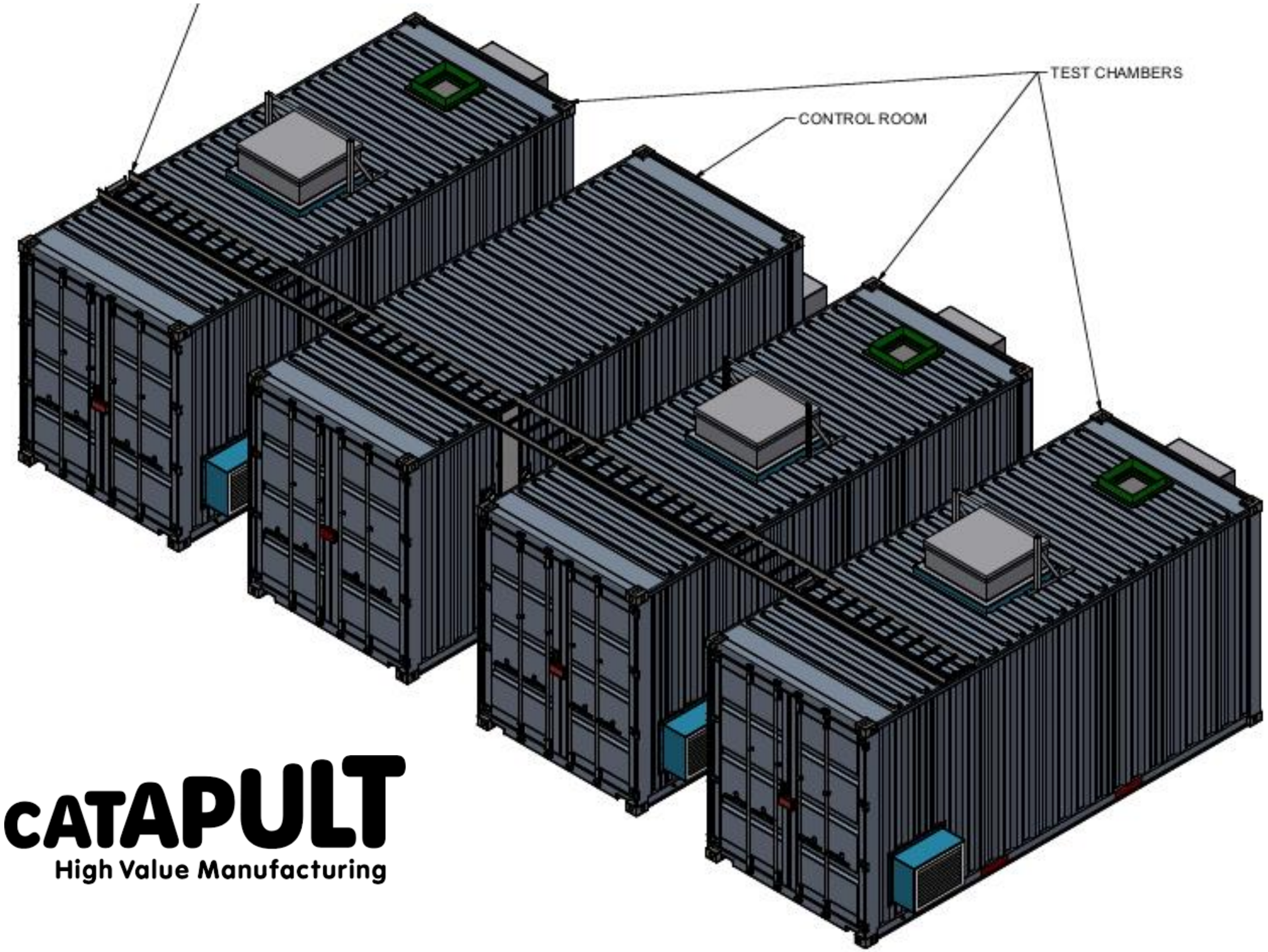
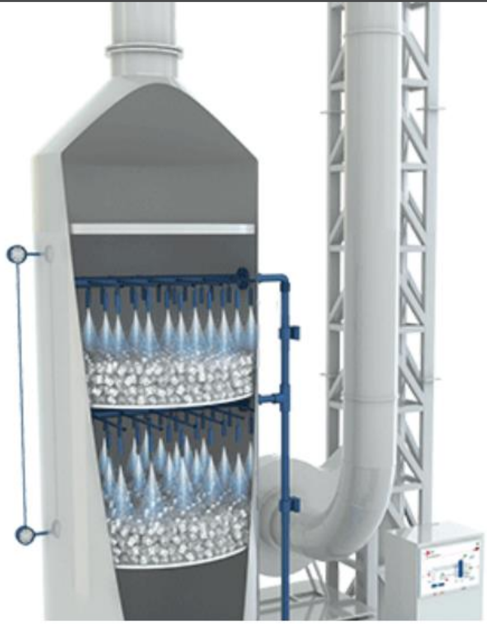
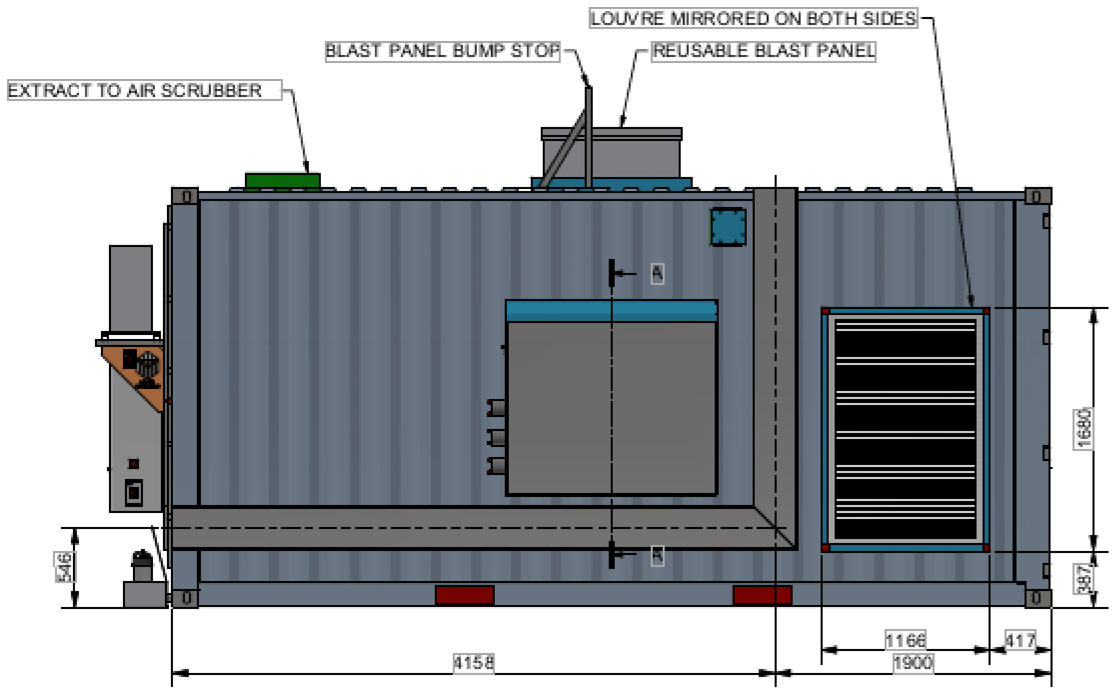




- £1.2M Investment
- Containerised facility
  - Three 20′ test chambers
  - Separate control room
  - High-capacity wet scrubber

CATAPULT
High Value Manufacturing

New WMG Battery Safety Centre



Features

- Capable of module level testing
- Blast panels
- Over-pressure measurement
- Gas alarms
- Water mist fire suppression
- FTIR/H_2/0_2 chamber gas measurement
  (can also serve as a room calorimeter)
- Stack Continuous Emissions System

New WMG Battery Safety Centre

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Vision

- Data rich Large Format Cell and module level testing
- Accurate characterisation of event severity
  - Over-pressure data
  - Real time toxicity and explosion risk
  - Module level calorimetry (heat release rates)
- Environmentally responsible

Thank you.

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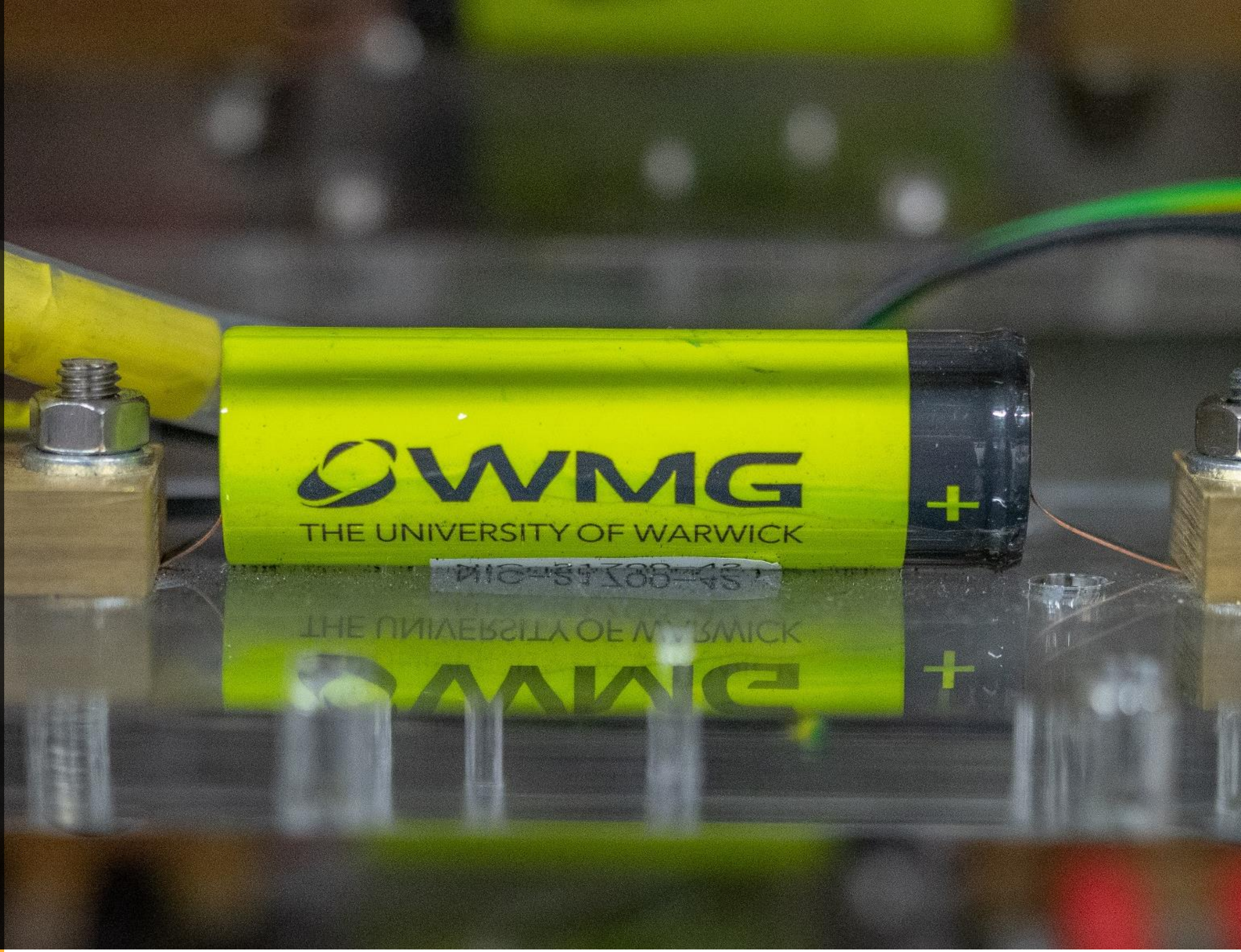
Developing methods for sidewall rupture evaluation in cylindrical lithium-ion cells



Elliott Read
Lead Engineer
WMG

Battery Safety UK

10th April 2025

WMG
THE UNIVERSITY OF WARWICK

Background

Graduated from The University of Sheffield (MChem)

July 2018

July 2019

Joined the HSE as a Battery Research Scientist

Joined WMG as a Project Engineer

January 2022

Oct 2022

Lead Engineer

Meant to be working with BritishVolt!

Joined the SafeBatt project

Sept 2023

April 2025

Battery Safety UK

Background

Sidewall rupture research

Joined WMG as a Project Engineer

January 2022

Oct 2022

Lead Engineer

Meant to be working with BritishVolt!

Joined the SafeBatt project

Sept 2023

April 2025

Battery Safety UK

Sidewall rupture (SWR)

What is it?

Why do we care?

What can we do about it?

Part 1

SWR: What is it?

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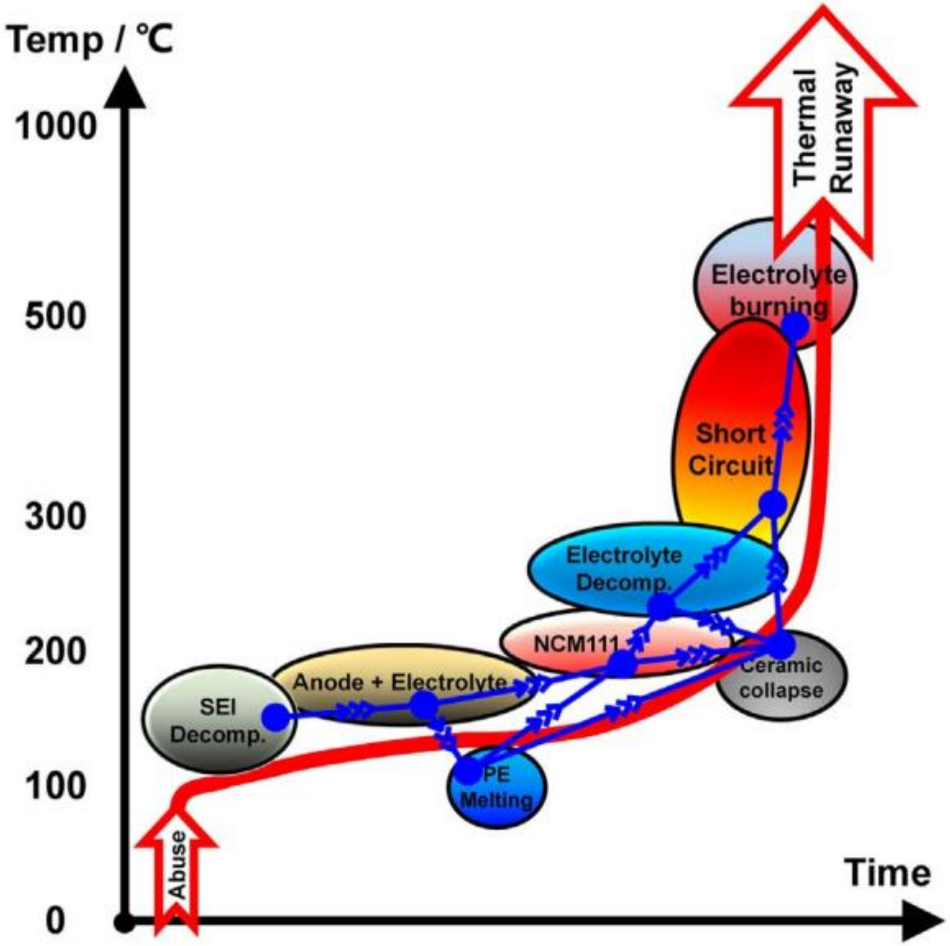
What is it?



[Thermal runaway mechanism of lithium ion battery for electric vehicles: A review]()

What is it?

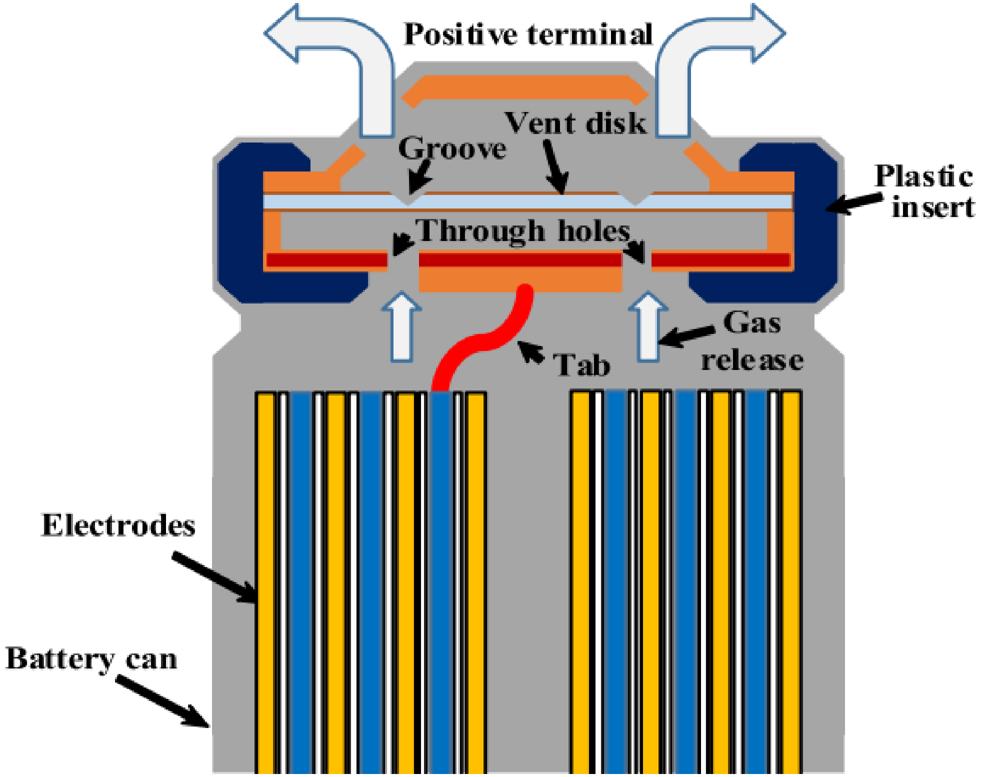


FIGURE 1. A typical safety vent in a cylindrical Li-ion battery. The hollow arrows indicate the pathway to release the gases inside the battery [34].

[Reliability of Cylindrical Li-ion Battery Safety Vents]

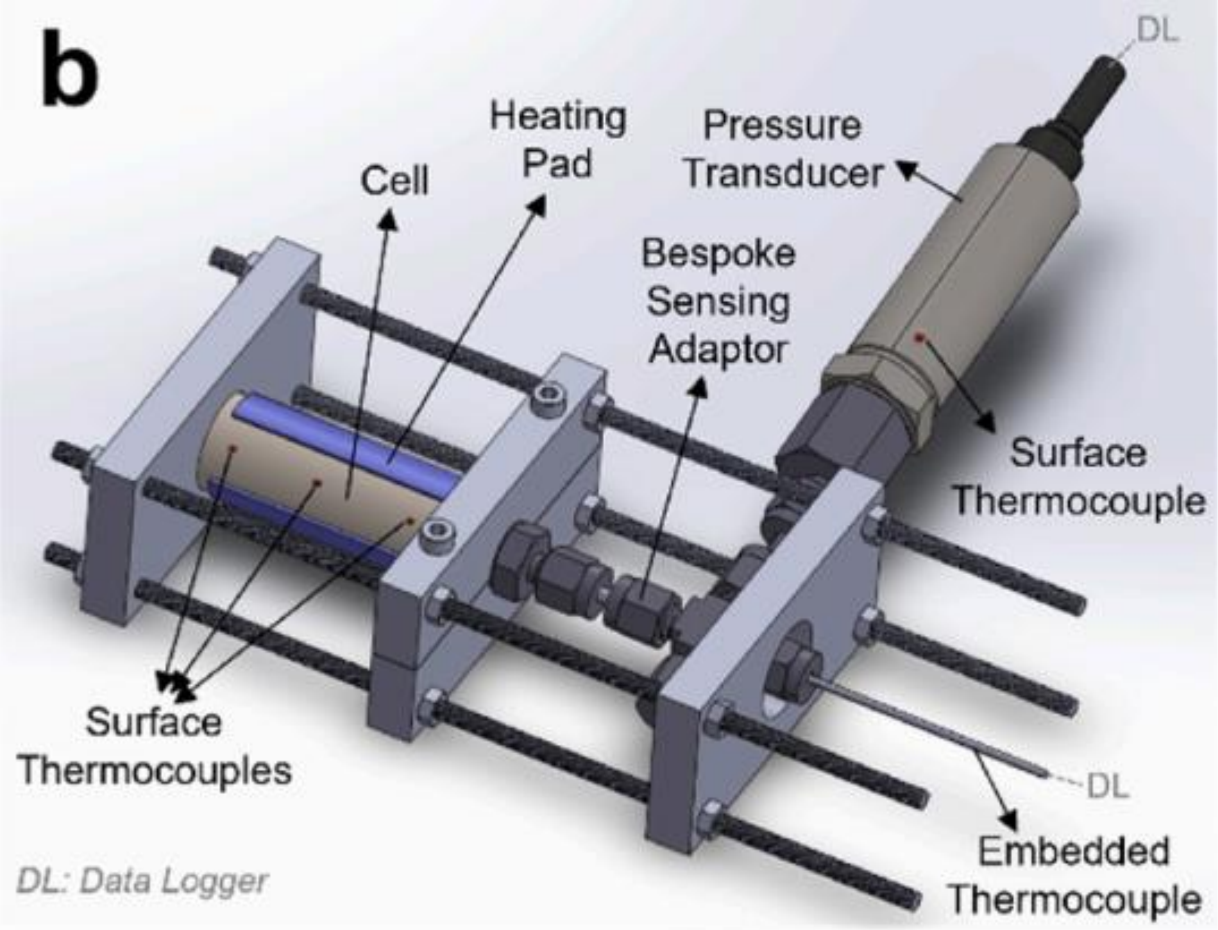
What is it?

[Identifying the Cause of Rupture of Li-Ion Batteries during Thermal Runaway]

What is it?

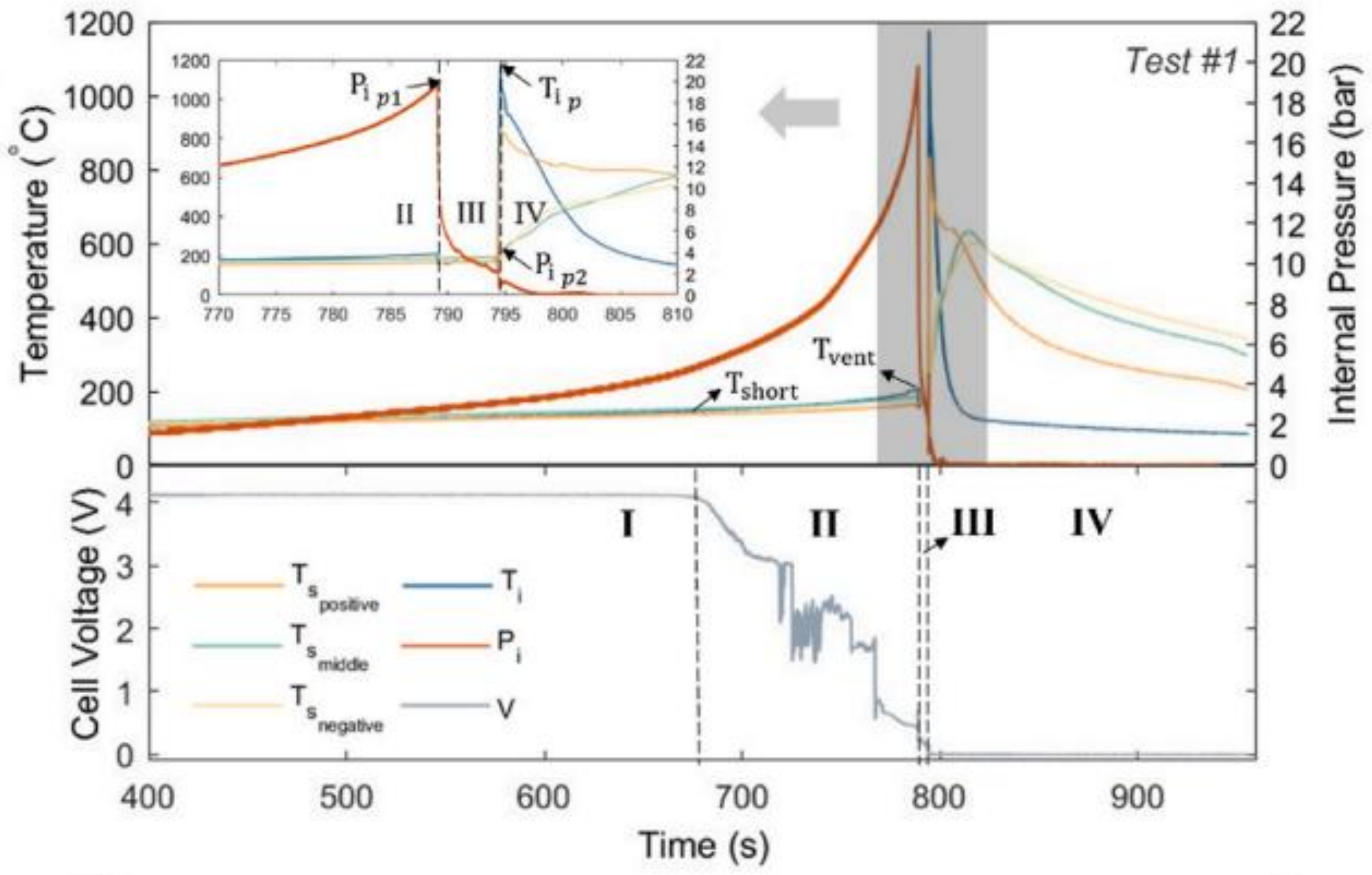
What is it?

Begum Gulsoy



[Real-time simultaneous monitoring of internal temperature and gas pressure in cylindrical cells during thermal runaway]

What is it?



Begum Gulsoy

~ 20 bar

Internal pressure at vent

~ 200 °C

Surface temperature at vent

Real-time simultaneous monitoring of internal temperature and gas pressure in cylindrical cells during thermal runaway

What is it?

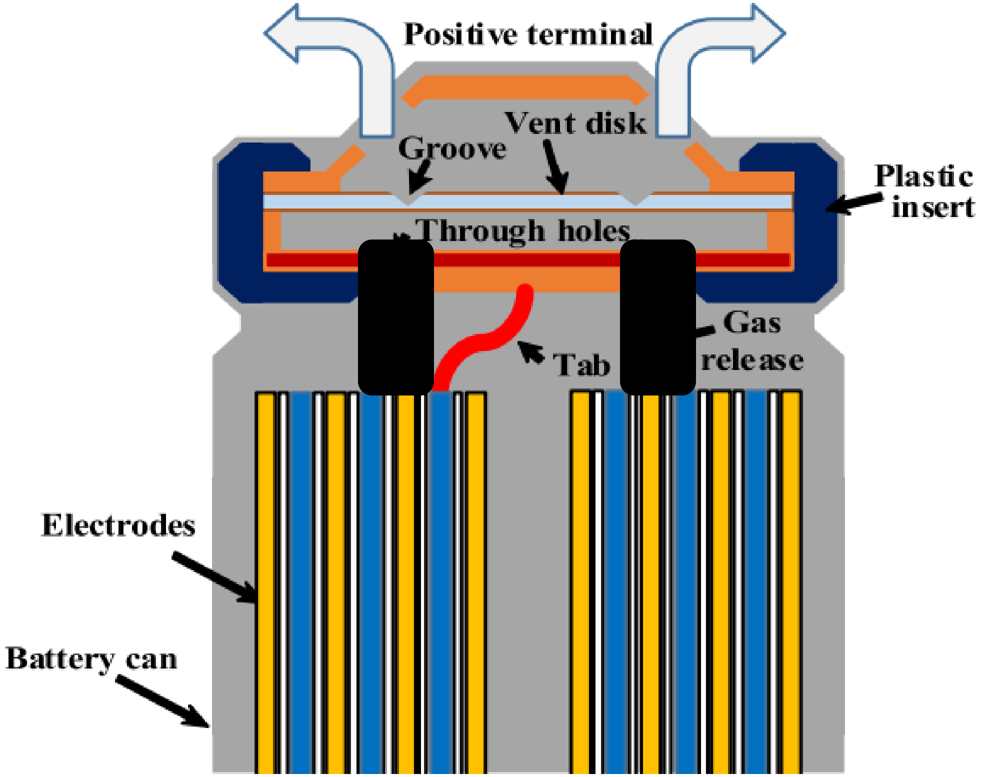


FIGURE 1. A typical safety vent in a cylindrical Li-ion battery. The hollow arrows indicate the pathway to release the gases inside the battery [34].

What if?

Clogging?

$$\frac{dP}{dt} > threshold\,?$$

[Identifying the Cause of Rupture of Li-Ion Batteries during Thermal Runaway]

What is it?

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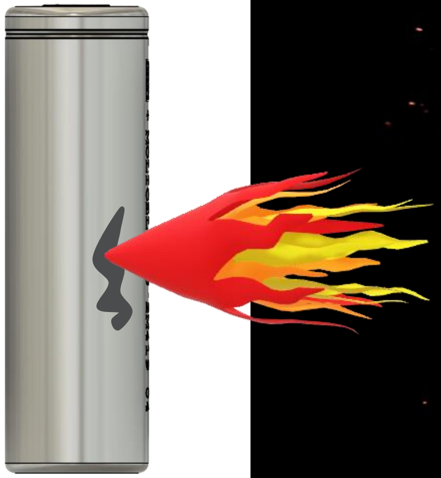

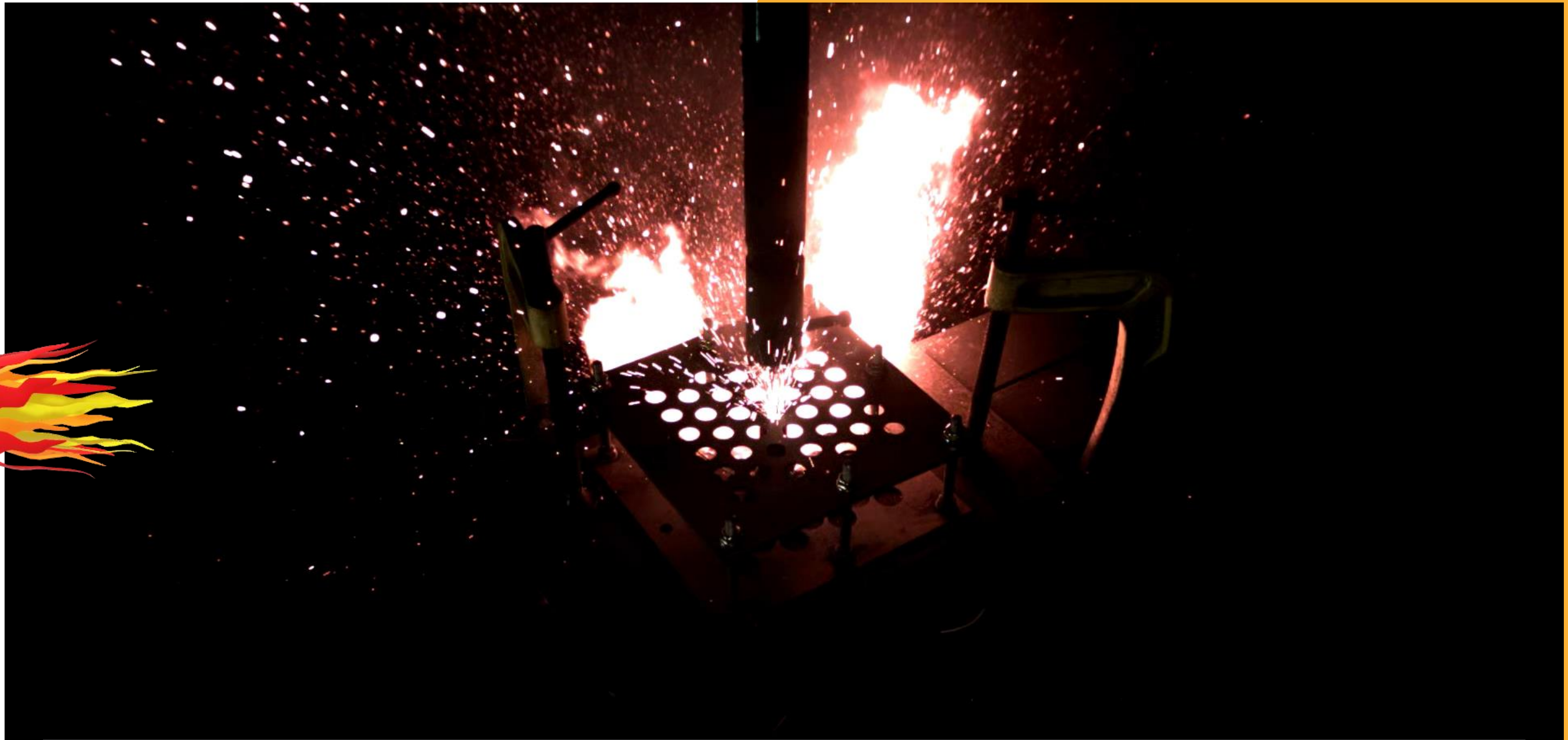

Sidewall rupture

What is it?

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*Sidewall rupture is a failure mode in cylindrical lithium-ion batteries. It is a **rare** but **severe** failure mode, exhibited when cell pressure relief safety mechanisms do not operate as designed. In sidewall rupture, **energy is released quickly**, often with high velocity directional jet flames, facilitated by the rupture of the sidewall of the cell casing.*

Part 2

SWR: Why do we care?

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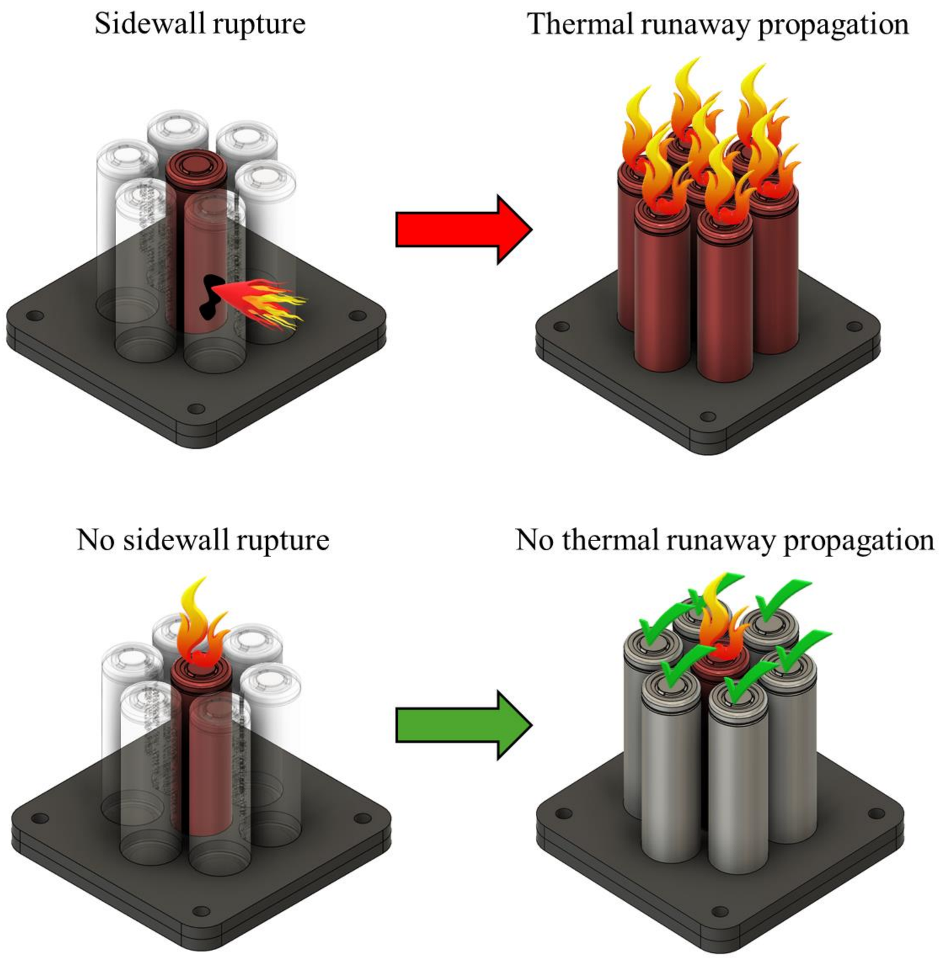
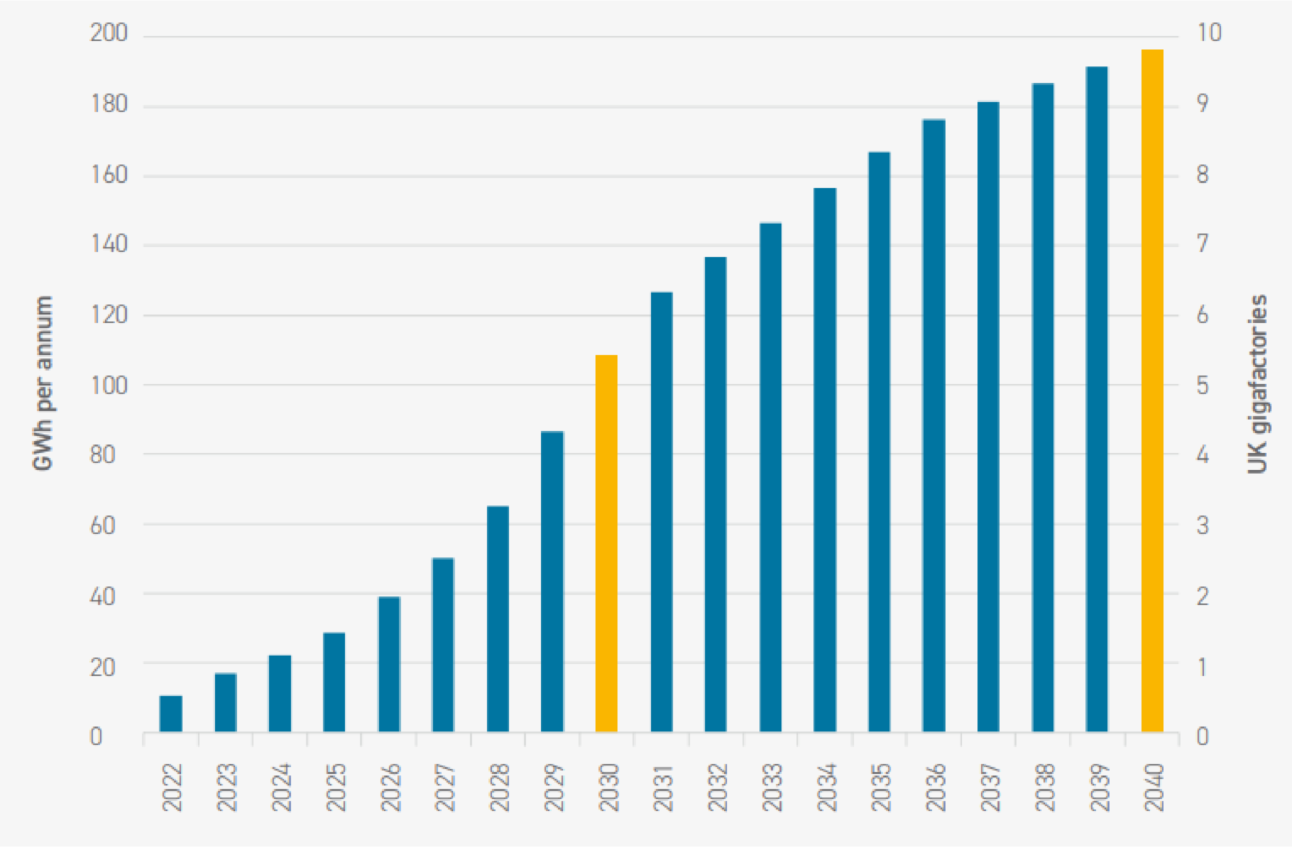
Why do we care?



SWR = TRP

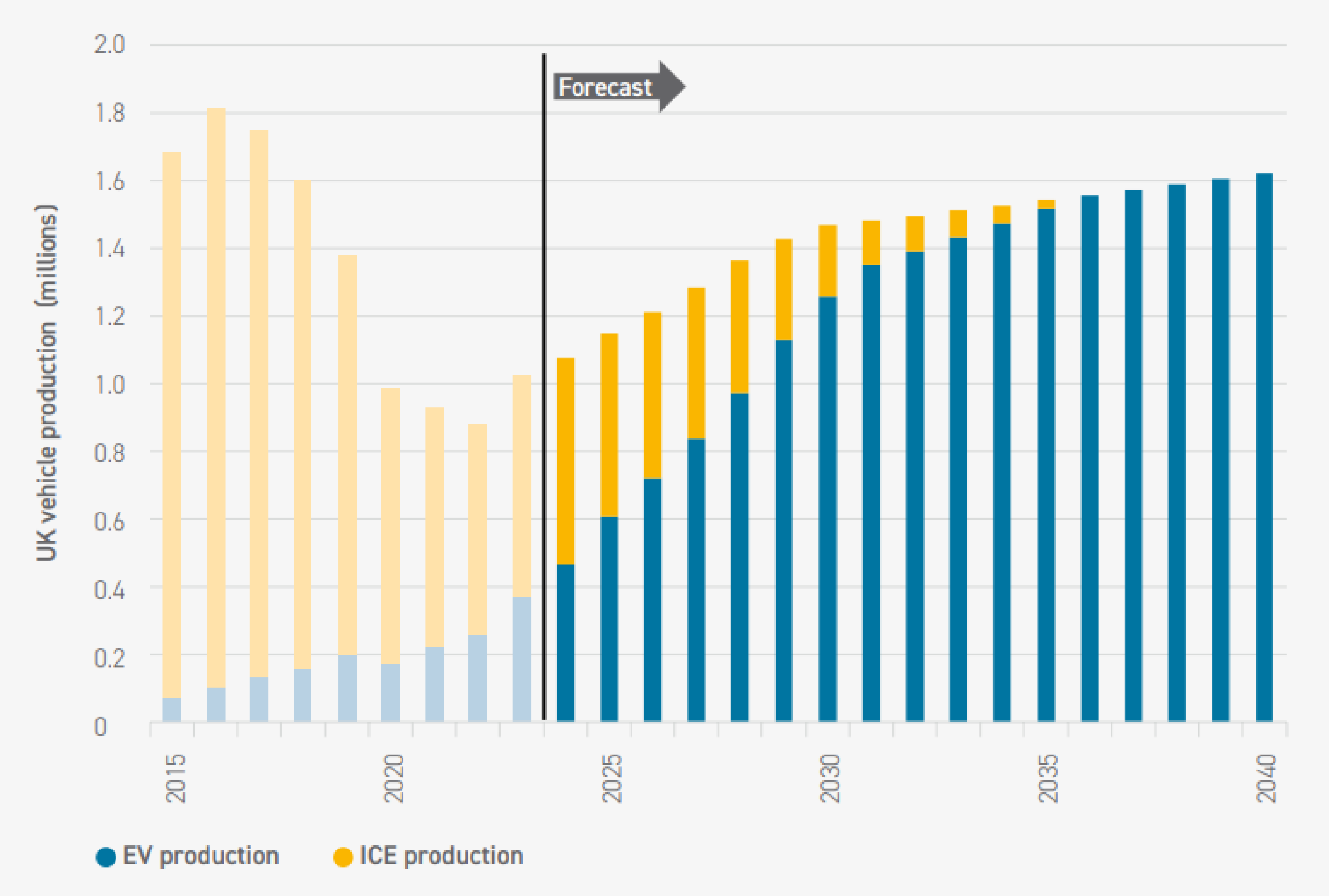
TRP = Thermal runaway propagation

Why do we care?



[Faraday Institution: UK Electric Vehicle and Battery Production Potential to 2040]

Why do we care?



[Faraday Institution: UK Electric Vehicle and Battery Production Potential to 2040]()

Why do we care?

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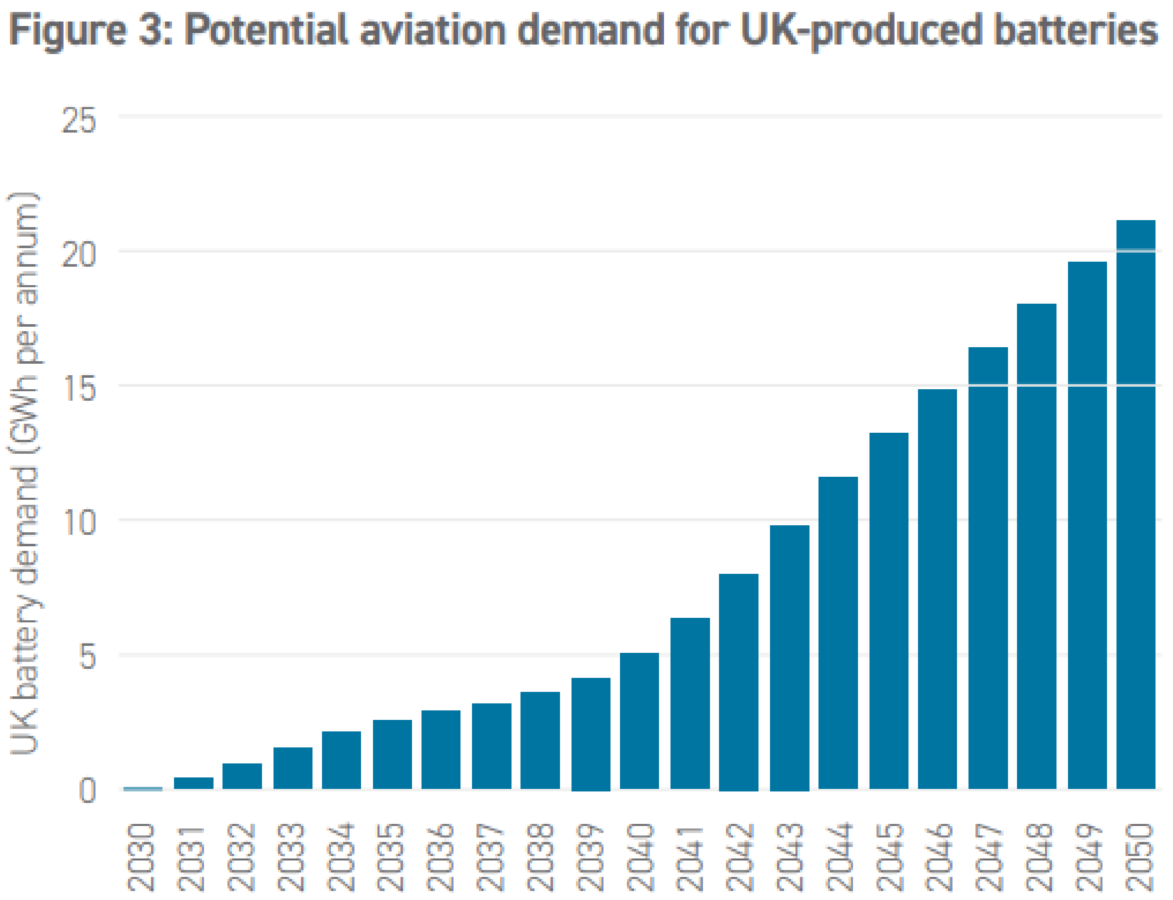
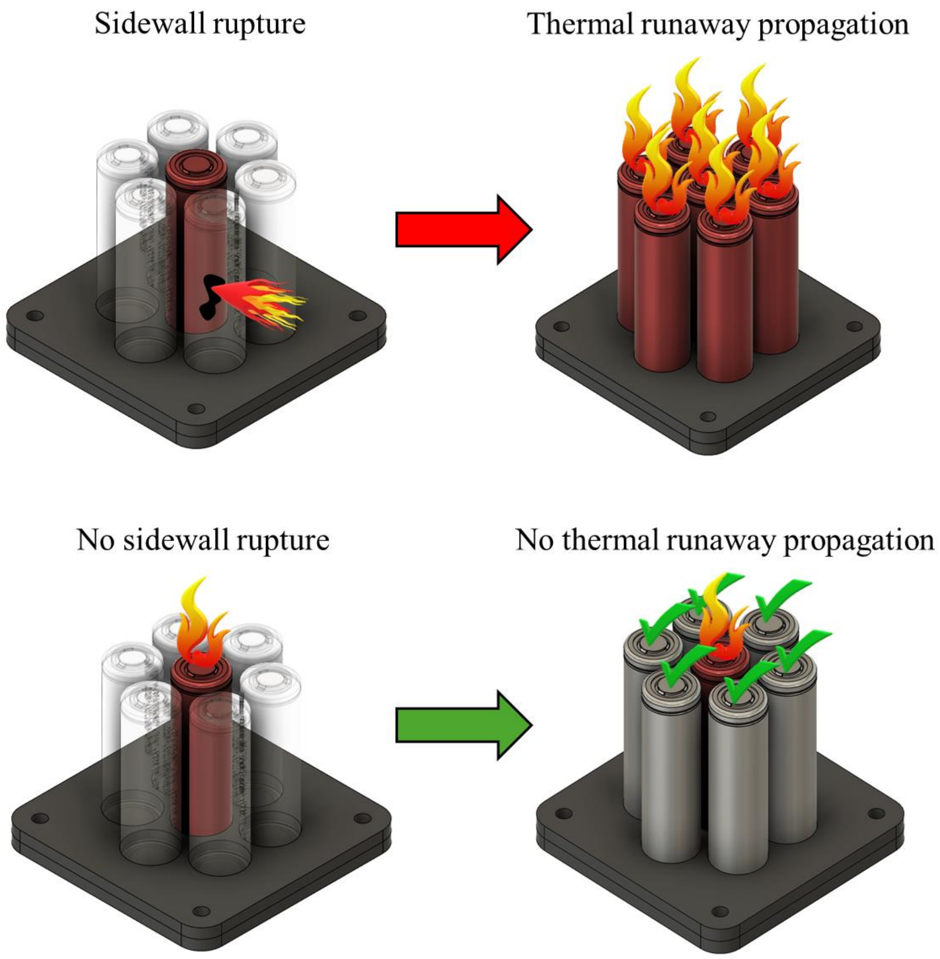


Faraday Institution Insights 19: Powering the Skies: The Rise of Electric and Low-Carbon Aircraft

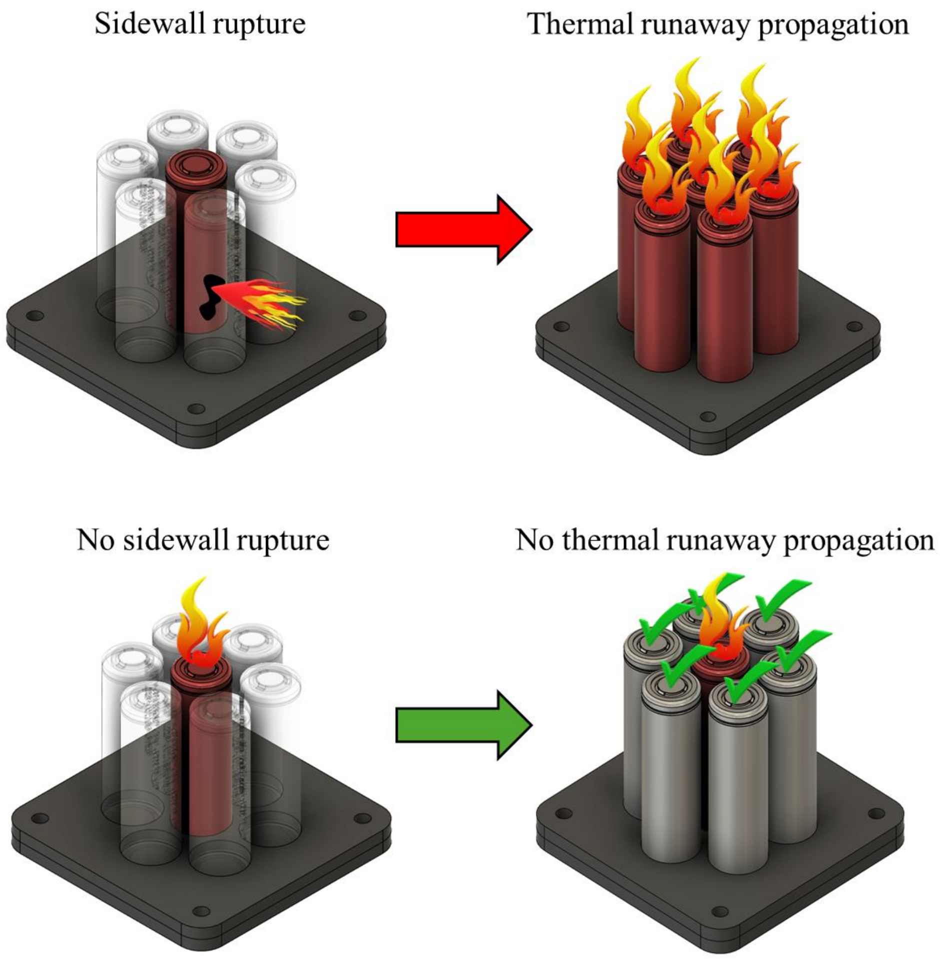
Why do we care?



SWR = TRP

TRP = Thermal runaway propagation

Why do we care?



?

SWR = TRP

TRP = Thermal runaway propagation

Studying SWR and TR Propagation

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Studying SWR and TR propagation

THE UNIVERSITY OF WARWICK

Does sidewall rupture result in an increased propensity for thermal runaway propagation in a battery system?

Studying SWR and TR propagation

THE UNIVERSITY OF WARWICK

Does sidewall rupture result in an increased propensity for thermal runaway propagation in a battery system?

Trigger sidewall rupture in a cell within a system and study the outcome

Studying SWR and TR propagation

WMG THE UNIVERSITY OF WARWICK

Sidewall rupture is a failure mode in cylindrical lithium-ion batteries. It is a ***rare*** *but* ***severe*** *failure mode, exhibited when cell pressure relief safety mechanisms do not operate as designed. In sidewall rupture,* ***energy is released quickly****, often with high velocity directional jet flames, facilitated by the rupture of the sidewall of the cell casing.*

Studying SWR and TR propagation

It is a ***rare*** failure mode,

How do we trigger SWR reliably?

Studying SWR and TR propagation

THE UNIVERSITY OF WARWICK

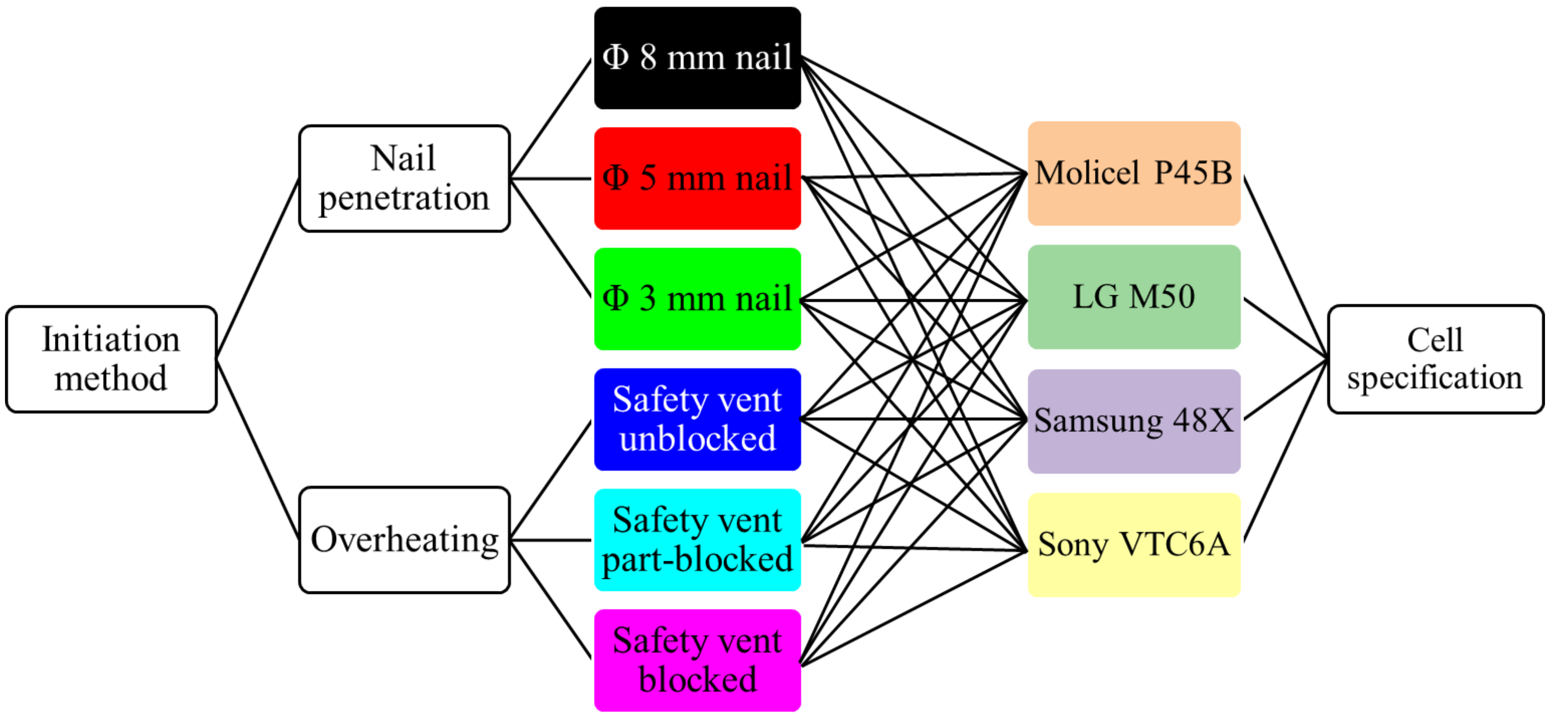
*Sidewall rupture is a failure mode in cylindrical lithium-ion batteries. It is a **rare** but **severe** failure mode, exhibited when cell pressure relief safety mechanisms do not operate as designed.*

Can we exploit this?...

***quickly,** often with high velocity directional jet flames, facilitated by the rupture of the sidewall of the cell casing.*

Reliably inducing SWR

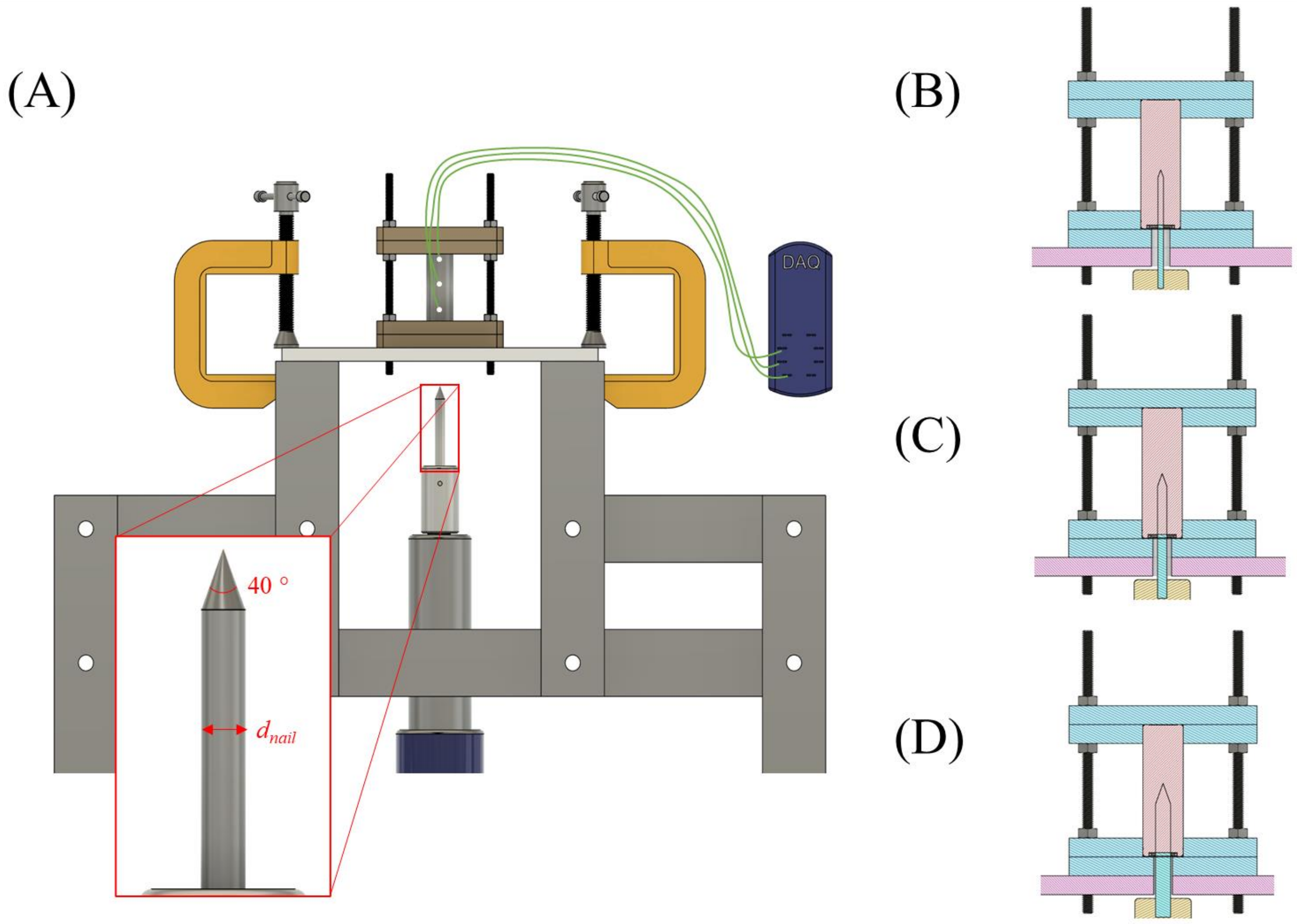
120 experiments



Methods to increase the probability of sidewall rupture in four types of 21700 lithium-ion cell using nail penetration and overheating – under review

Reliably inducing SWR

Nail penetration



Φ 3 mm

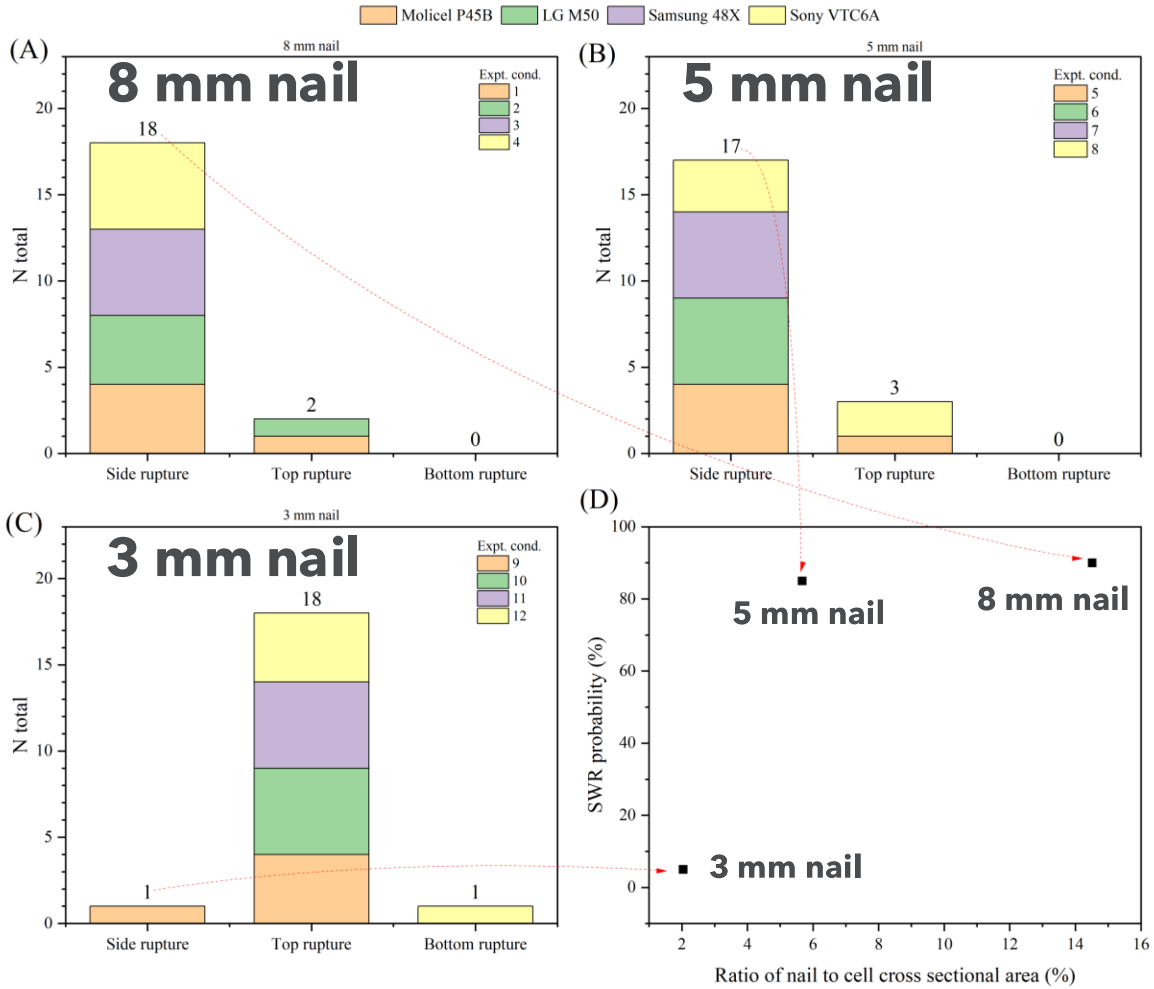
Φ 5 mm

Φ 8 mm

Methods to increase the probability of sidewall rupture in four types of 21700 lithium-ion cell using nail penetration and overheating – under review

Reliably inducing SWR

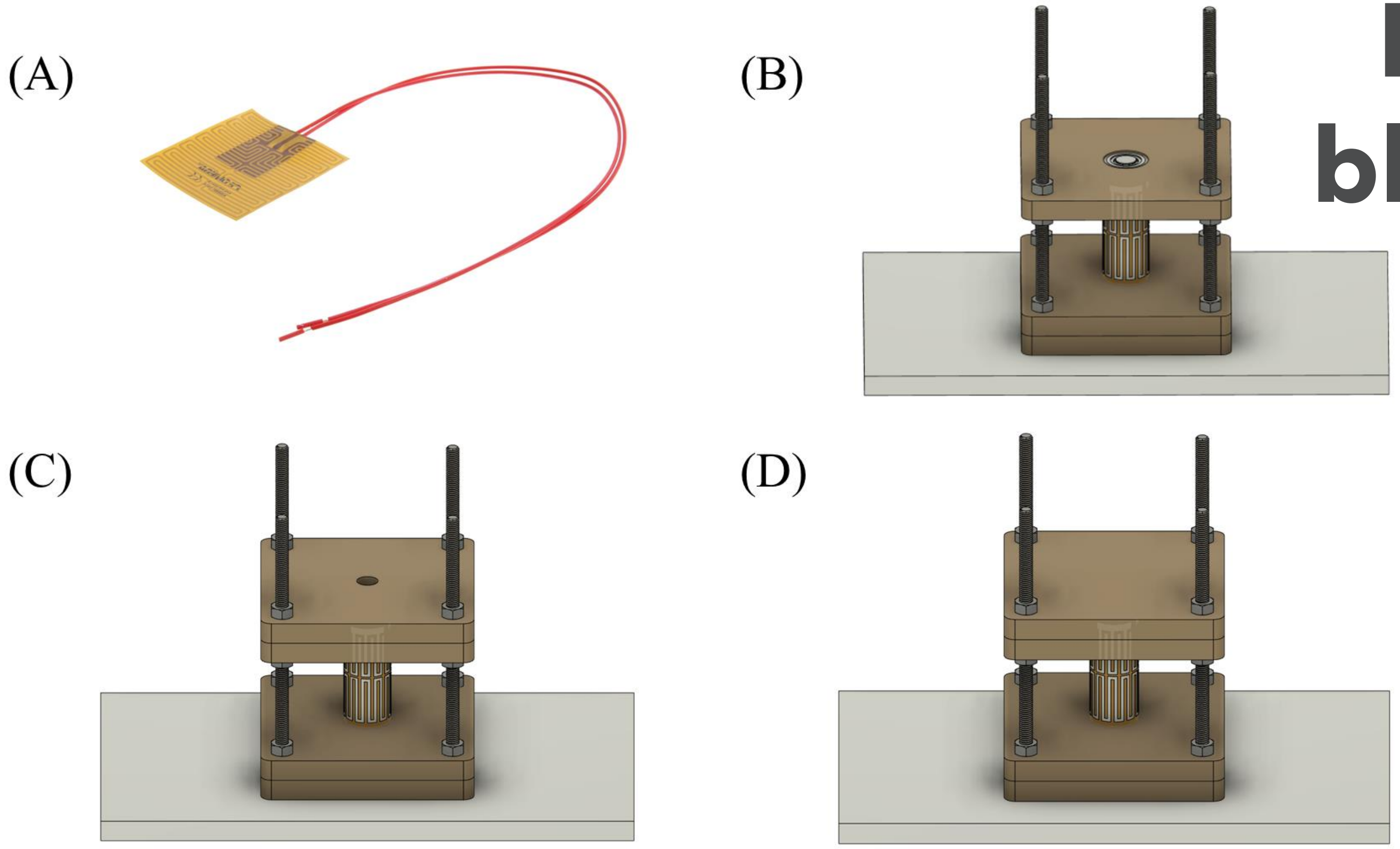
Nail penetration



Methods to increase the probability of sidewall rupture in four types of 21700 lithium-ion cell using nail penetration and overheating – under review

Reliably inducing SWR

Overheating



No block

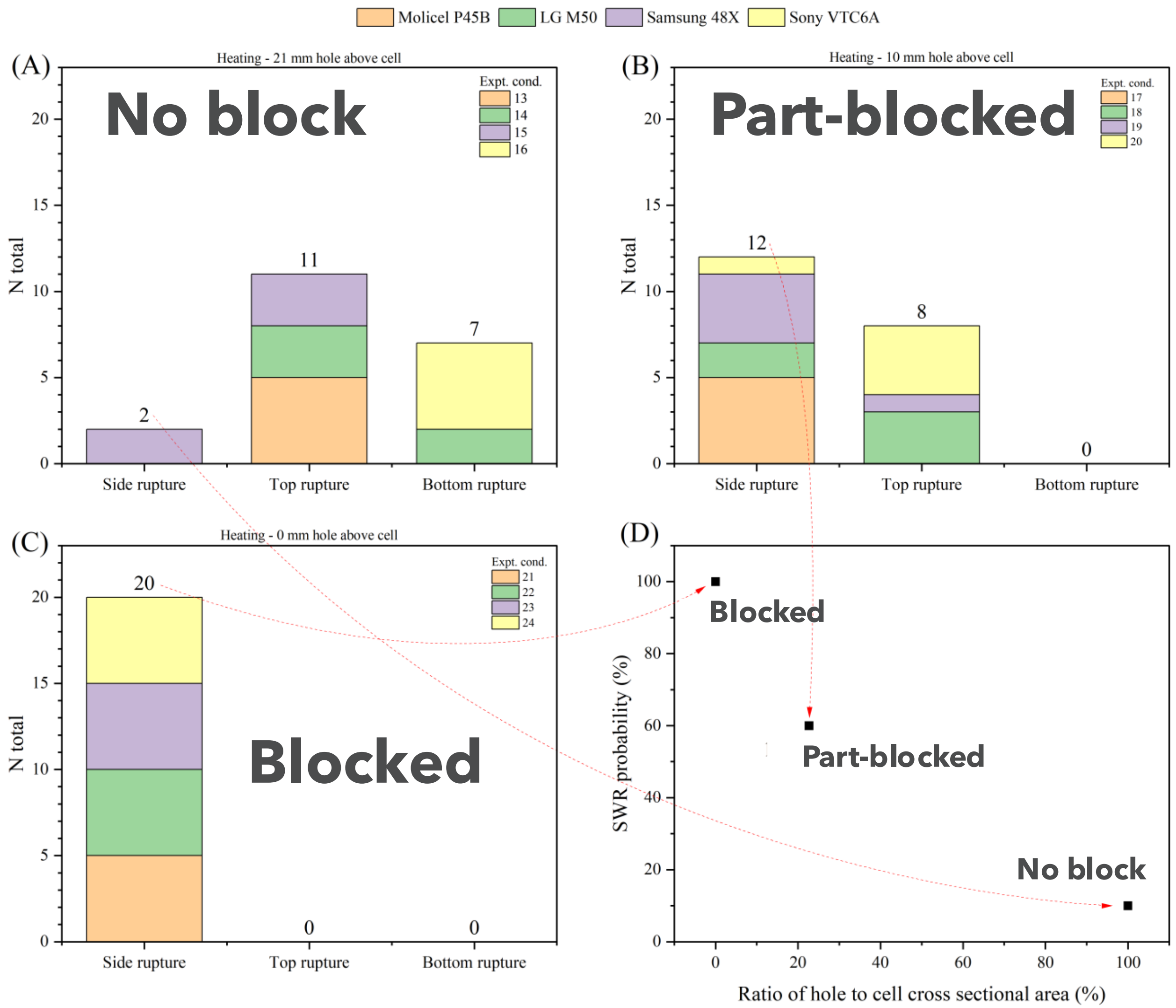
Part-blocked

Blocked

Methods to increase the probability of sidewall rupture in four types of 21700 lithium-ion cell using nail penetration and overheating – under review

Reliably inducing SWR

Overheating



Methods to increase the probability of sidewall rupture in four types of 21700 lithium-ion cell using nail penetration and overheating – under review

Reliably inducing SWR

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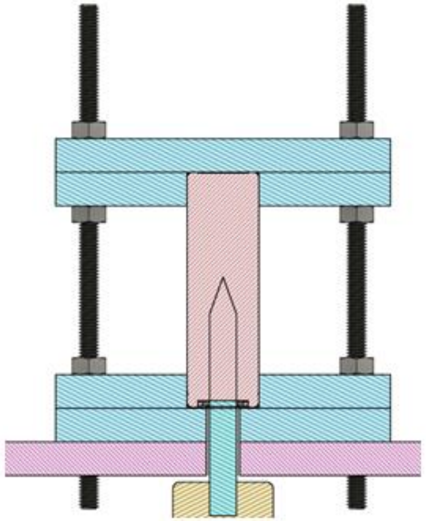
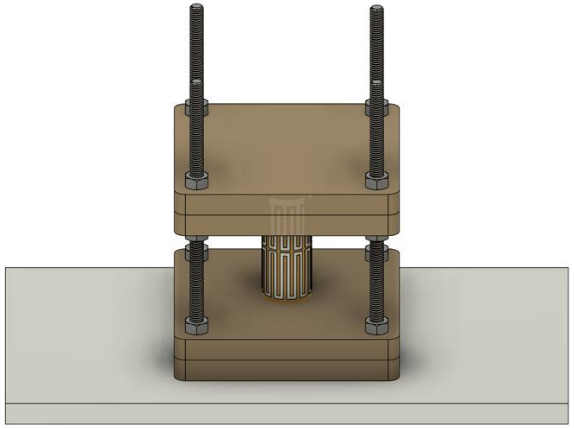
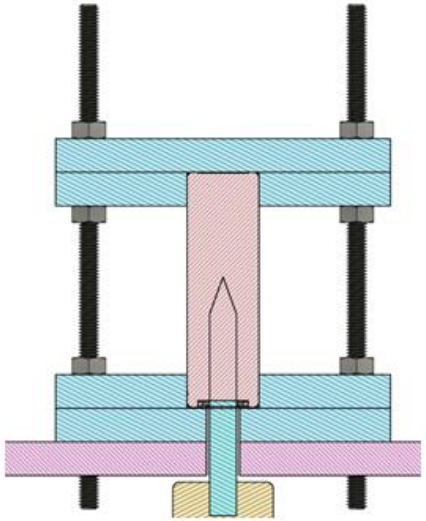


Φ 8 mm nail penetration through top cap



Overheating with vent opening blocked

Reliably inducing SWR



Φ 8 mm nail penetration through top cap

Overheating with vent opening blocked

Studying SWR and TR propagation

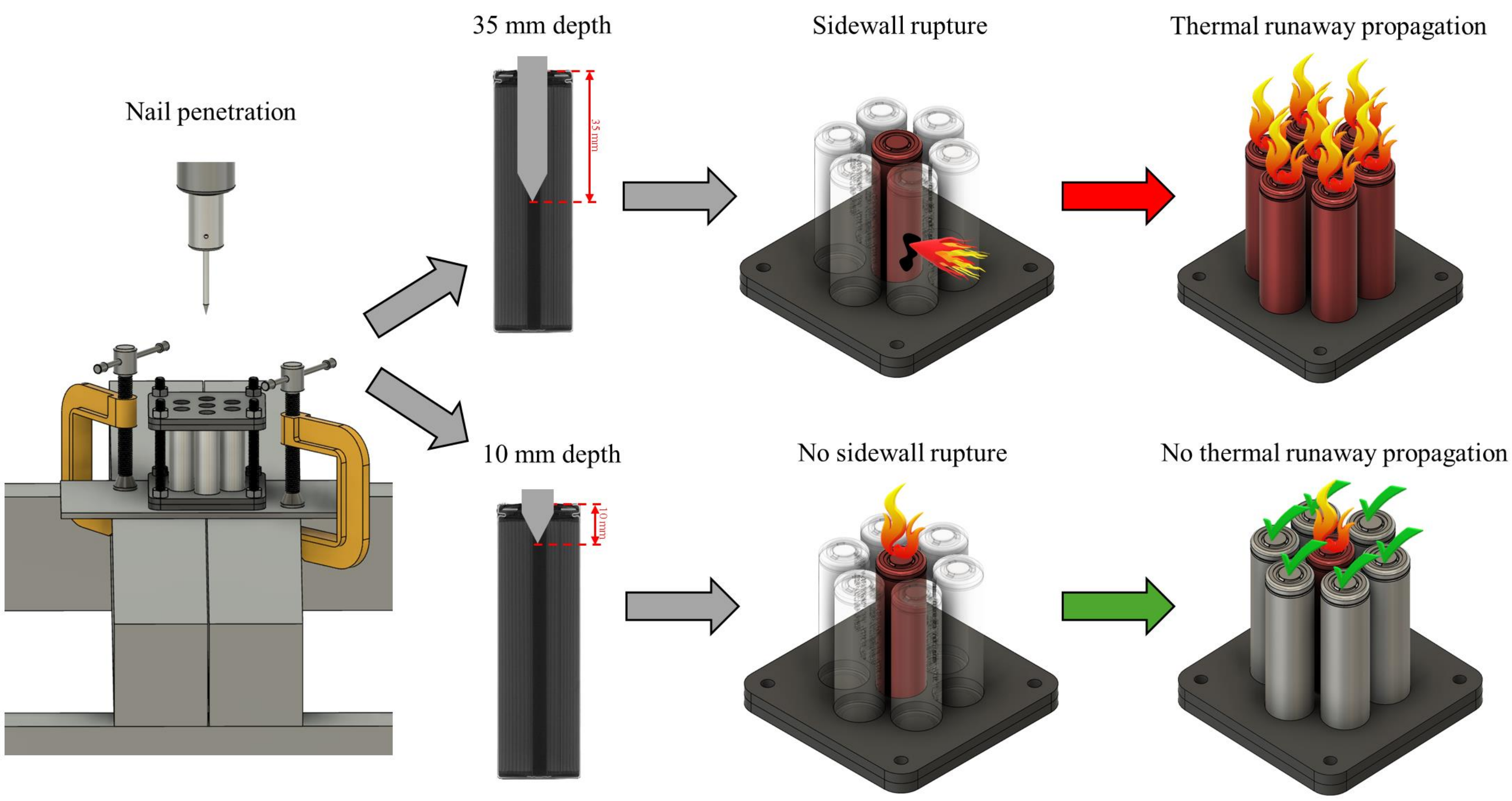
WMG
THE UNIVERSITY OF WARWICK

Does sidewall rupture result in an increased propensity for thermal runaway propagation in a battery system?

↓

Trigger sidewall rupture in a cell within a system and study the outcome

Studying SWR and TR propagation



?

SWR = TRP

[The effect of sidewall rupture on the propensity for thermal runaway propagation in a small lithium-ion battery module](#)

Studying SWR and TR propagation

No SWR = No TRP*

*In our test configuration !

Studying SWR and TR propagation

SWR = TRP

Studying SWR and TR propagation

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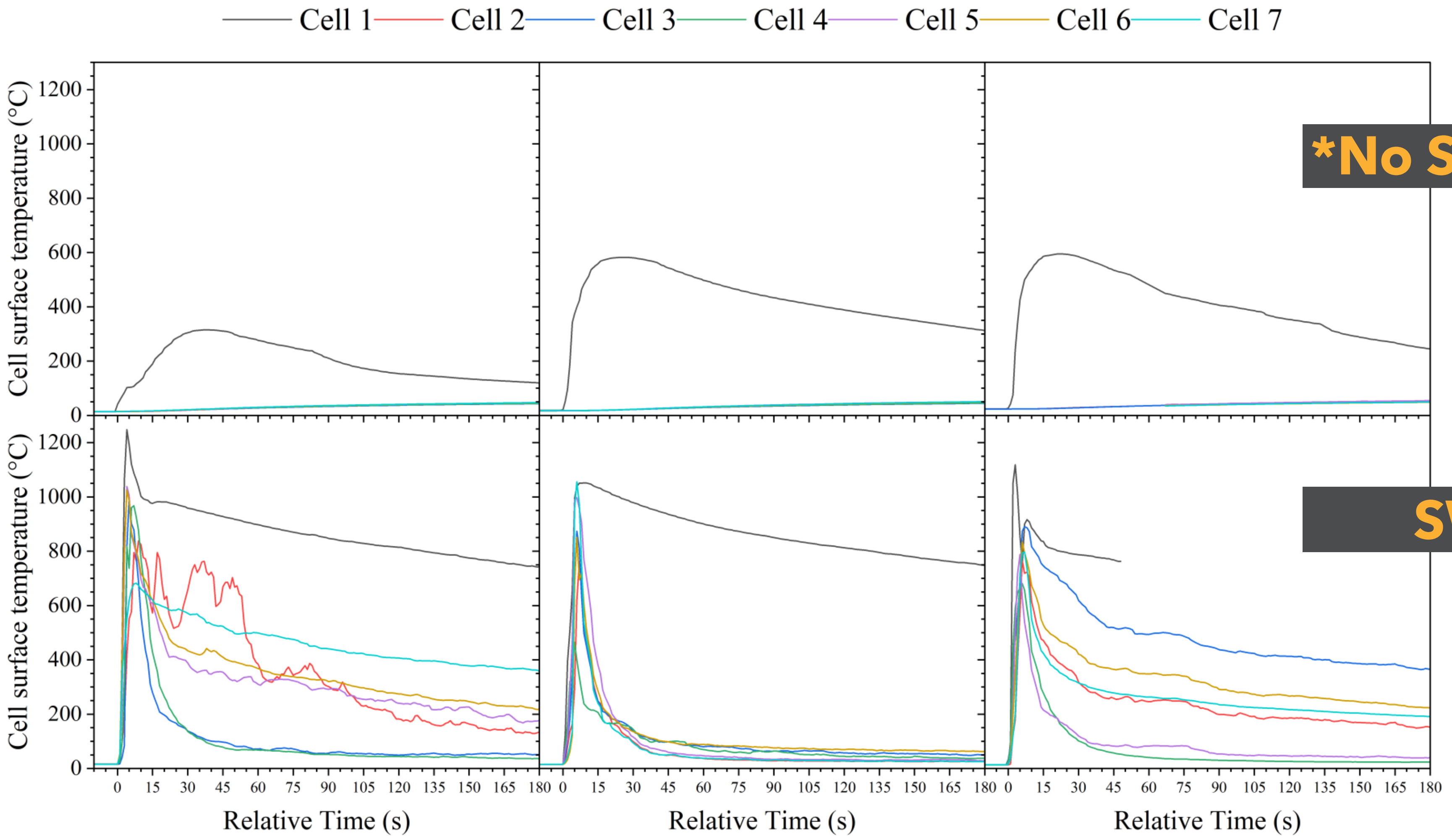


*In our test configuration!

***No SWR = No TRP**

SWR = TRP

[The effect of sidewall rupture on the propensity for thermal runaway propagation in a small lithium-ion battery module]

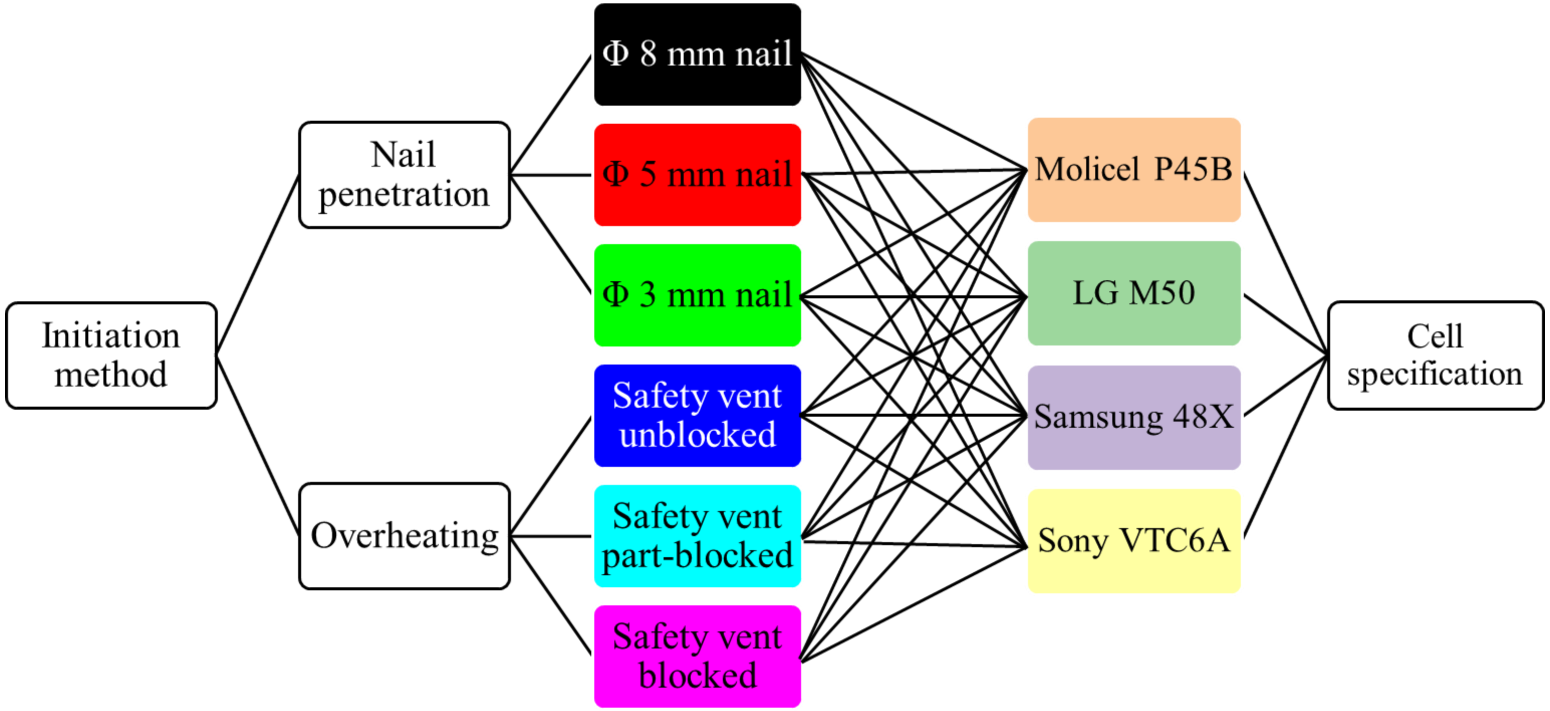
Part 3

SWR: What can we do about it?

THE UNIVERSITY OF WARWICK

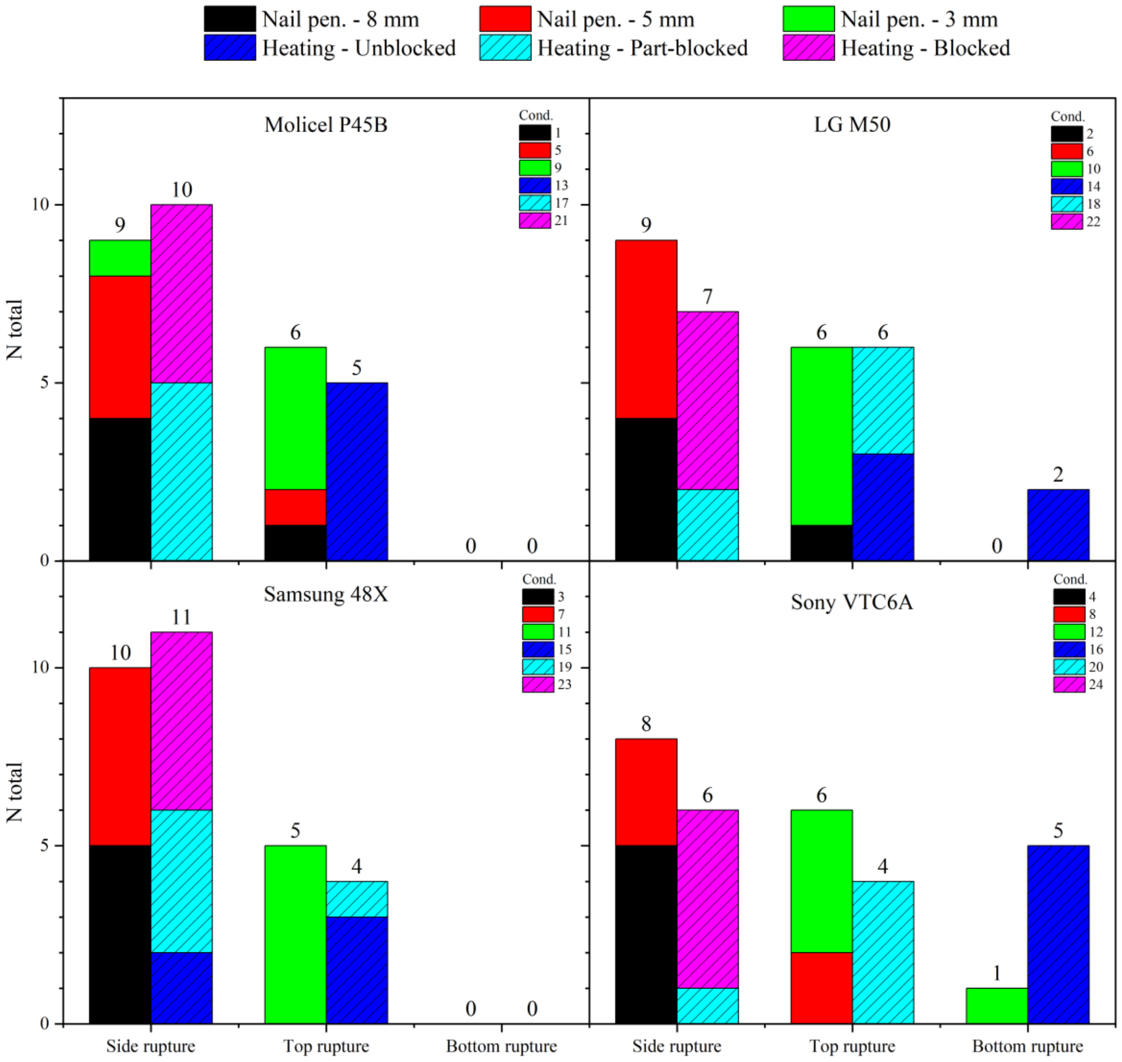
What can we do about it?

120 experiments



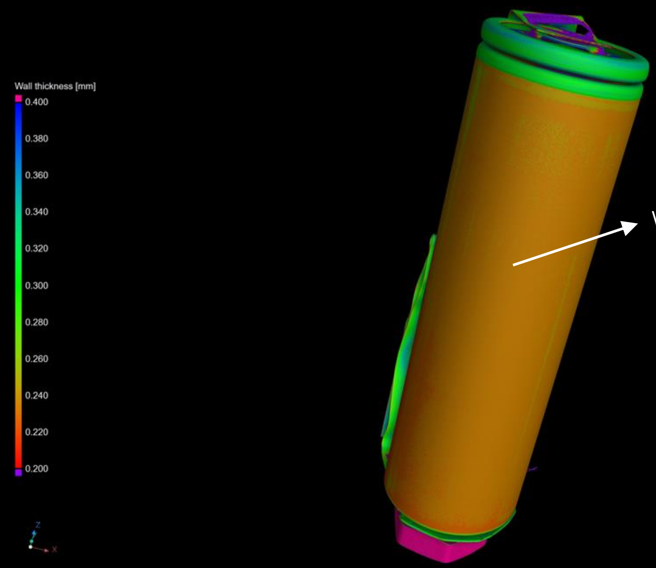
Methods to increase the probability of sidewall rupture in four types of 21700 lithium-ion cell using nail penetration and overheating – under review

What can we do about it?



Methods to increase the probability of sidewall rupture in four types of 21700 lithium-ion cell using nail penetration and overheating – under review

LG M50



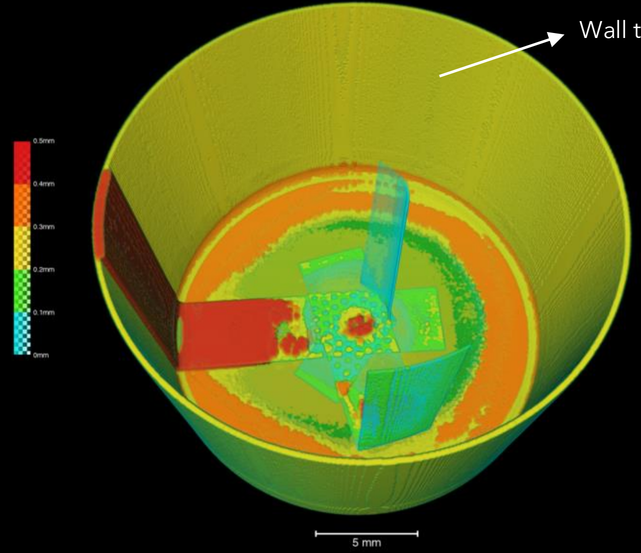
Wall thickness

Begum Gulsoy

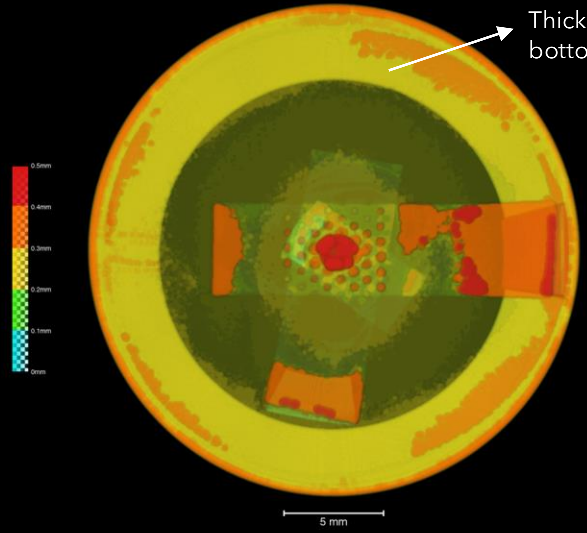
Paul Wilson

NXCT | National X-Ray Computed Tomography

Molicel P45B

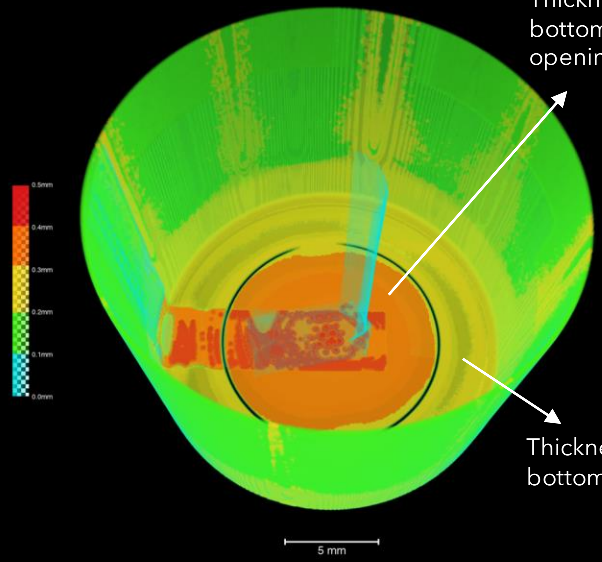


Wall thickness



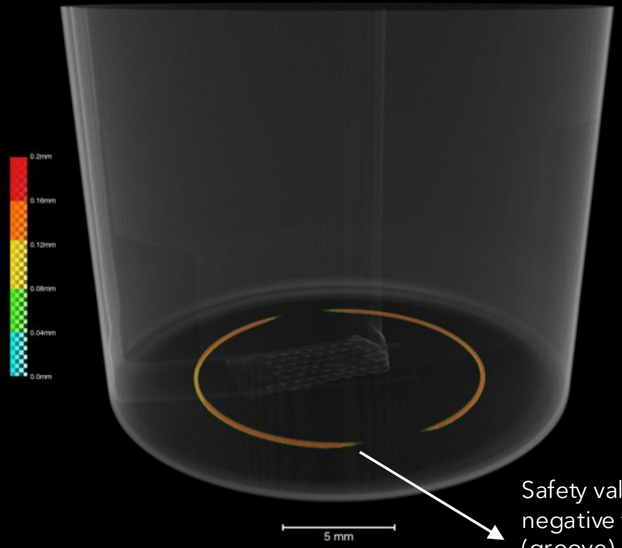
Thickness of cell bottom

Sony VTC6A



Thickness of cell bottom (safety opening)

Thickness of cell bottom



Safety valve on negative terminal (groove)

What can we do about it?

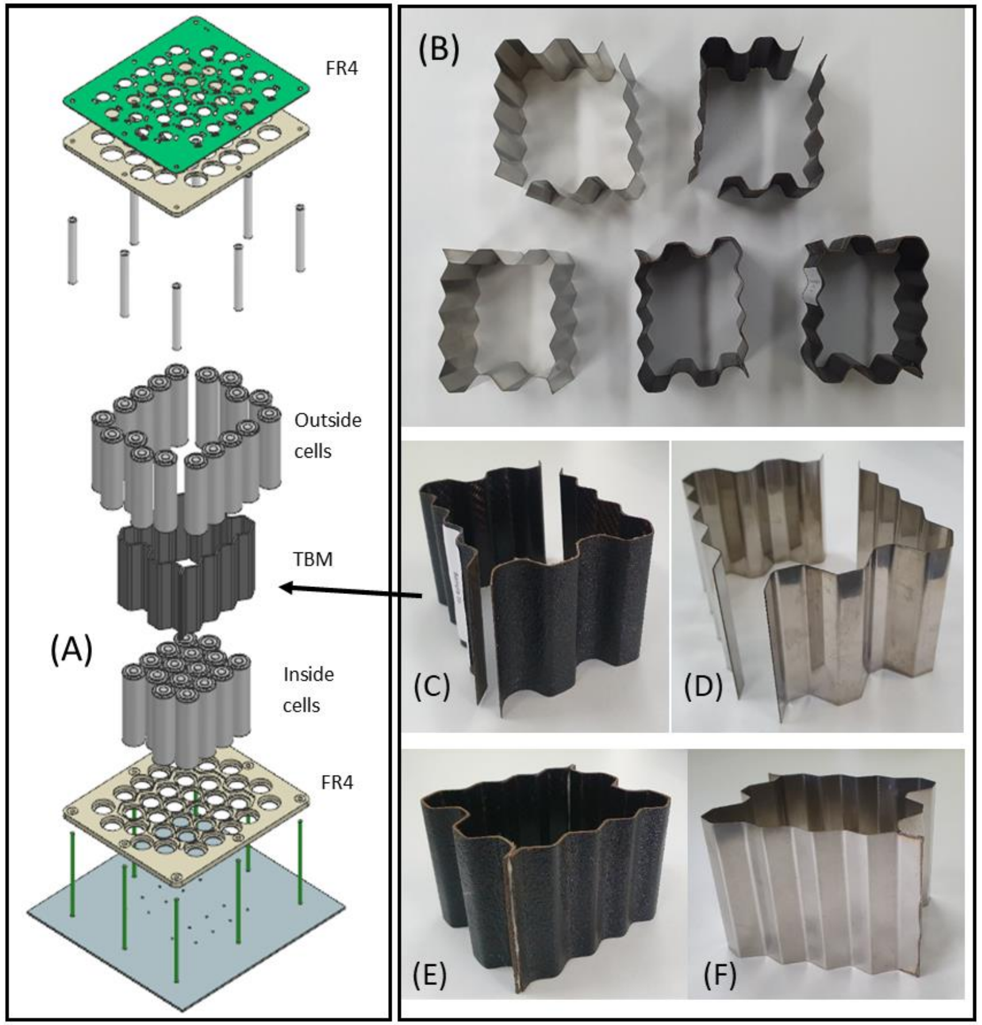
THE UNIVERSITY OF WARWICK

	Molicel P45B	LG M50	Samsung 48X	Sony VTC6A
Cathode	NCA	NMC 811	NMC 811	NCA
Nominal capacity	4.50 Ah	5.00 Ah	4.80 Ah	4.00 Ah
Max voltage	4.2 V	4.2 V	4.2 V	4.2 V
Energy density	242 Wh/kg	267 Wh/kg	256 Wh/kg	187 Wh/kg
Max discharge rate	10 C	1.5 C	1.0 C	10 C
Sidewall casing thickness	0.30 mm	0.24 mm	?	0.23 mm
Bottom vent?	No	No	No	Yes
SWR rate*	63 %	53 %	70 %	47 %

What other cell design parameters?

* Under conditions in our experiments, bias towards inducing SWR!

What can we do about it?



[Performance of interstitial thermal barrier materials on containing sidewall rupture and thermal runaway propagation in a lithium-ion battery module]

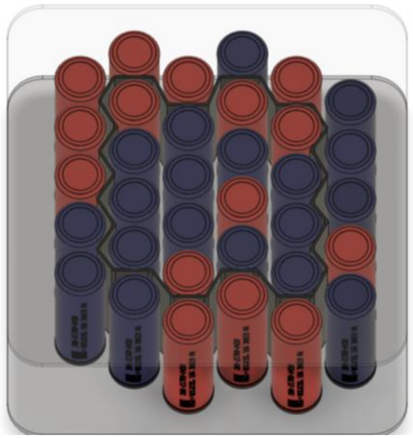
What can we do about it?

THE UNIVERSITY OF WARWICK

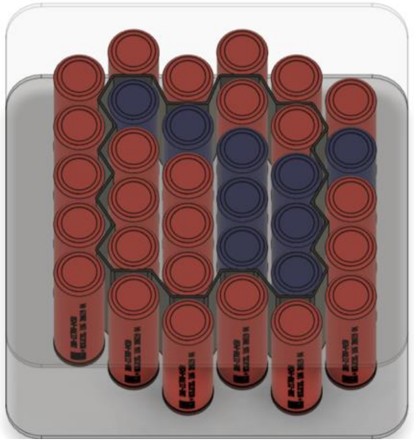
ROLLS ROYCE

AEROSPACE TECHNOLOGY INSTITUTE

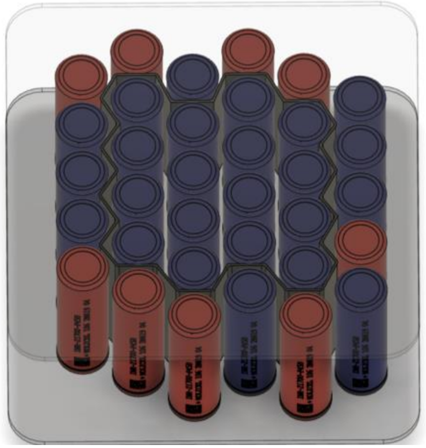
Material 1



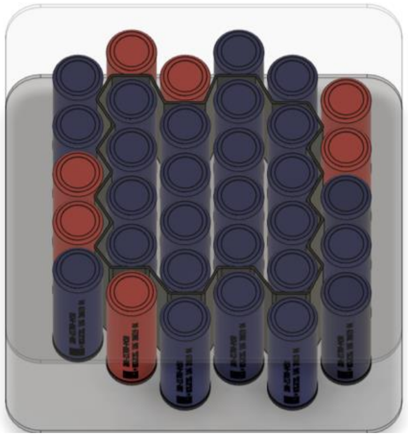
Material 2



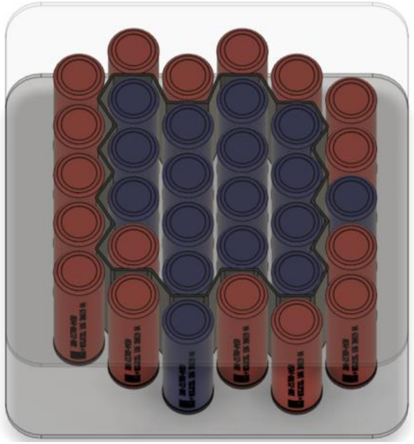
Material 3



Material 4



Material 5



No SWR

SWR

[*Performance of interstitial thermal barrier materials on containing sidewall rupture and thermal runaway propagation in a lithium-ion battery module*]

What can we do about it?

Preventing thermal runaway propagation and mitigating sidewall rupture in a small lithium-ion battery module using tubular interstitial thermal barrier materials – under review

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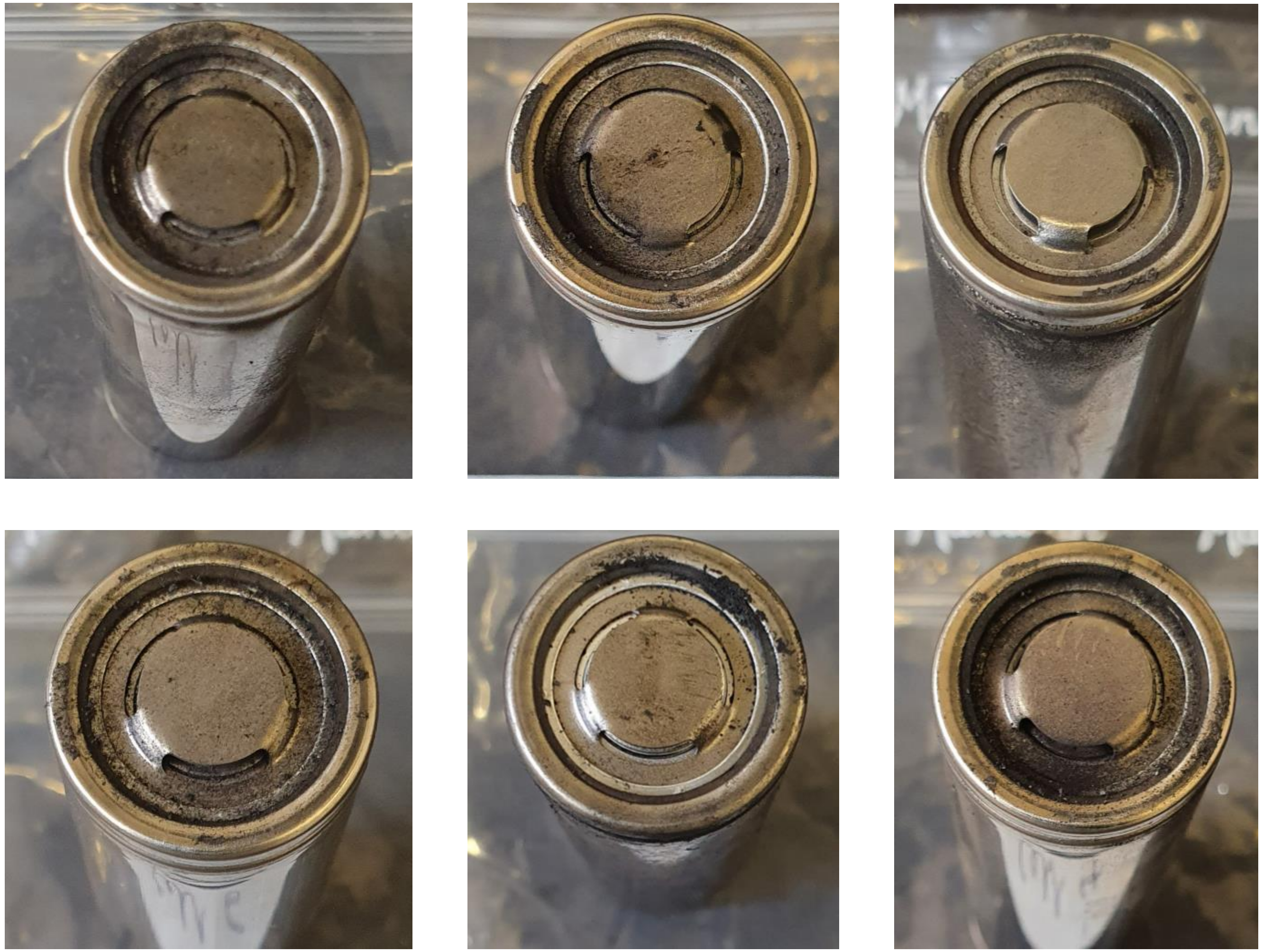


No TRP, even with SWR!

Preventing thermal runaway propagation and mitigating sidewall rupture in a small lithium-ion battery module using tubular interstitial thermal barrier materials – under review

What can we do about it?

WMG THE UNIVERSITY OF WARWICK

ROLLS ROYCE

AEROSPACE TECHNOLOGY INSTITUTE

Patent Application Publication Aug. 22, 2024 Sheet 3 of 8 US 2024/0283079 A1

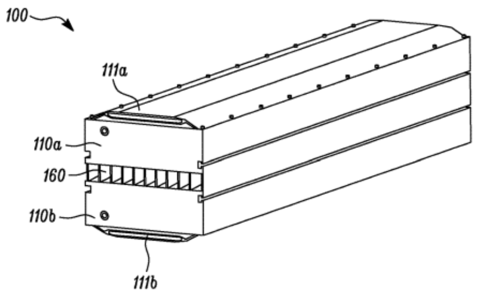


FIG. 3A

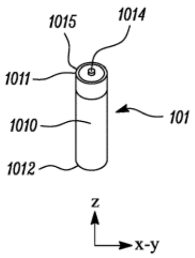


FIG. 3B

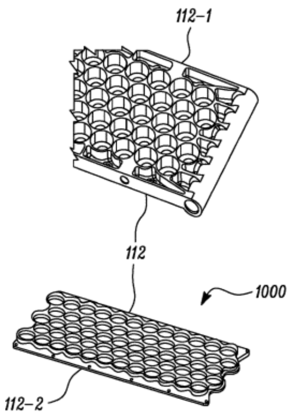


FIG. 3C

Patent Application Publication Aug. 22, 2024 Sheet 4 of 8 US 2024/0283079 A1

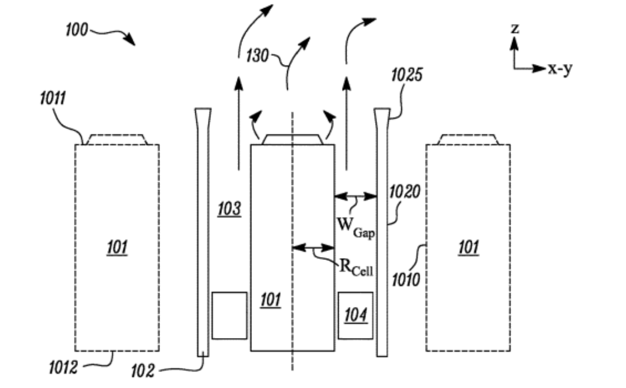


FIG. 4A

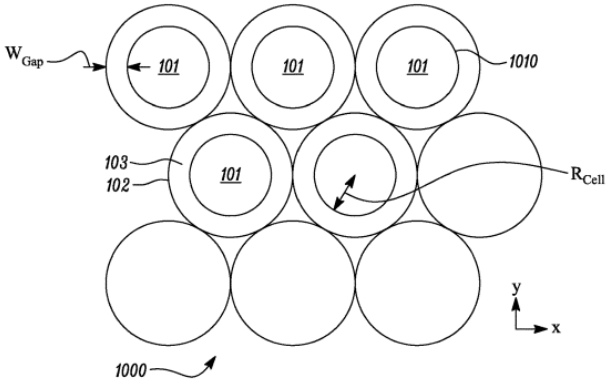


FIG. 4B

[US Patent Application - Preventing propagation of cell failures in battery packs]()

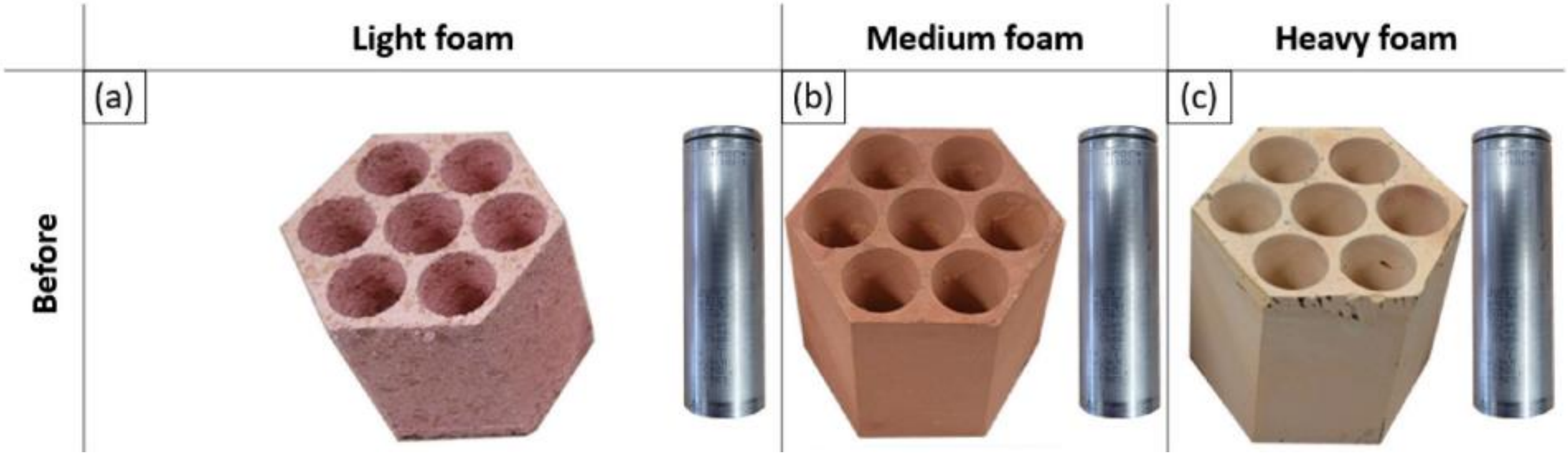
What can we do about it?

WMG THE UNIVERSITY OF WARWICK

Jonathan Allen

AIRBUS

UKRI Innovate UK



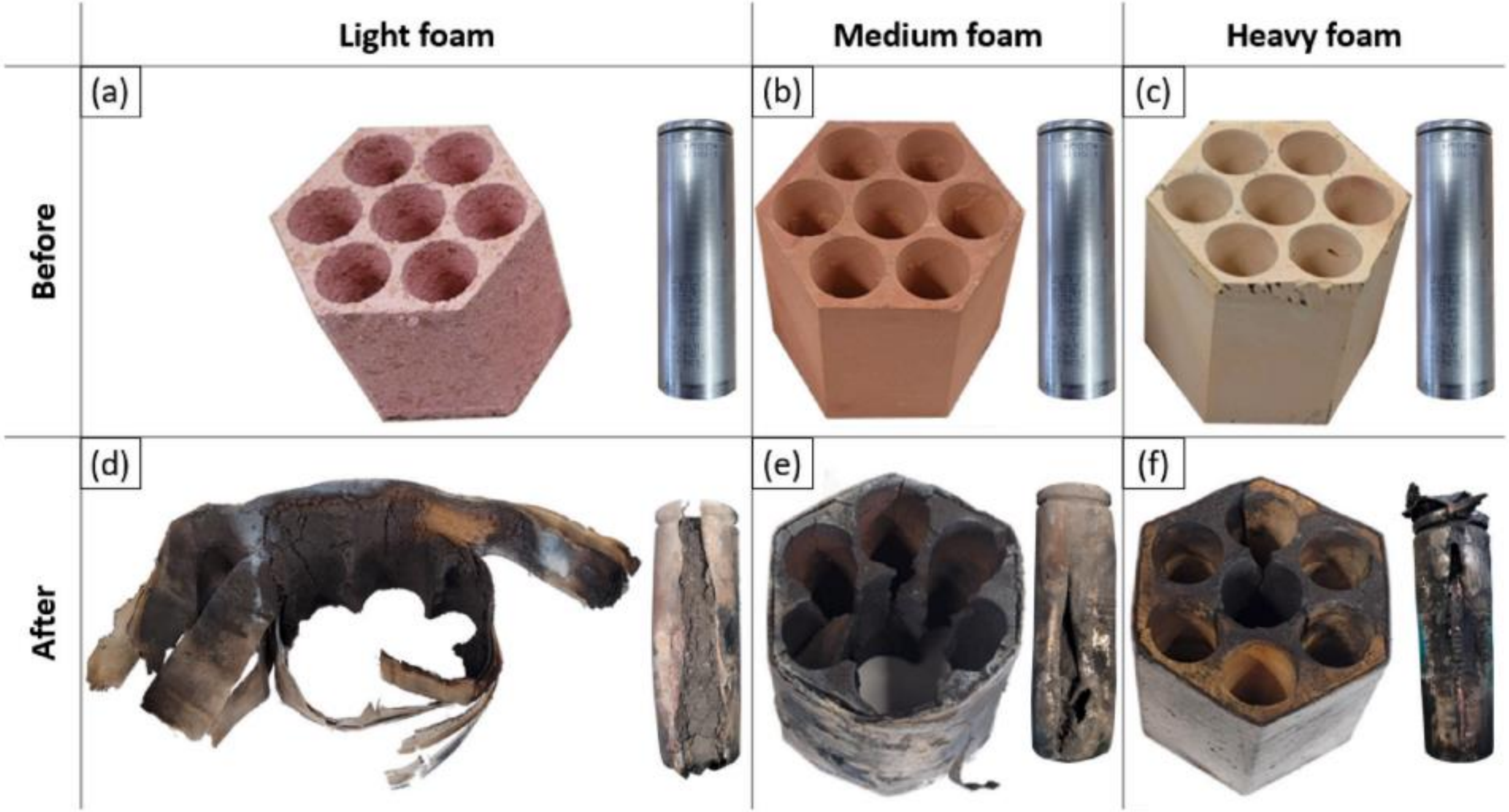
The novel use of foam-based solutions for the containment of thermal runaway sidewall rupture

What can we do about it?

Jonathan Allen

AIRBUS

UKRI Innovate UK



[The novel use of foam-based solutions for the containment of thermal runaway sidewall rupture]()

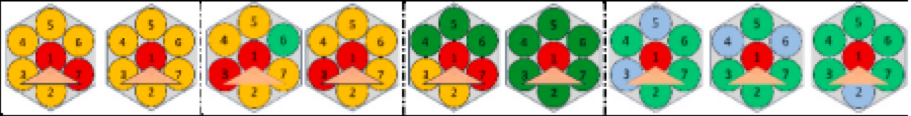
What can we do about it?

WMG THE UNIVERSITY OF WARWICK

Jonathan Allen

AIRBUS

UKRI Innovate UK

Cell number	Material	None	None	Light	Light	Medium	Medium	Heavy	Heavy	Heavy
	Pack ID	1	2	1	2	1	2	1	2	3
1	Cell masses (g)	34	37	11	35	28	41	37	33	29
2		40	33	32	38	42	20	68	64	64
3		33	31	12	11	14	12	67	63	65
4		32	37	34	9	13	17	67	63	65
5		36	35	11	37	14	11	66	65	66
6		41	35	68	10	13	12	66	66	65
7		43	43	14	10	24	11	68	65	64
1	Cell Voltages (V)	0	0	0	0	0	0	0	0	0
2		0	0	0	0	0	0	0	0	4.13
3		0	0	0	0	0	0	4.12	0	0
4		0	0	0	0	0	0	0	4.12	0
5		0	0	0	0	0	0	4.1	0	0
6		0	0	0	0	0	0	0	4.14	0
7		0	0	0	0	0	0	0	0	0
1	Failure rating	1	1	1	1	1	1	1	1	1
2		2	2	2	2	2	3	4	4	5
3		2	2	1	1	2	3	5	4	4
4		2	2	2	2	3	3	4	5	4
5		2	2	2	2	3	3	5	4	4
6		2	2	4	2	3	3	4	5	4
7		1	2	2	2	1	3	4	4	4
	Failure map									
	Average rating (cells 2 to 7)	1.83	2.00	2.17	1.83	2.33	3.00	4.33	4.33	4.17

1 Massive (SWR)
2 Localised (SWR)
3 Other failure
4 Voltage drop
5 No failure

Worst 1 3 5 Best

[The novel use of foam-based solutions for the containment of thermal runaway sidewall rupture]()

What can we do about it?

WMG
THE UNIVERSITY OF WARWICK

Jonathan Allen

AIRBUS

UKRI Innovate UK

Cell number	Material	None	None	Light	Light	Medium	Medium	Heavy	Heavy	Heavy
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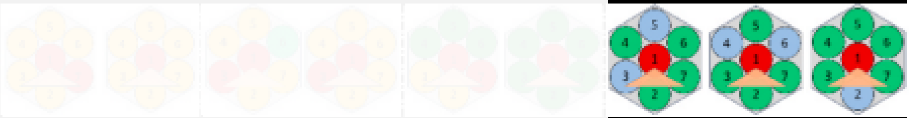
2		40	33	32	38	42	20	68	64	64
3		33	31	12	11	14	12	67	63	65
4		32	37	34	9	13	17	67	63	65
5		36	35	11	37	14	11	66	65	66
6		41	35	68	10	13	12	66	66	65
7		43	43	14	10	24	11	68	65	64
1	Cell Voltages (V)	0	0	0	0	0	0	0	0	0
2		0	0	0	0	0	0	0	0	4.13
3		0	0	0	0	0	0	4.12	0	0
4		0	0	0	0	0	0	0	4.12	0
5		0	0	0	0	0	0	4.1	0	0
6		0	0	0	0	0	0	0	4.14	0
7		0	0	0	0	0	0	0	0	0
1	Failure rating	1	1	1	1	1	1	1	1	1
2		2	2	2	2	2	3	4	4	5
3		2	2	1	1	2	3	5	4	4
4		2	2	2	2	3	3	4	5	4
5		2	2	2	2	3	3	5	4	4
6		2	2	4	2	3	3	4	5	4
7		1	2	2	2	1	3	4	4	4
	Failure map									
	Average rating (cells 2 to 7)	1.83	2.00	2.17	1.83	2.33	3.00	4.33	4.33	4.17



1 Massive (SWR)
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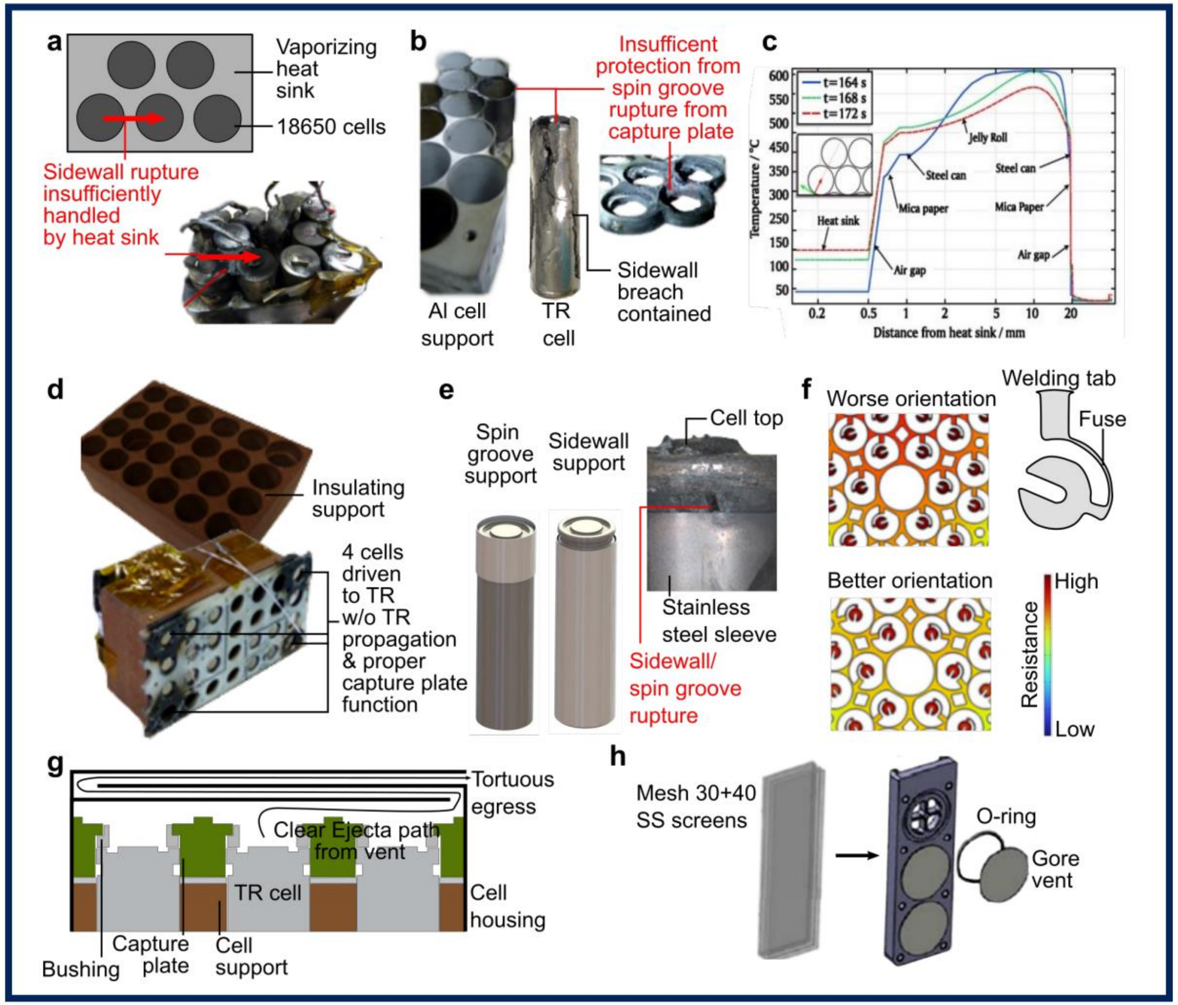
Worst 1 3 5 Best

No TRP, even with SWR!

[The novel use of foam-based solutions for the containment of thermal runaway sidewall rupture]()

What can we do about it?



[Achieving Passive Thermal Runaway Propagation Resistance in Li-ion Battery Packs]

What can we do about it?

THE UNIVERSITY OF WARWICK

Lots of different material choices!

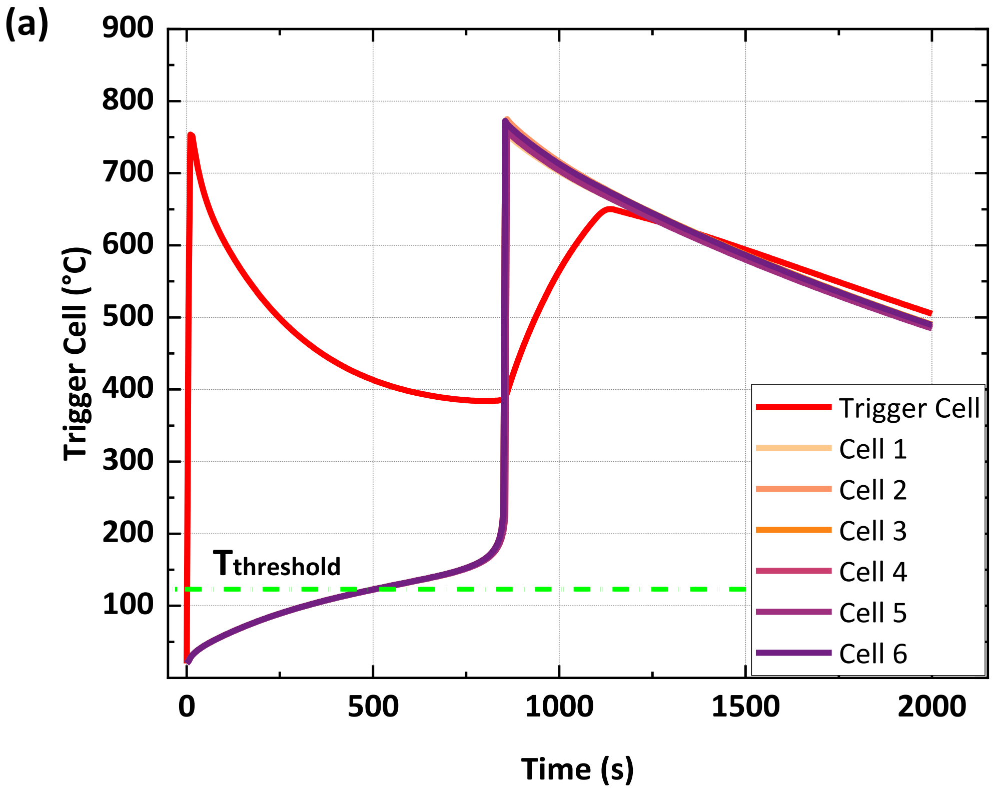
How do we narrow down the choice?...

What can we do about it?

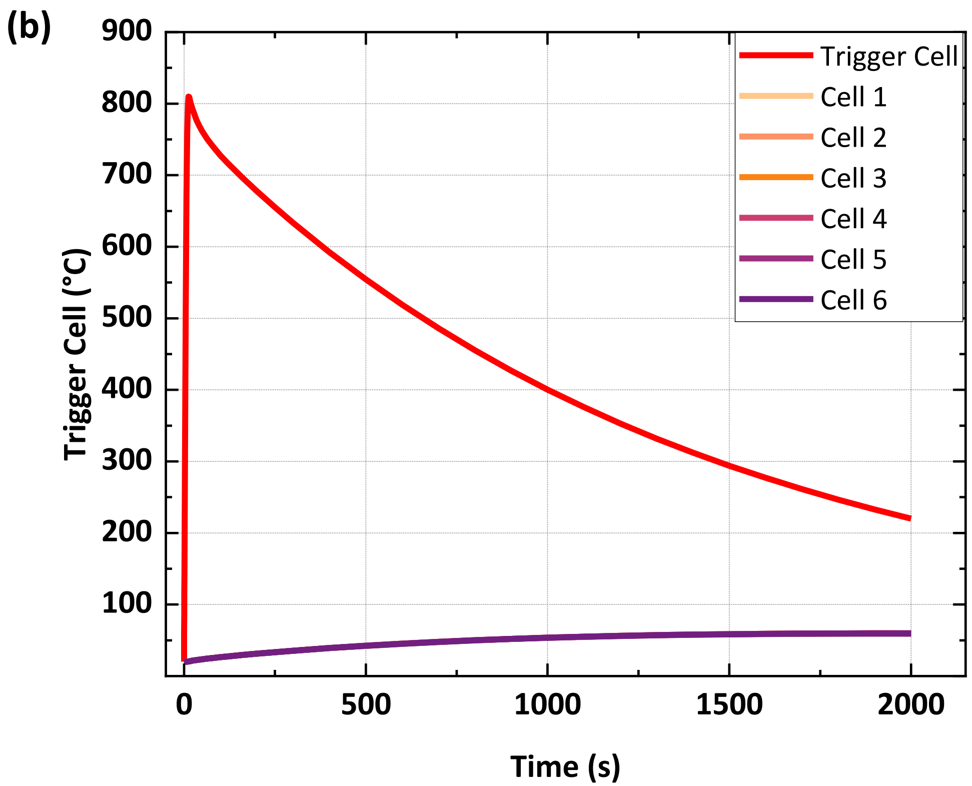
UNIVERSITY OF OXFORD

Zeyu Sun

Material 1



Material 2



Numerical and Experimental Characterization of Thermal Runaway Propagation of 21700 Lithium-ion Batteries Induced by Nail Penetration – under review

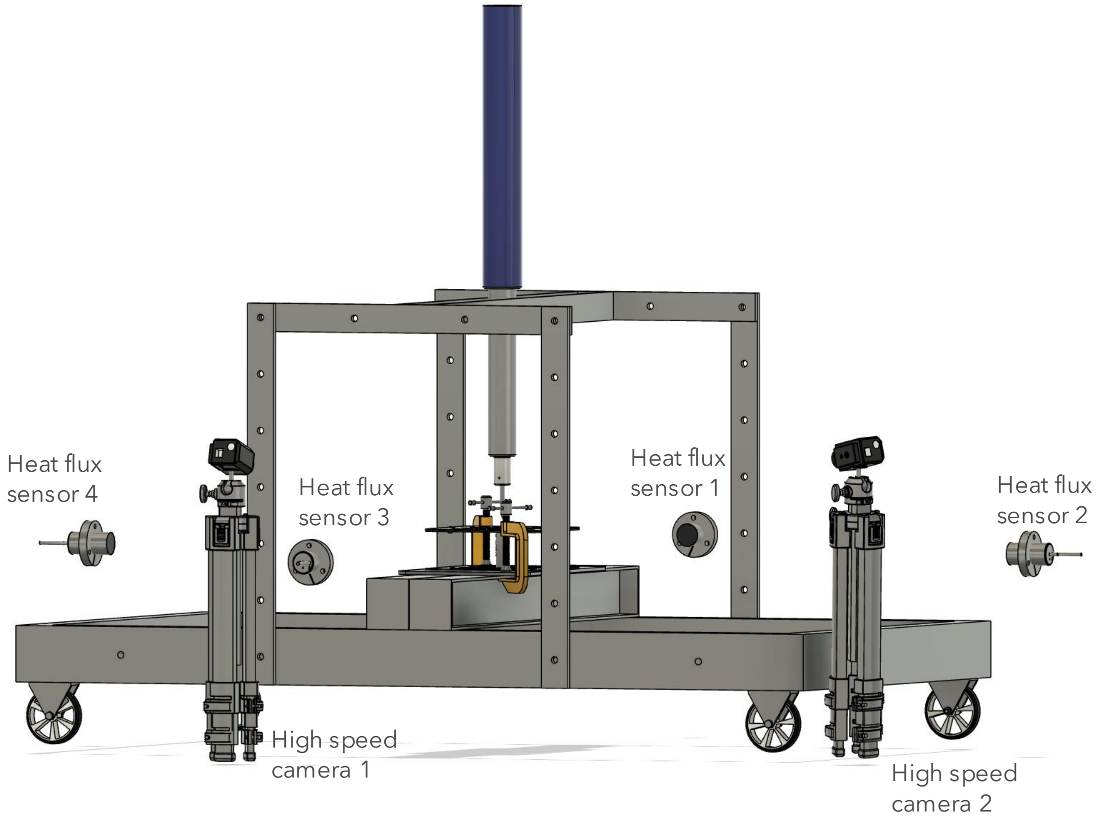
What can we do about it?

THE UNIVERSITY OF WARWICK

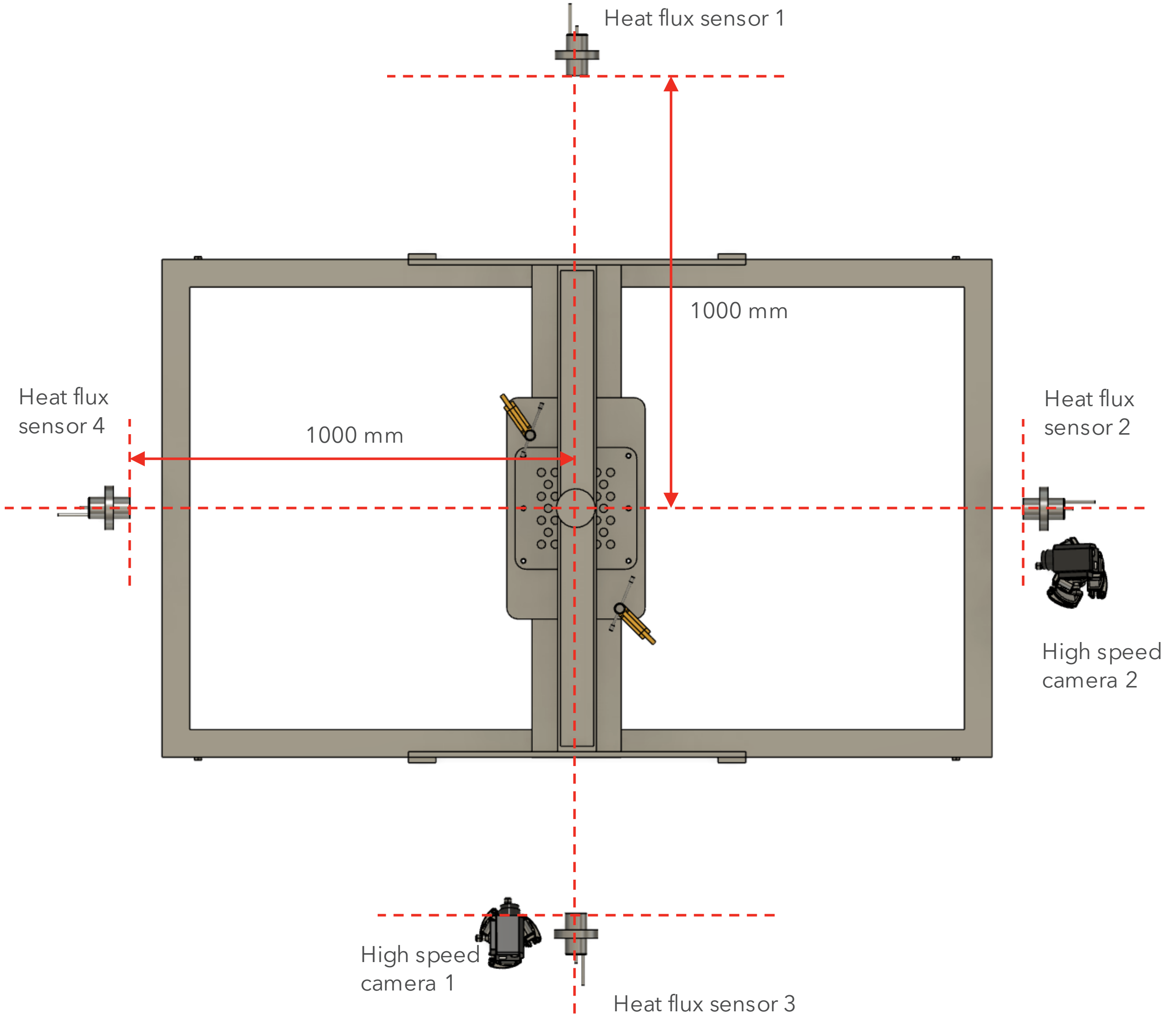
How do we improve our models?

More data! – Better characterising the event...

What is it?

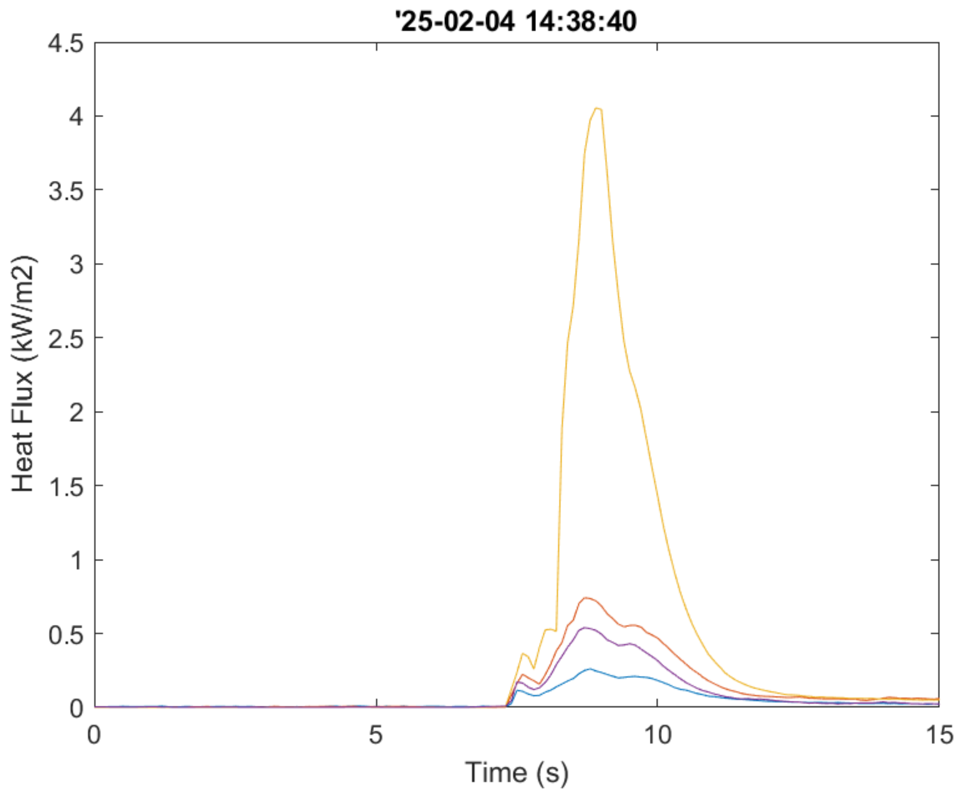


Heat flux sensor 4
Heat flux sensor 3
Heat flux sensor 1
Heat flux sensor 2
High speed camera 1
High speed camera 2

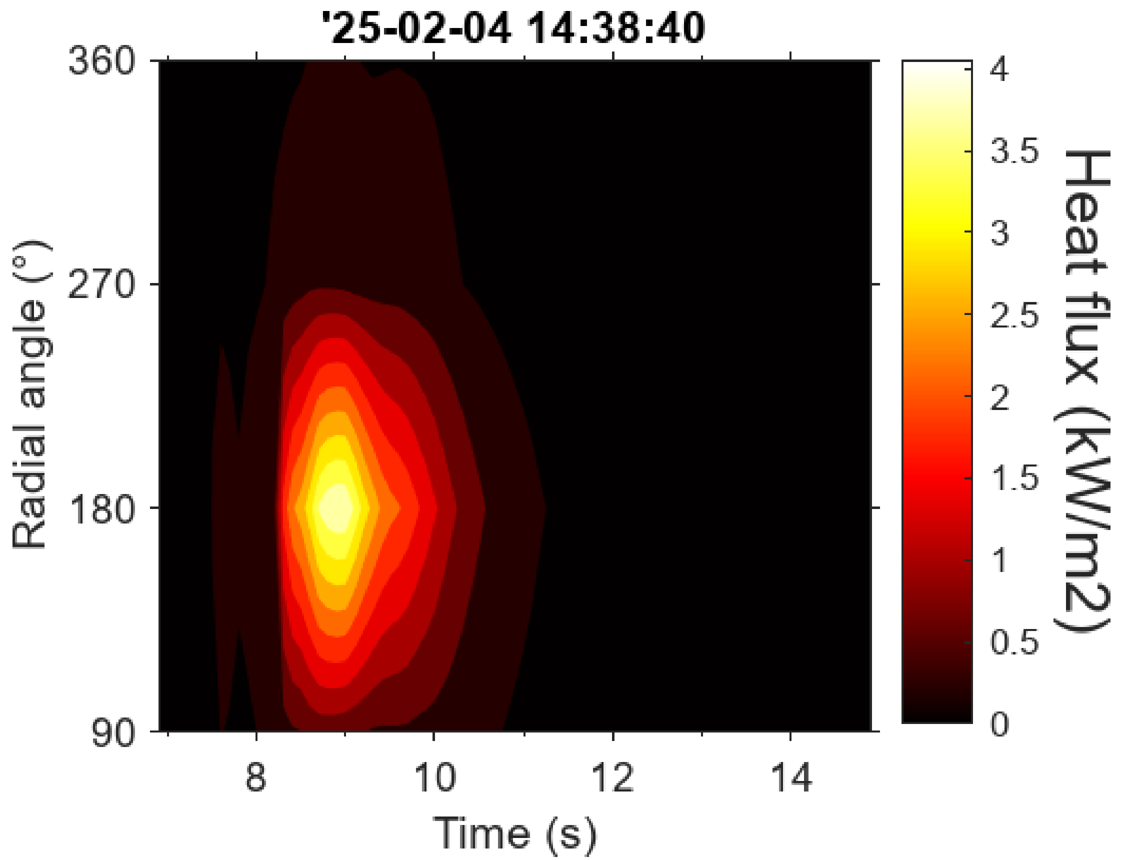


Heat flux sensor 1
1000 mm
Heat flux sensor 4
1000 mm
Heat flux sensor 2
High speed camera 2
High speed camera 1
Heat flux sensor 3

What is it?



'25-02-04 14:38:40
Heat Flux (kW/m2)
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0
5
10
15
Time (s)



'25-02-04 14:38:40
Radial angle (°)
360
270
180
90
8
10
12
14
Time (s)
Heat flux (kW/m2)
4
3.5
3
2.5
2
1.5
1
0.5
0

Summary

THE UNIVERSITY OF WARWICK

Summary

What is it?

SIDEWALL RUPTURE

- Rare, but severe, directional failure mode

Why do we care?

- Increased chance of TR propagation

What can we do about it?

- Improve cell design
- Improve system design

Acknowledgements

WMG

- Simon Jones
- James Marco
- Stene Charmer
- Begum Gulsoy
- Calum Briggs
- Jonathan Allen
- Judith Timms
- Marek Smalera
- Bogdan Alesca
- Malachy Hughes

THE FARADAY INSTITUTION
SCIENCE OF BATTERY SAFETY

SafeBatt

AEROSPACE TECHNOLOGY INSTITUTE

ROLLS ROYCE

UKRI Innovate UK

AIRBUS

Thank you.

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wmgwarwick

wmg-university-of-warwick

THE UNIVERSITY OF WARWICK

BROWN GROUP

University of Sheffield

Advancing Li-ion Battery Safety:
Modelling and uncertainty analysis of thermal runway behaviour

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Energy
Develop process and systems models for energy production, transport and storage.

Sustainability
Investigate sustainable energy systems (CCS, BECCS, H2, and Energy Storage)

Analysis
Perform statistical analysis and process optimisation

The Brown Group

Clean Energy & Process Systems Modelling

> Computational modelling of clean energy and process systems to **optimise** their **design**, **operation** and **safety**.

> Develop new **statistical** and **mathematical techniques** to quantitatively analyse systems, identify key factors and understand the impact of **uncertainty** on performance and behaviour.

- **Carbon capture (transport) utilisation and storage**
- **Hydrogen networks**
- **District heating**
- **Energy storage – flow batteries, Li-ion, Fuel Cells**
- **Process system optimisation – process plants, V2X systems**
- **Safety – Li-ion battery thermal runaway**
- **Machine Learning**
- **Economics of renewable systems**

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- Modelling
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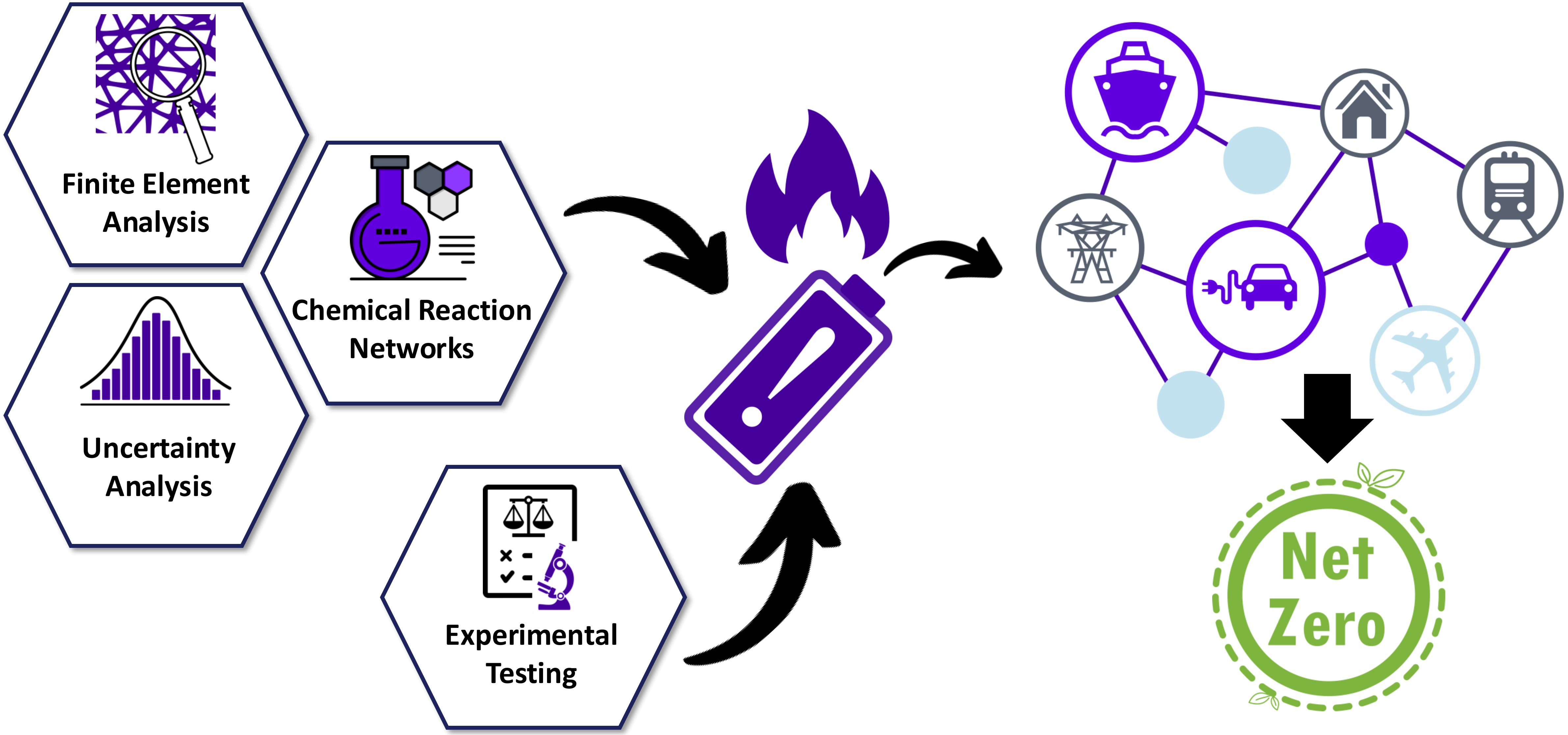
Our Aim For Battery Safety



Thermal Runaway Overview

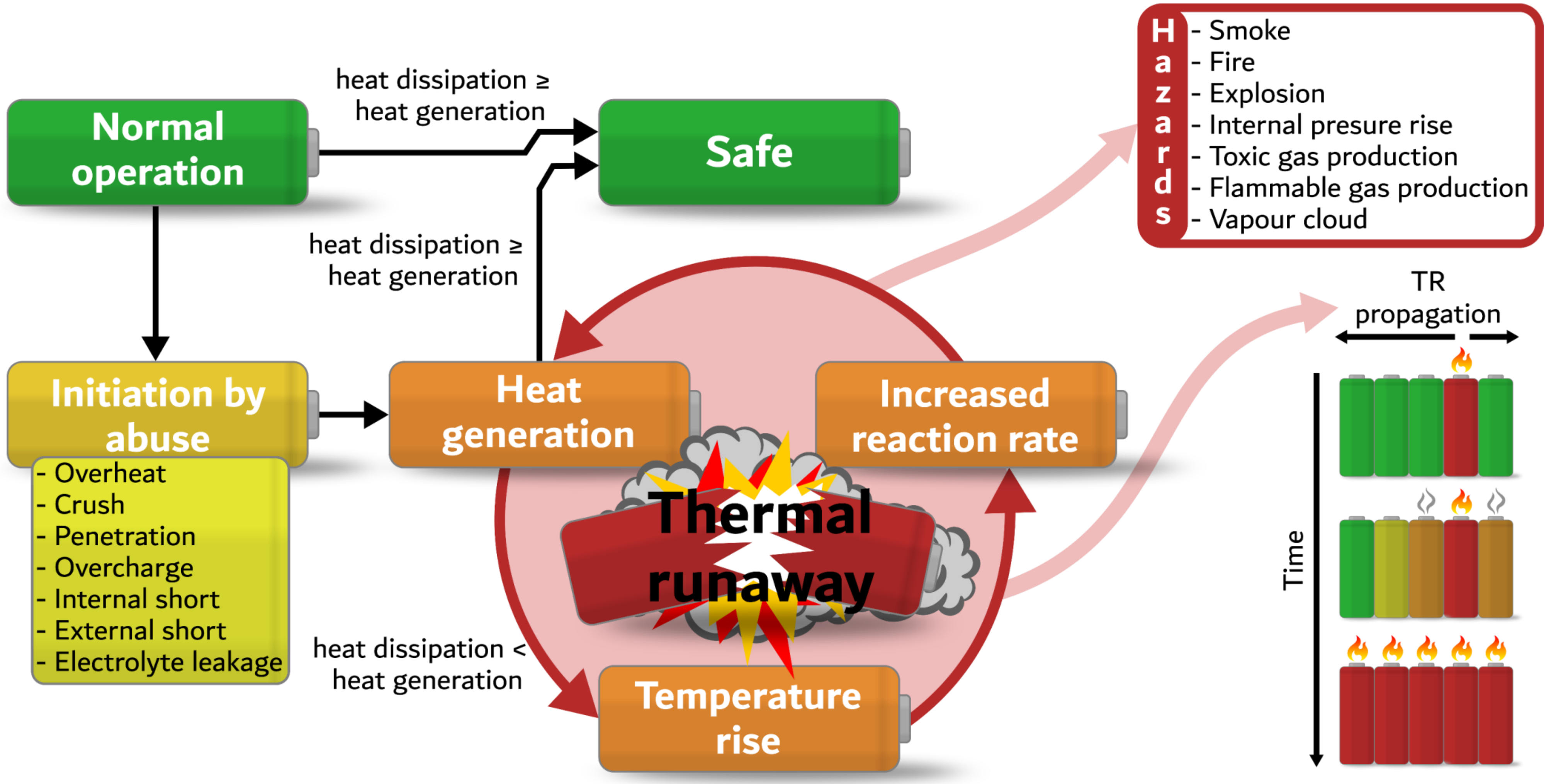
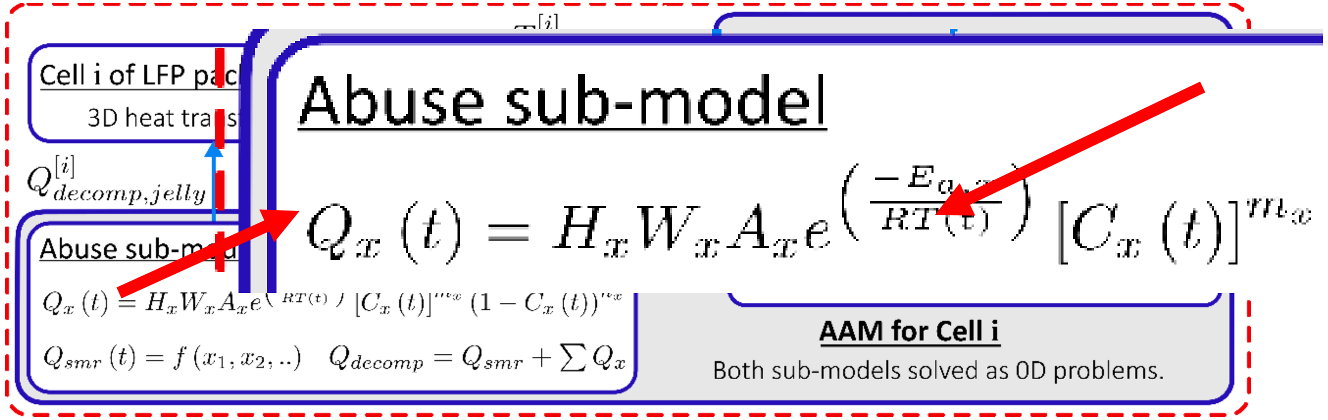


Figure: © P. Bugryniec
DOI: 10.13140/RG.2.2.34249.01120

Fundamental Modelling Principles

How do we model thermal runaway?

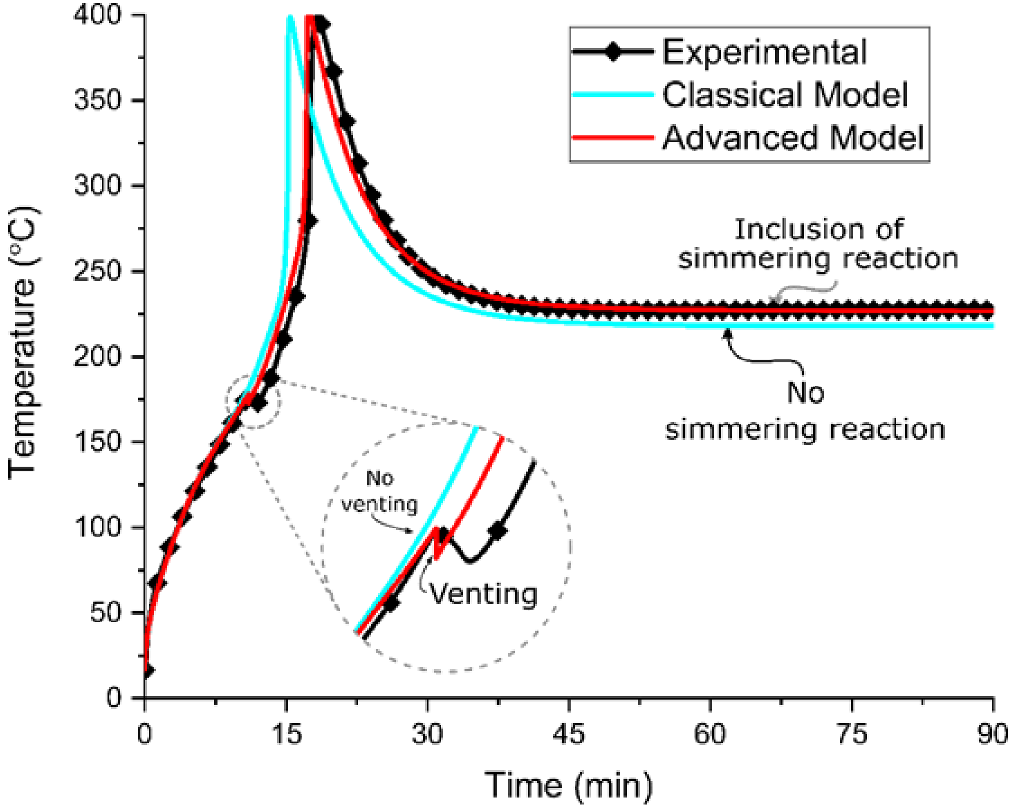


Reactions

- SEI
- Negative electrode – electrolyte
- Positive electrode – electrolyte
- Electrolyte

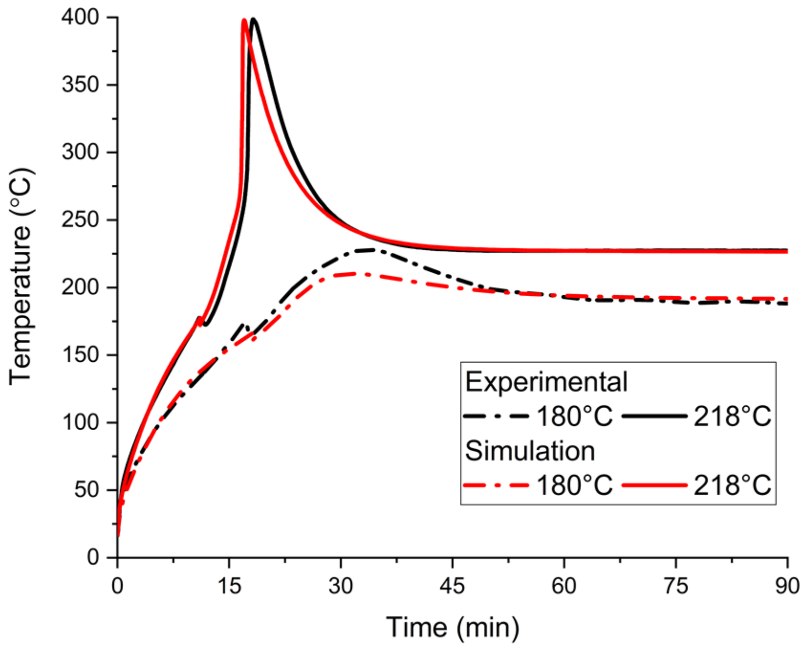
Improvements

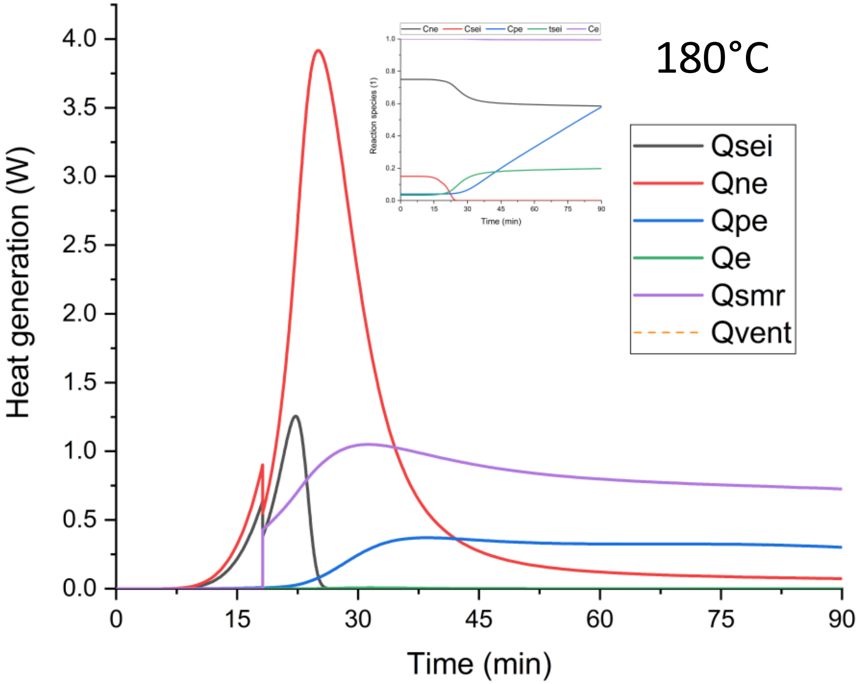
Inclusion of venting & Simmering reaction

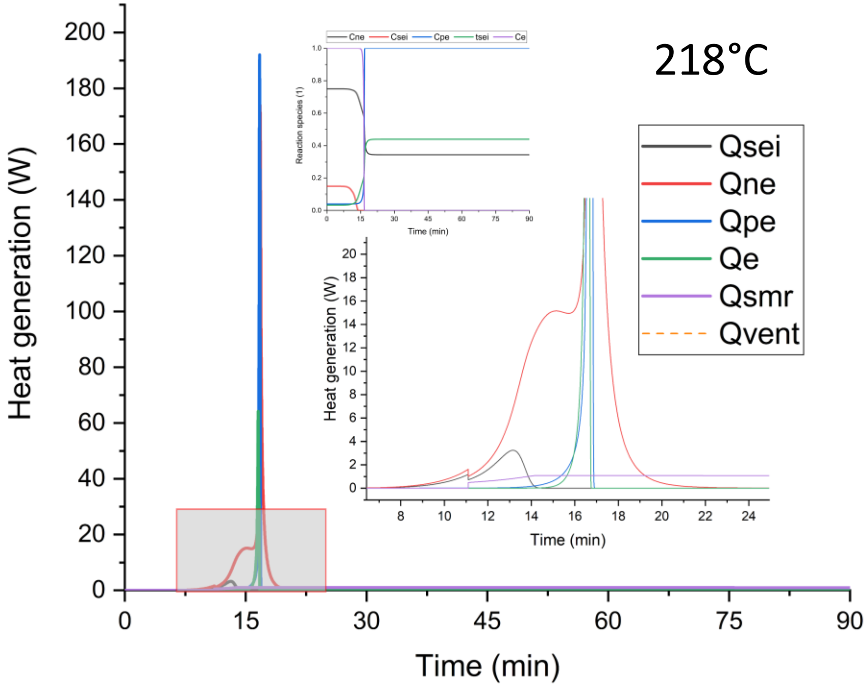


P. Bugryniec et al., "Advanced abuse modelling of Li-ion cells–A novel description of cell pressurisation and simmering reactions", Journal of Power Sources, 2020

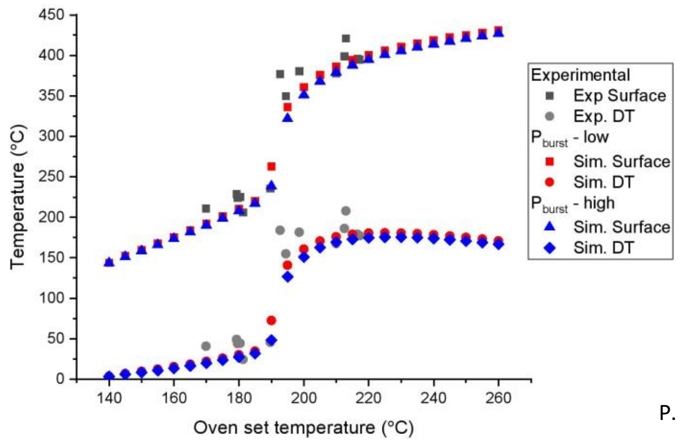
Understanding Reactions to Prevent Thermal Runaway







How predictions help…

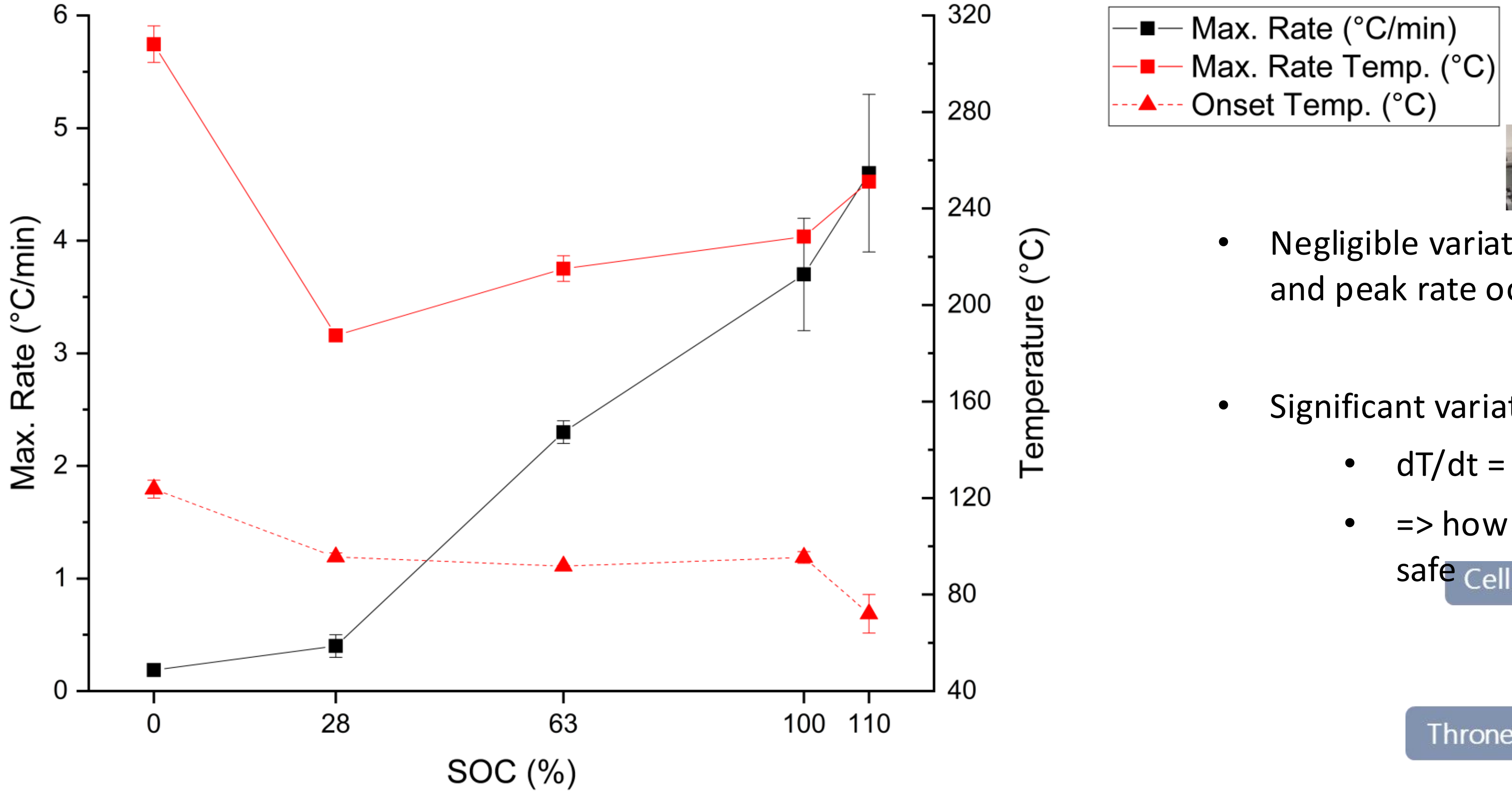


- Predict **critical region** – design a system to prevent occurrence
- **Materials engineering** – more stable, lower reaction heat, slower kinetics

P. Bugryniec et al., "Advanced abuse modelling of Li-ion cells–A novel description of cell pressurisation and simmering reactions", Journal of Power Sources, 2020

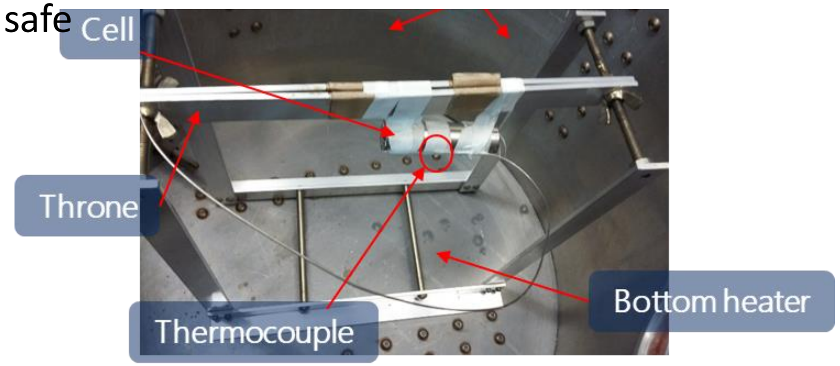
Importance of Uncertainty

Accelerated rate calorimetry data



- Negligible variation in temperature that TR starts and peak rate occurs

- Significant variation in **temperature rate**
  - dT/dt = heat generation (W)
  - => how difficult it is to mange T and stay safe

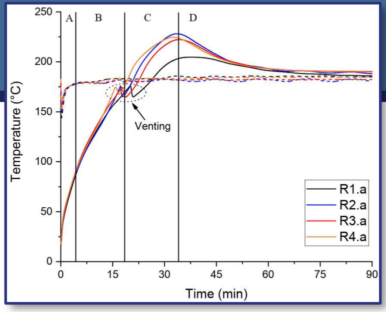


P. Bugryniec et al., "Pursuing safer batteries: thermal abuse of LiFePO4 cells", *Journal of Power Sources, 2019*

What does this mean in practice?

Challenge

What is the variation in TR?



Problem

How to account for this in physical model parameters?

Aim

To **determine the probability of cell failure** given the variations in cell properties.

Objectives:

1. Categorise the TR event from modelling studies against **EUCAR hazard levels;**
2. Predict **the frequency at which different hazard levels occur;**
3. **Determine the probability of cell failure** at different abuse conditions.

[1] P.J. Bugryniec, J.N. Davidson, D.J. Cumming, S.F. Brown, Pursuing safer batteries: thermal abuse of LiFePO4 cells, J. Power Sources 414 (2019) 557–568, https://doi.org/10.1016/j.jpowsour.2019.01.013.

[2] P.J. Bugryniec, J.N. Davidson, S.F. Brown, Advanced abuse modelling of Li-ion cells – A novel description of cell pressurisation and simmering reactions, J. Power Sources 474 (2020) 228396, https://doi.org/10.1016/j.jpowsour.2020.228396.

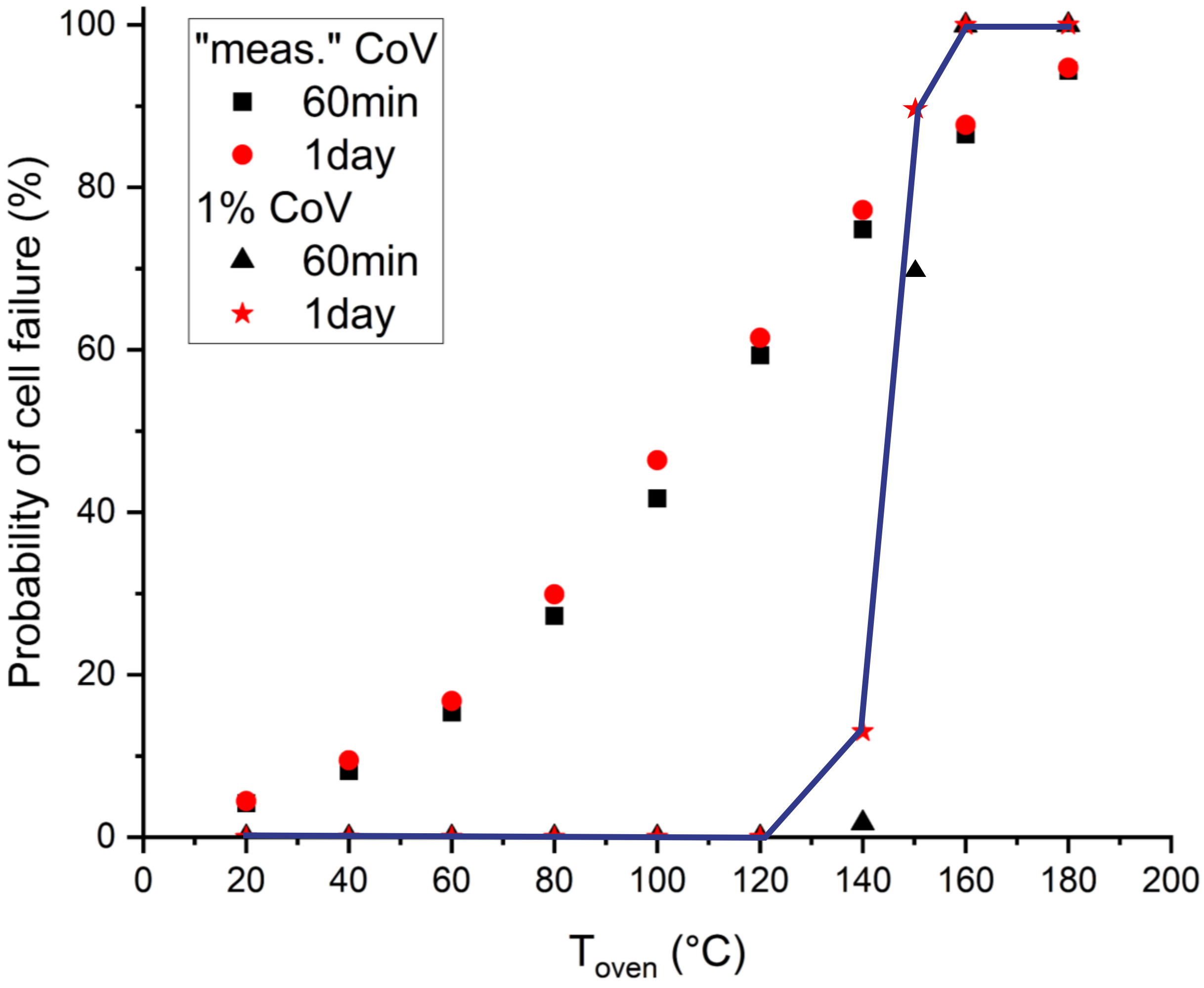
Hazard Level Assessment

EUCAR | **This work**

Classification Criteria & Effect	Description	Hazard Level	Description	Classification Criteria & Effect
No effect. No loss of functionality.	No effect	0	No effect	No exothermic reaction or thermal runaway. i.e. no increase in cell temperature above oven set temperature, no change in overall decomposition species, no heat generation.
No defect; no leakage; no venting, fire, or flame; no rupture; no explosion; no exothermic reaction or thermal runaway. Cell reversibly damaged. Repair of protection device needed.	Passive protection activated	1	n/a	n/a
No leakage; no venting, fire, or flame; no rupture; no explosion; no exothermic reaction or thermal runaway. Cell irreversibly damaged. Repair needed.	Defect/Damage	2	n/a	n/a
No venting, fire, or flame*; no rupture; no explosion. Weight loss	Leakage, Δmass < 50%	3	n/a	n/a
No fire or flame*; no rupture; no explosion. Weight loss ≥50% of electrolyte weight (electrolyte = solvent + salt).	Venting, Δmass ≥ 50%	4	Self-heating	Exothermic reactions, $\Delta T < 25$°C and $(dT/dt)_{max} < 10$°C min^{-1}
No rupture; no explosion (i.e., no flying parts).	Fire or Flame	5	Mild Thermal Runaway	Exothermic reactions, $\Delta T < 50$°C and $(dT/dt)_{max} < 100$°C min^{-1}
No explosion, but flying parts of the active mass.	Rupture	6	Moderate Thermal Runaway	Exothermic reactions, $\Delta T < 100$°C and $(dT/dt)_{max} < 1000$°C min^{-1}
Explosion (i.e., disintegration of the cell).	Explosion	7	Severe Thermal Runaway	Exothermic reactions, $\Delta T \geq 100$°C or $(dT/dt)_{max} \geq 1000$°C min^{-1}

[3] Doughty, D., Crafts, C., FreedomCAR: electrical energy storage system abuse test manual for electric and hybrid electric vehicle applications, Sandia National Laboratories (2006). https://doi.org/10.2172/889934

Probability of Failure (Hazard Level 4-7)

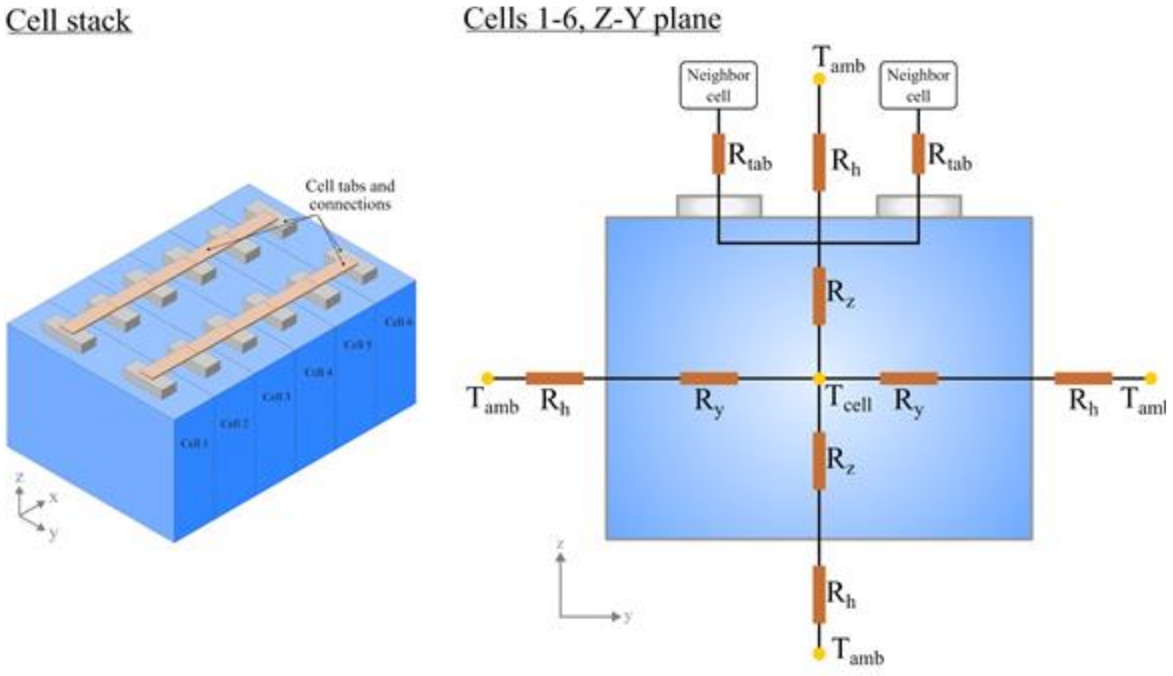


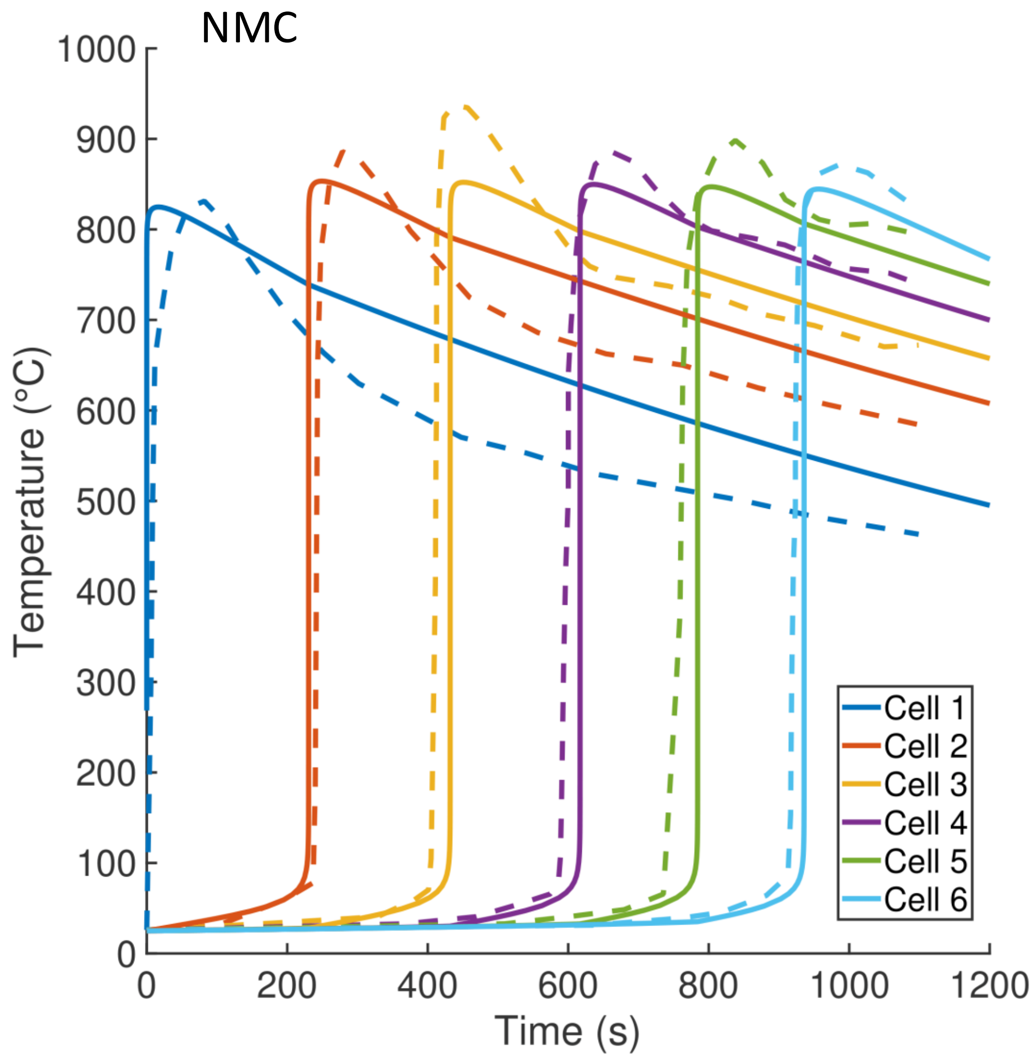
- Variation in case 1 leads to unrealistic predictions
- Case 2 shows that we can **predict the probability of failure** and how it **changes with exposure temperature**

What are the appropriate kinetic CoVs?

P. Bugryniec et al., "Predictive hazard level assessment of Li-ion cell thermal runaway failure", Energy Storage Conference, 2023

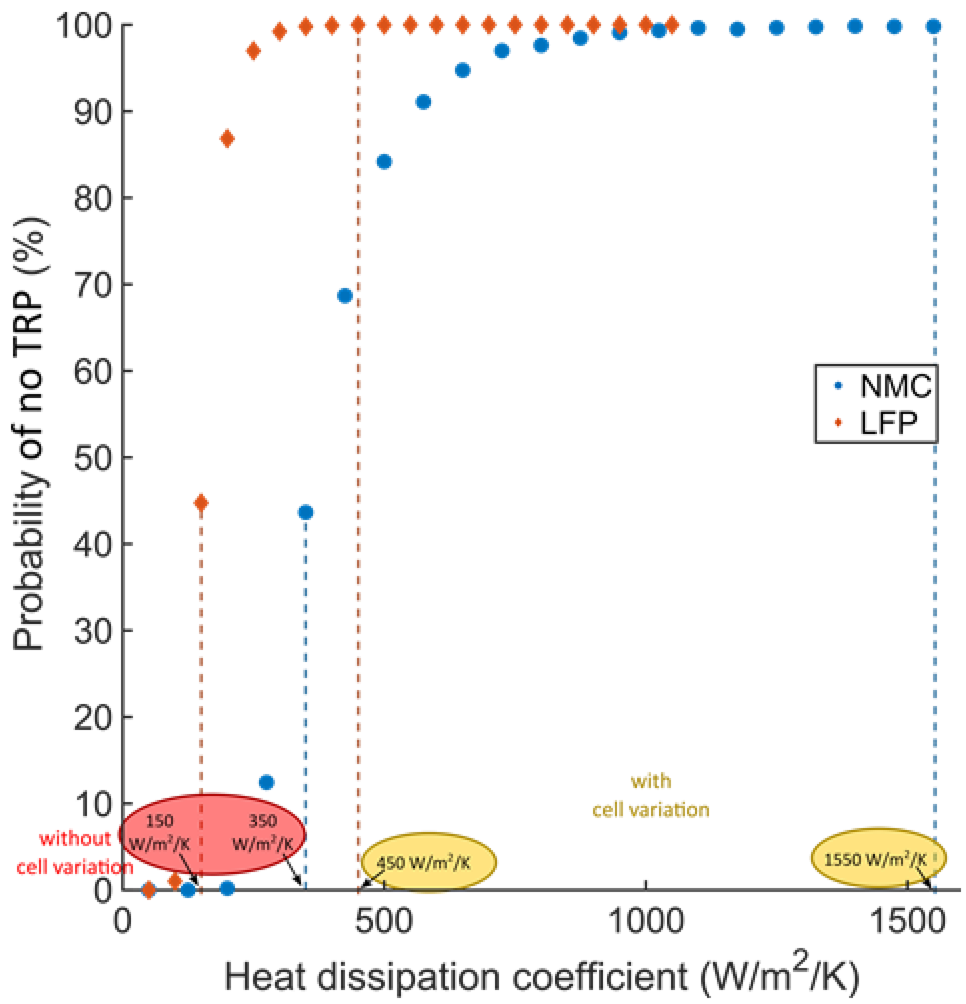
The effect of Uncertainty in Predicting Critical Parameters to Prevent Thermal Runaway Propagation





P. Bugryniec et al., "[Predicting Critical Parameters to Prevent Li-Ion Battery Thermal Runaway Propagation Considering Uncertainty]()", Electrochemical Society Meeting Abstracts PRIME, 2024

The effect of Uncertainty in Predicting Critical Parameters to Prevent Thermal Runaway Propagation



	Critical Heat Transfer (W/m2/K)		Possible solutions	
	No Cell Variation	Cell Variation	No Cell Variation	Cell Variation
NMC	341	1550	Heat pipes (500 W/m2/K) Oil or dielectric fluid (700-100 W/m2/K)	Liquid/vapour phase change
LFP	150	450	Forced air cooling (250 W/m2/K)	Heat pipes (500 W/m2/K)

- Cri... reater un...

The importance of cell uncertainty in TRP predictions is highlighted for better risk assessment

- Fr...

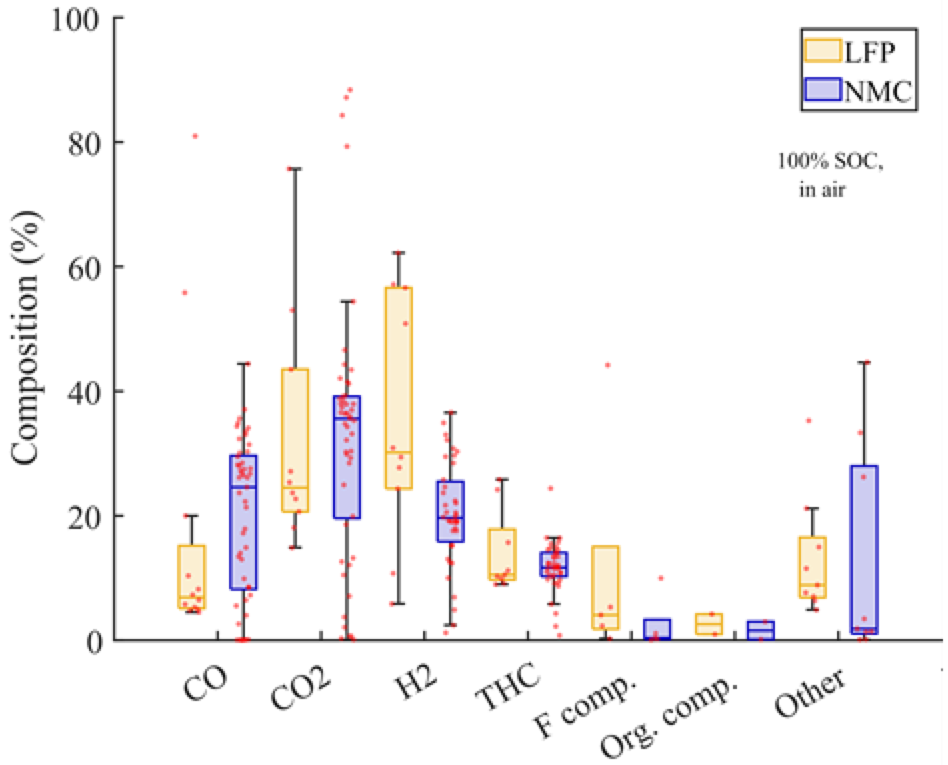
1. For LFP – **TRP prevention is theoretically possible** with practical cooling methods
2. ... putting
3. ... and TM

Future work: Extend to include electrochemical and fire

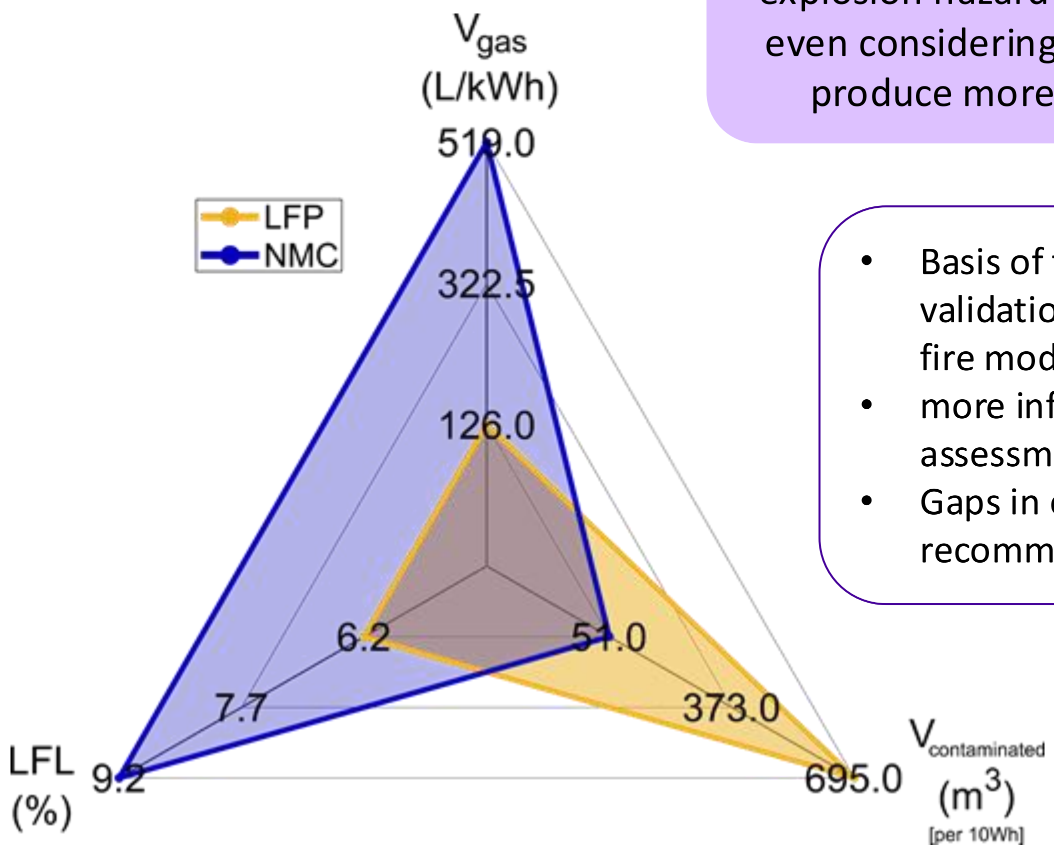
P. Bugryniec et al., "Predicting Critical Parameters to Prevent Li-Ion Battery Thermal Runaway Propagation Considering Uncertainty", Electrochemical Society Meeting Abstracts PRIME, 2024

Beyond the Thermal Hazard

Fire and Toxicity



P. Bugryniec et al., "[Review of gas emissions from lithium-ion battery thermal runaway failure — Considering toxic and flammable compounds](#)", *Journal of Energy Storage*, 2024



LFP battery TR presents a greater contamination and explosion hazard than NMC, even considering NMC cells produce more off-gas.

- Basis of future model validations – mechanistic fire models
- more informed risk assessments
- Gaps in existing research -> recommendations

1 Cell can contaminate an entire room

Conclusions

- Classic TR model applied to **determine the probability of TR failure**
- **UL oven test standard** is used as a case study
- **EUCAR Hazard Levels** redefined in terms of measurable quantities (T, dT/dt)
- For the UL test, the **example cell** undergoes no change, self-heating and TR 10%, 75% and 15% of the time respectively
- **Time period important**

There is a **need to better understand and refine the variance in cell parameters**

Future work: Extend to module studies **to understand how TR propagation changes**

P. Bugryniec et al., "Predictive hazard level assessment of Li-ion cell thermal runaway failure", Energy Storage Conference, 2023

Thank you

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