Scaling Safety at the Heavy Frontier

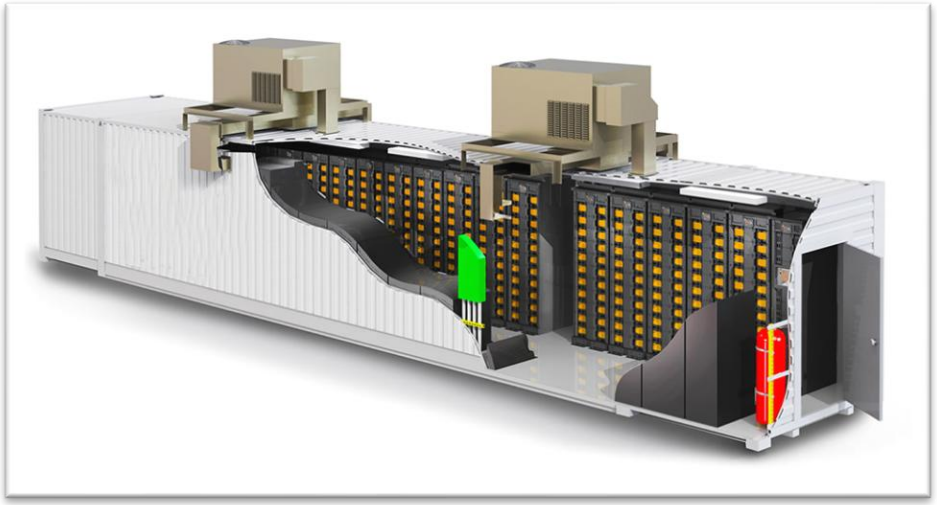
Why Battery Safety Breaks at Scale – and What to Do About It

Anne Seldon FSaRS

The contexts that shaped lithium-ion battery design

Most lithium-ion battery design and safety assumptions come from controlled applications

Consumer Electronics



Static Storage / Backup Systems

Automotive

SOTEIRA CONSULTING

Where these systems are now being deployed

- Multi-MWh battery systems
- Remote, production-critical assets
- Persistent contamination
- No viable fire response

SOTEIRA
CONSULTING

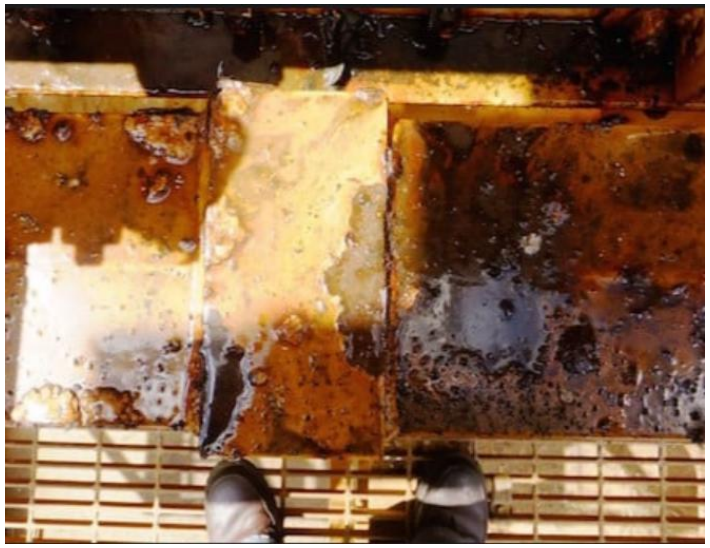
When design assumptions break down

SOTEIRA
CONSULTING

Environmental Degradation

Design and validation approaches remain misaligned with operational reality

Conductive Dust Contamination



Saline-Induced Corrosion and Tracking

High-Pressure Washdown and Forced Ingress

SOTEIRA CONSULTING

Fire Becomes Unmanageable

Mitigation strategies often assume conditions that do not exist in remote or heavy-duty operations

- Suppression depends on water, agents, and response time
- Remote sites have limited resources and access
- No widely effective system-level suppression solutions at this scale
- Charging and maintenance infrastructure concentrates risk

SOTEIRA
CONSULTING

Maintenance Becomes a Constraint

Limited access, capability, and intervals allow faults to persist and accumulate

- Maintenance facilities are not designed for high-voltage electrical repair
- High-voltage systems require specialist skills and procedures
- Distance from repair facilities limits timely intervention
- No clear pathway exists to transport damaged battery systems at this scale

Faults persist in service longer than design assumptions account for

Towards Active Lifecycle Safety Management

Safety must be approached as a system across the full lifecycle, not optimised at component level

System-Level Design Thinking

- Consider full system interactions, not just cells or components
- Account for environment, operations, and interfaces from the outset

Condition Awareness

- Monitoring beyond cell behaviour to system-level conditions
- Capture environmental and operational inputs (temperature, vibration, shock)
- Update degradation models using operational data

Validation & Testing Aligned to Reality

- Testing reflects actual environmental and operational conditions
- Moves beyond automotive/transport derived assumptions
- Covers cell > system > operational context

Maintenance Aware Engineering

- Systems must enable safe containment of damaged batteries at scale
- Clear and practical pathways required for transporting damaged systems
- Design must account for recovery, isolation, and removal from service

SOTEIRA CONSULTING

Designing for Operational Reality

Safety depends on how well we account for real-world conditions

SOTEIRA
CONSULTING

Thank you – Questions?

Read the full paper
soteiraconsulting.com/whitepapers

anne@soteiraconsulting.com

SOTEIRA CONSULTING

Applying Functional Safety to Battery Management Systems

Simon Burwood

Jonny Gale

Sustainability is our business

Simon Burwood

Eur Ing BEng (Hons.)
FSaRS RFSA CEng FS
Expert (TÜV Rheinland)

- 20+ years' experience in the specification, design, management, and assessment of safety-related systems
- Member of the BSI GEL/065/01 Committee and was appointed to the IEC 61508 and IEC 61511 Maintenance Committees (MT 61508 & MT61511) as a UK expert on Functional Safety.
- Chartered Engineer (CEng) and Fellow of the Safety and Reliability Society (SaRS)

Jonathan Gale

BEng FS Engineer
(TÜV Rheinland)

- 6 years' Functional Safety and Process Safety experience in multiple hazardous industries.
- FS Engineer (TÜV Rheinland) # 28757/ 24)
- Associate Member of the Institution of Chemical Engineers (IChemE)
- Operational experience as Technical Safety Engineer at Major Energy Operator

cass
Assessor ID: 23002

IEC

ESC
An ERM Group Company

ProSET
An ERM Group Company
The Complete Process Safety Evaluation Toolset

ERM

What is Functional Safety?

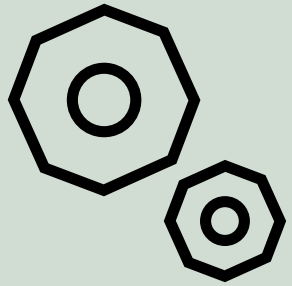
Functional safety (IEC 61508-4):

"part of the overall safety relating to the EUC and the EUC control system that depends on the correct functioning of the E/E/PE safety-related systems and other risk reduction measures"

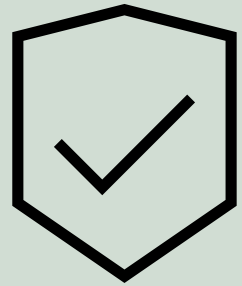
We prefer:

Achievement of safety through application of control systems

Two key concepts:

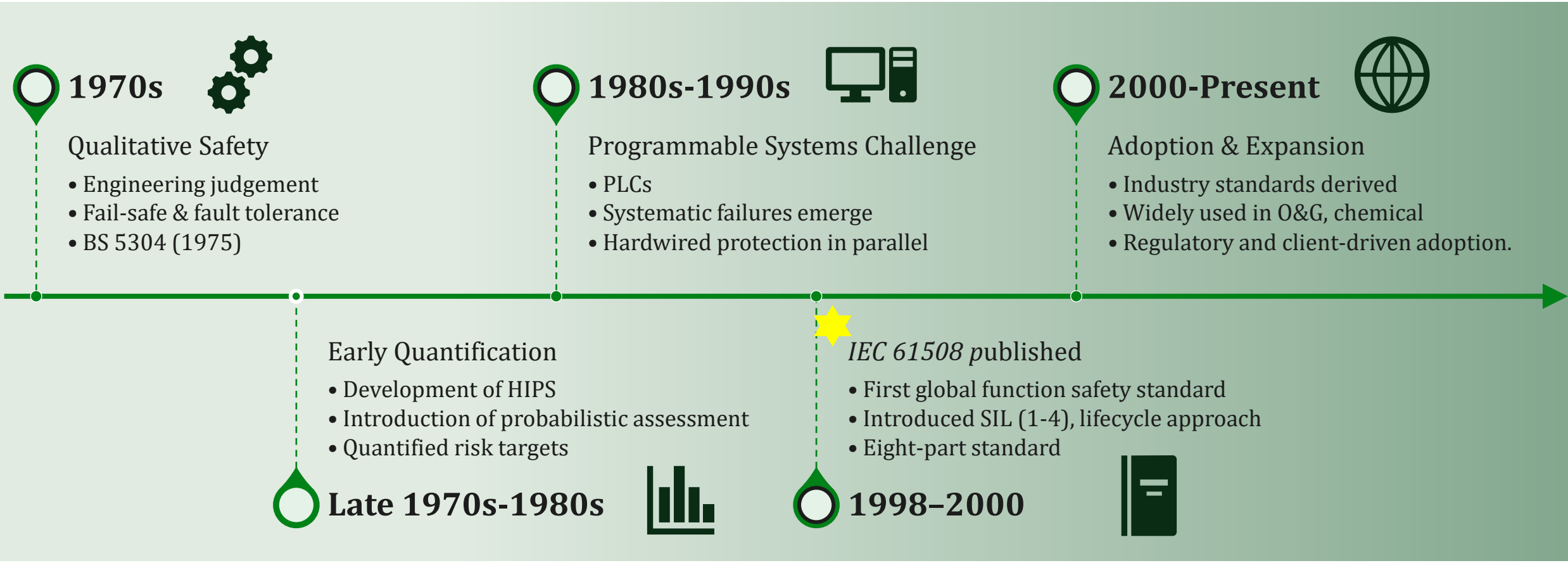


1. Functionality



2. Integrity

Origin of Functional Safety



Key Takeaway:
IEC 61508 transformed 'functional safety' into a **unified**, **quantitative**, **lifecycle-based approach** for managing risk in safety-related systems

EPRI BESS Failure Incident Database

46% of recorded BESS fires caused by control systems (EPRI BESS Failure Incident Database)

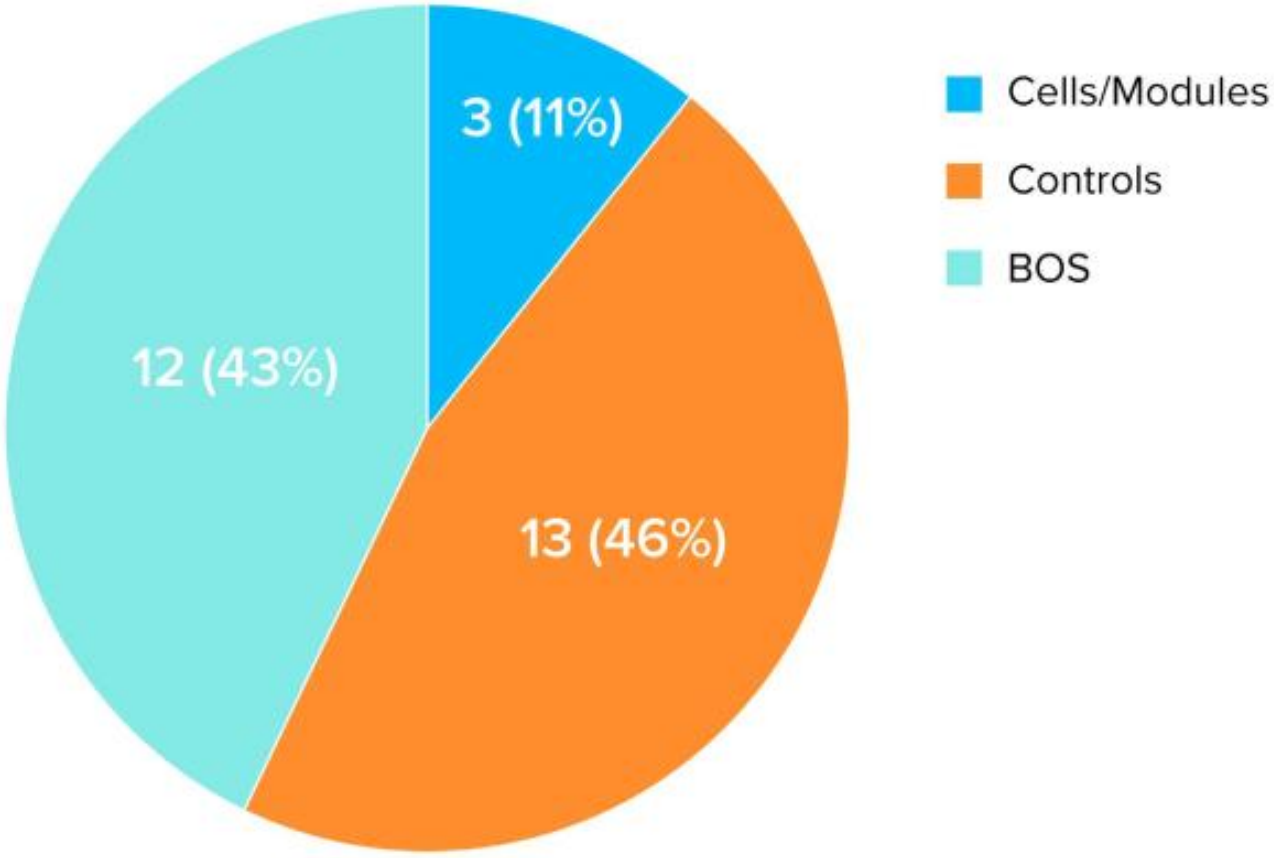


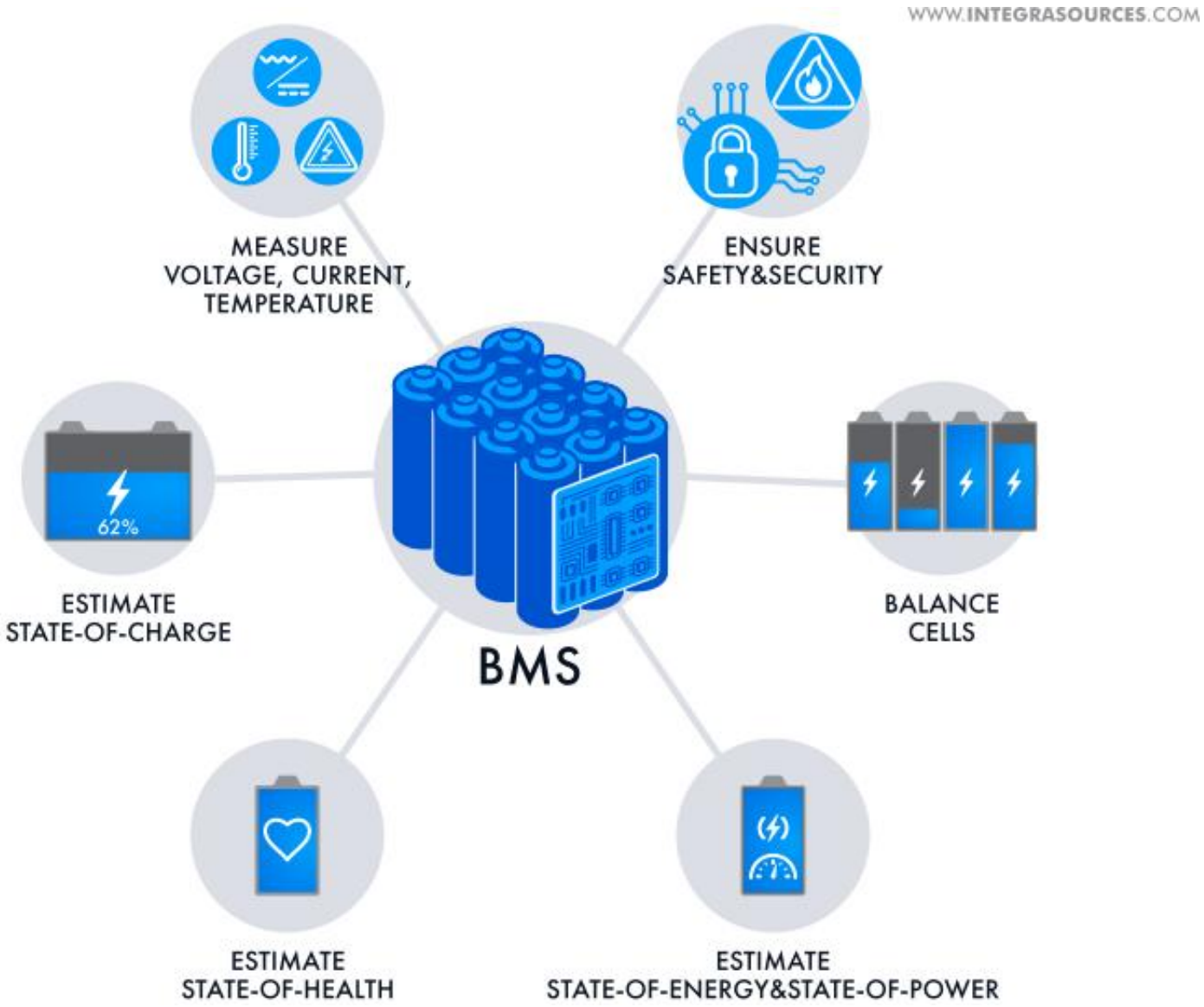
Figure 6. Breakdown of BESS Failures by Failed Element

Real-World Incident Examples

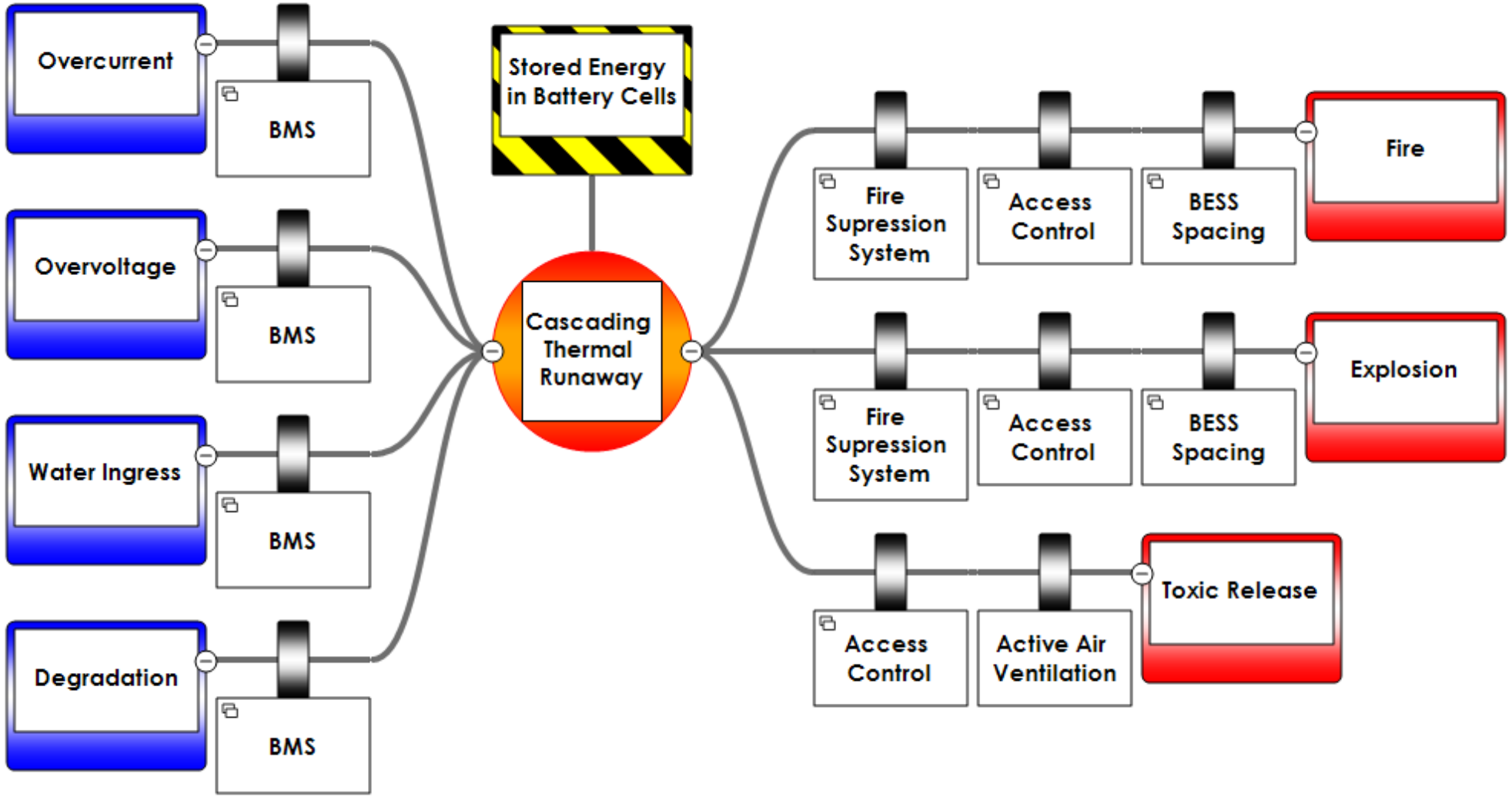
Location	Date	System Type	Control Failure Description	Outcome
Chandler, Arizona	April 2022	Containerised lithium-ion BESS	Automatic sprinkler system ran continuously; failure in fire suppression logic and thermal management controls.	Fire burned for over ten days; robot used to open container.
Gunwi-gun, South Korea	Jan 2022	Indoor BESS installation	BMS and supervisory systems failed to provide hazard warnings or containment; emergency protocols not triggered.	Fire brigade entered unaware of explosion risks; no explosion occurred.
South Korea (multiple sites)	2023	BESS units in large buildings	Lack of module separation and inadequate BMS fault isolation allowed thermal runaway propagation.	At least one of 24 BESS buildings completely destroyed.

BMS as a Safety-Related System (continuous mode safety function)

Under Functional safety standard **IEC 61508**, a **continuous mode safety function** is one that retains the Equipment Under Control (EUC) in a safe state as part of normal operation.



Bowtie Diagram – Barriers heavily weighted to RHS of bowtie



ERM

Preventative Safety Functions

Abnormal Condition
(Overcurrent, Overtemperature, Cell imbalance)

↓

Sensor & Diagnostics
Cell and module monitoring
Thresholds / plausibility checks
Diagnostics and fault detection

↓

BMS Safety Logic
(Current limitation, Cell / string isolation, Controlled shutdown)

↓

Safe State
Thermal runaway prevented

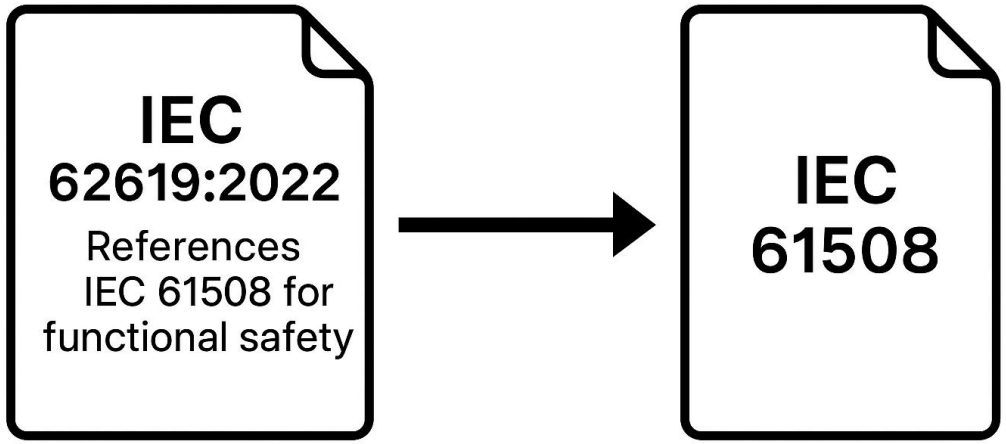
https://www.energy-storage.news/kwh-analytics-bess-safety-concerns-have-risen-following-fires/

ERM

What's Already Happening in Industry?

(IEC 62619:2022) International standard specifying safety requirements for secondary lithium cells and batteries used in industrial applications

Section 8.1 of IEC 62619 ("Battery system safety (considering functional safety)") explicitly lists IEC 61508 as a primary reference for evaluating the functional safety of Battery Management Systems (BMS).

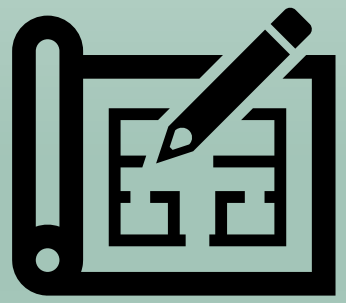


Manufactures already applying IEC 61508 to the BMS

Challenges to Expect

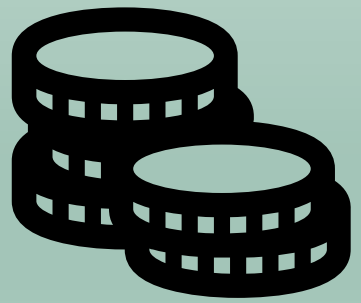
Design & Process Complexity

More structured and disciplined way of designing systems, particularly around requirements, verification, and lifecycle management



Financial Impact

Additional engineering effort, more rigorous testing, and often some level of independent assessment

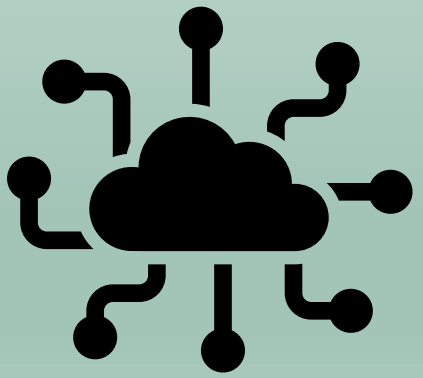


Evidence & Data Availability

Manufacturers need reliability data, failure rates, and diagnostic coverage that can stand up to scrutiny

Legacy BMS Architectures

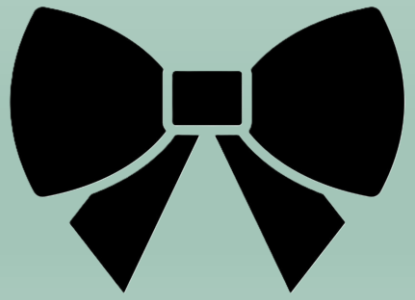
Retrofitting functional safety into those architectures can be difficult



Final Recommendations

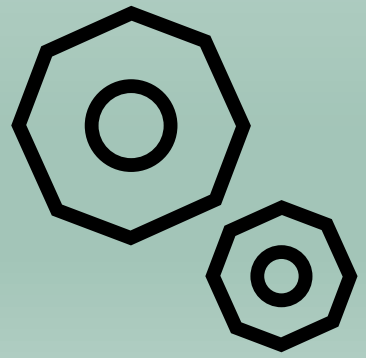
Treat the BMS as a preventative safety system

Responsible for intervening early to stop hazardous conditions from developing - not just as an optimisation or monitoring layer.



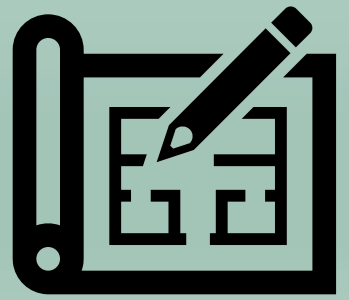
Define explicit safety functions

What the safety functions are, what conditions they need to detect, what actions they take, and how well they need to perform.



Apply IEC 61508 in Design

Helping manufacturers move beyond generic safety processes and towards explicit, demonstrable safety performance for BMS design.



Address functional safety early in the BMS lifecycle

Most effective when it's considered early in the BMS design lifecycle, rather than added on later as a compliance exercise.

Thank you

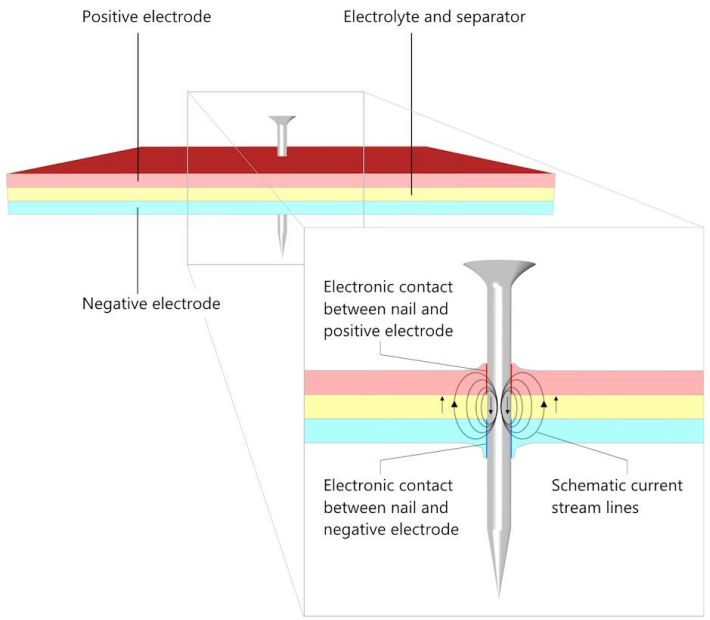
BESS: Li-Ion battery fire characterisation and PFP perspective

Owen Morris
Senior Fire Protection Specialist

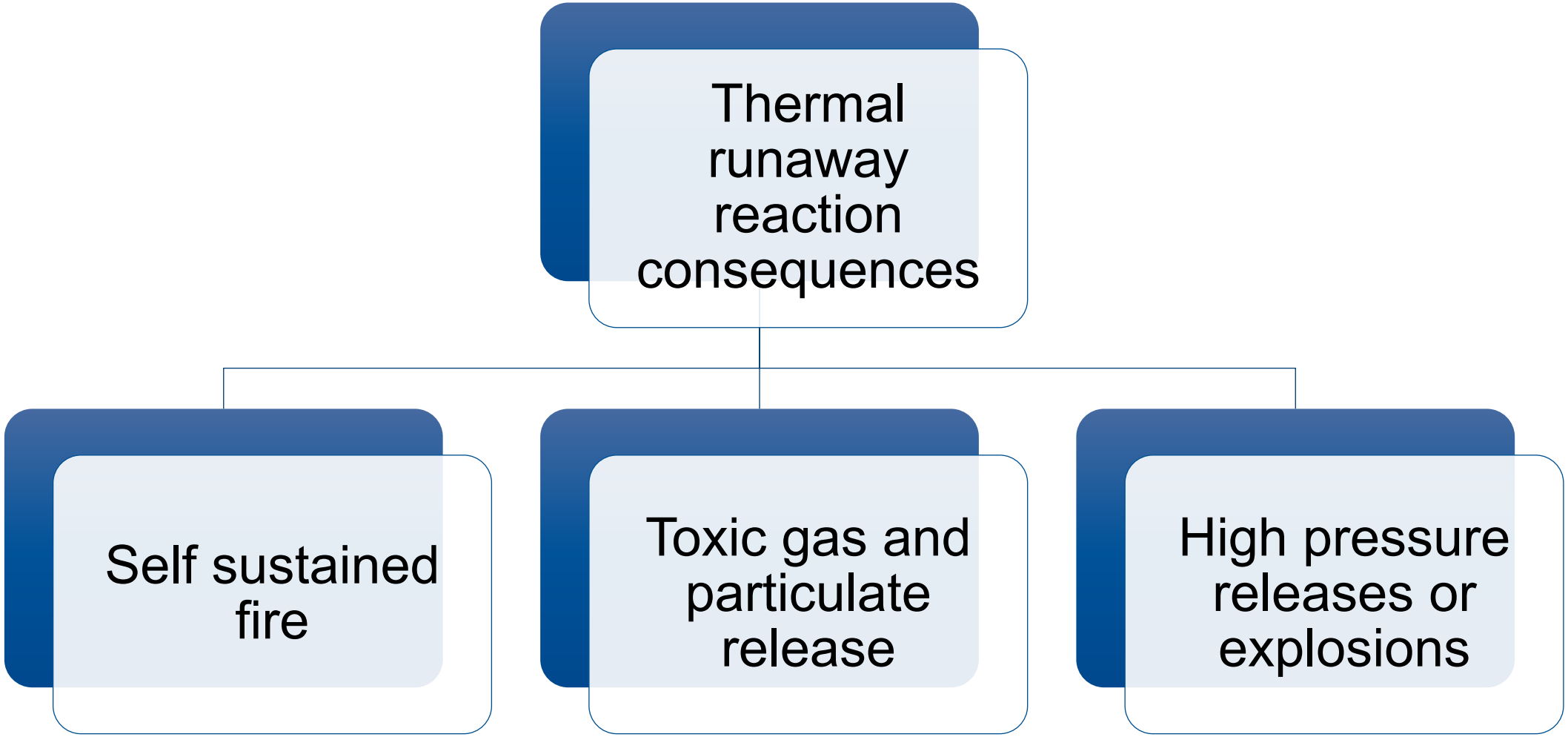
Thermal Runaway (TR) reaction

Uncontrolled, self-sustaining increase in temperature and pressure caused due to:

1. Mechanical Damage
2. Overheating
3. Overcharging
4. Internal short circuit
5. Manufacturing defect



Consequences



Lithium-Ion Battery Chemistry

Concerns:

- Little understanding of the escalation from thermal runaway reactions
- Battery technology evolution> understanding
- Increasing specific energy density
- Limited and restrictive standards

BESS key fire risks

Electrical faults (short circuit, overcharge).

Mechanical damage during transport or installation

Cooling system failure leading to hotspots

Accumulation of flammable gases inside enclosure

Thermal propagation between cells, modules, racks

How can Passive fire protection help?

- Limits thermal propagation inside modules/racks
- Maintains compartment integrity during fire from internal and external sources
- Protects nearby infrastructure and equipment
- Works without power and detection, even during system shutdown
- Supports compliance with fire codes and testing results

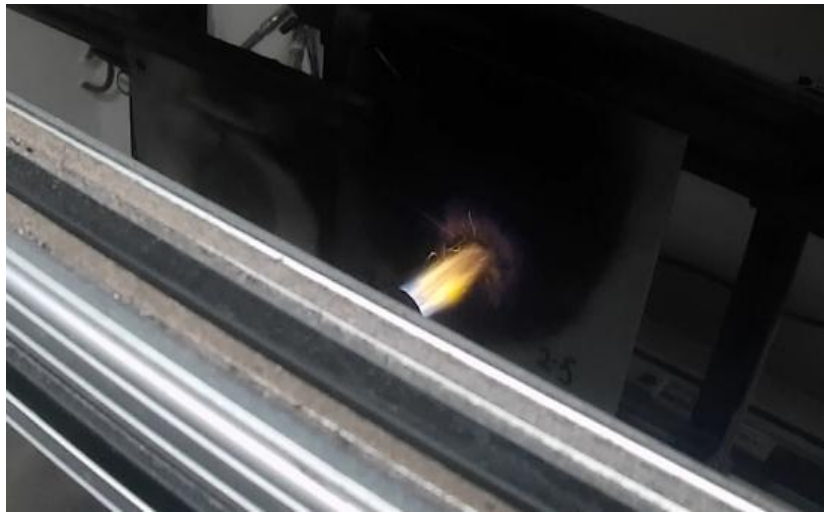
So, what’s the issue?

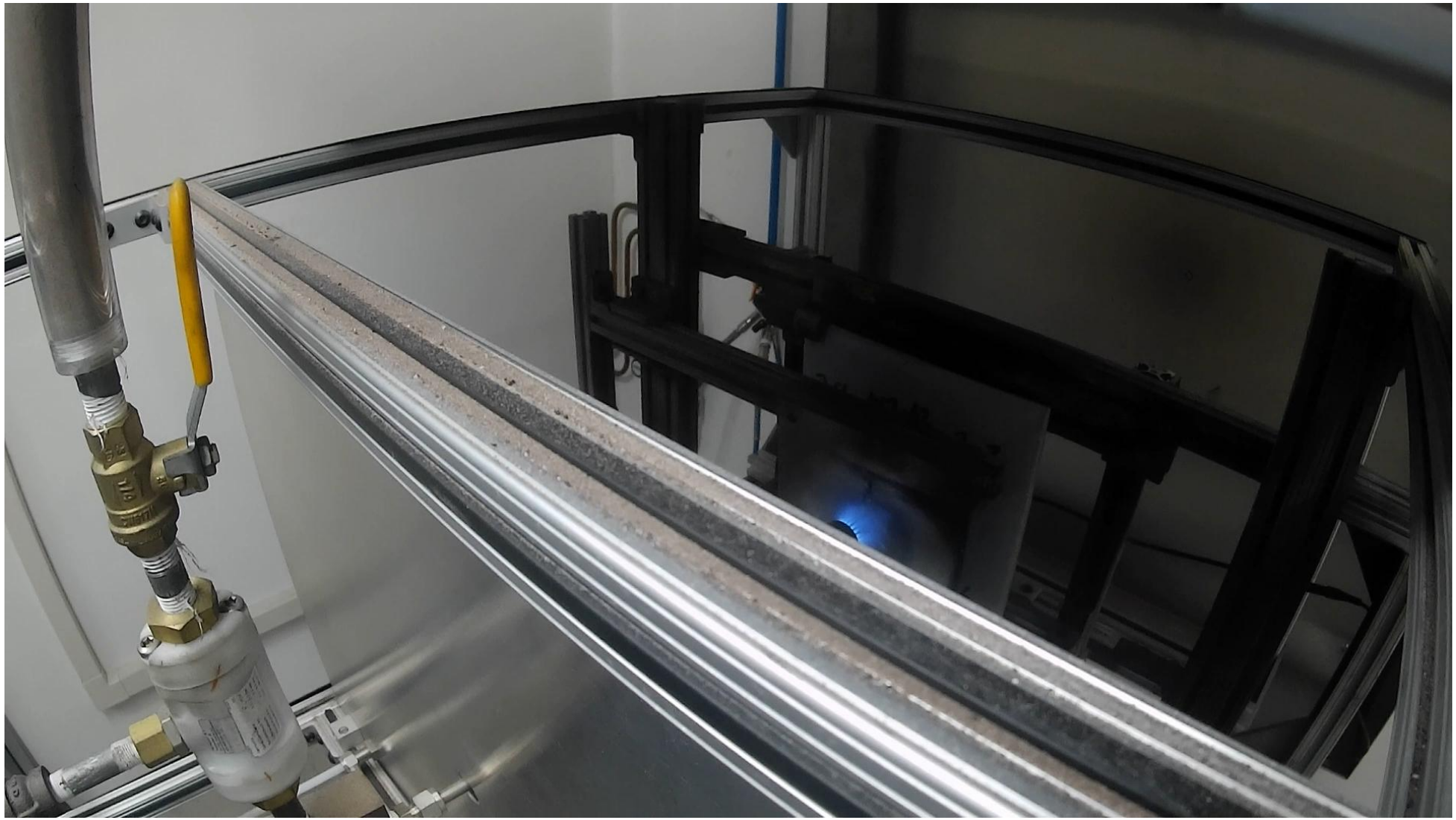
Limitations of standards

1. No standard directly evaluates PFP performance under Li-ion thermal runaway (TR) conditions
2. UL9540A records TR behaviour but does not test or rate PFP integrity, erosion, or durability
3. EN1364-1 building fire tests do not represent jet-like TR events or localized high-intensity heating
4. ISO 22899 hydrocarbon jet-fire tests omit hot solid particles and do not match Li-ion jet characteristics
5. No standardized tests for high-pressure, particle-laden jets, which can damage or penetrate coatings
6. Current standards ignore mechanical stresses, char disruption, and coating adhesion loss during TR venting
7. No pass/fail criteria or performance metrics for PFP inside BESS enclosures, leading to inconsistent industry practices

UL2596 Testing

1. Assesses resistance to:
2. Flame exposure
3. Hot particle impact (aluminium oxide abrasion)
4. Structural degradation
5. Duration: 200 seconds (10 cycles).
6. Each cycle: 15 s flame + 5 s grit





UL2596 Testing

WB 1k acrylic

- Performed as expected vs flame.
- Grit-exposed region heavily abraded.
- Unable to endure full 10 cycles—eroded to bare metal at impact site.

Epoxy amine

- Withstood all 10 cycles.
- Photographs show unreacted material remaining at impact site.

AkzoNobel

Are industry tests representative of real-world scenarios?

Test setup overview

AkzoNobel

Four tests completed so far.

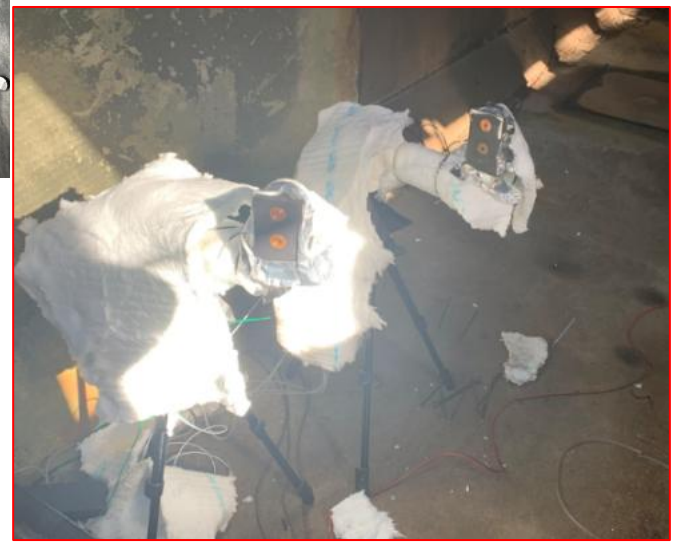
- Battery type: 40Ah NMC pouch cells.
- Tests include 1-cell and 3-cell configurations.
- Cells overcharged to initiate thermal runaway

Enclosure and instrumentation

Cells placed in a purpose-designed enclosure with variable vent size (supports up to 5 cells).

Instrumentation:

- Thermocouples on cells and vent orifice
- Pressure transducer
- Heat flux gauges & radiometers positioned at controlled distances




07/ 11/ 2025 15: 00: 20


07/ 11/ 2025 15: 00: 20

Test 1 results

- Vent gas velocity broke the closest plate support
- Jet flame lasted 3-4 seconds; did not reach the 1 m plate
- Dense black smoke released pre-ignition, coating all instrumentation
- Radiometers recorded no heat flux
- Approx. 70 kW/m² heat flux recorded briefly—data treated with caution

Test 2 and 3 results (single cell, repeat)

1. Heat flux gauges cleaned and moved closer with improved mounting
2. Heat flux gauge mounts changed to 2mm thickness
3. Increased vent size in Test 2; reduced vent size in Test 3
4. Hot particles chipped and later destroyed heat flux gauges
5. Jet flame characteristics similar to Test 1
6. Minimal usable heat flux data obtained

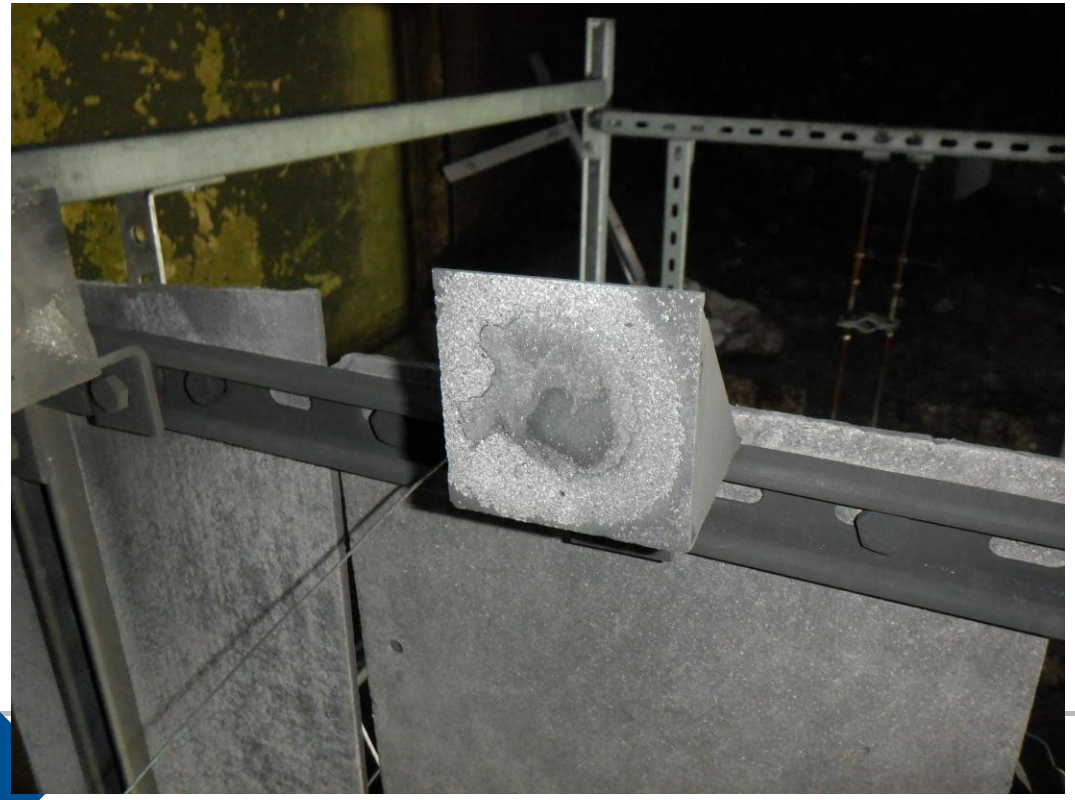
Test 4 setup

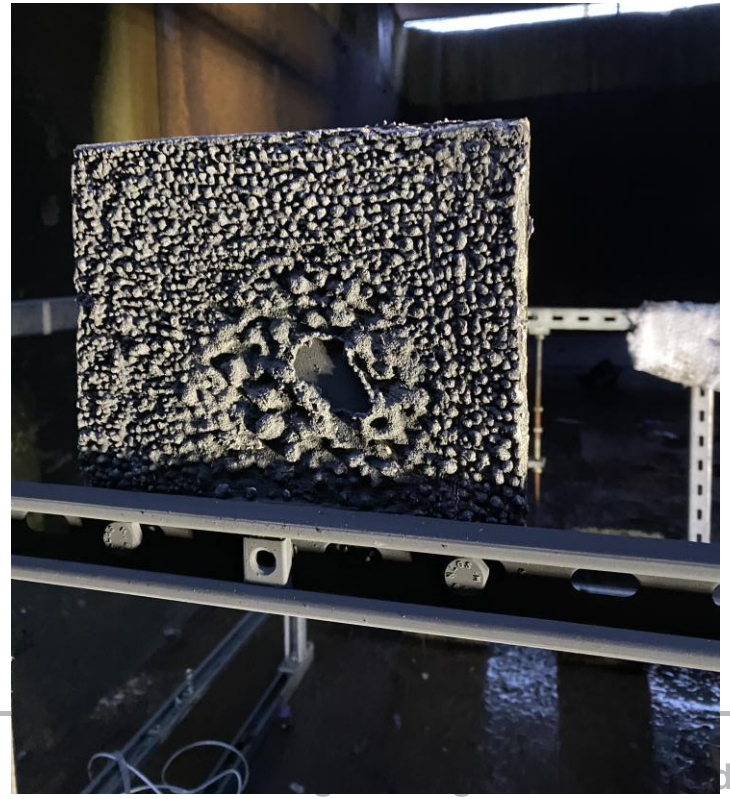
AkzoNobel

- A 200 × 200 × 2 mm coated steel plate placed at 0.5 m
- Increased number of cells (three) to generate stronger behaviour
- Generated a 33-second jet flame—much longer and more intense

Product outcomes

1. Expelled hot particles severely damaged the 1k acrylic coating
2. Damage mode similar to UL2596 “torch and grit” results
3. Confirms that erosive particle impact is a major challenge for PFP materials





AkzoNobel

Key learnings

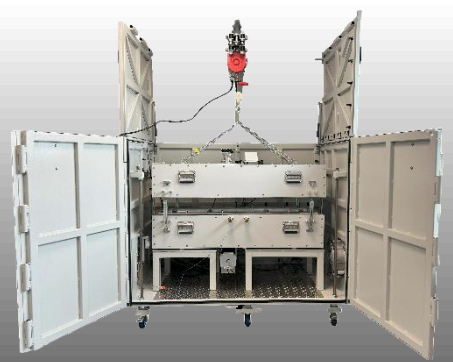
- Growing interest from BESS manufacturers in using PFP to mitigate TR propagation
- BESS manufacturers adopt inconsistent PFP approaches due to lack of standardized testing
- Existing standards (EN1364-1, ISO 22899) do not represent TR jet fire conditions
- TR events generate hot solid particles that can erode or damage PFP coatings
- Particle-laden jets complicate heat flux measurement and can impair coating integrity
- UL 2596 can indicate whether a coating is generally vulnerable to flame abrasive impact
- Not sufficient to rate, specify, or certify PFP coatings

AkzoNobel

Thanks to

- Dr Jason Gill, Principal scientist HSE
- Dr Paul Christensen, Professor Emeritus, Newcastle University
- Dr. Wojciech Mrozik, Faraday Institute Senior Research Fellow, Newcastle University

Quantitative Approach to Determine the Safety of Na-ion Batteries using Advanced Calorimetric Methods





Dunedin House • 3-4 Auckland Park • Bletchley
MK1 1BU • UK Tel +44 1908 646800
Email: info@thtuk.com • Web www.thtuk.com

Thermal Hazard Technology

Introduction to Thermal Hazard Technology

- Founded in 1996 focused on specialist calorimeters for the process safety industry. Continued to develop ARC systems for battery applications.
- Developed the world's first large adiabatic battery calorimeter (EV ARC)
- THT's headquarters in Bletchley UK is currently employing 40+ staff. There are sales offices in India and the USA, and distribution worldwide.
- Dedicated R&D department and calorimeter lab in UK

Sodium Ion Chemistry for Rechargeable Cells

Reasons for interest

- Abundant & low-cost – Sodium ~100× cheaper to source/process than lithium
- Low-temperature operation (electrolyte dependent)
- 0 V / 0% SOC safe storage & transport (not possible with li-ion as this can damage the cell)
- High cycle count (long life)
- 4V Max Charge Voltage
- Claimed improved safety performance – **FOCUS OF TODAYS PRESENTATION**

Main disadvantages

- Lower energy density
- Less researched/understood compared to Li-ion

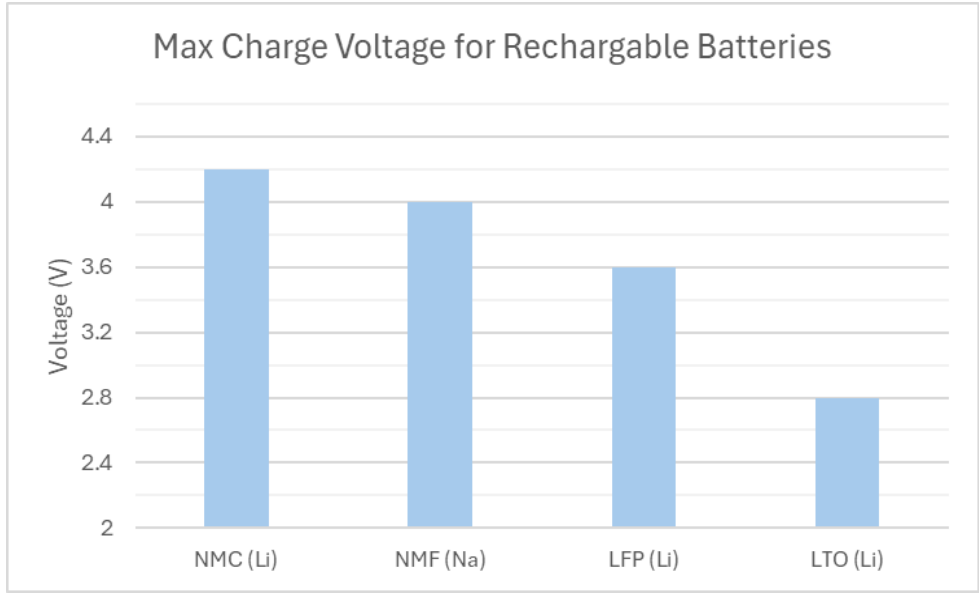
NEWS

‘A turning point’: CATL and HyperStrong sign 60GWh sodium-ion agreement

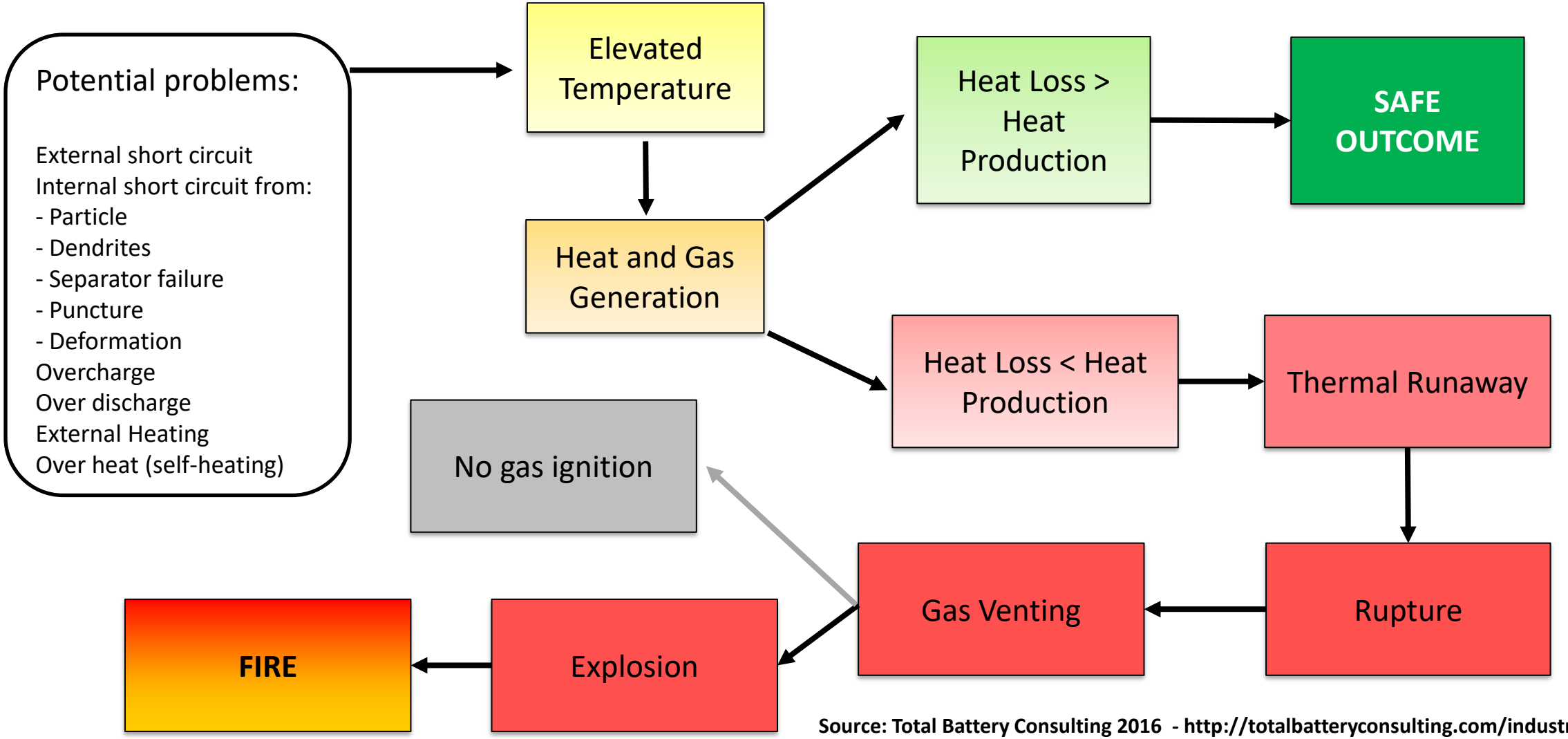
By Cameron Murray

April 27, 2026

Executives marking the agreement. Image: CATL / HyperStrong.

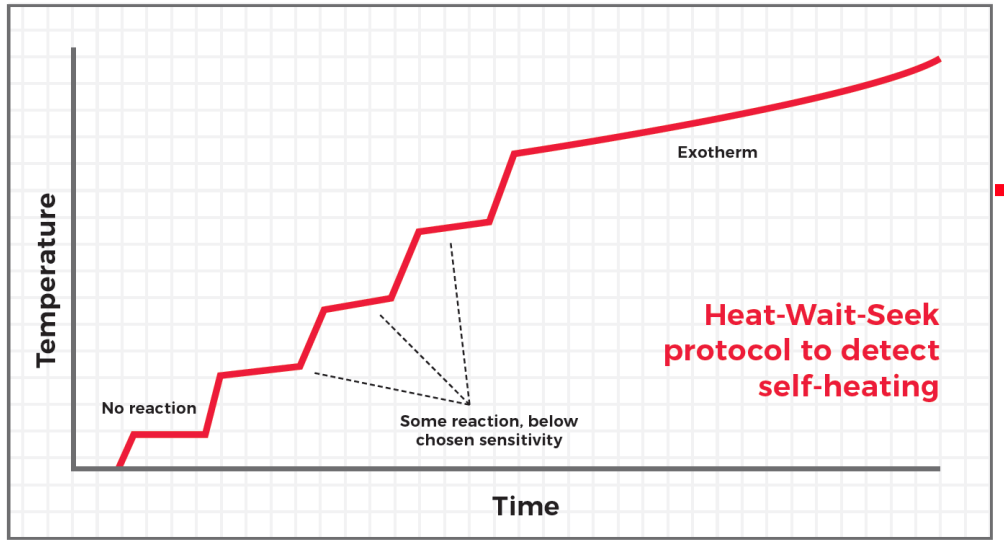


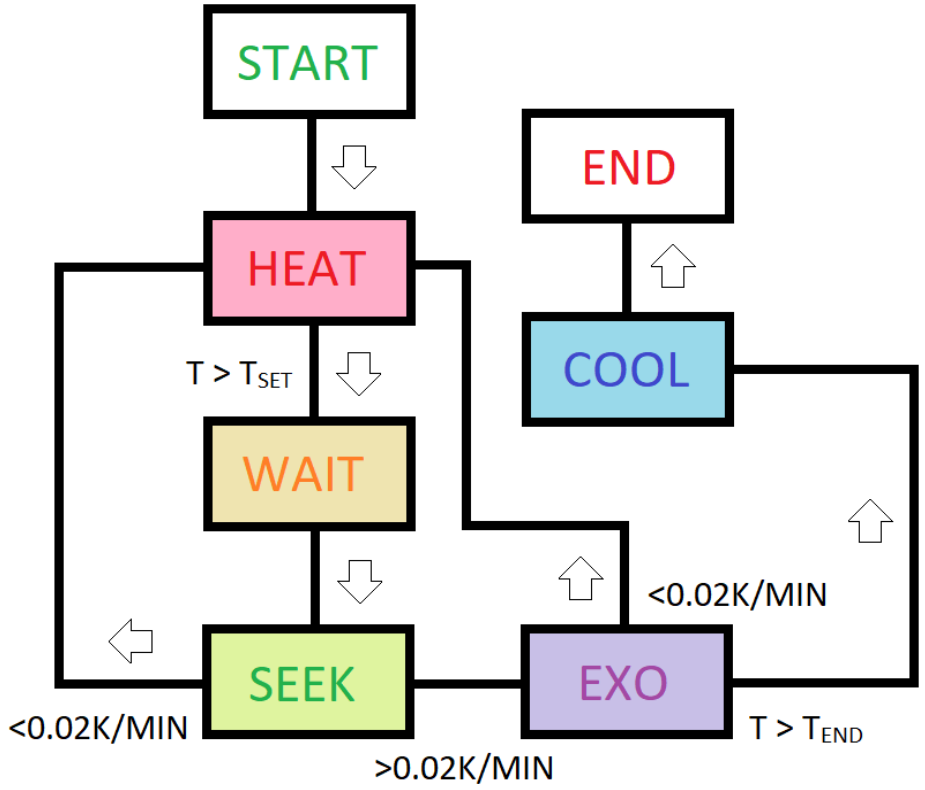
Thermal Runaway Flow Chart

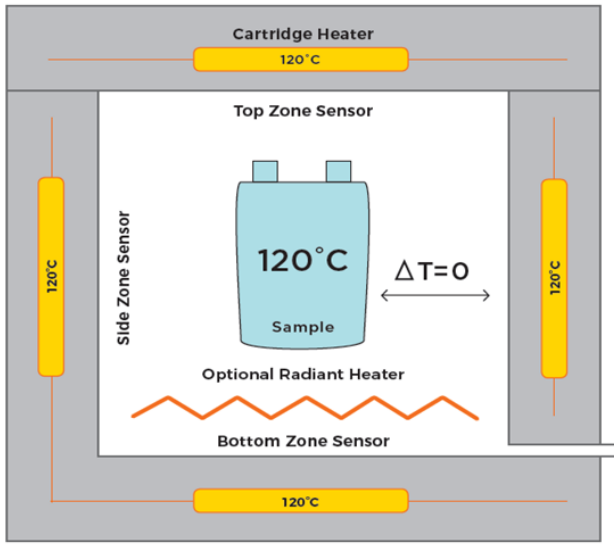


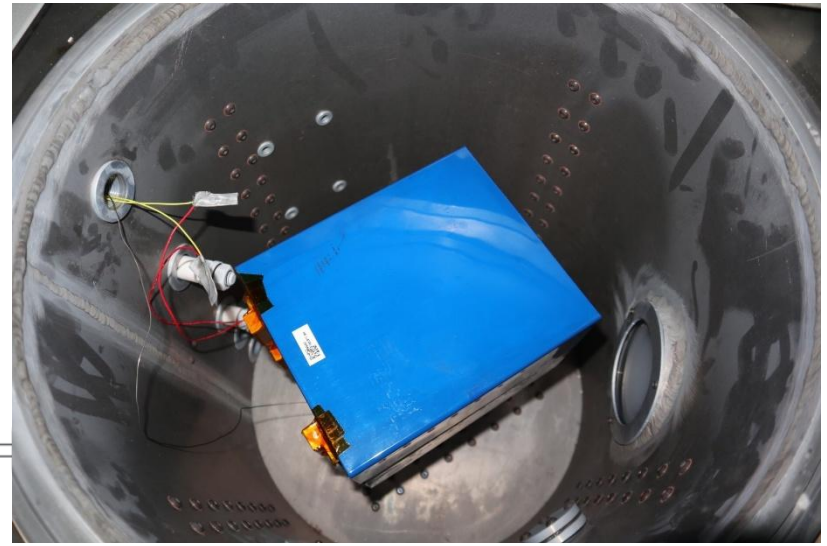
Source: Total Battery Consulting 2016 - http://totalbatteryconsulting.com/industry-reports/Battery-safety-report/overview.html

ARC - Heat-Wait-Seek Method









The heat wait seek method is a step-heating process followed by adiabatic measurement of sample self-heating.

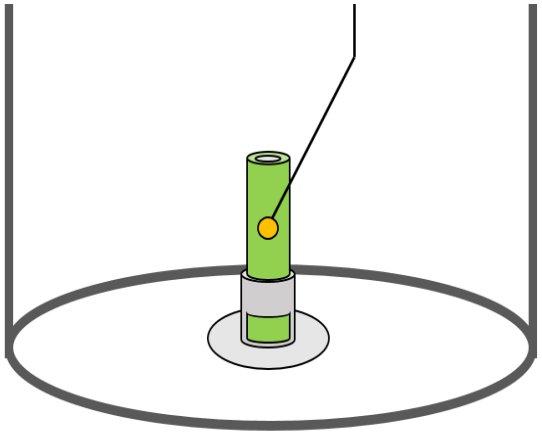
Once self-heating is detected, the instrument switches to adiabatic tracking mode to thermally characterise the reaction until full thermal runaway.

Using this method, the self-heating profile of various types and sizes of cells can be easily compared

Open / Closed HWS Methodology

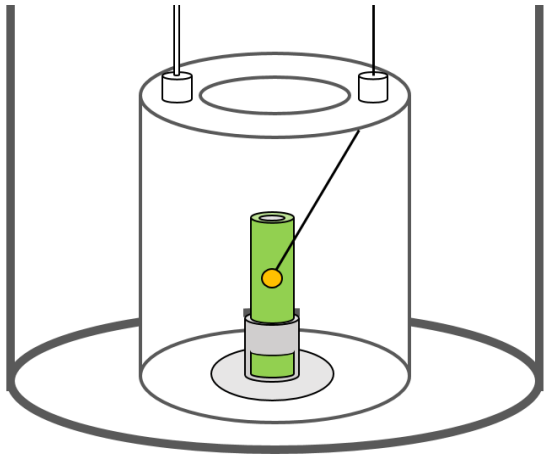
The two main test methods for the ARC battery testing are the open and closed test:

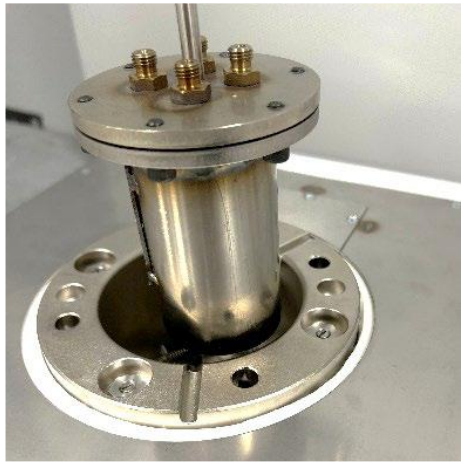
OPEN CONFIGURATION



Measures:
- Temperature
- Voltage

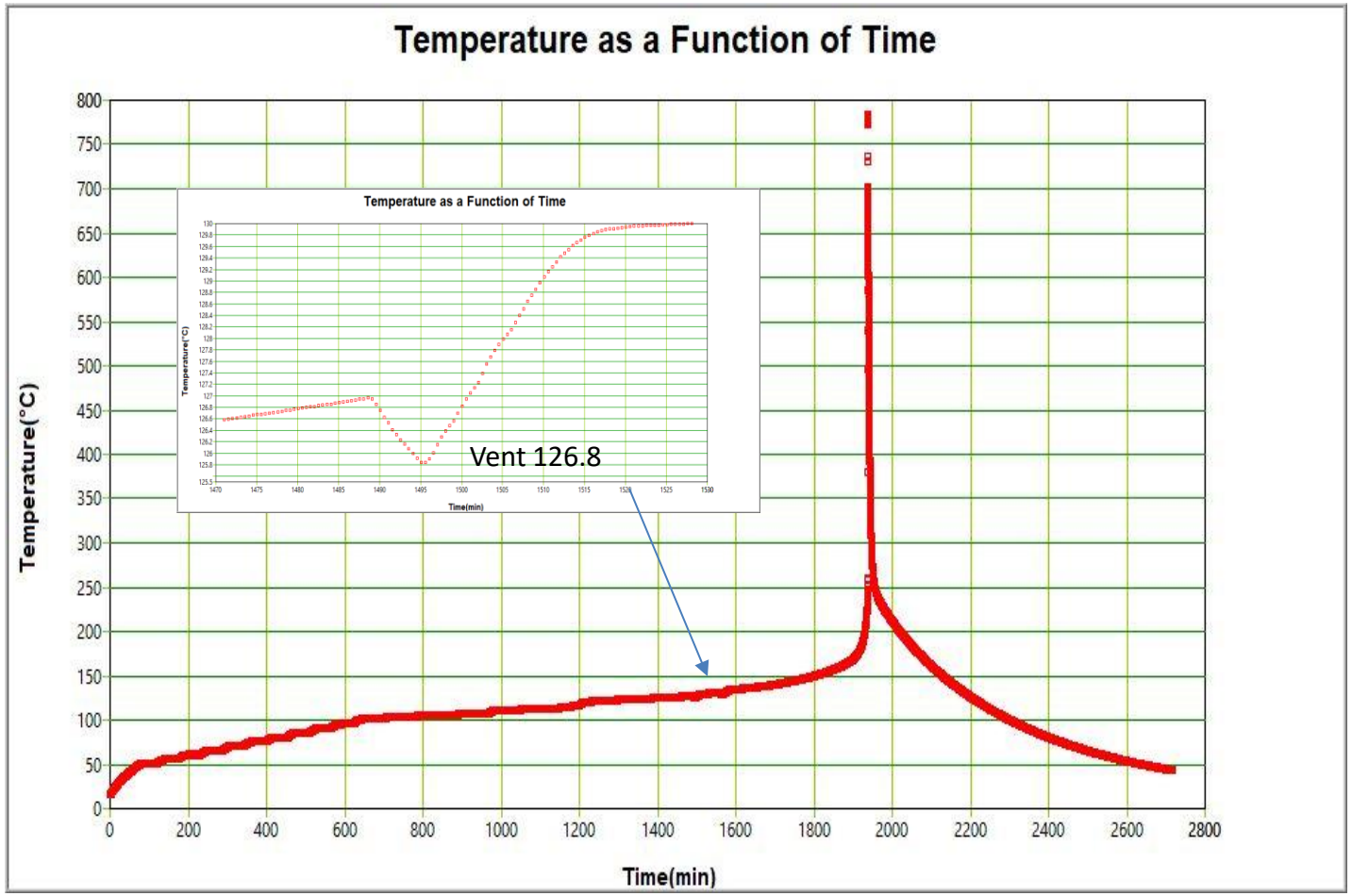
CLOSED CONFIGURATION





Measures:
- Temperature
- Pressure
- Voltage

Li-Ion 18650 Open HWS (ES ARC)

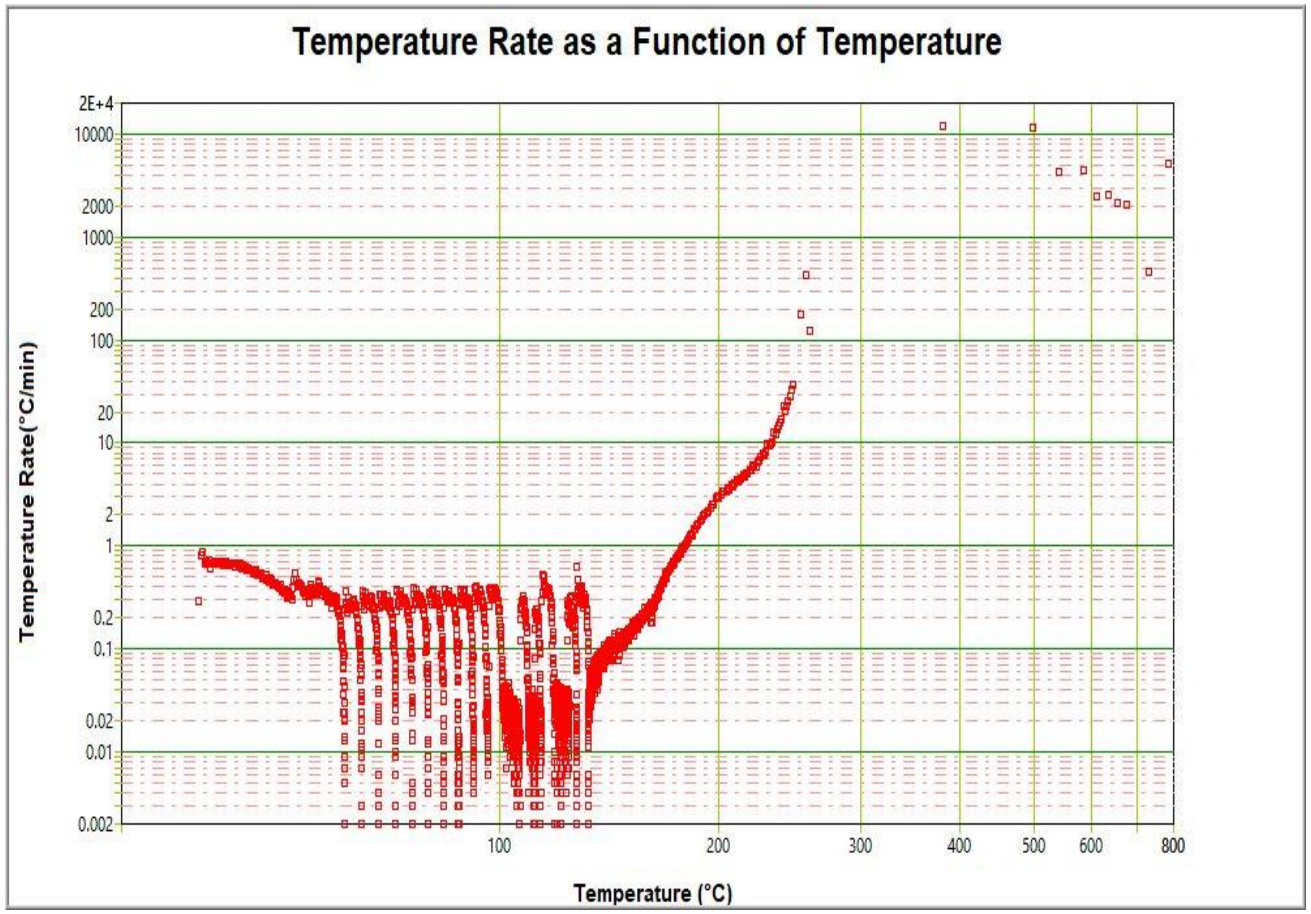


Brand: Molicel
Size: 18650
Chemistry: NMC
Nominal Voltage: 3.6V

3 6.94 Li lithium

Onset temperature:	**121.382**
Onset temperature rate:	**0.027°C/min**
Final adiabatic temperature:	**783.22°C**
Adiabatic temperature rise:	**661.838°C**

Li-Ion 18650 Open HWS (ES ARC)

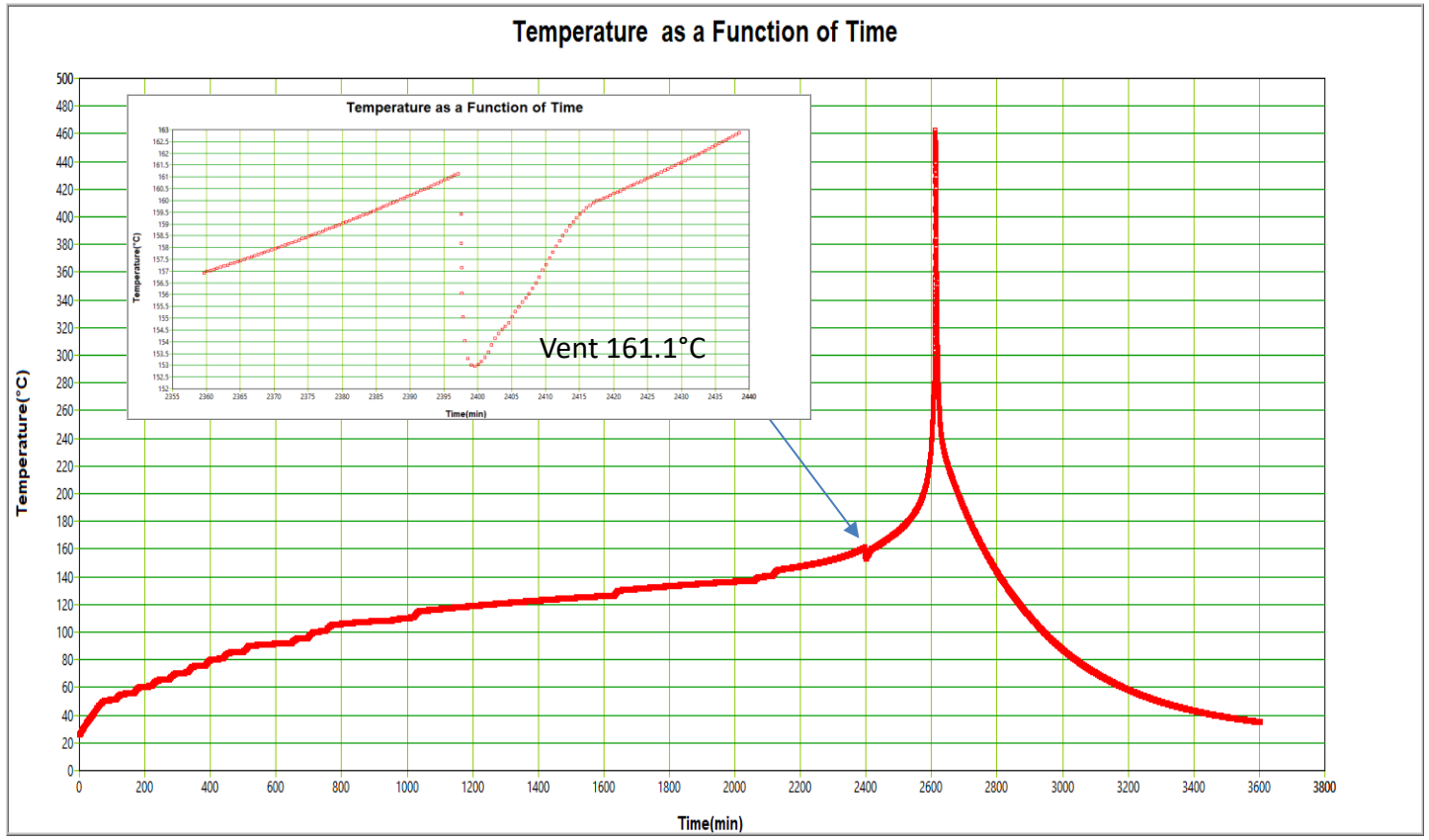


Brand: Molicel
Size: 18650
Chemistry: NMC
Capacity 2.8Ah
Nominal Voltage: 3.6V

3 6.94
Li
lithium

Maximum temp rate	**11953°C/min**
Max temp rate temperature	**379.86°C**

Na-Ion 18650 Open HWS (ES ARC)

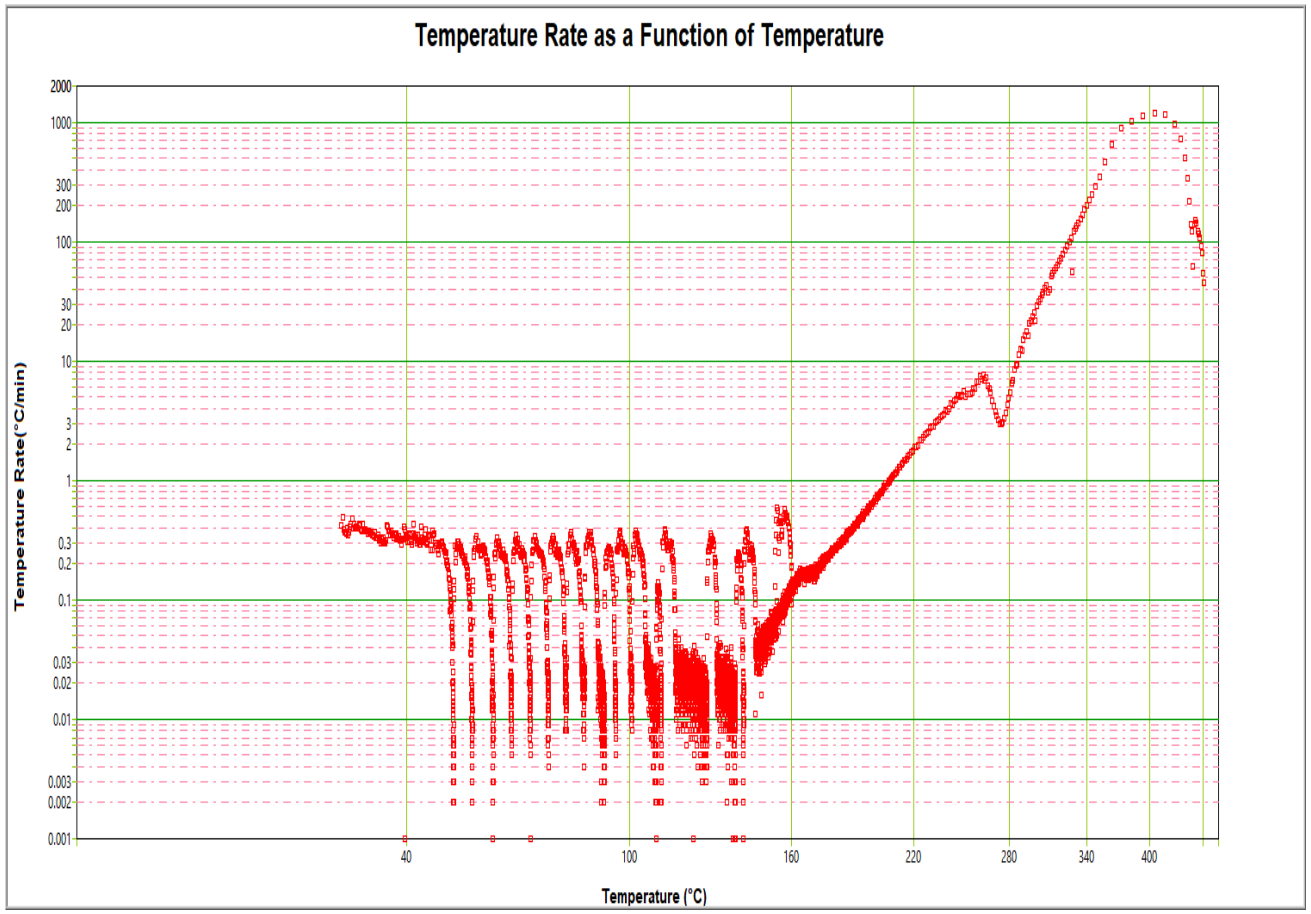


Size: 18650
Chemistry: Na-ion
Nominal Capacity: 1.4Ah
Voltage: 3.966V

11
Na
Sodium
22.990

Onset temperature:	**146.081**
Onset temperature rate:	**0.035°C/min**
Final adiabatic temperature:	**461.735°C**
Adiabatic temperature rise:	**315.654°C**

Na-Ion 18650 Open HWS (ES ARC)

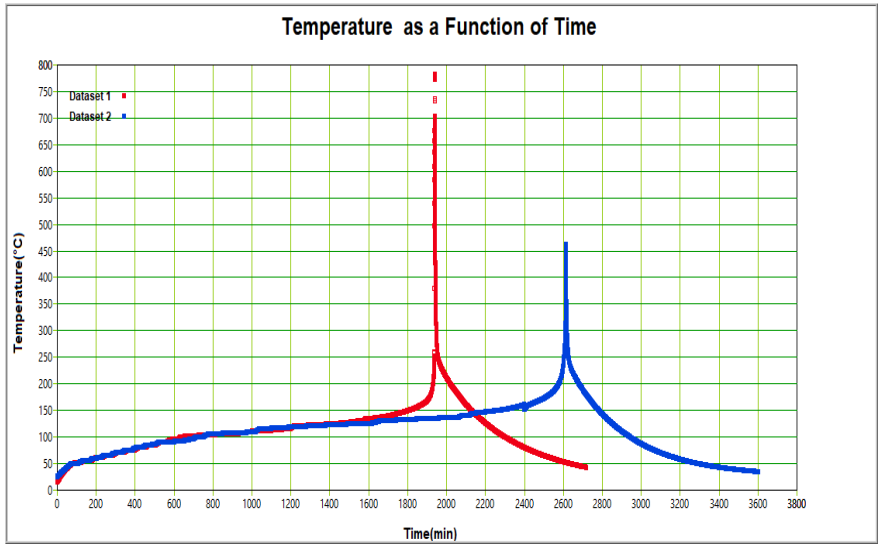


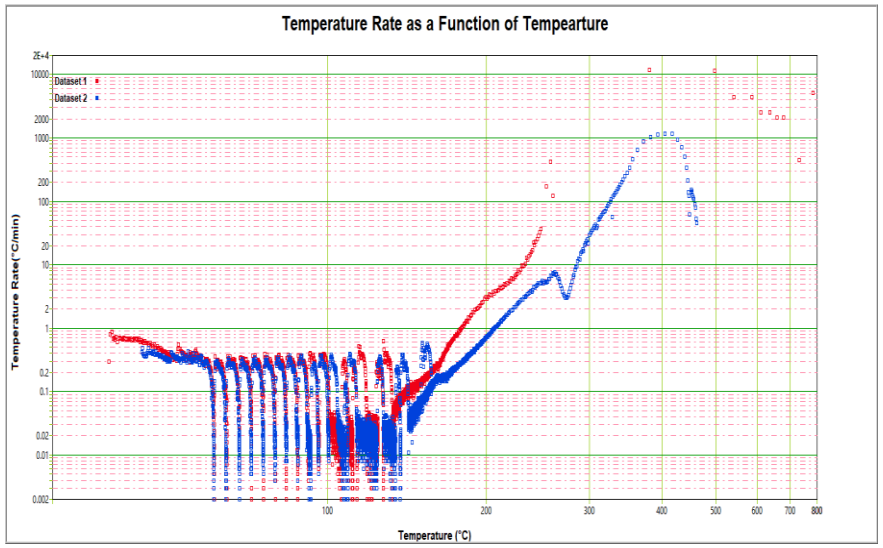
Size: 18650
Chemistry: Na-ion
Nominal Capacity: 1.4Ah
Voltage: 3.966V

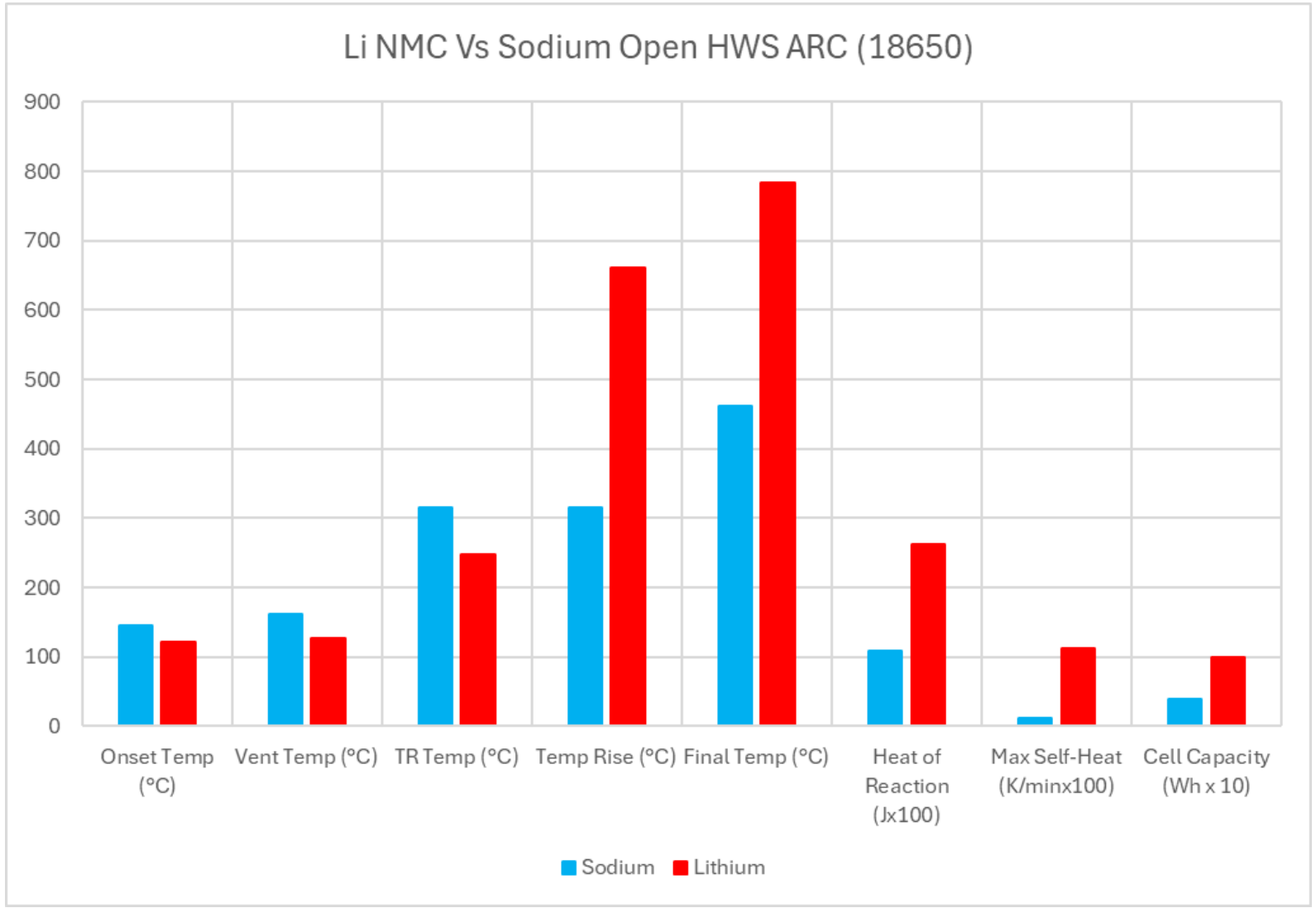
11
Na
Sodium
22.990

Maximum Temp Rate	**1185.00°C/min**
Max temp rate Temperature	**405.04°C**

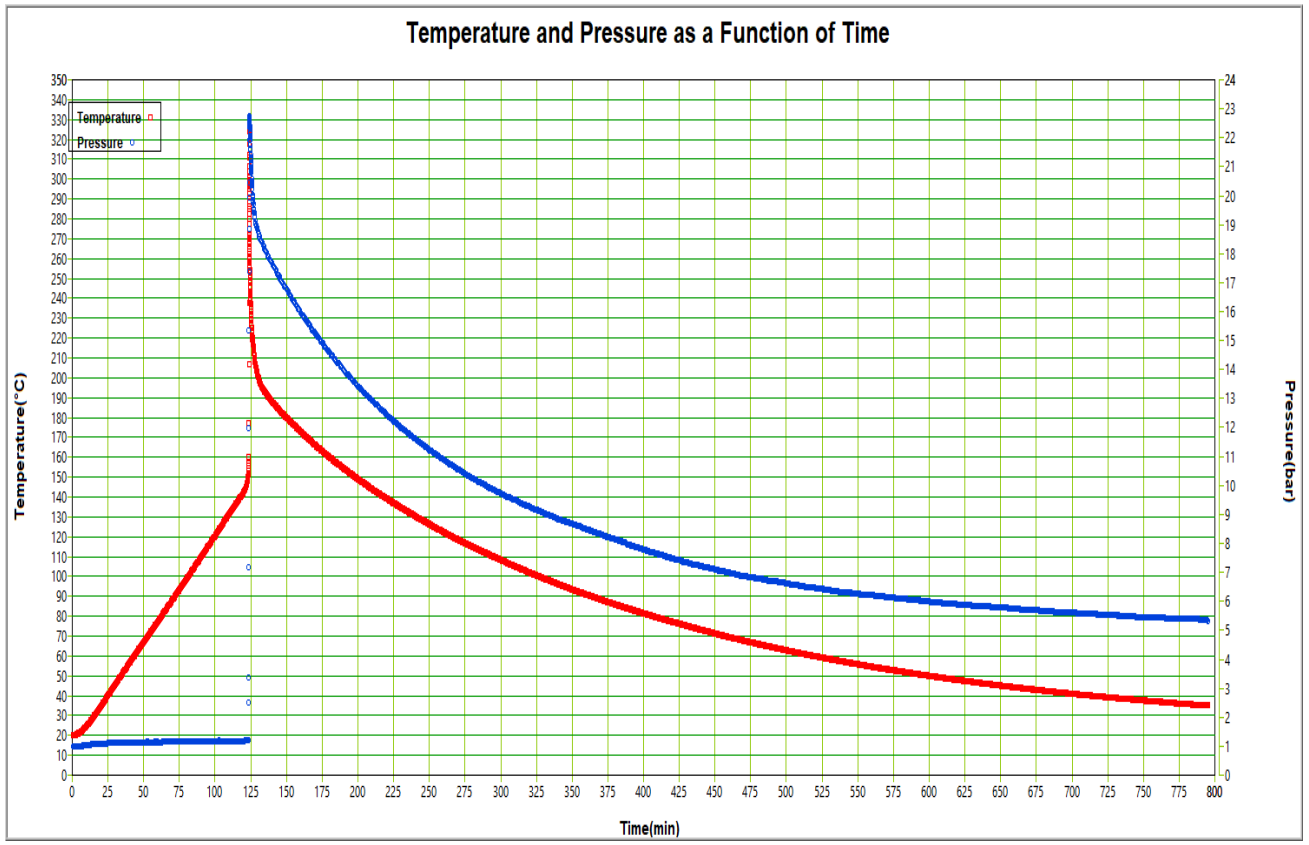
Comparison of ES-ARC Li-Ion and Na-Ion 18650 Open HWS

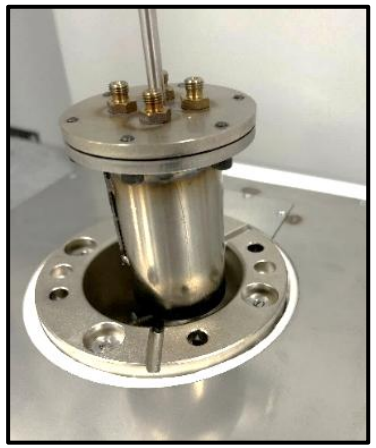






Na-Ion 18650 Closed Temperature Ramp Test (ES ARC)



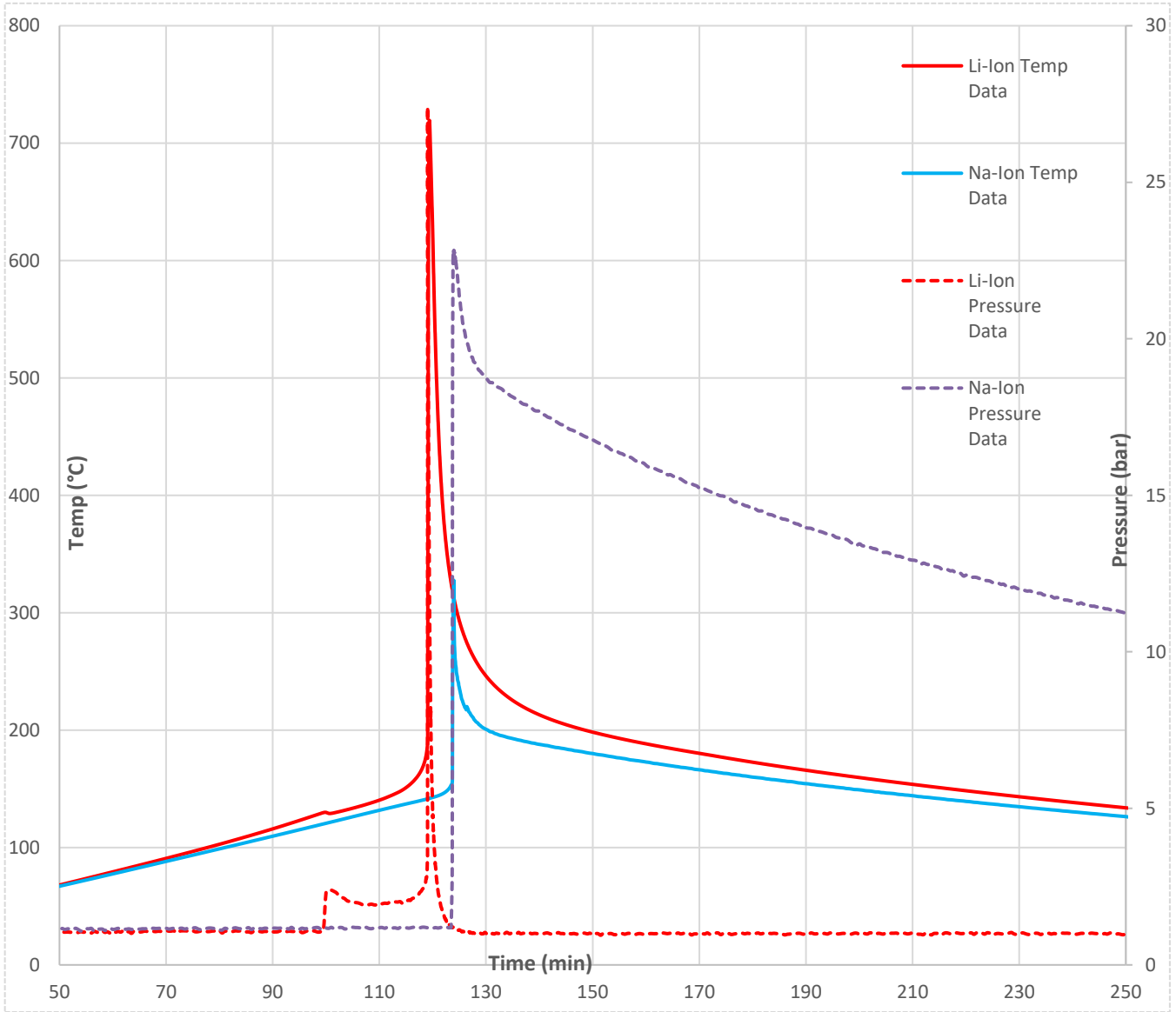


11
Na
Sodium
22.990

Temperature Data	ES ARC Closed Ramp
Maximum temperature rate	3073.532 °C/min
Temperature at max temp rate	237.572°C
Final adiabatic temperature	323.989°C
Adiabatic temperature rise	163.588

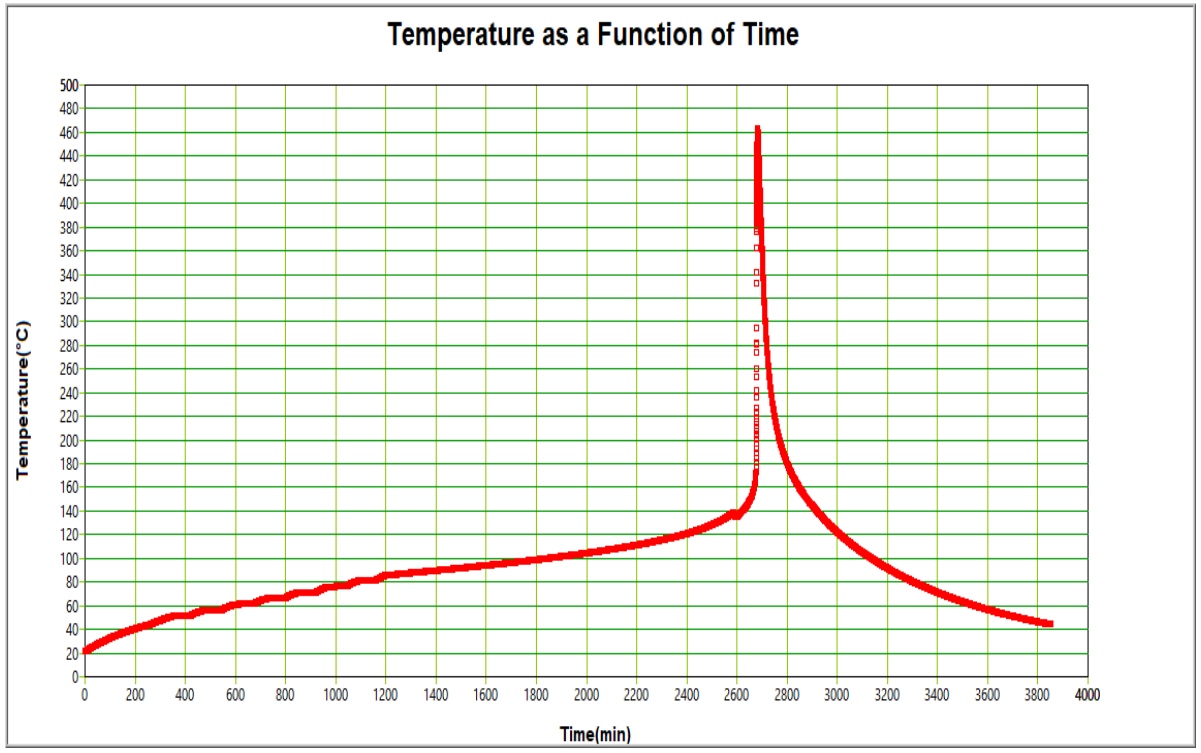
Pressure Data	ES ARC Closed Ramp
Peak Pressure (bar)	22.876
Air Pressure (bar)	1.942
Cell Gas Pressure Rise (bar)	20.933
Moles of Cell Gas	0.1132
Est Cell Gas Vol at STP (Litres)[1]	2.7

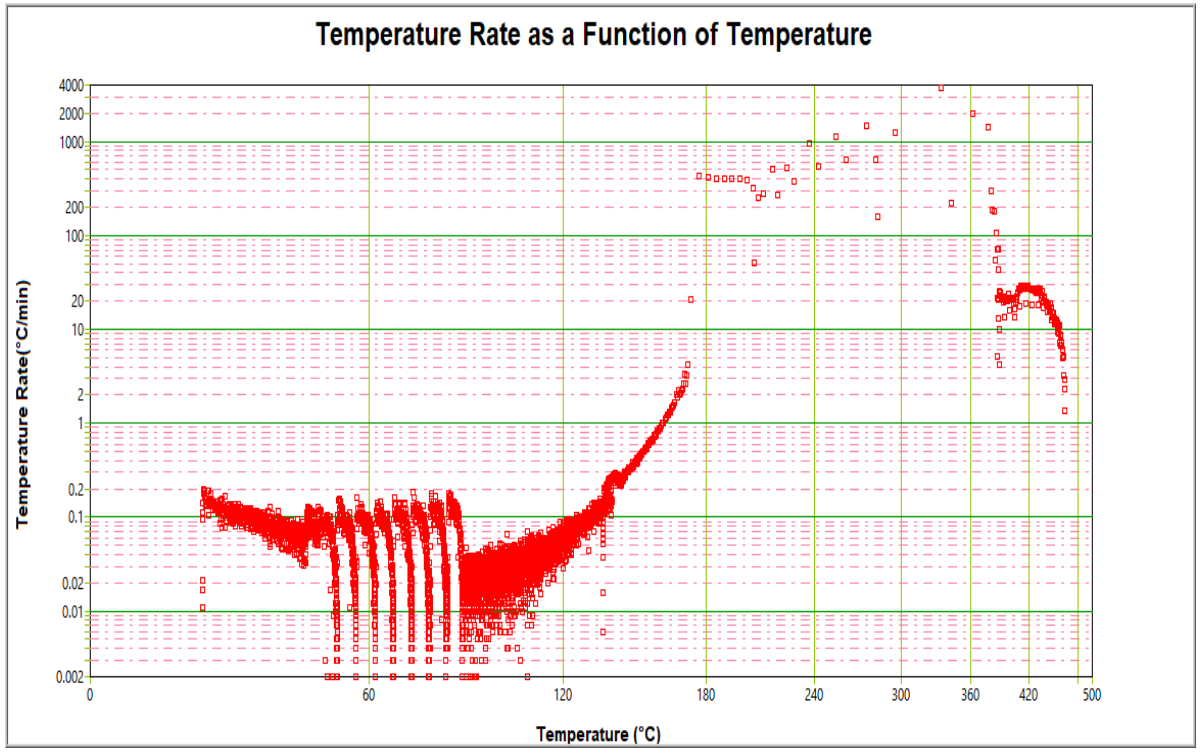
Comparison of Na-ion/Li-Ion 18650 Closed Temperature Ramp Test (ES ARC)

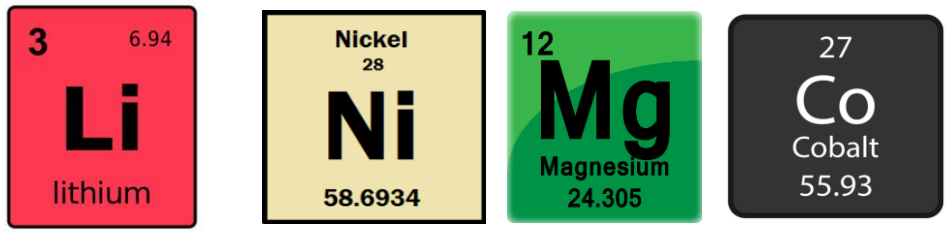


Pressure Data	Sodium ES ARC Closed Ramp	Lithium ES ARC Closed Ramp
Peak Pressure (bar)	22.876	27.402
Cell Gas Pressure Rise (bar)	20.933	24.038
Moles of Cell Gas	0.1132	0.1295
Est Cell Gas Vol at STP (Litres)[1]	2.7	3.2

EV_L: Test of 200Ah Li-ion NMC Prismatic Cell - Clamped



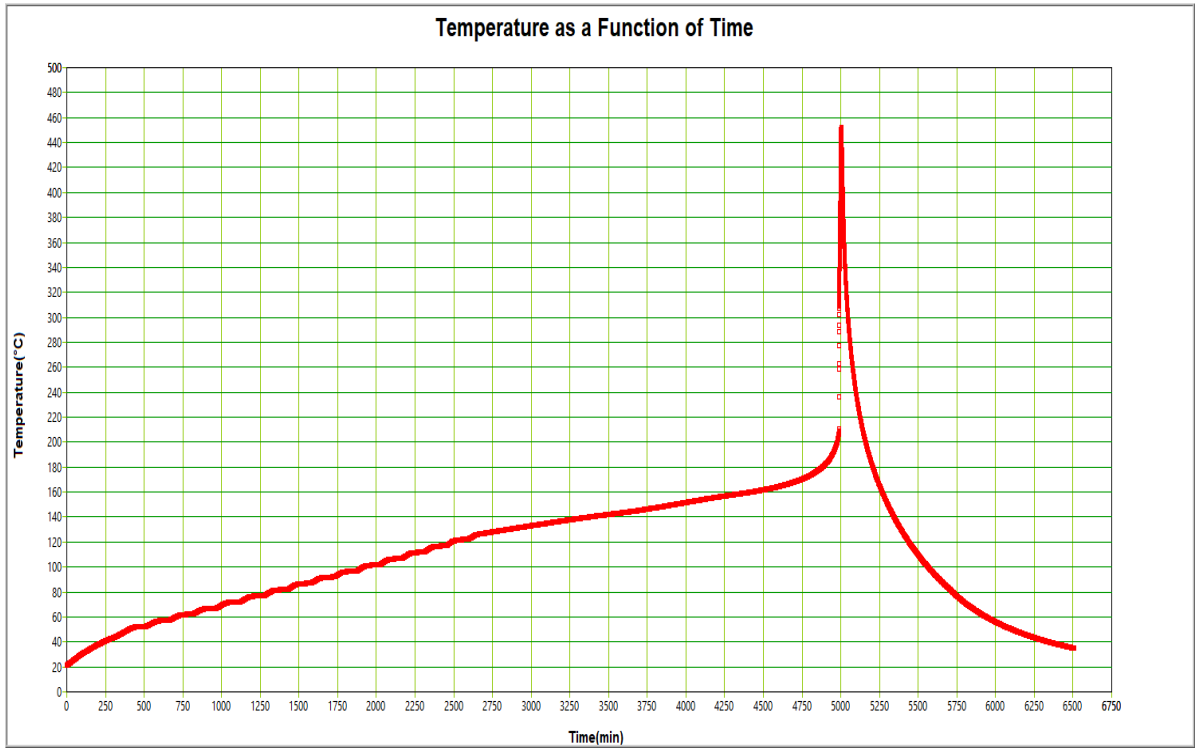


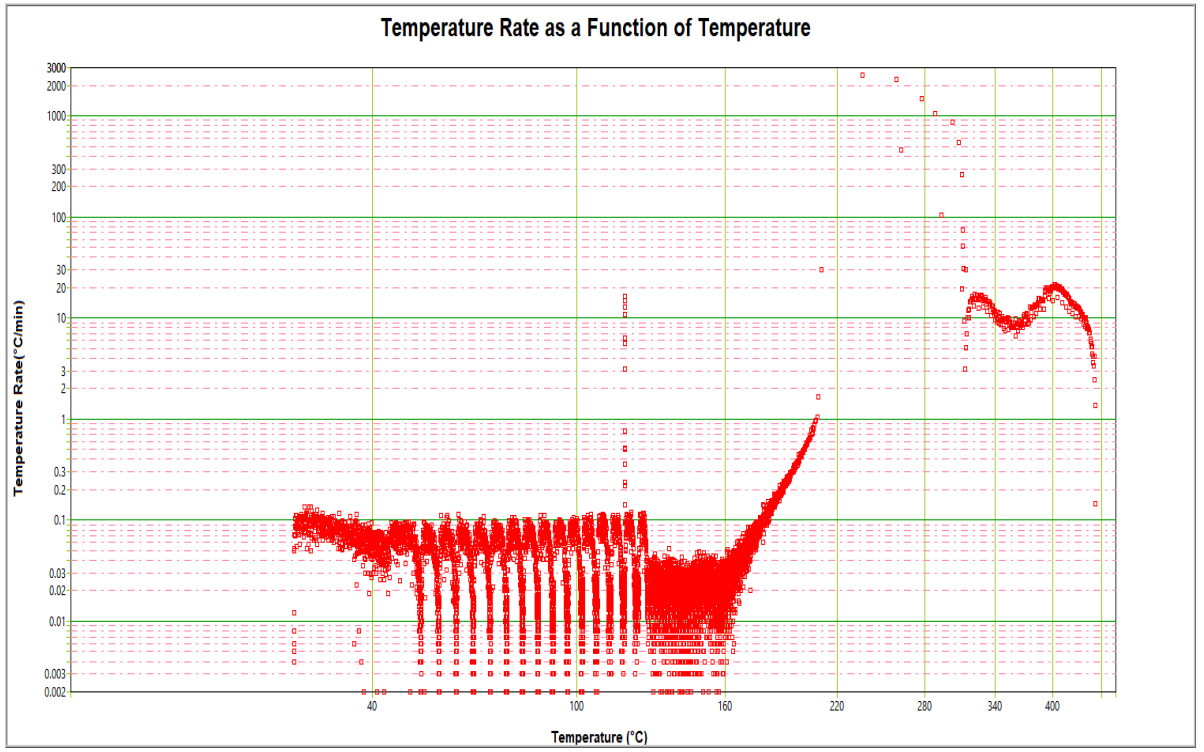


Onset Temperature (T_o): 87.335°C
Self-Heat Rate at To (M_o): 0.021 °C/min
Temp at Max Rate (T_{mr}) = 333.023°C
Heat of Reaction (MJ) = 1.52

Max Self-Heat Rate (M_{mr}): 3774.817
Final Adiabatic Temp (T_{ab}): 463.503°C
Adiabatic Temp Rise (δT_{ab}): 376.168°C

EV+ : Test of 200Ah Na-ion Prismatic Cell - Clamped



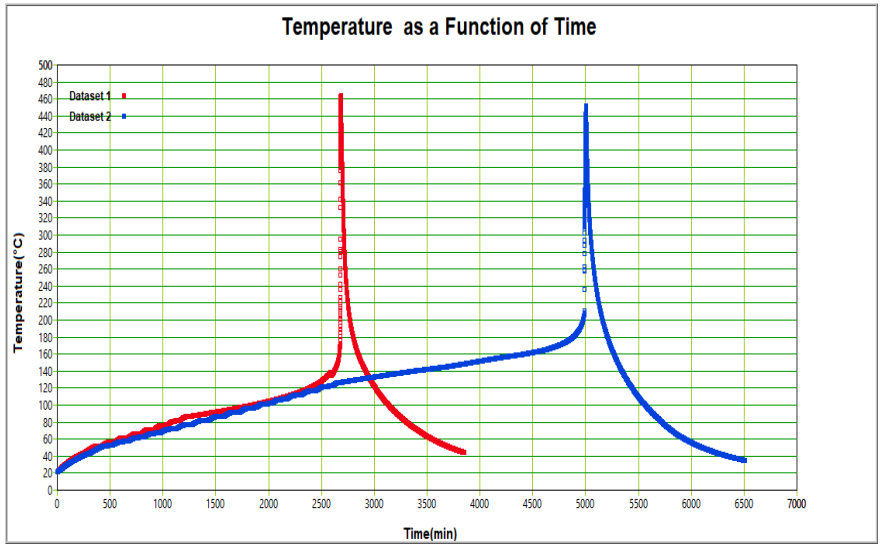


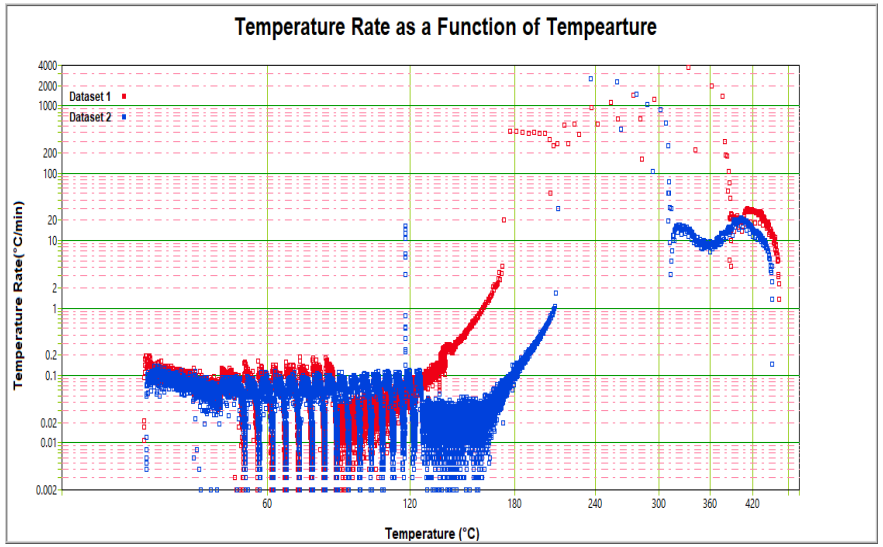
11
Na
Sodium
22.990

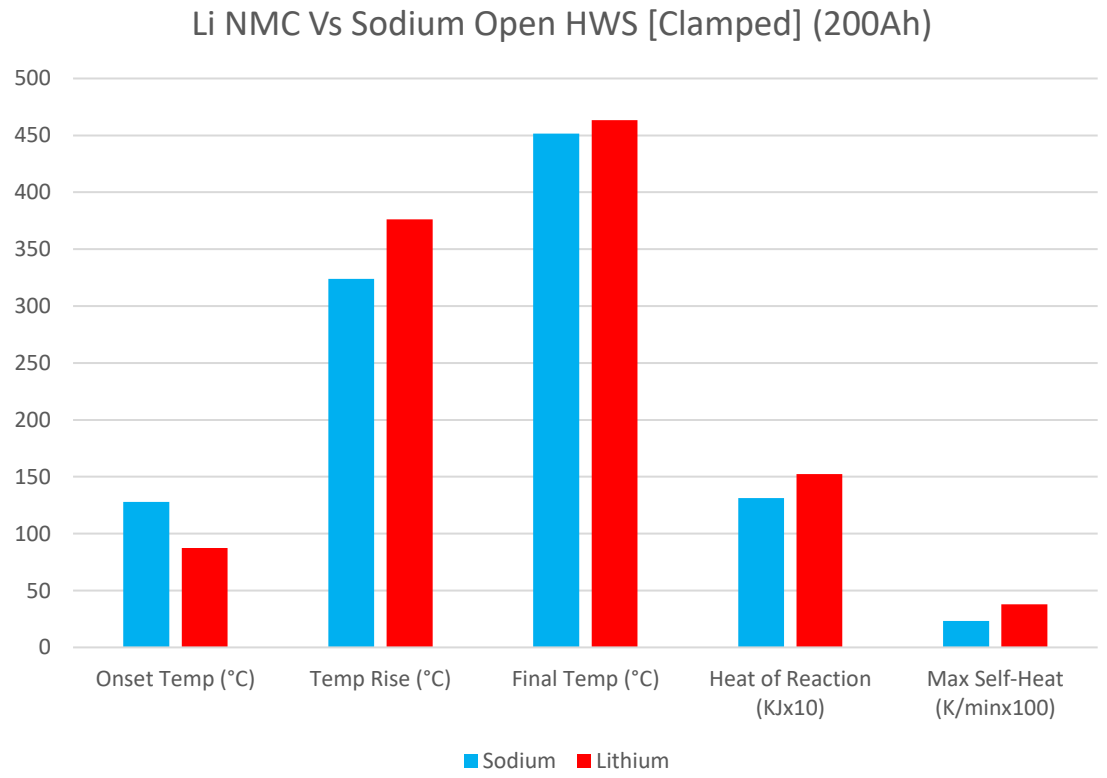
Onset Temperature (T_o): 127.88°C
Self-Heat at To (M_o): 0.021 °C/min
Adiabatic Temp (δT_{ab}): 323.8

Max Self-Heat Rate (M_{mr}): 2329.38
Final Adiabatic Temp (T_{ab}): 451.68°C
Heat of Reaction (MJ): 1.32

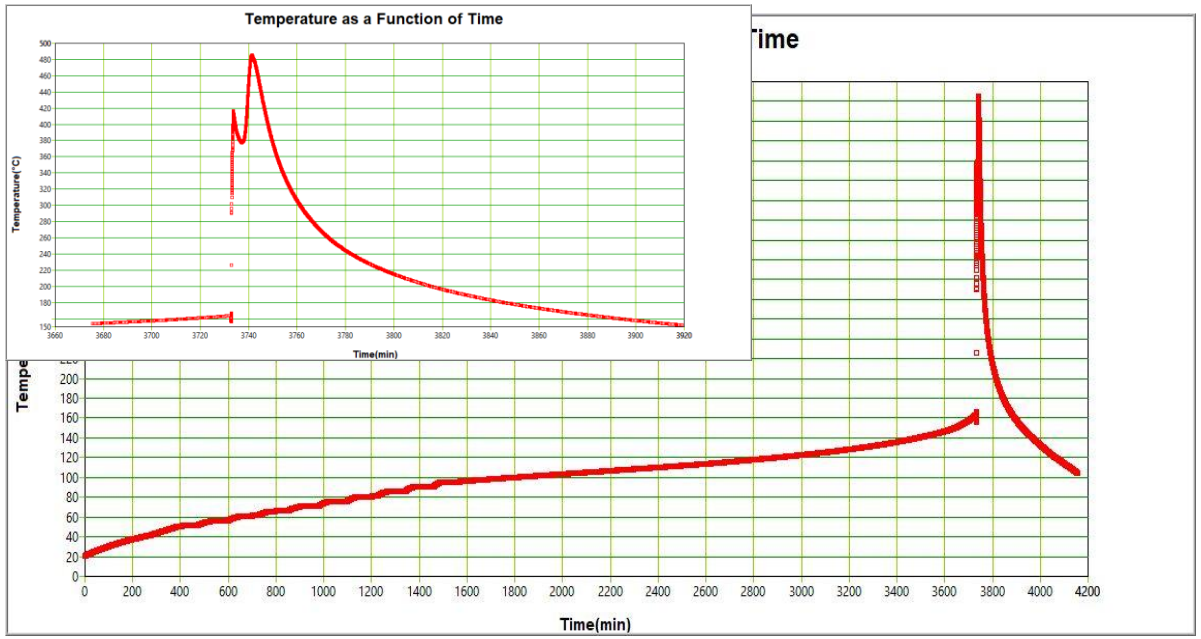
Comparison of Li-Ion (NMC) & Na-Ion, both 200Ah Open HWS - Clamped

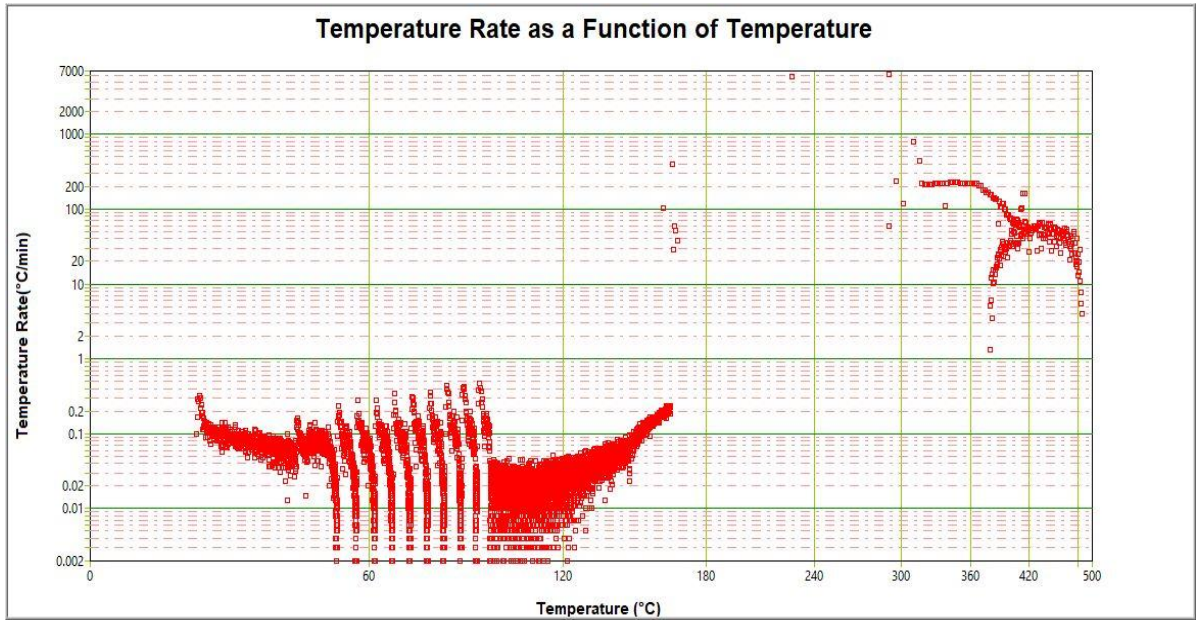






EV+ :Test of 200Ah Na-ion Prismatic Cell - Unclamped





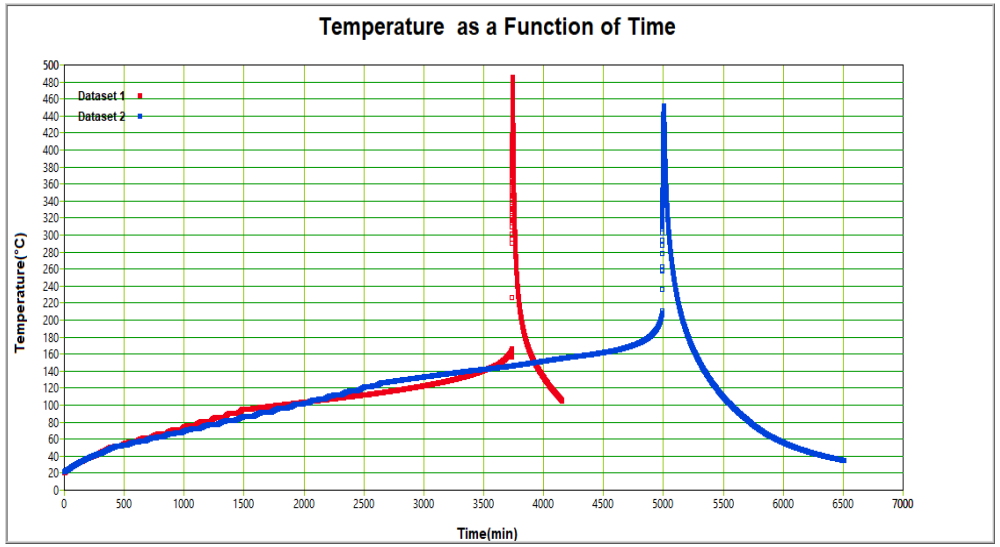
11
Na
Sodium
22.990

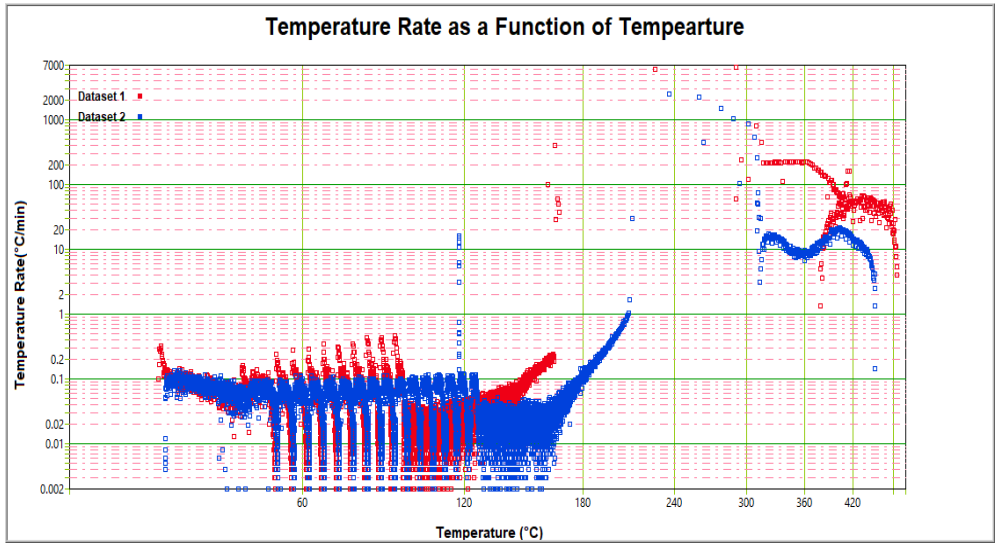
Onset Temperature (T_o): 96.118°C
Self-Heat at To (M_o): 0.021 °C/min
Temp at Max Rate (T_{mr}) = 290.343
Heat of Reaction (MJ) = 1.92

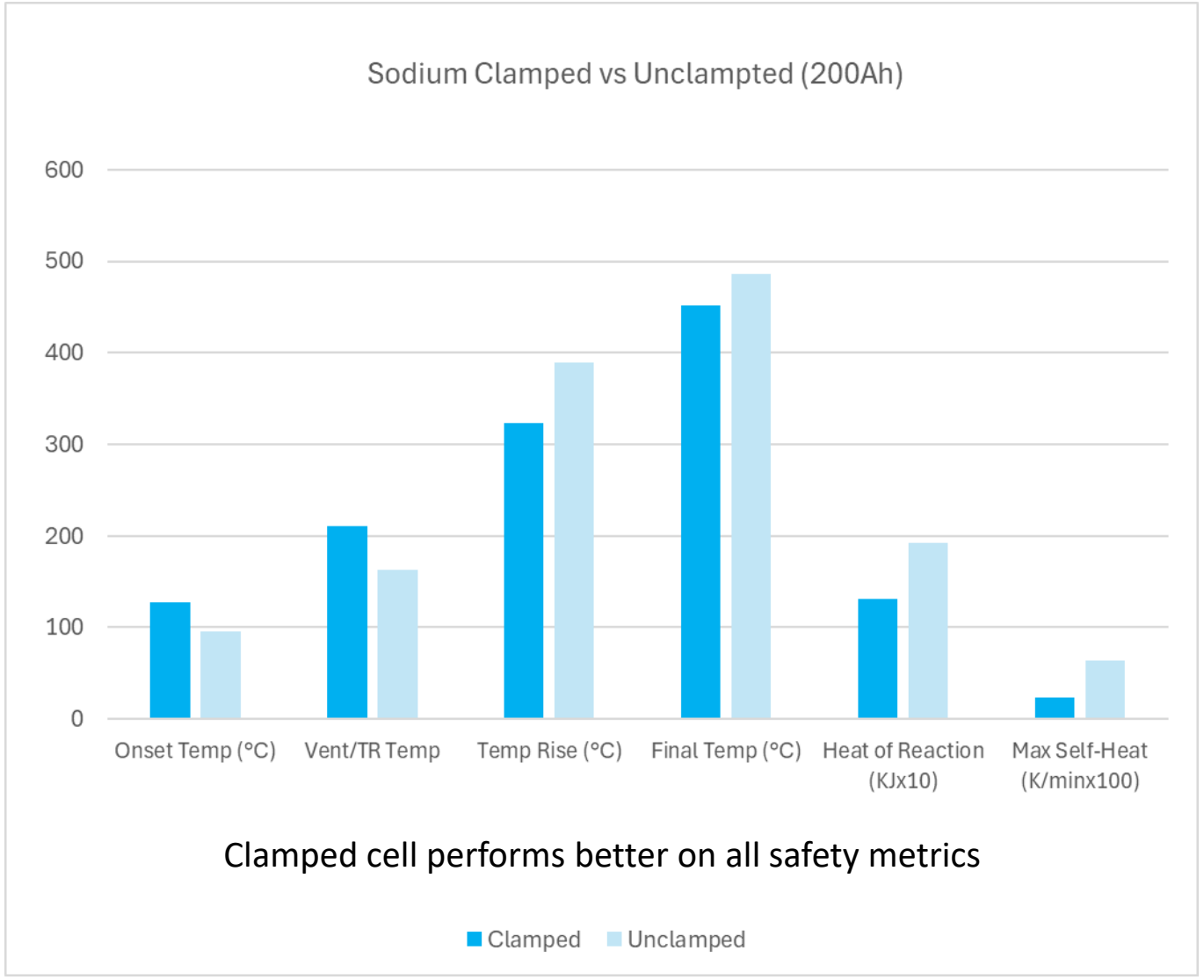
Max Self-Heat Rate (M_{mr}): 6396.017
Final Adiabatic Temp (T_{ab}): 416.385°C (first peak)
Adiabatic Temp Rise (δT_{ab}): 389.365°C (based on 2nd peak)

Cell should be clamped so burst disk functions correctly!

Comparison of Na-Ion 200Ah
Open HWS – Clamped and Unclamped

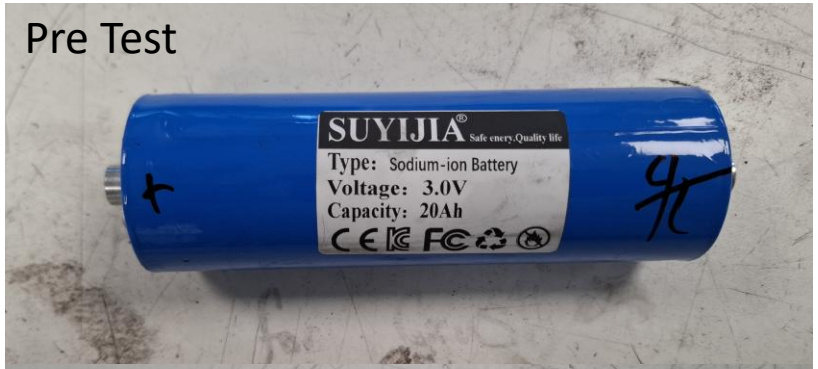






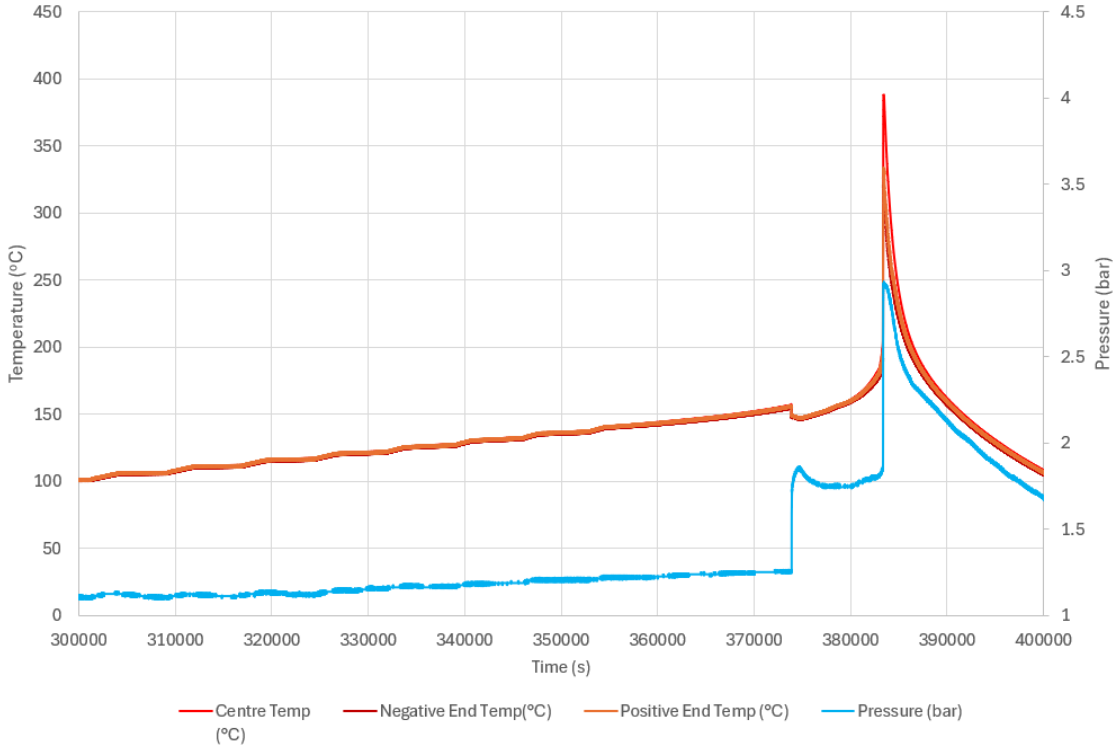
Clamped cell performs better on all safety metrics

20Ah Sodium-Ion Cylindrical Cell - Closed ARC Test



Negative

Positive (vent)

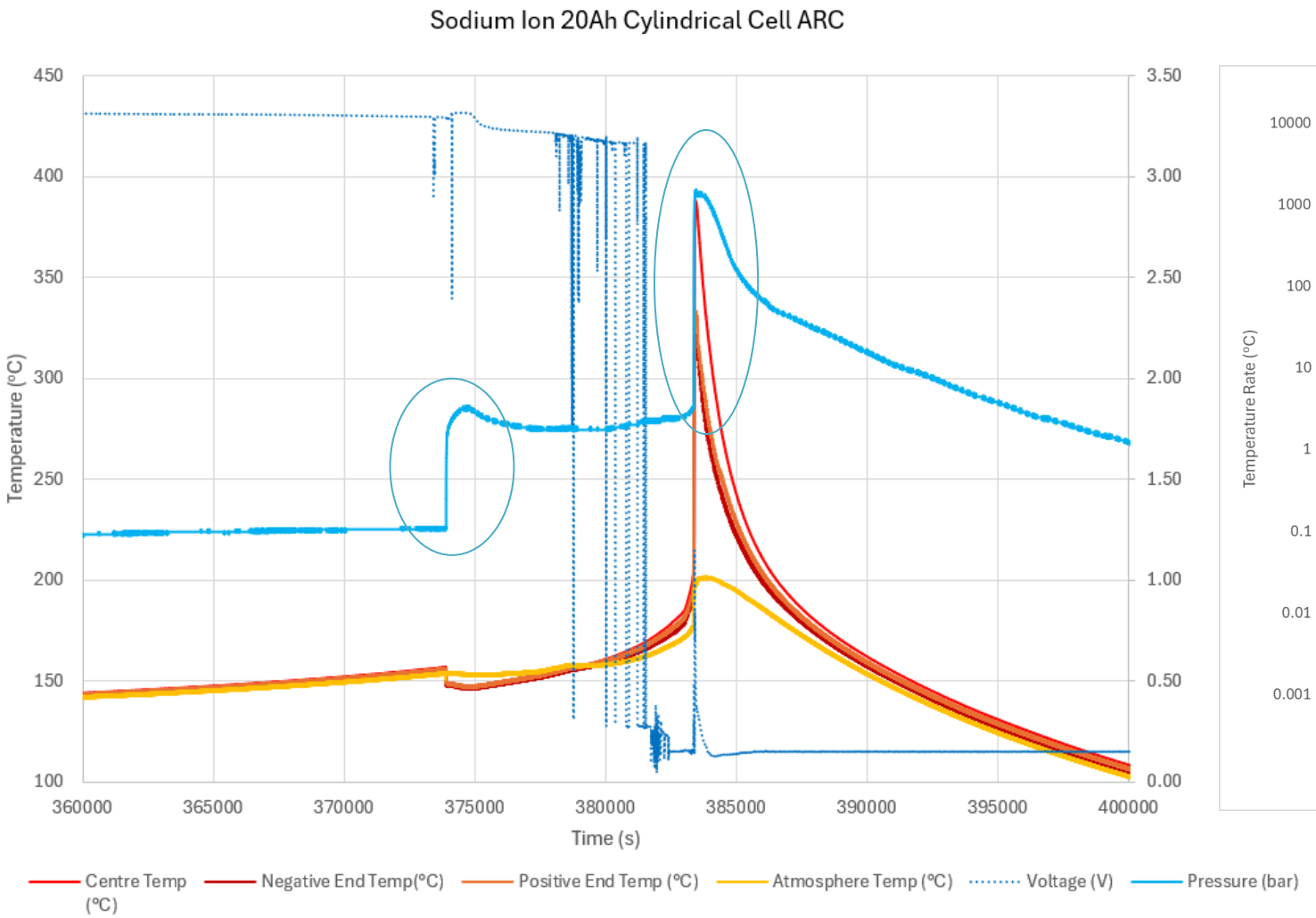


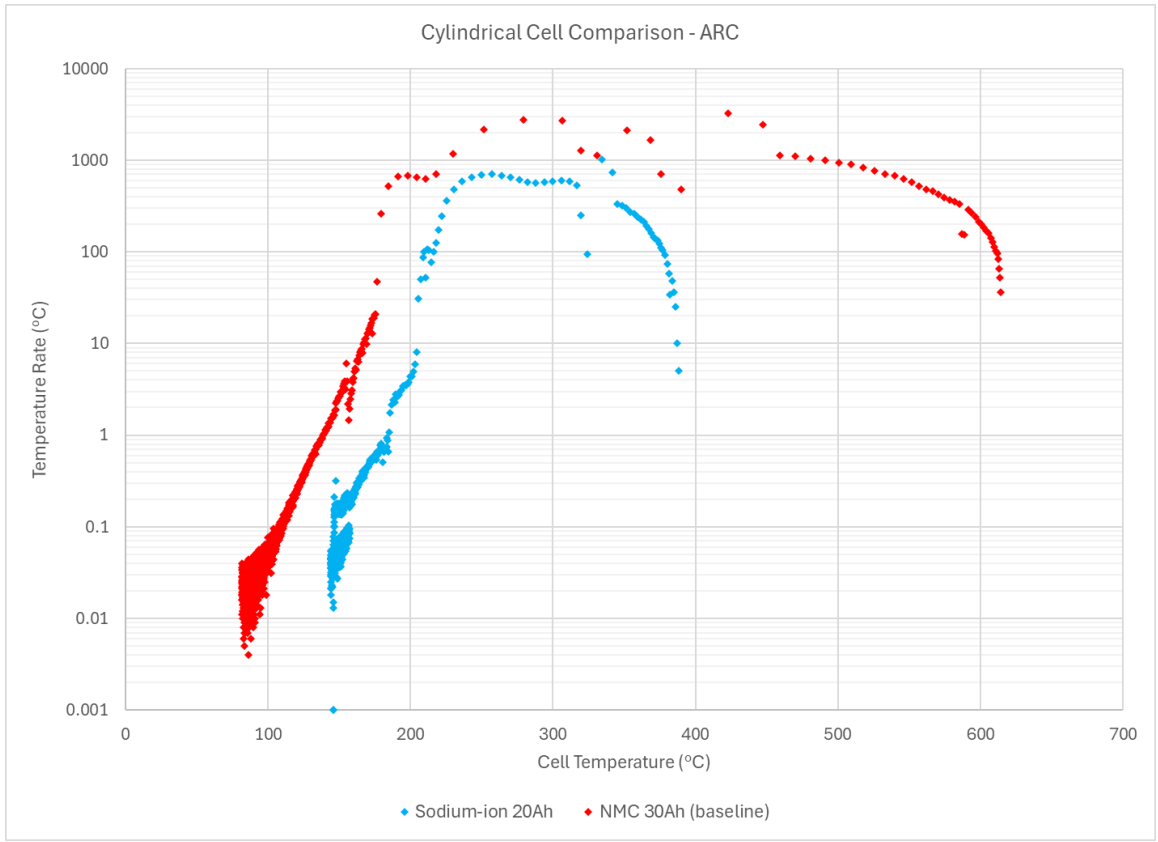
Temperature Data	EV+ ARC Closed HWS
Onset Temperature	143.90 °C
Vent Temperature	157.083 °C
Thermal Runaway Temperature	205.428 °C
Final adiabatic temperature	388.20 °C
Adiabatic temperature rise	244.30 °C

Na-ion Cell produces around 1L/Ah of gas

Pressure Data	EV+ ARC Closed HWS
Peak Pressure in 20L volume	2.932 (bara)
Air Pressure	1.603 (bara)
Cell Gas Pressure Rise	1.328 (bar)
Moles of Cell Gas	0.676
Est Cell Gas Vol at TR	26.31L
Est Cell Gas Vol at STP	16.57L

20Ah Sodium-Ion cylindrical cell data





Self-Heating rates compared to NMC 4690 cell

20Ah Sodium-Ion Cell Gas Analysis

Determinand	Units	LOD	Acc.	
Hydrogen	% (v/v)	0.05	U	0.05
Oxygen	% (v/v)	0.3	U	12
Nitrogen	% (v/v)	1.0	U	70
Carbon monoxide	% (v/v)	0.01	U	2.9
Carbon dioxide	% (v/v)	0.01	U	2.0
Methane	% (v/v)	0.01	U	1.6
Ethane	% (v/v)	0.001	N	0.6
Ethene	% (v/v)	0.001	N	1.7
C3 hydrocarbons as propane	% (v/v)	0.001	N	0.61
C4 hydrocarbons as n-butane	% (v/v)	0.001	N	0.5
C5 hydrocarbons as n-pentane	% (v/v)	0.001	N	0.24
C6+ hydrocarbons as n-hexane	% (v/v)	0.001	N	7.5

Determinand	Units	LOD	Acc.	
Nitrous oxide	µg	0.5	N	30
	mg/m³	Calc.	N	3017

Determinand	Units	LOD	Acc.	
Styrene	µg	1.0	N	9.1
	mg/m³	Calc.	N	18

Determinand	Units	LOD	Acc.	
HF [2]	µg	0.5	N	204
	mg/m³	Calc.	N	1020
HCl [1]	µg	0.5	N	1.9
	mg/m³	Calc.	N	9.7
HBr	µg	0.5	N	<0.5
	mg/m³	Calc.	N	<2.5

Determinand	Units	LOD	Acc.	
Dimethyl carbonate	µg	5.0	N	490 [1]
	mg/m³	Calc.	N	4900
Ethylene carbonate	µg	5.0	N	<5.0
	mg/m³	Calc.	N	<50
Ethylmethyl carbonate	µg	5.0	N	26
	mg/m³	Calc.	N	260
Propylene carbonate	µg	5.0	N	<5.0
	mg/m³	Calc.	N	<50
Vinylene carbonate	µg	5.0	N	<5.0
	mg/m³	Calc.	N	<50

[1] Sample required dilution due to the initial result falling outside of the calibration range of the instrument.

Determinand	Units	LOD	Acc.	
Benzene	µg	0.5	U	140
	mg/m³	Calc.	N	700
Propene	µg	5.0	N	78
	mg/m³	Calc.	N	390
Toluene	µg	0.5	U	57
	mg/m³	Calc.	N	285

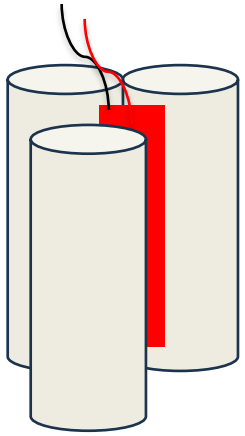
Determinand	Units	LOD	Acc.	
Formaldehyde	µg	0.2	U	<0.2
	mg/m³	Calc.	N	<4.0
Acetaldehyde	µg	0.2	U	150 [1]
	mg/m³	Calc.	N	3000

Determinand	Units	LOD	Acc.	
Moisture	mg	10	N	72
	mg/m³	Calc.	N	71700

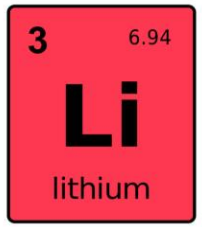
Post thermal runaway vent/decomposition gases were analysed at Marchwood analytical lab, Manchester

Very little hydrogen
Lots of C6+ hydrocarbons
Lots of nitrous oxide
Some HCl present which is not seen from lithium-ion cells
Lots of DMC
Lots of HF (!)
Lots of water
Little evidence of combustion.

ARC Heat Capacity Tests of 18650 Li-Ion and Na-Ion



$$C_p = \frac{UIt}{m\Delta T}$$



vs

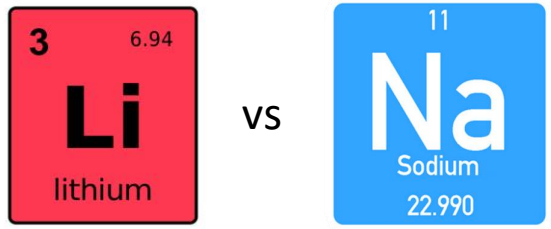
Cp = Specific Heat Capacity (J/gK)
U = Voltage (V)
I = Current (A)
T = Time (s)
M = Mass (g)
T = Temperature (K)

	Li – Ion (J/gK)	Na-ion (J/gK)
Cp at low temperature (30°C)	0.945	0.831
Cp at medium temperature (45°C)	0.950	0.853
Cp at high temperature (60°C)	0.954	0.884

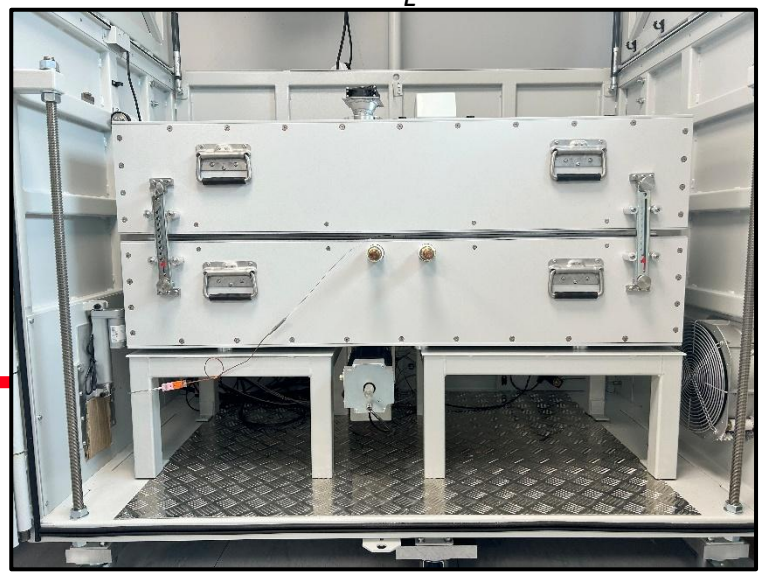
Higher heat capacity means smaller temperature changes for the same input energy.
Lower heat capacity cells are "easier" to thermally manage.
Higher heat capacity cells require more energy input to get to dangerous temperatures.

Summary of Testing

- Small and large cell formats tested and compared (NMC vs Na)
- Sodium-ion shows significantly higher onset temperature in both formats (25-50ºC higher), which means it is more thermally stable and can operate safety at higher temperature.
- Small format sodium-ion shows a significant reduction in peak temperature and energy release, but for a lower total capacity. Correcting for capacity the advantage is a 15% reduction. More testing is required in closed test conditions.
- Large format sodium-ion is 15% less energetic than equal capacity NMC cell, but the rate of energy release is around one third. This can help prevent propagation.
- Very different vent gases compared to either LFP or NMC – needs more investigation.
- Smaller volume of gas resulting from thermal runaway. Initial vent volume is similar to volume resulting from thermal runaway
- Sodium-ion will be slightly easier to thermally manage (10%)



THT EV_L ARC



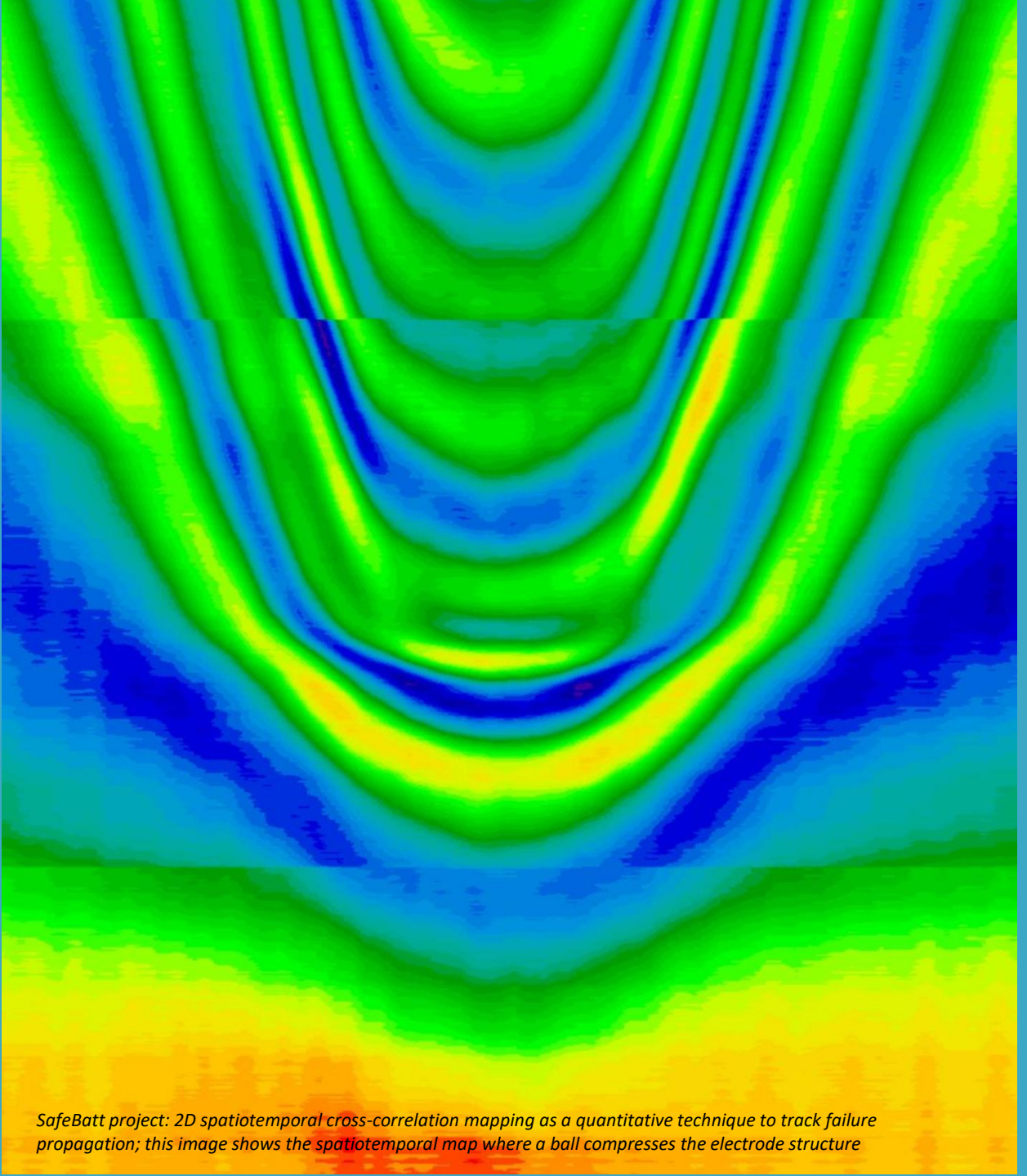
Areas of future research for Na-ion Safety

- Carry out a number of tests to assess repeatability.
- Compare nail penetration, short-circuit and overcharge behaviour.
- Compare sodium-ion to LFP (initial tests show slight advantage for LFP)

Selection of THT ARC Users

Questions

Danny Montgomery
Technical Services Manager
THT: Thermal Hazard Technology
+44 1908 646800 Switch Board
danny@thtuk.com



SafeBatt project: 2D spatiotemporal cross-correlation mapping as a quantitative technique to track failure propagation; this image shows the spatiotemporal map where a ball compresses the electrode structure

New Insight into Suppressing Lithium-Ion Battery Fires

Battery Safety UK 2026
WMG Coventry

6th May 2026

Wojciech Mrozik

THE FARADAY INSTITUTION
SCIENCE OF BATTERY SAFETY

SafeBatt

THE FARADAY INSTITUTION

The UK's flagship programme for electrochemical energy storage

- research
- skills development
- market analysis
- early-stage commercialisation

Bringing together research scientists and industry partners on projects with commercial potential that will:

- reduce battery cost, weight, and volume
- improve performance and reliability
- develop whole-life strategies including recycling and reuse

20+
Academic partners

50+
Industry partners

500+
Researchers from many disciplines

www.faraday.ac.uk
@FaradayInst
TheFaradayInstitution on LinkedIn

BIO

- Newcastle University, School of Engineering

THE FARADAY INSTITUTION SafeBatt SCIENCE OF BATTERY SAFETY

THE FARADAY INSTITUTION ReLiB REUSE & RECYCLING OF LITHIUM ION BATTERIES

- Report - **Safety of second life batteries in battery energy storage systems, BESI** https://www.gov.uk/government/publications/safety-of-second-life-batteries-in-battery-energy-storage-systems
- Consultancy & Training – e.g. for Polish FRS https://youtu.be/xGvaY2jjl1A
- Industrial collaboration
- Policy & Standards
  - UK National Expert - ISO/TC 21/SC 2/WG 7 "Classification of fires" – **ISO 3941:2026**
  - UK National Expert - CEN/TC 191/WG 6 "Gas extinguishing Systems and components"
  - BSI member - FSH/2/-/20 "Project group for Lithium/Ion battery"
  - BSI member - FSH/18/6 "Automatic fire extinguishing test protocol for fires of Lithium-Ion batteries"
- Google Scholar: https://scholar.google.com/citations?hl=en&user=Lfj5xTkAAAAJ&view_op=list_works&sortby=pubdate
- LinkedIn: https://www.linkedin.com/in/wojciech-mrozik-9058972

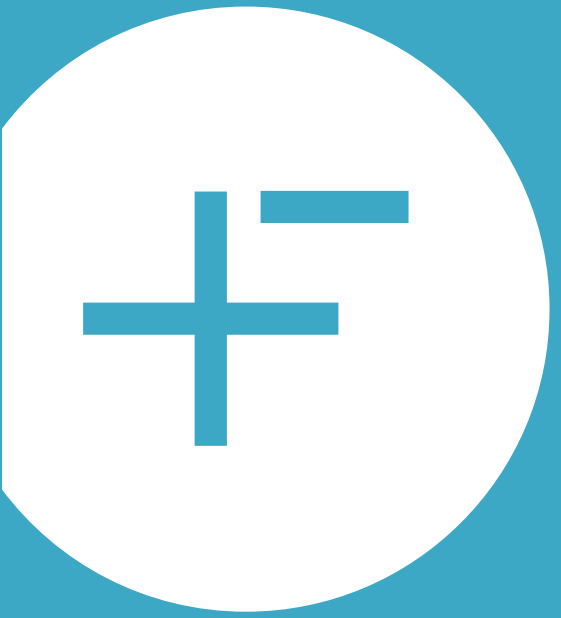
THE CONTEX

- **Critical knowledge gap** — no systematic, replicated comparison of suppression agents against (domestic-scale) BESS fires existed, despite the rapid proliferation of residential installations
- **Inadequacy of existing protocols** — traditional suppression strategies were developed for conventional fuels and had not been validated for the unique characteristics of LIB fires
- **Rising BESS fire incidents** — real-world events highlighted life, property, and environmental consequences of inadequate suppression, driving demand for evidence-based first responder guidance
- **Unverified manufacturer claims** — no standardised testing existed to validate agent performance claims (e.g., encapsulator agent's claimed 6–10× heat absorption improvement over water mist)
- **Overlooked vapour cloud hazard** — prior research focused on flame suppression only; this study was designed to initially assess both suppression performance and flammable/toxic vapour cloud production

EXTINGUISHING BATTERY “FIRES”

~~THERMAL RUNAWAY = FIRE~~

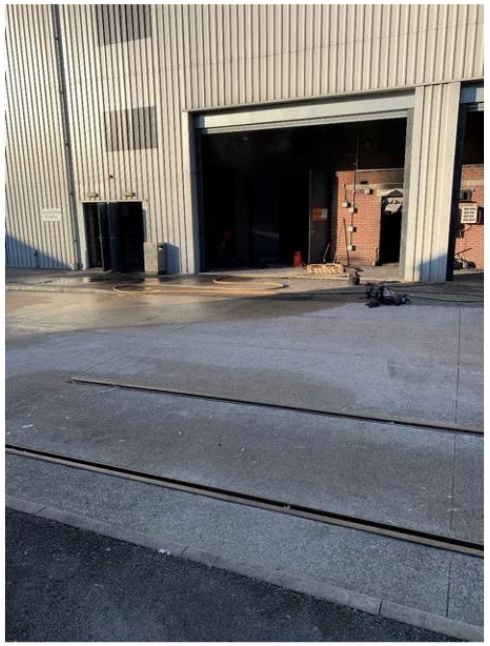
THERMAL RUNAWAY ≠ FIRE



BATTERY EXPERIMENTS

FACILITY

- Greater Manchester Fire Rescue Service Training Centre, Bury, UK
- Fitted with an industrial filter, extraction, and scrubber system to minimise pollution and displace gasses from the garage
- Primary aim was to assess the performance suppression agents for LIB fires at the system level
- Follow on from previous extinguisher tests conducted at County Durham & Darlington Fire Rescue Service - https://youtu.be/VL1HGWbJc6s

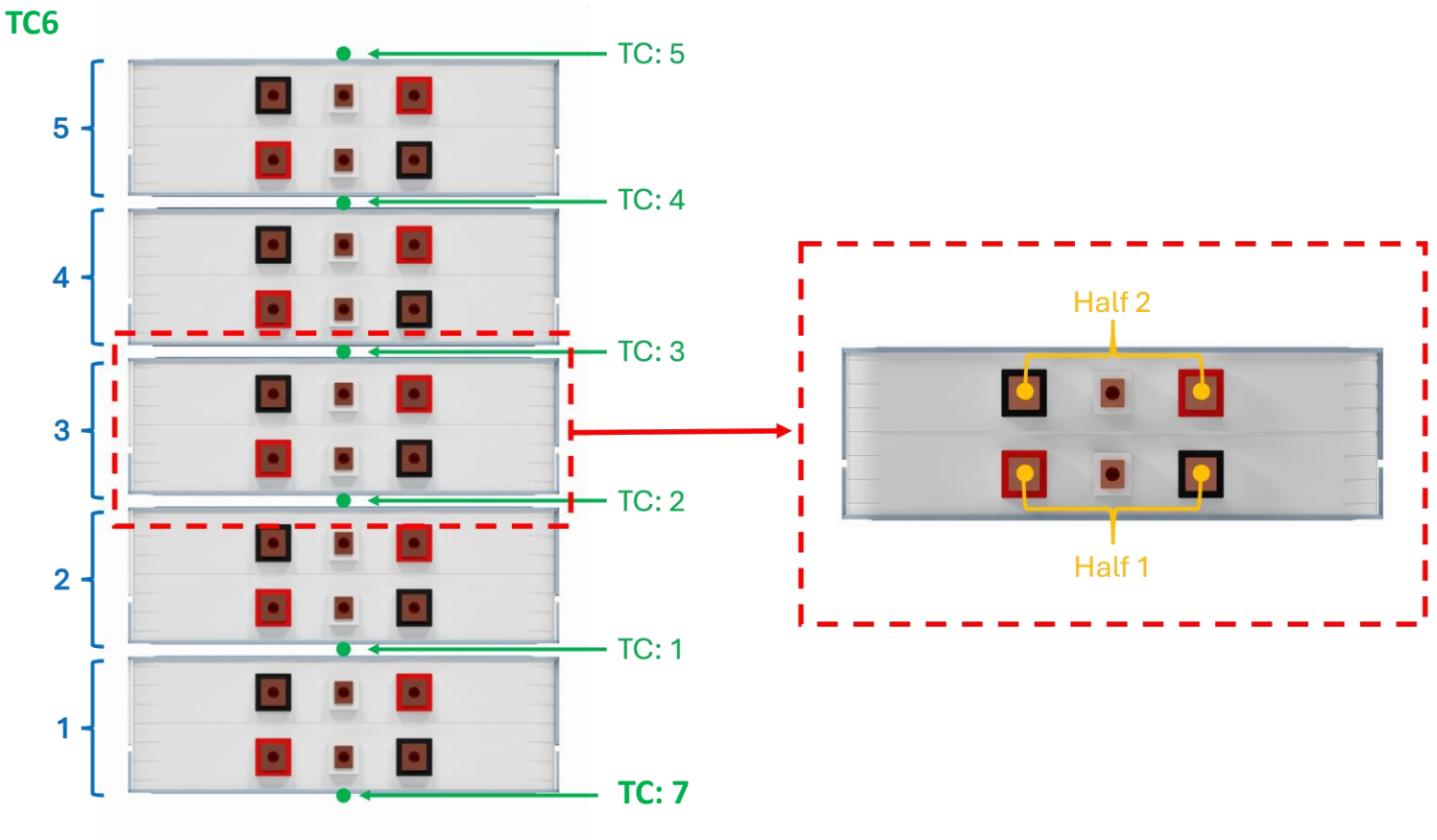


BATTERY MODULES

Specification	Value
Chemistry	NMC 532 ($LiNi_{0.5}Mn_{0.3}Co_{0.2}O_2$)
No. of Cells	8
Cell Capacity	56.3 Ah
Cell Voltage Range	2.5 – 4.2 V
Module Capacity	112.6 Ah
Module Voltage Range	10 – 16.8 V
Module Energy Range	1.13 – 1.89 kWh
Module Mass	8.5 kg

BATTERY ENERGY STORAGE SYSTEM (BESS)

- 5 modules assembled in an open-front steel container
- Imitating a small domestic BESS – around 8 kWh



EXPERIMENTAL PROTOCOL

1. Lower cell pair of module 2 OVERCHARGED at 1C (117 A)
2. Fire initiated from thermal runaway of cell pair (taken as 0 seconds)
3. Fire is allowed to burn for 1 minute
4. Suppressant agent is applied to the fire by trained firefighter

Fire Technology (2026) 62:3
https://doi.org/10.1007/s10694-025-01831-w

Check for updates

Performance of Extinguishing Agents against Lithium-Ion Battery Fires

Wojciech Mrozik[1,2] · Joseph McDonald[1,2] · Emma Shuttleworth[1,2] · Neville Dickman[1] · Paul Christensen[1,2] · Caroline Gaya[3] · Guy Marlair[3]

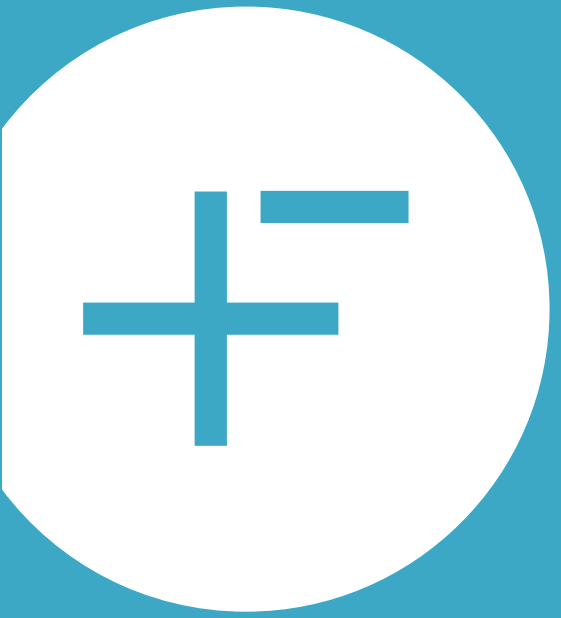
Received: 10 May 2025 / Revised: 2 October 2025 / Accepted: 18 November 2025 /
Published online: 6 January 2026

Abstract
This study presents a systematic evaluation of fire suppression strategies for lithium-ion Battery Energy Storage Systems (BESS), specifically examining thermal runaway propagation in small domestic system (8 kWh). Five distinct suppression methods were evaluated: water mist, encapsulator agent (water mist with proprietary encapsulator), carbonate agent (water mist with ammonium bicarbonate), mixed agent (containing boron compounds and surfactants), and liquid nitrogen. Performed experiments revealed significant differences between suppression methods. Water mist and encapsulator agents demonstrated better performance, extending propagation delay times by 179% and 167%, respectively, compared to control tests without a suppression method. Registered maximum temperatures varied across methods from 780° to 890 °C. However, none of the tested methods prevented thermal runaway propagation entirely and were able to save the system from being destroyed. Critical safety concerns emerged regarding vapour cloud

https://doi.org/10.1007/s10694-025-01831-w

EXTINGUIUSHING AGENTS

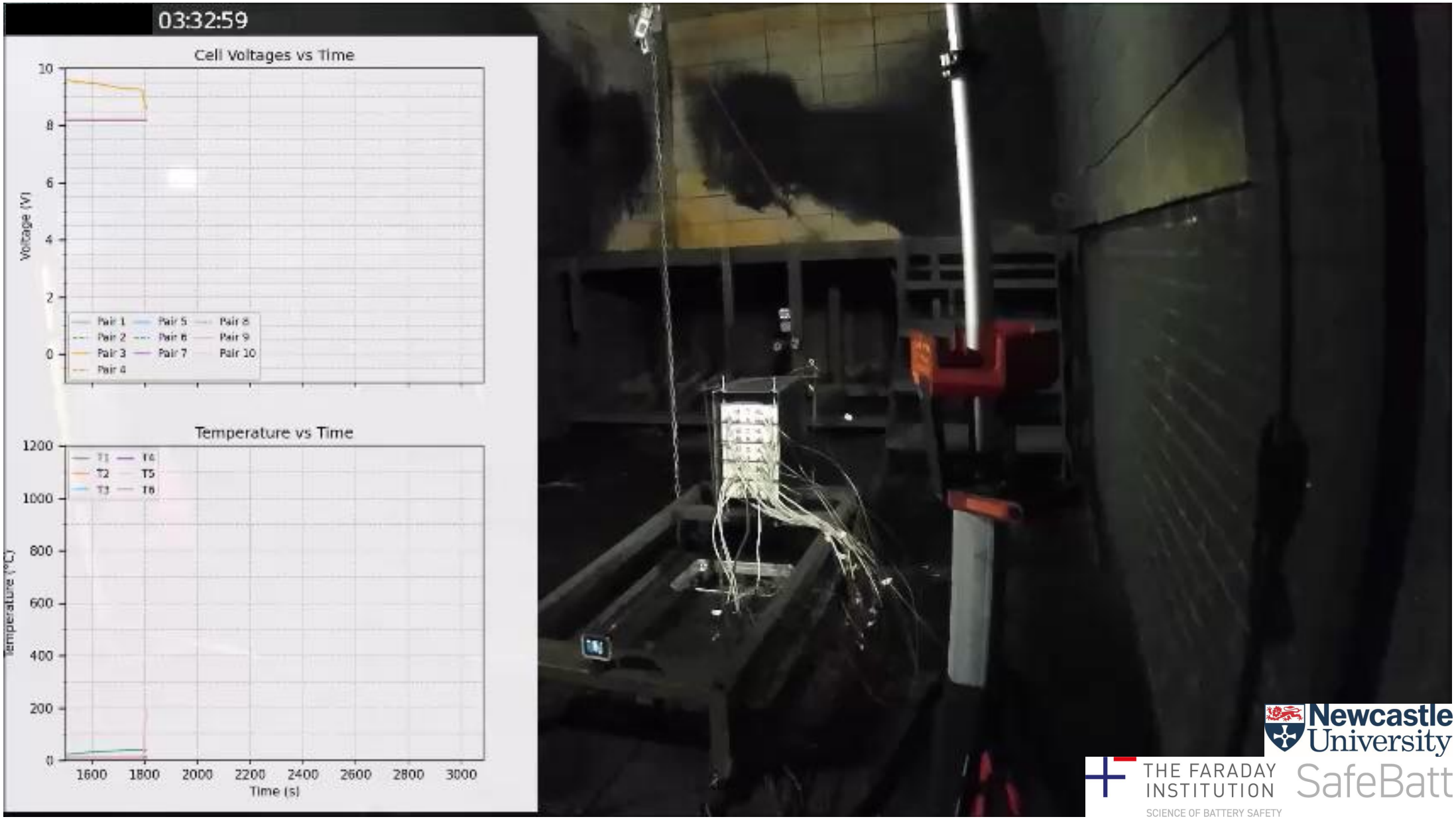
- Atomized Water
  - Control for additives, water with a mist nozzle
- Encapsulating Agent (one type)
  - Aqueous with surfactant additive, claims to exhibit more ‘heat absorption’ than standard water
- Carbonate Agent
  - Aqueous with ammonium bicarbonate additive, decomposes to release CO2, displaces and starves the fire of oxygen
- Mixed Agent
  - Aqueous with proprietary mix of compounds -> natural-born compounds, wetting agents, anionic detergents
- Liquid Nitrogen
  - Released via lance from 200L tank ~ 4 bars



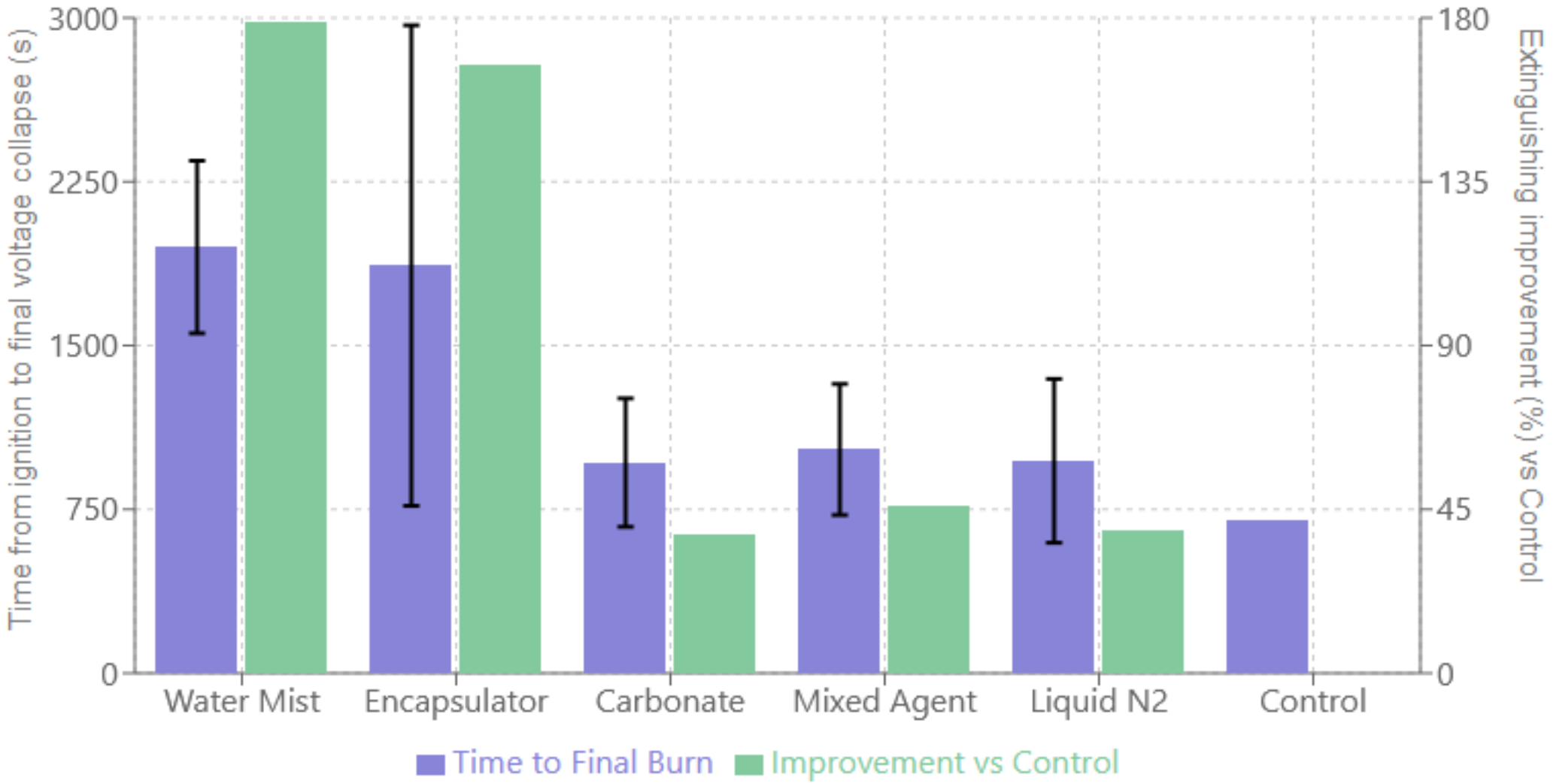
Results

ENCAPSULATING AGENT

CARBONATE AGENT

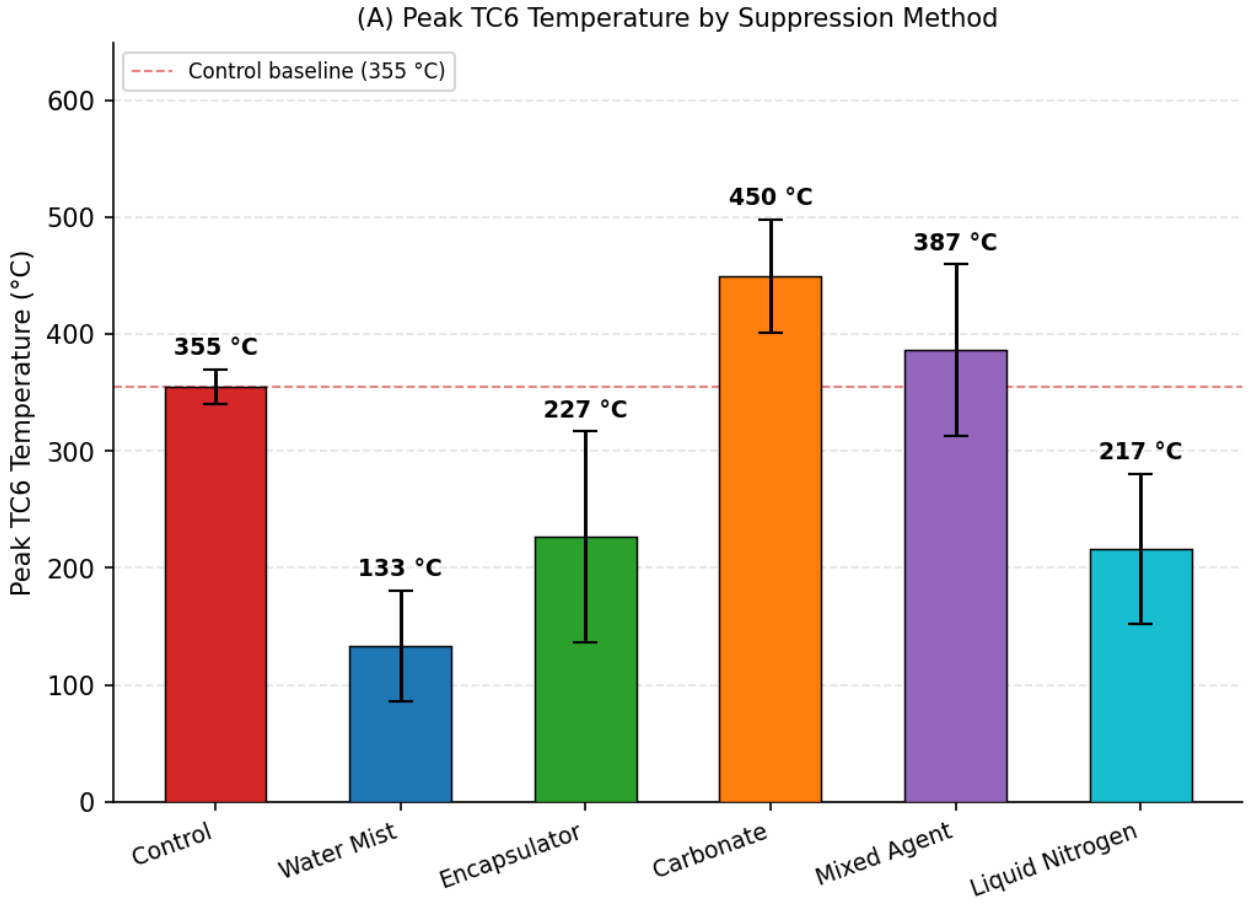


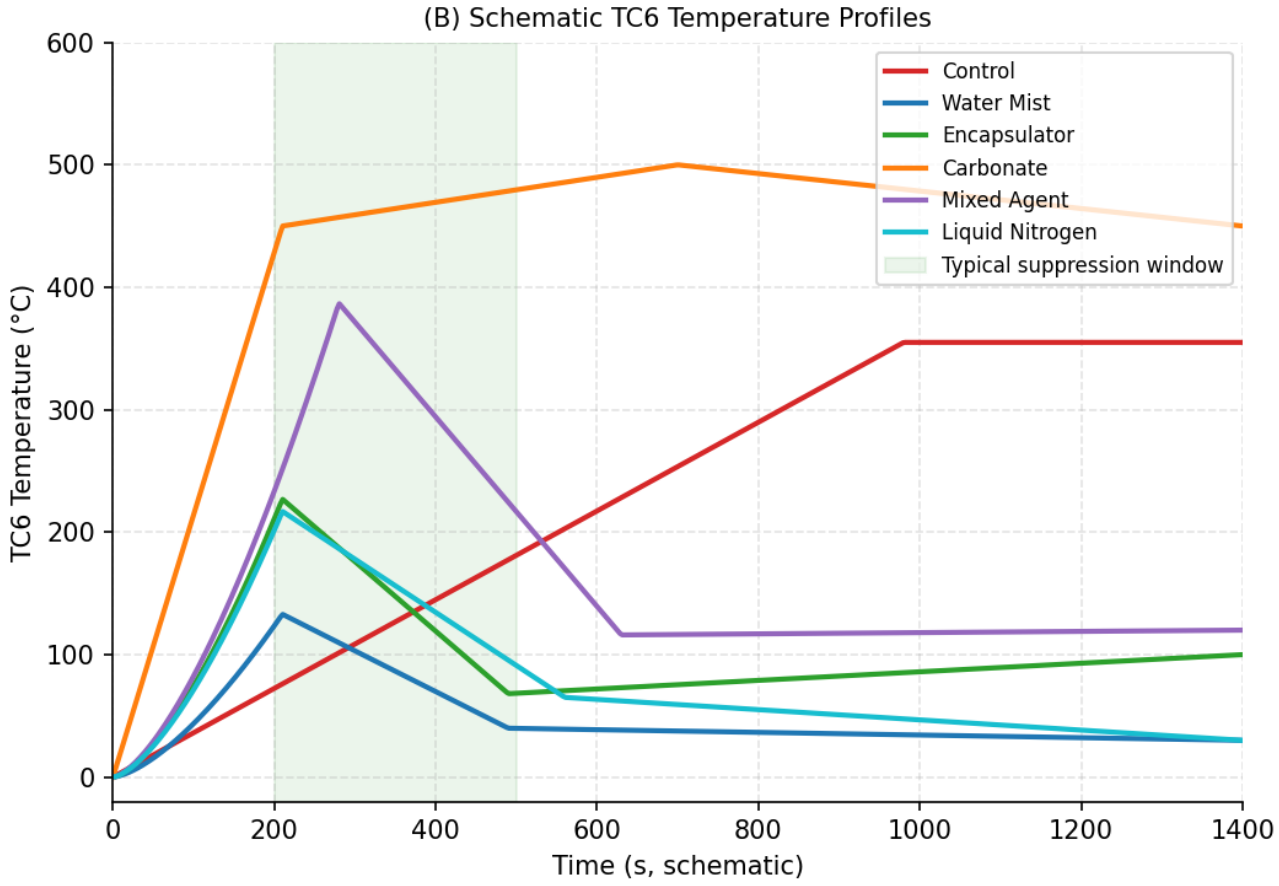
RESULTS


Time from ignition to final voltage collapse (s)
3000
2250
1500
750
0
Extinguishing improvement (%) vs Control
180
135
90
45
0
Water Mist
Encapsulator
Carbonate
Mixed Agent
Liquid N2
Control
Time to Final Burn
Improvement vs Control

TRANSFERABLE HEAT

TC6 – Rear Casing Thermocouple





CONCLUSION

- No tested method completely prevents thermal runaway propagation
- Time from ignition to final voltage collapse indicates that thermal runaway propagation can be delayed (to a degree)

- **Thermal runaway continues without fire -> producing heat and vapour cloud**

When extinguished

HAZARD SWITCHES FROM FIRE TO VAPOUR CLOUD

TOXICITY & EXPLOSION

LIMITATIONS

- **Open-fronted, non-commercial BESS configuration —** gave suppressants unrestricted access to battery modules, representing a best-case scenario that likely overestimates agent effectiveness compared to fully enclosed commercial BESS units.
- **Single battery chemistry and scale** - testing a single NMC 532 chemistry at 8 kWh scale limits the generalisability of results to other battery chemistries (e.g. LFP, NCA) and larger grid-scale systems where suppression efficiency scales non-linearly.
- **Manual, hand-held agent application by trained fire officers -** does not reflect real-world residential scenarios, introducing operator-dependent variability and limiting direct extrapolation to automatic suppression systems or untrained occupants.
- **HF (and other gases) concentrations** were not reported – gas sensors oversaturated – but initial concentrations were high
- **No quantification of vapour cloud explosion risk —** related to the above; no possibility to measure gas volume

ACKNOWLEDGEMNTS

Newcastle University

- Prof. Paul Christensen
- Emma Shuttleworth (PhD Student)
- Neville Dickman (Technician)
- Joe McDonald (Researcher/ PhD Student)

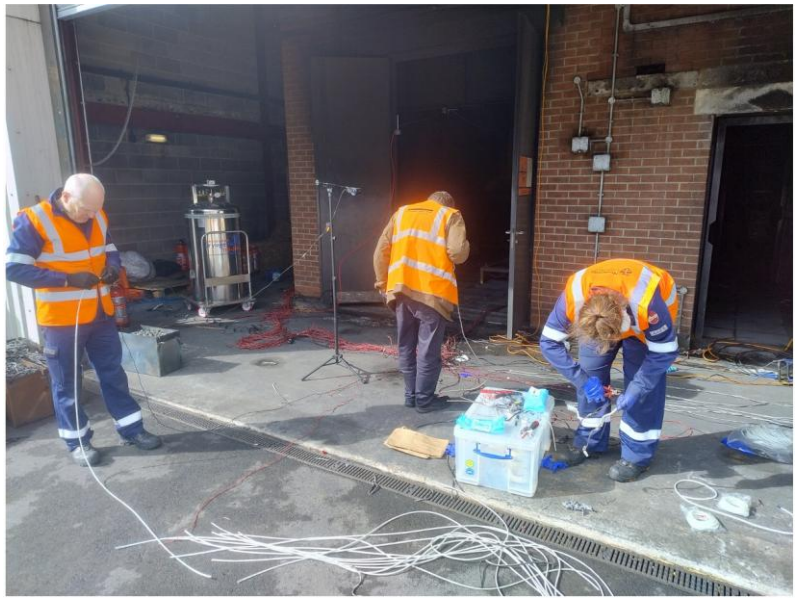
GMFRS

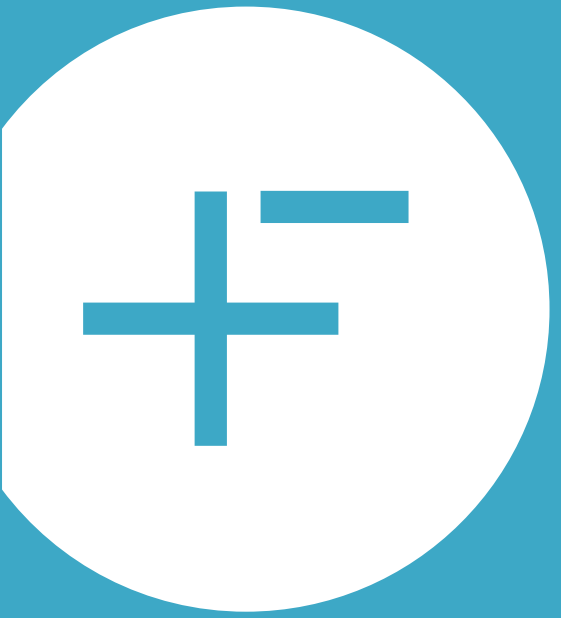
- Aiden Scott (Video Firefighter)
- Andrew Holden

FUNDING

- Fire Industry Association (FIA)
- SAFEBATT

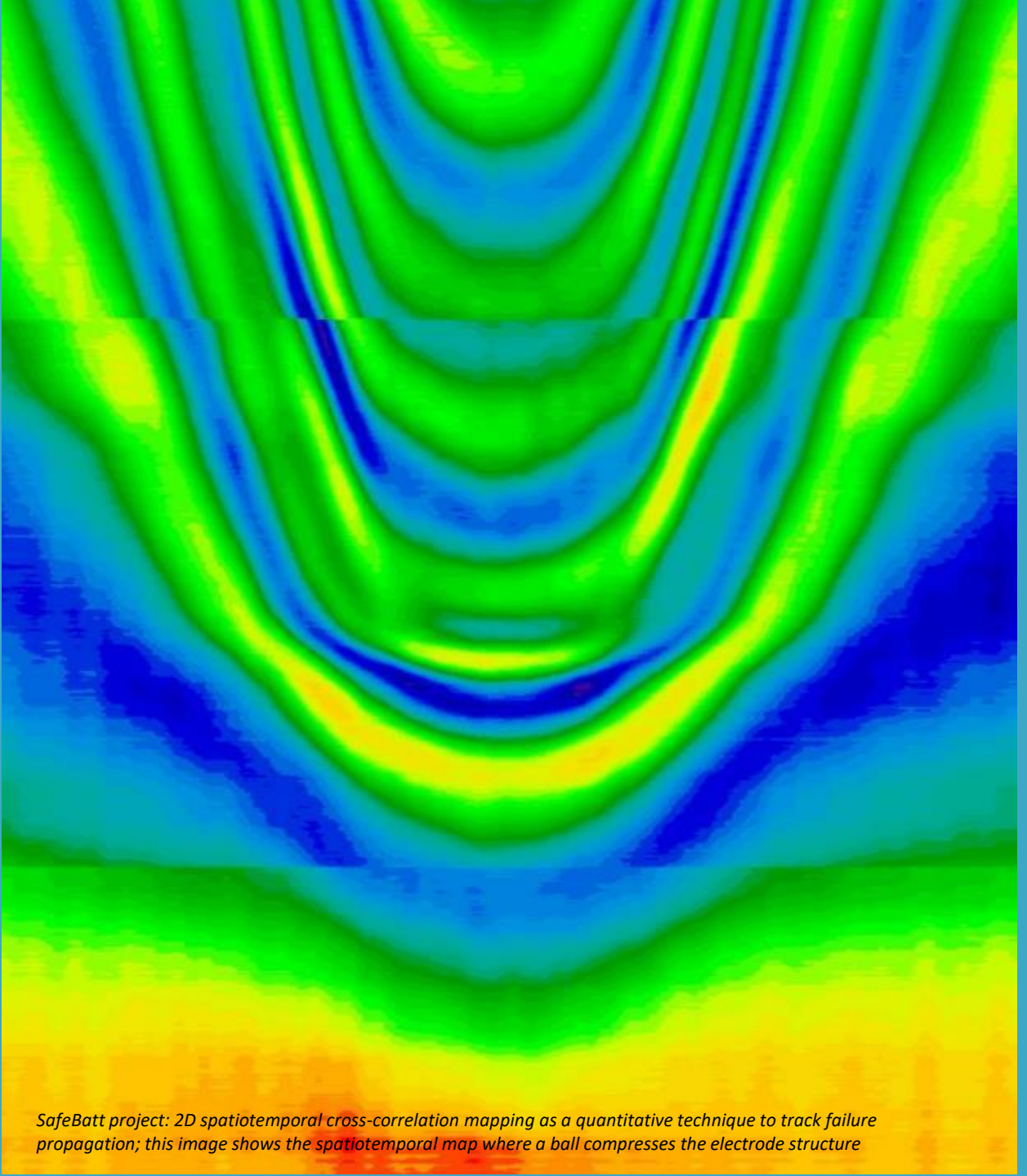
- Thermal Vision





Thank you

Newcastle University



SafeBatt project: 2D spatiotemporal cross-correlation mapping as a quantitative technique to track failure propagation; this image shows the spatiotemporal map where a ball compresses the electrode structure

Battery Safety UK 2026

Advanced Characterisation of Early Failure Signatures

Mel Loveridge – CoI Safebatt

May 2026

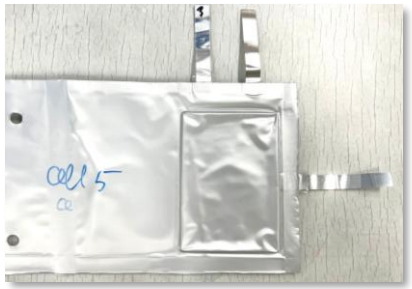
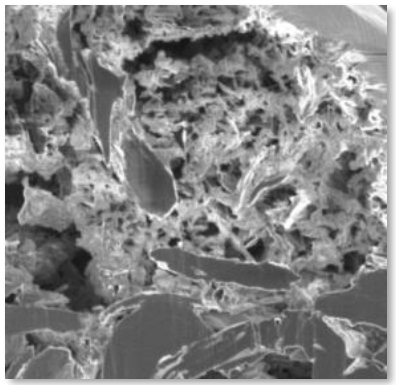
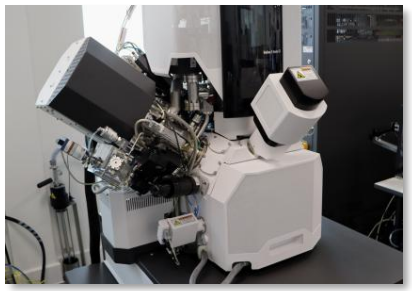
THE FARADAY INSTITUTION

SCIENCE OF BATTERY SAFETY

SafeBatt

OUTLINE



Introduction

- **Detecting Early Signatures of Failure**
- **Research Approach**
  - Non-destructive electrochemistry: 3E Cell Analysis
  - Destructive: Post-Mortem Analysis

Research

- **3E Cell Analysis**
  - 3E Cell Configuration
  - 3E Cell Profiles at Low Temperatures
  - Investigating Li-Plating Signatures
- **Advanced Characterisation (Post-Mortem)**
  - PFIB-SEM
  - HAXPES
  - XPS

Conclusion & On-Going Works

- **Impact of Research**
- **On-Going Works**

WP1.2 | DETECTING EARLY ONSET SIGNATURES OF FAILURE

WP1: Degradation / Safety Intersection

WP1.2: Detecting Early Signatures of Failure

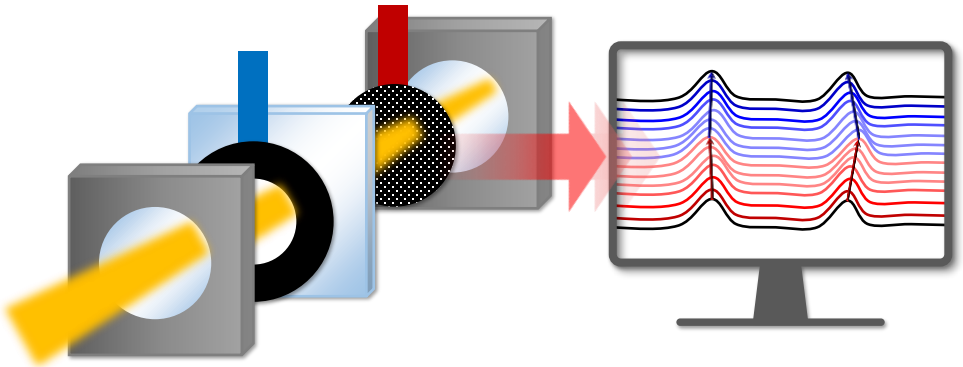
WMG
THE UNIVERSITY OF WARWICK

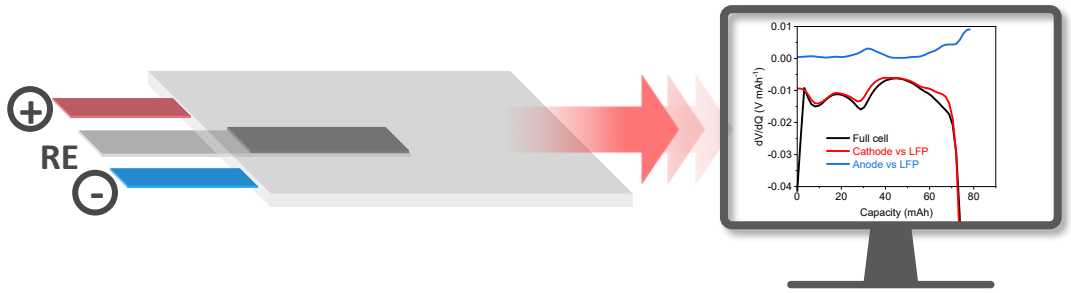
Destructive +
In situ

Advanced Characterisation

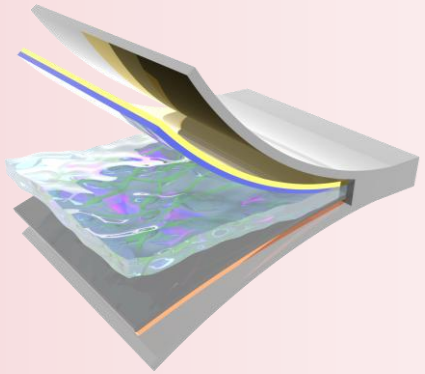
Comprehensive Electrochemical Analysis of 3E Cells

Non-destructive





3E CELL ANALYSIS – 2 USUAL APPROACHES



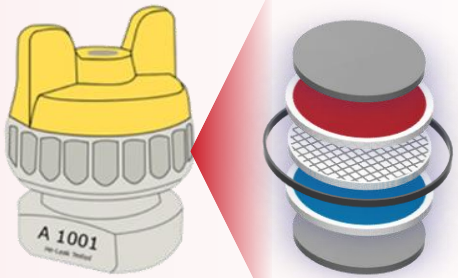
Commercial format

Cell teardown & reconstruction

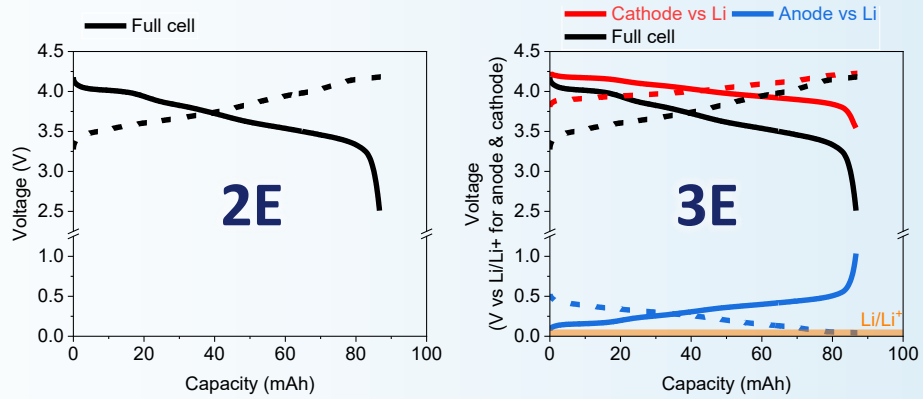
Half coin-cells

- Possible to **damage electrodes**
- Possible to **alter electrode properties**

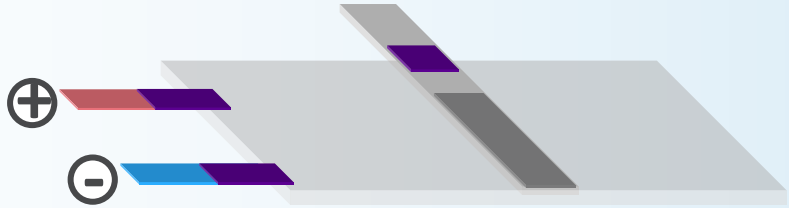
VS



3E PAT cell



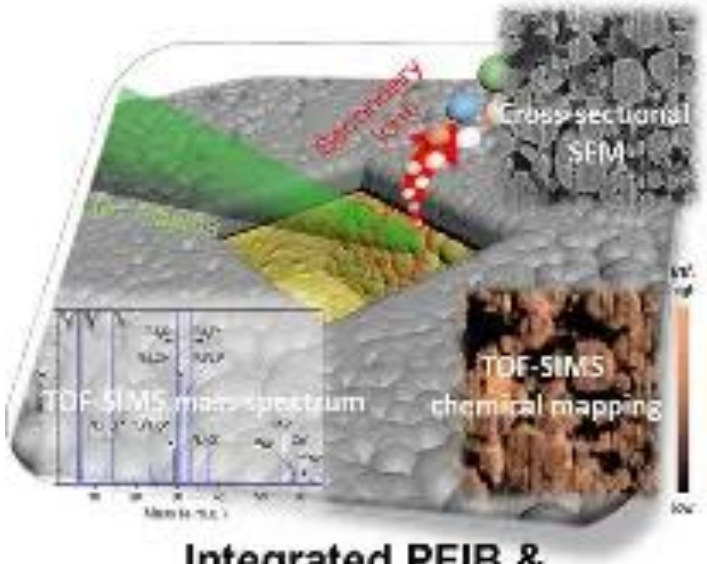
Third electrode (RE) insertion



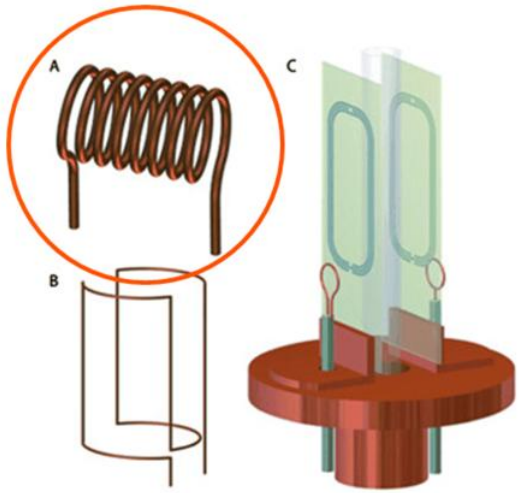
- Incorporation of RE while **not sacrificing cell performance** (Electrodes remain intact)
- Allowing **prompt Li-plating detection**
- Identifying onset of **lithium plating** to transfer this to **2E cells**

POST-MORTEM ANALYSIS – CHARACTERISATION TECHNIQUES

PFIB-SEM



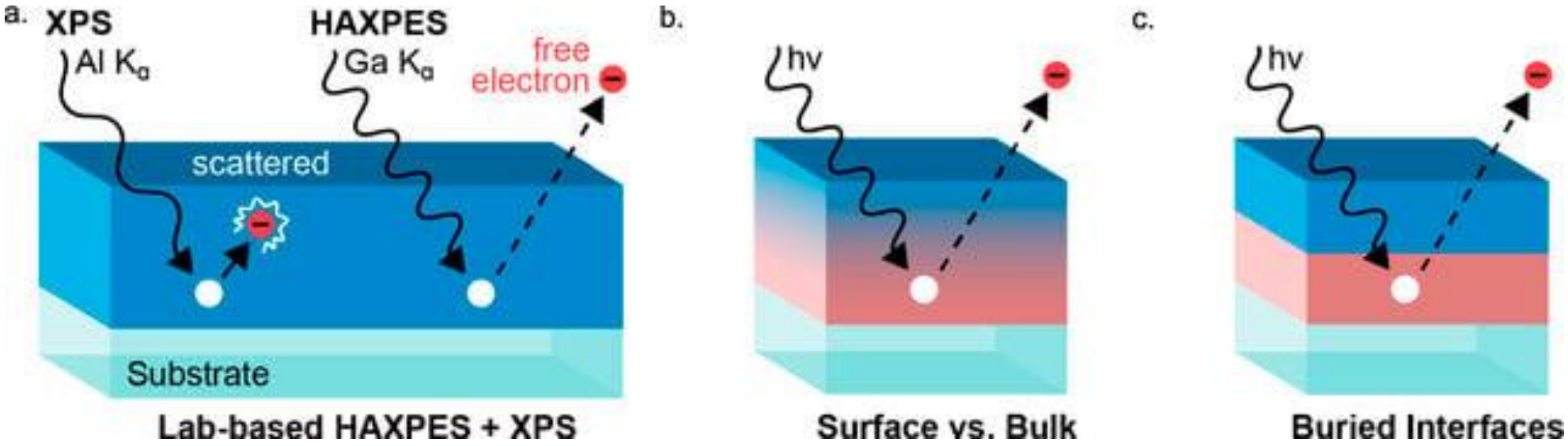
Integrated PFIB & ToF-SIMS characterisation



NMR

in situ and operando detection of Li-plating

XPS & HAXPES



Lab-based HAXPES + XPS

Surface vs. Bulk

Buried Interfaces

Research

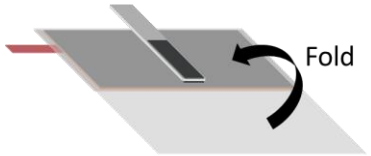
- **3E Cell Analysis**
  - 3E Cell Configuration
  - 3E Cell Profiles at Low Temperatures
  - Investigating Li-Plating Signatures
- **Advanced Characterisation (Post-Mortem)**
  - PFIB-SEM
  - HAXPES
  - XPS

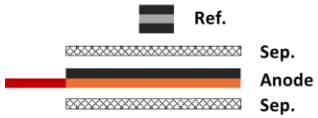
3E CELL FABRICATION AND TESTING

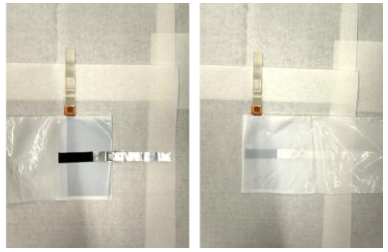
1 Place the anode on separator

2 Fold the separator over anode

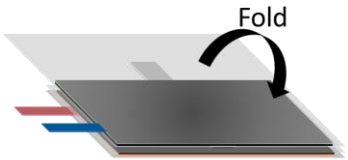
3 Place the RE and fold separator over RE

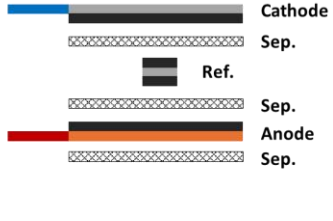


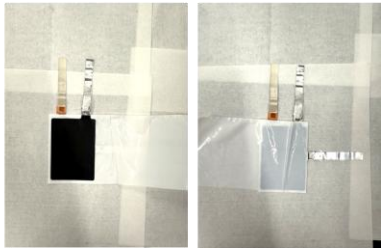




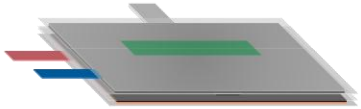
4 Place the cathode and fold separator over cathode

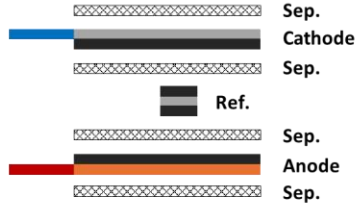


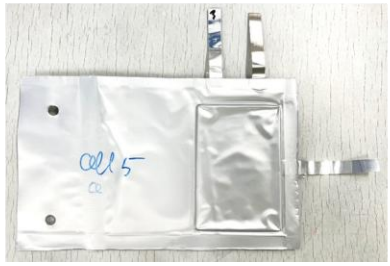




5 Complete the stack with tape







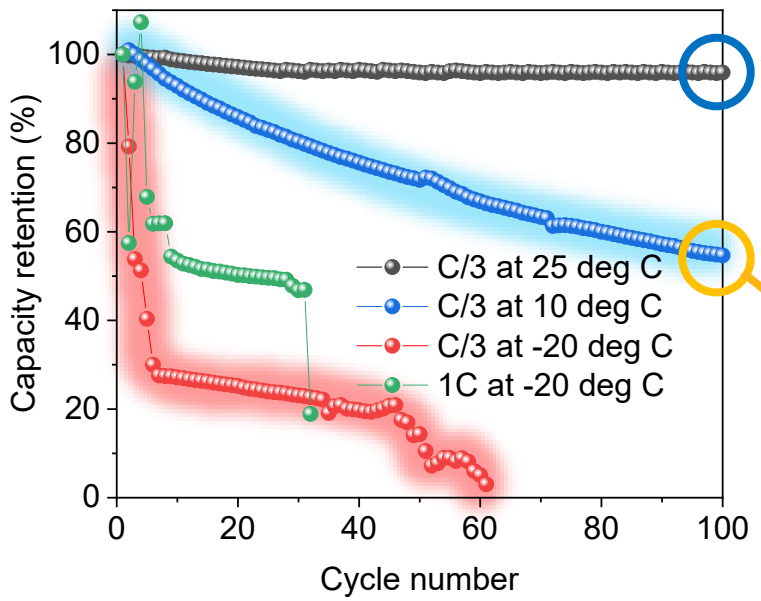
Cell Chemistry

Cathode: SC NMC811
Anode: Graphite
Electrolyte: 1.2M $LiPF_6$ in EC/EMC 3:7 v/v + 2% VC

Testing Conditions

Voltage: 2.5 – 4.2 V
C rates: C/3, 1C
Temperature: -20, 10, 25 °C

LOW-TEMPERATURE 3E CELL TESTS

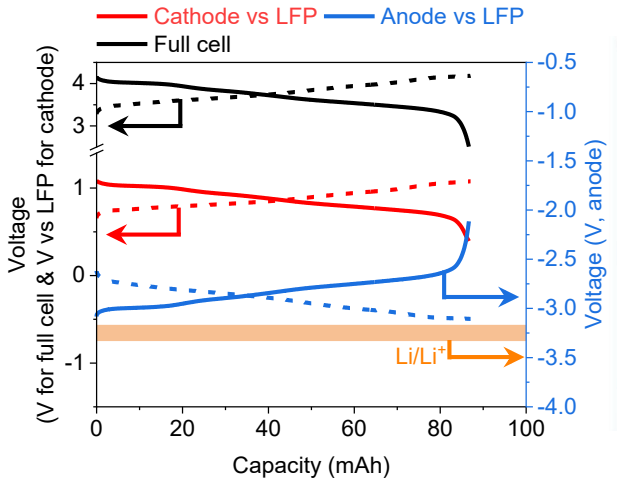


Healthy

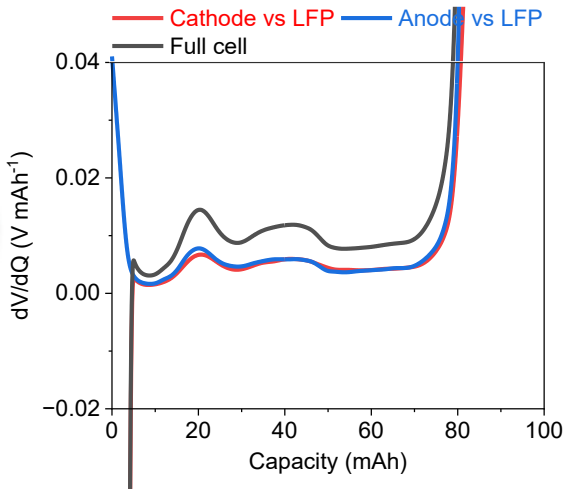
C/3 | 25 °C | 100th

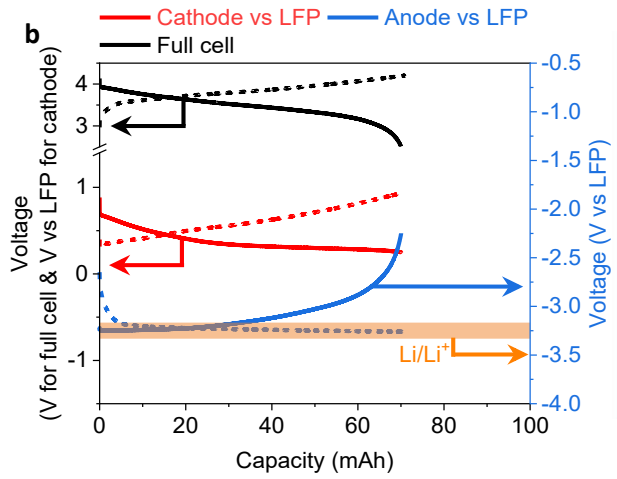
Unhealthy

C/3 | 10 °C | 100th

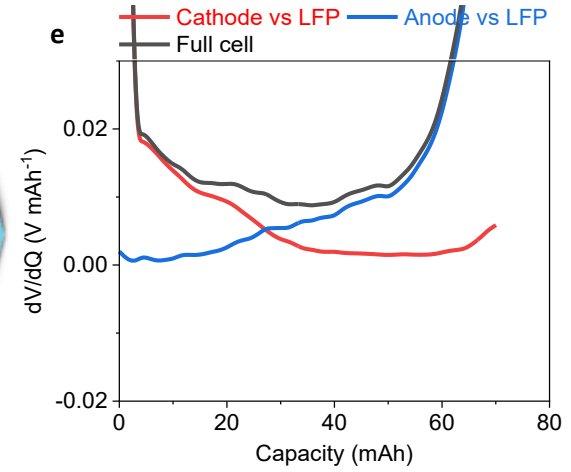


DVA





DVA



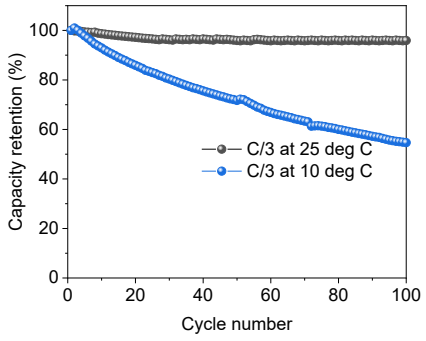
At low temperatures (10 and -20 °C)

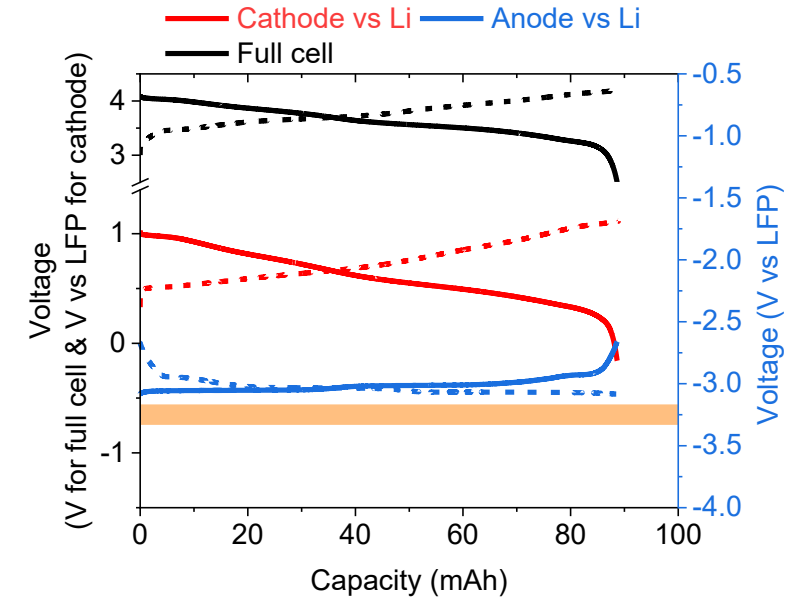
- phase transition peaks in DVA plots broadened
- New peaks appeared at nearly the end of discharge

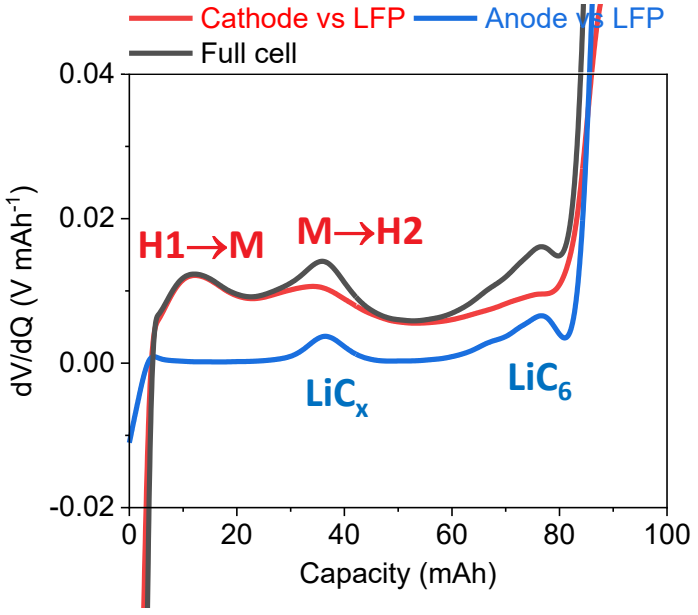
Suggesting **the lost of Li inventory** and **heterogeneous Li distribution due to Li plating/stripping.**

LOW-TEMPERATURE 3E CELL TESTS | 10 °C AT C/3 (1)

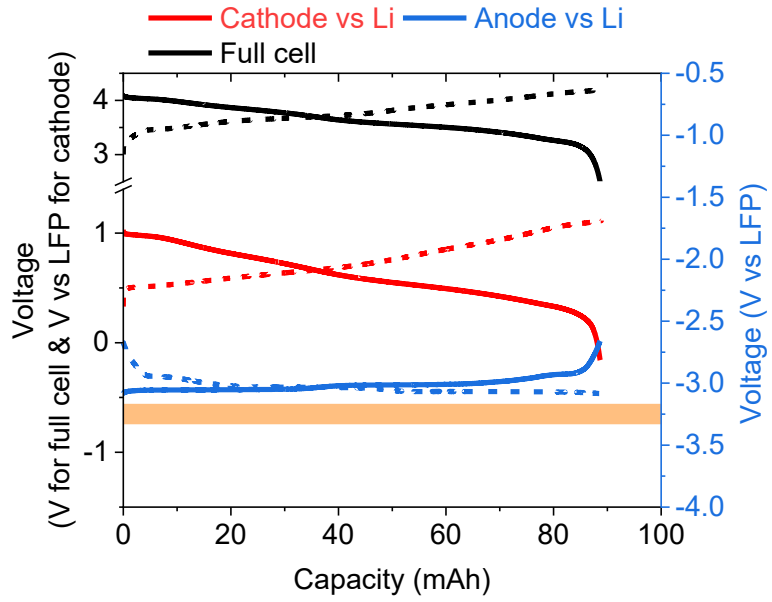
1st cycle

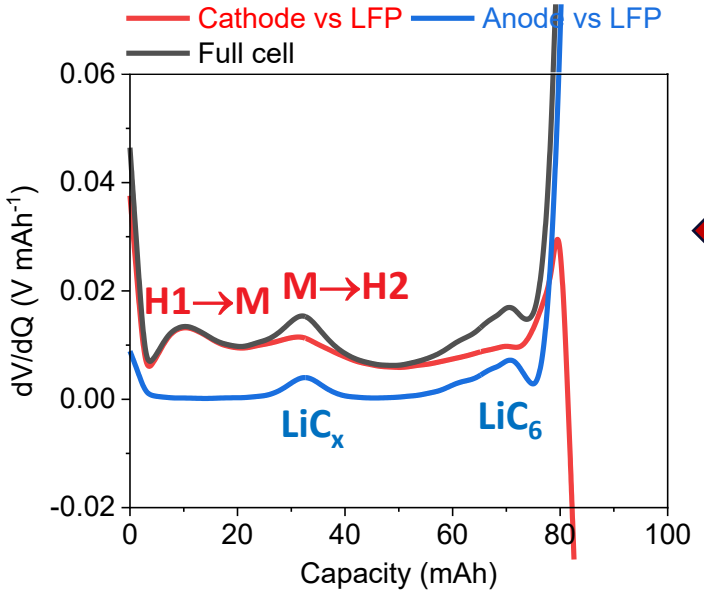


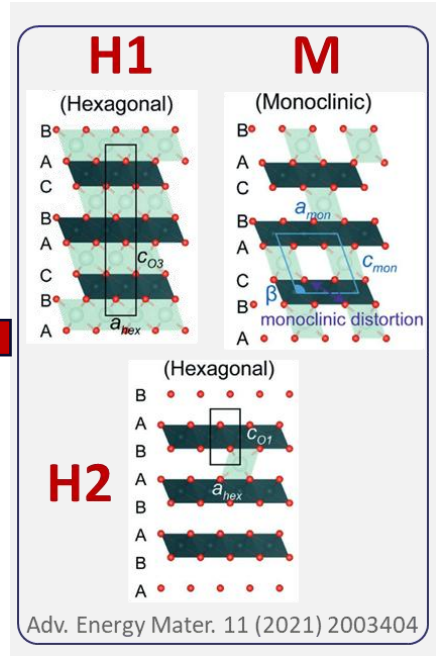




20th cycle

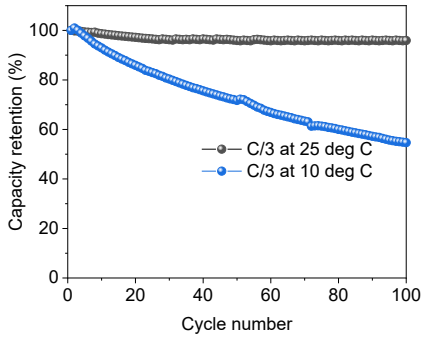


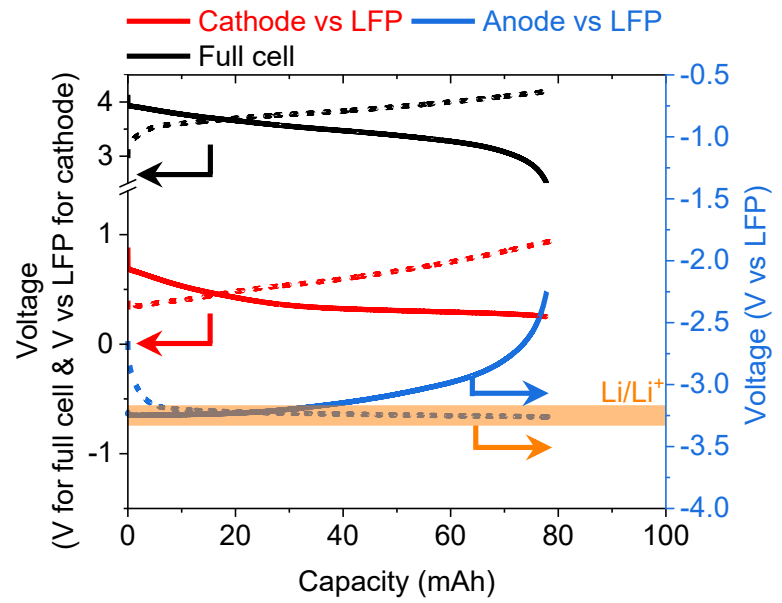


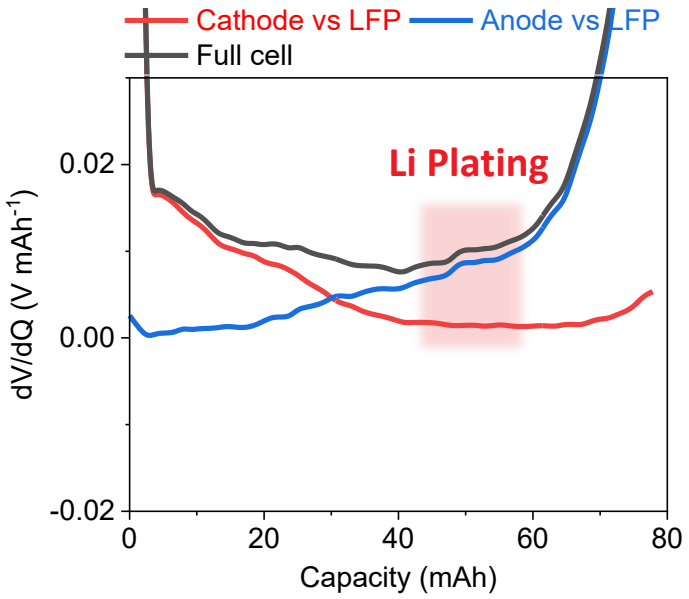


LOW-TEMPERATURE 3E CELL TESTS | 10 °C AT C/3 (2)

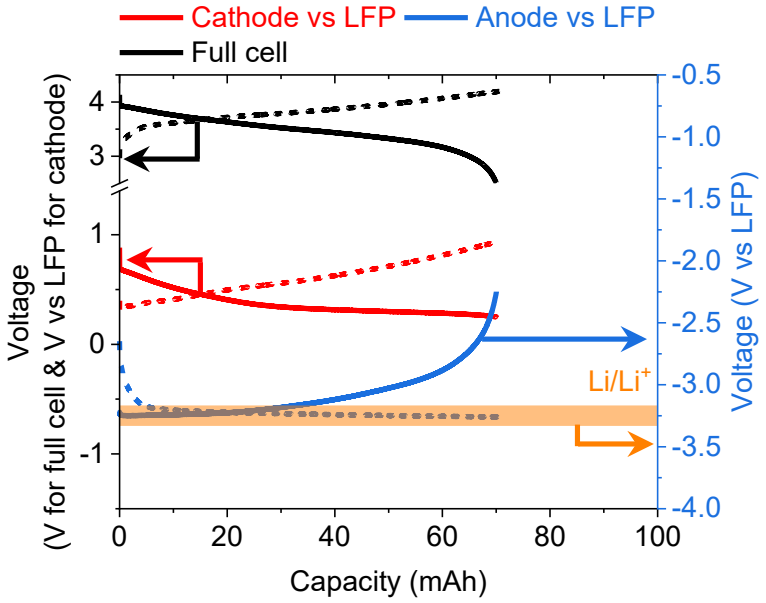
50th cycle

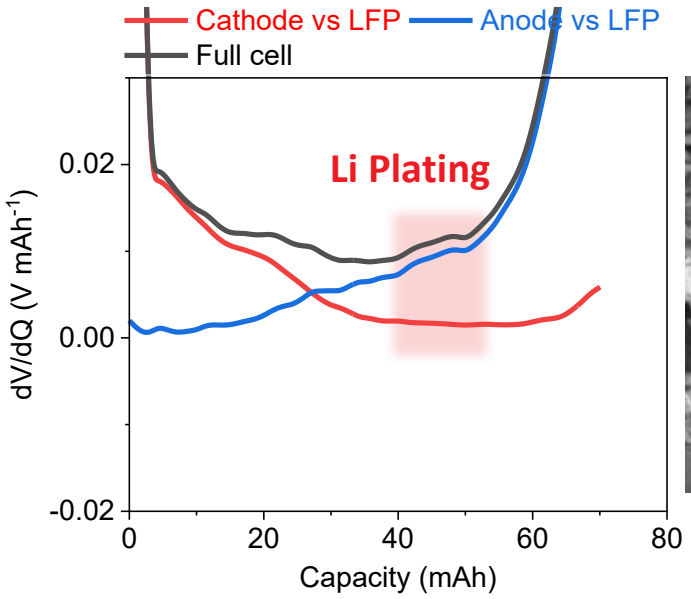


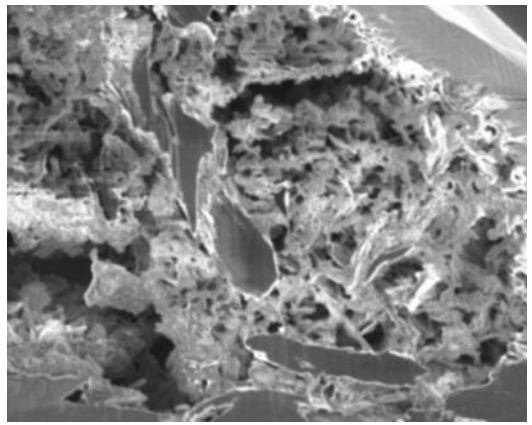




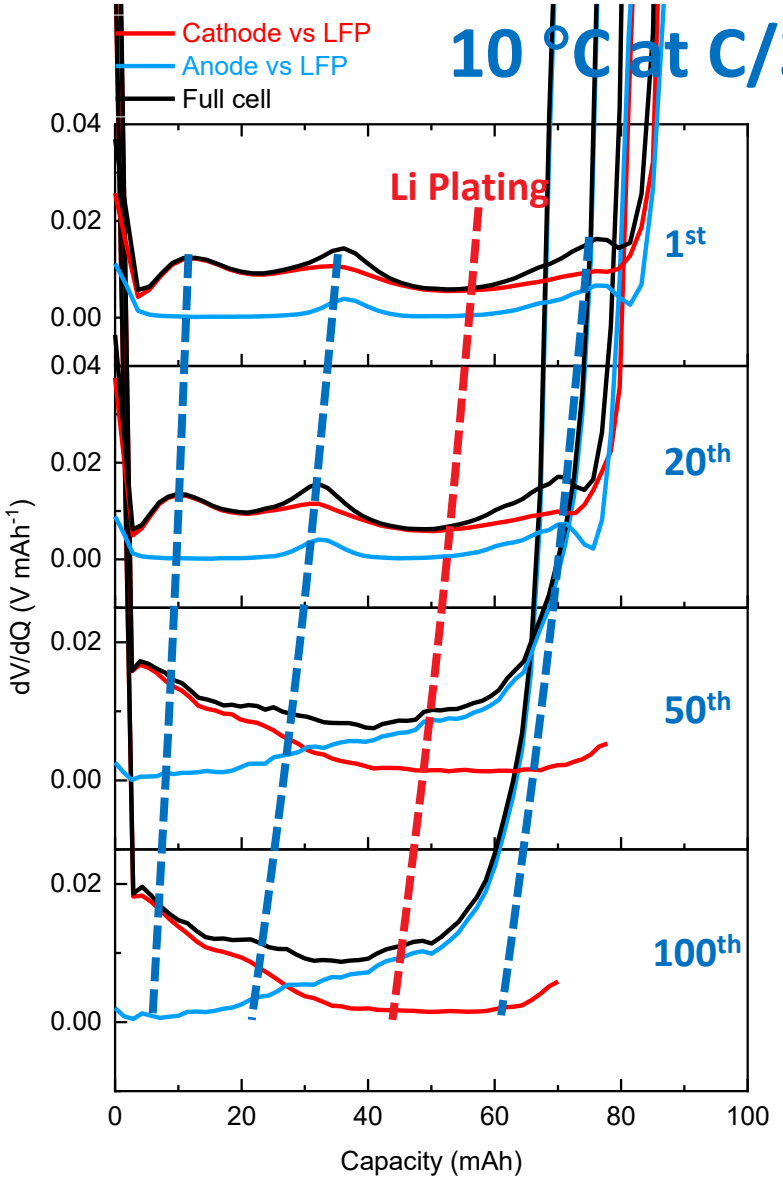
100th cycle

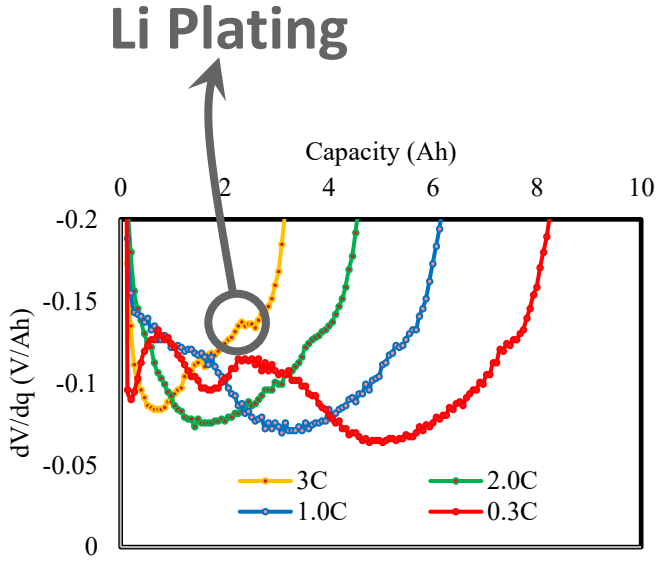






LI-PLATING SIGNATURES





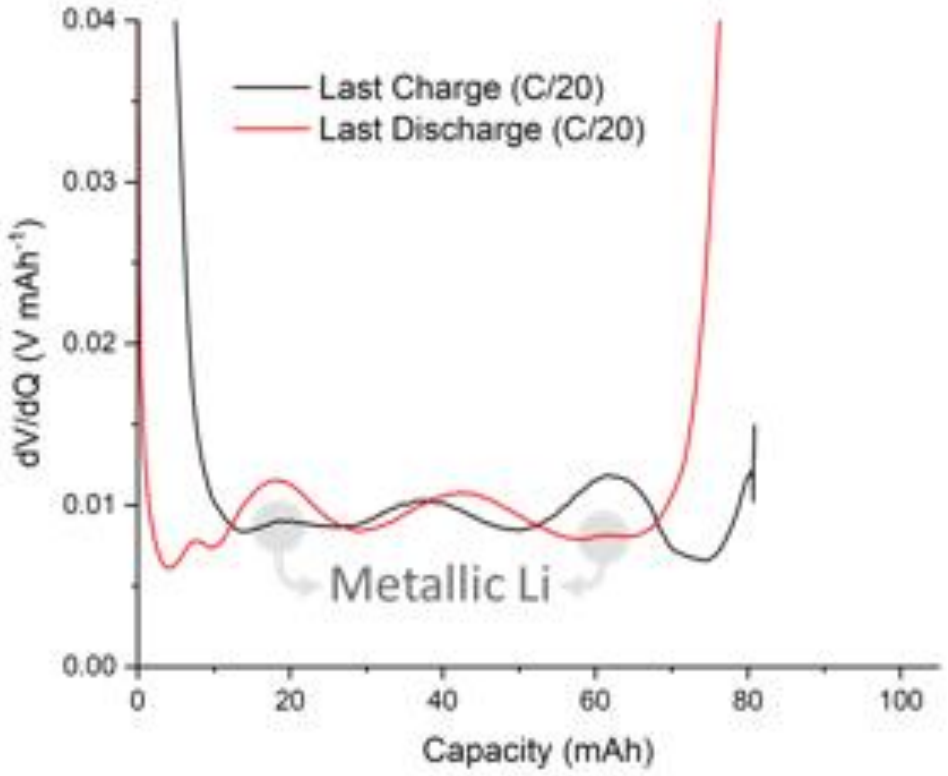
Supporting evidence from literature

Journal of Energy Storage 98 (2024) 112869

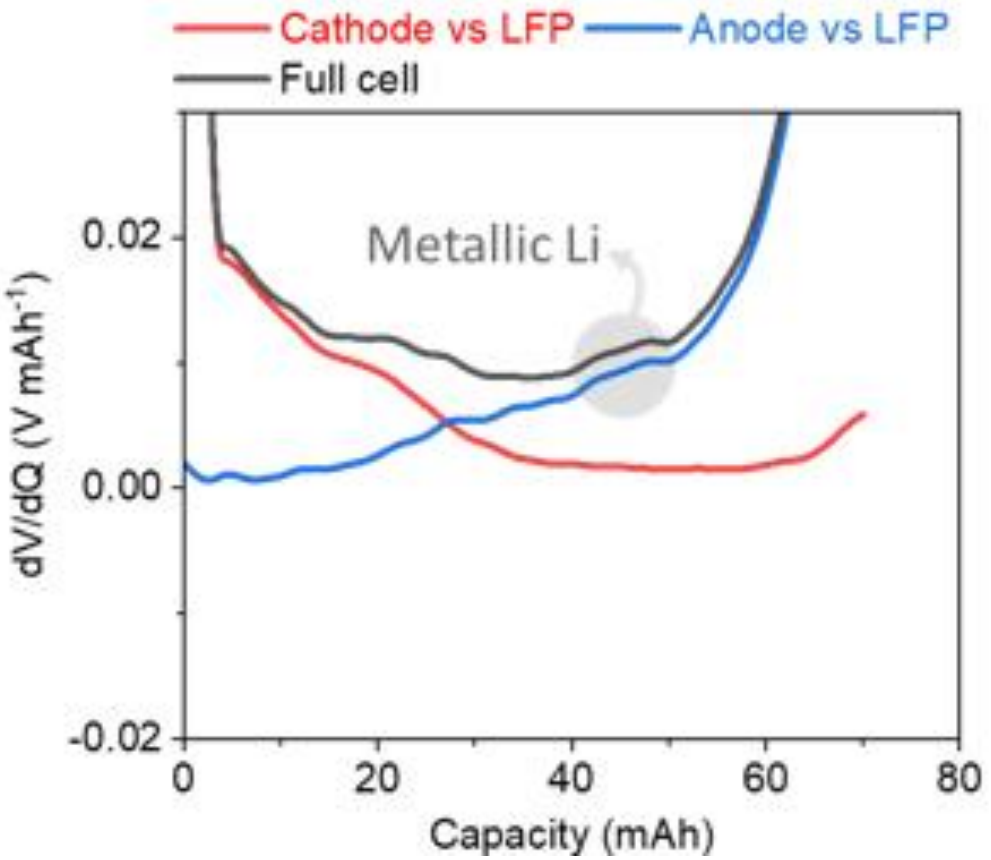
Li plating peaks become more pronounced near end of discharge

LI PLATING CONFIRMATION IN 2E CELLS

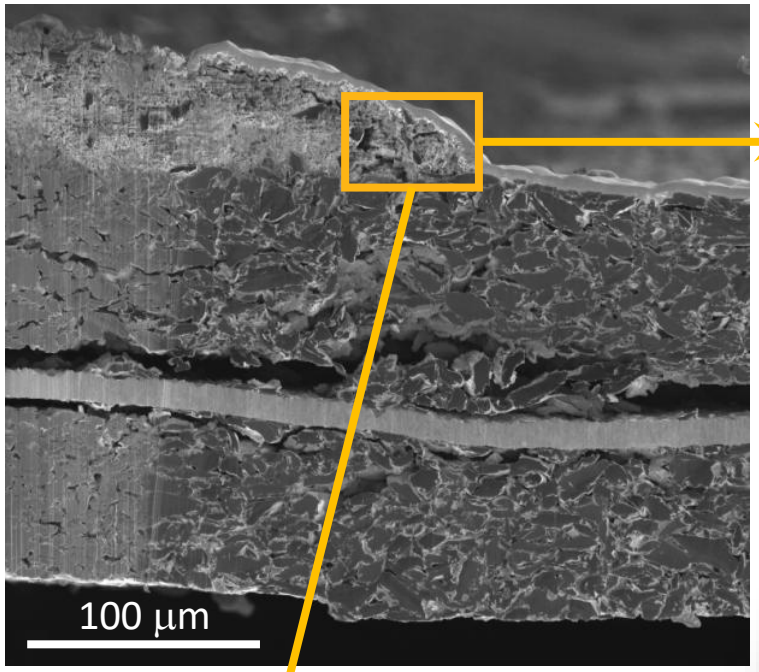
2E Cell

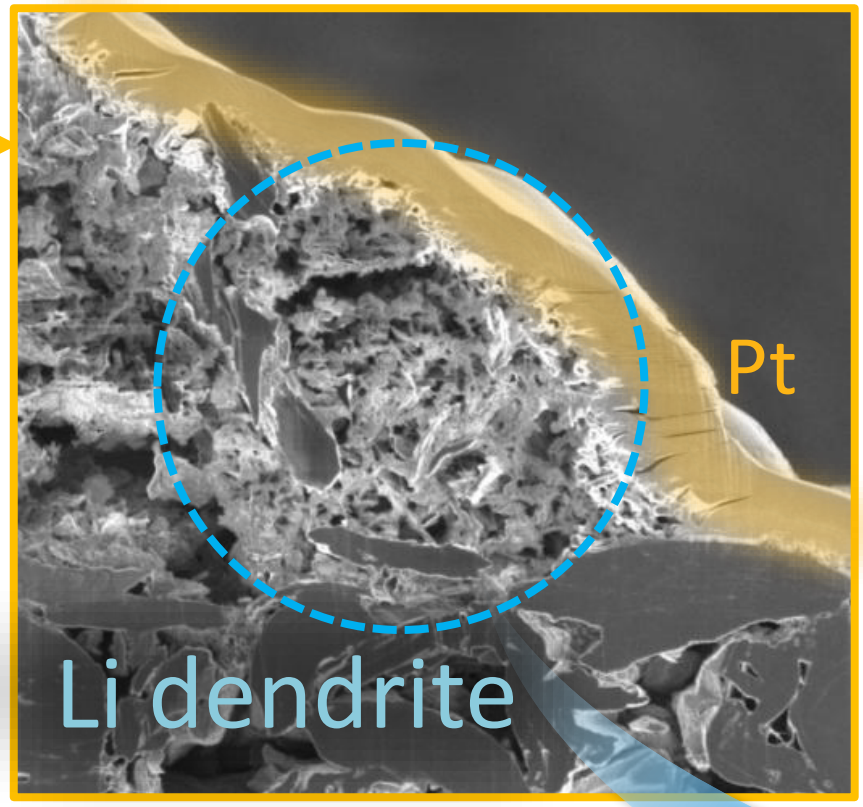


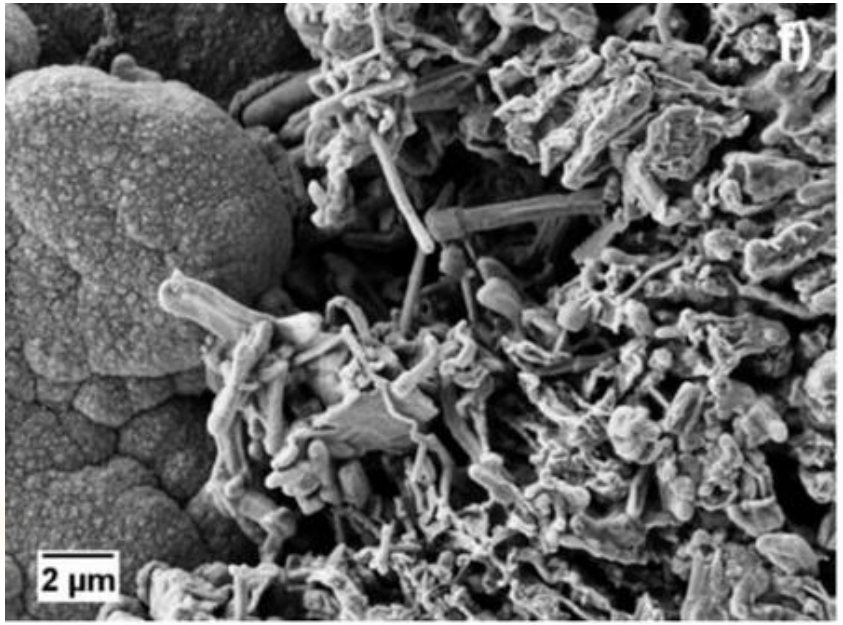
3E Cell



Cross-Section SEM | -20 °C at C/3

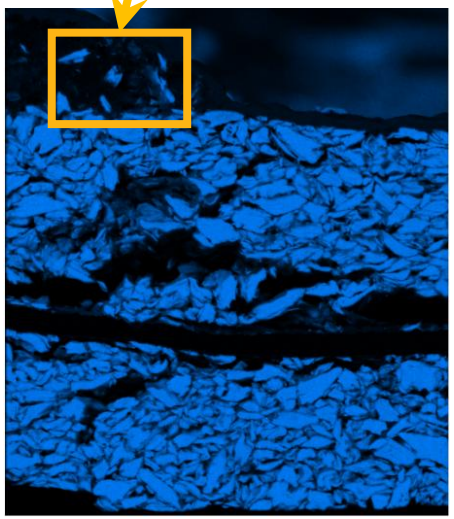






Adv. Energy Mater. 2021, 11, 2003756

C map

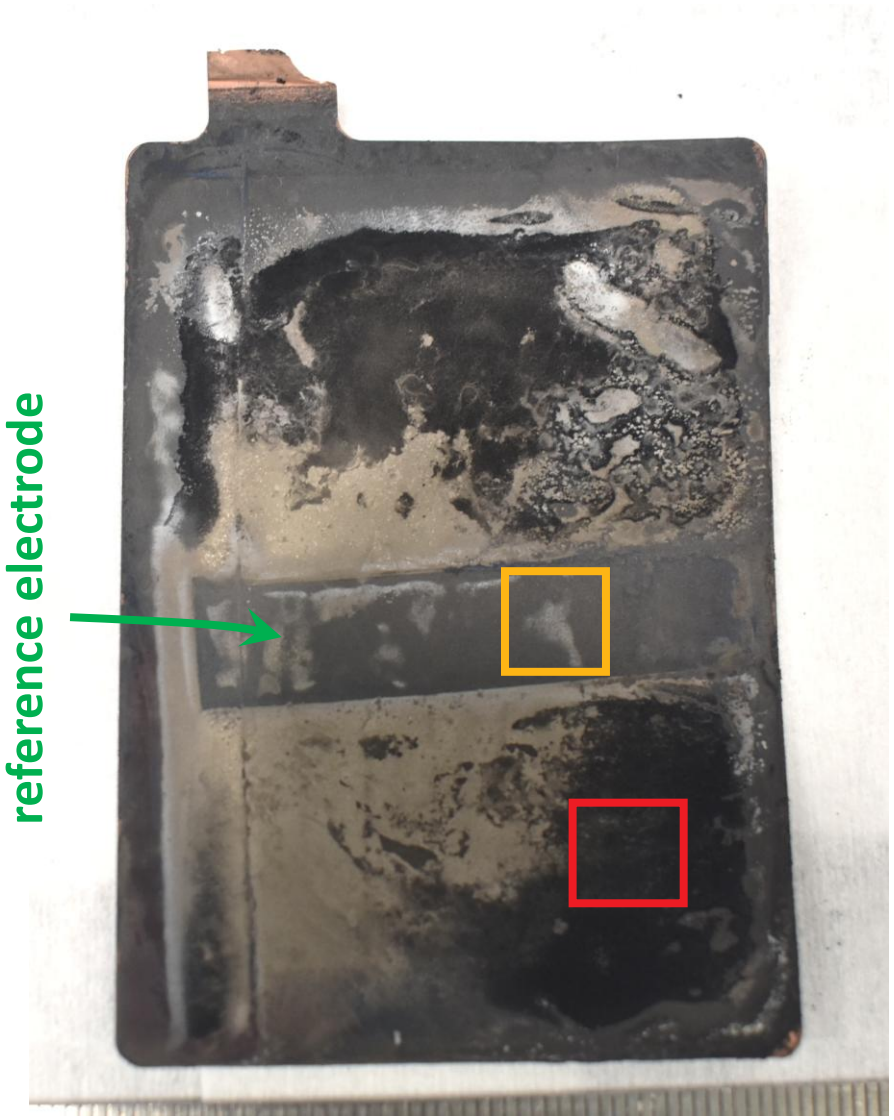


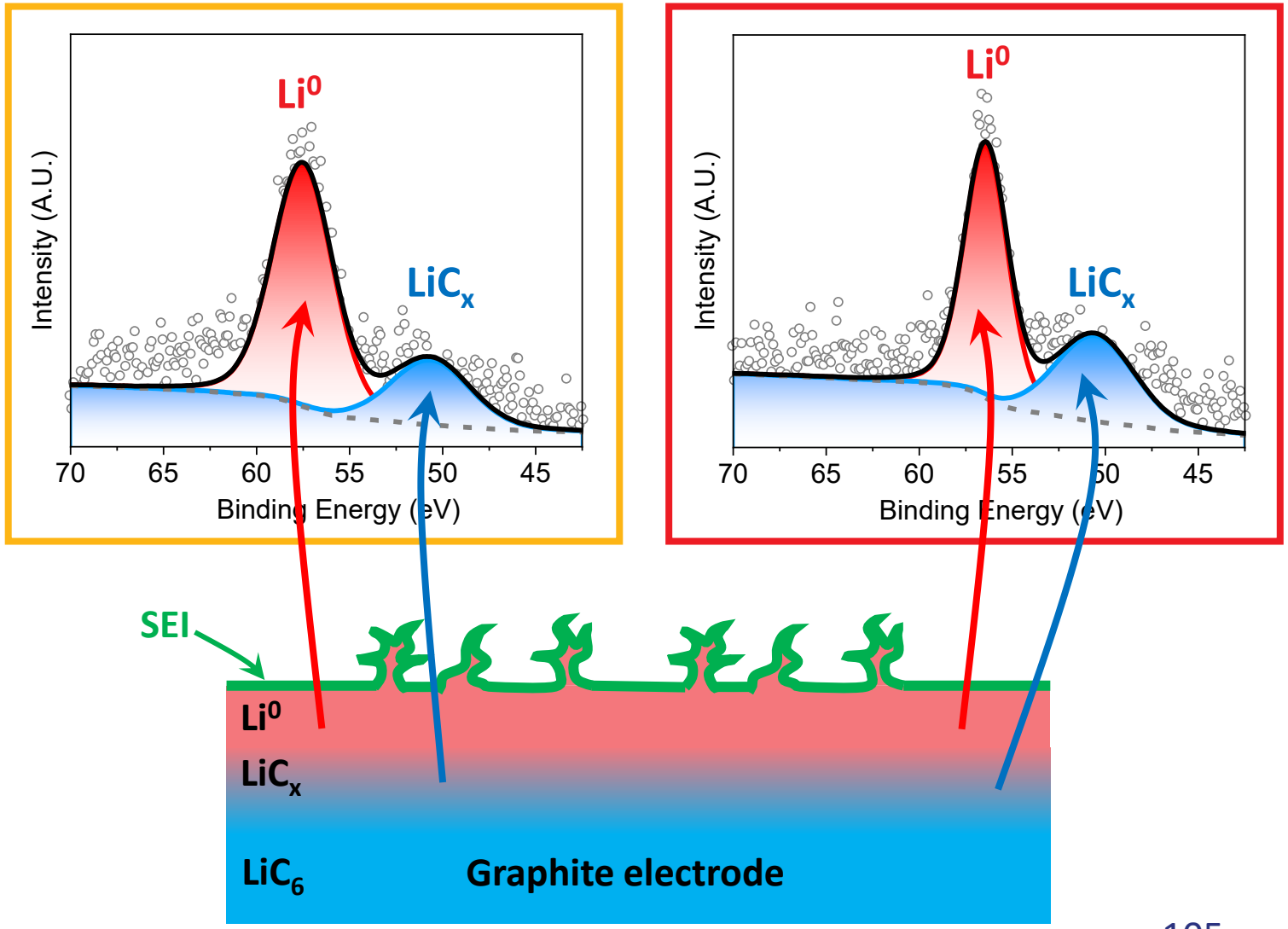
If the fibrous deposit was related to SEI or electrolyte salts, we would see carbon signal from Li_2CO_3

XPS & HAXPES to confirm

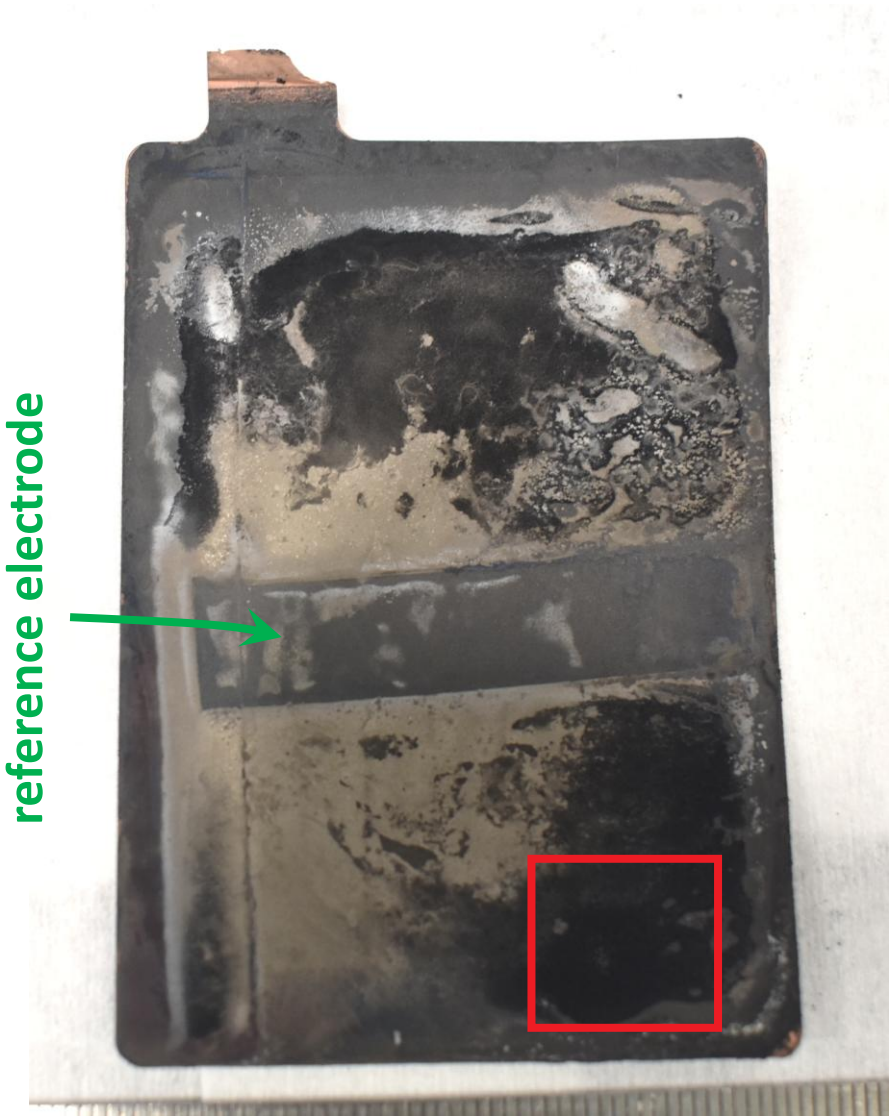
HAXPES | -20 °C at C/3

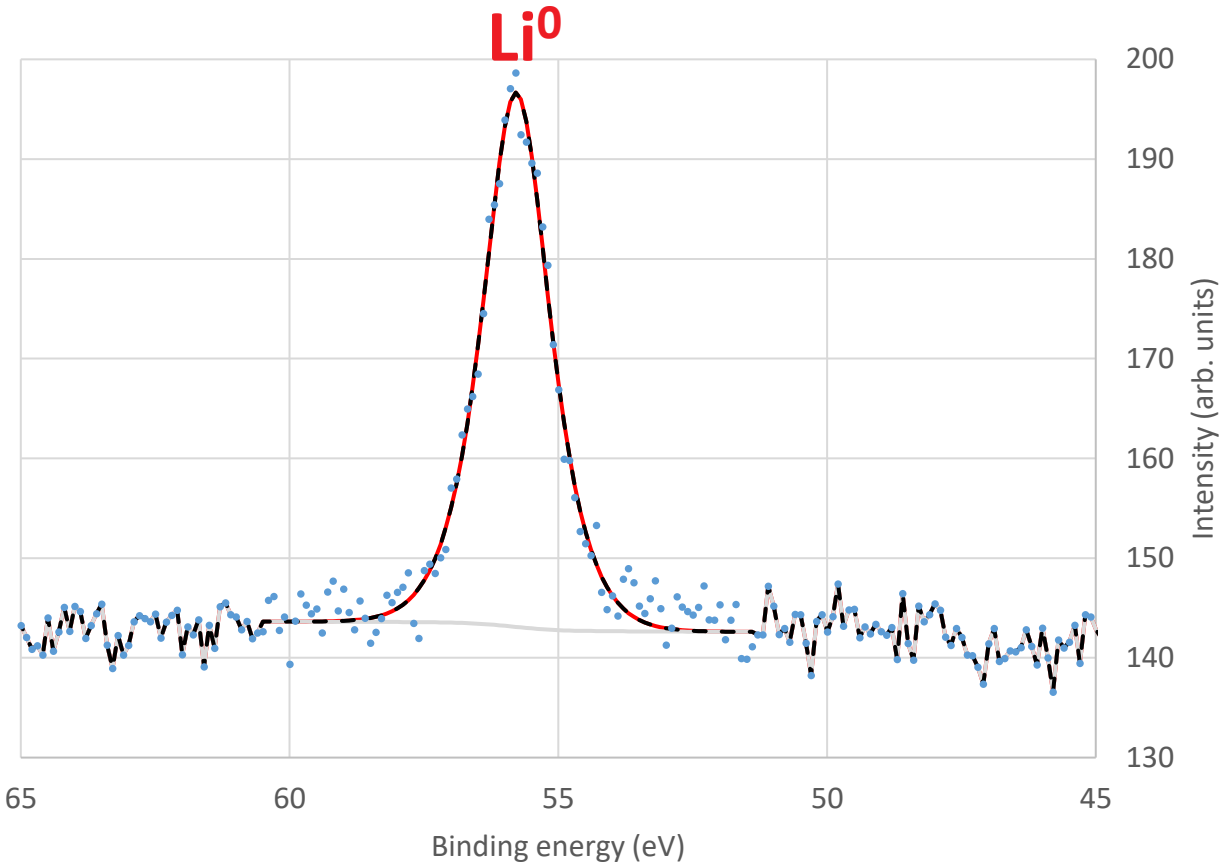
Li plating observed on anode and under reference electrode area





XPS | -20 °C at C/3

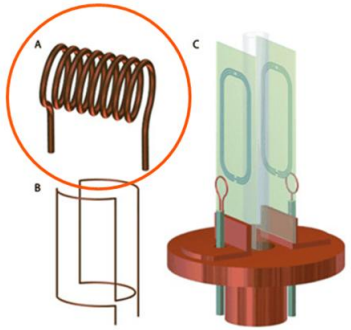




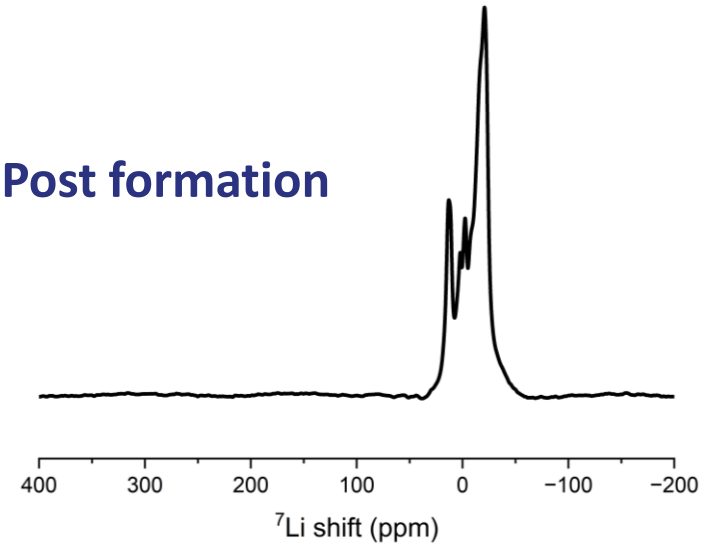
Li^0 signal is stronger than HAXPES due to surface penetration of X-ray (1-5 nm)

EX-SITU NMR

- **Characterisation plans**
  - NMR demonstration of Li-plating (on LiFun cell)
  - HAXPES and XPS on 10 °C samples

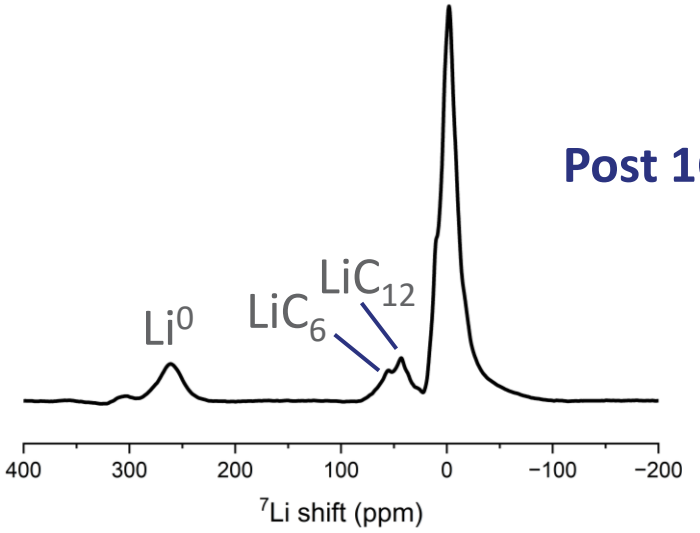


Post formation

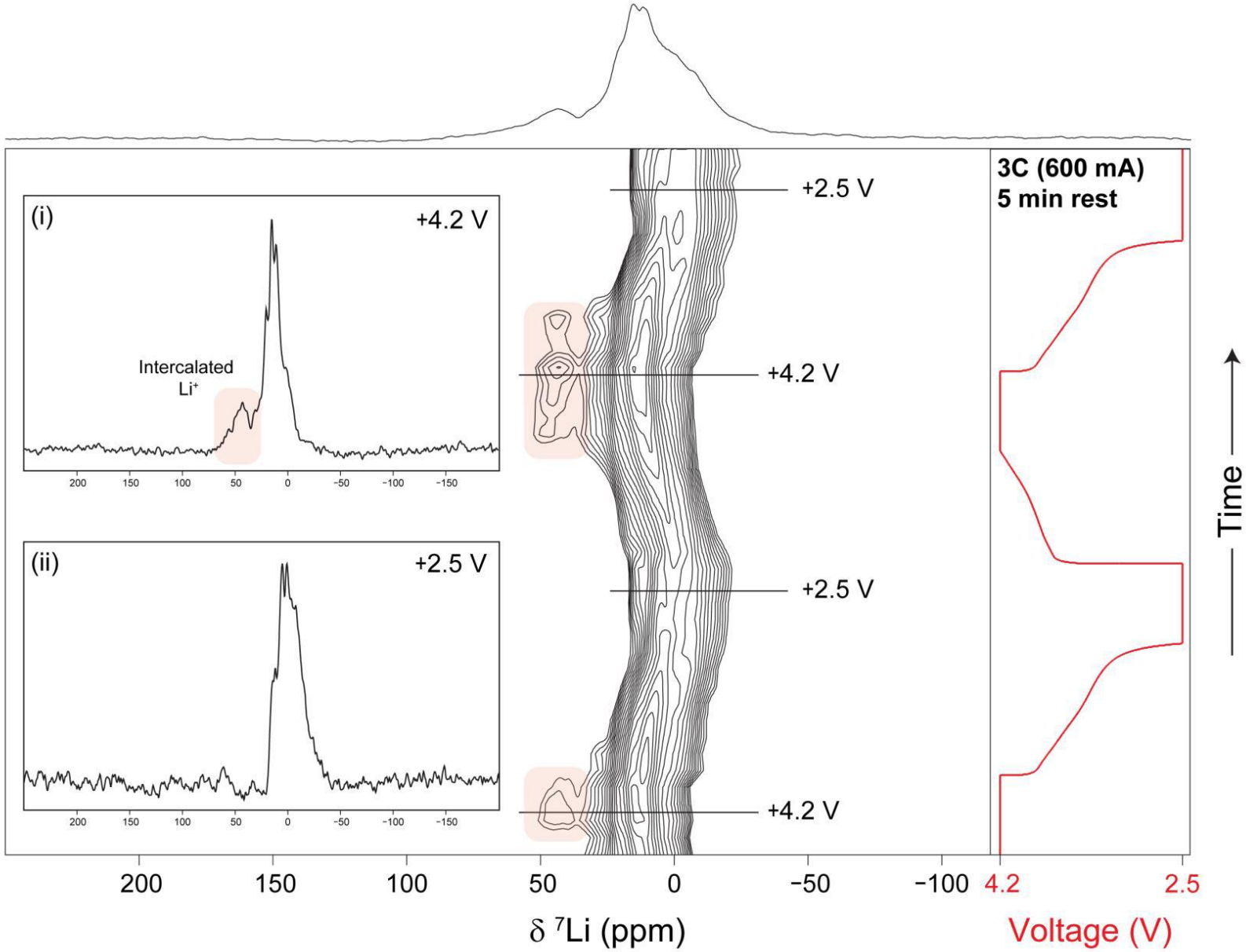


SEI and solvents

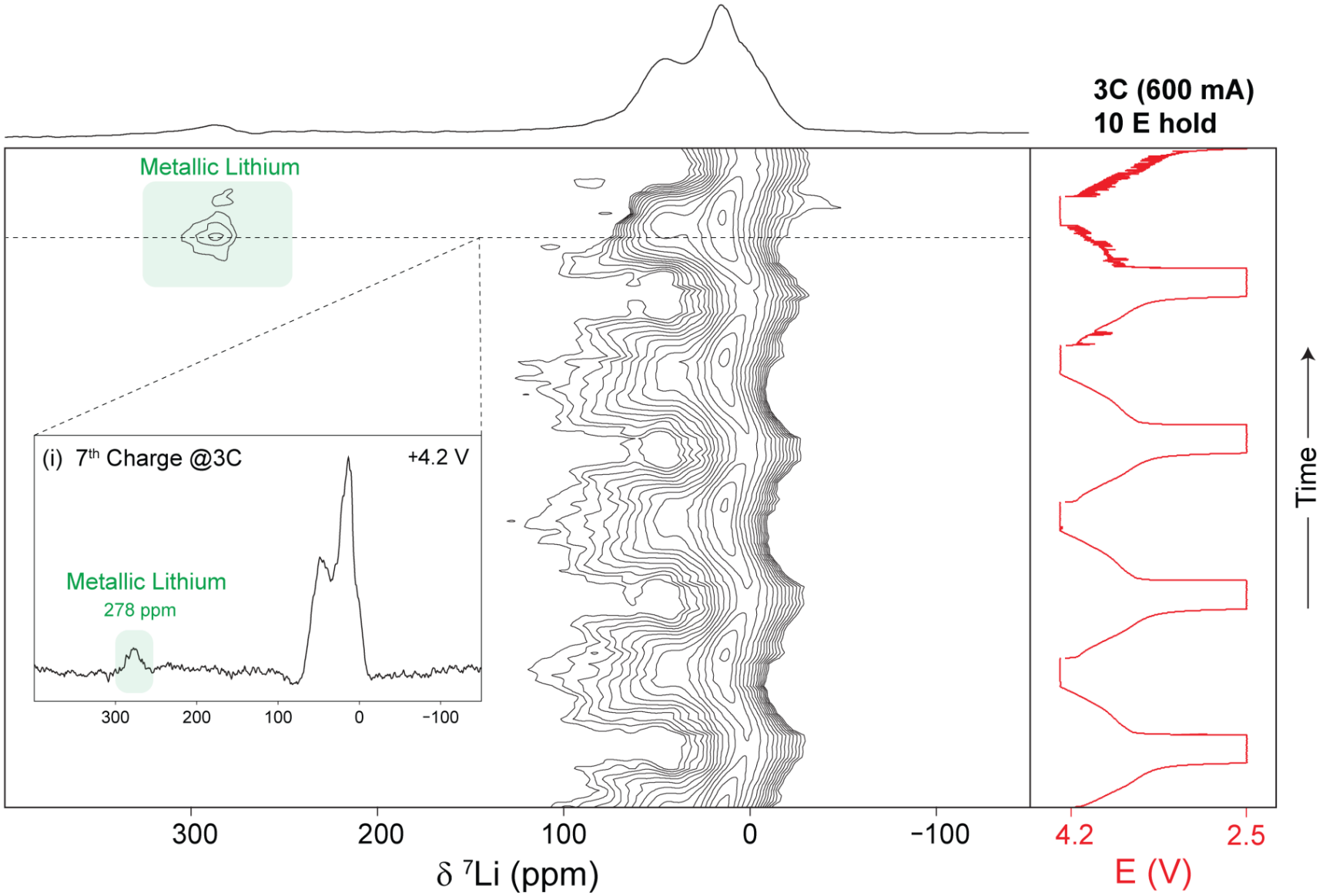
Post 1C-1C 200 cycles



OPERANDO ^{7}LI-NMR – CYCLE 1

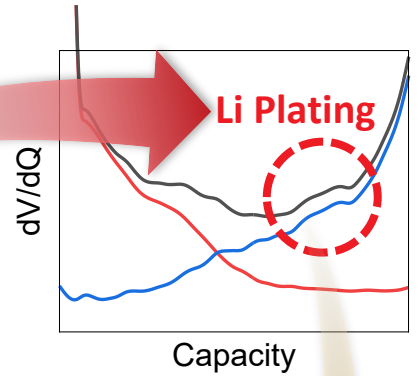


OPERANDO 7LI-NMR – CYCLE 3-7 @ 3C

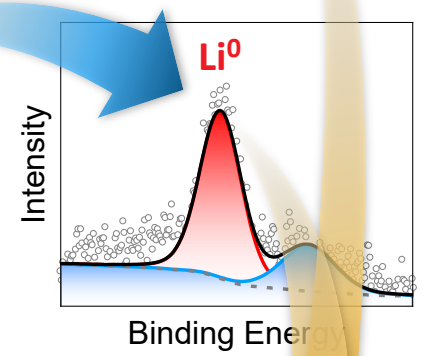


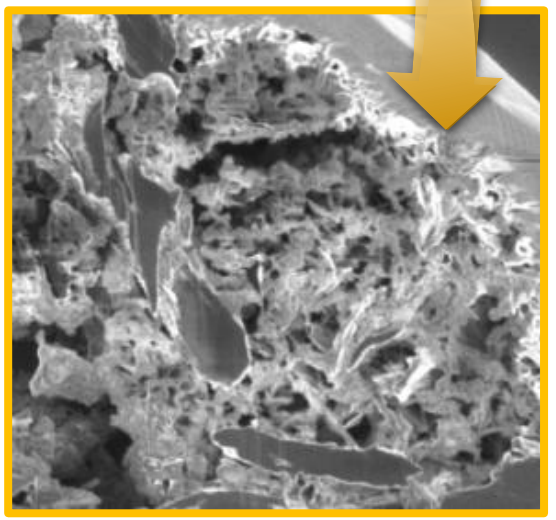
CONCLUSION

Li-plating on anode → **Li-plating identification methods** → **3E cell analysis (non-destructive)**



Li-plating identification methods → **Advanced characterisation (destructive + in situ): (XPS, HAXPES, SEM/SIMS)**

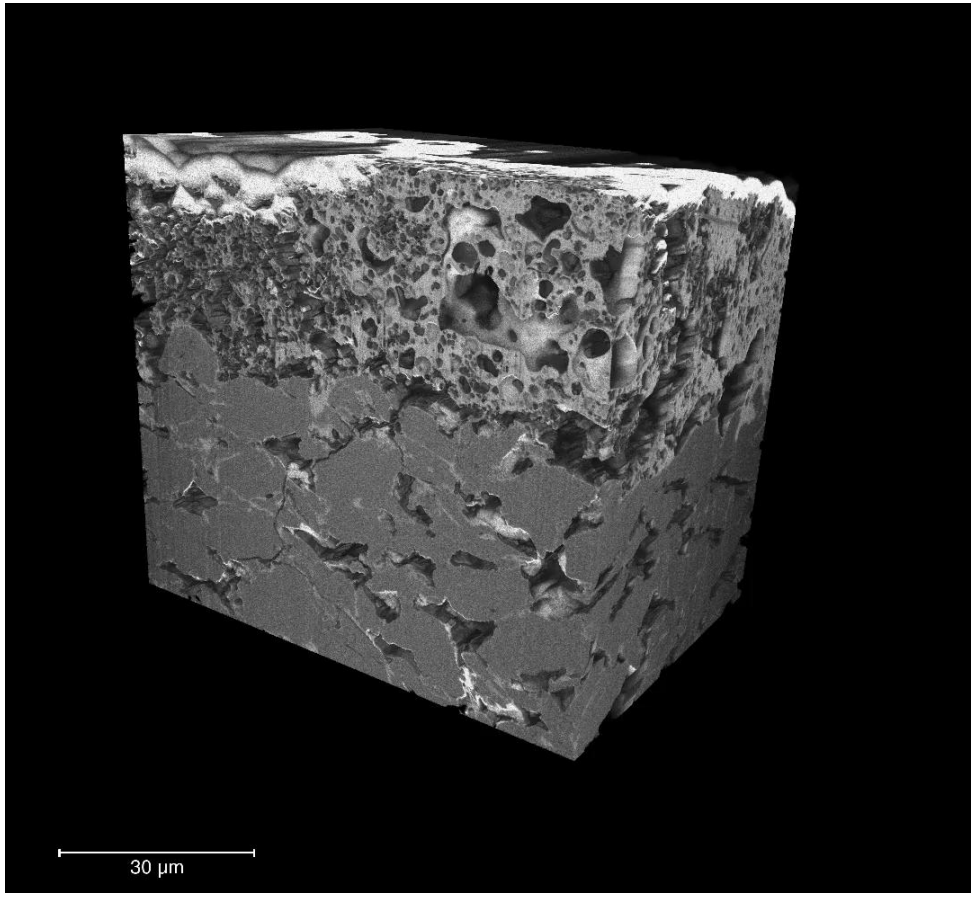


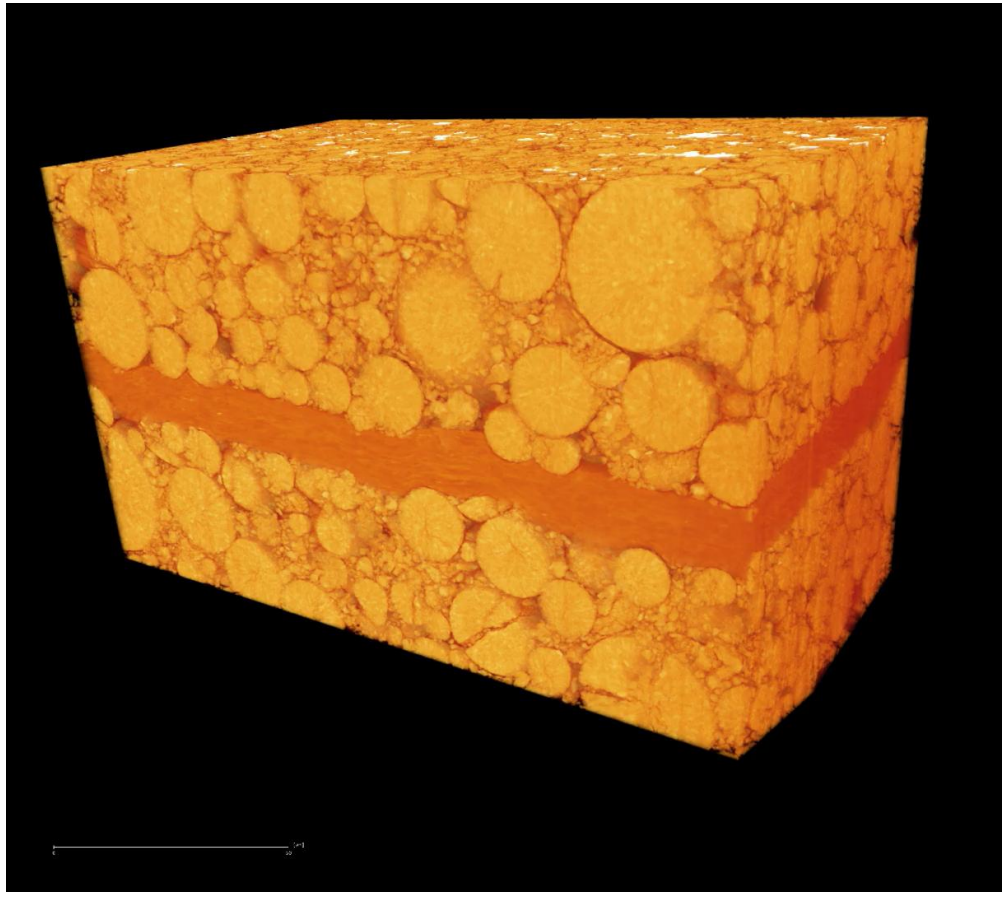


Key Impacts

- 3E understanding could be **translated to 2E profiles for commercial cells – critical for applicability in real world**
- **Monitoring DVA profile** changes can detect early Li-plating, which is important to **inform charging regime** conditions, ultimately could better inform **BMS responses**.
- Li-plating identification holds considerable promise for integration into future **onboard BMS with multi-signal detection**.

3D Scanning | Anode & Cathode | -20 °C at C/3

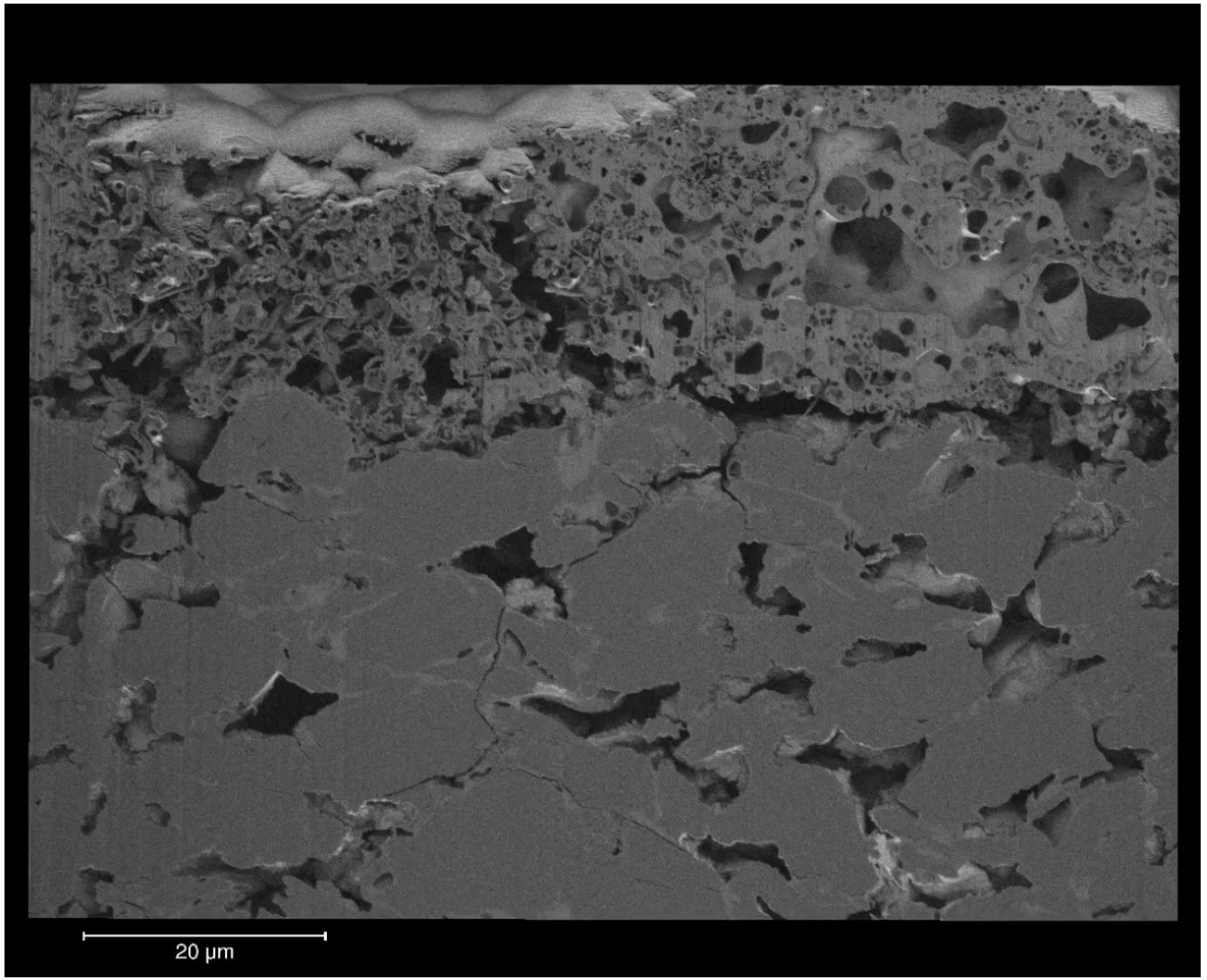




The 3D tomography **“slice-and-view”** technique uses a DualBeam PFIB-SEM, which combines an **SEM for imaging** with a **PFIB for milling**. The PFIB enables high throughput for large-volume reconstruction – useful for visualization of Li-plating.

Slice & View | Anode | -20 °C at C/3

Dendrite growth becomes evident

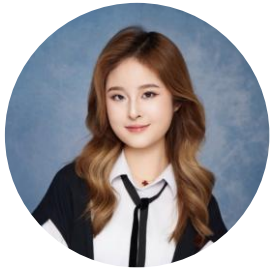


Heterogeneous nature of lithium plating evident on the graphite surface

SPECIAL THANKS







Veronika Majherova **Yazmin Monaghan** **Andrei-Mircea Top** **Aohan Zhang** **Tianxing Shi** **James Gott** **Melanie Loveridge**

THE FARADAY INSTITUTION
SCIENCE OF BATTERY SAFETY

SafeBatt

- **Julia Weaving @ UCL**
- **Rhodri Jervis @ UCL**
- **Xiaoxia Guo @ UCL**
- **Paul Shearing @ Oxford**

WMG
THE UNIVERSITY OF WARWICK

UCL

Thank you