



Quantification and comparison of lithium-ion battery fire hazards for emergency responders:

Recommendations for risk management and response

SARET Research Program

Publication No.: SRP-P1-002

Document ID: D26/65845

Issued: 30 April 2026

Quantification and comparison of lithium-ion battery fire hazards for emergency responders:
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Version	Date issued	Description
1.0	30 April 2026	Initial report approved for NSW Reconstruction Authority submission

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*ANSI/NISO Z39.104-2022, CRediT, Contributor Roles Taxonomy



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Funded under the NSW Government.

Although Funding for this Project has been provided by the NSW Government, the material contained herein does not necessarily represent the views of the NSW Government.



Publisher:

State of New South Wales and Fire and Rescue NSW

Date: 30th April 2026

Citation: Fire and Rescue NSW (2026) 'Quantification and comparison of lithium-ion battery fire hazards for emergency responders: Recommendations for risk management and response', Sydney, Australia: Fire and Rescue NSW

Cover: Fire and Rescue NSW

Acknowledgements

Fire and Rescue NSW would like to acknowledge the Safety of Alternative and Renewable Energy Technologies (SARET) Research Program team who contributed their time and expertise to the development of this research report.

The SARET Research Program team would like to acknowledge the contributions of our collaborative partners.

Acknowledgement is also given to the NSW Government for funding this project.

Executive Summary

Fire and Rescue New South Wales (FRNSW) conducts research that informs firefighter, community, and built environment fire and life safety. The battery technologies used in portable electronic devices such as e-cigarettes and vapes, mobile phones, tablets, laptops, and power tools, are now being used in increasingly larger applications, including electric scooters, electric bikes, electric vehicles, and battery energy storage systems. Lithium-ion batteries (LiBs) have usurped other battery chemistries due to their higher-energy density, high performance, low charge times, long cycle-life, and falling manufacturing costs, however they are also prone to catastrophic failure. These failures can result from internal faults and ageing, or from thermal, mechanical, or electrical abuse. For systems that are used in disaster prone areas, this can include mechanisms such as heat, ember or flame impingement from bushfire, and electrical or mechanical failure due to storms, flooding, or earthquakes.

For fire and emergency services responding to incidents related to LiBs, there are challenges related to fire intensity, exposure to toxic gases and effluents, deflagration risks in confined environments, stranded electrical energy hazards, protracted extinguishment and cooling, risks of secondary ignitions, rendering safe, containment of contaminated fire water, and the handling, transportation and disposal of affected batteries and battery systems. Although extremely beneficial to modern society, LiB's present a number of hazards when improperly managed and handled, which can cause property damage, injury or death. The proliferation of this technology through everyday devices also increases challenges regarding their safety, due to the large number of LiB's in circulation, rapid developments in technology and difficulties in educating the public regarding their correct use, storage and disposal.

The research activities were conducted in three parts. Part A initial testing aimed to answer Activity 1 by characterising single cell LiBs and exploring the ways that LiBs fail under various conditions and found that thermal runaway (TR) in LiBs present significant flammability, explosion, and human health hazards. The variability and characteristics of TR are highly dependent on the battery characteristics however due to the high variability of the TR, they conversely cannot be used as a predictor of the hazard profile and severity. The learnings from the initial testing were used to inform Part B and C. Activity 2 was addressed as two separate elements. Part B testing evaluated new and existing extinguishing methods on LiBs representative of an e-bike and found that water was the most effective extinguishment agent for cooling a LiB in TR. Part C testing involved a preliminary exploration into the effectiveness of the current decontamination and laundering procedures of FRNSW structural firefighting PPC, to assess if current practices are effective at decreasing contamination from LiB vapour exposure and found that on-site wet decontamination combined with the FRNSW laundering system was effective at reducing contaminants on testing structural firefighting PPC swatches. Activity 3 was addressed by a comprehensive review of completed experimentation outcomes and learnings to providing recommendations for LiB specific procedures, guidelines, and training materials. These recommendations, when implemented, have significant potential to mitigate the risk of LiB fires and emergencies to the community and built environment.

From this body of work, the following recommendations are provided:

Recommendation 1 – Emergency responders are recommended to approach all battery incidents as worst-case scenarios in the first instance.

Recommendation 2 – Atmospheric monitoring by emergency services for hazardous battery gas and vapour is recommended throughout the entire duration of an incident.

Recommendation 3 – It is recommended that conservative exclusion zones are set in place during incident management.

Recommendation 4 – Liquid extinguishment agents and mediums are more effective than fire blankets at cooling batteries and reducing the duration of thermal runaway.

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Recommendation 5 – Immersion is currently the most definitive method for thermal management of a battery fire. The application of liquid agents can have some stabilising effects that can create safer handling conditions. Thermal runaway may start, continue, and propagate while a battery is immersed in water.

Recommendation 6 – Immersion of a battery into water is effective at managing a battery fire. It is recommended that the battery is monitored after water immersion as cooling and extinguishment is not immediate and batteries may continue to off-gas and heat after immersion.

Recommendation 7 – Battery manufacturers are recommended to consider battery casing materials in designing for safety.

Recommendation 8 – It is recommended that emergency responders utilise self-contained breathing apparatus and appropriate personal protective clothing and equipment for the duration of the battery incident, including during post-incident battery handling and management.

Recommendation 9 – It is recommended that any personal protective clothing exposed to battery off-gassing is appropriately decontaminated and laundered using industrial procedures.

Recommendation 10 – It is recommended that any water run-off from battery incidents is appropriately captured, treated, and disposed of to mitigate environmental contamination and risk.

Recommendation 11 – Community education should consider the heightened risk of attempting to intervene and/or extinguish battery fires.

Recommendation 12 – Extinguishment agents or tools that require coming into proximity with a battery fire, such as portable fire extinguishers and fire blankets, should not be used without adequate personal protection.

Recommendation 13 – It is recommended that batteries are stored and charged on solid, non-flammable surfaces, away from other flammable items, and in a well-ventilated area.

Recommendation 14 – It is recommended that decontamination of surfaces and areas after a battery fire is considered at incident handover, prior to re-occupation.

The implementation of these recommendations can be used to meet project objectives to “Address gaps in the emergency services sector’s knowledge and understanding of LiB fires” and “Mitigate the risk of LiB fires to community and infrastructure in disaster/emergencies through research findings”.

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Acronyms

Acronym	Definition
BESS	Battery energy storage system
BMS	Battery management system
CCTV	Closed-circuit television
COLA	Covered outdoor learning area
CV	Coefficient variant
CV-AAS	Cold vapour atomic adsorption spectrophotometry
DAQ	Data acquisition system
EBCT	Empty bed contact time
EV	Electric vehicle
FRNSW	Fire and Rescue New South Wales
FPS	Frames per second
FTIR	Fourier Transform infrared
HRR	Heat release rate
ICP-OES	Inductively coupled plasma optical emission spectrophotometry
IQR	Inter-quartile range
ISE	Ion selective electrode
LFP	Lithium iron phosphate
LiB	Lithium-ion battery
NA	Not applicable
NFPA	National Fire Protection Association
NI	National Instruments
NMC	Nickel manganese cobalt
NSW RA	New South Wales Reconstruction Authority
OCC	Oxygen consumption calorimetry
OH	Occupational hygiene
PAH	Polyaromatic hydrocarbon
PPC	Personal protective clothing
PPE	Personal protective equipment
PQL	Practical quantification limit
PVC	Polyvinyl chloride
SARET	Safety of Alternative and Renewable Energy Technologies
SCBA	Self-contained breathing apparatus
SoC	State of charge
SOG	Standard operating guideline
SVOC	Semi-volatile organic compound
TC	Thermocouple
TIC	Thermal imaging camera
TR	Thermal runaway
VFD	Variable frequency drive

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Abbreviation/Symbol	Unit
~	approximate
cm	centimetre(s)
R ²	coefficient of determination
F-distribution	continuous probability distribution
°C	degrees Celsius
Δ	delta (difference)
F ⁻	fluoride ion
<i>g</i>	Hedges' <i>g</i>
<i>J</i>	Hedges' <i>g</i> correction factor
Hz	hertz
pH	hydrogen ion activity scale (acid-base scale)
kPa	kilopascal
kWh	kilowatt hour(s)
kW	kilowatt(s)
L	litre(s)
$\bar{x}$	mean
m	metre(s)
μg	microgram(s)
mAh	milliamp hour(s)
mg	milligram(s)
mm	millimetre(s)
min	minute(s)
nm	nanometre(s)
p-value	null-hypothesis significant test value
[number]s[number]p	number of cells in series and number of cells in parallel
Ω	Ohm
%	per cent
p	pixels
±	plus-minus
rpm	revolutions per minute
sec	second(s)
σ	standard deviation
<i>t</i>	time
v	volt(s)
v/v	volume per volume
Wh	watt hour(s)
W	watt(s)
w/v	weight per volume

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1 Introduction

In order to achieve net zero emissions by 2050 the Australian government committed \$20 billion to support alternative and renewable energy technologies. The accelerated push to adopt renewable energy technologies such as solar energy generation and associated residential and grid-scale battery energy storage systems, electric vehicles (EVs) and associated infrastructure has led to a proliferation of lithium-ion batteries (LiBs) within the global battery market. In Australia, whilst demand for other battery types will remain steady or decline, LiB sales are expected to increase six-fold to over 600,000 tonnes per year by 2050 (Battery Stewardship Council, 2020). LiBs have become the dominant energy storage technology across the consumer, residential, commercial, industrial, and transport sectors. The technologies used in portable electronic devices such as e-cigarettes and vapes, mobile phones, tablets, laptops, and power tools, are now being used in increasingly larger applications, including e-micromobility devices (such as electric scooters (e-scooters) and electric bikes (e-bikes)), EVs, and battery energy storage systems (BESS). LiBs have usurped other battery chemistries due to their higher-energy density, high performance, low charge times, long cycle-life, and falling manufacturing costs (Li *et al.*, 2017; Miao *et al.*, 2019; Ghafari *et al.*, 2023). LiBs are the most widely used technology in these alternative energy systems and are associated with risks related to thermal runaway (TR), the violent release of stored energy resulting in fire and explosions. These failures can result from internal faults and ageing, or from thermal, mechanical, or electrical abuse. For systems that are used in disaster prone areas, this can include mechanisms such as heat, ember or flame impingement from bushfire, and electrical or mechanical failure due to storms, floods, or earthquakes.

For fire and emergency services responding to incidents related to LiBs, there are challenges related to fire intensity, exposure to toxic gases and effluents, deflagration risks in confined environments, stranded electrical energy hazards, protracted extinguishment and cooling, risks of secondary ignitions, rendering safe, containment of contaminated fire water, and the handling, transportation and disposal of affected batteries and battery systems. Although extremely beneficial to modern society, LiB's present a number of hazards when improperly managed and handled, which can cause property damage, injury or death. The proliferation of this technology through everyday devices also increases safety challenges, due to the large number of LiB's in circulation, rapid developments in technology and difficulties in educating the public regarding their correct use, storage and disposal. This presents a unique challenge for fire services, with the growth in LiB technology use seeing a comparable increase in reported LiB-related fires and casualties. While there is a large volume of research being conducted world-wide to better understand the mechanisms and improve the technology, there is very little public information available to regulatory bodies and responding organisations on how best to mitigate these hazards.

Fire and Rescue New South Wales (FRNSW) conducts research that informs firefighter, community, and built environment fire and life safety. In the 2022 - 2023 period, FRNSW recorded a 66% increase in LiB-related fires attended, with LiB incidents four times more likely to result in injuries than all other fires and explosion incidents attended (FRNSW, 2024). In the period from January – July 2024, FRNSW attended 217 incidents related to LiB fires, rising from 1 in every 76 fires during 2023 to 1 in every 40 fires in 2024. Tragically, FRNSW also recorded the first deaths in a fire caused by a LiB. FRNSW utilises research outcomes to inform operational doctrine and training to prepare firefighters for new and emerging risks in the community, to inform fire safety policy, and to inform community risk reduction activities.

1.1 Safety of alternative and renewable energy technologies

FRNSW is conducting a collaborative research program, which involves full scale fire testing to address the gaps in knowledge. The Safety of Alternative and Renewable Energy Technologies (SARET) Research Program is a suite of research and experimental projects designed to address priority research questions around the management and mitigation of hazards associated with LiB incidents. SARET is divided into four priority project themes, each addressing a specific aspect of LiB safety and fire and emergency service response:

Project 1: Fire service response to lithium-ion battery fires

Project 1 assesses the effectiveness of new and existing agents, products and delivery systems for use in fires involving lithium-ion cells, batteries and battery systems in comparison with water. It will also provide guidance on the efficacy of current personal protective equipment (PPE) and clothing (PPC) in protecting firefighters from exposures to gases, vapours, liquid electrolytes, chemical residue and electrical energy present in LiB-related incidents.

Project 2: End-of-life lithium-ion battery hazard management

Project 2 informs the management of hazards related to battery recycling, and the handling, storage and transportation of damaged and fire-affected LiBs and battery systems to minimise the risks of exposure and secondary ignitions to first and secondary responders.

Project 3: Electric vehicle fires in structures

Project 3 investigates the unique challenges of EV fires in parking garages and car parks, with aims to quantify the differences between EVs and conventional vehicles with respect to fire severity and propagation, building performance, detection and suppression requirements, air handling and ventilation, access, and charging effects.

Project 4: Fire propagation in stationary energy storage systems

Project 4 aims to provide a better understanding of the fire propagation behaviours of various BESS to inform guidance on separation, detection and protection requirements for new installations, from residential size to commercial and grid scale applications.

To foster and strengthen research collaborations, FRNSW has partnered with industry, government, research institutions, and other fire services to support and partner on this vital program. To this end, FRNSW have received funding from the NSW Reconstruction Authority (NSW RA) Research and Knowledge Funding stream to conduct priority research activities that build knowledge about disaster risk and develop strategies to reduce impact on communities and critical infrastructure; effectively integrating disaster risk knowledge in future policies, programs, and enable informed investment decisions.

1.2 NSW reconstruction authority natural hazards research and knowledge fund

The NSW Reconstruction Authority (NSW RA) was established to proactively reduce the impact of future disasters across NSW and to help communities recover from them faster. NSW RA manages grants and funding programs such as the Natural Hazards Research and Knowledge Fund that support communities in building disaster resilience and reduce the risk of future hazards. Through this program, FRNSW was awarded funding to conduct research into fire service response to LiBs.

The funding was allocated to FRNSW SARET Project 1 research activities that could address the following recommendations from the Royal Commission into National Natural Disaster Arrangements (2020):

- Recommendation 6.1: Assessment of the capacity and capability of fire and emergency services in light of current and future natural disaster risk.
- Recommendation 9.4: Collective awareness and mitigation of risks to critical infrastructure.
- Recommendation 10.1: Disaster education for individuals and communities.
- Recommendation 19.4: National Construction Code.

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- Recommendation 20.1: Debris clean-up arrangements.

To address these recommendations, two key project objectives were identified:

1. Address gaps in the emergency services sector's knowledge and understanding of LiB fires, with the research finding used to:
 - a. Inform operational response procedures for emergency services (including response agencies other than FRNSW);
 - b. Assist in determining necessary equipment and safety requirements for emergency services.
2. Mitigate the risk of LiB fires to community and infrastructure in disaster/emergencies through research findings:
 - a. Informing any necessary legislation changes;
 - b. Informing the development of building codes and standards.

To achieve these objectives FRNSW proposed to conduct the following activities:

1. Quantify and compare the hazards associated with LiB fires with respect to cell chemistry, format, configuration, state of charge.
2. Test the efficacy and safety of new and existing extinguishing agents, methods, tools, and equipment on LiB-related fires, including safety of personal protective clothing and equipment.
3. Provide recommendation for updates to operational procedures and guidelines and materials for training of first responders in managing LiB-related fires.

The research activities were conducted in three parts. Part A initial testing aimed to address activity 1 by characterising single cell LiBs and exploring the ways that LiBs fail under various conditions. The learnings from the initial testing were used to inform Part B and C testing. Activity 2 was addressed as two separate elements. Part B testing evaluated new and existing extinguishing methods on LiBs representative of an e-bike and Part C testing involved a preliminary exploration into the effectiveness of the current decontamination and laundering procedures of FRNSW structural firefighting PPC, to assess if current practices are effective at decreasing contamination from LiB vapour exposure. Activity 3 was addressed by a comprehensive review of completed experimentation outcomes and learnings to provide recommendations for LiB specific procedures, guidelines, and training materials.

The following report describes these research and testing activities conducted by FRNSW to achieve the objectives outlined to NSW RA, organised per Parts A, B, and C. Activity 3 is addressed within each part.

2 Scope and limitations

The project is intended to deliver a measurable risk reduction benefit for NSW by contributing to emergency preparedness and safety in disasters and emergencies where renewable technologies are involved, and the inclusion of safety measures to mitigate the risks in related buildings and infrastructure. In turn, providing greater confidence in the transition to green energy sources for the state. The project was a fix-term research activity to deliver specific outcomes and activities, and as such, was limited in its scope and application.

2.1 In scope

The following items were within the scope of the project reported herein:

- Summary of critical review of existing research and consolidation of evidence regarding fire safety of LiBs¹
- Development of SARET library for external stakeholders to access and review research results
- Testing of commercially available LiB cells and modules
- Measurement and recording of LiBs in TR during experimentation

2.2 Out of scope

The following items were determined to be outside the scope of the project reported herein:

- Development of emergency response procedures for emergency services
- Position statements, technical advisory, and other consultation documentation advising building fire safety
- Proposals for change to building codes and standards
- Assessment of toxicology and ecotoxicology of LiBs in TR

2.3 Limitations and constraints

Due to funding and contractual arrangements with NSW RA, the activities conducted under this study were constrained by a number of factors. Primarily, this project was a fixed-term, fixed-budget study commissioned to investigate the above outcomes and as such was designed solely to meet the conditions of the funding award. Due to the limited term of the funding award, an extensive testing and research matrix was not achievable within the available timeframe, mainly due to the time involved in undertaking the necessary preparations for testing. Therefore, the results and outcomes obtained may be limited by the number of test repeats and variables explored.

While all reasonable efforts were made to procure test samples of analogous composition and manufacture, natural variability may be present within the battery batches purchased and received. Similarly, all reasonable efforts were made to ensure the reliability and accuracy of testing instrumentation and equipment used. Where limitations were identified within each testing series, these are disclosed within the methodologies of each part.

¹ FRNSW previously published a literature review titled “Management of Lithium-ion Battery Safety Risks” as a part of this project. Further information regarding the design, construction, failure pathways, and associated risks and hazards can be found in the literature review and will not be reproduced within this report. A copy of the publication can be found on the FRNSW SARET webpage at fire.nsw.gov.au/saret

3 Part A: Quantification and comparison of the hazards associated with lithium-ion battery fires

3.1 Background

The behaviour of a LiB's TR varies based on chemistry, format, state of charge (SoC), and the method of abuse (Fire and Rescue NSW, 2025). The composition of the battery's cathode can dictate to a large degree its thermal stability and respective safety (Jiang and Dahn, 2004; Ghiji *et al.*, 2020). LiBs with nickel manganese cobalt (NMC) chemistries are generally higher in energy density but have been found to have lower thermal stability (Yuan *et al.*, 2024). Conversely, lithium iron phosphate (LFP) cell chemistries are less energy dense but are more thermally stable (Golubkov *et al.*, 2015; Yuan *et al.*, 2024). Cell chemistry also influences TR off gassing; with Bugryniec *et al.* (2024) reporting that cells with a higher nickel content produce larger volumes of gas and while LFP cells produce less gas by volume, they were significantly more toxic than NMC cells. Additionally, SoC has been found to impact fire and explosion activity as well as vapour production (Larsson *et al.*, 2014; Bravo Diaz *et al.*, 2020; Wang *et al.*, 2022, 2023). Golubkov *et al.* (2015) found that as SoC increased, the severity of the TR event increased. For flaming events, TR in cells at higher SoC have reported a higher heat release rate (HRR) and increased vapour production, while at a lower SoC, the vapour produced was less likely to ignite into flaming TR (M. Chen *et al.*, 2018; Christensen *et al.*, 2021; Zhang, Liu and Wang, 2021; Wang *et al.*, 2023). Researchers have theorised that higher SoC increases the kinetic energy which leads for a faster transition from an oxygen-rich to an oxygen-lean environment, increasing H₂ and CO production, and therefore a more flammable environment (Golubkov *et al.*, 2015). Willstrand *et al.* (2023) also found that the faster the transition from an oxygen-rich to an oxygen-lean environment, the more severe the potential explosive event. Finally, LiB TR vapour production is a hazard in terms of its toxicity and as a fuel (Golubkov *et al.*, 2015; Willstrand, Pushp, Andersson, *et al.*, 2023). The way in which TR is induced can also influence the nature of the reaction and the resultant hazards.

The aim of this work was to measure differences in TR when comparing a battery's chemistry, SoC, format, and the abuse method. There are three main LiB cell formats that are currently widely produced: cylindrical, pouch and prismatic. The two most produced LiB cell chemistries are NMC and LFP. These cell types were selected for investigation within this body of work due to their prevalence within the consumer market.

3.2 Methodology

3.2.1 Test parameters

Nail penetration and external heating were selected as abuse methods to prioritise reproducibility and control the energy state at failure. External short-circuit was excluded as it has less predictable failures (Z. Chen *et al.*, 2018) and overcharging introduces variation in the total system energy (Wei *et al.*, 2022). A minimum of three repeat tests were conducted for each test scenario. All tests were conducted within a custom-built LiB testing chamber and the resultant TR behaviour was recorded through videography, gas analysis, temperature monitoring, and cell voltage monitoring. Table 1 and Table 2 show the number of tests that were conducted for each abuse method. A minimum of three repeat tests were conducted for each test scenario.

Table 1. Test matrix for overheating abuse single-cell LiB tests, with number of tests conducted per scenario.
Total tests n = 24.

Chemistry		NMC		LFP	
SoC (%)		30	100	30	100
Format	Cylindrical	3	3	3	3
	Pouch	3	3	3	3

Table 2. Test matrix for nail penetration abuse single-cell LiB tests, with number of tests conducted per scenario.
Total tests n = 24.

Chemistry		NMC		LFP	
SoC (%)		30	100	30	100
Format	Cylindrical	3	3	3	3
	Pouch	3	3	3	3

3.2.2 Test enclosure

A 500 kW sensible enthalpy calorimetry test chamber was constructed to enable measurement of heat release from LiB packs undergoing TR. Standard oxygen consumption calorimetry (OCC) was not selected for these experiments as previous evidence of battery testing indicates that OCC potentially under-estimates battery heat release due to additional chemical reactions and oxygen generation during TR (Voigt *et al.*, 2021; Willstrand, Pushp, Ingason, *et al.*, 2023), therefore this method of measurement was selected following review of literature (Fire and Rescue NSW, 2025).

The chamber was constructed of fibre-cement board, with a gap around the bottom to allow make-up air to be drawn through. Air and any combustion by-products from batteries in TR were drawn out of the top of the chamber through a stainless-steel duct. The duct included a mixing section followed by a flow straightener and a long straight segment that housed instrumentation (Section 3.2.5). The exhaust flow was controlled by a variable frequency drive (VFD) located in the control room below.

For single cell testing, an additional small plenary chamber was suspended inside the chamber for passive effluent-collection and thermal-containment. The small-scale plenary chamber measured 450 x 450 x 350 mm, with borosilicate glass front and side panels, to enable close-up video recording of the cell failure. The LiB cells were tested on a platform inside the small-scale chamber, which included cell parameter measurement instrumentation.



Figure 1. The small chamber in situ in the test chamber.

3.2.3 Test specimen preparation

New, unused LiB cells were sourced from online retailers. NMC and LFP cells of each format were selected as representatives of the most commonly available LiB types and to be as comparable as possible between each chemistry and format. The specifications of each cell are provided in Table 3.

Table 3. Single-cell test battery specifications.

	NMC		LFP	
	Cylindrical	Pouch	Cylindrical	Pouch
Voltage (v)	3.6	3.6	3.2	3.2
Capacity (mAh)	3,500	20,000	1,800	20,000
Energy (Wh)	12.5	72	5.76	64
Dimensions (W x L x D) (mm)	18 x 650	70 x 171 x 9.2	18 x 650	133 x 202 x 7.8

3.2.3.1 State of charge

An iMax B6AC V2 charger (SkyRC Technology Co. Ltd., Shenzhen, China) was used to discharge and charge cells to the desired levels based upon the outlined test matrix. Custom charging programs were written for the charger based upon the cell capacities and required SoC. All cells were discharged to 0% capacity then charged to the desired state prior to testing:

- For 100% SoC, cells were allowed to fully charge based upon the standard parameters of the charger, for the chemistry selected.
- For 30% SoC, cells were first completely discharged the lower nominal cutoff voltage of 2.0 V for LFP or 2.5 V for NMC and 30% capacity was calculated in mAh and allowed to charge to this limit specified within the charge parameters of the charger.

The cells were not conditioned or cycled otherwise.

3.2.3.2 Cylindrical cells

All NMC and LFP cylindrical cells were prepared in the same manner. A single 0.5 mm mono-core, fibreglass insulated k-type thermocouple (TC Measurement & Control Pty Ltd, Vic Australia) was attached to the centre of the cell by removing a small 5 mm x 5 mm section of the external heat-shrink wrap of the cells and attaching the thermocouple to the exposed cell casing using thermally conductive adhesive (MG Chemicals, Ontario, Canada). The thermocouple was then secured firmly with polyimide tape wrapped around the cell. Next, 100 mm long wires were spot-welded to the positive and negative terminals of the cell using a GLITTER 801H battery spot welder (Foshan Huanteng Technology Co. Ltd, Guangdong, China) and bullet connectors were crimped to the opposite end of the wires for connecting to the test stand. Once these components were attached to the cell, a final layer of polyimide tape was applied across the entire cell to ensure that all components remained in place during testing.

3.2.3.3 Pouch cells

All NMC and LFP pouch cells were prepared in the same manner.

The cell surface was covered with a single layer of polyimide tape. A single 0.5 mm mono-core, fibreglass insulated k-type thermocouple was attached to the centre of the cell. Next, 100 mm long wires were spot-welded to the positive and negative terminals of the cell using a GLITTER 801H battery spot welder (Foshan Huanteng Technology Co. Ltd, Guangdong, China) and bullet connectors were crimped to the opposite end of the wires for connecting to the test stand. Once these components were attached to the cell, a final layer of polyimide tape was applied across the entire cell to ensure that all components remained in place during testing.

3.2.4 Test abuse method

3.2.4.1 Overheating

The aim of this test scenario was to induce TR in a single LiB cell by external thermal abuse. To avoid creating any focused areas of heat transfer and evenly heat the entirety of the cell contents a 28-gauge nichrome wire (80% nickel, 20% chromium; Suzhou Nickel Alloy Co. Ltd., China) was wrapped around the cell.

For the cylindrical cells, nichrome wire was wrapped directly around the cells with approximately 2 - 3 mm of spacing. It was supplied 24 V constant voltage to achieve the heating rate. Polyimide tape was used to secure the nichrome wire across the surface of the cell to help prevent a short circuit and ensure the length of the

heating element had constant contact with the cell surface. Cells were secured to stainless-steel rings fitted to hold 18650 cells horizontally in-place during testing and using security wire to prevent ejection and movement during testing. An example of a prepared NMC and LFP cell is shown in Figure 2a and 2b. To initiate external thermal abuse, approximately 38.5 W was applied to the cell using the power source, resulting in 7 W/inch² of heating across the surface area of the test cell.

For pouch cells, nichrome wire length varied based on the size differences between cell chemistry. Methodology was standardised to provide approximately 4 W/inch² of heating to each cell, with voltage being altered to provide this desired outcome. Nichrome wire was run in 15 cm lengths from vertically along the cell. A 10 mm gap was left between each length of wire, with a short excess allowed for connecting to a power supply. Polyimide tape was used to secure the nichrome wire across the surface of the cell to help prevent a short circuit and ensure the length of the heating element had constant contact with the cell surface. Short wires were attached to the positive and negative terminals using alligator clips during each test to measure voltage. Cells were secured to stainless-steel 'o' rings using security wire to prevent ejection and movement during testing. An example of a prepared NMC and LFP cell is shown in Figure 2c and 2d. At the start of each test, a 60 s baseline was run before initiating the thermal abuse to allow for a baseline temperature, mass and gas readings to be gathered for each test. Cell heating was initiated via the NI-DAQ system following the baseline period, and continued for 30 mins, or until cell failure (whichever occurred first).

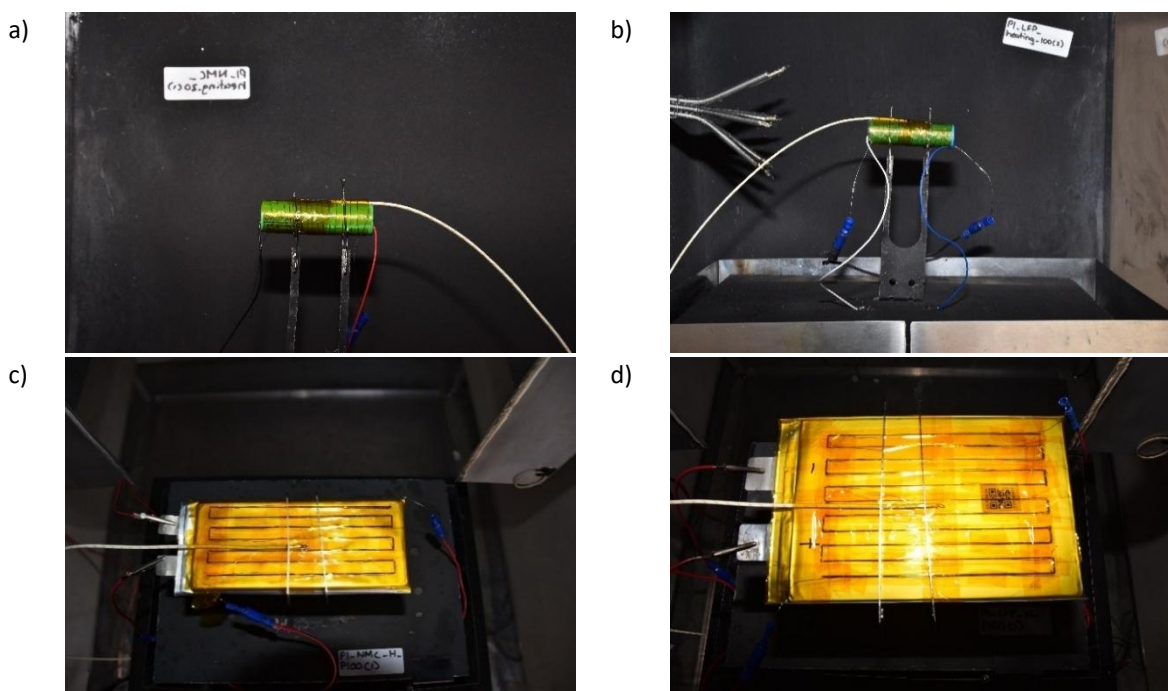


Figure 2. Example images of single-cell testing set-up prior to battery abuse for (a) NMC cylindrical cell (b) LFP cylindrical cell (c) NMC pouch cell and (d) LFP pouch cell prepared for overheating test scenario.

3.2.4.2 Nail penetration

The aim of this test scenario was to induce TR in a single LiB cell by external mechanical abuse. Nail penetration was achieved using a custom-built rig designed to drive a pre-sharpened stainless-steel nail vertically at a rate of 10 mm/min.

For cylindrical cells, a test stand was used with stainless-steel 'o' rings fitted to hold 18650 cells horizontally in-place during testing. To ensure cell penetration occurred as soon as the test was initiated, the nail was advanced, perpendicular to the cell, until the nail was touching the cell prior to test start. To initiate mechanical abuse, the

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nail was advanced for 30 secs (or until cell failure), driving the nail approximately 5 mm vertically into the side of the cell. The cell was then monitored for 30 mins or until TR. If TR occurred, monitoring was continued until the failure event had ceased and temperature was decreasing. An example of a prepared NMC and LFP cell can be seen in Figure 3a and 3b.

For pouch cells, a test stand was used with stainless-steel 'o' rings fitted to hold cells horizontally in-place during testing. To ensure cell penetration occurred as soon as the test was initiated, the nail was advanced, perpendicular to the cell, until the nail was touching the cell prior to test start. To initiate mechanical abuse, the nail was advanced for 30 secs (or until cell failure), driving the nail approximately 5 mm vertically into the side of the cell. The cell was then monitored for 30 mins or until TR. If TR occurred, monitoring was continued until the failure event had ceased and temperature was decreasing. An example of a prepared NMC and LFP cell can be seen in Figure 3c and 3d.

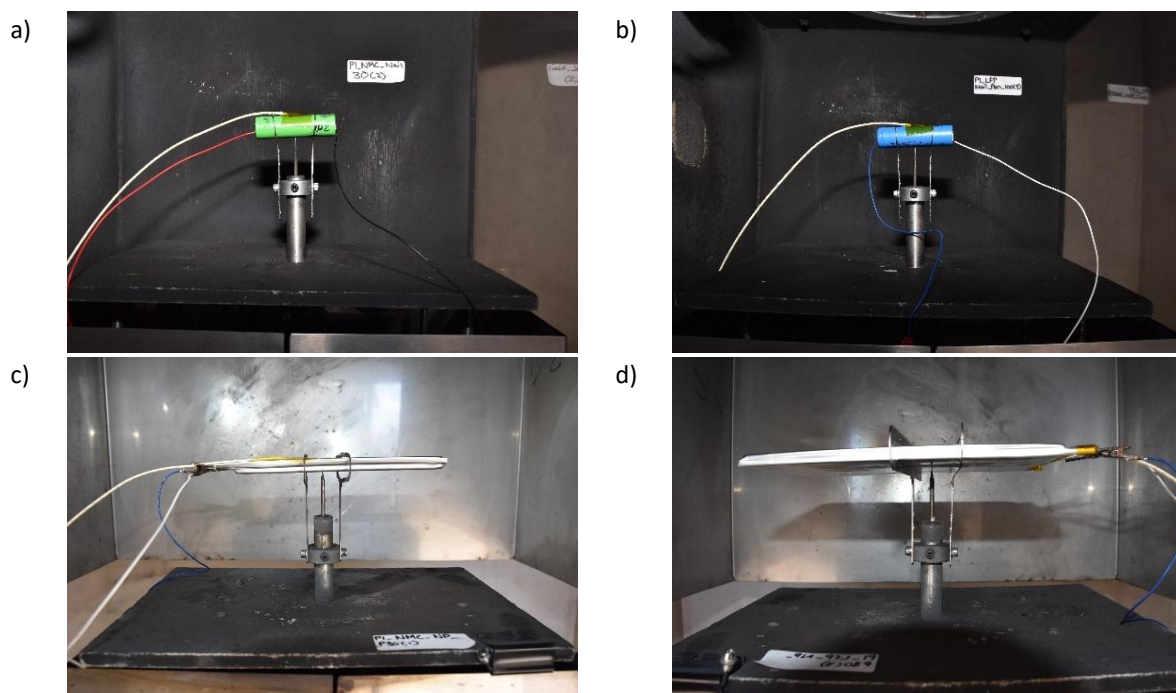


Figure 3. Example images of single-cell testing set-up prior to battery abuse (a) NMC cylindrical cell (b) LFP cylindrical cell (c) NMC pouch cell and (d) LFP pouch cell prepared for nail penetration test scenario.

3.2.5 Instrumentation

Temperature, voltage, and mass loss were recorded for all test scenarios using a National Instruments (NI) data acquisition system (DAQ) (National Instruments, Austin, TX) at a frequency of 10 Hz. Two (2) portable Fourier Transform Infrared (FTIR) gas analysers (Gasmeter Technologies Oy, Vantaa, Finland) were used to analyse off gassing during testing at a rate of one sample every one second. All other test variables, including weather conditions, cell details, and other visual observations were recorded at the time of testing.

Photography and videography were also captured prior to, during, and after each test. A Nikon D5600 DSLR camera was used to capture photos of the LiBs in-situ before and after each test. After tests, additional images were taken on a copy stand to capture detailed images of the cells after failure (see Appendix A.1). During each test, action cameras (GoPro Inc., California, USA) were used to capture high fidelity video (minimum 30 FPS at 1080p) of each test. Closed circuit television (CCTV) cameras were also located within the test chamber to allow remote monitoring of live test progress. Where CCTV cameras were damaged during testing they were replaced prior to commencement of subsequent tests.

3.2.5.1 Temperature and voltage

The DAQ consisted of NI hardware (PXIe-1085 chassis, PXIe-8880 controller, PXIe-4302, PXIe-4330, and PXI-6229 modules, and TB-4302 and TB-4330 terminal blocks) and was driven by LabVIEW 2019 full development software (National Instruments, Austin, TX).

3.2.5.2 Gas analysis

A Gasmet DX4000 portable FTIR spectrometers (Gasmet Technologies Oy, Vantaa, Finland) was used to simultaneously monitor and analyse the concentrations of gases in the test within the exhaust ducting of the test chamber. Gases were sampled at 4 L/min using high-temperature stainless-steel stinger probes connected to Ankersmid APP 100 portable gas sample probes (Ankersmid Sampling, Wilrijk, Belgium) mounted on steel frames outside the test unit. The gas samples were delivered to the Gasmet Portable Sampling Systems through a 5-metre heated sample line at 180 °C. The system was controlled, and the spectral data was captured, using Calcmeter 14 standard software (Gasmet Technologies Oy, Vantaa, Finland). Additional analysis parameters are outlined in Table 4. Table 5 outlines the compounds identified and hazard type they present during a LiB TR event.

Table 4. GASMET DX4000 portable FTIR spectrometer instrument parameters.

Sample line	1 m stainless steel stinger probe and 5 m heated line
System temperature	180 °C
Sampling volume	0.4 L
Flow rate	4 L/min
Carrier gas	N ₂
Path length	2.5 m
Resolution	4 cm ⁻¹
Range	900 - 4,200 cm ⁻¹
Analysis software	Calcmeter V12.18

Table 5. FTIR identification library used during testing LiB-specific analysis and compound hazards (PubChem, 2026).

Formula	Compound	Asphyxiant	Toxicant	Flammable	Explosive Risk
CH ₃ CHO	Acetaldehyde	–	✓	✓	✓
C ₂ H ₂	Acetylene	✓	–	✓	✓
C ₆ H ₅ CHO	Benzaldehyde	–	✓	✓	✓
C ₆ H ₆	Benzene	–	✓	✓	✓
CO ₂	Carbon dioxide	✓	–	–	–
CO	Carbon monoxide	✓	✓	✓	✓
COS	Carbonyl sulphide	✓	✓	✓	✓
C ₆ H ₅ Cl	Chlorobenzene	–	✓	✓	✓
C ₅ H ₁₀ O ₃	Diethyl carbonate	–	–	✓	✓
C ₃ H ₆ O ₃	Dimethyl carbonate	–	–	✓	✓
C ₄ H ₆ O ₃	Ethyl methyl carbonate	–	–	✓	✓
C ₂ H ₄	Ethylene	✓	–	✓	✓
C ₄ H ₄ O ₃	Ethylene carbonate	–	–	✓	–
C ₆ H ₁₄	Hexane	–	✓	✓	✓
HCN	Hydrogen cyanide	✓	✓	✓	✓
HCl	Hydrogen chloride	–	✓	–	–
HF	Hydrogen fluoride	–	✓	–	–
CH ₄	Methane	✓	–	✓	✓
C ₄ H ₆ O ₃	Propylene carbonate	–	–	✓	–
C ₆ H ₆	Styrene	–	✓	✓	✓
C ₇ H ₆	Toluene	–	✓	✓	✓

3.2.6 Data cleaning and analysis

3.2.6.1 Temperature and voltage

Time to TR was defined as the point at which cell voltage decreased by more than 0.5 V based on experimentally observed data, although nominal values for observed voltage drops may vary in real world scenarios based on a range of factors. It was observed during testing that if a voltage drop of at least 0.5 V could be seen, the cell would enter thermal runaway soon after. A mean ($\bar{x}$) and standard deviation (σ) were generated for each array (the three test repeats).

Temperature values represent the peak value per test. A mean and standard deviation were generated from these peak values for each array (the three test repeats). Data was processed and analysed using RStudio (2022.07.1) with packages 'Tidyverse' and 'cowplot' (Wickham, H *et al.*, 2019; Wilke, 2025).

3.2.6.2 Gas analysis

Data was processed and analysed using RStudio (2022.07.1) with packages 'Tidyverse' and 'cowplot' (Wickham, H *et al.*, 2019; Wilke, 2025).

To understand the potential hazards associated with single cell TR events, 16 test scenarios were investigated to understand potential differences in LiBs TR behaviour based on battery chemistry, abuse method, format type, and SoC (Table 6). Three replicates of each test scenario were conducted for a total of 48 tests. To normalise variations in the duration of each test, and to nominally isolate the peak gas hazard, the ten highest concentration peaks over time were extracted from each test to a total of 30 data points per test scenario for further analysis. Each data point represents a one second point in time gas concentration from each test scenario.

Table 6. Test scenarios for FTIR compound comparison of battery chemistry, abuse method, format type, and SoC.

Scenario	Battery Chemistry	Abuse Method	Format Type	SoC	Replicates
1	LFP	Heat	Cylindrical	100%	3
2	LFP	Heat	Cylindrical	30%	3
3	LFP	Heat	Pouch	100%	3
4	LFP	Heat	Pouch	30%	3
5	LFP	Nail pen	Cylindrical	100%	3
6	LFP	Nail pen	Cylindrical	30%	3
7	LFP	Nail pen	Pouch	100%	3
8	LFP	Nail pen	Pouch	30%	3
9	NMC	Heat	Cylindrical	100%	3
10	NMC	Heat	Cylindrical	30%	3
11	NMC	Heat	Pouch	100%	3
12	NMC	Heat	Pouch	30%	3
13	NMC	Nail pen	Cylindrical	100%	3
14	NMC	Nail pen	Cylindrical	30%	3
15	NMC	Nail pen	Pouch	100%	3
16	NMC	Nail pen	Pouch	30%	3

For comparison between the test scenarios, each scenario was broken down into arrays for comparison of a single variable (either battery chemistry, abuse method, format, or SoC), while controlling the remaining variables to highlight any differences in gas emission per comparative test scenarios (Table 7).

Table 7. Test scenarios controlling for key variables.

Array No.	Test scenario comparison	Control variable 1	Control variable 2	Control variable 3
1	LFP v NMC	Heat	Cylindrical	100%
2	LFP v NMC	Heat	Cylindrical	30%
3	LFP v NMC	Heat	Pouch	100%
4	LFP v NMC	Heat	Pouch	30%
5	LFP v NMC	Nail pen	Cylindrical	100%
6	LFP v NMC	Nail pen	Cylindrical	30%
7	LFP v NMC	Nail pen	Pouch	100%
8	LFP v NMC	Nail pen	Pouch	30%
9	Nail v Heat	LFP	Cylindrical	100%
10	Nail v Heat	LFP	Cylindrical	30%
11	Nail v Heat	LFP	Pouch	100%
12	Nail v Heat	LFP	Pouch	30%
13	Nail v Heat	NMC	Cylindrical	100%
14	Nail v Heat	NMC	Cylindrical	30%
15	Nail v Heat	NMC	Pouch	100%
16	Nail v Heat	NMC	Pouch	30%
17	Pouch v Cylindrical	Heat	LFP	100%
18	Pouch v Cylindrical	Heat	LFP	30%
19	Pouch v Cylindrical	Heat	NMC	100%
20	Pouch v Cylindrical	Heat	NMC	30%
21	Pouch v Cylindrical	Nail pen	LFP	100%
22	Pouch v Cylindrical	Nail pen	LFP	30%
23	Pouch v Cylindrical	Nail pen	NMC	100%
24	Pouch v Cylindrical	Nail pen	NMC	30%
25	30% v 100%	Heat	LFP	Cylindrical
26	30% v 100%	Heat	LFP	Pouch
27	30% v 100%	Heat	NMC	Cylindrical
28	30% v 100%	Heat	NMC	Pouch
29	30% v 100%	Nail pen	LFP	Cylindrical
30	30% v 100%	Nail pen	LFP	Pouch
31	30% v 100%	Nail pen	NMC	Cylindrical
32	30% v 100%	Nail pen	NMC	Pouch

Data was interpreted using standard boxplots with a minimum (min), quartile 1 (Q1), median, quartile 3 (Q3) and maximum (max) value, and sample size (n). Values for mean and standard deviation were also calculated. Differences between the test scenarios within each array were identified if the interquartile range (IQR) of the two test scenarios did not overlap. Within the parameters of the test array, these were denoted as 'distinct' for

the purpose of quantifying and comparing gas hazards associated with LiB fires with respect to the variables. Test arrays were presented here if they were identified as distinct. Results from all arrays are available in Appendix A.3.

3.3 Results and discussion

3.3.1 Temperature and voltage

Time to TR was defined as the point at which cell voltage decreased by more than 0.5 V (Figure 5).

Peak temperature comparisons between NMC and LFP chemistries indicate that NMC cells exhibit greater thermal variability than LFP cells (Figure 4). The increased variability was pronounced, with standard deviations in NMC cells exceeding 300 °C in some cases. For example, 100% SoC cylindrical NMC cells abused via nail penetration recorded a peak temperature of 569.6 ± 381.6 °C, compared to consistently lower variability in LFP cells, with calculated standard deviation generally <30 °C. For example, a 100% SoC, cylindrical LFP cells abused via overheating recorded a peak temperature of 480.7 ± 27.3 °C. These outcomes highlighting the highly volatile thermal behaviour of LiBs with NMC chemistry.

When comparing cell format (Table 8), a strong format-dependent effect was observed for NMC cells under heating conditions, with pouch cells producing substantially higher peak temperatures than cylindrical cells (Figure 4). For example, at 30% SoC under heating, pouch NMC cells reached 671.0 ± 40.3 °C, compared to cylindrical NMC cells at 204.6 ± 19.2 °C. At 100% SoC under heating, pouch NMC cells reached 805.9 ± 48.5 °C, compared to cylindrical NMC cells at 443.2 ± 143.6 °C (Table 8). In contrast, no consistent format-dependent trend was observed for LFP cells, where peak temperatures remained comparable between formats (i.e. at 30% SoC under heating, cylindrical LFP cells recorded peak temperatures of 255.5 ± 14.5 °C in comparison to pouch LFP cells peak temperature at 268.7 ± 3.76 °C (Table 8).

For NMC cells, nail penetration resulted in an almost immediate voltage drop regardless of format or SoC, with failure typically occurring within seconds (3.43 ± 0.25 s and 4.60 ± 1.14 s for cylindrical cells at 100% and 30% SoC, respectively) (Table 8). In contrast, pouch cells showed slightly longer responses (~37 to 49 s). Time to TR was substantially longer and more variable for pouch cells under heating conditions (Table 8), where NMC pouch cells reached 2484.00 ± 1523.95 s at 30% SoC compared to 351.53 ± 22.84 s for cylindrical NMC cells. At 100% SoC, NMC pouch cells showed delayed response (693.33 ± 200.06 s) compared to NMC cylindrical cells (269.20 ± 11.97 s) (Table 8). The difference in format voltage response times may be attributed to experimental setup, as cylindrical cells were heated circumferentially, promoting more uniform heat distribution, whereas pouch cells were heated from one side only. The variability between cell format may also be affected by the different cells' heating potential and size.

In contrast, many LFP cells, particularly pouch formats, did not exhibit a voltage drop exceeding 0.5 V. Among LFP cells, only cylindrical cells subjected to heating consistently met the TR voltage drop criterion (i.e. LFP cylindrical cells at 100% SoC entered TR after 266.73 ± 3.62 s (Table 8). Notably, peak temperatures for LFP cells under nail penetration remained relatively low (<100 °C), suggesting a less severe failure mechanism compared to NMC cells. A single pouch cell subjected to nail penetration was monitored for approximately 12 hours (~43,000 secs) demonstrating that voltage-based failure can occur on significantly longer timescales in LFP cells (Table 8). However, due to project constraints, repeat tests with these timeframes could not be conducted. Therefore, subsequent tests were terminated after one hour if no measurable change was observed. The absence of a ≥ 0.5 V drop in many of the LFP cell tests does not necessarily indicate the absence of TR but rather indicates that voltage may not be a reliable standalone indicator of cell failure for this chemistry under the tested conditions. The divergence between temperature response and voltage behaviour, particularly in LFP cells, underscores the importance of multi-parameter assessment when characterising TR.

The effect of abuse method on peak temperatures was evident for LFP cells, with heating resulting in substantially higher peak temperatures than nail penetration. For example, cylindrical LFP cells at 100% SoC that were abused via overheating recorded peak temperatures of 480.7 ± 27.3 °C in comparison to the same cells abused via nail penetration recorded peak temperatures of 78.9 ± 28.0 °C (Table 8). In contrast, NMC cells demonstrated a less consistent dependence on abuse method, with, heating generally recording higher peak temperatures than nail penetration in pouch formats, i.e. pouch NMC at 100% SoC abused via overheating recorded 805.9 ± 48.5 °C peak temperatures versus the same cells abused via nail penetration recorded 567.2 ± 67.1 °C peak temperatures (Table 8). Cylindrical NMC cells exhibited more variable behaviour.

No clear state of charge effects was observed across all conditions, although NMC cells generally exhibited higher peak temperatures at 100% SoC (nail penetration abuse peak temperature of 569.6 ± 381.6 °C) compared to 30% SoC, (nail penetration abuse peak temperature of 111.5 ± 70.0 °C (Table 8). LFP cells recorded smaller differences between SoC levels.

Within test arrays, NMC cells exhibited the greatest variability between replicates, particularly for cylindrical cells at 100% SoC (Figure 4). The large standard deviations observed in several NMC conditions indicate the presence of highly energetic and irregular failure events. Most other test conditions demonstrated relatively consistent temperature behaviour, particularly for LFP cells.

Table 8. Peak temperature and time to TR $\bar{x}$ and σ for each test scenario.

Chemistry	Abuse	Format	100% SoC (Peak °C)	30% SoC (Peak °C)	100% SoC (Time to TR, s)	30% SoC (Time to TR, s)
LFP	Heat	Cylindrical	480.7 ± 27.3 (3)	255.5 ± 14.5 (3)	266.73 ± 3.62 (3)	271.30 ± 14.12 (3)
LFP	Heat	Pouch	308.6 ± 10.9 (3)	268.7 ± 3.76 (3)	NA	NA
LFP	Nail pen	Cylindrical	78.9 ± 28.0 (3)	60.3 ± 9.66 (3)	16.60(1)	NA
LFP	Nail pen	Pouch	22.0 ± 1.3 (3)	25.7 ± 0.96 (3)	NA	42980.00 (1)
NMC	Heat	Cylindrical	443.2 ± 143.6 (3)	204.6 ± 19.2 (3)	269.20 ± 11.97 (3)	351.53 ± 22.84 (3)
NMC	Heat	Pouch	805.9 ± 48.5 (3)	671.0 ± 40.3 (3)	693.33 ± 200.06 (3)	2484.00 ± 1523.95 (3)
NMC	Nail pen	Cylindrical	569.6 ± 381.6 (3)	111.5 ± 70.0 (3)	3.43 ± 0.25 (3)	4.60 ± 1.14 (3)
NMC	Nail pen	Pouch	567.2 ± 67.1 (3)	439.6 ± 48.0 (3)	49.50 ± 19.52 (3)	37.00 ± 13.59 (3)

Quantification and comparison of lithium-ion battery fire hazards for emergency responders:
Recommendations for risk management and response

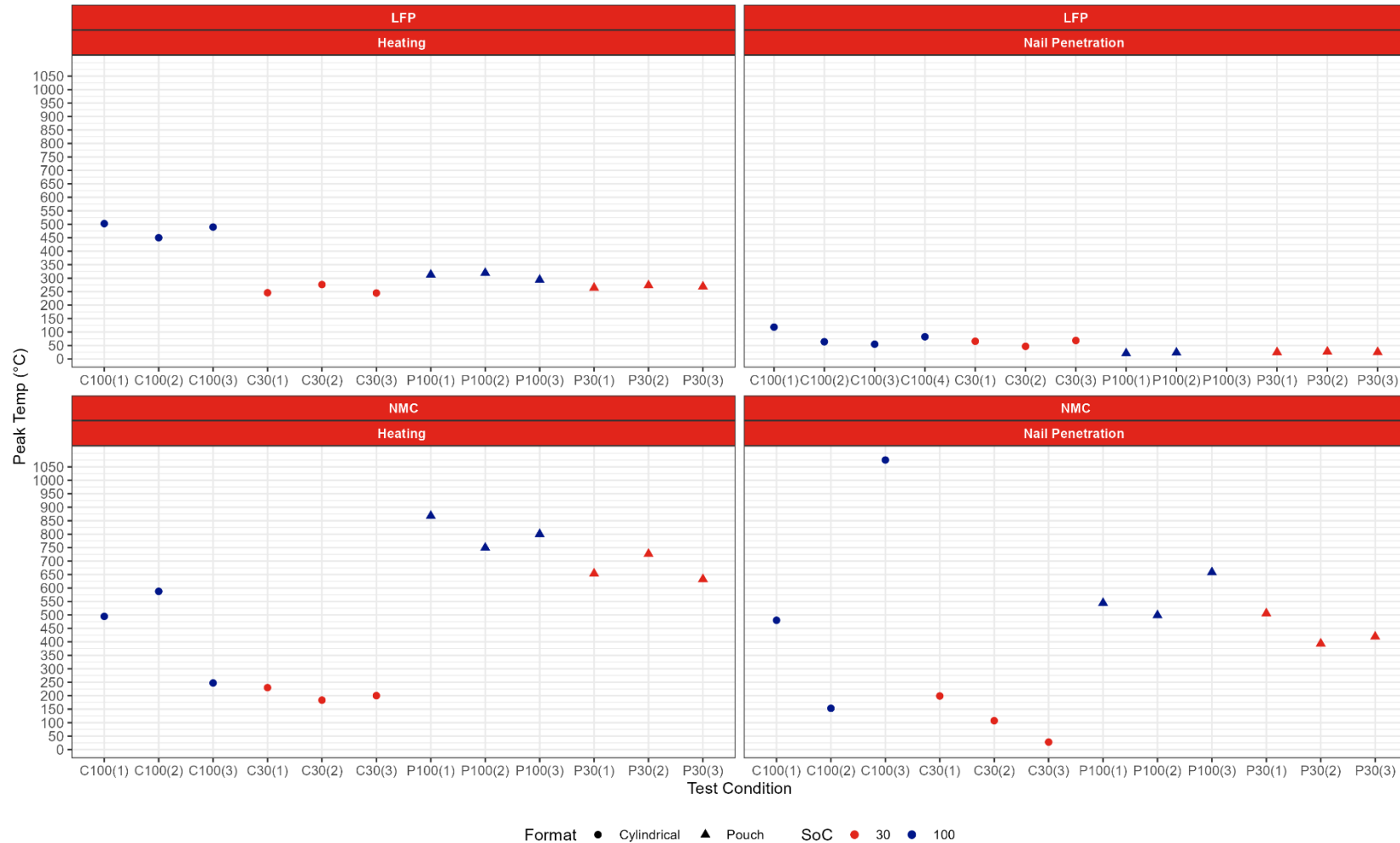


Figure 4. Graphical representation of each test scenario peak temperature $\bar{x}$.

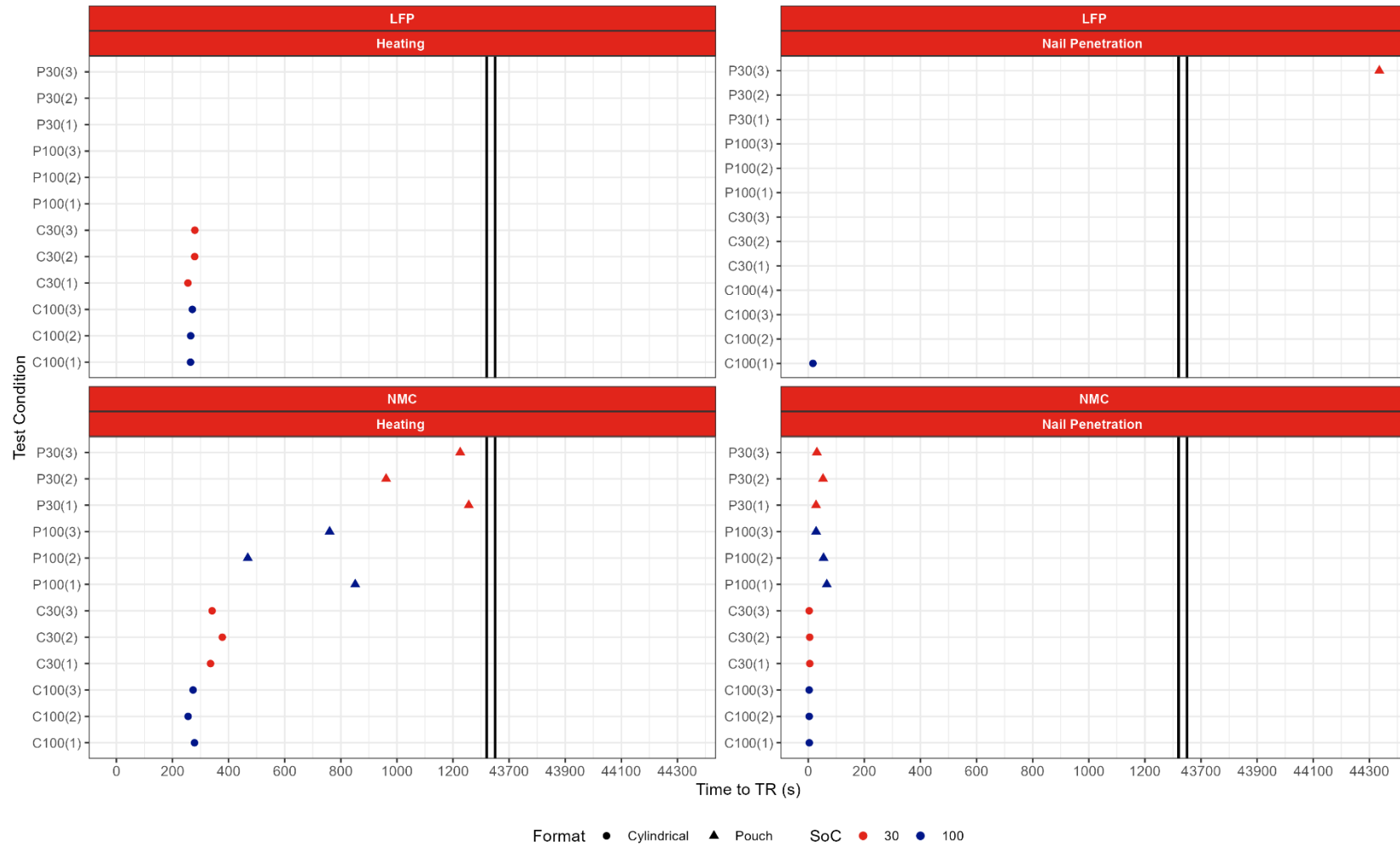


Figure 5. Graphical representation of each test scenario time to TR $\bar{x}$ based on the time taken to 0.5 V drop.

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TR behaviour varied across chemistry, abuse method, cell format, and SoC. Of these, chemistry showed the most consistent influence on both temperature and voltage response. The physical condition of the cells after testing reflected these findings, where LFP cells were more often left largely intact, while NMC cells typically showed much more severe damage under the same conditions.

Under nail penetration, NMC cells had the fastest voltage drop and some of the highest temperatures recorded, with similar peak temperatures between cylindrical (569.6 ± 381.6 °C) and pouch (567.2 ± 67.1 °C) formats. However, TR behaviour differed between formats. NMC tests were highly energetic and often resulted in explosive failure. In pouch cells, failure commonly occurred along the long side seam, suggesting a weak point in external cell packaging (**Figure 6** and Figure 7). In contrast, cylindrical cells tended to fail more violently, with deformation affecting the entire cell structure, indicating greater pressure containment prior to packaging rupture (Figure 8 and Figure 9).



Figure 6. NMC pouch cell at 100% SoC under nail penetration abuse was completely destroyed.



Figure 7. NMC pouch cell at 30% SoC under nail penetration abuse. Cell deformation has occurred, but the outside of the cell casing was still relatively intact.

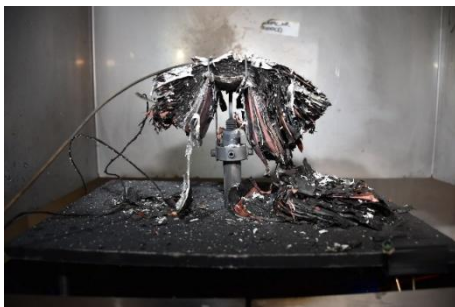


Figure 8. NMC cylindrical cell at 100% SoC under nail penetration abuse was burnt but did not have substantial cell structure deformation.



Figure 9. NMC cylindrical cell at 30% SoC under nail penetration abuse was explosive, destroying the whole cell casing.

In contrast to NMC, LFP cells displayed lower reactivity under nail penetration. Pouch cells did not exhibit any visible signs of TR or significant deformation, even after one hour of testing observation (Figure 10 and Figure 11). Temperatures remained close to ambient, with 100% SoC reaching 25.7 ± 0.96 °C and 30% SoC reaching 22.0 ± 1.3 °C, suggesting little to no exothermic reaction. Cylindrical LFP cells reached slightly higher temperatures (78.9 ± 28.0 °C at 100% SoC and 60.3 ± 9.66 °C at 30% SoC) and did not progress to flaming combustion. In some cases, electrolyte leakage was observed, although this did not lead to ignition (Figure 12 and Figure 13).

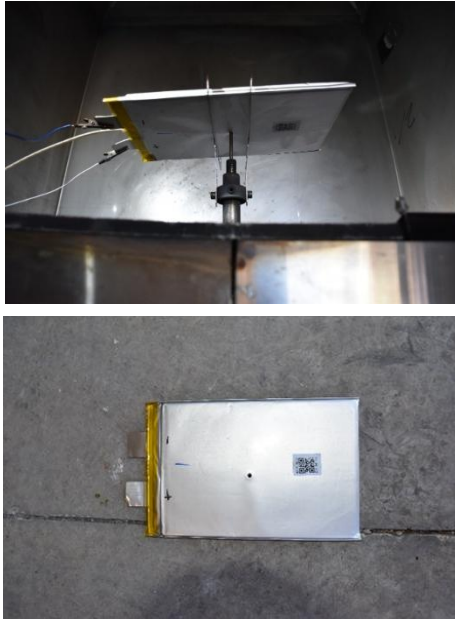


Figure 10. LFP pouch cells at 100% SoC under nail penetration abuse all showed little to no deformation in cell structure. Clear hole where nail has gone into battery can be observed.



Figure 11. LFP pouch cells at 30% SoC under nail penetration abuse all showed little to no deformation in cell structure. Clear hole where nail has gone into battery can be observed.

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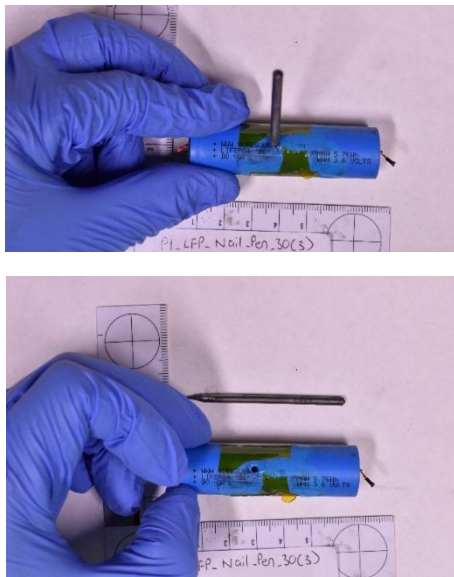


Figure 12. LFP cylindrical cells at 30% SoC under nail penetration abuse all showed little to no deformation in cell structure. Clear hole where nail has gone into battery can be observed.

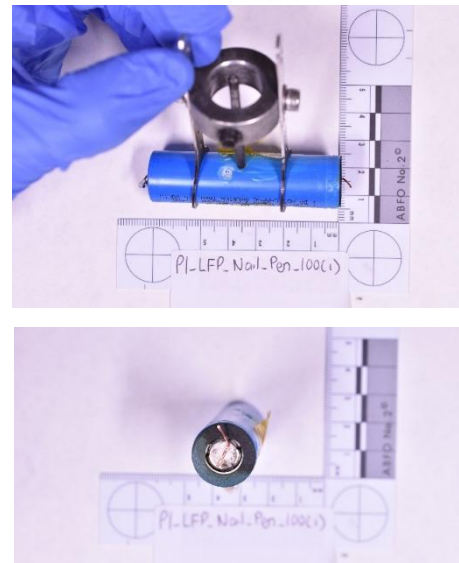


Figure 13. LFP cylindrical cells at 100% SoC under nail penetration abuse all showed little to no deformation in cell structure. Clear hole where nail has gone into battery can be observed. Electrolyte was seen dripping out from the safety vent end of the cell during test period leading to blackening around the safety vent end of the cell. There is also some deformation in the outer blue plastic layer.

Heating abuse recorded higher peak TR temperatures across all scenarios, but with longer and more variable times to TR compared to nail penetration. For NMC cells, pouch format reached the highest temperatures (805.9 ± 48.5 °C at 100% SoC and 671.0 ± 40.3 °C at 30% SoC) and consistently progressed to flaming combustion (Figure 14 and Figure 15). Cylindrical NMC cells reached lower peak temperatures (443.2 ± 143.6 °C at 100% SoC), but were often more energetic, with all 100% SoC tests resulting in an explosive failure (Figure 16). In one case, the explosive event tore the test stand off from the platform and damaged the testing chamber. At 30% SoC, cylindrical NMC cells remained highly energetic, with visible deformation of the test apparatus during failure (Figure 17).



Figure 14. NMC pouch cell at 100% SoC under heating abuse is destroyed - interior has fallen apart



Figure 15. NMC pouch cell at 30% under heating sustained damage with flaming combustion. While heavily damaged, most of the cell remained intact

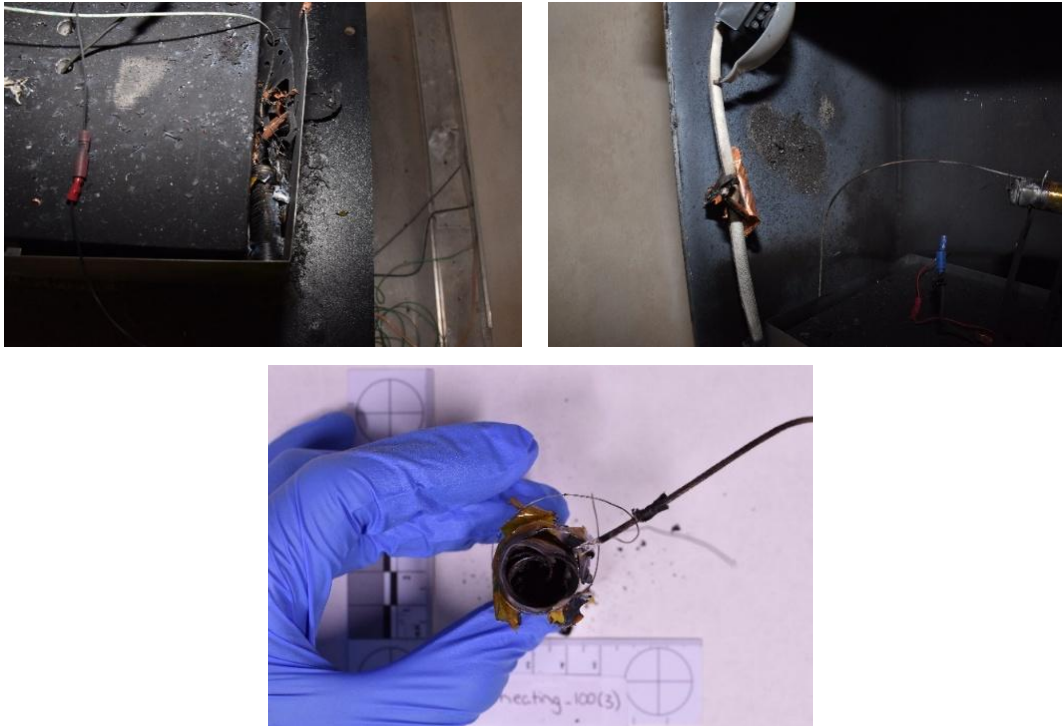


Figure 16. NMC cylindrical cell at 100% under heating. The whole jelly roll was ejected and test stand ripped off of test platform. Electrolyte and debris ejected onto the wall near the safety vent end of cell. This test also broke the test chamber with to its highly explosive behaviour.



Figure 17. NMC cylindrical cell at 30% under heating abuse. Jelly roll has been exploded out the safety vent end of the cell and test stand sustained damage due to explosive force.

LFP cells under heating demonstrated a less severe response compared to NMC. Pouch cells did not enter flaming combustion and instead expanded noticeably, before becoming rigid after cooling (Figure 18 and Figure 19). LFP pouch cells did not meet the 0.5 V decline that often signalled a combustion event was imminent. Cylindrical LFP cells reached higher temperatures than LFP pouch cells (Cylindrical at 100% SoC 480.7 ± 27.3 °C compared to pouch at 100% SoC 308.6 ± 10.9 °C) and in some cases had limited flaming combustion. However, they were observed to be less energetic than NMC and was typically localised near the venting end, suggesting ignition of released electrolyte rather than full-cell involvement (Figure 20 and Figure 21).

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Figure 18. LFP pouch cell at 100% SoC under heating abuse shows the ballooning consistently seen with LFP cells under heating abuse where there was a high build-up of pressure creating a ballooning effect of the cell wall. At the conclusion of the test the cell deflated and went rigid.

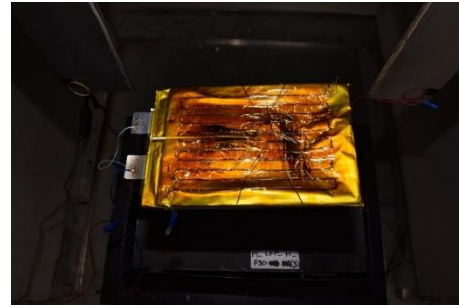


Figure 19. LFP pouch cell at 30% SoC under heating abuse had a build-up of pressure during heating abuse where there was a high build-up of pressure creating a ballooning effect of the cell wall. At the conclusion of the test the cell deflated and went rigid.

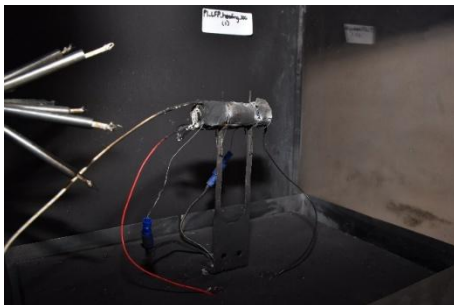


Figure 20. LFP cylindrical cell at 100% SoC under heating abuse showing how the cell is heat affected, and the safety valve has come off, but still intact.



Figure 21. LFP cylindrical cell at 30% SoC under heating abuse shows very little deformation or heat effect on the majority of the cell, though some flaming activity did occur, but likely due to liquid electrolyte coming into contact with heating wire.

TR behaviour was strongly governed by cell chemistry, with NMC cells consistently exhibiting higher temperatures, faster failure under mechanical abuse, and more energetic reactions compared to LFP cells. While cell format and SoC influenced the severity and progression of failure, these factors were less significant than chemistry-driven trends. Overall, the results highlight that NMC cells present a significantly greater hazard potential, particularly under rapid abuse conditions, whereas LFP cells demonstrate comparatively stable and less reactive behaviour across all scenarios tested.

3.3.2 Gas analysis

The gas effluent from the LiBs was sampled and analysed for gas species of concern. The identification library on the FTIR searched for 21 gas species which are suspected TR by-products (Lebedeva and Brett, 2016; Zhou et

al., 2023; Bugryniec *et al.*, 2024). Due to the volume of data generated from the gas analysis, for brevity only those gases that were denoted as ‘distinct’ (as described in Section 3.2.6.2) are reported within this section. The full dataset of analyses is presented within Appendix A.3.

The gases detected during TR events in this study demonstrate the complex interactions between battery chemistry, abuse method, cell format, and SoC, and their combined influence on flammability, explosion potential, and toxicity hazards. Substantial variability in peak concentrations was observed across all compounds, reflecting both the dynamic nature of TR events and the dependence of emissions on multiple interacting factors. Across all variables, flammable gases represented the dominant hazard class, followed by simple asphyxiants and then toxic or corrosive species.

3.3.2.1 Chemistry-dependent hazards

Battery chemistry exhibited a strong and consistent influence on gas generation. Differences between the test scenarios within each array were identified if the IQR of the two test scenarios did not overlap. Within the parameters of the test array, these were denoted as ‘distinct’ for the purpose of quantifying and comparing gas hazards associated with LiB fires with respect to the variables. All compounds had at least one scenario with distinct differences between NMC and LFP, with NMC cells producing higher peak concentrations in most cases. The largest differences were observed for carbon monoxide, carbon dioxide, acetylene, and hydrogen cyanide. These gases contribute significantly to flammability and explosion risk in confined environments and are asphyxiants (PubChem, 2026). Carbon monoxide presents an additional toxicological hazard due to oxygen displacement within the haemoglobin (Zhao *et al.*, 2025, p. 202; PubChem, 2026). Electrolyte solvents such as diethyl carbonate and propylene carbonate were also more frequently elevated in NMC cells. Diethyl carbonate, a linear carbonate with a low flash point (Bugryniec *et al.*, 2024; PubChem, 2026), will likely to combust early in TR, while propylene carbonate contributes to vapour cloud formation and increased heat release with a higher boiling point (Bugryniec *et al.*, 2024).

In contrast, hydrogen chloride and hydrogen fluoride were generally higher in LFP cells. These gases present significant toxicity and corrosivity hazards (PubChem, 2026). Their elevated presence in LFP batteries may reflect both compositional differences and prolonged non-flaming phases of TR in these chemistries, which favour accumulation of toxic combustion by-products.

Other compounds including acetaldehyde, benzaldehyde, carbonyl sulphide, chlorobenzene, ethyl methyl carbonate, hexane, methane, toluene, benzene, dimethyl carbonate, ethylene carbonate, ethylene, and styrene showed inconsistent or minor dependence on chemistry, indicating that chemistry alone may not distinguish emission characteristics.

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Table 9. Distinct compounds for chemistry-dependent hazards. ^ = scenario that was higher.

Array	Gas species	Scenario	$\bar{x}$	σ	Min	Q1	Median	Q3	Max
1	Carbon monoxide	LFP	87.11	55.29	30.49	45.94	70.93	115.86	219.50
		NMC^	321.24	244.46	73.25	119.62	223.33	491.47	912.10
	Hydrogen chloride	LFP^	1.53	0.27	1.20	1.32	1.45	1.70	2.20
		NMC	1.28	0.58	0.71	0.95	1.19	1.32	3.24
2	Acetylene	LFP	1.29	0.44	0.64	1.05	1.24	1.52	2.35
		NMC^	8.52	1.74	5.34	7.13	8.48	9.95	12.03
	Carbon monoxide	LFP	24.56	28.45	0.00	1.29	14.04	39.15	88.36
		NMC^	215.41	105.12	90.44	151.38	197.52	237.54	436.91
	Hydrogen chloride	LFP	0.99	0.34	0.54	0.73	0.94	1.13	2.17
		NMC^	1.77	0.93	0.86	1.18	1.41	2.05	4.29
	Hydrogen fluoride	LFP	0.81	0.34	0.35	0.52	0.81	1.07	1.57
		NMC^	1.52	0.32	1.10	1.31	1.45	1.81	2.30
	Hydrogen cyanide	LFP	3.07	0.88	2.20	2.62	2.95	3.19	5.90
		NMC^	10.92	2.78	6.68	7.61	11.64	12.85	15.19
3	Carbon dioxide	LFP	0.06	0.01	0.04	0.05	0.06	0.07	0.08
		NMC^	2.60	1.83	0.34	0.88	2.17	4.45	5.98
	Carbon monoxide	LFP	7.16	4.73	2.21	3.49	6.33	9.09	20.03
		NMC^	149.12	41.31	86.20	111.61	149.16	176.70	217.62
	Hydrogen chloride	LFP^	2.60	0.25	2.26	2.40	2.52	2.81	3.09
		NMC	1.94	0.30	1.52	1.75	1.88	2.04	2.95
	Hydrogen fluoride	LFP^	1.78	0.42	1.14	1.30	1.88	2.11	2.51
		NMC	1.15	0.20	0.94	1.03	1.06	1.21	1.79
	Hydrogen cyanide	LFP^	9.66	3.85	4.15	4.44	11.93	12.37	13.65
		NMC	4.16	0.86	3.01	3.87	4.06	4.25	7.97
4	Acetylene	LFP	1.65	0.79	1.12	1.32	1.41	1.55	5.18
		NMC^	4.90	2.99	2.52	2.74	4.01	6.00	15.09
	Carbon dioxide	LFP	0.02	0.00	0.02	0.02	0.02	0.02	0.03
		NMC^	1.13	0.58	0.43	0.63	0.91	1.64	2.22
	Carbon monoxide	LFP	3.51	1.41	1.59	2.45	3.20	4.48	6.09
		NMC^	747.47	583.01	34.23	36.78	775.39	1337.48	1493.09
	Diethyl carbonate	LFP	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		NMC^	242.98	316.98	0.00	0.43	99.06	462.76	1197.91
	Hydrogen cyanide	LFP	2.64	1.33	1.73	1.95	2.07	2.79	7.11
		NMC^	5.63	1.93	3.91	4.33	4.92	6.06	11.61
5	Propylene carbonate	LFP	0.95	1.35	0.00	0.00	0.175	1.81	4.04
		NMC^	61.45	61.54	2.51	2.82	45.65	91.85	188.48
	Acetylene	LFP	1.23	0.29	0.77	1.05	1.27	1.39	2.14
		NMC^	13.02	5.72	8.94	9.62	11.02	13.18	35.11
	Carbon dioxide	LFP	0.07	0.01	0.06	0.06	0.07	0.07	0.07
		NMC^	0.31	0.38	0.06	0.09	0.13	0.30	1.64
	Carbon monoxide	LFP	12.23	22.32	0.00	0.00	0.00	12.34	82.69
		NMC^	861.86	797.90	78.50	221.81	465.97	1281.25	2808.66
	Hydrogen chloride	LFP^	1.36	0.25	0.90	1.20	1.34	1.54	1.78
		NMC	1.37	1.89	0.26	0.65	0.80	1.01	8.98
	Diethyl carbonate	LFP	0.14	0.78	0.00	0.00	0.00	0.00	4.27
		NMC^	1.19	0.91	0.18	0.58	1.01	1.74	3.85
	Hydrogen cyanide	LFP	1.49	0.24	1.11	1.26	1.51	1.60	2.11
		NMC^	16.57	1.22	14.22	15.36	16.85	17.37	18.41
	Propylene carbonate	LFP	0.48	1.03	0.00	0.00	0.00	0.45	4.51
		NMC^	4.76	4.45	1.16	1.67	2.73	6.27	18.64

Table 9. Distinct compounds for chemistry-dependent hazards. ^ = scenario that was higher (cont.).

Array	Gas species	Scenario	$\bar{x}$	σ	Min	Q1	Median	Q3	Max
6	Carbon dioxide	LFP	0.05	0.01	0.04	0.04	0.04	0.06	0.09
		NMC^	0.10	0.05	0.06	0.07	0.07	0.11	0.25
	Hydrogen fluoride	LFP^	1.46	0.32	0.83	1.14	1.57	1.69	2.00
		NMC	0.55	0.38	0.06	0.27	0.39	1.00	1.16
7	Carbon dioxide	LFP	0.03	0.02	0.02	0.02	0.03	0.04	0.11
		NMC	2.18	1.17	0.51	1.11	2.23	3.22	4.23
	Carbon monoxide	LFP	0.92	1.11	0.00	0.00	0.48	1.48	3.74
		NMC^	497.52	159.32	246.60	374.44	486.81	657.53	791.47
	Hydrogen chloride	LFP^	2.21	0.27	1.94	2.01	2.15	2.33	3.02
		NMC	1.65	0.22	1.34	1.50	1.60	1.75	2.07
	Hydrogen fluoride	LFP^	1.47	0.15	1.19	1.39	1.46	1.50	1.93
		NMC	0.30	0.17	0.12	0.19	0.21	0.44	0.71
	Hydrogen cyanide	LFP	4.91	0.91	4.19	4.28	4.49	5.03	8.11
		NMC^	5.77	0.43	5.28	5.49	5.68	5.91	7.37
8	Acetylene	LFP	4.13	0.96	2.74	2.96	4.44	4.77	5.91
		NMC^	6.32	2.55	2.46	4.90	6.18	6.83	13.57
	Carbon dioxide	LFP	0.03	0.01	0.02	0.02	0.03	0.03	0.04
		NMC^	0.74	0.55	0.14	0.35	0.59	0.80	1.94
	Carbon monoxide	LFP	4.47	5.37	0.00	1.02	2.45	4.71	18.06
		NMC^	1472.06	935.20	194.84	356.59	1771.33	1932.89	3009.40
	Diethyl carbonate	LFP	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		NMC^	305.25	314.36	0.00	40.92	143.67	569.15	1002.56
	Hydrogen cyanide	LFP	3.86	0.50	3.15	3.60	3.90	4.04	5.61
		NMC^	6.55	2.21	3.92	4.51	6.29	8.54	10.91
	Propylene carbonate	LFP	0.91	1.235	0.00	0.00	0.13	1.472	3.97
		NMC^	88.70	73.33	5.69	15.63	73.51	156.29	218.62
	Hydrogen fluoride	LFP^	1.46	0.24	1.16	1.26	1.40	1.68	2.04
		NMC	0.96	0.25	0.58	0.77	0.94	1.13	1.57

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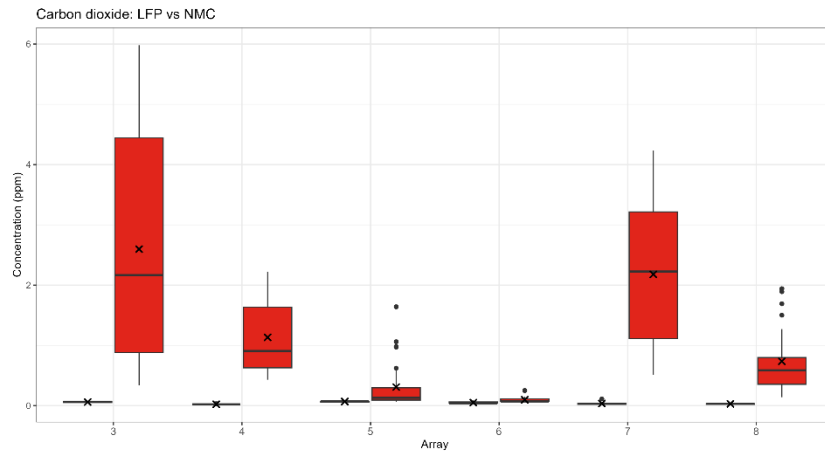


Figure 22. Carbon dioxide boxplot for chemistry comparison.

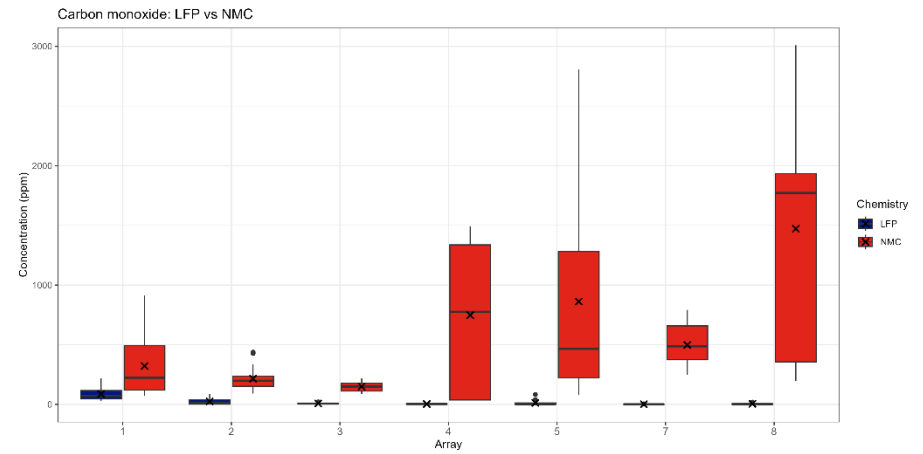


Figure 23. Carbon monoxide boxplot for chemistry comparison.

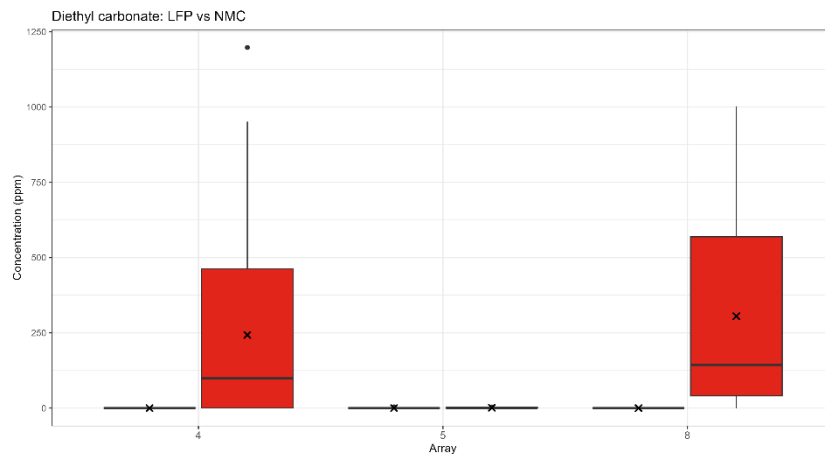


Figure 24. Diethyl carbonate boxplot for chemistry comparison.

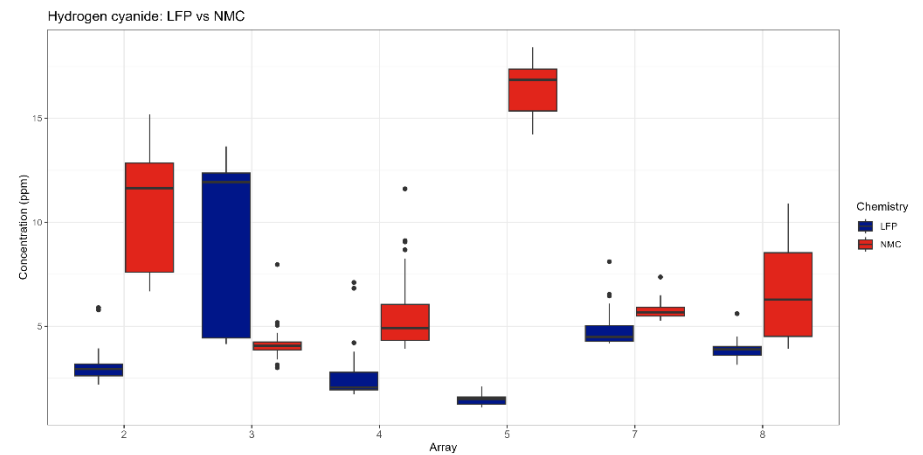


Figure 25. Hydrogen cyanide boxplot for chemistry comparison.

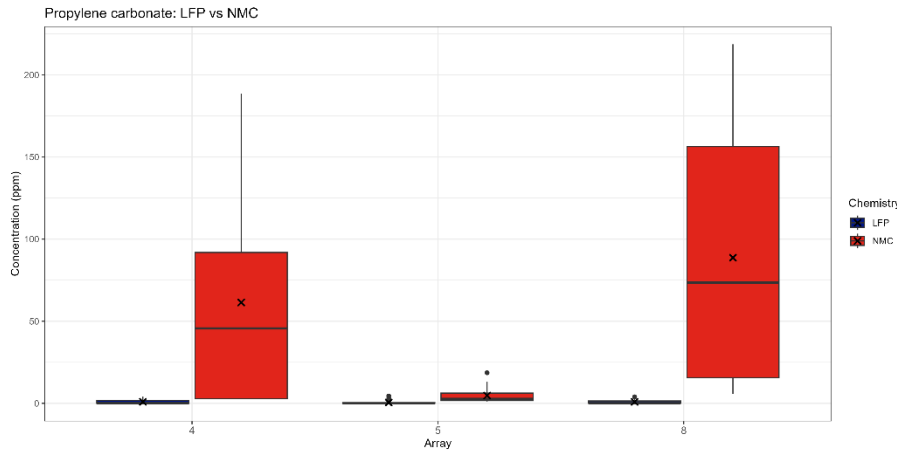


Figure 26. Propylene carbonate boxplot for chemistry comparison.

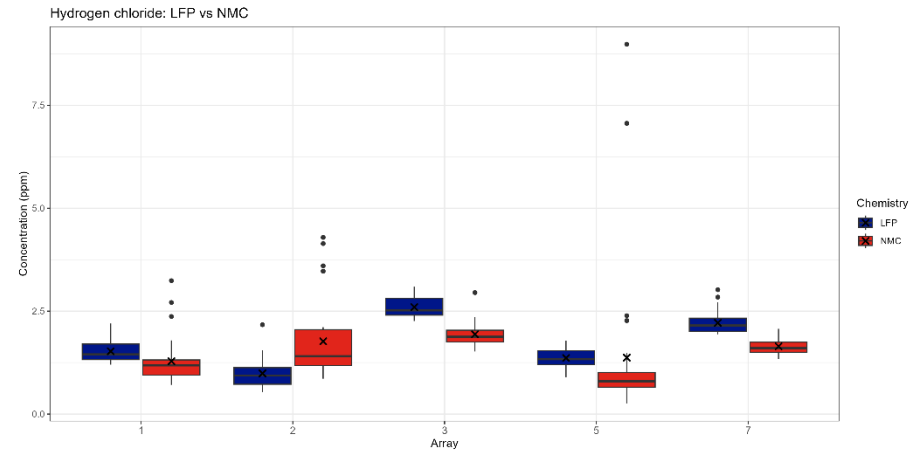


Figure 27. Hydrogen chloride boxplot for chemistry comparison.

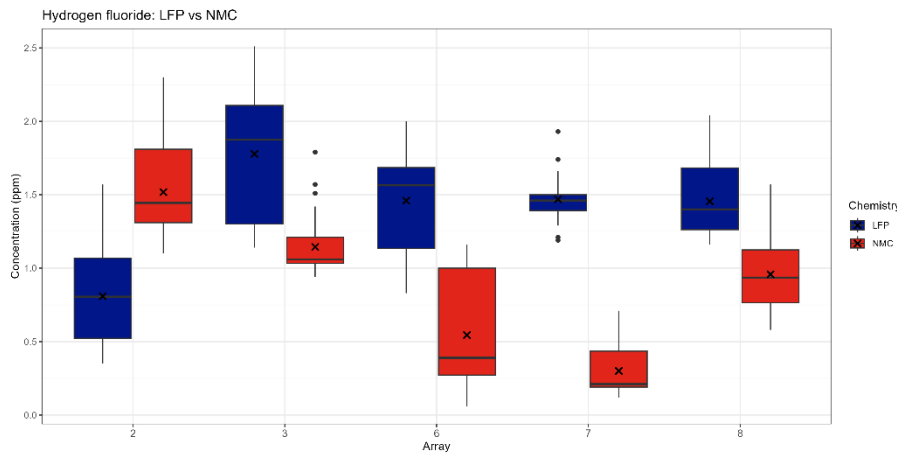


Figure 28. Hydrogen fluoride boxplot for chemistry comparison.

3.3.2 Abuse-dependent hazards

Abuse method comparison demonstrated a weaker and less consistent influence on emission characterisation in comparison to chemistry-dependent hazards. Heating abuse resulted in higher peak concentrations in approximately half of the tested compounds, indicating only a modest overall effect.

Ethyl methyl carbonate and benzaldehyde were most strongly associated with heating. Ethyl methyl carbonate readily volatilises due to its low boiling point (Bugryniec *et al.*, 2024; PubChem, 2026), contributing to pressure build-up and flammable vapour formation prior to venting. Benzaldehyde is both a flammability and health hazard, effecting the skin, eyes and respiratory tract if exposed (PubChem, 2026).

No gas concentrations were consistently higher in the nail penetration tests, in comparison to heating. Instead, most compounds, including hydrogen chloride, methane, benzene, chlorobenzene, ethylene carbonate, toluene, hydrogen cyanide, acetylene, dimethyl carbonate, diethyl carbonate, propylene carbonate, carbonyl sulphide, hexane, carbon dioxide, carbon monoxide, acetaldehyde, hydrogen fluoride, ethylene, and styrene showed inconsistent or minor dependence on abuse method. Abuse method alone was therefore not a reliable predictor of peak gas concentrations and must be considered in conjunction with chemistry, format, and SoC.

Table 10. Distinct compounds for abuse-dependent hazards. ^ = scenario that was higher.

Array	Gas species	Scenario	$\bar{x}$	σ	Min	Q1	Median	Q3	Max
9	Ethyl methyl carbonate	Heat^	154.90	93.55	43.39	89.94	116.98	224.58	377.24
		Nail	34.32	57.24	0.00	0.00	0.00	48.46	168.83
	Benzaldehyde	Heat^	1.49	0.23	1.06	1.37	1.52	1.66	1.99
		Nail	0.01	0.02	0.00	0.00	0.00	0.00	0.11
10	Ethyl methyl carbonate	Heat^	181.87	95.70	75.73	115.07	148.91	239.55	448.81
		Nail	0.09	0.34	0.00	0.00	0.00	0.00	1.36
11	Ethyl methyl carbonate	Heat^	27.13	33.97	0.32	3.42	15.44	33.83	118.64
		Nail	0.05	0.09	0.00	0.00	0.00	0.06	0.32
13	Ethyl methyl carbonate	Heat^	25.84	10.48	10.29	15.57	26.85	30.84	49.13
		Nail	6.39	11.29	0.00	0.46	0.88	3.58	38.89
	Benzaldehyde	Heat^	1.89	0.75	1.22	1.33	1.61	2.28	4.85
		Nail	0.38	1.32	0.00	0.00	0.00	0.03	6.60
14	Ethyl methyl carbonate	Heat^	42.15	12.93	13.31	35.44	41.19	51.89	69.49
		Nail	15.48	12.58	0.17	5.76	11.19	26.40	40.45
	Benzaldehyde	Heat^	1.97	1.38	0.00	1.10	2.34	3.23	3.51
		Nail	0.15	0.44	0.00	0.00	0.00	0.00	1.88
15	Ethyl methyl carbonate	Heat^	15.63	11.12	0.43	3.01	18.87	25.40	29.96
		Nail	2.09	2.21	0.59	0.69	1.02	2.40	9.52
	Benzaldehyde	Heat^	1.44	0.60	0.69	0.80	1.57	1.76	3.48
		Nail	0.23	0.40	0.00	0.00	0.00	0.30	1.38

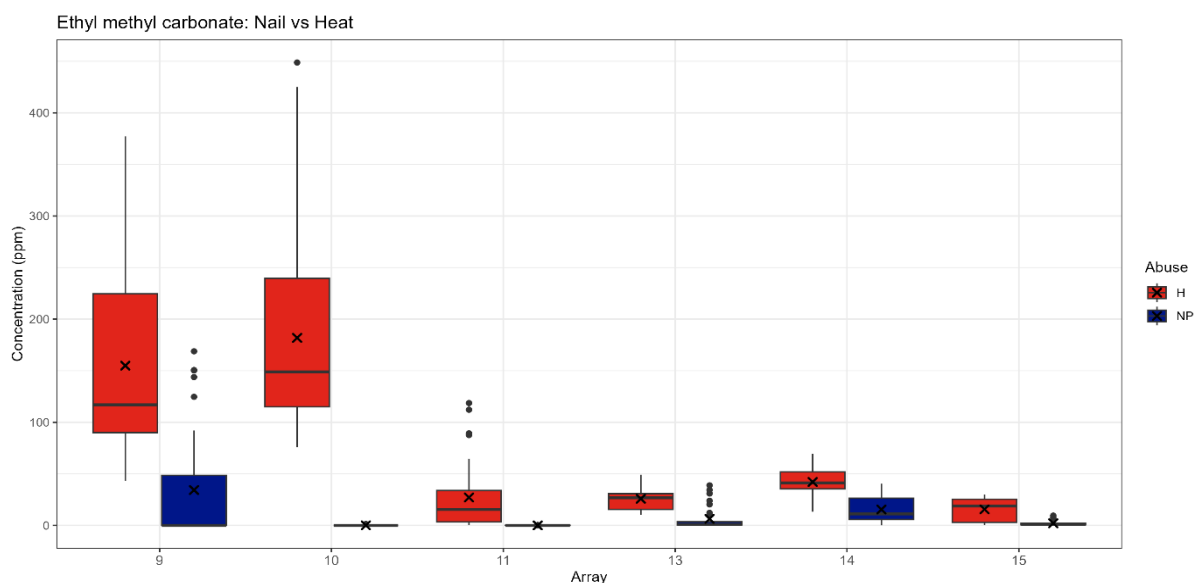


Figure 29. Ethyl methyl carbonate boxplot for abuse comparison.

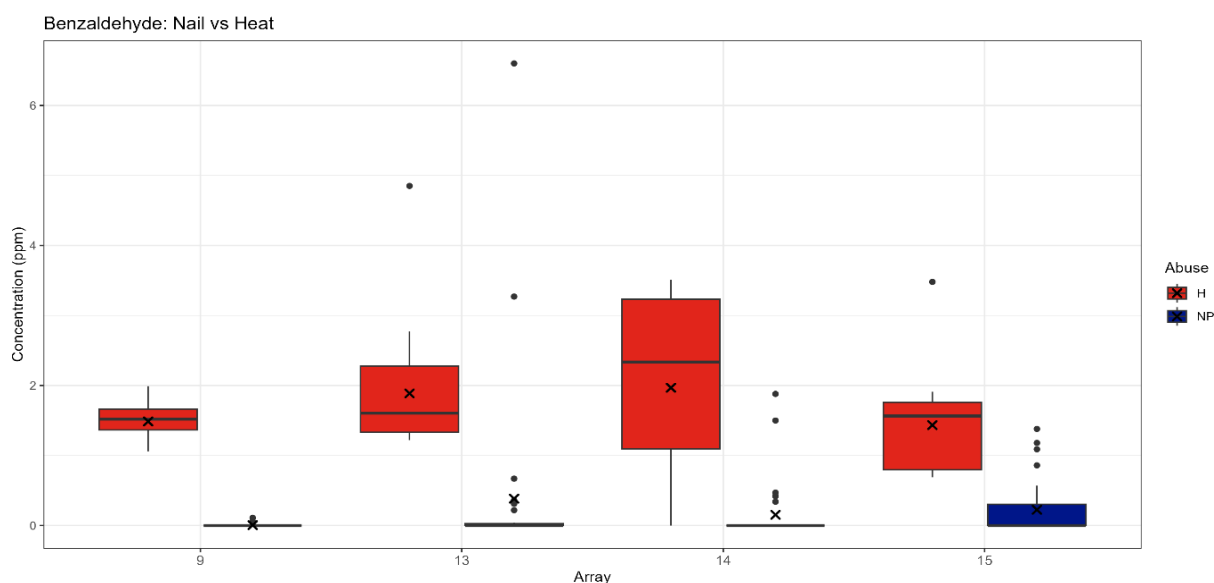


Figure 30. Benzaldehyde boxplot for abuse comparison.

3.3.2.3 Format-dependent hazards

Cell format exhibited some of the strongest and most consistent influence on emission characteristics. Pouch cells produced higher peak concentrations across the majority of compounds and scenarios. Hydrogen chloride was particularly influenced by format, with all test scenarios showing higher peak concentrations in pouch cells compared to cylindrical cells, this represents the most consistent observation across all variables tested. Methane, benzene, chlorobenzene, and toluene also consistently recorded higher peaks in pouch cells, contributing to flammability, toxicity, and asphyxiation hazards (PubChem, 2026). The absence of controlled venting in pouch cells may resulting in these sharper, higher gas peak concentrations. In contrast, cylindrical cells incorporate engineered pressure relief mechanisms that favour more gradual gas release.

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Ethylene carbonate was the only compound to show a strong bias toward higher peak concentrations in cylindrical cells. As a high-boiling-point electrolyte component (Bugryniec *et al.*, 2024; PubChem, 2026), this may reflect differences in electrolyte composition or degradation pathways, as well as the influence of thermal profiles and TR duration on its release behaviour.

Other compounds including benzaldehyde, hydrogen cyanide, acetylene, dimethyl carbonate, ethyl methyl carbonate, diethyl carbonate, propylene carbonate, carbonyl sulphide, hexane, carbon dioxide, carbon monoxide, acetaldehyde, hydrogen fluoride, ethylene, and styrene showed inconsistent or minor dependence on format.

Table 11. Distinct compounds for format-depended hazards. ^ = scenario that was higher.

Array	Gas species	Scenario	$\bar{x}$	σ	Min	Q1	Median	Q3	Max
17	Hydrogen chloride	Cylindrical	1.53	0.27	1.20	1.32	1.45	1.70	2.20
		Pouch^	2.60	0.25	2.26	2.40	2.52	2.81	3.09
	Ethylene	Cylindrical^	139.27	348.58	33.15	35.04	42.89	47.07	1572.05
		Pouch	82.20	24.52	47.99	52.72	80.31	104.13	126.41
18	Hydrogen chloride	Cylindrical	0.99	0.34	0.54	0.73	0.94	1.13	2.17
		Pouch^	2.44	0.22	2.15	2.28	2.39	2.64	2.90
	Methane	Cylindrical	50.66	7.82	42.59	44.73	48.21	54.58	65.94
		Pouch^	75.29	19.76	62.47	64.68	66.95	76.27	131.21
	Benzene	Cylindrical	9.94	5.99	3.85	5.64	9.35	11.96	34.60
		Pouch^	27.69	8.85	17.40	20.32	26.25	32.79	52.50
	Chlorobenzene	Cylindrical	8.34	4.90	0.00	5.33	8.61	11.47	22.43
		Pouch^	25.99	5.73	18.90	22.24	25.06	28.39	38.08
	Ethylene	Cylindrical^	57.02	25.61	44.79	46.73	48.57	51.38	159.28
		Pouch	45.48	15.73	37.36	39.39	40.96	44.72	123.12
19	Hydrogen chloride	Cylindrical	1.36	0.25	0.90	1.20	1.34	1.54	1.78
		Pouch^	2.21	0.27	1.94	2.01	2.15	2.33	3.02
	Methane	Cylindrical	40.70	6.58	33.90	36.59	39.32	43.73	59.91
		Pouch^	59.03	10.21	43.76	51.51	55.06	67.66	77.14
	Benzene	Cylindrical	3.34	6.86	0.00	0.00	0.00	1.76	25.80
		Pouch^	24.98	10.01	12.80	17.95	24.15	28.23	55.90
	Chlorobenzene	Cylindrical	16.46	7.04	2.45	12.33	15.79	22.07	30.40
		Pouch^	37.51	8.21	27.25	32.03	35.40	41.20	55.01
	Toluene	Cylindrical	7.07	16.35	0.00	0.00	0.00	6.19	80.20
		Pouch^	47.02	9.47	36.03	41.14	43.38	50.79	73.78
	Ethylene	Cylindrical	38.49	9.31	29.49	32.87	36.20	40.33	77.21
		Pouch^	62.88	28.36	39.97	45.94	52.72	67.00	151.09
20	Hydrogen chloride	Cylindrical	1.20	0.27	0.73	1.06	1.14	1.30	2.07
		Pouch^	2.33	0.34	1.80	2.02	2.41	2.52	3.11
	Methane	Cylindrical	40.12	31.28	3.97	20.99	35.40	44.75	140.46
		Pouch^	134.68	69.52	52.94	62.24	143.74	181.28	274.99
	Benzene	Cylindrical	4.43	7.62	0.00	0.00	0.00	7.73	27.30
		Pouch^	15.74	9.32	3.28	8.30	14.30	22.93	35.30
	Toluene	Cylindrical	3.70	7.91	0.00	0.00	0.00	0.00	27.65
		Pouch^	64.53	42.27	29.42	37.75	50.42	66.05	212.67
21	Hydrogen chloride	Cylindrical	1.28	0.58	0.71	0.95	1.19	1.32	3.24
		Pouch^	1.94	0.30	1.52	1.75	1.88	2.04	2.95
	Methane	Cylindrical	33.57	18.54	16.95	21.12	27.85	35.97	83.30
		Pouch^	61.49	9.68	49.70	55.27	57.78	68.06	85.22
	Chlorobenzene	Cylindrical	18.61	7.36	8.10	12.38	18.50	22.07	37.39
		Pouch^	44.59	4.49	39.24	41.15	43.37	46.65	55.31

Table 11. Distinct compounds for format-depended hazards. ^ = scenario that was higher (cont.).

Array	Gas species	Scenario	$\bar{x}$	σ	Min	Q1	Median	Q3	Max
22	Hydrogen chloride	Cylindrical	1.77	0.93	0.86	1.18	1.41	2.05	4.29
		Pouch^	3.21	1.47	1.80	2.07	2.55	4.09	6.71
		Pouch^	134.68	69.52	52.94	62.24	143.74	181.28	274.99
	Benzene	Cylindrical	3.31	6.37	0.00	0.00	0.00	6.23	31.10
		Pouch^	32.51	8.78	21.00	25.18	31.80	38.02	51.30
	Chlorobenzene	Cylindrical	7.71	8.80	0.00	0.05	5.35	10.66	31.50
Pouch^		44.25	5.93	35.49	39.12	43.89	47.92	56.45	
23	Hydrogen chloride	Cylindrical	1.37	1.89	0.26	0.65	0.80	1.01	8.98
		Pouch^	1.65	0.22	1.34	1.50	1.60	1.75	2.07
	Methane	Cylindrical	50.80	60.41	0.00	0.22	37.10	75.89	197.19
		Pouch^	88.91	14.99	76.35	79.25	81.46	96.77	128.73
	Toluene	Cylindrical	13.16	57.13	0.00	0.00	0.00	0.00	306.58
		Pouch^	63.77	18.00	40.85	50.41	60.47	71.35	122.18
24	Hydrogen chloride	Cylindrical	0.99	0.60	0.17	0.63	0.87	1.30	2.47
		Pouch^	3.47	1.39	1.66	2.28	3.35	4.20	6.91
	Methane	Cylindrical	39.18	16.50	7.47	30.07	39.35	42.78	71.48
		Pouch^	196.70	107.79	36.11	69.74	237.75	280.27	339.55
	Benzene	Cylindrical	5.34	7.45	0.00	0.00	2.73	6.52	25.60
		Pouch^	23.14	12.14	8.30	14.33	19.84	29.23	56.40
	Chlorobenzene	Cylindrical	4.19	5.58	0.00	0.00	0.25	7.01	22.60
		Pouch^	34.67	6.52	25.49	29.95	32.49	40.28	47.24
	Ethylene	Cylindrical	46.82	14.06	1.06	43.97	48.68	53.18	62.99
Pouch^		1757.02	1671.72	239.24	585.23	1260.21	2205.74	7276.14	

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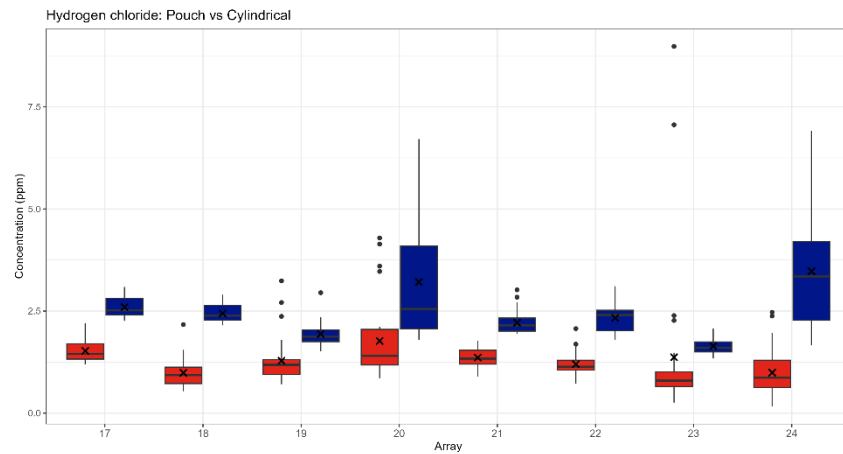


Figure 31. Hydrogen chloride boxplot for format comparison.

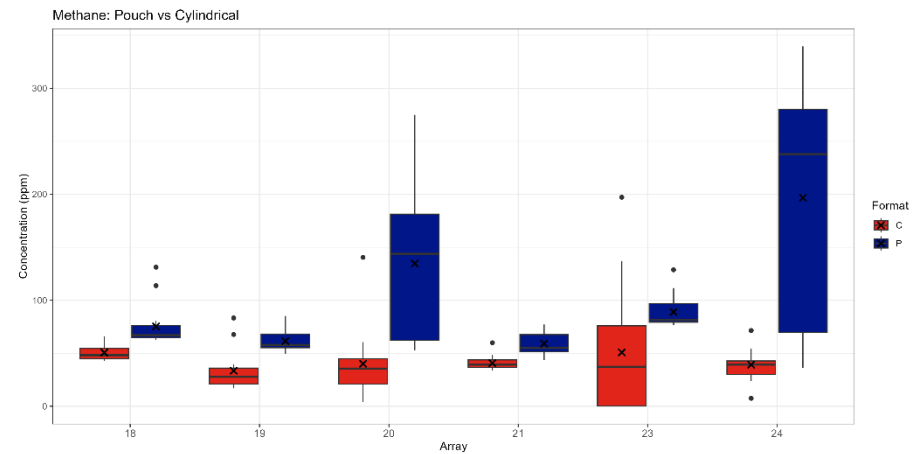


Figure 32. Methane boxplot for format comparison.

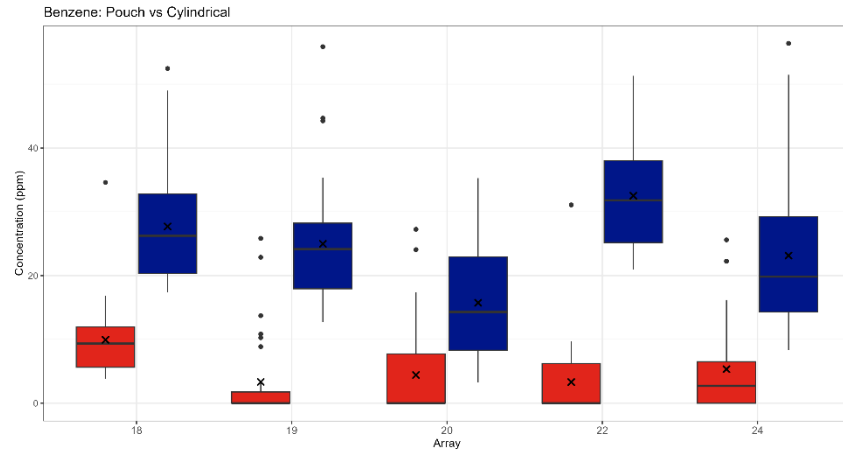


Figure 33. Benzene boxplot for format comparison.

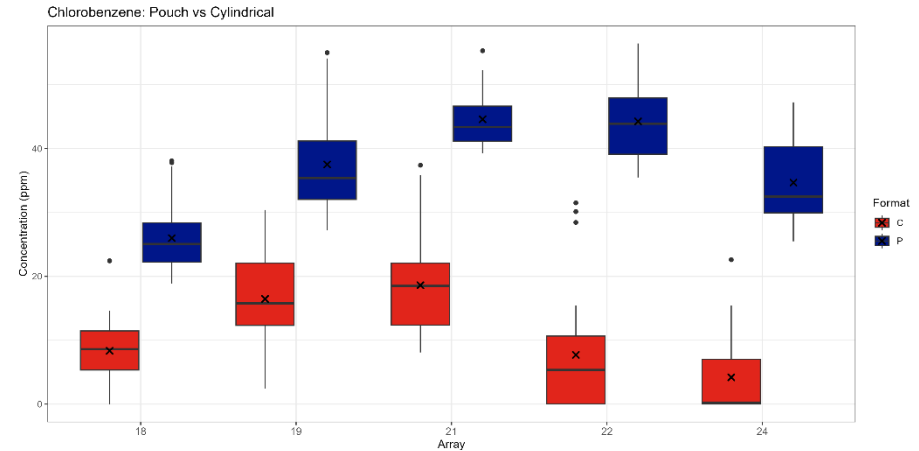


Figure 34. Chlorobenzene boxplot for format comparison.

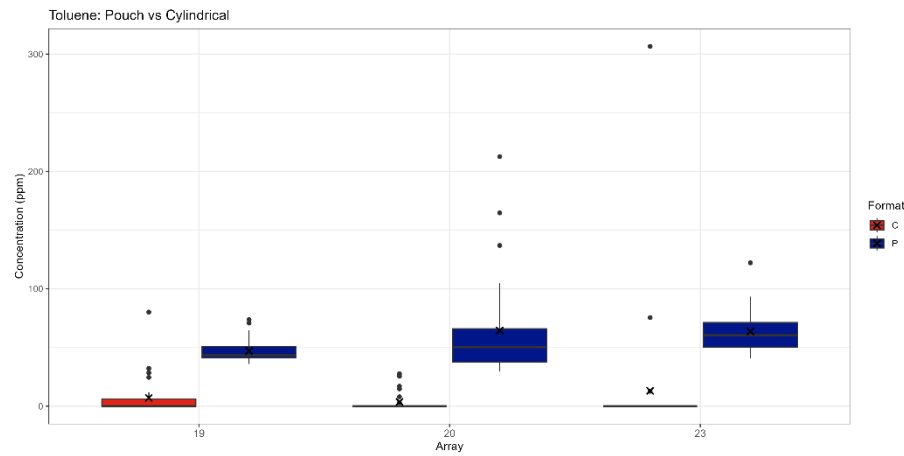


Figure 35. Toluene boxplot for format comparison.

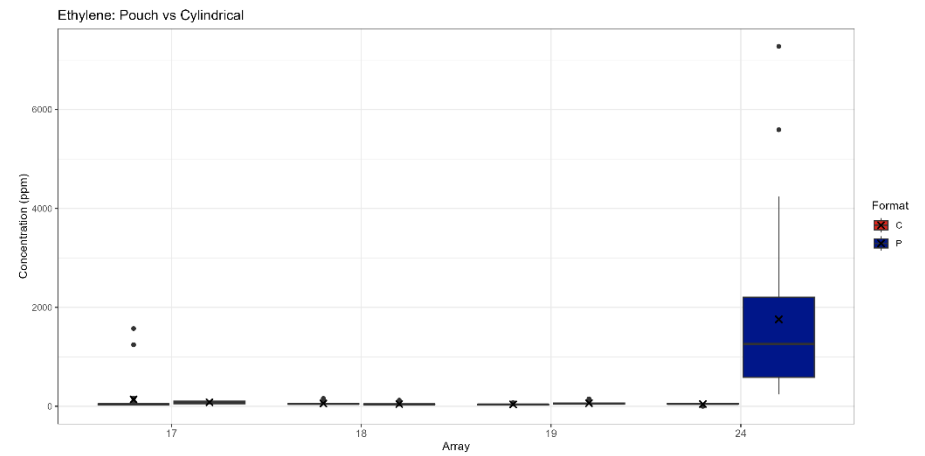


Figure 36. Ethylene boxplot for format comparison.

3.3.2.4 State-of-charge-dependent hazards

State of charge demonstrated the weakest and most variable influence on gas concentration of the four variables compared. Most compounds did not exhibit a consistent relationship between 30% and 100% SoC, with relatively few scenarios showing distinct differences.

Carbon dioxide more frequently produced higher peak concentrations at 100% SoC compared to 30% SoC, which aligns with previous studies by (Zhang *et al.*, 2022) who reported increased total gas production, particularly CO₂, at higher SoC, or relatively stable production across SoC levels (Qi *et al.*, 2025). Increased combustion intensity at higher SoC likely contributes to these elevated peaks (Zhang *et al.*, 2022).

Ethylene carbonate demonstrated an opposing trend, where higher peak concentrations observed more frequently at 30% SoC. As a key electrolyte solvent with a relatively high boiling point component (Bugrynec *et al.*, 2024; PubChem, 2026), this behaviour may reflect slower, more prolonged decomposition under lower energy conditions. Additionally, its lower volatility may allow it to persist longer during the heating phase, leading to higher measured peak concentrations compared to the more rapid volatilisation observed at higher SoC.

Hydrogen chloride, methane, benzene, chlorobenzene, ethylene carbonate, toluene, benzaldehyde, hydrogen cyanide, acetylene, dimethyl carbonate, ethyl methyl carbonate, diethyl carbonate, propylene carbonate, carbonyl sulphide, hexane, carbon dioxide, carbon monoxide, acetaldehyde, hydrogen fluoride, ethylene, and styrene showed inconsistent or minor SoC dependency, indicating that SoC alone does not fully determine their emission behaviour.

Table 12. Distinct compounds for SoC-dependent hazards. ^ = scenario that was higher.

Array	Gas species	Scenario	$\bar{x}$	σ	Min	Q1	Median	Q3	Max
25	Carbon dioxide	100%^	0.14	0.09	0.06	0.08	0.10	0.17	0.39
		30%	0.05	0.01	0.04	0.05	0.06	0.06	0.07
26	Carbon dioxide	100%^	0.06	0.01	0.04	0.05	0.06	0.07	0.08
		30%	0.02	0.00	0.02	0.02	0.02	0.02	0.03
	Ethylene carbonate	100%^	1.51	0.90	0.12	0.39	1.89	2.30	2.38
		30%	0.22	0.14	0.07	0.09	0.23	0.32	0.55
27	Ethylene carbonate	100%	1.74	0.31	1.32	1.35	1.81	1.89	2.34
		30%^	6.08	2.77	2.14	3.77	6.12	7.61	12.50
29	Ethylene carbonate	100%	0.36	0.31	0.14	0.17	0.26	0.32	1.29
		30%^	1.87	1.32	0.78	0.97	1.00	3.66	3.75
30	Ethylene carbonate	100%^	0.41	0.25	0.17	0.26	0.33	0.51	1.04
		30%	0.24	0.06	0.17	0.20	0.22	0.25	0.42
32	Carbon dioxide	100%^	2.18	1.17	0.51	1.11	2.23	3.22	4.23
		30%	0.74	0.55	0.14	0.35	0.59	0.80	1.94
	Ethylene carbonate	100%	0.02	0.04	0.00	0.00	0.00	0.01	0.19
		30%^	41.29	34.18	5.54	14.31	34.72	58.16	143.03

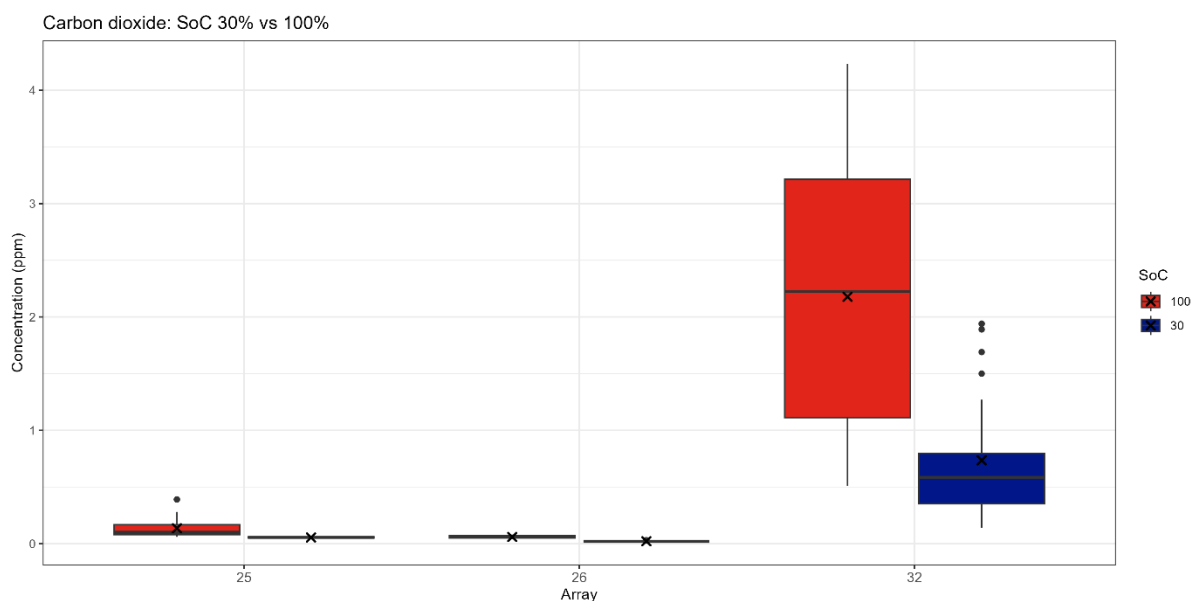


Figure 37. Carbon dioxide boxplot for SoC comparison.

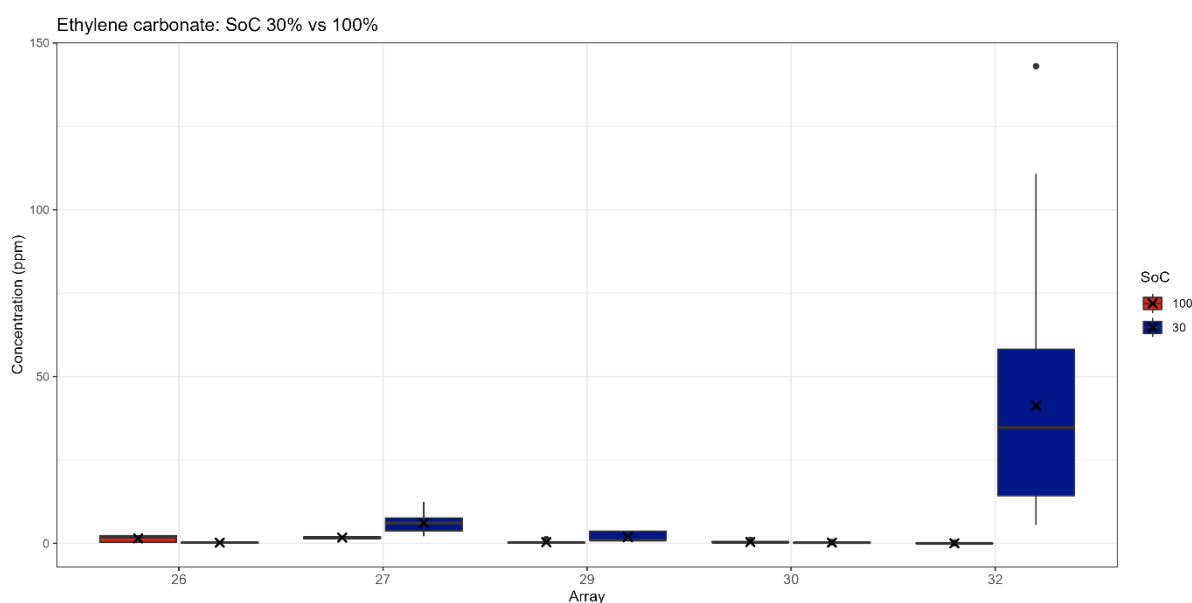


Figure 38. Ethylene carbonate boxplot for SoC comparison.

3.3.2.5 Implications for emergency response and safety management

The findings of this study support the understanding that LiB TR present significant flammability, explosion, and human health hazard risks. The hazard profile of the TR emissions was observed to be driven primarily by battery chemistry and cell format. The predominance of flammable gases, including hydrogen cyanide, methane, and acetylene, alongside VOCs, indicates a high potential for rapid fire spread and vapour cloud explosion, particularly in confined or poorly ventilated environments. Explosion risk may be amplified in pouch cell formats, which consistently produced higher peak gas concentrations.

In parallel, the presence of toxic and corrosive gases, particularly carbon monoxide, hydrogen cyanide, hydrogen fluoride, and hydrogen chloride, are substantial risks to human health. Carbon monoxide contributes to acute

toxicity through the generation of a low oxygen environment, decreasing blood oxygen levels (Zhang *et al.*, 2022; McMahon and Launico, 2026), while hydrogen cyanide, hydrogen fluoride and hydrogen chloride present severe respiratory and dermal hazards (Zhang *et al.*, 2022; Bugryniec *et al.*, 2024; PubChem, 2026), with the potential for both immediate and delayed health effects. The elevated presence of these gases in certain chemistries, particularly LFP systems, highlights the need to consider toxicity alongside fire behaviour when assessing incident risk.

For emergency response agencies these findings support the need to treat all TR events as multi-hazard incidents. Operationally, this includes the establishment of conservative exclusion zones, particularly for incidents involving pouch cells or occurring in enclosed environments, where there is an increased risk of explosion. Continuous atmospheric monitoring for flammable gases, carbon monoxide, and where possible, acid gases should be implemented to inform dynamic risk assessment. The routine use of self-contained breathing apparatus (SCBA) and full structural PPE is essential to mitigate inhalation and contact hazards. Ventilation strategies should be applied cautiously to reduce gas accumulation while avoiding unintentional ignition. Additionally, decontamination procedures and post-incident monitoring should be incorporated due to the persistence of toxic and corrosive by-products.

Overall, the variability and peak behaviour of emitted compounds demonstrate that no single factor reliably predicts hazard severity. As such, a precautionary, worst-case approach to incident management, supported by gas monitoring, appropriate PPE and PPC, and clear zoning, is critical to ensuring responder safety.

3.4 Study limitations

Several limitations should be considered when interpreting these findings.

Only three repeats were conducted per condition, limiting statistical robustness and potentially amplifying the influence of variability inherent to TR events. Some observed trends may therefore reflect outlier behaviour.

The study was limited to 21 targeted compounds, meaning additional gases, particularly transient or low-concentration species, may not have been captured. As such, the hazard environment may be broader than reported.

Cells were matched by size rather than capacity, introducing variability in stored energy and potentially influencing emission magnitude independently of chemistry or format.

Finally, not all tests progressed to complete destruction of the cell. Partial decomposition may underestimate peak emissions and associated hazards.

Despite these limitations, the dataset provides valuable insight into emission trends and hazard characteristics. Therefore, results should be interpreted as indicative rather than definitive.

4 Part B: Efficacy and safety of new and existing extinguishing agents and methods on lithium-ion battery fires

4.1 Background

The frequency and magnitude of e-mobility fires have introduced a new and complex hazard for emergency services. The toxic vapour clouds, intense heat flux, and flaming projectiles generated in these events can cause rapid fire propagation and injury. This study seeks to quantify the risks by characterising the thermal and temporal signatures of e-bike-scale battery packs and assess the efficacy and impacts of current firefighting tactics.

The approach herein focuses on the interaction between battery architecture and emergency intervention and identified casing material as the primary governor of fire behaviour. Three common configurations of steel, aluminium, and shrink-wrap battery enclosures were therefore assessed. By establishing baseline characteristics for these events, the effect of the suppression agents and tactics can be measured.

The study utilises statistical modelling, including one-way ANOVA and Hedges' g effect size analysis, to determine how these interventions compress the fire timeline and reduce thermal volatility. This methodology allows for the precise quantification of agent efficacy, providing a data-driven baseline for modern e-mobility firefighting tactics.

4.2 Methodology

4.2.1 Test parameters

To determine the efficacy of the test extinguishment agents, 45 tests were conducted using batteries reflective of those used in high-capacity e-micromobility devices such as e-bikes and e-scooters. These batteries were selected for the extinguishment tests as they are portable and can be moved into indoor or enclosed environments. These types of batteries have featured in incident data (FRNSW, 2024) for both frequency and severity of the fire outcomes. It is well understood that charging and storage of e-micromobility batteries in indoor settings poses great risk to occupants, therefore these scenarios were prioritised for extinguishment efficacy and safety assessment.

4.2.1.1 Battery preparation

The test batteries were constructed from three separate packs of 18650 NMC cylindrical cells arranged in 13s5p for a total of 65 cells per module (Figure 39). The nominal capacity was labelled as 650 Wh. Each module had cell separators on both ends with nickel bus bars connecting the rows and battery management system (BMS), charge, and output wiring at one end of the module (Figure 40). The whole assembly was encased with fibreglass adhesive tape, solid fibreglass panels and PVC shrink wrap.

To prepare the battery packs for testing, the modules were opened and the BMS from each was removed. An alternative BMS was used for capacity testing and recharging each pack. At 100% SoC pack capacities exhibited significant variance, ranging from a minimum of 466 Wh to a maximum of 667 Wh ($\bar{x}$ = 605 Wh).

Three modules were matched for a total capacity of approximately 1.8 kWh. They were then re-sealed with high-temperature polyimide film tape and assembled with an outer enclosure.

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Figure 39. (a) The test pack (b) The packs with outer fibreglass panels and shrink-wrap casing removed. NMC 18650 cells in 13s5p arrangement.

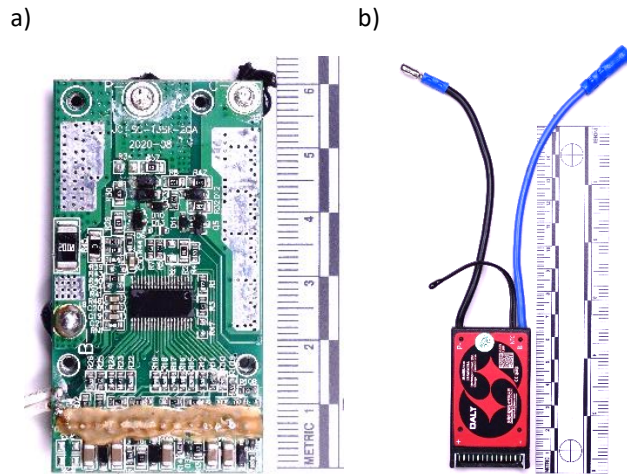


Figure 40. (a) The BMS removed from the pack (b) The 48 V 14S 20 A BMS modified for charging and capacity testing.

Four 0.5 mm mono-core fibreglass insulated K-type thermocouples were placed in the centre between packs along the length of the battery. And two further thermocouples were placed on top of and below the outer enclosure when the battery was in test position (Figure 41).

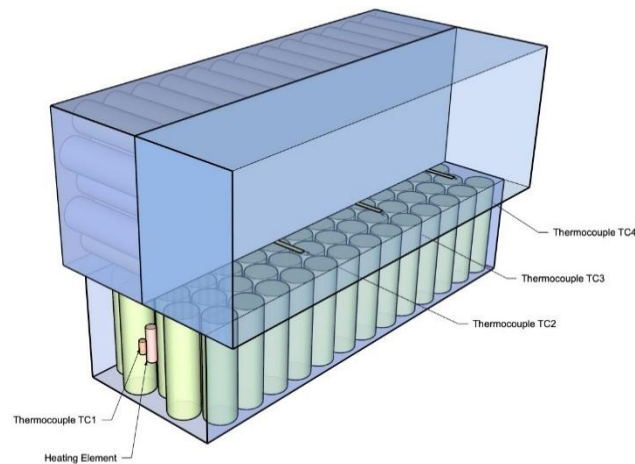


Figure 41. Diagram of thermocouple and heating element position within test unit.

4.2.1.2 Battery enclosures

Three pre-prepared packs were covered in PVC shrink tubing (shrink wrap) before fitted inside purpose made enclosures to form the test battery pack (Figure 42). The cases were constructed from 0.95 mm 250 grade mild

steel or 1 mm 5005 aluminium. The steel² and aluminium³ cases were intermittent chain welded along the seams. Slip-fit lids of the same material were secured by screws to the case. One 10 mm hole on the lid allowed pass-through of internal sensors and the heating element.

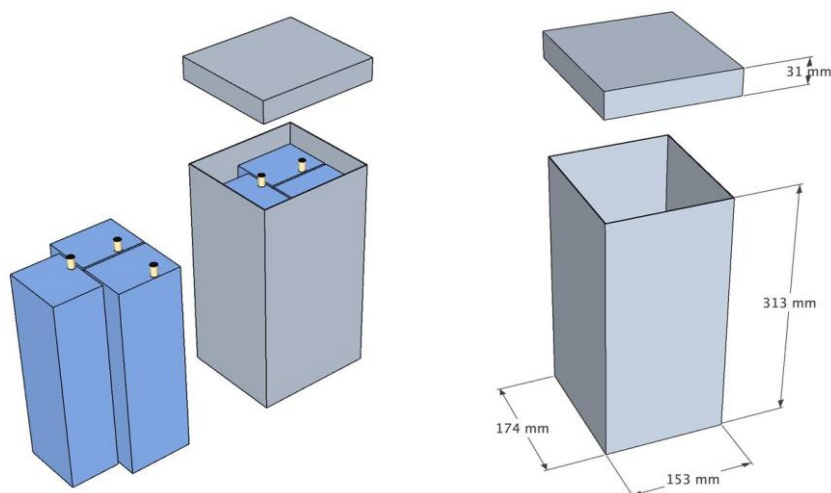


Figure 42. The arrangement of packs inside the battery enclosure and the internal dimensions of the aluminium and steel enclosures.

4.2.1.3 Extinguishing media

Two suppression methods were selected for assessment: water extinguishment with and without encapsulating additive and fire blankets, both conventional and LiB specific.

- Standard fire blanket - Advertised as compliant with AS/NZS 3504, constructed from woven fibreglass material, measuring 1.2 m x 1.8 m and a dry weight of approximately 1.1 kg.
- Lithium-ion battery-specific fire blanket – marked as compliant with AS/NZS 3504:2006 and EN 13501-1:2018. The markings state a continuous temperature resistance of 550 °C with short-duration spike resistance up to 750 °C, and suitability for batteries up to 1.2 kWh. The blanket had equivalent physical dimensions (1.2 m x 1.8 m) and dry weight (approximately 1.1 kg) to the standard fire blanket for comparative purposes.
- Water – municipal water, without any additives or treatment.
- Encapsulating agent Class A foam – foam concentrate mixed with municipal water to a 4% concentration, per manufacturer recommendations.

The media were tested against NMC batteries at 100% SoC based on thermal volatility observed in previous testing. The test matrix for this set of testing is provided in Table 13.

² 250 grade steel has a solid melting point of ~1425 °C and a liquid melting point of ~1530 °C. From: ASM International. Handbook Committee, 1990. Properties and Selection--Irons, Steels, and High-performance Alloys (Vol. 1). ASM international.

³ 5005 grade aluminium has a solid melting point of ~630 °C – 632 °C and a liquid melting point of 650 °C – 657 °C. From: ASM Handbook Committee, 1990. Properties and selection: nonferrous alloys and special-purpose materials. ASM international.

Table 13. Test matrix for efficacy and safety of extinguishing agent tests.

Chemistry	SoC (%)	Casing	Extinguishing treatment	Test
NMC	100	Shrink wrap	Free burn	1 – 3
		Shrink wrap	Standard fire blanket	4 – 6
		Shrink wrap	LiB fire blanket	7 – 9
		Shrink wrap	Water	10 – 12
		Shrink wrap	Encapsulating agent	13 – 15
		Aluminium	Free burn	16 – 18
		Aluminium	Standard fire blanket	19 – 21
		Aluminium	LiB fire blanket	22 – 24
		Aluminium	Water	25 – 27
		Aluminium	Encapsulating agent	28 – 30
		Steel	Free burn	31 – 33
		Steel	Standard fire blanket	34 – 36
		Steel	LiB fire blanket	37 – 39
		Steel	Water	40 – 42
		Steel	Encapsulating agent	43 – 45

4.2.2 Test location

The tests were conducted in open air on a large concrete staging area designed for the collection of contaminants and water. The battery packs were placed in the centre of a 1.8 x 1 m stainless steel tray.

4.2.3 Test abuse method

To induce TR, a 40 W cylindrical heating element connected to a DC bench power supply was placed at one end of the battery packs using a copper wedge and thermally conducting paste. Cell heating was selected for experimental reproducibility and its naturalistic analogue as both endogenous and exogenous failure modes. One thermocouple was placed adjacent to the heating element and TR was initiated by applying approximately 40 W of heating. Heating was ceased when TR was visually confirmed. Firefighting activities were commenced five minutes ($t = 300$ s) from this time point.

4.2.4 Firefighting method

All extinguishment was conducted by researchers who are also active, operational firefighting personnel wearing structural firefighting PPC and SCBA. A helmet-mounted camera recorded first-person video footage of each test and extinguishment activity and a hand-held firefighting thermal imaging camera (TIC) with recording capability was also used to document thermal behaviour and assess extinguishment effectiveness.

Two firefighters were stationed adjacent to the test area and observed the test both directly and via live multi-camera video feed. A five-minute intervention timer was initiated at the point when the first signs of TR were observed. This period allowed a high variation in the failure conditions of the test battery and reflected a realistic operational response time. Once the timer had elapsed, the firefighters commenced the suppression tactics.

For firefighting intervention using fire blankets, two types of fire blankets were evaluated. Both blankets were applied using standard first-attack firefighting best practice. Blankets were furled over gloved hands to improve control and provide thermal protection during placement. Where practical, firefighters approached upwind of the smoke and vapour plumes. Avoiding projectile and thermal hazards were prioritised when necessary but were difficult to predict. Efforts were made to minimise air entrainment during application. Due to the fire dynamics in some tests, the blankets could not easily be applied in a way that adequately minimised airflow to the fire. Where safe, firefighters adjusted the blanket during the initial application to improve coverage.

For firefighting intervention using liquid extinguishing agent tests, a portable firefighting pump (Aussie Pumps, QP205SE) with a 750 kPa pressure and up to 450 litres per minute flow rating were used. Media was delivered through a single nitrile rubber/PVC fire hose (FireStrike 38 mm) and applied using a pistol-grip firefighting branch (Protek 366). The branch operating pressure was 700 kPa, with a selectable flow rate of 115, 230, 360, or 475 litres per minute. A flow of 115 L/min was used for most tests and was generally sufficient when direct access to burning materials was achieved.

The firefighters emulated fire attack procedures used in a residential unit fire originating from a LiB failure. This scenario-based approach was used to replicate realistic firefighting constraints, specifically the need to balance suppression efficacy against the unintentional damage caused by excessive liquid application.

The effectiveness of fire control was determined by the firefighter observing of the quantity of smoke and vapours, flame behaviour and TIC temperature readings. When the battery was deemed safe to move, a long shovel handle was used to manipulate and immerse the battery in a water bath positioned close to the test area and was instrumented to monitor water temperatures. In some tests, to protect the integrity of the plastic drum floor, the battery was suspended in the water to allow further cooling prior to being fully submerged.

After each test, the firefighter filled out a survey to record their actions and characterise them by rating the smoke and vapour production, projectiles, explosions and thermal risks. They also recorded their perception of personal risk from these factors as well as an overall risk perception score.

4.2.5 Instrumentation

4.2.5.1 Temperature, heat flux, and mass

The battery was instrumented with four (4) internal and two (2) external k-type thermocouples. Two (2) Hukseflux heat flux gauges were placed orthogonally 1.8 m from the test battery. Four (4) load cells were used to monitor real-time mass loss; however, this data were discarded as they were significantly confounded by the unknown quantity of ejected materials and the dynamic forces of combustion-induced thrust.

4.2.5.2 Gas analysis

Gas analysis was conducted using the same method as described in Section 3.2.5.2. The FTIR sampling probe was placed 1 m away and aimed directly at the test battery pack.

4.2.5.3 Other

Environmental monitoring was achieved using a Davis 7509L weather station mounted to a 10 m mast located adjacent to the testing stage.

Multiple video cameras were placed between 1 and 10 m away to provide a variety of viewpoints and the security of the wider test area.

At the start of each test, a 60 s baseline was run before heating was initiated to allow for a baseline temperature, mass and gas readings to be gathered for each test. Cell heating was initiated via the NI-DAQ system and ceased when TR was visually confirmed.

4.2.5.4 Liquid extinguishing agent mass

The liquids used in the test were quantified via an instrumented 1000 L intermediate bulk container (IBC). Four load cells were placed underneath the container for mass and flow rate calculations.

4.2.6 Data analysis

4.2.6.1 Extinguishment effectiveness and TR characterisation

TR events were evaluated using two distinct metrics. Visual TR was identified by the presence of flames, smoke and/or vapour. In addition, a numerical derived duration was recorded using internal thermal data. TR period was isolated using temperature and slope thresholds. A battery segment was determined to be no longer in TR once a cooling logic was satisfied, defined by a sustained downward temperature slope and the absence of future acute heating events. The cooling behaviour of the control tests was analysed, yielding an average cooling constant of $k = 0.0008$. Cooling constant was used to formulate of a predicted cooling curve, which was applied to extinguishment data to compare cooling efficacy.

The coefficient of variation (CV) represents the relative dispersion of data points in a data series around the mean. Expressed as a percentage, it is calculated by dividing the standard deviation (σ) by the mean ($\bar{x}$) ($CV = \sigma/\bar{x}$). A value of 0 - 10% represents high predictability, 10 - 20% shows trends but has included experimental noise and >30% indicates volatile or inconsistent results. CV provides a standardised metric to disaggregate the data.

To quantify the impact of test variables, standardised effect sizes were calculated using Hedges' g to provide a bias-corrected estimate the effect size of suppression on peak temperatures and event durations. Hedges' g incorporates a correction factor (J) to provide a more reliable measure of intervention effectiveness in small samples sizes (Borenstein *et al.*, 2013) (Table 14). For analysis of event duration, interventions with negative g value represent a reduction in TR duration relative to the control. Positive g values represent prolonged durations.

A one-way analysis of variance (ANOVA) was used to evaluate whether the extinguishing media significantly affected peak internal temperatures. The method partitions the total observed variance into between-group and within-group components to assess if the differences in group means are greater than the variability inherent to the fire events. The analysis was performed with a significance threshold of 0.05.

Table 14. Hedges' g values and corresponding effect magnitudes (Borenstein *et al.*, 2013).

Hedges' g Value	Effect Size
0 to -0.2	Negligible: The intervention demonstrates no meaningful impact. The differences are statistically indistinguishable from baseline control variance.
-0.2 to -0.5	Small: A marginal effect. The magnitude remains within the threshold of experimental noise. Efficacy cannot be reliable determined at this value.
-0.5 to -0.8	Medium: An evident shift in the result. While the effect is demonstrably active, a degree of distributional overlap exists between the treatment and control datasets.
-0.8 to -1.2	Large: High practical significance. The effect has a substantial and reliable effect on the result. These values represent a statistically robust effect size.

A description of the equations used for these analyses and further results are provided in Appendix B.

4.2.6.2 Projectiles and ejecta

Following each test (prior to site remediation), any ejecta from TR was recorded, and the distance was measured from the centre of the test battery. Ejecta was classified to two main categories: a debris field and significant projectiles. The debris field was classified as the area directly around the failure event which demonstrated a high density of debris, which could consist of fine particulates, whole cell casings, electrode material and battery housing material. When a debris field was present, the diameter was recorded (in metres (m)).

Although there was a wide range of materials ejected during battery failure, a significant projectile was counted when either cell casing or electrode material that had been ejected outside of the debris field. The distance and relative location from the battery's location was recorded after each test in which 'significant projectiles' were

present. Some ejected material, such as small amounts of electrode foil, were outside of the debris field but were not recorded. Examples of the debris field and a significant projectile can be found below (Figure 43 and Figure 44).



Figure 43. Example of an ejecta classified as a 'Significant Projectile', approximately 13 m from point of origin .

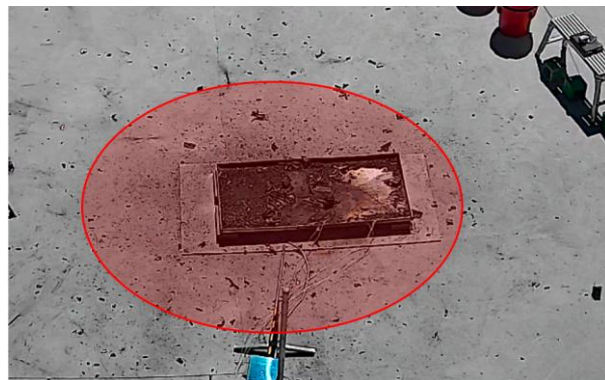


Figure 44. Example of area surrounding test battery denoted as the 'debris field'.

During data analysis, the testing area was divided into octants, as seen in Figure 45. Information including projectile location (based on octant location), case types, firefighter intervention time was noted.

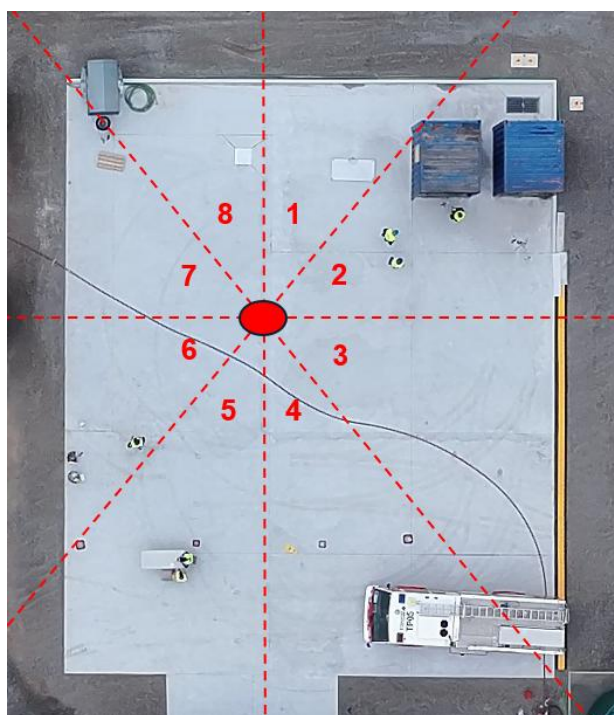


Figure 45. Overhead view of test location and segmentation of octant designations for analysis.

4.3 Results and discussion

4.3.1 Characterisation of baseline visual thermal runaway event duration

A total of nine, free-burning control tests were performed. Across all tests, the visual TR period exceeded the numerically derived duration (Table 15).

Casing material was identified a key factor in the lack of uniformity in the baseline thermal behaviour of this test group (Figure 46). The control tests showed a global mean duration of 829 s and CV of 30.2%. Trends emerged when the control tests were disaggregated by casing material. The aluminium housed batteries had the most predictable visual TR duration ($t_{avg} = 863$ s) and the lowest CV of 5.4%. The shrink-wrapped batteries had the most prolonged durations ($t_{avg} = 1061$ s) and moderate repeatability (CV = 16.1%). The steel cases had the shortest mean test duration ($t_{avg} = 563$ s) but were the least repeatable (CV = 30.9%).

Table 15. Average visual TR periods for all free burn tests and descriptive statistics.

	Average visual TR duration (s)	σ (s)	CV (%)
All Free Burning Control Tests	829	250	30.2
Aluminium	863	47	5.4
Steel	563	174	30.9
Shrink Wrap	1061	171	16.1

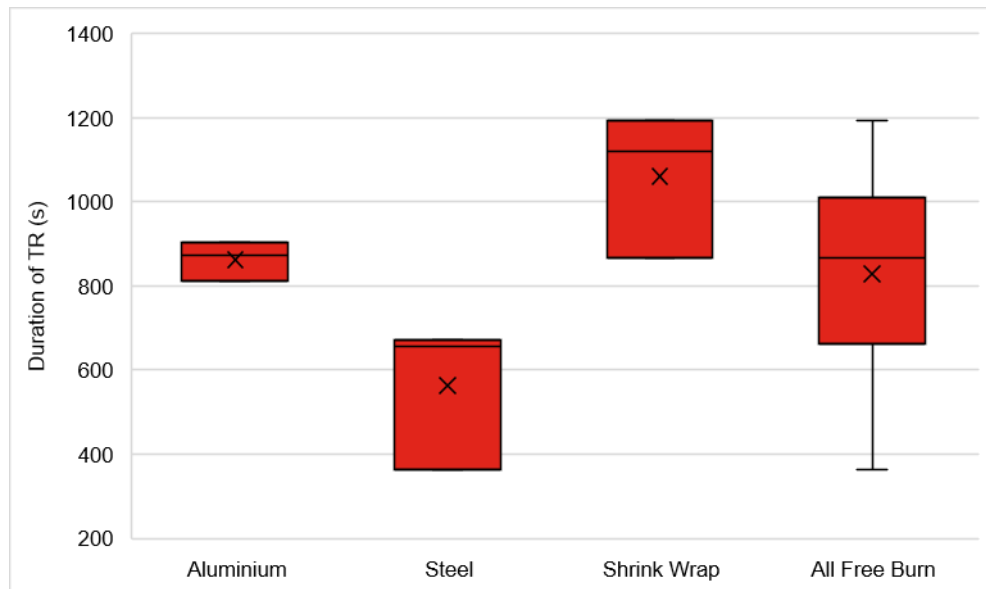


Figure 46. The distribution of TR durations across the nine baseline control tests.

The test with the longest visual TR was a shrink wrap free burn which lasted 1,194 seconds and was characterised by many ejection events dispersed amongst a baseline of low energy flaming combustion. Cells or groups of cells were ejected from the battery and were observed to begin flaming TR once separated (Figure 48). These events likely minimised their contribution to failure propagation within the battery.

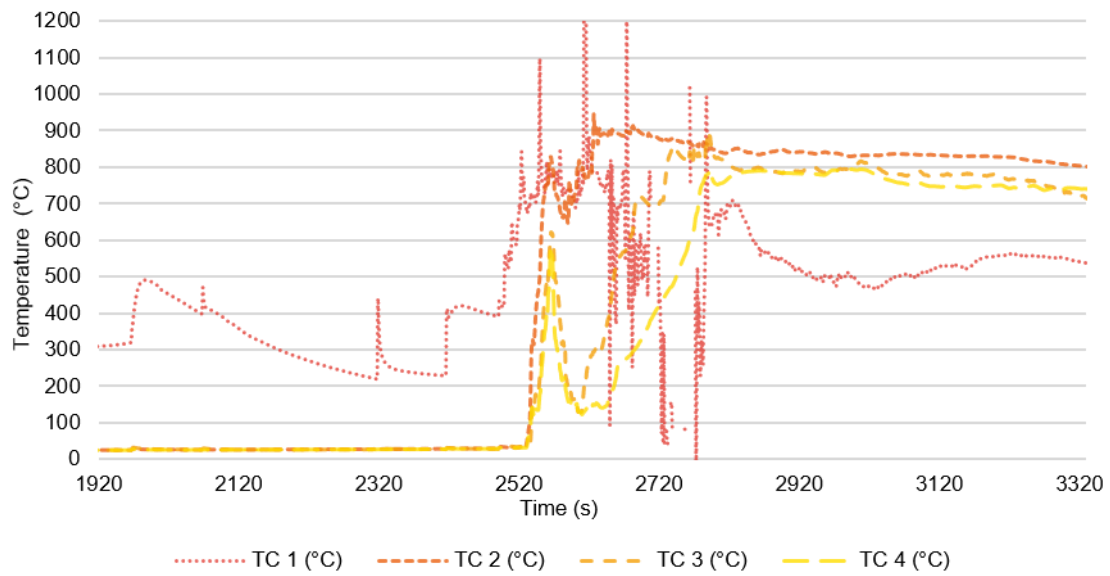


Figure 47. 'Test 16: Aluminium, Free burn', the control test closest to the mean duration of 863 s.

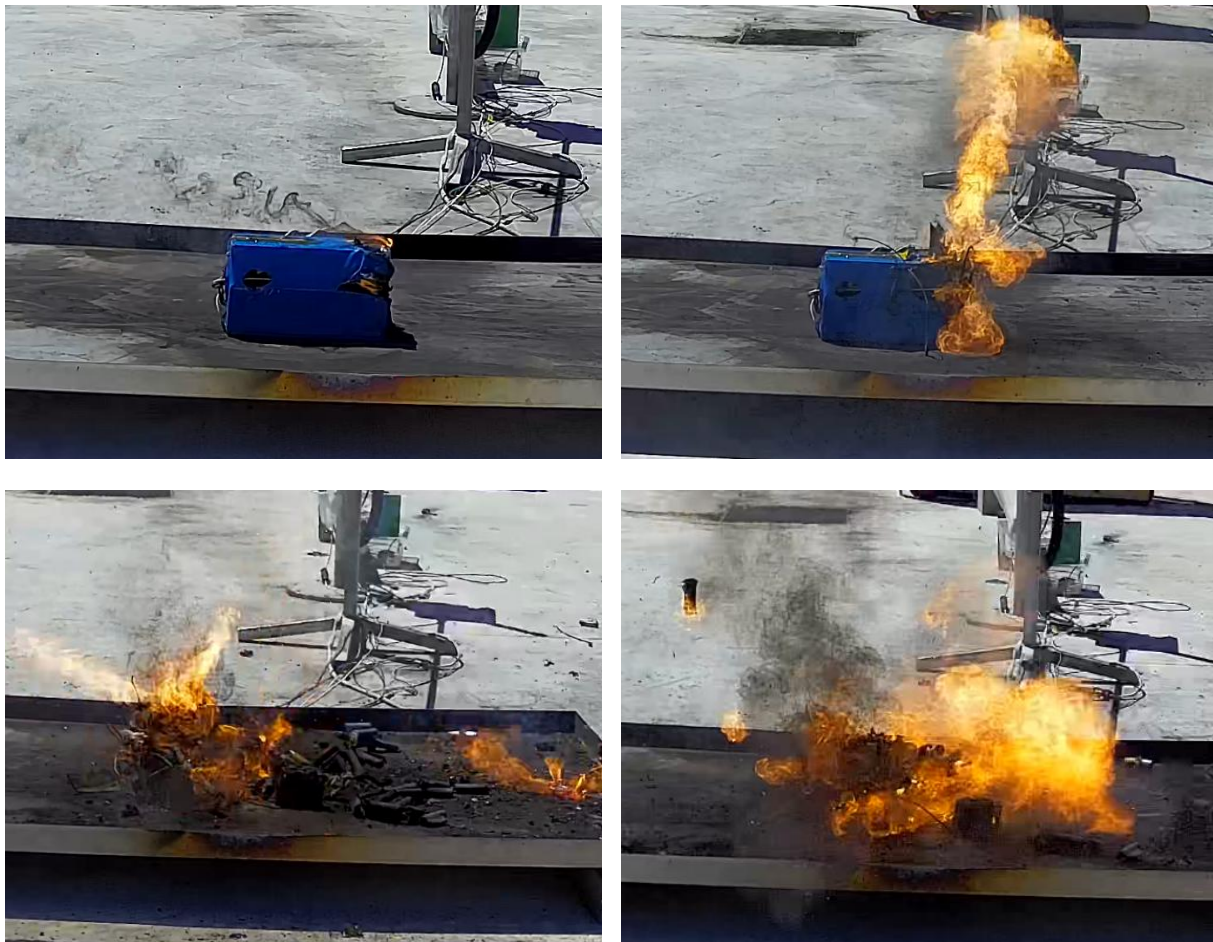


Figure 48. The failure propagation from the longest duration test 'Test 1: Shrink wrap, Free burn'.

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The steel encased specimens demonstrated the fastest TR reactions ($t_{avg} = 563$ s), with a mean duration approximately 47% shorter than those in the shrink-wrap group. The steel encased group exhibited the lowest predictability with a variance of 174 seconds and CV of 30.9%. The most rapid failure was seen in a 'Test 32: Steel, Free burn' test which lasted 362 seconds and was characterised by high volume of vapour through sustained high-pressure venting (Figure 49). The battery enclosure generally maintained its structural integrity as the vapour and solid ejecta escaped the enclosure seams and a penetration in the battery lid. The battery was observed to move and jump with these acute venting episodes. Ignition occurred when the enclosure burst open along a welded seam. Multiple cells were ejected with an acute jet-flaming event (Figure 50). The enlargement of the opening coincided with a notable reduction in both venting velocity, smoke and vapour production, and smoke opacity.



Figure 49. High rate of vapour production from high-pressure venting immediately prior to ignition in test 'Test 32: Steel, Free burn'.



Figure 50. Jet-flaming event from 'Test 32: Steel, Free burn', the shortest duration test.

4.3.1.1 Initial heating rates and event duration

To identify thermal predictability, the time between the onset of TR and the peak temperature of thermocouple 1 (TC1) was compared to the overall duration of visual TR. Linear regression analysis indicates initial heating slopes were a poor predictor of overall event duration across all casing materials (Figure 51). There was a moderate correlation for shrink wrap ($R^2 = 0.3146$), followed by aluminium ($R^2 = 0.2202$). Steel exhibited very low correlation ($R^2 = 0.0292$).

The high structural integrity of steel can act as a pressure vessel which can store heat and pressure requiring an energetic event to create an opening to the vessel. The unpredictable size of the openings can constrain the quantity of heat released. Conversely, the shrink-wrap casing has low structural integrity. The initial heating correlated better with the total event duration without the casing insulation to store heat or redirect jets.

The aluminium-cased group had a low correlation value of ($R^2 = 0.2202$) however the group did have the most consistent duration (CV = 5.4%). Although the tests had the most consistent duration, the initial thermal conditions were a bad predictor of later conditions.

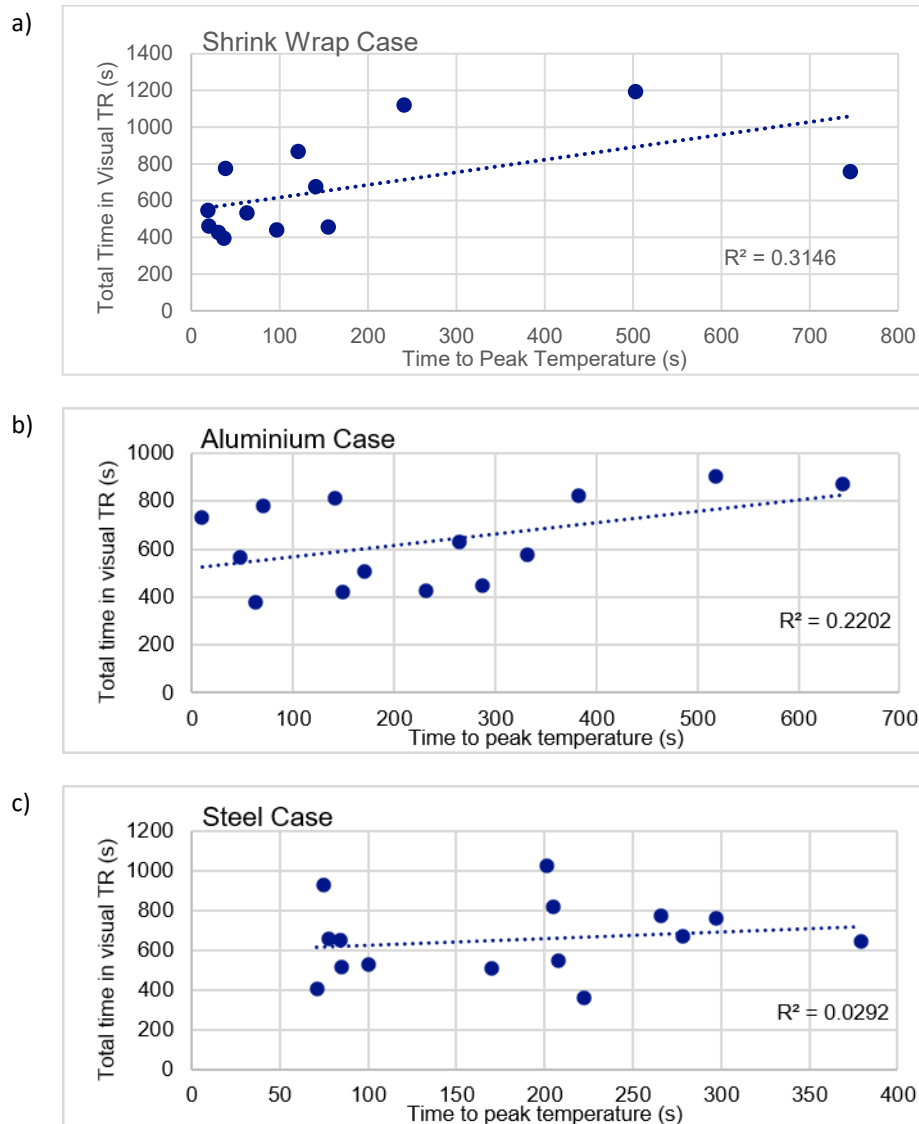


Figure 51. Time to peak temperature and the total time of the event for (a) shrink wrap case, (b) aluminium case, and (c) steel case.

The variation in R^2 values suggests the significance of the battery casing material in the thermodynamic consistency of the failure event. The absence of a rigid thermal barrier in the shrink-wrapped batteries allows the internal chemical kinetics to govern the propagation of the failure. The near-zero correlation in steel-cased tests implies the increased influence of the exogenous variables such as heat retention and internal gas dynamics.

The lack of correlation presents challenges for fire modelling that use steady growth rates. Specifically, the low R^2 results indicate that initial heating phases may be poor predictors of total fire duration for LiBs. The complexity of modelling battery fire growth is exacerbated by the high degree of variability in battery enclosure design including cells arrangement, quantity, and format. These results underscore the stochastic nature of multi-cell battery fires as nonlinear and chaotic series of interconnected processes.

4.3.2 Effects of extinguishing on thermal runaway event duration

The durations of the control tests were compared with 36 extinguishment tests using water, encapsulating agent solution in water, fire blankets, and LiB blankets (Table 16). The data in Figure 52 illustrates the effectiveness of active agents (water, encapsulating agents) in compressing the TR timeline compared to the blankets and unmitigated free-burn.

Table 16. Average visual TR periods for all extinguishment tests and descriptive statistics.

	Average Time in Visual Thermal Runaway (s)	σ (s)	CV (%)
Water	539	181	33.6
Encapsulating Agent	551	196	35.6
LiB Blanket	649	130	20.1
Blanket	694	120	17.3
Free Burn	829	250	30.2

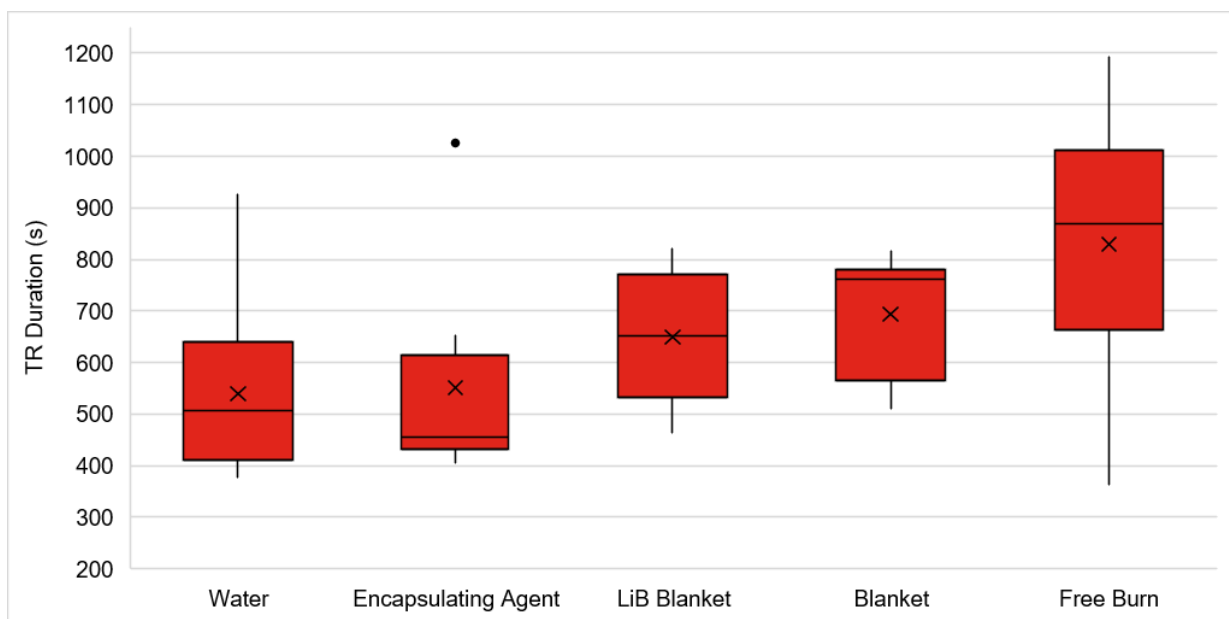


Figure 52. The distribution of visual TR durations across suppression methods and baseline controls.

The suppression effectiveness and predictability of liquid agents (water and encapsulating agent) were skewed by two anomalous tests durations $t = 927$ s and $t = 1025$ s ('Test 40: Steel, Water' and 'Test 45: Steel, Encapsulating Agent'). In both instances, the battery housing maintained structural integrity, acting as a physical barrier and impeding the extinguishing medium from contacting the cells. In 'Test 40: Steel, Water', 324.9 L of water was used prior to the battery being immersed.

In test 'Test 40: Steel, Water', water was applied to the battery with one of the four internal segments exhibiting signs of TR. Under almost continuous application of water, the failure propagated from the first segment to the remaining three. Temperature rose from ambient conditions to peak temperatures in 117 s, 139 s, and 101 s,

respectively. From the peak temperatures, there was close agreement with the predicted cooling curve (cooling constant $k = 0.0008$), suggesting water was not cooling these segments between 230 s and 439 s, after which point a cooling slope of < -2 °C/s was achieved. When water was first applied, there was no instantaneous cooling effect on three of the four internal thermocouples, which recorded a rate of change of 0.4 °C/s, 13.9 °C/s, and 1.3 °C/s at TC2, TC3, and TC4, respectively (Figure 53). Water vapour was observed rising vertically from the seam of the battery case. Simultaneously, darker vapours from TR escaped tangentially (Figure 54).

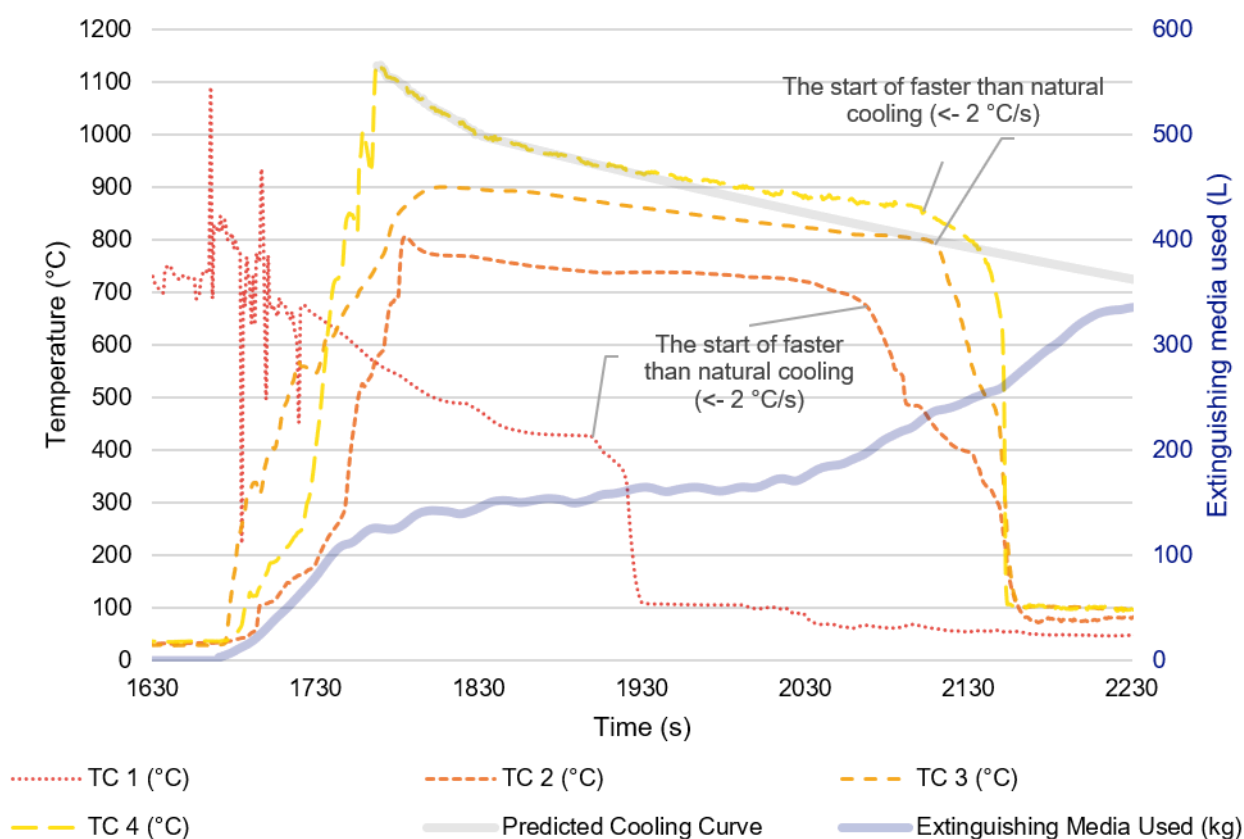


Figure 53. Internal battery temperature and extinguishment water used in 'Test 40: Steel, Water'. TC1-TC4 reached a cooling slope of < -2 °C/s in 230 s, 395 s, 439 s, and 431 s.

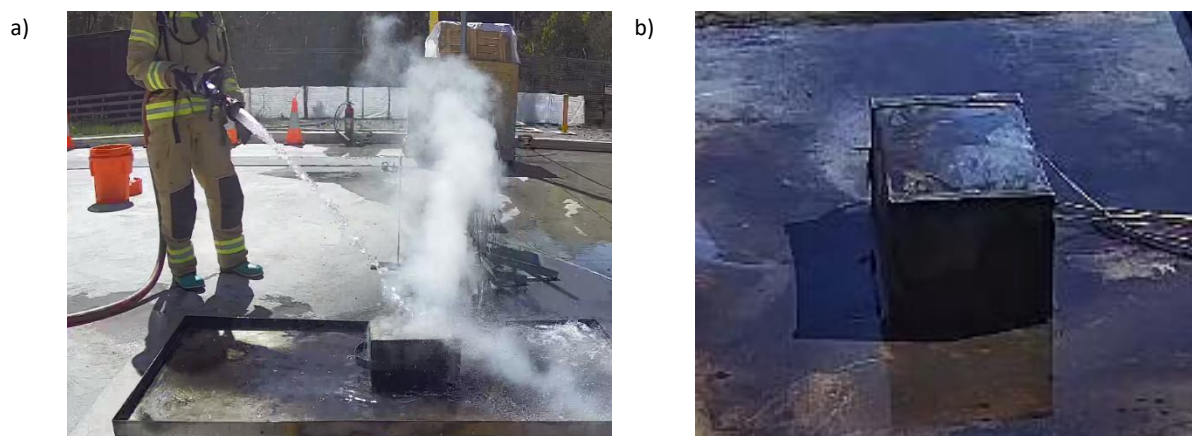


Figure 54. (a) The reaction to water extinguishment in test 'Test 40: Steel, Water', and (b) the case after extinguishment.

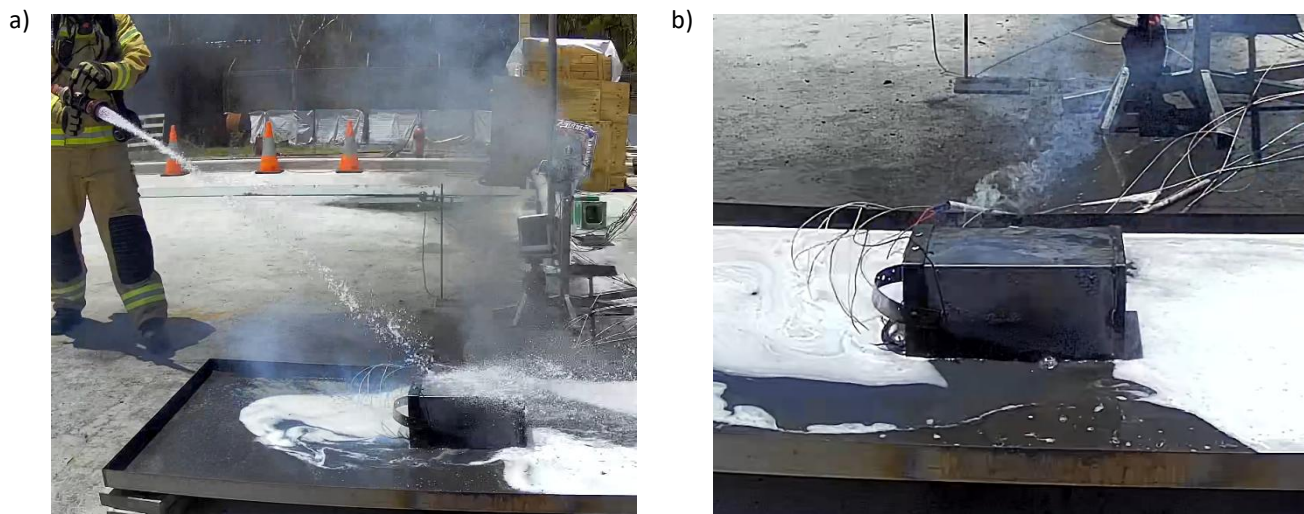


Figure 55. (a) The encapsulating agent being applied ('Test 45: Steel, Encapsulating agent'). (b) The case integrity after the application of the liquid agent, note the vapour escaping through the thin seam of the case.

'Test 44: Steel, Encapsulating agent' recorded a visual TR period of less than half of the above two tests ($t = 403$ s). The casing burst open along the long seam immediately prior to extinguishment. The subsequent orifice had a wide aperture that allowed the liquid to enter and pool within the case. Immediately upon the application of the liquid, energetic ejections and a distinct increase in smoke and vapour opacity and volume were observed (Figure 56). The orifice aperture and case allowed for liquid to pool and submerge the cells (Figure 57). In total, 32.8 L of liquid encapsulating agent was used in the extinguishment.

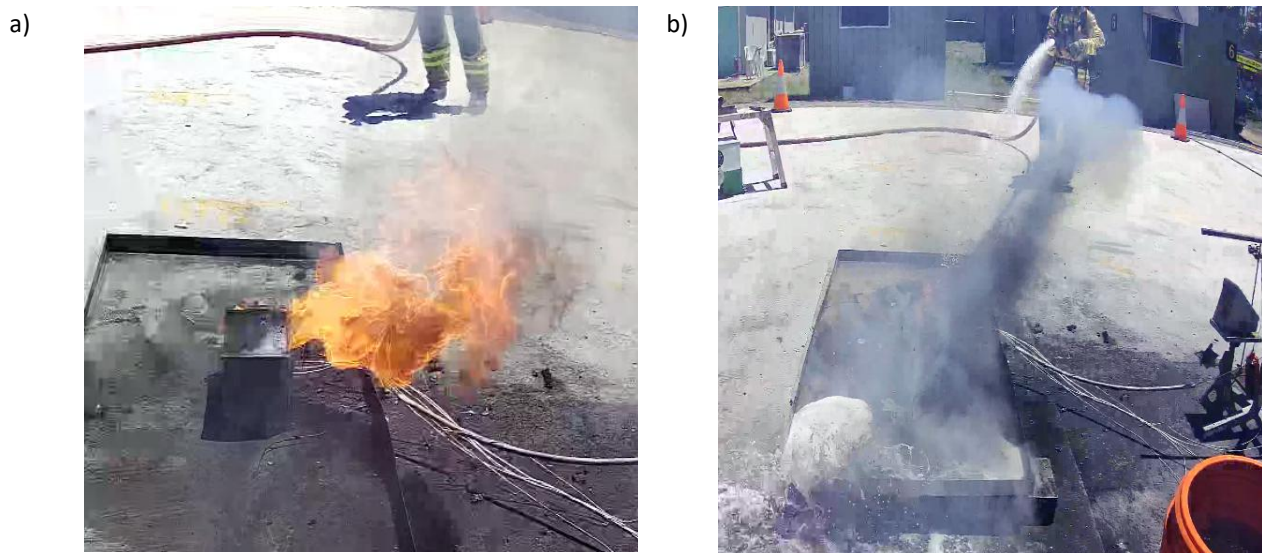


Figure 56. (a) The battery casing burst open along the long seam immediately prior to extinguishment, there was flaming combustion with vapour and smoke ('Test 44: Steel, Encapsulating agent'). (b) The encapsulating agent was applied. Acute ejections and a distinct increase in smoke and vapour opacity and volume were observed.



Figure 57. The battery casing opening along the seam. Encapsulating agent can be seen to pool in the case as water vapour continues to be emitted ('Test 44: Steel, Encapsulating agent').

The shortest TR duration recorded with extinguishment was $t = 376$ s ('Test 27: Aluminium, Water'), characterised by a transient, high-velocity venting of vapours through a small opening in the case followed by a significant ignition event. These narrow orifices intensified the jet flaming. At the commencement of extinguishment ($t = 300$ s), the combustion intensity had declined to a localised low-energy flame. Approximately 50% the casing was destroyed allowing extinguishing water to reach the remaining cells (Figure 58).

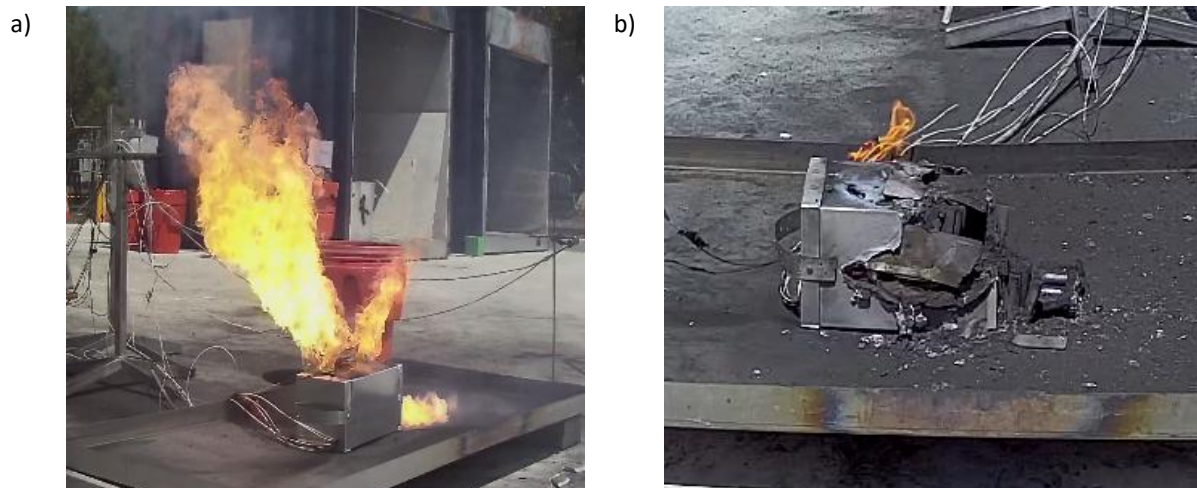


Figure 58. (a) The jet-flaming through narrow orifices ('Test 27: Aluminium, Water'). (b) The battery casing immediately prior to the application of water ($t = 300$ s).

4.3.2.1 Extinguishing effect size - Hedges' analysis

Internal thermal behaviour was analysed to determine individual TR durations, volatility, slope, peak temperatures, and to calculate failure propagation times. The resultant duration values were analysed to compare the strength of each intervention against each battery casing type (Figure 59).

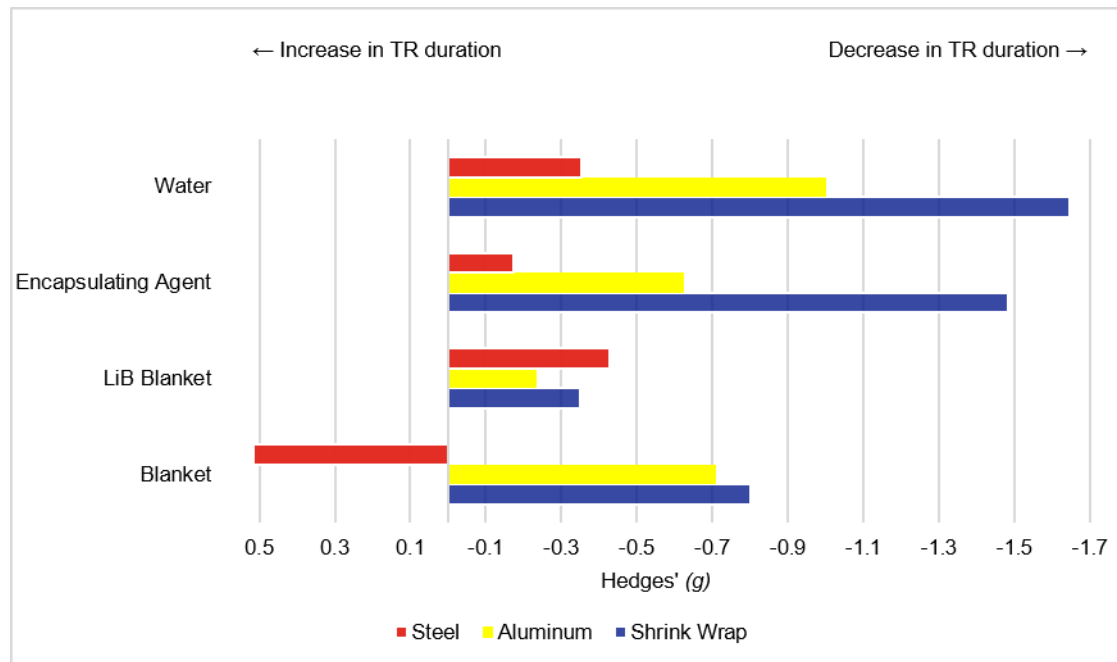


Figure 59. The effect size of each extinguishing agent on TR duration separated by battery case material.

Hedges' analysis provides an overview of how the battery casing affects fire suppression. As much of the shrink-wrapped battery casing material were consumed prior to the application of the agent, it offered less physical protection from external cooling and thereby resulted in the highest suppression efficacy amongst all enclosure materials. The values for tests using both the encapsulating agent ($g = -1.48$) and water ($g = -1.65$) represent very large effect sizes.

The tests with aluminium-encased batteries had reliable suppression with lower magnitudes than shrink wrapped batteries. Water was also the most effective agent amongst these tests ($g = -1.00$).

A steel-cased battery had the only positive effect size across the tests where the event duration increased with the application of the fire blanket ($g = 0.52$). Apart from this result, each combination of case material and agent resulted in a reduced TR duration (negative g).

4.3.2.2 Extinguishing effect size on temperature

A one-way ANOVA analysis was conducted to compare the effect of extinguishing media on peak temperatures (Figure 60). There was a statistically significant difference between groups ($F(4,163) = 15.30$, $p < 0.001$) most notably within the liquid agents. The encapsulating agent demonstrated the highest performance with the lowest mean peak temperature (609.2 °C), a 42.8% reduction compared to the controls (1065.4 °C). The encapsulating agent group also exhibited the highest variance (223,709.5), with a wider range of thermal outcomes compared to the blanket interventions. Water also reduced mean peak temperature (861.3 °C). Both the standard fire blanket and the LiB Blanket remained closer to the control values, with mean temperatures exceeding 1000 °C, indicating their limited capacity for heat extraction during the peak TR phase.

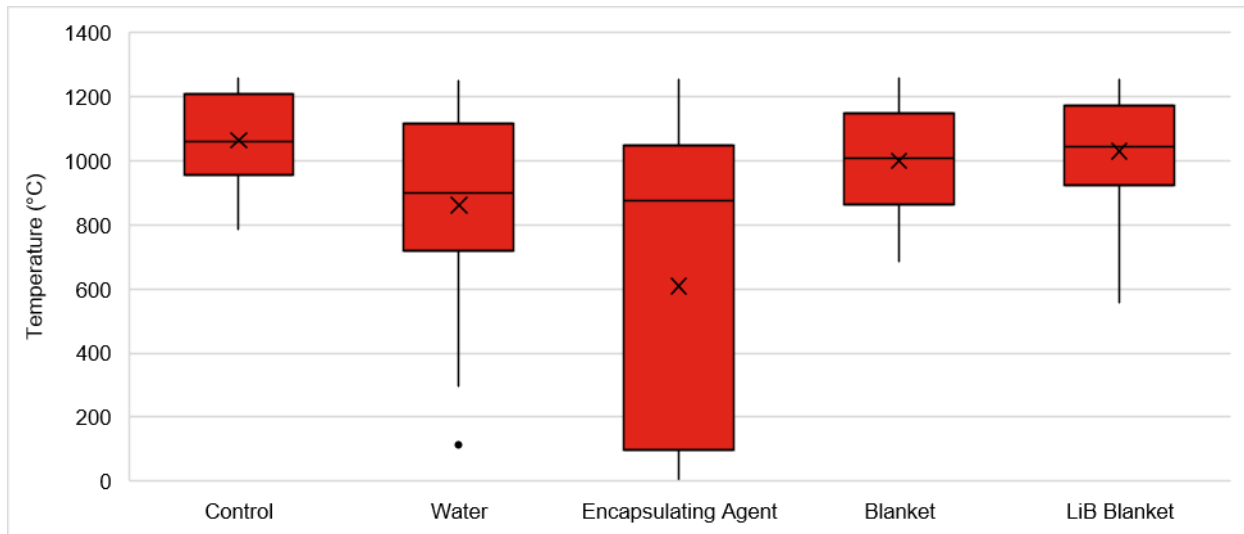


Figure 60. Peak test temperatures grouped by extinguishing agents.

Hedges' analysis on peak temperatures indicate that the encapsulating agent provided the most substantial reduction ($g = -1.3$), though it exhibited significantly higher variance compared to the control group. Water also had a large effects size ($g = -0.9$) on peak temperature. Both the fire blankets and LiB blanket had limited effect sizes ($g = -0.4$ and $g = -0.2$, respectively) (Figure 61).

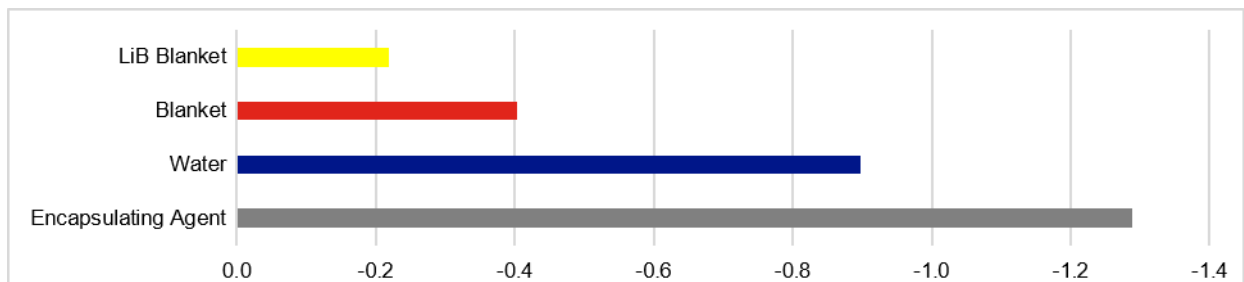


Figure 61. Hedges' g effect size of extinguishing agents on peak temperatures.

The highly variable progress of the failure propagation for each test was a large contributing factor to the variability in the results of the encapsulating agent. Three of the 45 tests had not propagated from initial TR to the remaining segments of the battery. As an example in 'Test 30: Aluminium, Encapsulating agent', at 300 s when the extinguishment was applied, the remaining segments in the packs were measured at <10 °C above ambient conditions. The progress of the initial failure was also a contributing factor as the time to peak temperature for TC1 was $t = 332$ s, 136 s later than the average (mean time to peak for TC1 was 196 s). The remaining segments continued to display a slow rate of heating but never exceeded temperatures likely to induce TR (Figure 62).

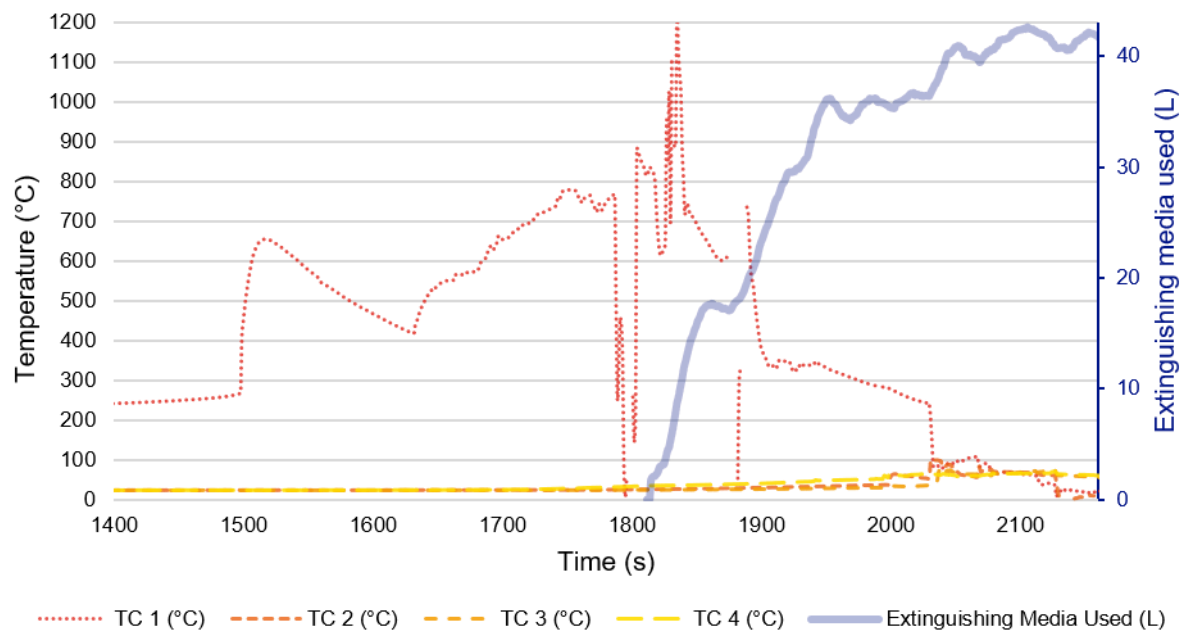


Figure 62. The test chart from 'Test 30: Aluminium, Encapsulating agent' where there was no failure propagation to TC 2 - 4.

4.3.2.3 Instantaneous extinguishing effectiveness

To quantify the instantaneous efficacy of the suppression method, a differential analysis of the heating rate (dT/dt) was performed. The background thermal conditions ($t = -10$ to 0 s) were subtracted from the post-application slope ($t = 0$ to 10 s) to form a 20-second window, centred on the moment of agent application, to provide an instantaneous rate of change $d(dT/dt)$ that represents the thermal behaviour the moment the suppression agent was applied.

Where liquid agents were used, this value can also demonstrate their ability to reach the effected cells. Where the liquid agent made unobstructed contact with the cells, the cooling effects were observed by acceleration of the cooling slope. When the battery casing physically obstructed the liquid agent, continuation of TR, failure propagation, naturalistic cooling rate, and heat transfer were all observed (Table 17).

Table 17. Descriptive statistics of the instantaneous cooling rate ($d(dT/dt)$) for various extinguishing agents.

Metric	Water	Encapsulating Agent	Blanket	LIB Blanket
$\bar{x}$ (°C/s)	-10.97	-4.00	-0.55	0.07
Standard Error	4.13	2.65	2.11	2.44
σ	24.78	15.47	10.74	13.39
Skewness	-1.19	-1.28	-1.38	-0.32
Count (n)	36	34	26	30
Confidence Level (95.0%)	8.38	5.40	4.34	5.00

Liquid suppressants demonstrated the highest instantaneous cooling efficacy with varying degrees of stability. Water had the highest mean temperature reduction ($\bar{x} = -10.97$ °C/s), the most significant peak cooling impulse ($Min = -86.98$ °C/s), the highest volatility ($\sigma = 24.78$) and range of outcomes (132.28 °C/s). The encapsulating agent

recorded a more predictable performance with mean cooling ($\bar{x} = -4.00$ °C/s) and a narrow standard deviation ($\sigma = 15.47$).

Both the fire and LiB blanket interventions demonstrated negligible immediate thermal impact, with mean values approximating zero ($\bar{x} = -0.55$ and 0.07 °C/s), suggesting a lack of instantaneous cooling (Figure 63 and Figure 64).

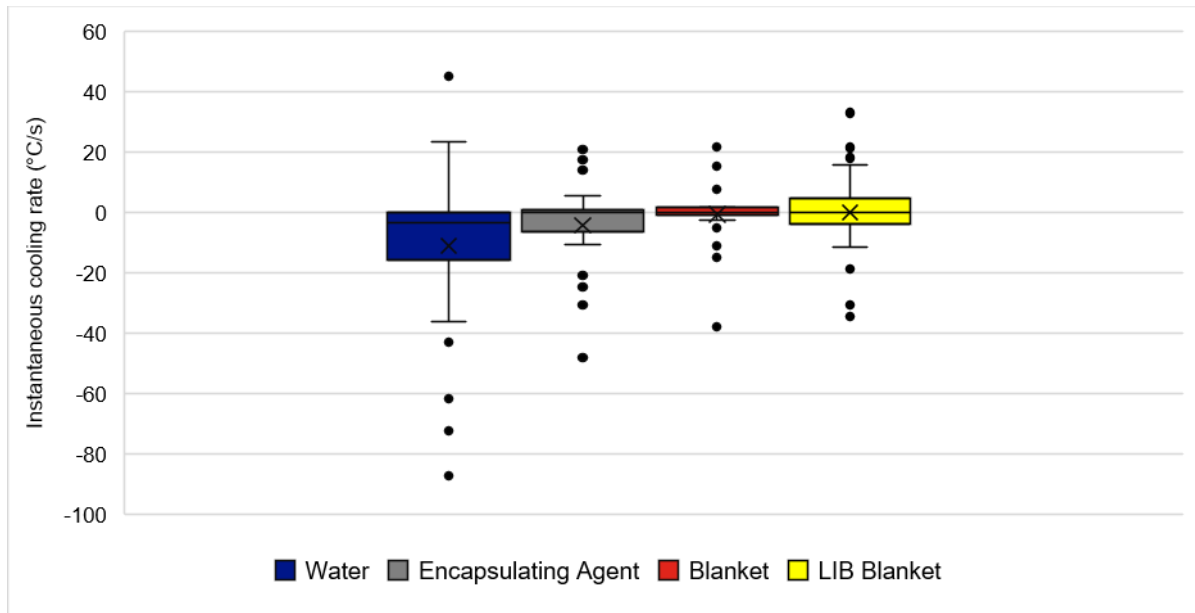


Figure 63. Instantaneous cooling rate $d(T/dt)$.

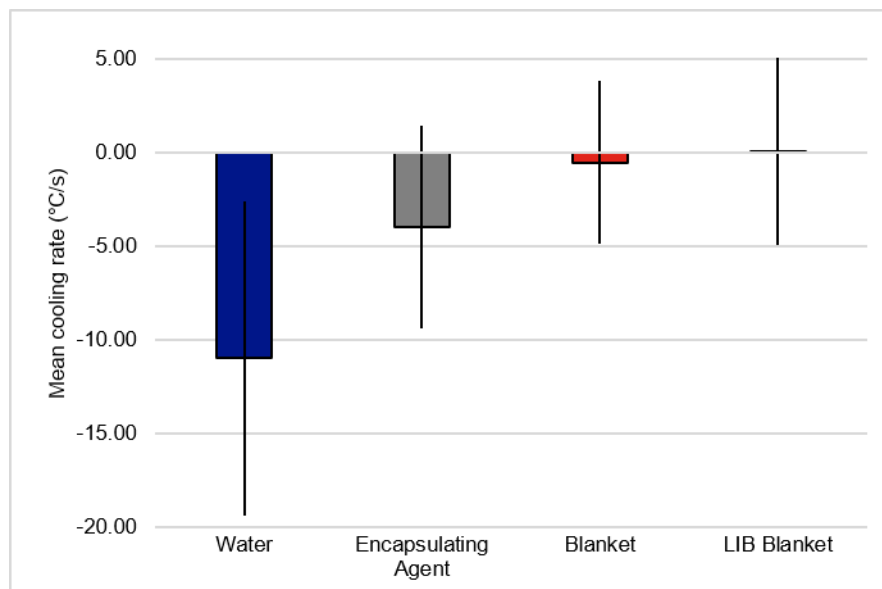


Figure 64. Mean instantaneous cooling rate for each agent. Error bars represent the 95% confidence interval (CI_{95}). Significant overlap in CIs between the blankets suggests no statistical difference in their immediate thermal impact.

In test 'Test 10: Shrink wrap, Water' much of the case wrapping and packaging was consumed, exposing the cells to the direct water stream. A conservative flow rate of 38.3 L/min was applied over a 72 s period. The instantaneous cooling was calculated as -39.2 °C/s, -87 °C/s, -9.1 °C/s, and -26.4 °C/s for TC1 - TC4, respectively, at the commencement of water application. TC1 and TC4 had near-linear falls in temperatures <100 °C in 4 s and 6 s.

TC2 and TC3 fell below 100 °C in 30 s and 34 s. TC3 had the only positive heating rate during the application of water (Figure 65).

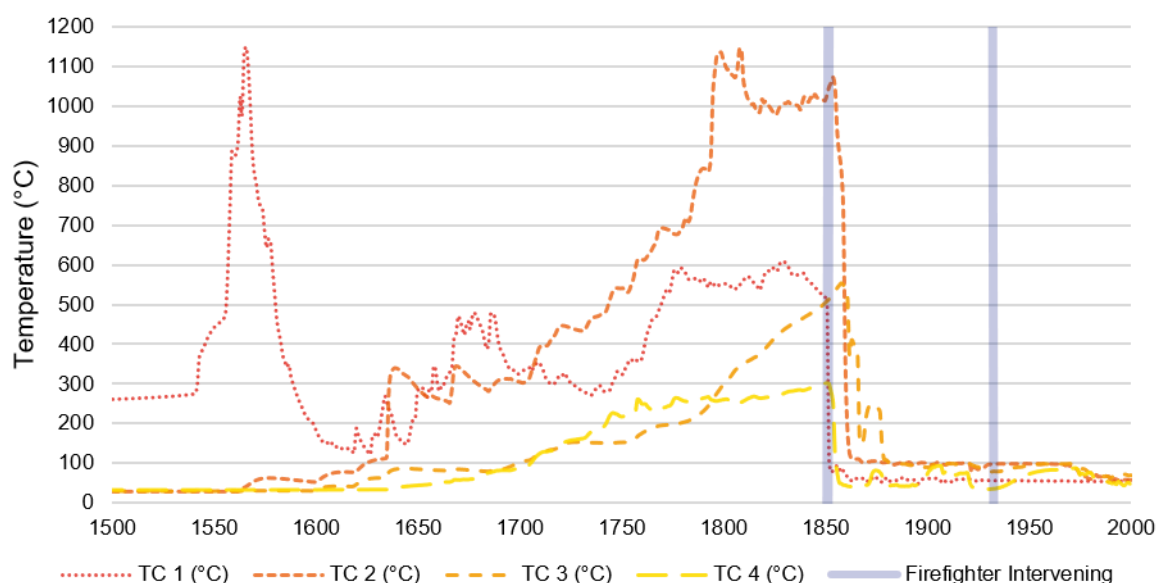


Figure 65. 'Test 10: Shrink wrap, Water' Steep rates of cooling under water extinguishment.

4.3.2.4 Extinguishing effect on thermal volatility

The variability in heating rates was evaluated to determine the impact of extinguishing media on thermal stability. The raw temperature data was taken from the isolated TR period and the rate of change per second was calculated (dT/dt). The standard deviation of the heating rate was calculated and hereafter referred to as 'thermal volatility' to represent the turbulence of the heat release.

The thermal volatility of the control group had the highest median and the largest IQR with a median standard deviation of approximately 42 °C/s and an outlier exceeding 150 °C/s. The inherently chaotic nature of unmitigated TR was suggested by the several high-value outliers (above 140 °C/s).

All interventions successfully reduced the median volatility (Figure 66). Both blanket types had a significant reduction in the spread of the data compared to the control, although the standard fire blanket had a high-value outlier. The encapsulating agent had the most stabilising effect with the lowest median volatility (approx. 9 °C/sec) and the most constrained IQR.

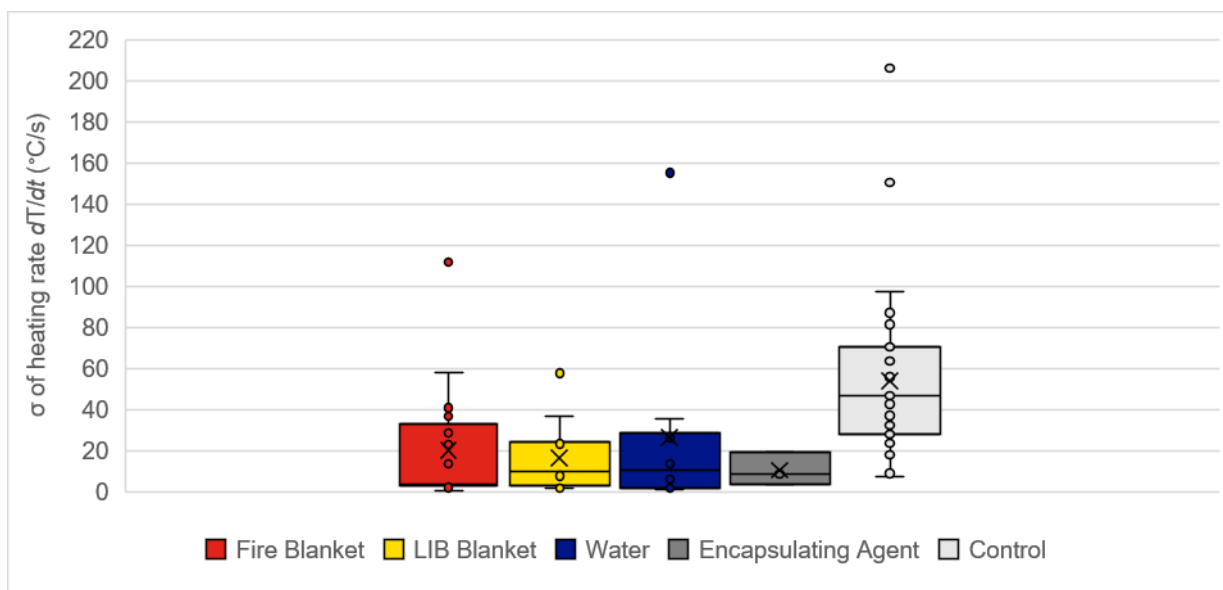


Figure 66. The thermal volatility of each suppression agent group and the controls.

These results suggest a strong correlation between extinguishing agent and the thermal predictability of the runaway event. The high volatility in the control group indicates that unmitigated TR is stochastic with high-energy fluctuations in heat release. The significant reduction in standard deviation observed for all suppression methods shows a measurable minimising effect on thermal volatility.

4.3.2.5 Extinguishing effect on propagation

Analysis of the heat propagation of the TR events was conducted. For all control tests, TR propagated across each instrumented segment of the battery. Failure of each cell within modules could not be confirmed. In the extinguishment tests, there were six instances where TR did not propagate to all the segments.

In test 'Test 11: Shrink wrap, Water' at 300 s, two of the four thermocouples were indicating TR (TC1 = 707 °C and TC2 = 679 °C), the other two were heating at 3.42 °C/s and 3.75 °C/s. The combustion destroyed much of the case wrapping and packaging, exposing the cells to the direct water stream. A conservative flow rate of 21.3 L/min was applied for 113 s. Individual cells entering flaming TR were observed even during direct water application. The instantaneous cooling effect was calculated as -72.3 °C/s, -2.1 °C/s, -2.9 °C/s, and -2.8 °C/s for TC1 - TC4 respectively at the commencement of water application. TC4 experienced immediate and sustained cooling as this portion of the pack had not entered TR. TC1 experienced immediate cooling with the steepest cooling slope falling from 70 °C to 105.2 °C in 16 s. TC2 began a sustained cooling slope (<-2 °C) in 18 s. TC3's heating rate slowed but remained positive for 41 s of water suppression (Figure 67 and Figure 68). The test shows both cell failure under suppression and the successful thermal decoupling with neighbouring cells. The disparity in cooling rates indicate that while water may not stop TR, it may remove the heat required to trigger the neighbouring cells into TR.

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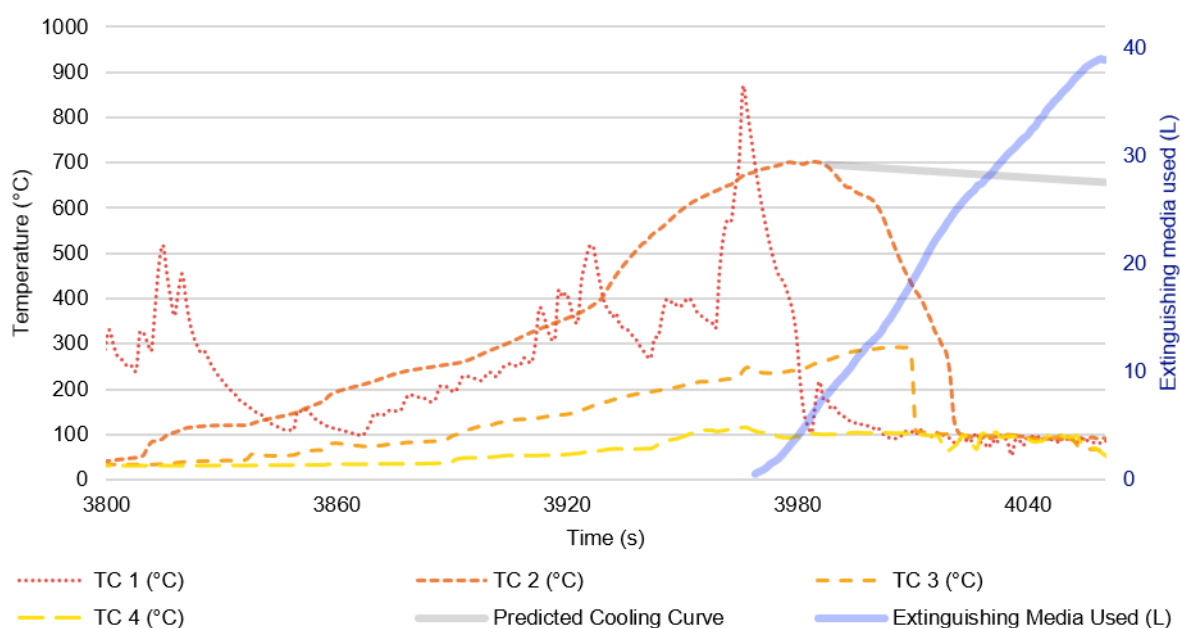


Figure 67. Internal temperatures and extinguishing water used in 'Test 11: Shrink wrap, Water'.

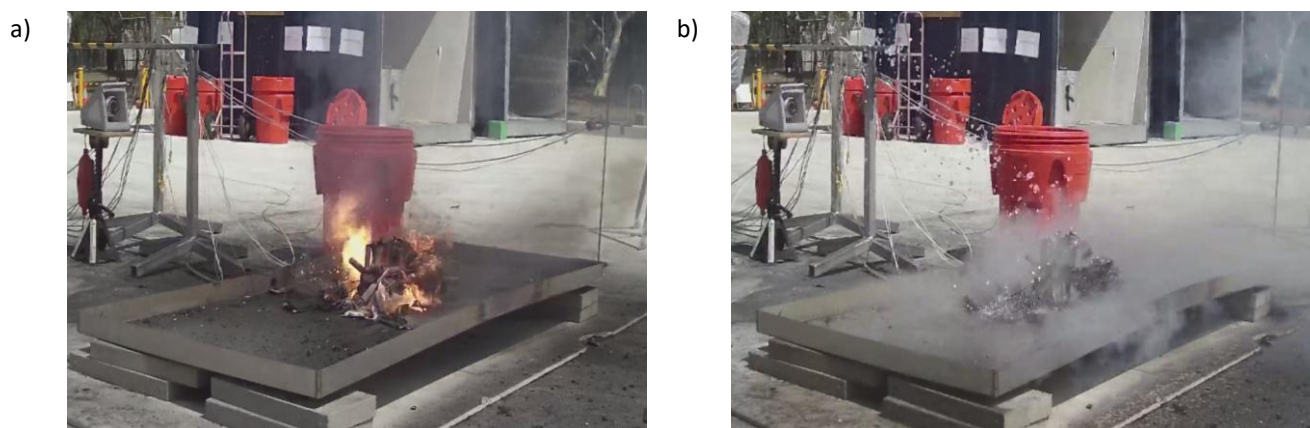


Figure 68. (a) The battery immediately prior to the application of water in test 'SW_LS(2)'. (b) Water applied at ~21.2 L/min.

4.3.3 Effectiveness of fire blankets and LiB blankets

The standard fire blankets and LiB-specific blankets were observed externally to act as barriers, suppressing flaming combustion, and reducing external heat flux in several tests. Their application also had a noticeable immediate impact on vapour quality. Often smoke and vapour opacity increased upon their deployment. Data analysis indicates that both blanket types provided a negligible instantaneous cooling effect ($\bar{x} = -0.55$ to 0.07 °C/s), only a marginal reduction effect in peak temperatures ($g = -0.2$ to -0.4) and a moderate effect on thermal volatility (σ of $dT/dt = 29.1$ and 16.6).

The notable shift in effluent dynamics suggests that blankets may be excluding some oxygen and terminating the visible fire and thereby promoting a concentrated accumulation of smoke and vapour. Vapours were also observed to permeate and re-ignite on the external surface of the material/blanket.

The application of blankets presented significant safety risks to operators due to the proximity required for deployment. Researchers were exposed to higher concentrations vapours, thermal impingements, and ejections due their proximity. Where the risk of explosion or severe venting were deemed too high, application was delayed by as much as 47 s ('Test 9: Shrink wrap, LiB fire blanket') to ensure operator safety.

Variable jet flame and venting events further complicated the use of the blankets which required adjustment to the original deployment in 56% of the tests. The buoyancy of the venting gases presented a turbulent barrier during deployment; in 'Test 35: Steel, Standard fire blanket' the upward force of the flame and vapour lifted the blanket away from the battery pack during initial deployment (Figure 69).



Figure 69. The high volume and pressure of venting making application of the fire blanket difficult (Test 35: Steel, Standard fire blanket').

blankets suffered a complete thermal breach (burn-through) demonstrating the insufficient material resilience of both types of blankets. In test 'Test 34: Steel, Standard fire blanket' thermal breach occurred in two seconds when the standard fire blanket was applied to a very focused jet flame. Similarly, in 'Test 22: Aluminium, LiB fire blanket', the LiB blanket burned through in four seconds (Figure 70).

The application of fire blankets transformed the event from a pseudo-localised to a distributed thermal hazard. While the blankets momentarily suppressed flame energy and prevented some projectile spread, they functioned as a very temporary measure. The blankets forced combustible vapours to the periphery, where they frequently re-ignited at the edges of the blanket, moving thermal impingement to a broad perimeter and increasing the heat flux applied to the test tray underneath. In several instances, the application of the fire blanket appeared to catalyse ignition, transitioning from venting to sustained flaming. This phenomenon may be attributed to the blanket creating a localised environment conducive to ignition.

Additionally, the blanket was displaced by both gas expansion and cell ejections, with one specific event lifting the blanket and re-exposing the battery (Figure 71). The blanket textile suffered heat damage, with a large section disintegrating, highlighting the material's susceptibility to localised high temperatures (Figure 72).

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Figure 70. The battery in test 'Test 22: Aluminium, LiB fire blanket' prior to the application of the LiB blanket and 4 s after application, a jet flame burned through.

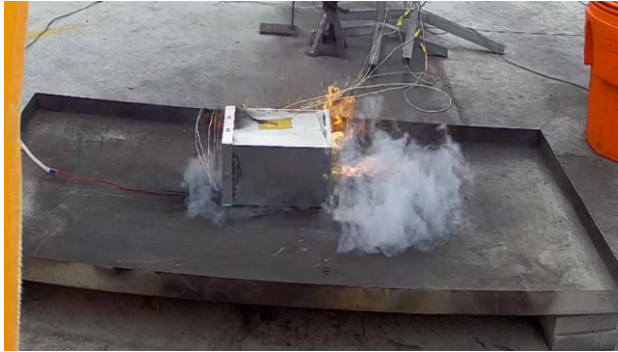


Figure 71. The gas expansion and explosions lifting and moving the blanket ('Test 22: Aluminium, LiB fire blanket').



Figure 72. The final position of the blanket and battery at the conclusion of the test and the damage to the blanket ('Test 22: Aluminium, LiB fire blanket').

In test 'Test 23: Aluminium, LiB fire blanket', the LiB blanket was applied to a battery in less energetic TR. Flames were extinguished prior to the vapours at the edge of the blanket re-igniting after 3 s. The vapour production was observed to accelerate along all edges of the blanket followed by global re-ignition. The blanket burned through 2 min 53 s after it was applied (Figure 73).



Test 23: Aluminium, LiB fire blanket, the battery immediately prior to the application of the LIB blanket.



$t = 0 \text{ s}$

The blanket was deployed.



$t = 3 \text{ s}$

Vapours at the corners reignited.

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$t = 38 \text{ s}$

The vapour production accelerated. The opacity of the vapour increased.



$t = 143 \text{ s}$

Most of the escaping vapour ignited.



$t = 173 \text{ s}$

The blanket was burned through by jet flame.

Figure 73. 'Test 23: Aluminium, LiB fire blanket' photo series at distinct timepoints during the test.

The blankets can act as momentary barriers to suppress flames and reduce external heat flux. Their application would also have noticeable immediate impact on effluent dynamics which may promote a concentrated accumulation of smoke and vapour. The application of blankets also presented significant safety risks due to the proximity required for deployment. In most instances, the blanket could not have been safely applied without donning full structural firefighting PPC. While the blankets may mitigate some risk of fire spread, they extended

the duration of high-temperature contact with the flooring and could increase the risk of structural degradation or secondary ignition of materials underneath and adjacent to the blanket.

4.3.4 Liquid extinguishing agent volumes

Liquid agents were applied with intent to extinguish and/or stabilise of the hazard to facilitate safe handling. Where the casing prevented a direct breach, prolonged application served to suppress external flaming and reduce the surface temperature of the enclosure to a manageable threshold for handling and movement. Cooling tactics were employed to allow researchers to stabilise the pack before immersion in water. Consequently, the recorded liquid volumes represent the combined requirement for active fire mitigation (Figure 74), the cooling of enclosure materials, and the preparation of the battery for safe immersion in water.

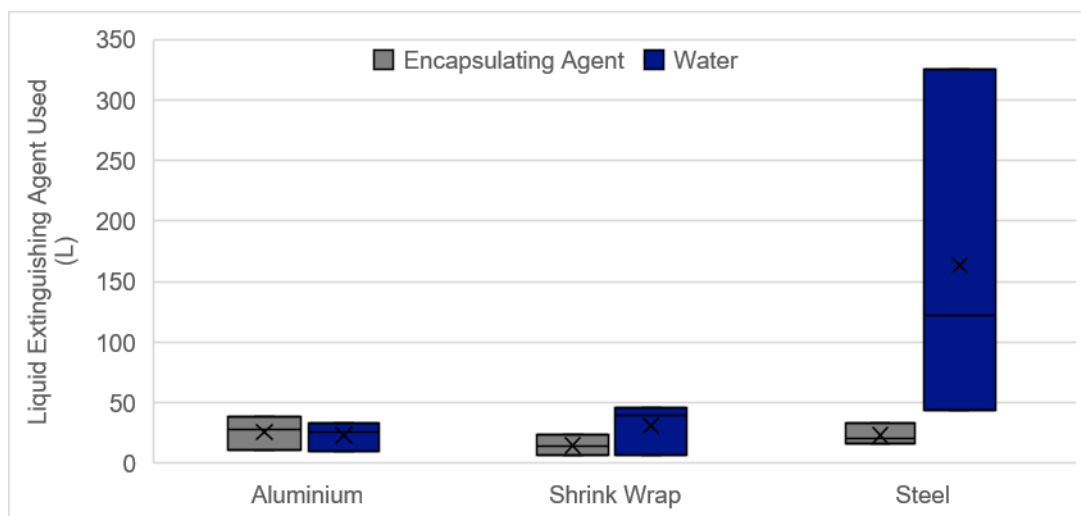


Figure 74. Liquid Extinguishing agent volumes used during suppression activities.

The volumes used for suppression were primarily dictated by the residual fuel load at the time of application. Although the precise value was not known, the firefighters had observed nine free-burning control tests to develop a base understanding of the spectrum of failure dynamics and event durations. Additionally, the firefighters were able to observe the initial 5 mins of TR where the changes in venting pressures and flame volumes gave some indication of internal thermal conditions. Although initial heating rates offered little predictive value for the end of the event, these external observations provided insight as to the internal conditions and remaining fuel load.

The aluminium and shrink-wrap enclosures had less physical resistance to the liquid media. Due to this, agent application remained predictable and typically fell below 46 L. In contrast, the steel-cased batteries exhibited extreme volatility, with water usage reaching a peak of 324.9 L in test 'Test 40: Steel, Water'. The volume disparity was driven by the variable remaining fuel load at the beginning of the suppression activities. As an example, both agents recorded test minimums of agent usage of 7 L, in tests that were energetic with short propagation times. The low amount of water used was sufficient to allow safe handling for eventual water immersion.

There were two outlier results that exceeded the average 46 L total, both tests were on steel-encased batteries that inhibited water from cooling the cells.

While most suppression showed external signs of reducing thermal volatility and extinguishing or reducing flaming combustion, there were notable external reactions that changed the perceived risk profile of TR events. These included the immediate changes in cell ejections and the quantity and quality of smoke and vapours. The change has also been observed in other research that investigated extinguishing efficacy on prismatic LFP cells (Mrozik *et al.*, 2026). In test 'Test 41: Steel, Water' water suppression was applied, extinguishing the flames with an

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immediate dark and high-pressure venting event occurring that may be explained by water making ingress into the case, vaporising, and subsequently forming an instance of high pressure inside the battery case (Figure 75). The battery continued to produce vapours upon immersion in water, where steam production and localised agitation in the water was observed for over 11 min (Figure 76).

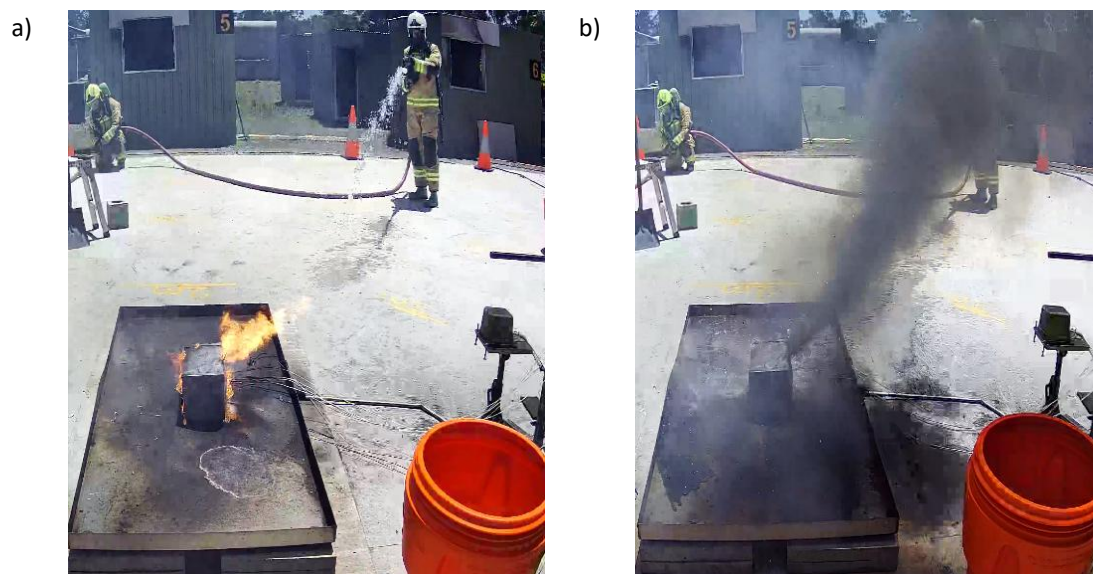


Figure 75. (a) Test ‘Test 41: Steel, Water’ immediately prior to water suppression. (b) 2 s into suppression, there was no flaming combustion, a distinct dark and high-pressure venting event occurs that may be explained by water making ingress into the case.

The primary utility of the liquid agents was hazard stabilisation. When unable to arrest TR propagation, they were applied until the point where the thermal risks had reduced enough to allow safer handling for water immersion.



Figure 76. Test ‘Test 41: Steel, Water’ external signs of TR were observed under application of 122 L of water over 2 min 8 s.

4.3.5 Limitations of time-dependant extinguishment commencement

A time-dependant suppression threshold was used to ensure the results maintain field-relevance by focussing on mitigation rather than prevention. Suppression operations commenced 300 s from the beginning of visual TR as a compromise between the observed duration of the control tests and realistic response time of emergency fire services arriving at an incident.

The data demonstrates the very wide spread of reaction rate and event duration resulting from the suppression agents being applied to a variable spectrum of both instantaneous thermal activity and residual fuel loads. These variables could be better controlled for by using an HRR rather than a time-dependant threshold, however accurate measurement of HRR in these type of events has proven to be a difficult metric to quantify (Wise *et al.*, 2023).

In addition, there were tactical delays during the use of fire and LiB blankets. The firefighters needed to defer suppression activities in instances of increased thermal, projectile, and explosion risk. Unlike liquid agents that allow for standoff distances, the application of blankets required close physical proximity. The delay in blanket deployment introduced a safety bias into the data where the most violent fires had the longest delays in blanket application (Figure 77).

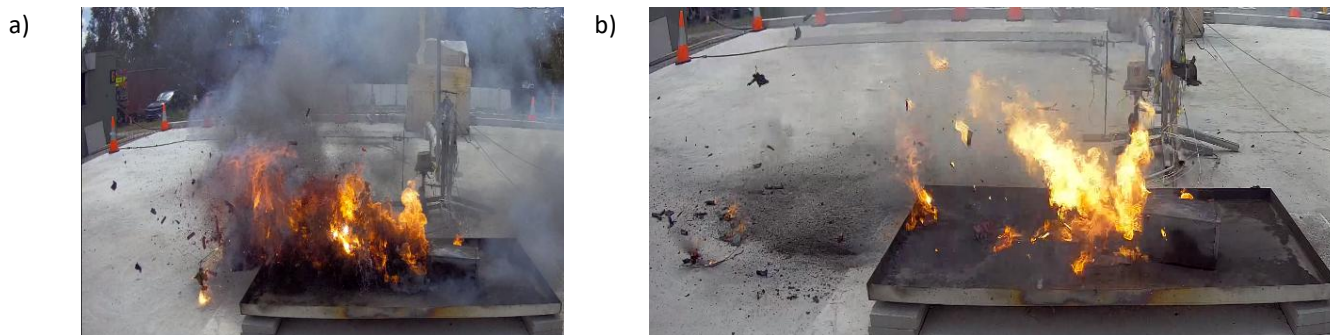


Figure 77. (a) 'Test 38: Steel, LiB fire blanket' The multiple cells exploding from the top of the battery case 37 s prior to the designated deployment of the blanket. (b) Multiple cells continued energetic ejections.

At 300 s, the thermodynamic state of each pack segment was highly variable. In test 'Test 30: Aluminium, Encapsulating agent' (Figure 62) TC2-4 were close to the ambient starting temperature. In test 'Test 11: Shrink wrap, Water' (Figure 67), TC1-2 were close to peak temperature and in test 'Test 12: Shrink wrap, Water' (Figure 78) three of four the internal thermocouples indicated that the battery had entered the decay period. These tests explain some of the high variance (CV%) recorded in the liquid agent results.

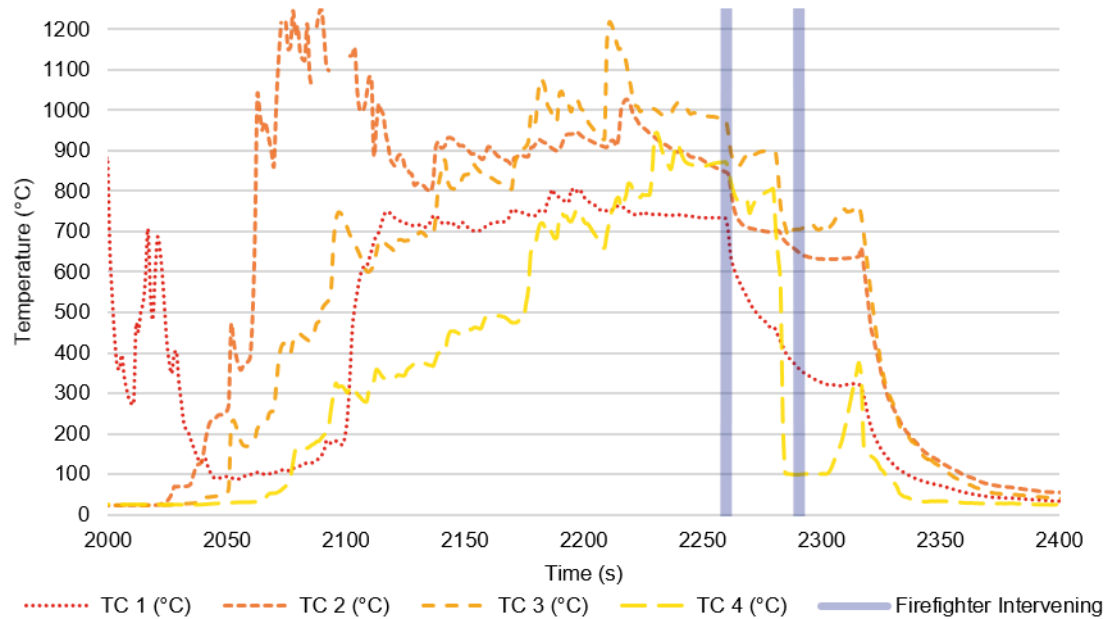


Figure 78. Test chart from ‘Test 12: Shrink wrap, Water’ 3 of the 4 battery segments were in a cooling phase at the commencement of water suppression.

4.3.6 Projectiles and ejecta

In all tests the battery ejected solid matter, with acute expulsion events significantly increasing the quantity and velocity of these projectiles. The internal components were ejected in various stages of thermal activity. Cells or groups of cells were observed already in TR, others were ejected whole, with no signs of failure, but ignited after ejection.

These projectiles observed add fire propagation risk as well as and thermal and kinetic injury. These materials can act as an ignition source, capable of setting spot fires beyond the initial area of origin. The high-velocity expulsion can pose a direct mechanical and thermal trauma risk to exposed persons (Figure 79).



Figure 79. Example of a ‘Significant Projectile’ still flaming 7 s after being ejected from pack.

A total of 118 ‘significant projectiles’ were observed in 32.61% (n = 15) tests, indicating that they were a relatively common occurrence during LiB failure.

4.3.6.1 Battery enclosure type

Ejecta was first assessed in relation to the casing type used during testing, which can be seen in Table 18.

Table 18. Summary of ejecta results.

	Case Type			
	Overall	Shrink Wrap	Steel	Aluminium
Significant projectiles (Total tests = 46)	15	9	3	3
Total observed projectiles (%) (total projectiles = 118)	100%	75.4% (n = 89)	9.3% (n = 11)	15.3% (n = 18)
Average debris field (m)	4.81	5.09	4.71	4.45

The box-and-whisker plot below (Figure 80) demonstrates the spread of projectile distances between enclosure types.

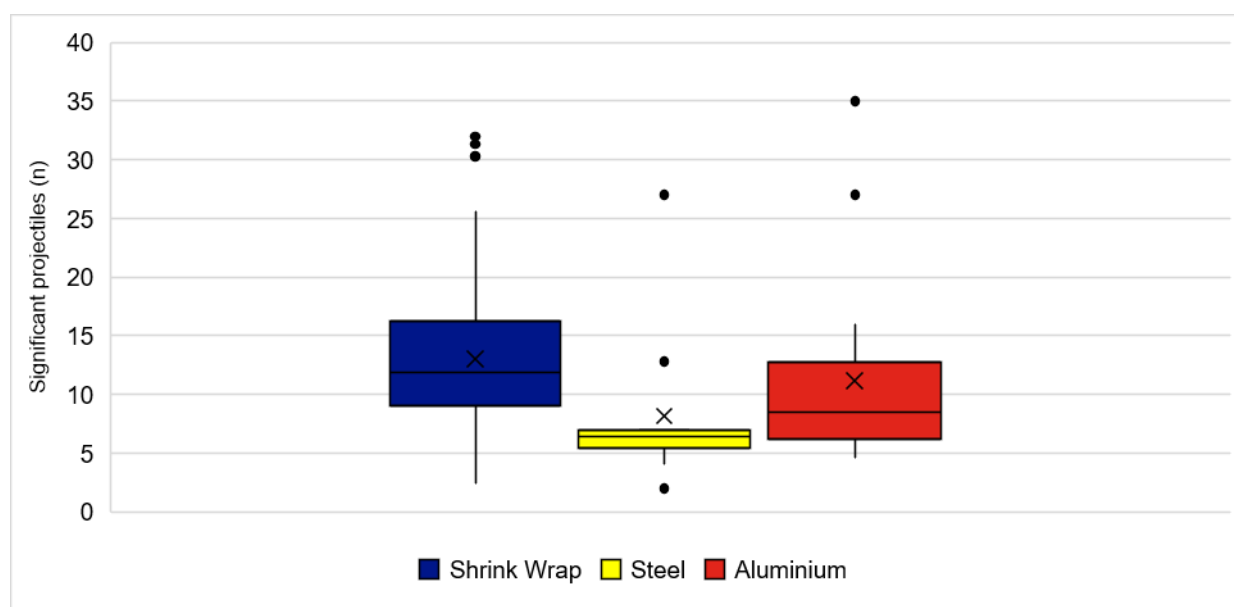


Figure 80. Boxplot of projectiles observed.

The shrink wrap encasing demonstrated the highest percentage of significant projectiles 75.4%, and the largest average debris field (5.09 m). Shrink wrap casing had 56.3% tests with a significant projectile. It was observed that the shrink wrap was consumed quickly and offer no resistance to ejection soon after the battery entered TR. The shrink-wrapped batteries had the highest average distance for projectiles (13.03 m), and the largest IQR (7.25 m). In multiple instances, energetic reactions were observed to rapidly disassemble the battery, resulting in a wide spread of ‘significant projectiles’. Some tests in which TR did not propagate fully throughout the battery, resulted in minimal projectiles. Examples of these scenarios are shown in Figure 81.

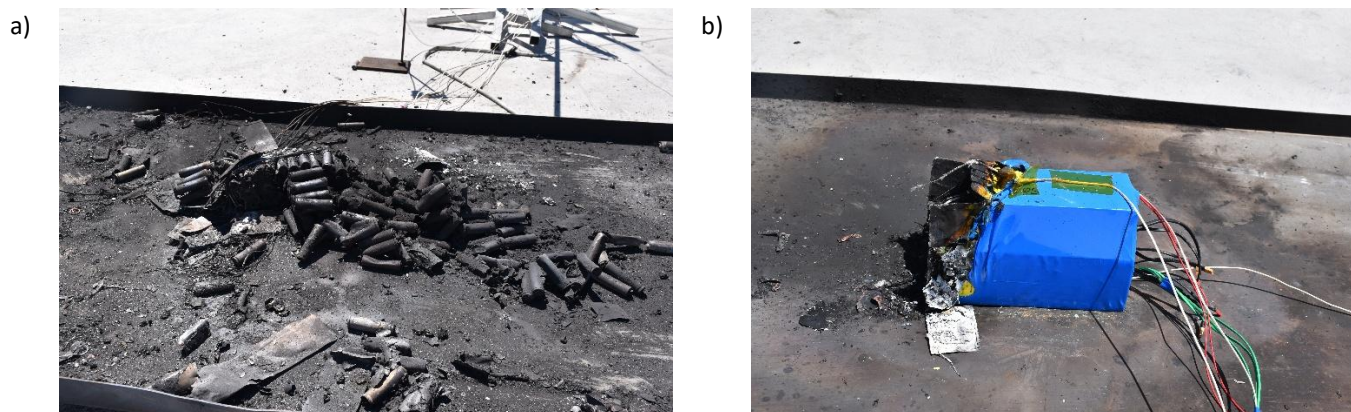


Figure 81. (left) 'Test 9: Shrink wrap, LiB fire blanket' – showing completely dismantled battery (right) 'Test 5: Shrink wrap, Standard fire blanket' – showing a scenario where battery is still in good condition after TR.

Aluminium and steel encasings provided higher strength structural protection of the inner cells, and this was reflected in the lower number of tests with 'significant projectiles' and decreased number of observed projectiles within these tests. For both casing types only three tests were observed to have significant projectiles (out of a total 15 completed tests), however steel had a lower number of total observed projectiles ($n = 11$) when compared to aluminium ($n = 18$). The increased strength of the steel encasing also influenced the projectile distances, resulting in lowest mean (8.18 m) and lowest IQR (1.6 m). In tests where 'significant projectiles' were observed, it was observed that the steel case had a large failure (such as rupturing of casing seams), which would have allowed cells to escape the enclosure. In particular, a single test ('Test 38: Steel, LiB fire blanket') was responsible for over 50% of projectiles (6/11) for steel encasing types due to a catastrophic failure in which the lid was blown off the enclosure. In general, the casing materials were intact after testing, with some small expansion around the seams that allowed vapour to escape. Examples are shown in Figure 82 and Figure 83.

Although there was a substantially lower number of observed projectiles when compared to shrink wrap, the mean for aluminium (11.18 m) and IQR (6.5 m) were similar. During testing, it was observed that under an intense TR event, the aluminium enclosure would fail with large openings created in almost all tests (14/15). While these openings may have presented the opportunity for cells to be ejected unimpeded and increase the distance they travel, it was unclear why there was substantially decreased number of observed projectiles when compared to shrink wrap casing material. Examples of aluminium casings are shown in Figure 84 and Figure 85.



Figure 82. Test 38: Steel, LiB fire blanket showing catastrophic case failure.



Figure 83. Test 34: Steel, Standard fire blanket showing minimal case failure and a small amount of bulging.



Figure 84. Test 26: Aluminium, Water showing a large hole in aluminium case, representative of majority of tests.



Figure 85. Test 27: Aluminium, Water test with least amount of damage to casing.

Generally, the enclosure types followed expectations, with steel providing the most resistance and shrink wrap providing the least resistance to containing internal battery cells in TR. It appeared that the strength of the encasing material played an important role in containing the failure event, however projectiles still occurred in all scenarios.

4.3.6.2 Extinguishment type

‘Significant projectiles’ were investigated in the context of the extinguishment method utilised. Results can be found in Table 19.

Table 19. ‘Significant projectiles’ recorded per enclosure type.

	Intervention Type					
	Total	Nil (Free Burn)	Fire blanket Standard	LiB-specific fire blanket	Water	Encapsulating agent
Completed tests with significant projectiles	15	5	2	4	2	2
Total observed projectiles	100% (118)	33.05% (39)	22.03% (26)	30.51% (36)	8.47% (10)	5.93% (7)
Avg debris field (m)	4.81	4.62	6.07	5.83	4.27	2.8

Additionally, a box-and-whisker plot below (Figure 86) demonstrates projectile distance in relation to intervention type.

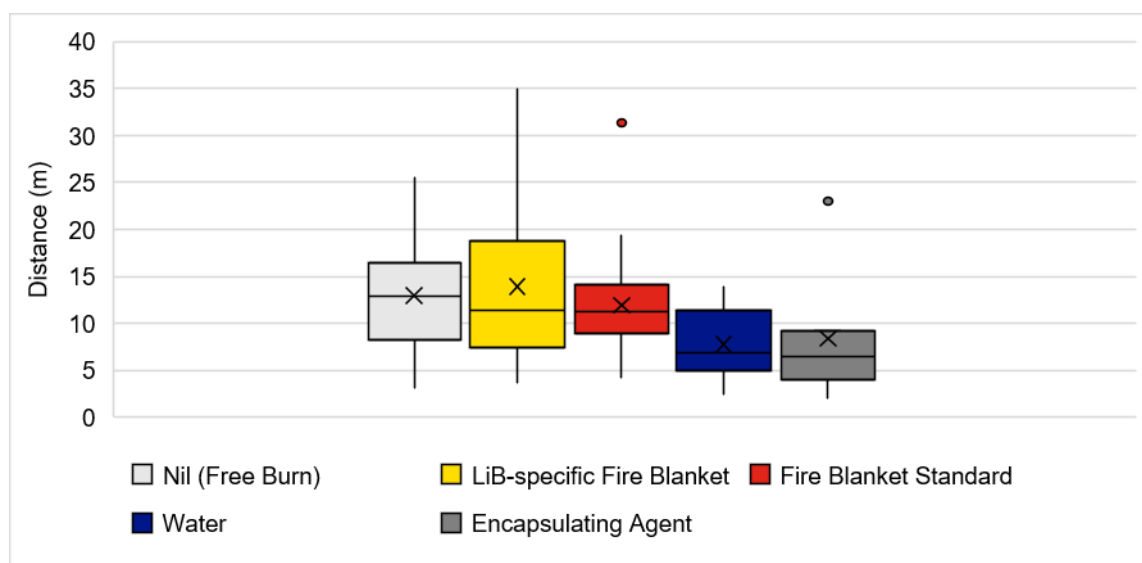


Figure 86. Boxplot of 'significant projectiles' recorder per enclosure type and their distances ejected.

In tests where any form of intervention applied, significant projectiles were observed 27.78% of the time in contrast to free burn tests (no intervention) which recorded 'significant projectiles' in 55.56% of tests. It was unclear if the intervention type was mechanically responsible for decreasing the total number of projectiles or if a reduced duration of the test (due to intervention) was responsible for decreasing the opportunity for additional projectiles to be ejected, however it does appear that intervention may play a role in reducing 'significant projectiles'.

4.4 Summary

The control tests exhibited unpredictable event durations with a high CV of 30.2%. In aggregate, these types of events do not follow a uniform timeline but rather an erratic temporal range. Isolating the results by the case material was the dominant factor determining the TR duration.

Aluminium cases had the most predictable results (CV 5.4%) as they usually melt or fail early in the test, allowing for a more consistent release of energy with a mean duration of 863 s. Shrink wrap casing produced the longest and moderately predictability durations (1061 s). The lack of a rigid enclosure allowed cells to eject and burn more independently, which slowed overall failure propagation. The steel cased batteries exhibited the most volatile and shortest events (563 s). The case maintained structural integrity longer, allowing internal heat and pressure to build to more acute, violent events. These rapid energy releases however made the timing of the failures highly unpredictable (CV 30.9%).

Similar unpredictability trends were observed by linear regression analysis of initial thermal hazard and event duration. The initial thermal activity was a very poor predictor of overall event duration, further highlighting the stochastic nature of battery fires. The lack of correlation presents challenges for fire modelling that use steady growth rates. While single cell testing benchmarks established a baseline of high variability, the multi-cell systems further compounds uncertainty through more complex failure propagation.

The liquid suppression agents were superior to fire blankets in compressing the event duration and reducing peak temperatures however their success was governed by the dynamics introduced by the battery enclosure. The encapsulating agent indicated the most effective stabiliser of thermal volatility and a 42.8% reduction in mean peak temperatures. The data demonstrated that water had the highest instantaneous cooling power (mean = -10.97 °C/s).

The mechanics of the battery casing also had a very large effect on how the liquid extinguishing agent was able to reach the cells. The shrink wrap and aluminium cases allowed for very predictable quantity of liquid to suppress the TR propagation. The failure configuration of the steel and aluminium cases were observed to dictate the efficacy of the extinguishment as some would allow the agent to pool and submerge the cells, in other instances, the steel case integrity would deflect the liquid sufficiently to allow TR to continue and propagate.

Each suppression agent was able to reduce the thermal volatility of the event with the encapsulating agent offering the most constrained and predictable effect. The liquid agents were able to stop failure propagation by removing enough surrounding heat and decoupling the cell-to-cell heat transfer. All agents displayed the ability to alter the volume and nature of the airborne effluents of the event. Where the flaming ignition was suppressed, immediate changes to the vapour quality were observed. Where water was introduced inside the battery casing, the venting and ejection characteristics also shifted.

Both types of blankets exhibited negligible instantaneous cooling effects and marginal internal peak temperature reduction. In the tests with steel cased enclosures, the blankets prolonged the TR duration ($g = 0.52$). Both blankets also could not suppress concentrated jet flames, with burn-through occurring in as little as two to four seconds. The blankets also distributed the thermal hazard across a wider area increasing flux to the covered and surrounding areas. The blankets also proved difficult to deploy due to the kinetic force of venting gases and jet flames disrupting their placement or by the proximity required for them to be applied. Even with improvements on the material durability, their use-case remains limited.

The quantity of extinguishing liquids used in these tests typically fell below 46 L. In instances where the liquid was able to reach the cells, the volumes used were primarily dictated by the residual fuel load at the time of application. The firefighters had observed a minimum of nine free-burning control tests. Their observations of the initial five minutes of TR in each test allowed them to assess the event conditions and apply proportional tactics. The battery casings were found to inhibit the accurate monitoring of internal thermal states. Observations via TIC demonstrated reduced external casing temperatures, where internal temperatures remained persistently high. This highlights the limitations of surface-level thermography in assessing internal runaway progression particularly in large and multi-cell batteries.

The application of suppression agents altered the observable characteristics of the TR events, thereby modifying associated risk profiles. Immediate changes were observed to cell ejection dynamics, the transition between flaming and non-flaming TR, and the volume, opacity and morphology of smoke and vapours produced.

In 33% of tests ($n = 15$), projectiles were generated averaging eight per event with a maximum travel distance of 35 m. Standard structural firefighting PPE and SCBA are likely sufficient to protect personnel from the mechanical and thermal impact of the projectiles generated during this study, however, they can pose a significant risk for secondary fire spread. The experimental results indicate that manual intervention with handheld extinguishers poses an unacceptable risk profile. The proximity required for their discharge could expose unprotected operators to acute thermal hazards, toxic effluents, and projectile risk. Furthermore, the shielding inherent in battery and product enclosures could render these attempts ineffective.

The primary obstacle to fire suppression remains the delivery of suppressant to the reactive cells inside the battery. In operational environments, this is exacerbated by complex, nested configurations, i.e. e-bike batteries having primary battery casings being further shielded by the bicycle's structural frame. As this study evaluated only a narrow subset of available battery housing types, further research is required to address the high degree of variability.

5 Part C: Efficacy of personal protective clothing decontamination and laundering procedures

5.1 Background

Firefighters are exposed to a wide variety of hazardous material during the course of their firefighting activities. Carcinogens, hazardous organic compounds, polycyclic aromatic hydrocarbons (PAHs), particulate matter, and other toxic compounds in air and water are a continuous threat to firefighter health and safety. While PPC and PPE employed on scene reduce exposure pathways, the effectiveness of the decontamination procedures of equipment and clothing that are re-used after exposure still need to be determined in the context of emergent hazards such as LiBs.

Advancements in technologies, particularly LiB's presents a new array of challenges and hazardous materials that firefighting personnel may be faced with while attending an incident. Improvements with laundry procedures, increases in laundering frequency, and advancements in materials used for PPC have all led to improvements in efficiency and safety of cleaning procedures (Horváth and Pántya, 2024). While it is accepted that PPC used during common structure fires is clean and intrinsically safe for use after decontamination and laundry procedures following exposure, the same may not be true for alternative hazard types not captured under existing standards (Fire and Rescue NSW, 2025). Any potential deficiencies with firefighting garments, such as the contaminant permeation (Horváth and Pántya, 2024), require further investigation to protect firefighter health and safety.

Run-off water is a concern when attending incidents, both from firefighting activities and decontamination procedures. Pollution from LiB events presents some challenges with the variety of metals and electrolyte materials which may be introduced to the environment, and the proliferation of devices containing LiBs (including increases in size). Understanding the run-off water toxicity is critical to determine further information on whether contamination in run-off water from LiBs is an extraneous concern or whether further studies should be conducted to understand the extent to which LiB run-off water may contaminate the environment.

Testing was conducted focused on investigating FRNSW's current procedures in place for structural firefighting garment decontamination, and how they relate to contaminants which may be encountered when attending an event with a LiB in TR and whether run-off water from wet decontamination procedures contains swatch contaminants. Primarily, this experimentation served to act as preliminary investigation into this area of study and will be used to inform future testing design and outcomes.

The following aims were investigated:

1. Evaluate on a small-scale the efficacy of current laundry service and procedures in place regarding firefighter PPC contamination and basic decontamination procedures after responding to an incident involving a LiB,
2. Provide an understanding of what types of contaminants may be present on firefighter PPC after exposure to LiB failure events, and
3. Provide initial insight into areas which may be of future interest for a more fully developed investigation into firefighter PPC.

5.2 Methodology

5.2.1 Test enclosure and contamination method

The LiB exposure scenario selected was of a prismatic LFP cell in TR from overheating abuse. The overheating method outlined in Section 3.2.2 was adapted for the larger cells being used.

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The medium size chamber is 600 x 600 x 600 with a 300 mm tall square-to-round frustum. Into the side of the small-scale chamber, is a second Gasmet DX4000 probe and analyser (Figure 87).



Figure 87. Medium sized chamber used during PPC testing.

To prepare the cells for testing, a single, mono-core, fibreglass insulated k-type thermocouple was attached to the centre of the cell using polyimide tape. Then, 2 m of 28-gauge nichrome wire were wrapped at intervals of 5 - 7 mm (approximately 26.6 Ω resistance). The heating element was connected to a power supply, set to 24 V (constant voltage). A total of approximately 170 W was applied to the cell, resulting in 7 W/inch² of heating applied across the entire surface area of the cell. Based on preliminary testing, this heating rate was found to reliably initiate TR within reasonable timeframes. Polyimide tape was used to secure the nichrome wire across the surface of the cell (Figure 88).

Short wires were attached to the positive and negative terminals using alligator clips during each test to measure voltage.

An iMax B6AC V2 charger (SkyRC Technology Co. Ltd., Shenzhen, China) was used to discharge and charge cells to the desired levels based upon the outlined test matrix. Custom charging programs were written for the charger based upon the cell capacities and required SoC. All cells were discharged to 0% capacity then charged to the desired state prior to testing:

- For 100% SoC, cells were allowed to fully charge based upon the standard parameters of the charger.
- For 30% SoC, cells were first completely discharged to 2.0 V for LFP and 30% capacity was calculated in milliamp hours and allowed to charge to this limit specified within the charge parameters of the charger.

The cells were not conditioned or cycled otherwise.



Figure 88. Prepared LFP LiB cell for PPC decontamination tests.

Each cell was prepared individually, and new thermocouples and heating elements were prepared for each test to prevent cross contamination and component degradation. Voltage and temperature were measured throughout these tests for test monitoring purposes only.

5.2.2 Test parameters

To determine the efficacy of on-site decontamination and laundry processes for structural firefighting garments, six burns were conducted using LFP prismatic cells (with a nominal capacity of ~39,000 mAh, 3.2 v). Previous testing and a review of literature demonstrated that a combination of LFP chemistry and prismatic format was likely to produce large volumes of off-gassing, and a reduced tendency for intense flaming events which were anticipated to be ideal conditions for exposing PPC swatch material without risking damage in the process. Additionally, the larger capacity would result in greater volume of gas production and therefore more akin to that which operational firefighters may encounter. Testing was completed inside the test chamber utilised in Part A with slight modifications made to the internal set up to support PPC swatch exposure. A three-part decontamination test was performed to determine if there were any differences between each stage of the decontamination process. Samples were either 1) exposed to LiB in TR, denoted as 'contaminated', 2) exposed to LiB in TR and washed with water post exposure, denoted as 'wet decontaminated', or 3) exposed to LiB in TR, washed with water post exposure then bagged and sent for professional laundering through FRNSW laundry system, denoted as 'wet decontaminated and laundered'. The PPC swatches were also exposed to two different LiB conditions: triplicate repeats at 30% SoC and triplicate repeats at 100% SoC. The test matrix for this set of testing is provided in Table 20.

Table 20. Test matrix of LFP LiB burns for PPC decontamination tests.

SoC	Burn #	Sample #	Treatment Type	Position
30%	1	1	Nil	A
		2	Wet decontaminated	B
		3	Wet decontaminated then laundered	C
	2	4	Nil	C
		5	Wet decontaminated	A
		6	Wet decontaminated and laundered	B
	3	7	Nil	B
		8	Wet decontaminated	C
		9	Wet decontaminated and laundered	A
100%	4	10	Nil	B
		11	Wet decontaminated	C
		12	Wet decontaminated and laundered	A
	5	13	Nil	A
		14	Wet decontaminated	B
		15	Wet decontaminated and laundered	C
	6	16	Nil	C
		17	Wet decontaminated	B
		18	Wet decontaminated and laundered	A
N/A	N/A	19 - 24	Blank controls	N/A

After the treatment methods, swatches were packaged and sent to an external laboratory for chemical analysis.

5.2.3 Test specimen preparation

Custom swatch samples were procured from FRNSW structural uniform supplier. The swatches were made to the required specifications and are representative of FRNSW's current structural firefighting ensembles. Each swatch was 20 x 10 cm and consisted of three layers; an outer layer, a moisture and thermal barrier layer, and an inner lining layer, seen in Figure 89, and sewn shut on all sides. Through consultation with operational firefighters and

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experience in structural firefighting, prior to each test, swatches were dampened with tap water to replicate conditions which may be encountered in real emergency situations such as mist from firefighting operations and sprinklers within structures.

Swatches were suspended within the centre of the test chamber, directly above the LiB, in positions A, B, or C (corresponding to left, middle and right respectively). The LiB was heated until it entered TR and allowed to proceed fully through TR until self-extinguishment. Exhaust extraction during the test was reduced to support increased swatch exposure of battery effluent. Swatches were removed and treated once TR had ceased and all vapour was evacuated from the test chamber. Swatches were always handled with clean, new, nitrile gloves to assist in preventing cross-contamination.



Figure 89. Example images of PPC swatches and arrangement within test chamber.

5.2.3.1 Swatch exposure method

For each test burn, three swatches were exposed then either preserved, wet decontaminated, or wet decontaminated and laundered. 'Contaminated' swatches were exposed and immediately placed into a labelled glass sample jar. Wet decontamination was guided by current FRNSW Standard Operational Guideline (SOG) 10.4 decontamination guide. 'Decontaminated' swatches were treated with "copious" amounts of water on-site (Figure 90) and placed into a glass sample jar. The 'laundered' swatch was wet decontaminated as above, placed into a glass jar and then sent to be laundered as per FRNSW laundry procedure. A control sample was also produced using three unexposed swatches and are hereafter denoted as 'blank controls'. 'Blank controls' were dampened prior to being placed in a glass jar, to ensure pre-test treatments were the same across all tests and were then sampled in the same manner as exposed swatches. Samples were stored in a refrigerator until ready for transport. Samples were placed within an icebox with an icepack above and below the samples and transported directly for analysis or laundering.



Figure 90. Example image of wet decontamination procedure.

5.2.3.2 Swatch sample method

Upon receipt at the laboratory, each swatch was removed from their storage jars with tweezers from the relevant glass jars and cut with cleaned scissors to approximately 3 cm widths so that 6 strips result from each swatch, each with an area of approximately 30 cm². The tweezers and scissors were cleaned with isopropyl alcohol wipes and high purity water prior to each swatch being removed and subsequently cut into strips. The tweezers and scissors had water rinsed from them post a cleaning cycle and analysed for metals, no detections above the Practical Quantitation Limits (PQLs) were found. Two strips from each swatch were analysed for semi-volatile organic compounds (SVOCs), metals, combined pH and fluoride, respectively for 'A' and 'B' technical replicates (Figure 91).

Note that while SVOC analysis was conducted, the results from the testing were inconclusive and required further investigation and processing. Due to the constraints of this project, SVOC results were not able to be investigated and verified for reporting, and as such the remainder of the results and discussion in this chapter will present the pH and fluoride and metal analysis results only.

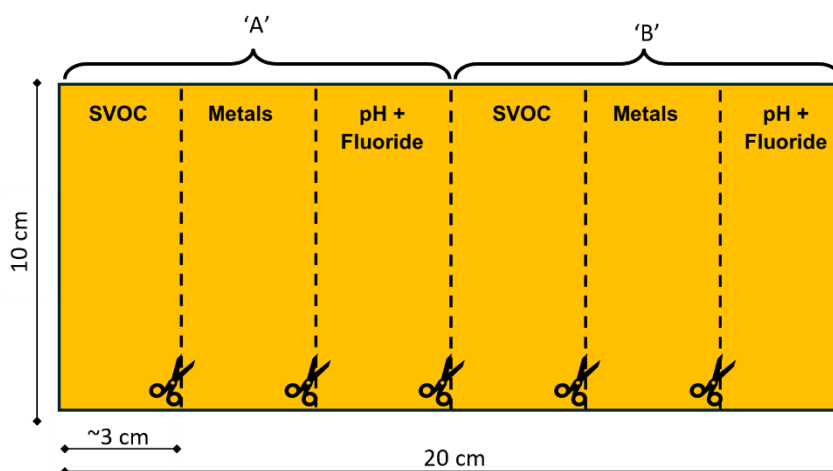


Figure 91. PPC swatch sampling diagram

5.2.3.3 Swatch water sample method

Water samples were collected from the run-off produced during on-site wet decontamination procedure to determine whether contaminants were detected in the run-off water. Run-off water was initially captured in a small, clean paint tin and then transferred to a polytetrafluoroethylene container for storage and transport. Run-off water was analysed using the same methods as the PPC swatches. Two baseline water samples were also collected from the same on-site source used in the decontamination procedure and analysed in the same manner to allow for differentiation between baseline water contaminants and contaminants from the exposed swatches.

5.2.4 Instrumentation

5.2.4.1 pH and fluoride

The pH and Fluoride were determined from an ultra-high purity (UHP) water extraction. A 50 mL aliquot of UHP water was added to each individual strip of swatch and sonicated for an hour then tumbled end over end for several hours. The pH of the resulting extract was then measured with a pH electrode and water-soluble fluoride was measured with a fluoride specific Ion Selective Electrode (ISE).

5.2.4.2 Metals

Swatches to be analysed for metals were prepared by acid digestion with strong mineral acids, hydrochloric acid and nitric acid, at 90 – 98 °C. The samples are digested at this temperature range for several hours before dilution and analysis of the digestates via Inductively Coupled Plasma Optical Emission Spectrophotometry (ICP-OES) and Cold Vapour Atomic Adsorption Spectrophotometry (CV-AAS - Mercury only).

The acidic sample extract was introduced as an aerosol into an inductively coupled plasma spectrometer via a peristaltic pump, spray chamber, and crossflow nebuliser. The sample then underwent de-solvation, vaporisation, atomisation (with excitation yielding characteristic atomic emission lines on relaxation) and ionisation (with excitation yielding characteristic ionic emission lines on relaxation). The intensity of the emitted electromagnetic radiation is proportional to the concentration of the analyte present in solution. The instrument utilises a spectrometer whereby the radiation is dispersed according to wavelength. The diffraction lines are simultaneously detected by a specially designed charge coupled detector which measures both ultraviolet and visible range simultaneously. The instrument is calibrated from 0 – 20 mg/L, typically using at least five (5) calibration standards plus the calibration blank. Additional instrument parameters are provided in Table 21.

Table 21. ICP-OES instrument parameters for metals analysis.

Radio Frequency Power	1300 W
Nebuliser Argon Flow	0.70 L/min
Auxiliary Argon Flow	1-2.25 L/min
Plasma Argon Flow	15 L/min
Pump Rate	~0.6 – 1.0 mL/min
Equilibration Time	varies (sec)
Uptake Delay	35 secs
Instrument Stabilisation Delay	15 secs
Replicates	3
Replicate Read Time	3 secs

Mercury vapour was generated from the acidic sample extract using tin chloride at 5% w/v SnCl_2 in 7% v/v hydrochloric acid. The mercury vapour is carried into the absorbance cell with argon gas and analysed with a QuickTrace™ M-7600 Mercury Analyzer equipped with an ASX-520 Autosampler. The instrument uses a long path (220 mm) absorbance cell with spectrometer absorption at 253.7 nm. The instrument was calibrated over the

range 0 – 10 µg/L typically using at least five calibration standards plus the calibration blank. Additional instrument parameters are provided in Table 22.

Table 22. CV-AAS instrument parameters for mercury analysis.

Gas Flow	90 mL/min
Pump Rate	40%
Read Delay	56 secs
Replicates	4
Read Start	16 secs
Read Start	20 secs

Data analysis was completed within Microsoft Excel for Microsoft Office 365 (version 2512).

5.2.4.3 Fluoride and pH contamination data analysis

Technical replicates were first averaged to avoid any pseudo-replication. The results for pH and fluoride tests were ordered within their treatment type in ascending order based on pH level. These results were then graphed on a scatterplot with straight lines and markers as a visual representation of the relationship between these variables across all treatments.

Percentage difference was calculated to compare fluoride levels before and after treatment was applied. Percentage difference was calculated using the following:

$$\Delta\% = \frac{(Treatment\ X - Treatment\ Y)}{Treatment\ Y}$$

Percent difference was calculated for each repeat and averaged.

5.2.4.4 Metal contamination data analysis

Results from testing for metals were reported in micrograms (µg). There were several metals in which all results were below PQLs, across all treatments. In these cases, these results were disregarded for further analysis. Four metals of interest (aluminium, copper, iron, and lithium) were highlighted for further analysis based on their presence within the LiB cells tested.

Following this, results for the metals of interest had any values below the PQL substituted with *PQL/2* (Hornung and Reed, 1990; Girase, Thompson and Ormond, 2023). Technical replicates were averaged for each treatment level to avoid pseudo-replication. The three test replicates for each treatment type were then averaged, resulting in a single value reflecting the average contamination for each treatment type.

During testing, the swatches were passively exposed across both faces. A 3 x 10 cm was sub-sampled for metal analysis, with an equivalent surface area of 60 cm² (accounting for both exposed faces) and it was assumed that the concentration was reflective of this surface area and thus, could be expressed as µg/60 cm². Results were converted to milligram per metre squared (mg/m²) using the following formula:

$$Metal\ level\ (mg/m^2) = \frac{Metal\ level\ (\mu g/60cm^2)}{6}$$

To determine laundry efficiency, the percentage reduction of the contaminants was then calculated using the following formula:

$$\Delta\% = \frac{(\text{Treatment X} - \text{Treatment Y})}{\text{Treatment Y}}$$

From this calculation, negative values represent a reduction in contamination levels, i.e. a -50% difference represents that Treatment X has a value 50% lower than Treatment Y, and inversely a +50% represents an increase in contamination level of Treatment X when compared to Treatment Y.

Percentage of change was calculated based on *NFPA 1850, Standard on Selection, Care, and Maintenance of Protective Ensembles for Structural and Proximity Firefighting and Open-Circuit Self-Contained Breathing Apparatus (SCBA)* (2026), which stipulates “The cleaning process shall provide a 50 per cent or greater average cleaning efficiency for the average of all semi-volatile organic compounds and the average of all surrogate heavy metal contaminants, separately” (Chapter 11.6 Optional Verifications for Contaminant Removal). Based on this, contaminated and decontaminated swatches were compared against the laundered swatches to determine the percentage of contaminants that had been removed, with values greater than or equal to 50% being considered an effective laundry procedure.

Although contaminated, decontaminated and laundered samples were taken from three separate swatches, it was assumed that contamination levels would be equivalent across each prior to any treatment occurring, and as such the contaminated samples represent the level of metals present on laundered and decontaminated samples prior to any treatment application, with any changes in metal levels attributed to the procedures used. Due to the rotation of swatch location in position A, B or C and the averaging of these results, swatch position was not deemed to have any effect on contamination level.

5.3 Results and discussion

5.3.1 pH and fluoride

Hydrogen fluoride (HF) is a commonly discussed chemical of concern in the release of LiB vapour due to its ability to be generated through the decomposition of common LiB electrolyte solutions (Lebedeva and Brett, 2016). HF is a highly toxic and corrosive compound and exposure to liquid or fumes can cause severe burns, ulceration, and severe, rapid hypocalcaemia. While there are large differences between LiBs, HF production has been shown to increase inversely with SoC (Larsson *et al.*, 2014; Lecocq *et al.*, 2016). A further understanding of the risks associated with HF production and inhalation during LiB failure events is crucial for ensuring safe working practices for emergency workers.

Unfortunately, HF is an extremely reactive and highly soluble compound, making it difficult to characterise during a LiB failure event, as such, HF was not directly tested for. Instead, quantifications of fluoride ions (F⁻) and pH were tested as a proxy to the presence of HF, and comparisons were made post-laundry procedures. It was assumed that an elevated level of F⁻ was correlated with a low pH, and thereby indicative of the presence of HF. It should be noted that other acidic compounds (such as hydrogen chloride) may also be present and responsible for decreasing the pH of swatches. Values for pH and F⁻ concentration (µg/60cm²) can be found in Table 23. These values can be seen graphically in Figure 92 and Figure 93.

Table 23. pH and F⁻ analysis results.

SoC	Contaminated				Decontaminated				Laundered			
30%	Sample #				Sample #				Sample #			
	1	4	7	$\bar{x}$	2	5	8	$\bar{x}$	3	6	9	$\bar{x}$
pH	3.50	3.15	4.85	3.83	3.35	3.70	3.05	3.37	4.75	4.75	4.75	4.75
F ⁻ (ug/60cm ²)	480	1250	185	638	845	485	1900	1077	103	90	130	110
100%	Sample #				Sample #				Sample #			
	10	13	16	$\bar{x}$	11	14	17	$\bar{x}$	12	15	18	$\bar{x}$
pH	3.80	3.65	3.40	3.62	4.35	3.95	3.45	3.92	5.1	5.25	4.75	5
F ⁻ (ug/60cm ²)	410	355	530	432	320	395	655	457	85	91	115	103
Blank	Sample #				Sample #				Sample #			
	19	20	21	$\bar{x}$	22	23	$\bar{x}$	24	25	26	27	$\bar{x}$
pH	5.45	5.55	5.60	5.53	5.30	5.55	5.42	5.70	5.70	5.70	5.70	5.70
F ⁻ (ug/60cm ²)	3.75	2.5	2.5	2.58	5.25	2.5	3.87	2.5	2.5	2.5	2.5	2.50

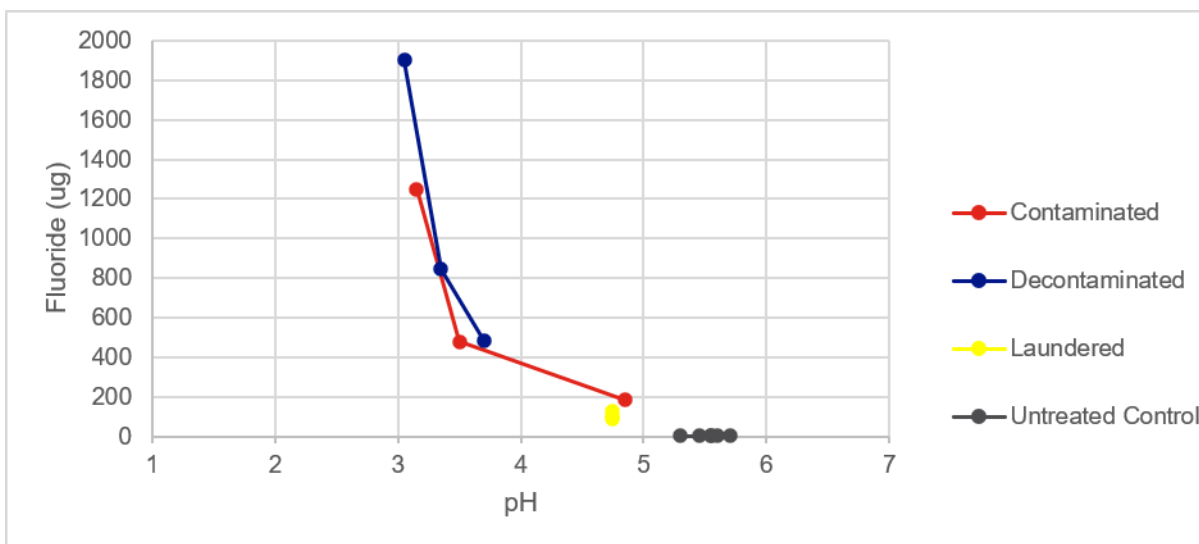


Figure 92. pH and F⁻ analysis results for PPC exposed to 30% SoC LFP battery vent gas.

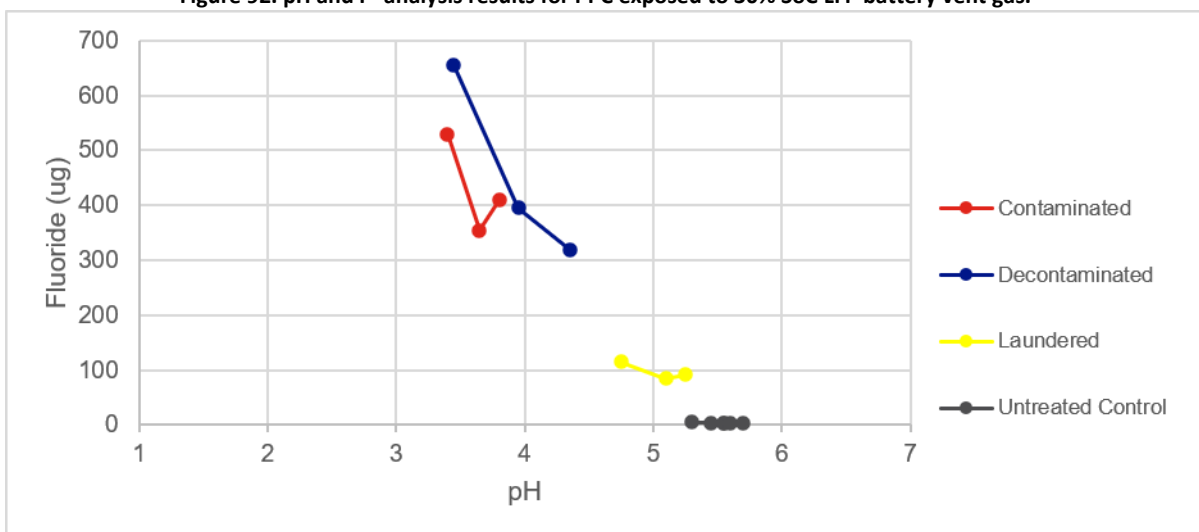


Figure 93. pH and F⁻ analysis results for PPC exposed to 100% SoC LFP battery vent gas.

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The percentage of F⁻ removed by the laundry procedure can be found below in Table 24.

Table 24. pH and F⁻ Δ% per PPC decontamination treatment method.

SoC	Treatment		Repeat			$\bar{x}$
	X	Y	1	2	3	
30%	Untreated	Contaminated	15,058%	39,374%	5,742%	20,058%
	Contaminated	Decontaminated	76%	-61%	927%	314%
	Contaminated	Laundered	-79%	93%	-30%	-67%
	Decontaminated	Laundered	-88%	-81%	-93%	-87%
100%	Untreated	Contaminated	121,847%	11,111%	16,637%	13,532%
	Contaminated	Decontaminated	-22%	11%	24%	4.3%
	Contaminated	Laundered	-79%	-74%	-78%	-77%
	Decontaminated	Laundered	-73%	-77%	-82%	-78%

Visually, there appeared to be an inverse relationship between pH level and fluoride ion concentration at both 30% and 100% SoC, with pH level decreasing as fluoride ion concentration increases. For both SoC there was a clear reduction in fluoride ion concentration and increase in pH level for laundered samples. Post-laundry pH levels returned to the baseline level of untreated blank samples. OEKO-TEX Standard 100 (International Association for Research and Testing in the Field of Textile and Leather Ecology, 2026) recommend pH levels between 4.0 - 7.0 for garments that have direct contact with skin. Values for laundered samples are within this recommended range, while contaminated and decontaminated samples mostly fall outside of this range.

The majority of workplace exposure standards relating to HF or metallic fluorides suggest exposure limits based on inhalation, as the respiratory route is the primary route for exposure. While these results cannot be directly assessed against suggested exposure limits, the per cent decrease can provide some information on the effectiveness of the laundry procedures. Results showed that at both SoC the laundry procedure was able to effectively decrease fluoride ion contamination by at least 70% in almost all samples taken. Additionally, all laundered samples were returned to concentrations <150 µg/60 cm², which is noticeably lower than contamination observed prior to the laundry process.

From this testing, it can be surmised that the laundry procedures currently employed are effective at both remediating pH to acceptable levels indicated by OEKO-TEX Standard 100 and removing a substantial portion of fluoride ions. The laundry procedures were able to effectively remove a substantial portion of fluoride ions and mitigate pH at 30% SoC, which was positive considering the increased contamination level observed. Further research should be conducted to investigate the long-term effects of acidic compounds on operational PPC and the permeation of acidic compounds onto the skin to further improve staff safety.

Fluoride and pH levels within the run-off water do not appear to increase due to the wet decontamination procedure. The pH levels recorded from the run-off water remain relatively stable, with an average of 7.02 and 6.27 for 30% and 100% SoC test burns respectively. Additionally, the fluoride ion level remains below 5 µg in ten out of 12 of the tested samples, however an increase was noticed when compared to one of the blank samples. Sample number six (6) presented a noticeable increase in fluoride ions and decrease in pH level. Similarly, another blank sample was the highest level of fluoride ions at 20 µg, which was over 20 times higher than the other blank sample analysed. It is unknown where the increase in results could have originated from and these outliers warrant further testing in order to be clearly understood. Generally, it appears that fluoride ions were not being distributed into the run-off water and the pH of water was thereby relatively unaffected.

5.3.2 Metal contamination

The average metal contamination and percentage differences for the chosen metal species can be found for each treatment type below in Table 25. Of the metals identified, four can be reasonably attributed to the vapour from the LiB failure event – aluminium (Table 26), copper (Table 27), iron (Table 28), and lithium (Table 29).

Table 25. Metals analysis results per sample. $\bar{x}$ = average concentration over repeat tests.

Metal (mg/m²)	Contaminated				Decontaminated				Laundered				
30%	Sample #												
	1	4	7	$\bar{x}$	2	5	8	$\bar{x}$	3	6	9	$\bar{x}$	
	Al	1.333	4.250	1.083	2.222	1.833	2.333	2.333	2.167	0.417	0.417	0.417	0.417
	Cu	0.750	0.667	0.667	0.694	0.500	0.583	0.583	0.556	0.667	0.750	0.583	0.667
	Fe	8.917	3.333	1.917	4.722	2.250	4.500	2.500	3.083	0.417	1.333	0.417	0.722
	Li	0.100	0.142	0.042	0.094	0.042	0.142	0.042	0.075	0.042	0.042	0.042	0.042
100%	Sample #												
	10	13	16	$\bar{x}$	11	14	17	$\bar{x}$	12	15	18	$\bar{x}$	
	Al	1.417	1.417	2.750	1.861	3.833	1.500	3.750	3.028	0.417	0.417	0.417	0.417
	Cu	1.008	0.850	0.853	0.897	0.842	0.583	0.750	0.725	0.583	0.667	0.750	0.667
	Fe	2.750	2.167	2.417	2.444	4.833	2.333	2.667	3.278	1.583	1.167	1.250	1.333
	Li	0.167	0.417	0.333	0.306	0.242	0.167	0.333	0.247	0.042	0.042	0.042	0.042
Blank	Sample												
	19	20	21	22	23	24	$\bar{x}$						
	Al	0.417	0.417	1.000	1.417	0.417	1.167	0.806					
	Cu	0.667	0.925	0.583	0.500	0.500	0.500	0.613					
	Fe	1.917	1.833	2.000	3.000	1.667	1.833	2.042					
	Li	0.042	0.042	0.042	0.042	0.042	0.042	0.042					

Table 26. Aluminium $\Delta\%$ per PPC decontamination treatment method. $\bar{x}$ = average concentration change over repeat tests.

SoC	Treatment		Repeat			
	X	Y	1	2	3	$\bar{x}$
30%	Untreated	Contaminated	66%	428%	34%	176%
	Contaminated	Decontaminated	38%	-45%	115%	36%
	Contaminated	Laundered	-69%	-90%	-62%	-73%
	Decontaminated	Laundered	-77%	-82%	-82%	-81%
100%	Untreated	Contaminated	76%	76%	241%	131%
	Contaminated	Decontaminated	171%	6%	36%	71%
	Contaminated	Laundered	-71%	-71%	-85%	-75%
	Decontaminated	Laundered	-89%	-72%	-89%	-83%

Table 27. Copper $\Delta\%$ per PPC decontamination treatment method. $\bar{x}$ = average concentration change over repeat tests.

SoC	Treatment		Repeat			
	X	Y	1	2	3	$\bar{x}$
30%	Untreated	Contaminated	22%	9%	9%	13%
	Contaminated	Decontaminated	-33%	-13%	-13%	-19%
	Contaminated	Laundered	-11%	13%	-13%	-4%
	Decontaminated	Laundered	33%	29%	0%	21%
100%	Untreated	Contaminated	65%	39%	36%	46%
	Contaminated	Decontaminated	-17%	-31%	-10%	-19%
	Contaminated	Laundered	-42%	-22%	-10%	-25%
	Decontaminated	Laundered	-31%	14%	0%	-5%

Table 28. Iron $\Delta\%$ per PPC decontamination treatment method. $\bar{x}$ = average concentration change over repeat tests.

SoC	Treatment		Repeat			
	X	Y	1	2	3	$\bar{x}$
30%	Untreated	Contaminated	337%	63%	-6%	131%
	Contaminated	Decontaminated	-75%	35%	-30%	-3%
	Contaminated	Laundered	-95%	-60%	-78%	-78%
	Decontaminated	Laundered	-81%	-70%	-83%	-78%
100%	Untreated	Contaminated	35%	6%	18%	20%
	Contaminated	Decontaminated	76%	8%	10%	31%
	Contaminated	Laundered	-42%	-46%	-48%	-46%
	Decontaminated	Laundered	-67%	-50%	-53%	-57%

Table 29. Lithium $\Delta\%$ per PPC decontamination treatment method. $\bar{x}$ = average concentration change over repeat tests.

SoC	Treatment		Repeat			
	X	Y	1	2	3	$\bar{x}$
30%	Untreated	Contaminated	140%	240%	0%	127%
	Contaminated	Decontaminated	-58%	0%	0%	-19%
	Contaminated	Laundered	-58%	-71%	0%	-43%
	Decontaminated	Laundered	0%	-71%	0%	-24%
100%	Untreated	Contaminated	300%	900%	700%	633%
	Contaminated	Decontaminated	45%	-60%	0%	-5%
	Contaminated	Laundered	-75%	-90%	-88%	-84%
	Decontaminated	Laundered	-83%	-75%	-88%	-82%

5.3.2.1 Contamination of PPC swatches

The blank (untreated) swatches measured low concentration for most metals tested with an average below 1 mg/m². Iron results were consistently higher than the other metals tested, on average of 2 mg/m². The elevated

iron levels may be due to background contaminants present within the manufacturing process, i.e. from steel sewing needles and cutters. Post-exposure to LiB fire and vent gases, a two-fold increase in contamination was measured, with metals increasing greater than 120% on baseline results, with the exception of copper which measured a 13 - 46% average increase and iron during the 100% SoC tests which increased in average 20% in comparison to the baseline untreated values.

Between the 30% SoC tests and the 100% SoC tests, there was no clear correlation between the level of contamination and the originating battery SoC.

5.3.2.2 On-site wet decontamination efficacy

On-site wet decontamination demonstrated mixed results. In some instances, the average metal concentration increased (i.e. average aluminium concentration for 100% SoC tests increased from 1.861 mg/m² to 3.028 mg/m² between the 'contaminated' and 'decontaminated' samples, respectively) and in other the concentration decreased (i.e. average aluminium concentration for 30% SoC tests decreased from 2.222 mg/m² to 2.167 mg/m² between the 'contaminated' and 'decontaminated' samples, respectively). The inverse was true for iron, where the average iron concentration for 100% SoC tests decreased from 4.722 mg/m² to 3.083 mg/m² between the 'contaminated' and 'decontaminated' samples, respectively, and for the 30% SoC tests increased from 2.444 mg/m² to 3.278 mg/m² between the 'contaminated' and 'decontaminated' samples, respectively. While copper and lithium average concentration decreased after wet decontamination, the variability in the aluminium and iron results indicate a degree of uncertainty. Due to the small sample size, the cause for the uncertainty is difficult to elucidate as there are limited opportunities to control for the test and sampling variables using the analysis results alone.

5.3.2.3 Laundry system decontamination efficacy

After laundering, the swatches returned lower concentrations of metals than the decontaminated swatch samples. Except for copper, the degree of change in contamination ranged from -4% to 21%. With regard to the 30% test burns; after wet decontamination, there was a clear reduction in copper concentration detected, however, after laundering, the concentration of copper was slightly higher than the decontaminated sample, yet still below the average concentration of the contaminated sample. The copper results for the 100% test burns were more consistent with the expected trends, where detected copper concentrations were reduced as the swatches underwent the different decontamination treatments, although the degree of contamination reduction were not as significant in comparison to the other metals (degree of change in copper contamination from 100% SoC test burns ranged from -5% to -25%). Further work is required to investigate the cause of these spurious results.

The laundering process also reduced the overall average of iron detected in the baseline swatch samples (from 2.04 mg/m² to 1.026 mg/m² across all test samples). Indicating that the background contamination of iron could be reduced through regular wash and wear cycles. The results from the water run-off analyses are presented below, separated by SoC (Figure 95).

Table 30. PPC decontamination treatment run-off water analysis results.

SOC		Run Off				Blank Water			
		Al	Cu	Fe	Li	Al	Cu	Fe	Li
30%	Average	133.33	162.5	120.83	38.33	25	160	25	2.5
	Maximum	350	350	200	60	25	170	25	2.5
	IQR	212.5	156.25	156.25	22.75	0	20	0	0
100%	Average	54.17	81.67	75	16.67	25	160	25	2.5
	Maximum	62.5	140	100	45	25	170	25	2.5
	IQR	18.75	60	50	27.5	0	20	0	0

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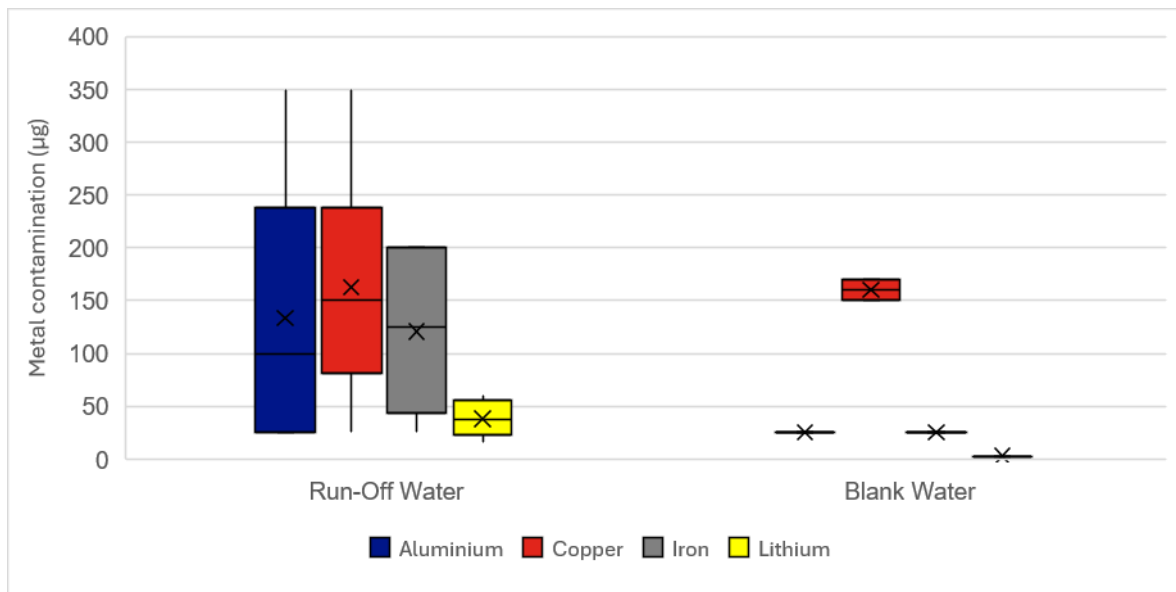


Figure 94. PPC decontamination treatment run-off water analysis results for PPC exposed to 30% SoC LFP battery vent gas.

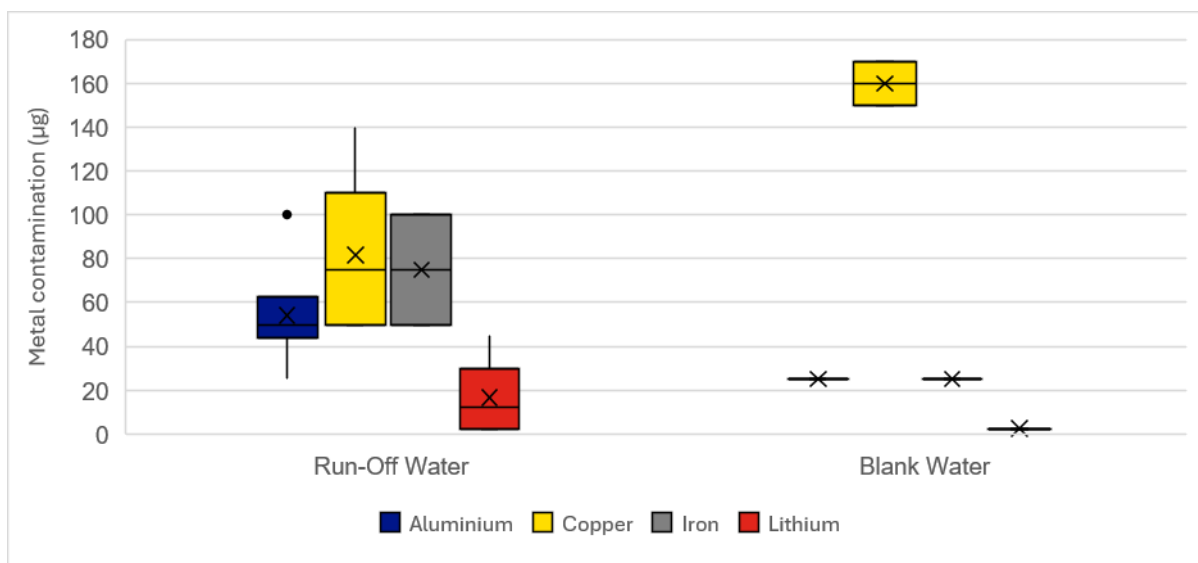


Figure 95. PPC decontamination treatment run-off water analysis results for PPC exposed to 100% SoC LFP battery vent gas.

In both scenarios the metals were detected in the run-off water were most likely originating from the wet decontamination procedure. These results show considerable variation, both between the different SoCs and within the SoC tests. Copper levels appeared to be elevated in the blank water samples. Copper contamination in the blank water samples may be introduced from brass hose fittings used through the water source. The copper residue may transfer to the swatch material during wet decontamination and therefore increasing the level of contamination detected after wet-decontamination treatment, thereby artificially inflating the results obtained in above.

While the results are quite varied, average metal contamination was higher for all metals from the 30% SoC tests. Excessive vapour production that was observed during lower states of charge may be responsible for elevated levels of contamination. The average per cent increase of each metal is presented in Table 31.

Table 31. Average $\Delta\%$ change in run-off water contamination levels (compared to blank water samples).

SoC	Al	Cu	Fe	Li
30	433%	2%	383%	1433%
100	117%	-49%	200%	567%

The data shows that the average per cent increase in water contamination is higher in 30% SoC batteries, indicating that the on-site decontamination procedures are removing contaminants.

Responsible management of firefighting run-off should be considered at all events, especially those involving LiBs. Testing demonstrated that metal contamination was present in run-off water from decontamination of exposed PPC.

5.4 Study limitations

There are several key limitations within this study which must be considered and can be used when developing future research.

A major limiting factor in this study was the small number of repeats across each test and variable. Throughout this experiment, sample size was low when investigating individual factors, such as treatment type for a particular SoC which limits the statistical power that can be applied to the results and increases the difficulties in assessing outliers and accuracy of results. It should be noted that due to time and budget constraints of the project, this sample size was specifically chosen to a) act as a screening mechanism to inform future testing, b) be a manageable sample size for analysis, and c) provide some repetition of testing to assess results. Additionally, technical replicates were taken from each sample to assist in reducing outliers and increase homogeneity.

Further, the results were bound by the sample swatch size. While the scenario presented in this testing may not be a true reflection of a complete structural PPC ensemble in a residential fire scenario, the use of an individual cell with a swatch of clothing was used to represent a scale of a realistic contamination scenario. It is also unlikely that a fire fighter would be present while a single LiB cell is progressing through each stage of TR. Due to the swatch 'over washing' of the swatches may have occurred due to the volume of the laundering machines used. To assist in preventing this, swatches were washed with new, un-used PPC ensembles acting as ballast to prevent excessive dilution or inadvertently increase the dilution of contaminants.

Overall, the study presented herein was used to demonstrate a proof-of-concept for future PPC decontamination and laundering effectiveness research. The learnings observed will be used to inform future testing.

5.5 Summary

The testing completed here demonstrated that heavy metals, that could be reasonably attributed to originated from a LiB, were found on the exposed PPC swatches. It was also found that exposed swatches demonstrated an increase in fluoride concentration, and a decrease in pH level. Contamination for both heavy metals and pH/fluoride was detected at a higher degree on swatches exposed to a 30% SoC LiB undergoing TR.

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The effectiveness of the on-site decontamination procedures utilised throughout this experiment were mixed. However, from this preliminary testing, the laundry procedures currently followed were effective at removing contamination when considering the NFPA 1850 guidelines, which dictate a 50% reduction in heavy metals. The effectiveness of the laundry procedure is also supported by the concentration of heavy metals in laundered swatches closely resembling those of untreated swatches.

Furthermore, the laundry procedure was effective at remediating pH levels and considerably decreasing the concentration of fluoride ions. Across the majority of tests, the laundered swatches were returned to a pH level within the OEKO-TEX Standard 100 guidelines, while contaminated and decontaminated swatches remained outside of this range. F^- concentrations were reduced by more than 65% on average for 100% and 30% SoC.

Future testing is required to explore the permeability of PPC garments, to further understand how these contaminants move through the layers of the PPC ensembles and therefore how operational staff are protected while engaging in firefighting activities involving LiBs. Testing needs to be conducted on larger scale LiB events such as EVs or BESS failures, in which there may be the propensity for extended off-gassing periods, larger volumes of off-gassing, and increased requirements for firefighting intervention. Additionally, testing should aim to incorporate realistic firefighting movement and actions to introduce air entrainment to the PPC exposure and to assess inner layers firefighting PPC such as undergarments, to provide a more holistic approach to improving operational staff safety. A larger sample size would also improve applicability of results and allow for meaningful statistical analysis.

6 Supplementary exploratory studies

6.1 Environmental impact mitigation

6.1.1 Background

During the design and development of the testing enclosures for this project, environmental impact mitigation strategies were considered to reduce the impact of LiB risk and hazards on FRNSW testing facilities and the local environment and community. Air quality was of particular concern, leading to exploratory work in fit-for-purpose smoke handling and mitigation systems.

Using literature understanding of the quantity and composition of the smoke and vapour produced by LiB fires, a prototype gas scrubber using activated carbon pellets was designed and constructed to test its effect on the effluents of fire testing.

6.1.2 Design and construction

Potassium hydroxide impregnated activated carbon pellets were selected as a filter medium for its ability to capture volatile organic compounds (VOCs) which comprise of a large component of battery electrolyte vapours. An impregnated carbon was selected as it has moderate ability to capture hydrogen fluoride and hydrogen sulphide. In addition, it may also trap heavy metal particles. Table 32 below provides the specifications of the activated carbon pellets.

Table 32. Activated carbon pellet specifications.

Parameter	Requirement
Potassium Hydroxide	Up to 10%
Moisture Content	15% maximum
Apparent Density	0.45 - 0.62 g/ml
Ball-Pan Hardness	95 minimum
Particle Diameter	4 mm
Particle Length	6 mm
Mean Particle Diameter	3.6 to 4.7 mm
Surface Area	1000 m ² /g minimum
Total Ash Content	13% maximum
Hydrogen Sulphide Breakthrough Capacity	0.12 H ₂ S g/cm ³

A centrifugal fan and variable speed controller were mounted to a cylindrical vessel. The vessel had a permeable sieve mounted to hold the carbon pellet bed. A FTIR gas analyser was mounted to both the inlet and outlet of the scrubber (Figure 96).

The extraction rate was selected to balance the capture of the effluent and to allow for the longest interaction time with the carbon bed, also known as empty bed contact time (EBCT).



Figure 96. The scrubber testing configuration.

6.1.3 Test methodology

The test battery and scrubber inlet were placed inside a semi-enclosed fire hood to collect the gases and vapours. A prismatic LFP cell (~39,000 mAh, 3.2 v) at 30% SoC was used based on the gas production rate observed in earlier testing.

Two tests were conducted. A Gasmet FTIR gas analyser measured from the filtered outlet stream in trial 1, see Figure 100. In trial 2, the measurements were made from the unfiltered inlet stream, see Figure 101. Unfortunately due to an instrument error, only the FTIR results from the outlet in Trial 1 and the inlet from Trial 2 were able to be reported.

To initiate TR, approximately 2 m of 28-gauge nichrome wire was wrapped at intervals of 5 - 7 mm (~44 Ω resistance). The heating element was connected to a power supply supplying 220 W of heating to the cell. Polyimide tape was used to secure the nichrome wire across the surface of the cell.

Inlet and outlet temperatures were recorded and two HD cameras recorded video.

Table 33. The key parameters used in the scrubber tests.

Parameter	Trial 1	Trial 2
Fan (rpm)	1716	2860
Air speed at outlet (m/sec)	7.37	7.65
Q volume flow (m ³ /sec)	0.13	0.14
Bed depth (m)	0.085	0.38
Cross sectional area of bed (m ²)	0.255	0.26
Face velocity (m/sec)	0.51	0.53
Empty bed contact time (sec)	0.17	0.72
Carbon apparent density (g/mL)	0.5	0.5
Total carbon (kg)	10.8	48.5
Total carbon volume (m ³)	0.0217	0.10

6.1.4 Results

For both trials, the scrubber inlet flow was sufficient to collect gases and vapours from the fire hood. In trial 1, there was a moment where the vapour production overwhelmed the inlet draw and a small amount of vapour was lost to atmosphere. In trial 2 there was a brief ignition period followed by an extending venting period. In both trials, some white vapour was observed being expelled from the outlet of the scrubber.



Figure 97. The battery venting into the fire hood.



Figure 98. The vapours in the outlet charge at their most visible period in from Trial 1.



Figure 99. The vapours in the outlet charge at their most visible period in from Trial 2.

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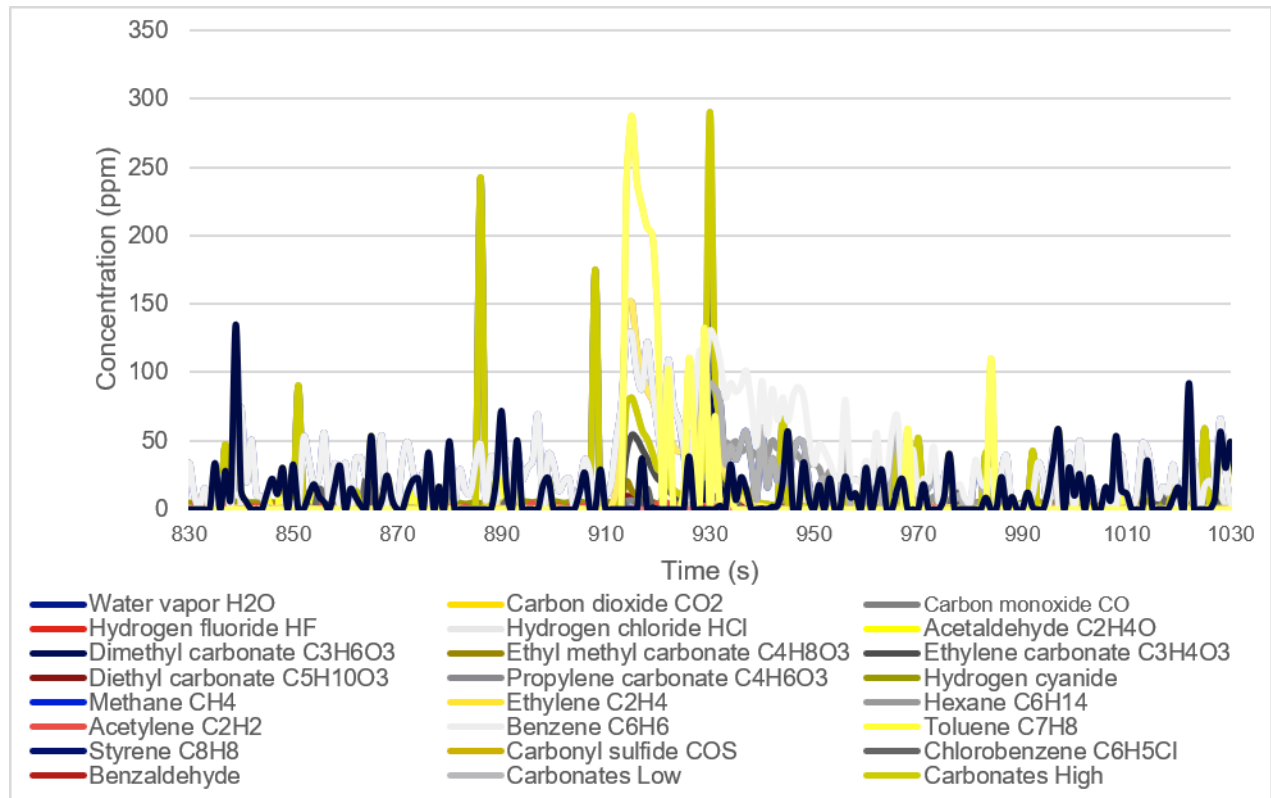


Figure 100. Trial 1 outlet gas analysis results.

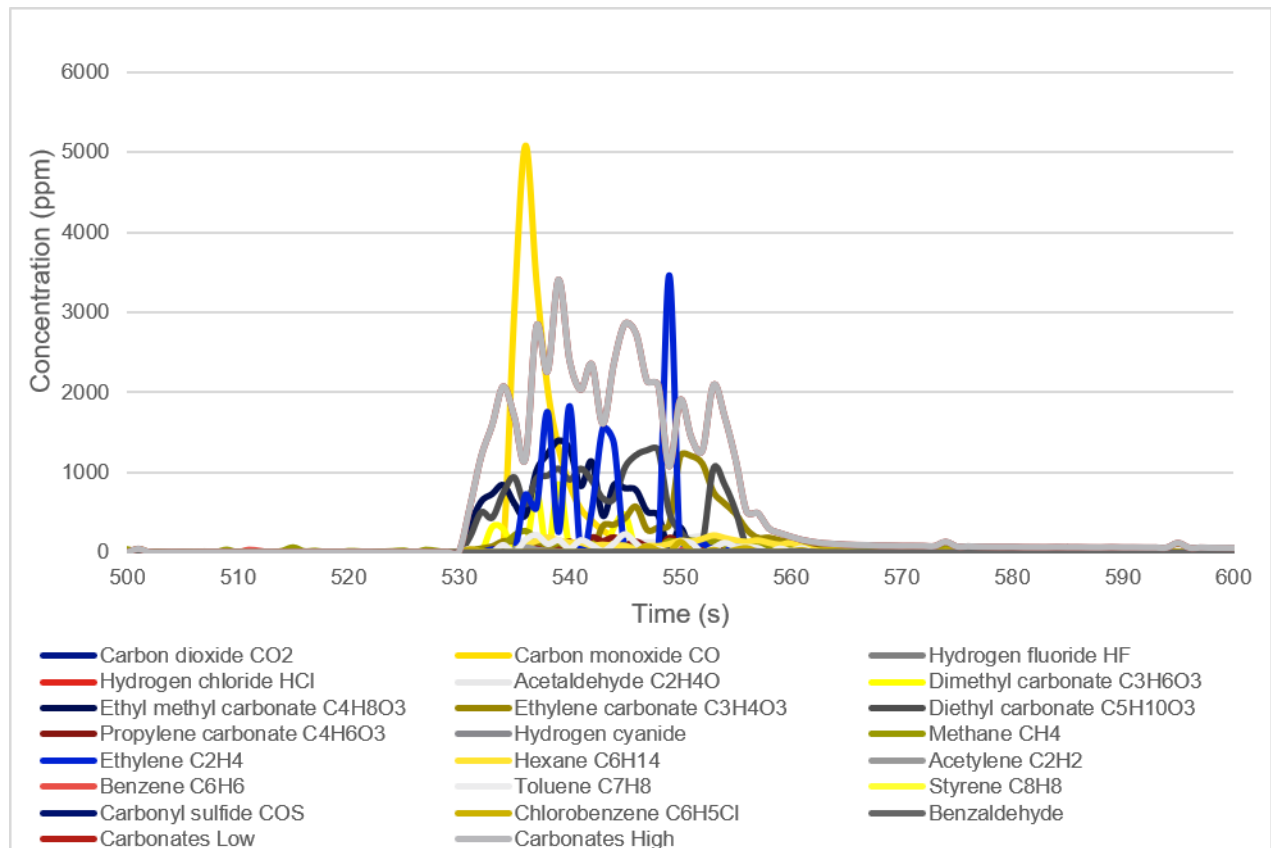


Figure 101. Trial 2 inlet gas analysis results.

Table 34. Trial 1 Peak Concentrations of filtered outlet.

Compound	ppm	Compound	ppm
Carbon dioxide	0.23	Methane	129.14
Carbon monoxide	151.57	Ethylene	287.48
Hydrogen fluoride	3.11	Hexane	50.39
Hydrogen chloride	2.1	Acetylene	7.95
Acetaldehyde	4.01	Benzene	72.68
Dimethyl carbonate	272.81	Toluene	80.02
Ethyl methyl carbonate	20.49	Styrene	0
Ethylene carbonate	54.15	Carbonyl sulphide	0.29
Diethyl carbonate	9.54	Chlorobenzene	39.95
Propylene carbonate	9.56	Benzaldehyde	3.08
Hydrogen cyanide	7.84	Carbonates (Low)	289.78

Table 35. Trial 2 peak concentrations of unfiltered inlet.

Compound	ppm	Compound	ppm
Carbon dioxide	4.13	Methane	268.93
Carbon monoxide	5079.49	Ethylene	3460.8
Hydrogen fluoride	5.13	Hexane	213.15
Hydrogen chloride	6.2	Acetylene	63.15
Acetaldehyde	203.92	Benzene	48.14
Dimethyl carbonate	852.88	Toluene	227.46
Ethyl methyl carbonate	1398.95	Styrene	0
Ethylene carbonate	1207.12	Carbonyl sulphide	0.56
Diethyl carbonate	1279.66	Chlorobenzene	129.33
Propylene carbonate	189.09	Benzaldehyde	13.62
Hydrogen cyanide	8.08	Carbonates (Low)	3408.2
		Carbonates (High)	3408.2

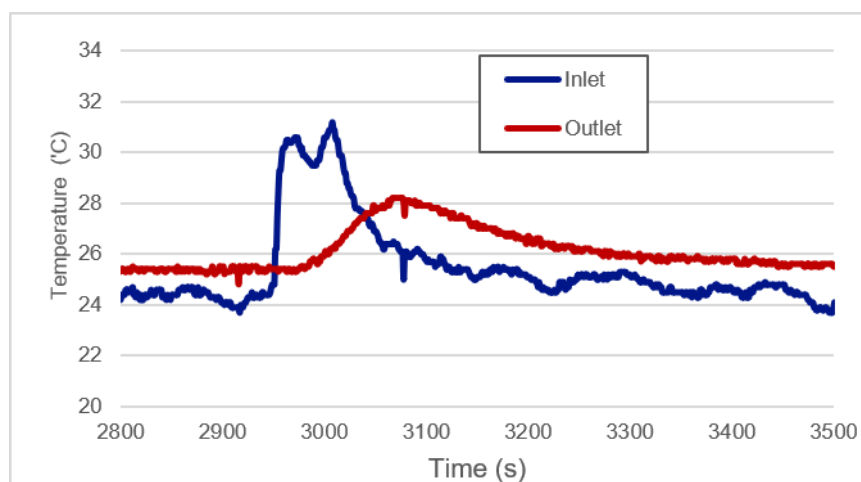


Figure 102. Trial 1 inlet and outlet temperatures, the vented gases and vapours measure a small difference over ambient temperatures.

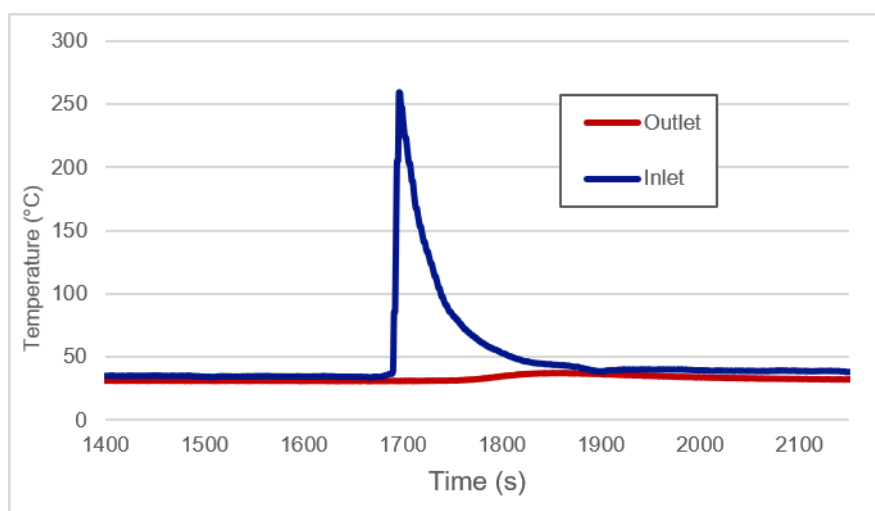


Figure 103. Trial 2 inlet and outlet temperatures, the trial had a period of flaming combustion shown in the acute temperature spike.

6.1.5 Discussion

In both trials, the flows through the scrubber were 0.13 and 0.14 m³/s. In trial 1 the flow was drawn through a smaller volume of carbon (0.0217 m³) giving an interaction time of 0.17 s. Trial 2 was conducted with 0.1 m³ of carbon giving an interaction time of 0.72 s. The flow rates of the scrubber were able to contain the vapour production rate for most of the trial duration.

Although both the trial batteries and ignition method were mirrored between tests, the failure mechanisms were dissimilar as Trial 1 did not reach flaming ignition while Trial 2 did.

In both tests white vapours were observed from the scrubber outlet. Without obscuration measurements, it was difficult to visually observe the level of filtration between the inlet and outlet flows.

Given the limited scope of this work, the results from this pilot study show some promising observations. Future testing would benefit from more repeat testing and the use of a second FTIR analyser. Trial 2 used almost four times the quantity of activated carbon, outlet gases would likely show lower concentrations than recorded in Trial 1.

There are many scrubbing methods used each with their own relative benefits and failings. Each of the airborne effluents of a battery fire require unique conditions to capture or treat. More research and development is required in order to validate the implementation of an active bed carbon filter in this type of testing.

6.2 Testing facility and workplace health and safety

6.2.1 Occupational hygiene

6.2.1.1 Single cell test area

Part way through the single cell test series, an occupational hygienist (OH) was engaged to provide an independent assessment of the test site to ensure that working conditions were being maintained and that cleaning routines were adequate. A range of areas were identified for testing, including the test chamber, office space, kitchen, workshop, and covered outdoor learning area (COLA) (Figure 104).

The OH report found that surface wipe sampling was effective in identifying chemical residues associated with LiB testing, including lithium, manganese, cobalt, nickel, and other metals. Residues were predominantly localised to test equipment and the immediate testing areas, with only trace levels detected in surrounding non-test areas such as offices, kitchens, and general workspaces.

Overall, the findings were positive, with contamination largely contained to operational areas where testing had occurred. The only exceedance of relevant surface contamination occupational guidance values was lithium within the burn cell testing area, even after cleaning had been completed. A range of precautionary measures were recommended to ensure safe working conditions could be maintained, all of which were subsequently adopted.

An important learning from this report was that areas close to the incident site may become, and potentially remain, significantly contaminated with heavy metals if not adequately cleaned and remediated post-incident. While contamination was shown to be largely contained under controlled conditions, elevated residues within primary incident areas highlight the potential for persistent localised contamination. Further assessment is required to ensure safety advice is appropriate when returning sites to owners/occupiers.



Figure 104. Overhead view of the single cell testing areas and workflow.

6.2.1.2 Pack test area

During the pack testing, there was a significant increase in site impact due to the scaling up of battery size, resulting from larger vapour clouds and expanded material deposition zones. To maintain a safe working environment, recommendations from the initial OH assessment were adapted to suit the new test area and the increased scale of hazards (Figure 105). Site cleaning and maintenance practices were also enhanced to ensure that debris spread was rapidly contained following testing.

At the conclusion of pack testing, a full site decontamination was undertaken. The test area, along with all equipment and materials used during testing, was washed using an alkaline-based cleaning solution in water applied through high-pressure sprayer.

Following this, the OH was re-engaged to assess residual contamination levels after cleaning and remediation. Surface wipe sampling again identified the presence of metals and anions associated with LiB testing; however, these were present only at trace levels across sampled locations. Importantly, no tested metals exceeded applicable workplace exposure or surface contamination guidance values, indicating that remediation measures were effective.

Elevated chloride levels were observed in some areas, though these can be attributed to common sources such as sweat, food, and cleaning products rather than battery-related contamination.

Due to poor weather conditions on the sampling day, external areas—including the hot zone and surrounding building facades—could not be assessed, limiting full site characterisation. Despite this limitation, the overall findings remained positive, and no additional site improvement recommendations were identified.



Figure 105. Overhead view of the pack testing areas and workflow.

6.2.2 Water analysis

All liquid effluent generated during pack-level LiB testing was collected and transferred into IBCs for appropriate handling and disposal. The run-off comprised a mixture of battery test water, encapsulating agent (Class A foam) run-off, and cleaning solutions used during post-test remediation. At the conclusion of testing, approximately two and a half IBCs of liquid waste had been accumulated (Figure 106).

To support appropriate waste classification and disposal, targeted sampling of the collected effluent was undertaken to characterise its composition. The analysis considered a broad range of contaminants typically associated with LiB failure events, including dissolved metals, inorganic salts, organic compounds, and trace substances.

The wastewater was characterised by elevated dissolved contaminants, particularly high concentrations of salts, lithium, fluoride, and organic load (COD), along with measurable levels of battery-derived metals such as aluminium, nickel, cobalt, and manganese. In contrast, VOCs (including BTEX) and most PFAS compounds were below detectable limits, indicating they were not significant contributors to the contamination profile. Overall, the results indicate that contamination was dominated by dissolved inorganic and electrolyte-related species rather than volatile or trace organic compounds.

From a management perspective, these findings highlight that containment and controlled collection are effective strategies for managing wastewater generated during large-scale battery testing. Post-test maintenance should prioritise thorough flushing, neutralisation where required (due to elevated alkalinity), and verification that drainage systems have not retained contaminated residues. More broadly, effective site management should focus on maintaining liquid containment integrity, implementing corrosion-aware cleaning practices, and undertaking verification sampling of wastewater prior to disposal.



Figure 106. Example image of LiB effluent IBC.

7 Outcomes and recommendations

The above report describes research and testing activities conducted by FRNSW to achieve RA NSW objectives to proactively reduce the impact of future disasters across NSW and to help communities recover from them faster. These objectives can be achieved through research and knowledge that aid in evidence-based strategy and decisions making. To this end, the following activities were identified for testing to achieve the objectives of the project:

- 1) *Quantify and compare the hazards associated with LiB fires with respect to cell chemistry, format, configuration, state of charge.*
- 2) *Test the efficacy and safety of new and existing extinguishing agents, methods, tools, and equipment on LiB-related fires, including safety of personal protective clothing and equipment.*
- 3) *Provide recommendations for updates to operational procedures and guidelines, and materials for training of first responders in managing LiB-related fires.*

Each testing activity and the associated findings are summarised below.

Following the testing activity summaries, the findings from this research are discussed with respect to the project outcomes.

7.1.1 Quantify and compare the hazards associated with LiB fires with respect to cell chemistry, format, configuration, state of charge

Quantification and comparison of hazards associated with LiB fires was conducted using small-scale LiB cells. The following key findings were observed from the results and discussions of the testing activities:

- TR in LiBs present significant flammability, explosion, and human health hazard risks.
 - The hazard profile of the TR emissions was observed to be driven primarily by battery chemistry and cell format.
 - The predominance of flammable gases, including hydrogen cyanide, methane, and acetylene, alongside VOCs, indicates a high potential for rapid fire spread and vapour cloud explosion, particularly in confined or poorly ventilated environments.
- The elevated presence of toxic and corrosive gases in certain battery chemistries highlights the need to consider toxicity alongside fire behaviour when assessing incident risk.
- Overall, the variability and peak behaviour of emitted compounds demonstrate that no single factor reliably predicts hazard severity. As such, a precautionary, worst-case approach to incident management, supported by atmospheric monitoring is critical to ensuring responder safety.

7.1.2 Test the efficacy and safety of new and existing extinguishing agents, methods, tools, and equipment on LiB-related fires, including safety of personal protective clothing and equipment.

The efficacy and safety of new and existing extinguishing agents was conducted through practical, real-world assessment of their efficacy on LiB packs representative on e-micromobility devices. In comparison to free-burn scenarios, the extinguishment agent test results and discussions demonstrated the following findings:

- Global TR fire durations were highly stochastic with a CV of 30.2%. The initial heating inertia of TR was a poor predictor of total TR fire duration.
- The enclosure material of the battery was the dominant factor in TR characteristics and suppression efficacy, where TR in aluminium encased batteries was the most predictable, steel was the most violent/volatile, and shrink-wrapped batteries produced the longest durations.
- In terms of extinguishment efficacy, liquids significantly outperformed the fire blankets tested. The encapsulating agents provided stabilisation to TR volatility, while water demonstrated an instantaneous cooling effect.
- The casing integrity during TR was a determining factor for liquid extinguishing contact with cells in TR. Rigid enclosures can shield cells from suppressants, thereby inhibiting their effectiveness, or retention of liquids allowing it to pool and interrupt heat transfer, thereby increasing its contact and cooling of cells in TR.
- Both standard fire blankets and LiB-specific fire blankets provided negligible cooling, suffered rapid burn-through (within two to four seconds after application) of the heat-resistant materials and prolonged the TR fire events in batteries with steel enclosures.

Further, the efficacy of FRNSW's PPC decontamination procedures was assessed to provide an indication of the appropriateness of these protocols and their effectiveness in protecting the health and safety of firefighters. Through this testing the following findings were detailed:

- Contamination for both heavy metals and pH/fluoride was detected on the exposed PPC swatches at a higher degree on swatches exposed to a 30% SoC LiB undergoing TR than a battery at 100% SoC.
- The effectiveness of the on-site decontamination procedures utilised throughout this experiment were mixed. However, from this preliminary testing, the current laundry procedures were effective at removing contamination per NFPA 1850 guidelines, which dictate a 50% reduction in heavy metals as effective.
- The laundry procedure was also effective at remediating pH levels and considerably decreased the concentration of fluoride ions. Across the majority of tests, the laundered swatches were returned to a pH level within the OEKO-TEX Standard 100 guidelines, while contaminated and decontaminated swatches remained outside of this range. Fluoride ion concentrations were reduced by more than 65% on average for both 100% and 30% SoC test scenarios.

7.1.3 Provide recommendations for updates to operational procedures and guidelines, and materials for training of first responders in managing LiB-related fires

For emergency response agencies these findings support the need to treat all TR events as multi-hazard incidents. Operationally, this includes the establishment of conservative exclusion zones, particularly for incidents involving enclosed environments, where that is an increased risk of explosion. It is also important for continuous atmospheric monitoring activities for flammable and toxic gases be deployed to inform risk assessment during firefighting operations and advice for community safety. Monitoring should be incorporated throughout the duration of an incident due to the persistence of toxic and corrosive by-products. Ventilation strategies should also be applied cautiously in order to reduce gas accumulation and vapour cloud explosion potential.

Recommendation 1 – Emergency responders are recommended to approach all battery incidents as worst-case scenarios in the first instance.

Recommendation 2 – Atmospheric monitoring by emergency services for hazardous battery gas and vapour is recommended throughout the entire duration of an incident.

Recommendation 3 – It is recommended that conservative exclusion zones are set in place during incident management.

In terms of extinguishment, there was a clear delineation between liquid extinguishment agents and fire blankets tested. The liquid suppression agents had a measurable impact on event duration and reduction of peak temperature. Importantly, the liquid used was reflective of the needs for active fire mitigation and immediate cooling to prepare the battery for safe handling for water immersion. These results are critical to operational procedures and guidelines as they help guide extinguishment tactics and training materials. It was also determined that the casing material of the battery was a critical factor in extinguishment and intervention effectiveness. Therefore, operational procedures may be tailored to the type of casing encountered.

Recommendation 4 – Liquid extinguishment agents and mediums are more effective than fire blankets at cooling batteries and reducing the duration of thermal runaway.

Recommendation 5 – Immersion is currently the most definitive method for thermal management of a battery fire. The application of liquid agents can have some stabilising effects that can create safer handling conditions. Thermal runaway may start, continue, and propagate while a battery is immersed in water.

Recommendation 6 – Immersion of a battery into water is effective at managing a battery fire. It is recommended that the battery is monitored after water immersion as cooling and extinguishment is not immediate and batteries may continue to off-gas and heat after immersion.

Recommendation 7 – Battery manufacturers are recommended to consider battery casing materials in designing for safety.

The findings have highlighted the criticality of the routine use of SCBA and full structural PPE and PPC ensembles to mitigate exposure to both air-borne and liquid hazards. Additionally, preliminary assessment of wet decontamination procedures and laundry procedures demonstrated an effectiveness at removing global contaminants. However, these findings require further study under more realistic conditions. Furthermore, the run-off water from battery extinguishment may have elevated levels of environmental contaminants. As such, appropriate water run-off management procedures are necessary to mitigate any potential environmental hazards.

Recommendation 8 – It is recommended that emergency responders utilise self-contained breathing apparatus and appropriate personal protective clothing and equipment for the duration of the battery incident, including during post-incident battery handling and management.

Recommendation 9 – It is recommended that any personal protective clothing exposed to battery off-gassing is appropriately decontaminated and laundered using industrial procedures.

Recommendation 10 – It is recommended that any water run-off from battery incidents is appropriately captured, treated, and disposed of to mitigate environmental contamination and risk.

Generally, TR characteristics were measured and observed that provide valuable insight and evidence to support community prevention and education measures. The difficulties and risk to researchers during application of extinguishment agents and blankets in proximity to a failing battery highlighted the criticality of maintaining a safe distance from a failing battery, as well as the risk of secondary spot fires from hot and flaming projectiles. Surface areas close to the incident site may become, and potentially remain, significantly contaminated if not adequately cleaned and remediated post-incident.

Recommendation 11 – Community education should consider the heightened risk of attempting to intervene and/or extinguish battery fires.

Recommendation 12 – Extinguishment agents or tools that require coming into proximity with a battery fire, such as portable fire extinguishers and fire blankets, should not be used without adequate personal protection.

Recommendation 13 – It is recommended that batteries are stored and charged on solid, non-flammable surfaces, away from other flammable items, and in a well-ventilated area.

Recommendation 14 – It is recommended that decontamination of surfaces and areas after a battery fire is considered at incident handover, prior to re-occupation.

7.2 Address gaps in the emergency services sector’s knowledge and understanding of lib fires, with the research findings

The research findings above can be used to address gaps in emergency sector knowledge and understanding of LiB fires through implementation of these results in tactical and strategic decision-making.

Through implementation and utilisation of research results and findings in operational guidelines and practice these findings inform operational response procedures for emergency services (including response agencies other than FRNSW). The results and discussions presented throughout this report provide emergency services with additional knowledge and understanding of the hazard and risk profile of LiBs in TR, and the underlying forces with which TR can be influenced.

Further, utilisation of these findings assist in determining necessary equipment and safety requirements for emergency services to mitigate and manage the risks of LiBs in TR. The initial assessment of LiB-specific extinguishment methods demonstrated their effectiveness on LiB packs of various enclosure materials. Each extinguishment method has their own merits; water continues to prove to be the most effective at battery cooling and therefore reduction in TR duration.

On-site wet decontamination and appropriate, effective laundry procedures have been demonstrated to be critical in reducing structural garment contamination. It is therefore imperative for emergency services to enforce comprehensive decontamination protocols within their safety management systems to help alleviate firefighter exposure to LiB effluent on their PPE and PPC.

7.3 Mitigate the risk of lib fires to community and infrastructure in disaster/emergencies through research findings

To mitigate the risk of LiB fire and emergencies to the community and to the built environment, the findings from this research project can be used to inform potential legislation changes in LiB risk mitigation. These changes require evidence-based strategies that effectively and efficiently alleviate the complex hazard profile presented by

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LiBs and the environments and conditions in which they can fail. The work conducted has demonstrated that LiBs present many differing and complex hazards dependent on the conditions and specifications of the battery and the way it failed. As such, in order to mitigate the risk to communities and infrastructure, any mitigation strategies and protocols should encompass and balance the broad range of risks.

Community risk management can be mitigated through public policy and safe consumer practices. Further, the research findings can be used to inform the development of building codes and standards, particularly where they require a comprehensive understanding of the impact that LiB failures and TR events can have on building materials and environments.

8 Future works and lessons learnt

8.1 Monitoring and evaluation

The project was monitored throughout its lifecycle and evaluated at various stages to assess research progress and governance. The purpose of the evaluation was to review the effectiveness and efficiency of the project, including what components worked well and which did not work as planned. It also identified lessons learnt that can be considered in future research funding schemes and outline recommendations for future work associated with achieving the anticipated benefits of the project outcomes.

The following key outcomes and benefits were identified during project evaluation:

End of program outcomes:

1. Community members are better equipped with ways to respond to bushfire and other natural disaster risks.
2. NSW Government has implemented (or is progressing) relevant research related recommendations from enquiries and reviews.
3. Data and research produced informs new regulations, standards and guidelines.
4. NSW Government agencies and other emergency services sector have improved (and faster) access to evidence based research, quality data and technology.
5. Partnerships and networks are strengthened among government agencies, research organisations, NGOs, peak bodies and community.
6. NSW Government has improved knowledge about disaster risk and strategies to reduce impact on communities and critical infrastructure.
7. Government and response agencies can better predict and are prepared for bushfires and other natural disaster events.
8. NSW Government and agencies implement a more coordinated approach to bushfire and natural disaster mitigation, planning and response.

Benefits:

1. Enable communities, government agencies and industry to be educated on how to deal with LiB related fires.
2. Best Practice guidelines developed regarding battery safety.
3. Decision makers will be able to use data sets and test results to make evidence-based informed decisions to develop their LiB disaster risk reduction programs.
4. FRNSW, AFAC and member fire and emergency service organisations can adopt best practice recommendations regarding standard operating procedures/guidelines and any tools, equipment, extinguishing agents, and/or PPC/PPE that may required/aid in response to LiB related fires.

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5. Regulatory bodies can adopt best practice recommendations, including changes to regulations, standards and legislation.
6. Emergency services agencies, business, industry and academia can use the Research Reports to develop the most effective LiB safety preparedness programs for communities and at-risk groups.
7. State and territory governments can use the Research Reports to develop, evaluate and improve LiB safety programs aimed at promoting disaster resilience for individuals and communities.
8. Collaboration between government, emergency services agencies, businesses and industry will be enhanced as a recognised researched LiB data set will enable them to develop LiB safety preparedness programs together.
9. Emergency services agencies, business, industry and academia can use the Research Reports to assess whether their current LiB safety programs and tools meet new recommendations arising from inquiries/reviews into natural disaster events and update their preparedness programs accordingly.
10. NSW government agencies and other key sector stakeholders can use the Research Reports to address priority issues and gaps in the emergency services sector's knowledge and understanding of the impact that LiB technology can have during natural disasters such as bushfires and floods and can translate these findings into developing strategies and practical applications in the prevention, preparedness, response and recovery phases of disaster management.

As can be seen above, the key to achieving all these benefits is having research reports based on evidence from testing of the various knowledge gaps that are addressed through the literature review. Whilst the scope of testing undertaken as part of the project will not answer all questions, it will build on the knowledge base available to assist in realising these benefits. The activities undertaken will naturally lead to the outputs listed which will result in the Research Reports being delivered and subsequently enabling the end of program outcomes to be achieved in the future.

It is noted that some of the benefits will not be realised immediately upon completion of the project. For example, as the project outcome is to produce a research report to inform regulations, standards, guidelines, etc., the benefits of this would not be achieved until some time after the project has concluded as it will take time for agencies and other stakeholders to review and implement the findings of the research project.

Similarly, FRNSW could liaise with NSW Rural Fire Service and other agencies to ascertain how the findings of the research has resulted in better preparation for bushfire season. However, as the project outcome is information to inform operational procedures, safety, etc., the benefits of this would not be achieved until some time after the project has concluded as it will take time for agencies to review and implement the findings of the research project.

8.1.1 Royal Commission into National Natural Disaster Arrangements

As previously discussed, the funding was allocated to FRNSW SARET Project 1 research activities that could address recommendations from the Royal Commission into National Natural Disaster Arrangements (2020). The table below describes how the project achievements align with these recommendations.

Table 36. FRNSW comments from Project 1 outcomes to recommendations from the Royal Commission into Natural Disaster Arrangements (2020).

Recommendation from Royal Commission into Natural Disaster Arrangements	FRNSW Comments on Project 1 outcomes
Recommendation 6.1 Assessment of the capacity and capability of fire and emergency services in light of current and future natural disaster risk <i>State and territory governments should have a structured process to regularly assess the capacity and capability requirements of fire and emergency services, in light of both current and future natural disaster risk.</i>	Flooding and bushfire exposure to items that contain lithium-ion batteries, such as electric vehicles and battery storage systems, may lead to damaged batteries that subsequently progress to a fire or other incident. The research findings will assist to achieve these outcomes by ensuring that FRNSW and other emergency services have further knowledge to inform equipment requirements and operational procedures, training, etc. required to respond to potential incidents involving lithium-ion batteries.
Recommendation 9.4 Collective awareness and mitigation of risks to critical infrastructure	Similar to the above, should critical infrastructure include the use of battery energy storage systems and the like, the potential impacts of flooding and bushfire on these systems needs to be understood. Such infrastructure could include large battery farms providing power to regional towns, or simply be a backup system to other buildings. Whilst not a focus of this research, the findings do highlight the risks associated with failure of lithium-ion batteries and the need to provide appropriate protection of such infrastructure to mitigate potential causes of failure.
Recommendation 10.1 Disaster education for individuals and communities <i>State and territory governments should continue to deliver, evaluate and improve education and engagement programs aimed at promoting disaster resilience for individuals and communities.</i>	As part of the findings of the research, recommendations were made that can inform the development of safety information to help communities prevent and respond to incidents involving items that contain lithium-ion batteries, such as electric vehicles and battery storage systems, including when they have been impacted by floods, bushfires, etc.
Recommendation 19.4 National Construction Code	Similar to Recommendation 9.4 above, whilst not a focus of this research, the findings do highlight the risks associated with failure of lithium-ion batteries and the need to provide

The Australian Building Codes Board, working with other bodies as appropriate, should:

appropriate protection to mitigate potential causes of failure.

(1) assess the extent to which AS 3959:2018 Construction of buildings in bushfire-prone areas, and other relevant building standards, are effective in reducing risk from natural hazards to lives and property, and conduct an evaluation as to whether the National Construction Code should be amended to specifically include, as an objective of the code, making buildings more resilient to natural hazards.

The findings of the research provide further information to inform requirements associated with how to respond to such failures that result in fire, such as the need to provide adequate fire fighting water.

Recommendation 20.1 Debris clean-up arrangements

Governments should create and publish standing policy guidance on whether they will or will not assist to clean-up debris, including contaminated debris, resulting from natural hazards.

The findings of the research highlight that TR in LiBs present significant flammability, explosion, and human health hazard risks and that a precautionary, worst-case approach to incident management, supported by atmospheric monitoring is critical to ensuring responder safety. Such findings can also be used to inform debris clean-up arrangements.

8.2 Future research needs

The work described herein pertains to a small portion of the research needs for risk management and response to LiB fire hazards. While this research provides valuable insight into LiB risks and hazards, there are many questions that still require exploring to prepare, protect, respond, and recover effectively from LiB emergencies.

8.2.1 Emergency service response to lithium-ion battery fires

The NSW RA funding was allocated to initiate FRNSW SARET Project 1 research activities. Project 1 aims to assesses the effectiveness of new and existing agents, products and delivery systems for use in fires involving Lithium-ion cells, batteries, and battery systems in comparison with water. It also aims to provide guidance on the efficacy of current PPE and PPC in protecting firefighters from exposures to gases, vapours, liquid electrolytes, chemical residue, and electrical energy present in LiB-related incidents. While this body of work has spoken to some of these project aims, further research is required to achieve the total project goals.

As some of the study limitations discussions above have described, further work is required in characterisation of LiBs failure events in order to comprehensively understand the risks and hazards of these events and thereby in order to effectively mitigate and manage these issues for first responders and the community alike. Continued testing with the conditions outlined in this project is needed to strengthen the statistical significance of these findings, in addition to further testing utilising alternative battery chemistries, cell arrangements, SoC, larger capacities, and other critical failure variables is needed to develop a comprehensive risk matrix of LiB failure events.

The research described within this report conducted pair-wise comparison of two extinguishment methods, liquid extinguishment and fire blanket suppression. There are a myriad of other liquid extinguishment and suppression agents, tools, blankets, and methods that are available to emergency responder and the community in the event of LiB failure, and these similarly need to be assessed for efficacy and safety. Other tools and equipment should also be independently assessed prior to their deployment within the emergency sector.

Where liquids were able to reach the effected cells, their efficacy has been established. Further work can be undertaken to determine optimal delivery methods that can introduce the agents quicker and with greater penetration.

Further studies into the effectiveness of PPE/PPC decontamination procedures is also required. The study conducted in Part C was preliminary in nature and not an accurate reflection of real-world environments which first responders encounter. The preliminary study here also did not assess the permeability of the PPC to LiB effluent and residual breakthrough to undergarment layers and subsequent skin exposure. Additional factors need to be explored such as the assessment of complete firefighting ensembles and more accurate exposure scenarios.

Finally, further environmental monitoring and assessment is required to ensure that necessary environmental controls are implemented congruent to the hazards posed by large LiB failure events.

9 Concluding remarks

The NSW Reconstruction Authority was established to proactively reduce the impact of future disasters across NSW and to help communities recover from them faster. The funding was allocated to FRNSW SARET Project 1 research activities that could address identified recommendations from the Royal Commission into National Natural Disaster Arrangements (2020). To address these recommendations, two key project objectives were identified:

1. Address gaps in the emergency services sector's knowledge and understanding of LiB fires, with the research finding used to:
 - a. Inform operational response procedures for emergency services (including response agencies other than FRNSW);
 - b. Assist in determining necessary equipment and safety requirements for emergency services.
2. Mitigate the risk of LiB fires to community and infrastructure in disaster/emergencies through research findings:
 - a. Informing any necessary legislation changes;
 - b. Informing the development of building codes and standards.

To achieve these objectives FRNSW proposed to conduct the following activities:

1. Quantify and compare the hazards associated with LiB fires with respect to cell chemistry, format, configuration, state of charge.
2. Test the efficacy and safety of new and existing extinguishing agents, methods, tools, and equipment on LiB-related fires, including safety of personal protective clothing and equipment.
3. Provide recommendation for updates to operational procedures and guidelines and materials for training of first responders in managing LiB-related fires.

The research activities were conducted in three parts. Part A initial testing aimed to answer Activity 1 by characterising single cell LiBs and exploring the ways that LiBs fail under various conditions and found that TR in LiBs present significant flammability, explosion, and human health hazards. The variability and characteristics of TR are highly dependent on the battery characteristics however due to the high variability of the TR, they conversely cannot be used as a predictor of the hazard profile and severity. The learnings from the initial testing were used to inform Part B and C.

Activity 2 was addressed as two separate elements. Part B testing evaluated new and existing extinguishing methods on LiBs representative of an e-bike and found that water was the most effective extinguishment agent for cooling a LiB in TR. Part C testing involved a preliminary exploration into the effectiveness of the current decontamination and laundering procedures of FRNSW structural firefighting PPC, to assess if current practices are effective at decreasing contamination from LiB vapour exposure and found that on-site wet decontamination combined with the FRNSW laundering system was effective at reducing contaminants on testing structural firefighting PPC swatches.

Activity 3 was addressed by a comprehensive review of completed experimentation outcomes and learnings to providing recommendations for LiB specific procedures, guidelines, and training materials. These recommendations, when implemented, have significant potential to mitigate the risk of LiB fires and emergencies to the community and built environment. From this body of work, recommendations are provided to meet the project objectives.

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10 Glossary

Note: This is not intended to be a comprehensive list.

The following definitions apply in this report.

Term	Definition
(LiB) cell	A single unit that stores and releases energy through electrochemical reactions.
(LiB) module	Several cells connected in series or parallel, encased in a frame.
(LiB) pack	Consists of multiple modules, often connected to a Battery Management System.
Asphyxiant	An agent (as a gas) capable of causing asphyxia.
Carcinogen	A substance or agent causing cancer.
Class A fires/foam	Fires involving ordinary combustible materials like paper, wood, and cloth. They are the most common type of fire. Class A fire extinguishers typically use water or foam to extinguish flames.
e-micromobility	A lightweight, usually single-person electric transportation vehicle (such as bicycles and scooters).
Encapsulating agent	A coating or carrier material to surround, entrap, or shield a core active substance.
Explosive	Any substance or device that can be made to produce a volume of rapidly expanding gas in an extremely brief period.
Face Velocity	The speed at which a gas and vapour stream enters the cross-sectional area of filter bed.
Flammable	Capable of being easily ignited and of burning quickly.
Instantaneous cooling power	The comparison of the mean rate of temperature change before and after suppression intervention.
Jet flame	A type of fire that occurs during a high-pressure release of a flammable material, such as gas or vapour, which forms a jet or vapour plume that burns.
Natural cooling	The passive dissipation of thermal energy to the ambient environment without the influence of suppression agents.
Personal protective clothing	Engineered clothing which provides a barrier against intense heat, flames, and chemicals while allowing for movement and flexibility.
Personal protective equipment	Specialised uniforms and equipment designed to provide a critical barrier between firefighters and hazardous environments.
Propagation	Refers to a process in which an effect or condition is spread to neighbouring battery cells or modules.
State of charge	A measure of the remaining charge in a battery or supercapacitor, expressed as a percentage, where 100% indicates a fully charged cell and 0% indicates a fully discharged cell.
Thermal Volatility	The standard deviation of the rate of temperature change over a specified duration.
Toxicant	Refers to any chemical substance, whether naturally occurring or artificially produced, that has the potential to cause harm or damage to living organisms.



OFFICIAL

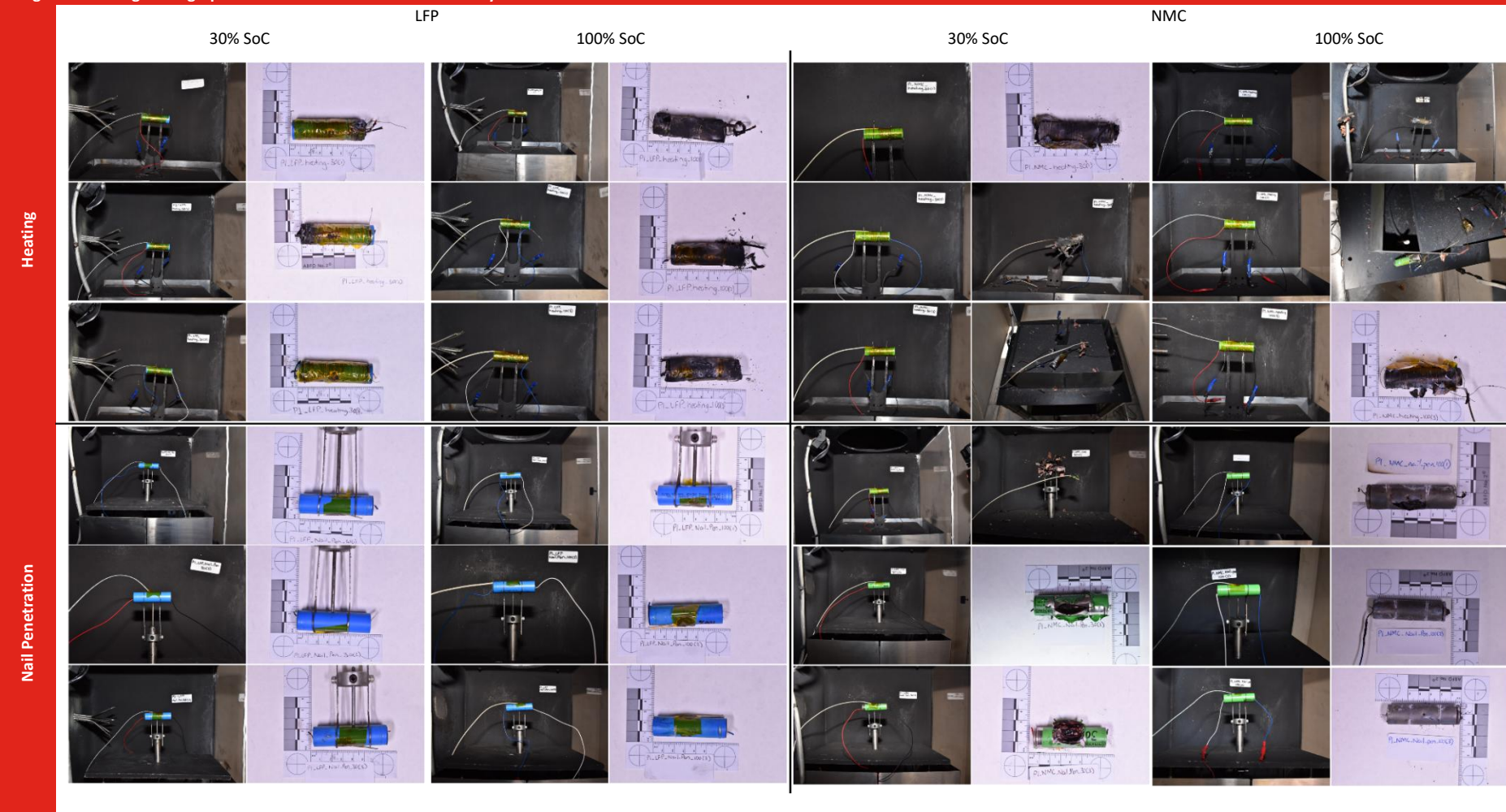
Quantification and comparison of lithium-ion battery fire hazards for emergency responders: Recommendations for risk management and response

Appendix A Supplementary single-cell gas analysis results

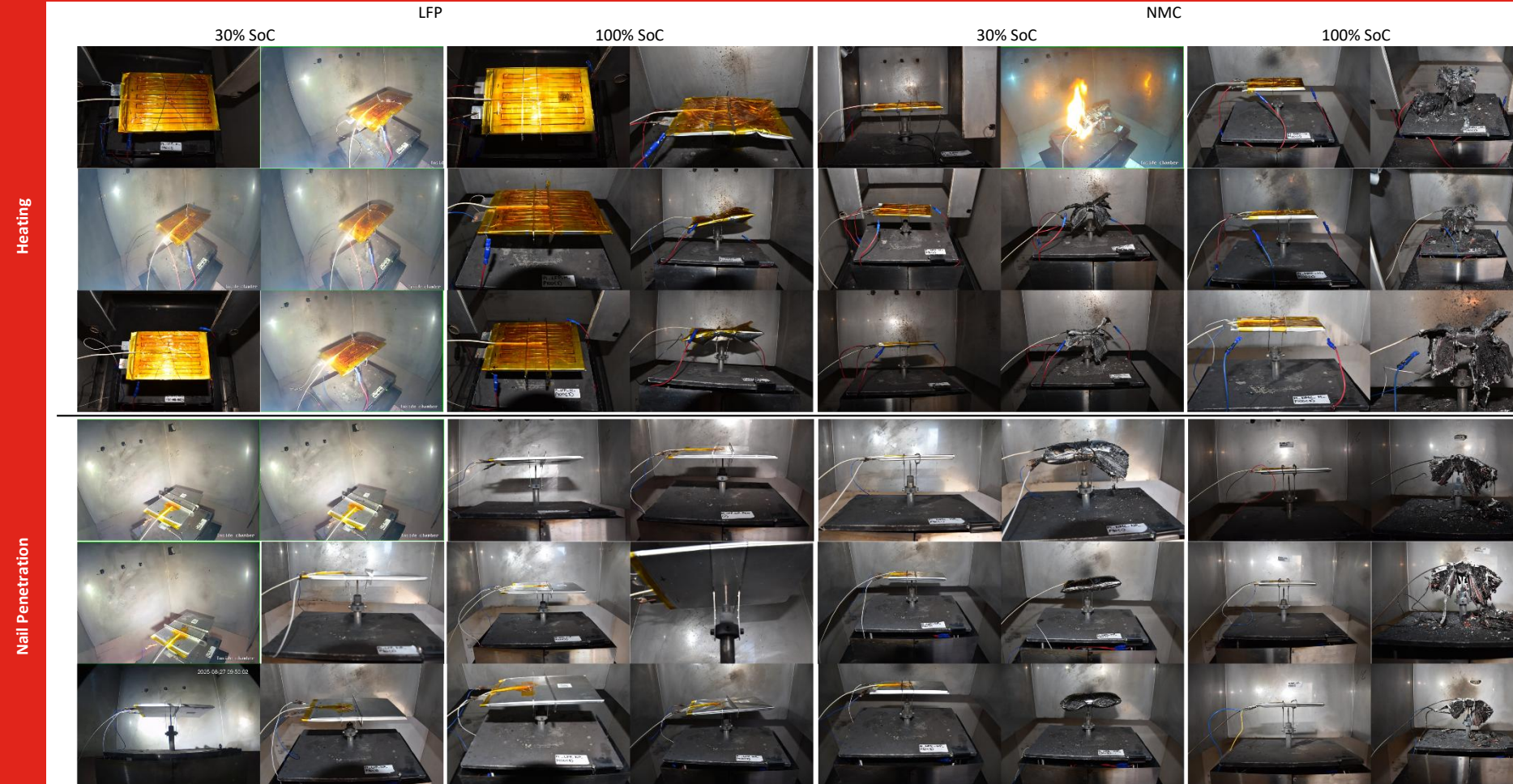
Quantification and comparison of lithium-ion battery fire hazards for emergency responders:
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A.1 Supplementary testing photographs

Single Cell Testing Photographs – Before and After Abuse Tests – Cylindrical Cells



Single Cell Testing Photographs – Before and After Abuse Tests – Pouch Cells



Quantification and comparison of lithium-ion battery fire hazards for emergency responders:

Recommendations for risk management and response

Pack Testing Photographs – Before and After Extinguishment Tests

Free Burn



Pack Testing Photographs – Before and After Extinguishment Tests
Water



Quantification and comparison of lithium-ion battery fire hazards for emergency responders:
Recommendations for risk management and response

Pack Testing Photographs – Before and After Extinguishment Tests
Encapsulating Agent Class A Foam



Pack Testing Photographs – Before and After Extinguishment Tests
Standard Fire Blanket



Quantification and comparison of lithium-ion battery fire hazards for emergency responders:

Recommendations for risk management and response

Pack Testing Photographs – Before and After Extinguishment Tests

Lithium-ion Battery Fire Blanket

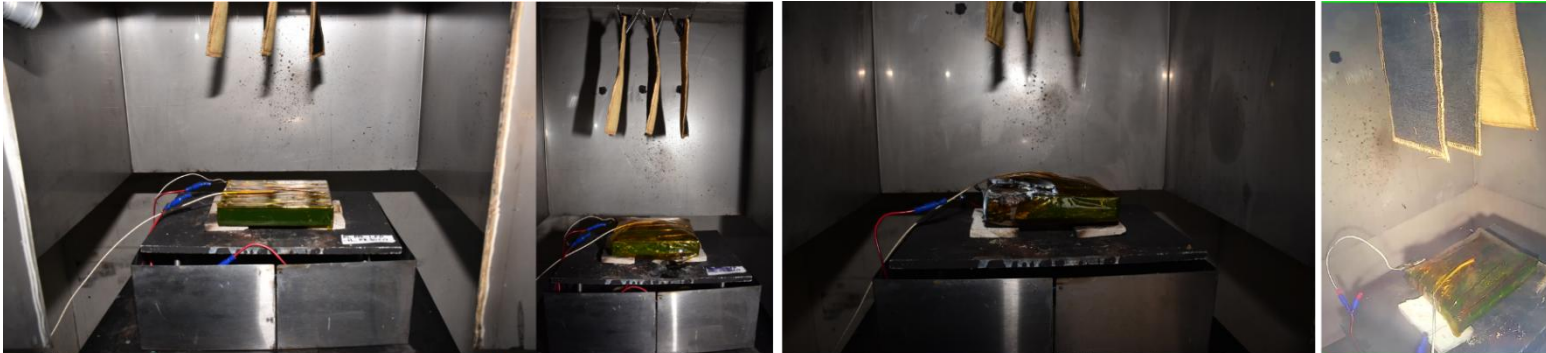


PPC Testing Photographs – Before and After Abuse Tests

30% SoC

100% SoC

1



2



3



Quantification and comparison of lithium-ion battery fire hazards for emergency responders:
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A.2 Temperature and voltage results

Table A- below presents all temperature and voltage comparison results.

Table A-1. Temperature and voltage comparison results for peak TR temperatures and time to TR.

Cylindrical vs Pouch	Chemistry	SoC	Abuse	Cylindrical (Peak °C)	Pouch (Peak °C)	Cylindrical (Time to TR, sec)	Pouch (Time to TR, sec)
	LFP	100	Heat	480.7 ± 27.3 (3)	308.6 ± 10.9 (3)	266.73 ± 3.62 (3)	NA
	LFP	30	Heat	255.5 ± 14.5 (3)	268.7 ± 3.76 (3)	271.30 ± 14.12 (3)	NA
	LFP	100	Nail Pen	78.9 ± 28.0 (3)	22.0 ± 1.3 (3)	16.60 ± NA (1)	NA
	LFP	30	Nail Pen	60.3 ± 9.66 (3)	25.7 ± 0.96 (3)	NA	42980.00 ± NA (1)
	NMC	100	Heat	443.2 ± 143.6 (3)	805.9 ± 48.5 (3)	269.20 ± 11.97 (3)	693.33 ± 200.06 (3)
	NMC	30	Heat	204.6 ± 19.2 (3)	671.0 ± 40.3 (3)	351.53 ± 22.84 (3)	2484.00 ± 1523.95 (3)
	NMC	100	Nail Pen	569.6 ± 381.6 (3)	567.2 ± 67.1 (3)	3.43 ± 0.25 (3)	49.50 ± 19.52 (3)
	NMC	30	Nail Pen	111.5 ± 70.0 (3)	439.6 ± 48.0 (3)	4.60 ± 1.14 (3)	37.00 ± 13.59 (3)
NMC vs LFP	Format	SoC	Abuse	LFP (Peak °C)	NMC (Peak °C)	LFP (Time to TR, sec)	NMC (Time to TR, sec)
	Cylindrical	100	Heat	480.7 ± 27.3 (3)	443.2 ± 143.6 (3)	266.73 ± 3.62 (3)	269.20 ± 11.97 (3)
	Cylindrical	30	Heat	255.5 ± 14.5 (3)	204.6 ± 19.2 (3)	271.30 ± 14.12 (3)	351.53 ± 22.84 (3)
	Cylindrical	100	Nail Pen	78.9 ± 28.0 (3)	569.6 ± 381.6 (3)	16.60 ± NA (1)	3.43 ± 0.25 (3)
	Cylindrical	30	Nail Pen	60.3 ± 9.66 (3)	111.5 ± 70.0 (3)	NA	4.60 ± 1.14 (3)
	Pouch	100	Heat	308.6 ± 10.9 (3)	805.9 ± 48.5 (3)	NA	693.33 ± 200.06 (3)
	Pouch	30	Heat	268.7 ± 3.76 (3)	671.0 ± 40.3 (3)	NA	2484.00 ± 1523.95 (3)
	Pouch	100	Nail Pen	22.0 ± 1.3 (3)	567.2 ± 67.1 (3)	NA	49.50 ± 19.52 (3)
	Pouch	30	Nail Pen	25.7 ± 0.96 (3)	439.6 ± 48.0 (3)	42980.00 ± NA (1)	37.00 ± 13.59 (3)
Heat vs Nail Pen	Chemistry	SoC	Format	Heat (Peak °C)	Nail Pen (Peak °C)	Heat (Time to TR, sec)	Nail Pen (Time to TR, sec)
	LFP	100	Cylindrical	480.7 ± 27.3 (3)	78.9 ± 28.0 (3)	266.73 ± 3.62 (3)	16.60 ± NA (1)
	LFP	30	Cylindrical	255.5 ± 14.5 (3)	60.3 ± 9.66 (3)	271.30 ± 14.12 (3)	NA
	LFP	100	Pouch	308.6 ± 10.9 (3)	22.0 ± 1.3 (3)	NA	NA
	LFP	30	Pouch	268.7 ± 3.76 (3)	25.7 ± 0.96 (3)	NA	42980.00 ± NA (1)
	NMC	100	Cylindrical	443.2 ± 143.6 (3)	569.6 ± 381.6 (3)	269.20 ± 11.97 (3)	3.43 ± 0.25 (3)
	NMC	30	Cylindrical	204.6 ± 19.2 (3)	111.5 ± 70.0 (3)	351.53 ± 22.84 (3)	4.60 ± 1.14 (3)
	NMC	100	Pouch	805.9 ± 48.5 (3)	567.2 ± 67.1 (3)	693.33 ± 200.06 (3)	49.50 ± 19.52 (3)
	NMC	30	Pouch	671.0 ± 40.3 (3)	439.6 ± 48.0 (3)	2484.00 ± 1523.95 (3)	37.00 ± 13.59 (3)
100% vs 30% SoC	Chemistry	Abuse	Format	100% SoC (Peak °C)	30% SoC (Peak °C)	100% SoC (Time to TR, sec)	30% SoC (Time to TR, sec)
	LFP	Heat	Cylindrical	480.7 ± 27.3 (3)	255.5 ± 14.5 (3)	266.73 ± 3.62 (3)	271.30 ± 14.12 (3)
	LFP	Heat	Pouch	308.6 ± 10.9 (3)	268.7 ± 3.76 (3)	NA	NA
	LFP	Nail Pen	Cylindrical	78.9 ± 28.0 (3)	60.3 ± 9.66 (3)	16.60 ± NA (1)	NA
	LFP	Nail Pen	Pouch	22.0 ± 1.3 (3)	25.7 ± 0.96 (3)	NA	42980.00 ± NA (1)
	NMC	Heat	Cylindrical	443.2 ± 143.6 (3)	204.6 ± 19.2 (3)	269.20 ± 11.97 (3)	351.53 ± 22.84 (3)
	NMC	Heat	Pouch	805.9 ± 48.5 (3)	671.0 ± 40.3 (3)	693.33 ± 200.06 (3)	2484.00 ± 1523.95 (3)
	NMC	Nail Pen	Cylindrical	569.6 ± 381.6 (3)	111.5 ± 70.0 (3)	3.43 ± 0.25 (3)	4.60 ± 1.14 (3)
	NMC	Nail Pen	Pouch	567.2 ± 67.1 (3)	439.6 ± 48.0 (3)	49.50 ± 19.52 (3)	37.00 ± 13.59 (3)+BB4:142

A.3 Gas analysis results

The following results are presented per gas detected using the FTIR during the single-cell TR tests. Each compound detected is presented alphabetically, for each of the 16 test scenarios.

A.3.1 Acetaldehyde

Top 10 Peak Distribution per Replicate Compound: Acetaldehyde

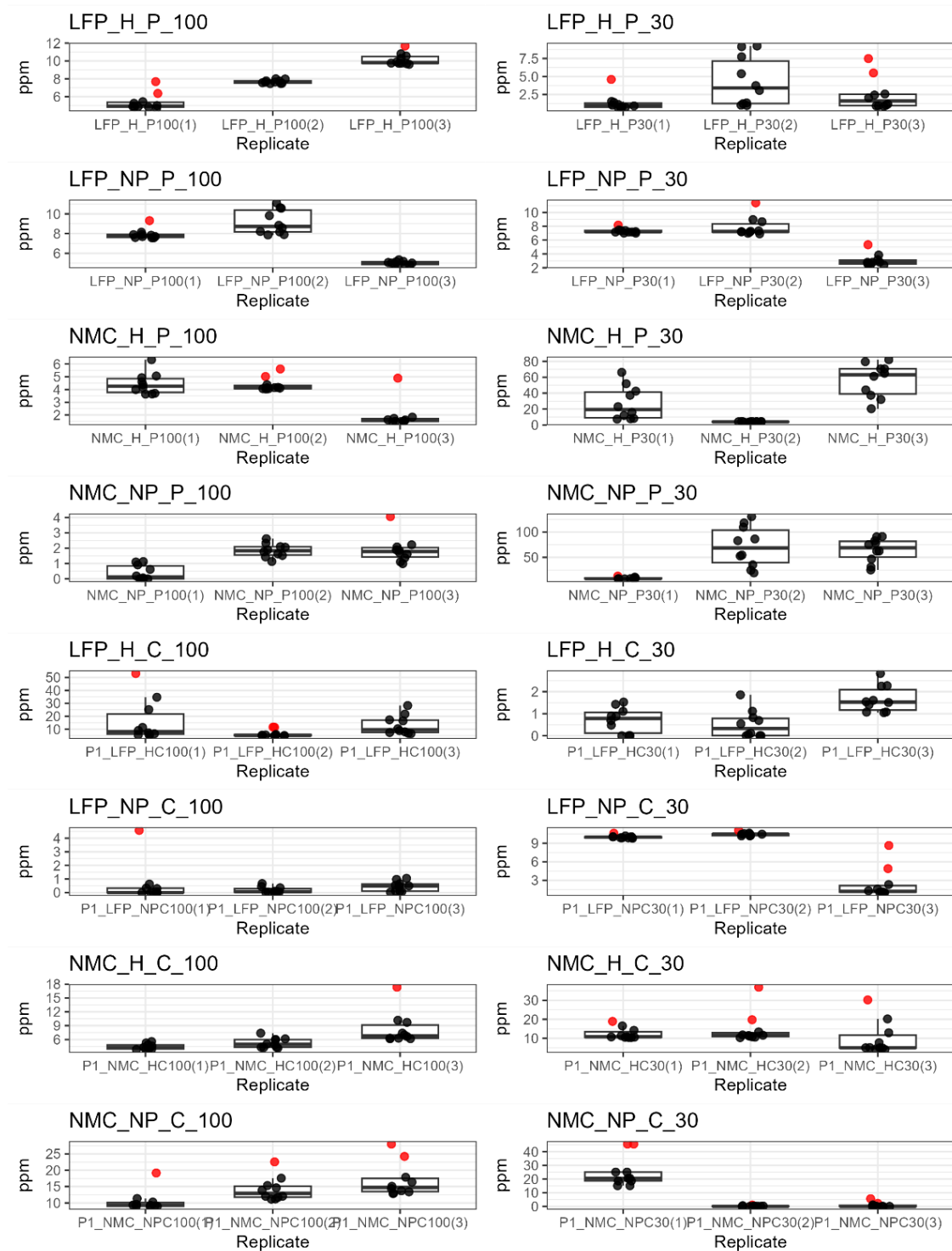


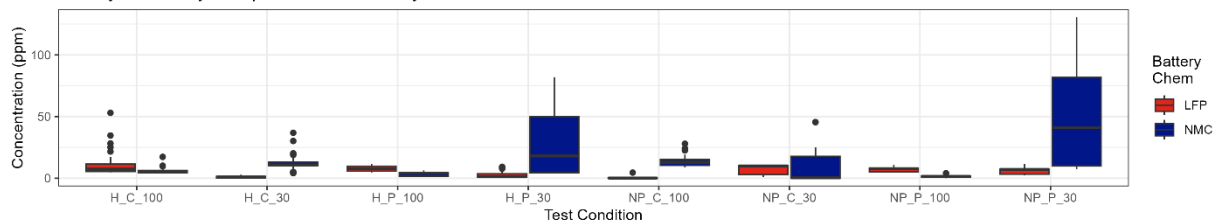
Figure A-1. A boxplot with the top 10 highest peaks of acetaldehyde per test condition. Each plot is a test condition. Y-axis represents acetaldehyde ppm and the X-axis is the three test replicates for each test condition. Red dots indicate any potential outliers within that test replicate.

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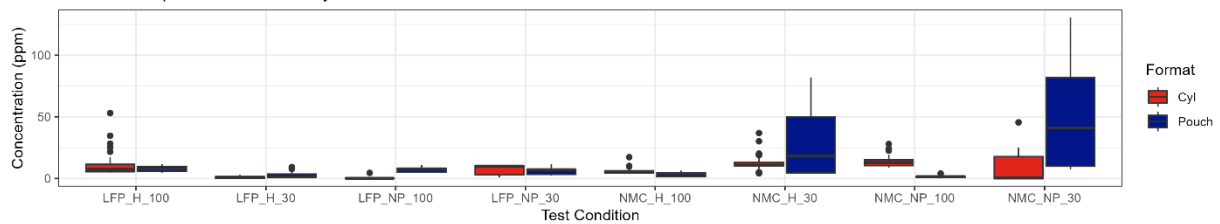
Table A-2. Highest 30 peaks of acetaldehyde per test condition. Mean, Min, Q1, Median, Q3, and Max all in ppm.

Test Scenario	Chem	Abuse	Format	SoC (%)	Mean	sd	Min	Q1	Median	Q3	Max	n
1	LFP	H	C	100	12.00	10.88	4.89	5.51	7.33	11.55	53.03	30
2	LFP	H	C	30	0.96	0.77	0.00	0.20	0.98	1.49	2.83	30
3	LFP	H	P	100	7.74	2.10	4.70	5.66	7.66	9.73	11.68	30
4	LFP	H	P	30	2.70	2.66	0.60	0.96	1.29	3.57	9.23	30
5	LFP	NP	C	100	0.41	0.85	0.00	0.01	0.11	0.49	4.58	30
6	LFP	NP	C	30	7.63	4.01	1.01	2.96	9.97	10.26	11.07	30
7	LFP	NP	P	100	7.37	1.93	4.80	5.16	7.77	8.20	11.12	30
8	LFP	NP	P	30	6.10	2.39	2.38	3.33	7.15	7.32	11.39	30
9	NMC	H	C	100	6.01	2.67	3.84	4.32	5.42	6.29	17.33	30
10	NMC	H	C	30	12.38	7.20	4.09	10.36	10.82	13.26	36.85	30
11	NMC	H	P	100	3.58	1.44	1.45	1.76	4.06	4.38	6.34	30
12	NMC	H	P	30	29.20	27.37	3.78	4.41	18.15	49.92	82.01	30
13	NMC	NP	C	100	13.86	4.75	8.93	10.48	12.91	15.26	27.99	30
14	NMC	NP	C	30	8.69	13.35	0.00	0.00	0.42	17.77	45.50	30
15	NMC	NP	P	100	1.38	0.93	0.00	0.93	1.48	1.89	4.06	30
16	NMC	NP	P	30	48.35	38.46	7.53	9.99	41.01	81.74	130.54	30

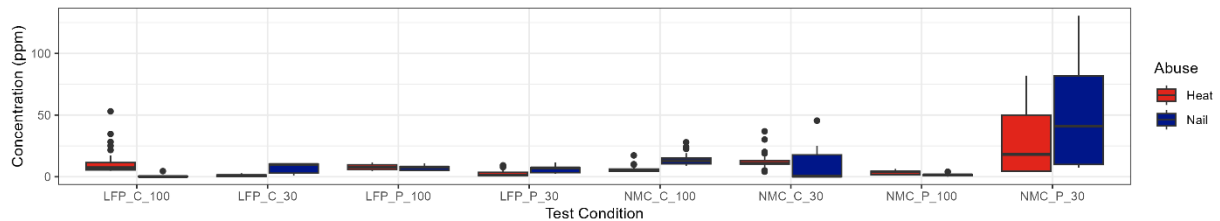
A Battery Chemistry Comparison - Acetaldehyde



B Format Comparison - Acetaldehyde



C Abuse Method Comparison - Acetaldehyde



D Battery SoC Comparison - Acetaldehyde

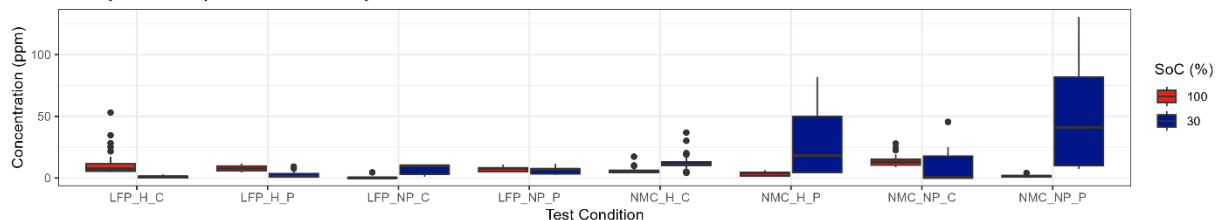


Figure A-2. Boxplot with all test conditions broken up into test scenarios. Y-axis represents acetaldehyde ppm and the X-axis is the test scenario. (a) battery chemistry, (b) cell format (c) abuse type, and (d) battery state of charge.

A.3.2 Acetylene

Top 10 Peak Distribution per Replicate Compound: Acetylene

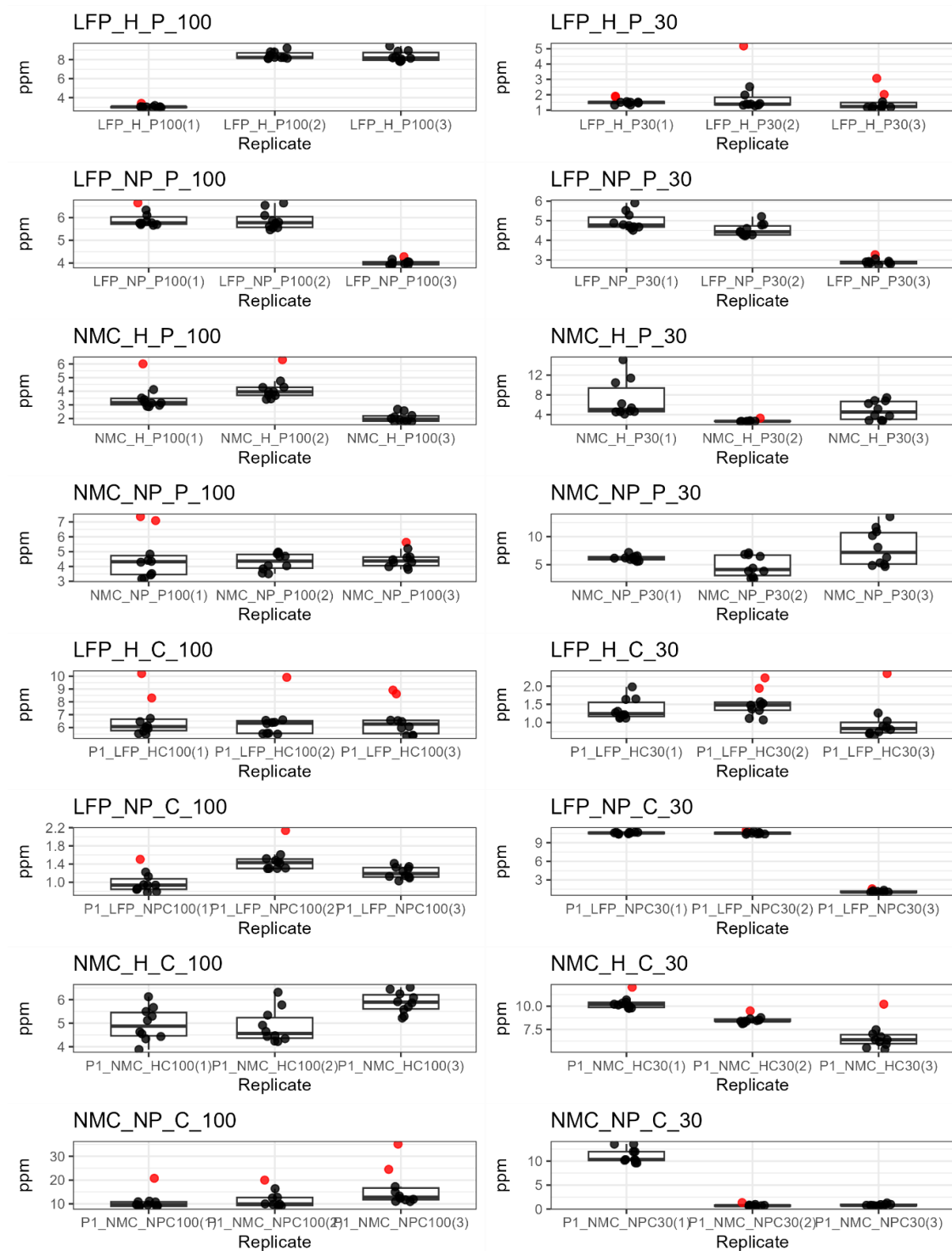


Figure A-3. A boxplot with the top 10 highest peaks of acetylene per test condition. Each plot is a test condition. Y-axis represents acetylene ppm and the X-axis is the three test replicates for each test condition. Red dots indicate any potential outliers within that test replicate.

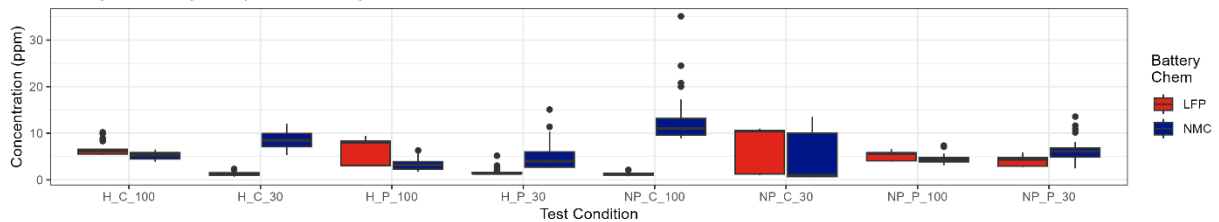
Quantification and comparison of lithium-ion battery fire hazards for emergency responders:

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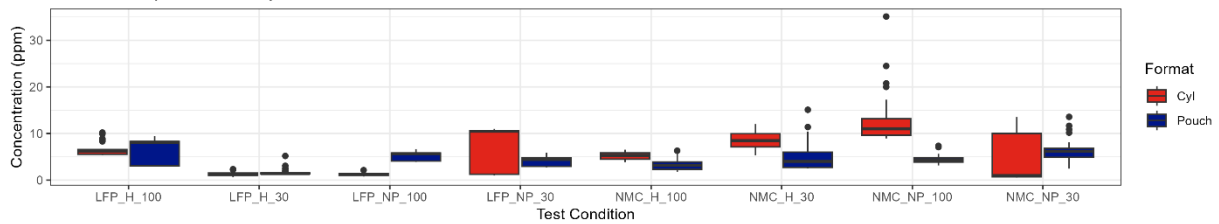
Table A-3. Highest 30 peaks of acetylene per test condition. Mean, Min, Q1, Median, Q3, and Max all in ppm.

Test Scenario	Chem	Abuse	Format	SoC (%)	Mean	sd	Min	Q1	Median	Q3	Max	n
1	LFP	H	C	100	6.54	1.32	5.36	5.55	6.22	6.57	10.21	30
2	LFP	H	C	30	1.29	0.44	0.64	1.05	1.24	1.52	2.35	30
3	LFP	H	P	100	6.61	2.59	2.89	3.08	8.12	8.29	9.44	30
4	LFP	H	P	30	1.65	0.79	1.12	1.32	1.41	1.55	5.18	30
5	LFP	NP	C	100	1.23	0.29	0.77	1.05	1.27	1.39	2.14	30
6	LFP	NP	C	30	7.43	4.54	0.95	1.27	10.47	10.63	11.00	30
7	LFP	NP	P	100	5.28	0.95	3.91	4.09	5.68	5.82	6.65	30
8	LFP	NP	P	30	4.13	0.96	2.74	2.96	4.44	4.77	5.91	30
9	NMC	H	C	100	5.24	0.77	3.88	4.49	5.30	5.85	6.53	30
10	NMC	H	C	30	8.52	1.74	5.34	7.13	8.48	9.95	12.03	30
11	NMC	H	P	100	3.26	1.16	1.75	2.31	3.17	3.90	6.31	30
12	NMC	H	P	30	4.90	2.99	2.52	2.74	4.01	6.00	15.09	30
13	NMC	NP	C	100	13.02	5.72	8.94	9.62	11.02	13.18	35.11	30
14	NMC	NP	C	30	4.25	5.01	0.56	0.71	0.97	10.01	13.52	30
15	NMC	NP	P	100	4.45	0.96	3.16	3.87	4.32	4.80	7.36	30
16	NMC	NP	P	30	6.32	2.55	2.46	4.90	6.18	6.83	13.57	30

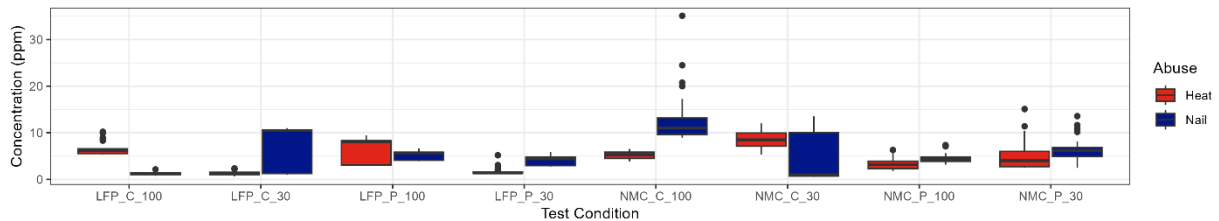
A Battery Chemistry Comparison - Acetylene



B Format Comparison - Acetylene



C Abuse Method Comparison - Acetylene



D Battery SoC Comparison - Acetylene

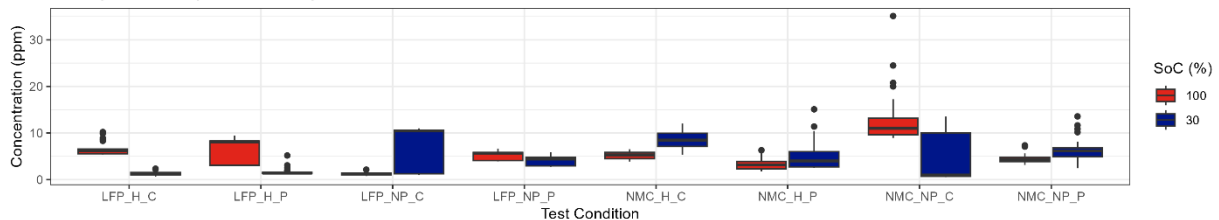


Figure A-4. Boxplot with all test conditions broken up into test scenarios. Y-axis represents acetylene ppm and the X-axis is the test scenario. (a) battery chemistry, (b) cell format (c) abuse type, and (d) battery state of charge.

A.3.3 Benzaldehyde

Top 10 Peak Distribution per Replicate Compound: Benzaldehyde

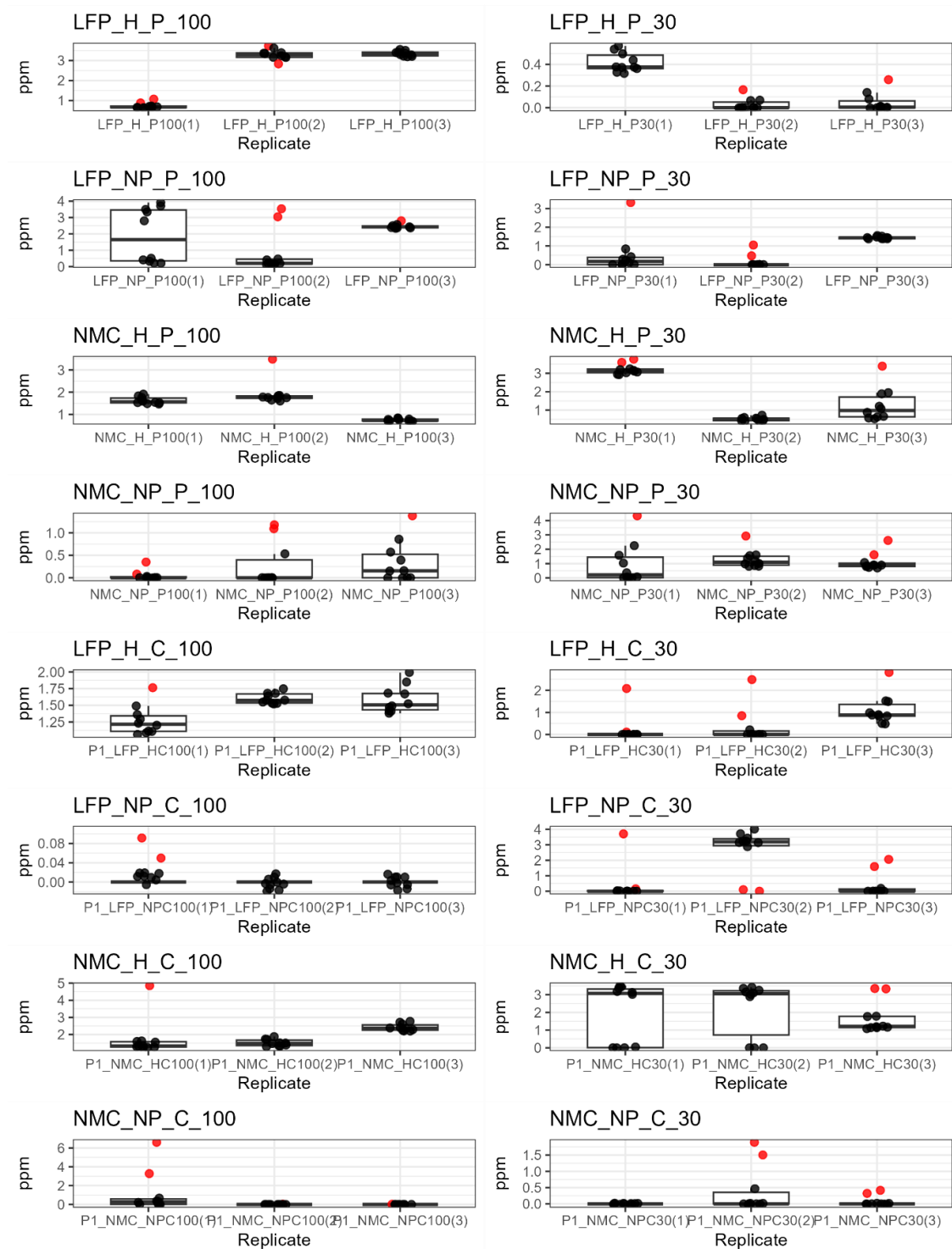


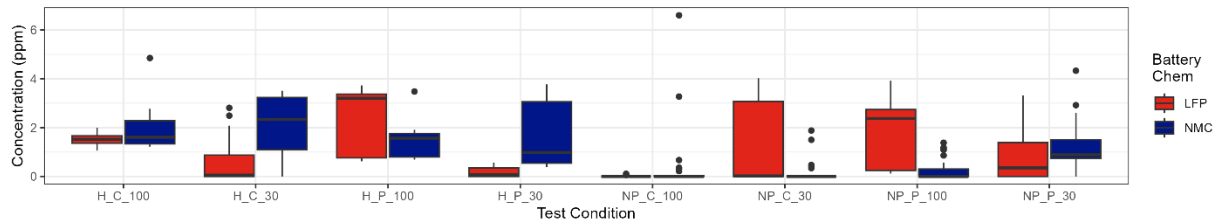
Figure A-5. A boxplot with the top 10 highest peaks of Benzaldehyde per test condition. Each plot is a test condition. Y-axis represents benzaldehyde ppm and the X-axis is the three test replicates for each test condition. Red dots indicate any potential outliers within that test replicate.

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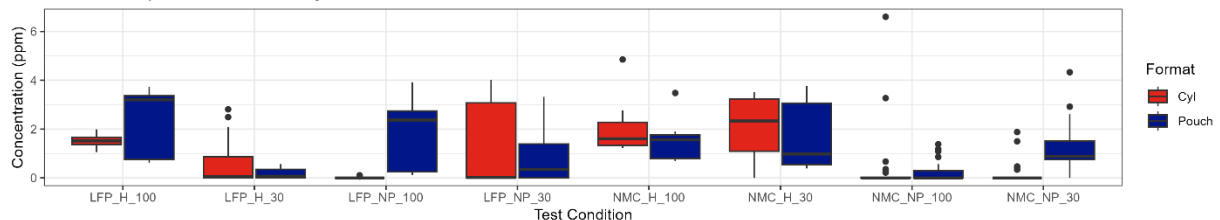
Table A-4. Highest 30 peaks of benzaldehyde per test condition. Mean, Min, Q1, Median, Q3, and Max all in ppm.

Test Scenario	Chem	Abuse	Format	SoC (%)	Mean	sd	Min	Q1	Median	Q3	Max	n
1	LFP	H	C	100	1.49	0.23	1.06	1.37	1.52	1.66	1.99	30
2	LFP	H	C	30	0.57	0.80	0.00	0.00	0.06	0.87	2.81	30
3	LFP	H	P	100	2.46	1.26	0.62	0.76	3.20	3.37	3.73	30
4	LFP	H	P	30	0.17	0.20	0.00	0.00	0.07	0.35	0.57	30
5	LFP	NP	C	100	0.01	0.02	0.00	0.00	0.00	0.00	0.11	30
6	LFP	NP	C	30	1.15	1.57	0.00	0.00	0.02	3.08	4.02	30
7	LFP	NP	P	100	1.74	1.36	0.12	0.25	2.37	2.74	3.92	30
8	LFP	NP	P	30	0.70	0.82	0.00	0.00	0.35	1.39	3.32	30
9	NMC	H	C	100	1.89	0.75	1.22	1.33	1.61	2.28	4.85	30
10	NMC	H	C	30	1.97	1.38	0.00	1.10	2.34	3.23	3.51	30
11	NMC	H	P	100	1.44	0.60	0.69	0.80	1.57	1.76	3.48	30
12	NMC	H	P	30	1.66	1.27	0.39	0.55	0.98	3.06	3.77	30
13	NMC	NP	C	100	0.38	1.32	0.00	0.00	0.00	0.03	6.60	30
14	NMC	NP	C	30	0.15	0.44	0.00	0.00	0.00	0.00	1.88	30
15	NMC	NP	P	100	0.23	0.40	0.00	0.00	0.00	0.30	1.38	30
16	NMC	NP	P	30	1.13	0.94	0.00	0.75	0.89	1.51	4.33	30

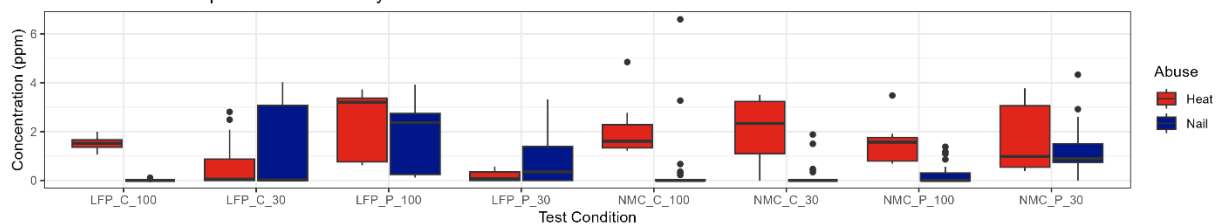
A Battery Chemistry Comparison - Benzaldehyde



B Format Comparison - Benzaldehyde



C Abuse Method Comparison - Benzaldehyde



D Battery SoC Comparison - Benzaldehyde

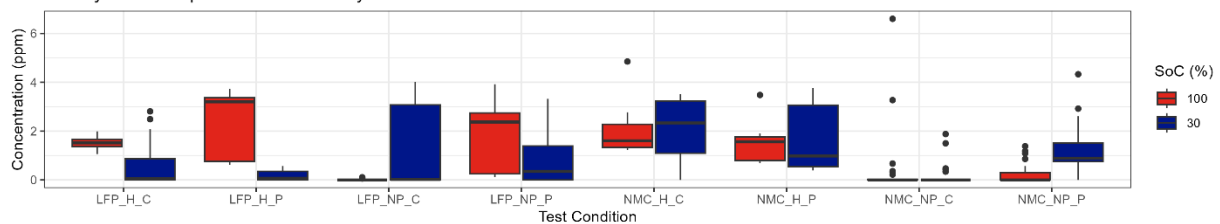


Figure A-6. Boxplot with all test conditions broken up into test scenarios. Y-axis represents benzaldehyde ppm and the X-axis is the test scenario. (a) battery chemistry, (b) cell format (c) abuse type, and (d) battery state of charge.

A.3.4 Benzene

Top 10 Peak Distribution per Replicate Compound: Benzene

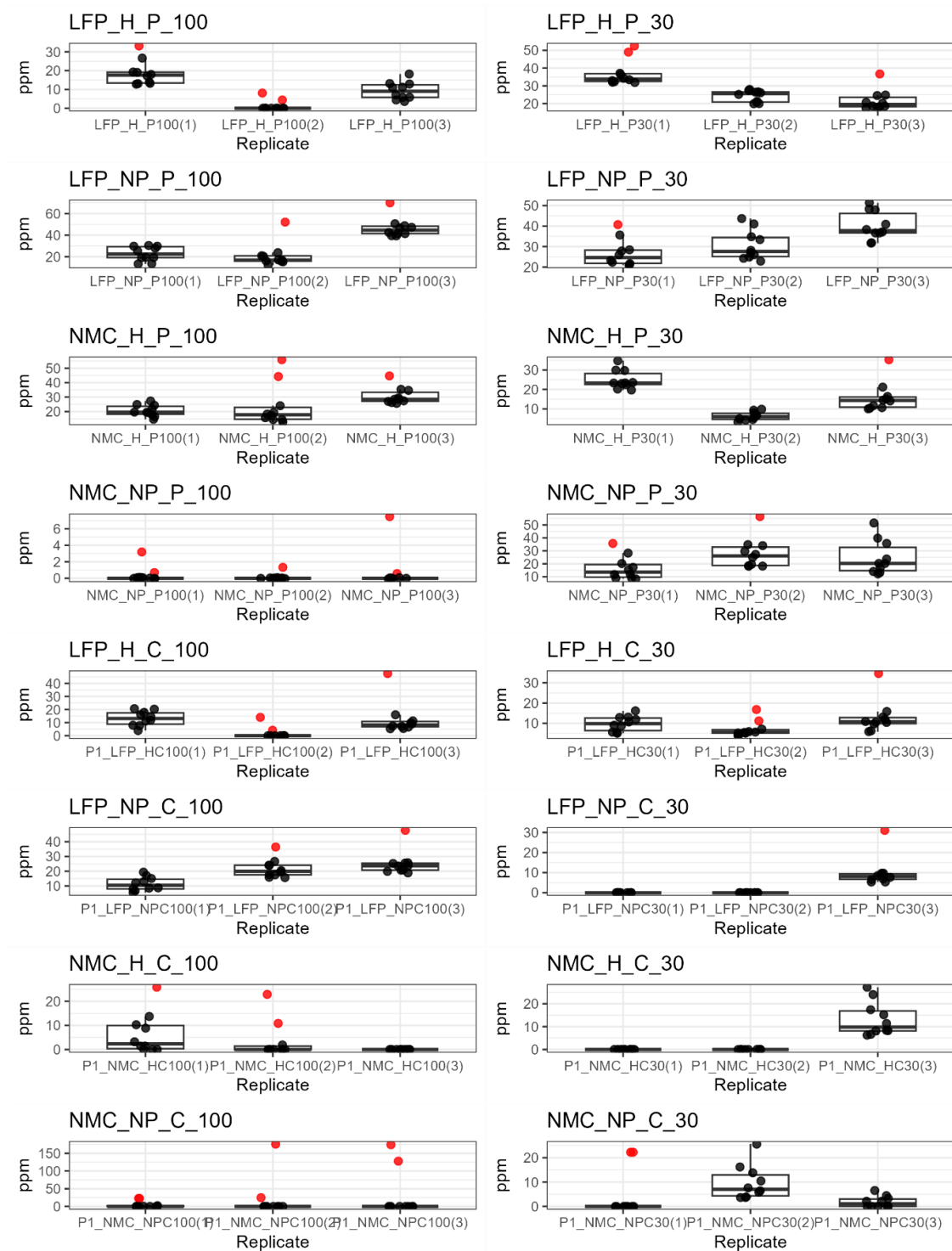


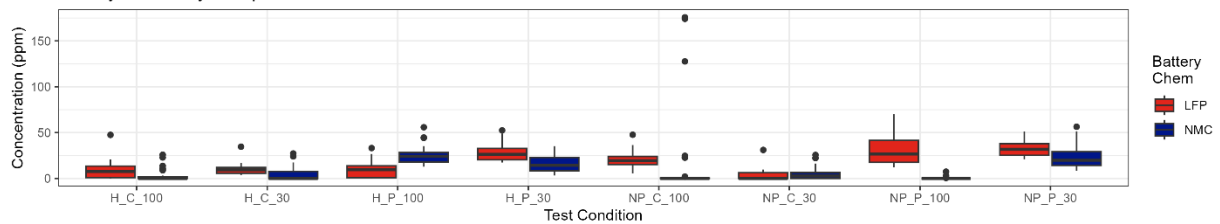
Figure A-7. A boxplot with the top 10 highest peaks of benzene per test condition. Each plot is a test condition. Y-axis represents benzene ppm and the X-axis is the three test replicates for each test condition. Red dots indicate any potential outliers within that test replicate.

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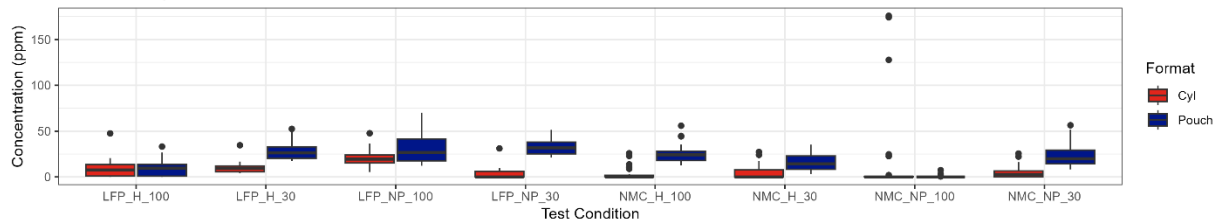
Table A-5. Highest 30 peaks of benzene per test condition. Mean, Min, Q1, Median, Q3, and Max all in ppm.

Test Scenario	Chem	Abuse	Format	SoC (%)	Mean	sd	Min	Q1	Median	Q3	Max	n
1	LFP	H	C	100	9.21	9.71	0.00	0.99	7.58	13.47	47.53	30
2	LFP	H	C	30	9.94	5.99	3.85	5.64	9.35	11.96	34.60	30
3	LFP	H	P	100	9.74	8.67	0.00	0.90	9.57	13.75	33.14	30
4	LFP	H	P	30	27.69	8.85	17.38	20.32	26.25	32.79	52.45	30
5	LFP	NP	C	100	19.43	8.75	5.44	15.20	19.40	23.99	47.70	30
6	LFP	NP	C	30	3.31	6.37	0.00	0.00	0.00	6.23	31.08	30
7	LFP	NP	P	100	30.22	14.93	12.20	17.61	26.68	41.54	70.05	30
8	LFP	NP	P	30	32.51	8.78	20.98	25.18	31.80	38.02	51.31	30
9	NMC	H	C	100	3.34	6.86	0.00	0.00	0.00	1.76	25.84	30
10	NMC	H	C	30	4.43	7.62	0.00	0.00	0.00	7.73	27.25	30
11	NMC	H	P	100	24.98	10.01	12.75	17.95	24.15	28.23	55.87	30
12	NMC	H	P	30	15.74	9.32	3.28	8.30	14.30	22.93	35.27	30
13	NMC	NP	C	100	18.35	48.81	0.00	0.00	0.00	0.46	175.80	30
14	NMC	NP	C	30	5.34	7.45	0.00	0.00	2.73	6.52	25.60	30
15	NMC	NP	P	100	0.44	1.45	0.00	0.00	0.00	0.00	7.38	30
16	NMC	NP	P	30	23.14	12.14	8.30	14.33	19.84	29.23	56.39	30

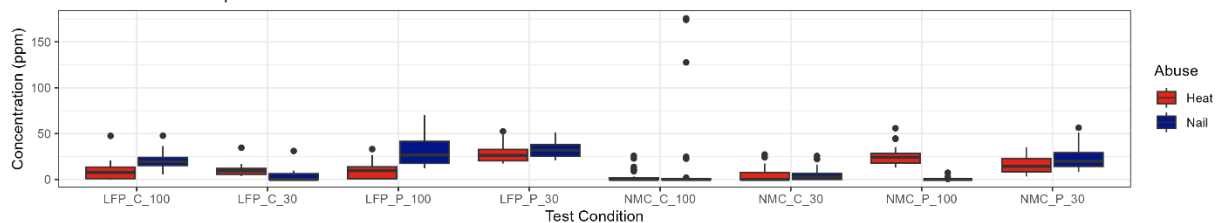
A Battery Chemistry Comparison - Benzene



B Format Comparison - Benzene



C Abuse Method Comparison - Benzene



D Battery SoC Comparison - Benzene

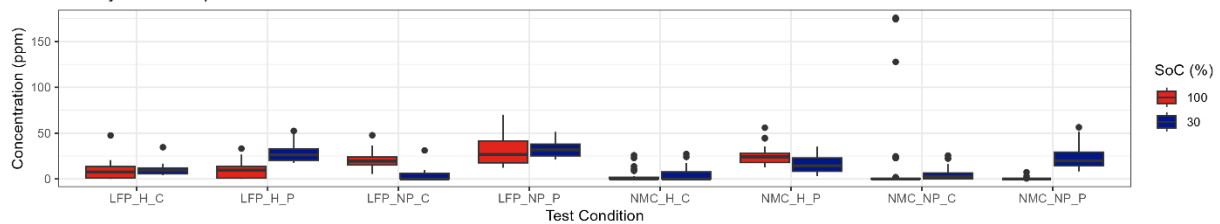


Figure A-8. Boxplot with all test conditions broken up into test scenarios. Y-axis represents benzene ppm and the X-axis is the test scenario. (a) battery chemistry, (b) cell format (c) abuse type, and (d) battery state of charge.

A.3.5 Carbon dioxide

Top 10 Peak Distribution per Replicate Compound: Carbon dioxide

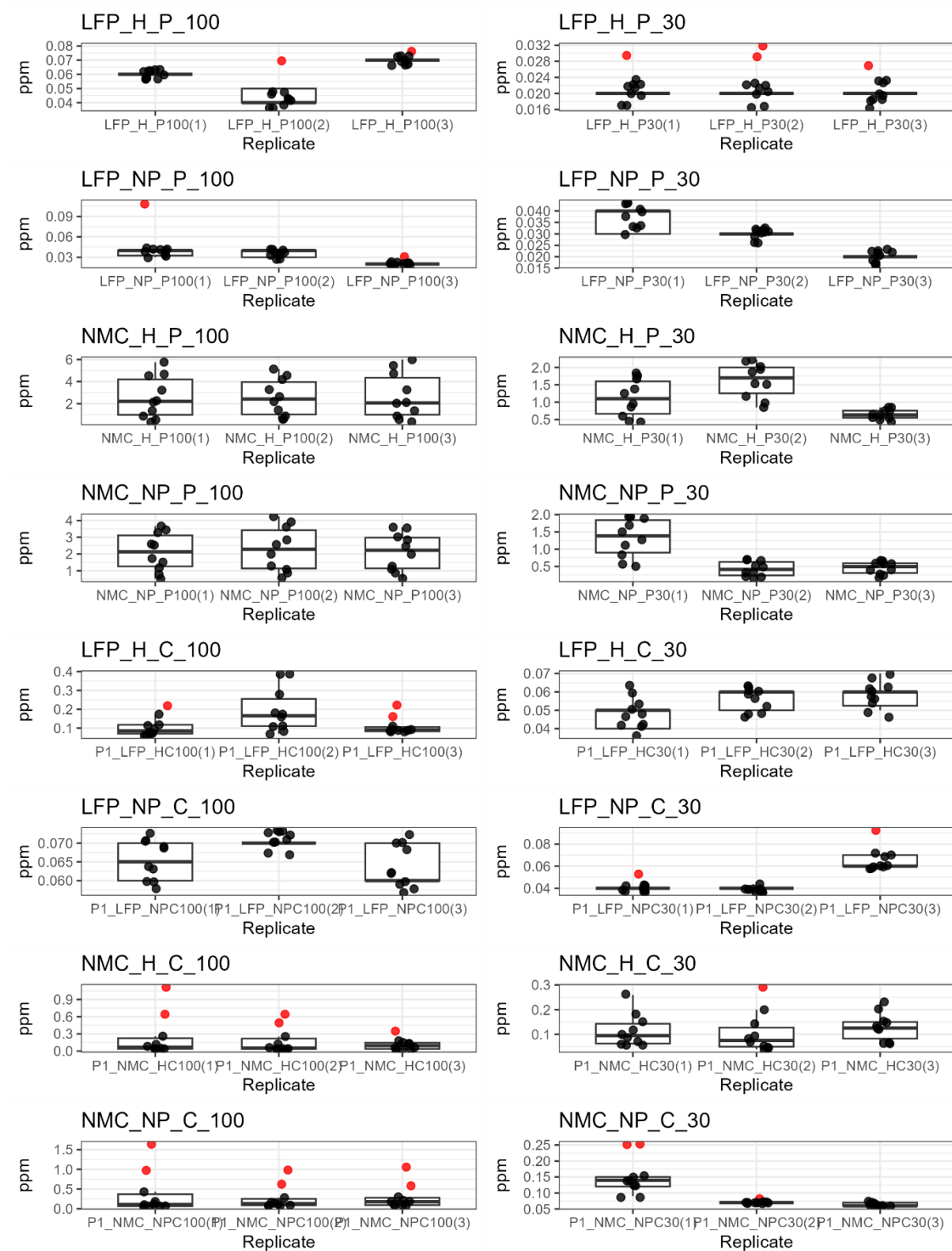


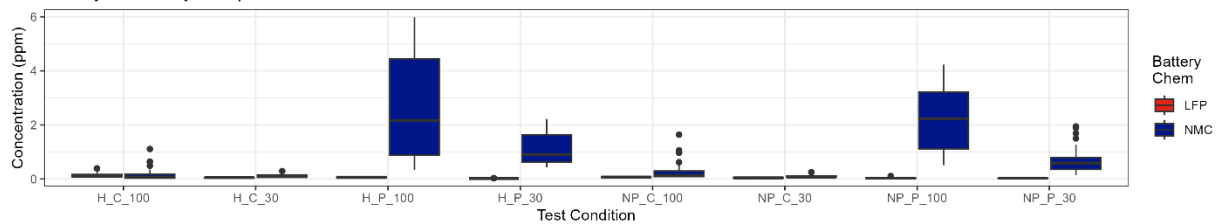
Figure A-9. A boxplot with the top 10 highest peaks of carbon dioxide per test condition. Each plot is a test condition. Y-axis represents carbon dioxide ppm and the X-axis is the three test replicates for each test condition. Red dots indicate any potential outliers within that test replicate.

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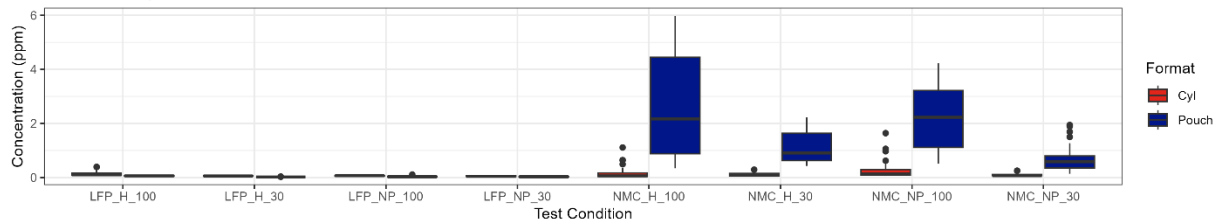
Table A-6. Highest 30 peaks of carbon dioxide per test condition. Mean, Min, Q1, Median, Q3, and Max all in ppm.

Test Scenario	Chem	Abuse	Format	SoC (%)	Mean	sd	Min	Q1	Median	Q3	Max	n
1	LFP	H	C	100	0.14	0.09	0.06	0.08	0.10	0.17	0.39	30
2	LFP	H	C	30	0.05	0.01	0.04	0.05	0.06	0.06	0.07	30
3	LFP	H	P	100	0.06	0.01	0.04	0.05	0.06	0.07	0.08	30
4	LFP	H	P	30	0.02	0.00	0.02	0.02	0.02	0.02	0.03	30
5	LFP	NP	C	100	0.07	0.01	0.06	0.06	0.07	0.07	0.07	30
6	LFP	NP	C	30	0.05	0.01	0.04	0.04	0.04	0.06	0.09	30
7	LFP	NP	P	100	0.03	0.02	0.02	0.02	0.03	0.04	0.11	30
8	LFP	NP	P	30	0.03	0.01	0.02	0.02	0.03	0.03	0.04	30
9	NMC	H	C	100	0.18	0.25	0.03	0.04	0.06	0.17	1.11	30
10	NMC	H	C	30	0.12	0.07	0.04	0.06	0.10	0.15	0.29	30
11	NMC	H	P	100	2.60	1.83	0.34	0.88	2.17	4.45	5.98	30
12	NMC	H	P	30	1.13	0.58	0.43	0.63	0.91	1.64	2.22	30
13	NMC	NP	C	100	0.31	0.38	0.06	0.09	0.13	0.30	1.64	30
14	NMC	NP	C	30	0.10	0.05	0.06	0.07	0.07	0.11	0.25	30
15	NMC	NP	P	100	2.18	1.17	0.51	1.11	2.23	3.22	4.23	30
16	NMC	NP	P	30	0.74	0.55	0.14	0.35	0.59	0.80	1.94	30

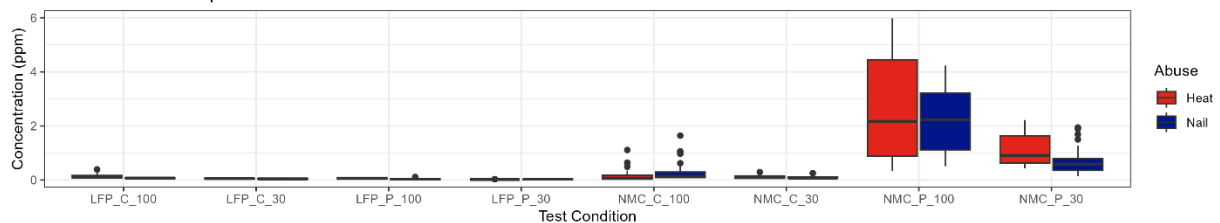
A Battery Chemistry Comparison - Carbon dioxide



B Format Comparison - Carbon dioxide



C Abuse Method Comparison - Carbon dioxide



D Battery SoC Comparison - Carbon dioxide

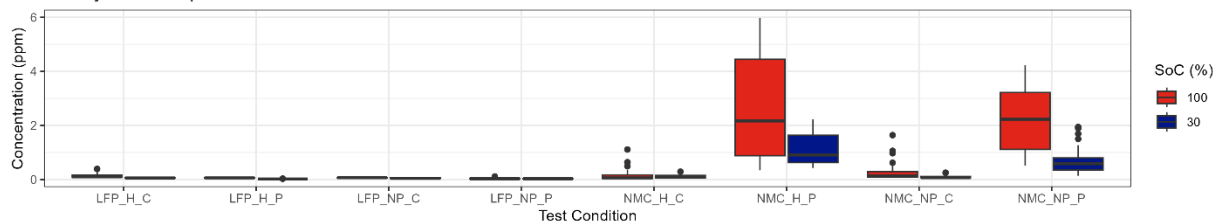


Figure A-10. Boxplot with all test conditions broken up into test scenarios. Y-axis represents carbon dioxide ppm and the X-axis is the test scenario. (a) battery chemistry, (b) cell format (c) abuse type, and (d) battery state of charge.

A.3.6 Carbon monoxide

Top 10 Peak Distribution per Replicate Compound: Carbon monoxide

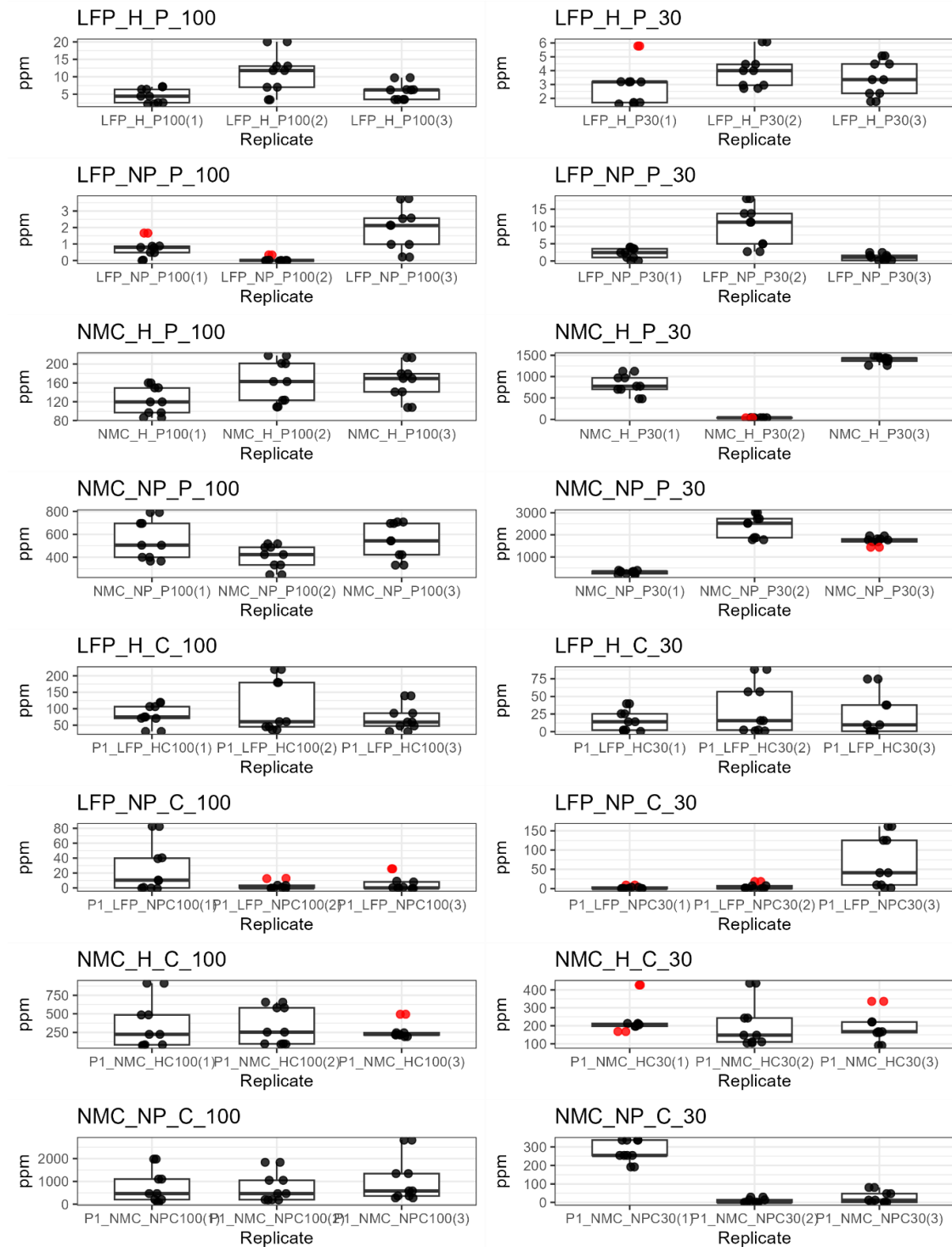


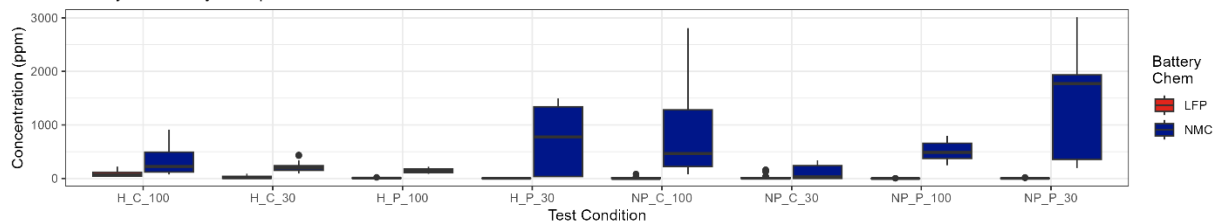
Figure A-11. A boxplot with the top 10 highest peaks of carbon monoxide per test condition. Each plot is a test condition. Y-axis represents carbon monoxide ppm and the X-axis is the three test replicates for each test condition. Red dots indicate any potential outliers within that test replicate.

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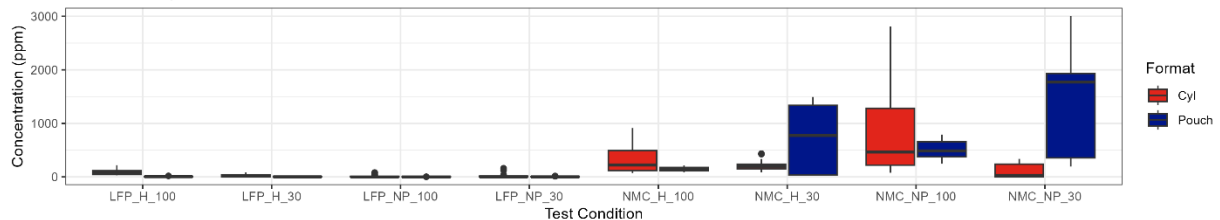
Table A-7. Highest 30 peaks of carbon monoxide per test condition. Mean, Min, Q1, Median, Q3, and Max all in ppm.

Test Scenario	Chem	Abuse	Format	SoC (%)	Mean	sd	Min	Q1	Median	Q3	Max	n
1	LFP	H	C	100	87.11	55.29	30.49	45.94	70.93	115.86	219.50	30
2	LFP	H	C	30	24.56	28.45	0.00	1.29	14.04	39.15	88.36	30
3	LFP	H	P	100	7.16	4.73	2.21	3.49	6.33	9.09	20.03	30
4	LFP	H	P	30	3.51	1.41	1.59	2.45	3.20	4.48	6.09	30
5	LFP	NP	C	100	12.23	22.32	0.00	0.00	0.00	12.34	82.69	30
6	LFP	NP	C	30	25.24	48.84	0.00	0.07	3.39	16.10	161.83	30
7	LFP	NP	P	100	0.92	1.11	0.00	0.00	0.48	1.48	3.74	30
8	LFP	NP	P	30	4.47	5.37	0.00	1.02	2.45	4.71	18.06	30
9	NMC	H	C	100	321.24	244.46	73.25	119.62	223.33	491.47	912.10	30
10	NMC	H	C	30	215.41	105.12	90.44	151.38	197.52	237.54	436.91	30
11	NMC	H	P	100	149.12	41.31	86.20	111.61	149.16	176.70	217.62	30
12	NMC	H	P	30	747.47	583.01	34.23	36.78	775.39	1337.48	1493.09	30
13	NMC	NP	C	100	861.86	797.90	78.50	221.81	465.97	1281.25	2808.66	30
14	NMC	NP	C	30	103.98	129.04	0.00	0.61	29.03	238.90	337.09	30
15	NMC	NP	P	100	497.52	159.32	246.60	374.44	486.81	657.53	791.47	30
16	NMC	NP	P	30	1472.06	935.20	194.84	356.59	1771.33	1932.89	3009.40	30

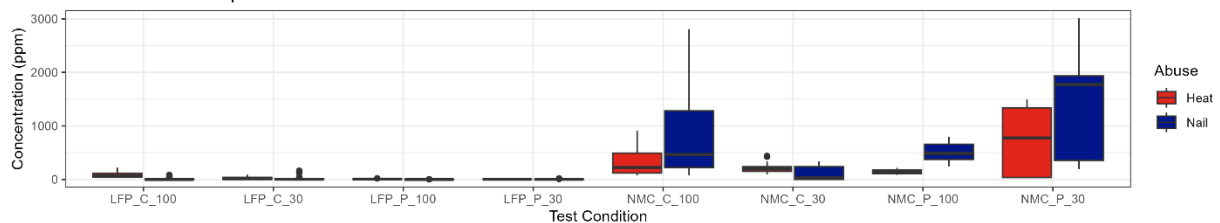
A Battery Chemistry Comparison - Carbon monoxide



B Format Comparison - Carbon monoxide



C Abuse Method Comparison - Carbon monoxide



D Battery SoC Comparison - Carbon monoxide

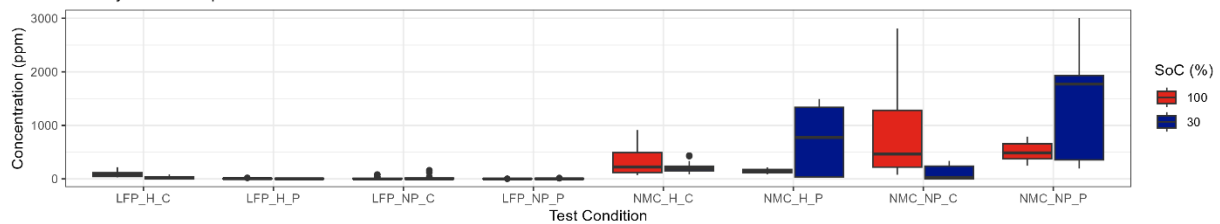


Figure A-12. Boxplot with all test conditions broken up into test scenarios. Y-axis represents carbon monoxide ppm and the X-axis is the test scenario. (a) battery chemistry, (b) cell format (c) abuse type, and (d) battery state of charge.

A.3.7 Carbonyl sulphide

Top 10 Peak Distribution per Replicate Compound: Carbonyl sulphide

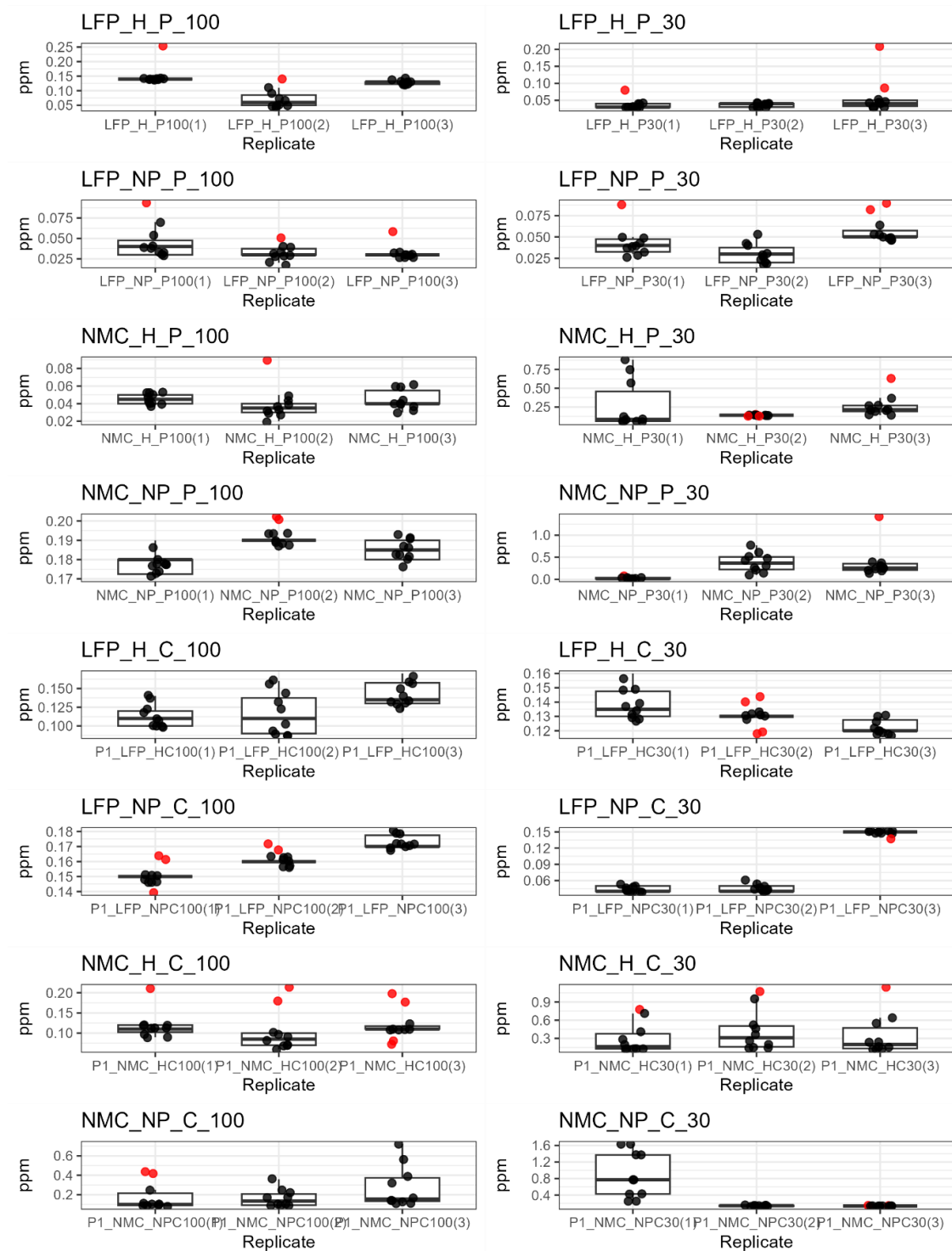


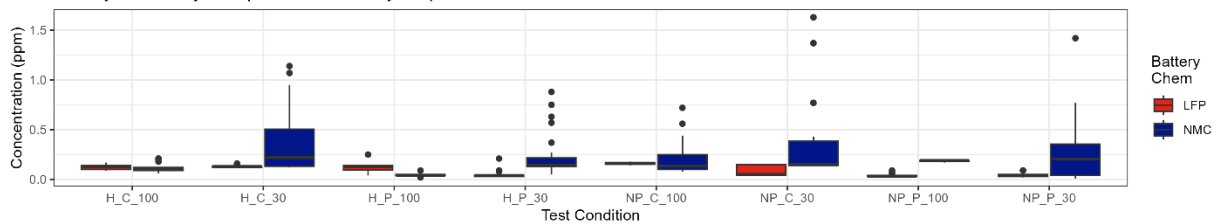
Figure A-13. A boxplot with the top 10 highest peaks of carbonyl sulphide per test condition. Each plot is a test condition. Y-axis represents carbonyl sulphide ppm and the X-axis is the three test replicates for each test condition. Red dots indicate any potential outliers within that test replicate.

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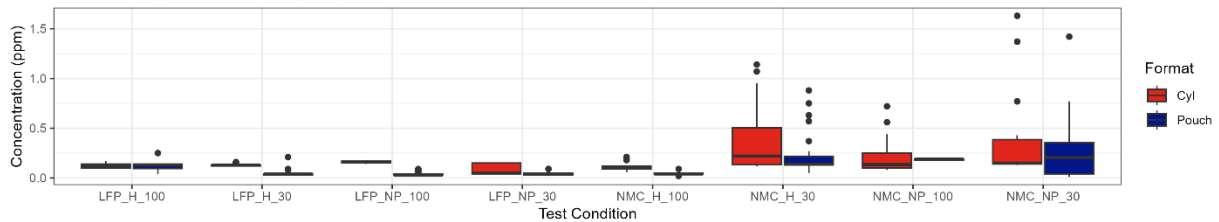
Table A-8. Highest 30 peaks of carbonyl sulphide per test condition. Mean, Min, Q1, Median, Q3, and Max all in ppm.

Test Scenario	Chem	Abuse	Format	SoC (%)	Mean	sd	Min	Q1	Median	Q3	Max	n
1	LFP	H	C	100	0.12	0.02	0.09	0.10	0.13	0.14	0.17	30
2	LFP	H	C	30	0.13	0.01	0.12	0.12	0.13	0.13	0.16	30
3	LFP	H	P	100	0.12	0.04	0.04	0.10	0.13	0.14	0.25	30
4	LFP	H	P	30	0.05	0.03	0.03	0.03	0.04	0.04	0.21	30
5	LFP	NP	C	100	0.16	0.01	0.14	0.15	0.16	0.17	0.18	30
6	LFP	NP	C	30	0.08	0.05	0.04	0.04	0.05	0.15	0.15	30
7	LFP	NP	P	100	0.04	0.02	0.02	0.03	0.03	0.04	0.09	30
8	LFP	NP	P	30	0.04	0.02	0.02	0.03	0.04	0.05	0.09	30
9	NMC	H	C	100	0.11	0.04	0.06	0.09	0.11	0.12	0.21	30
10	NMC	H	C	30	0.36	0.30	0.12	0.13	0.22	0.51	1.14	30
11	NMC	H	P	100	0.04	0.01	0.02	0.04	0.04	0.05	0.09	30
12	NMC	H	P	30	0.23	0.21	0.05	0.13	0.14	0.22	0.88	30
13	NMC	NP	C	100	0.21	0.16	0.08	0.10	0.14	0.25	0.72	30
14	NMC	NP	C	30	0.39	0.48	0.13	0.14	0.15	0.39	1.63	30
15	NMC	NP	P	100	0.19	0.01	0.17	0.18	0.19	0.19	0.20	30
16	NMC	NP	P	30	0.26	0.30	0.01	0.04	0.21	0.36	1.42	30

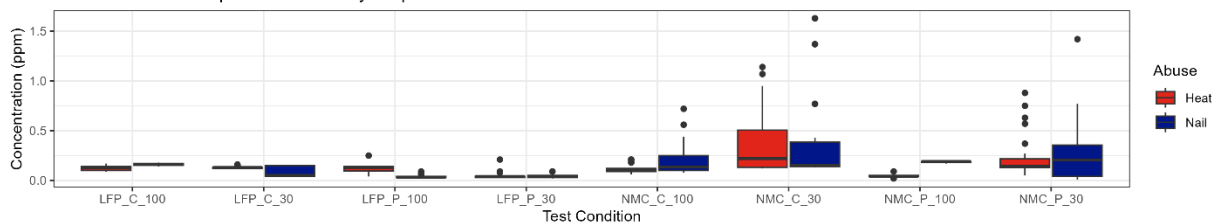
A Battery Chemistry Comparison - Carbonyl sulphide



B Format Comparison - Carbonyl sulphide



C Abuse Method Comparison - Carbonyl sulphide



D Battery SoC Comparison - Carbonyl sulphide

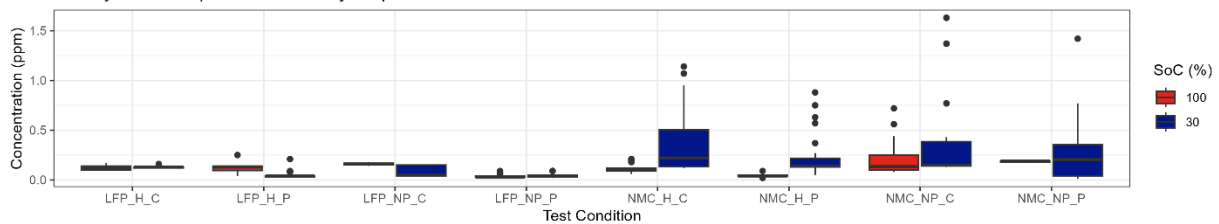


Figure A-14. Boxplot with all test conditions broken up into test scenarios. Y-axis represents carbonyl sulphide ppm and the X-axis is the test scenario. (a) battery chemistry, (b) cell format (c) abuse type, and (d) battery state of charge.

A.3.8 Chlorobenzene

Top 10 Peak Distribution per Replicate Compound: Chlorobenzene

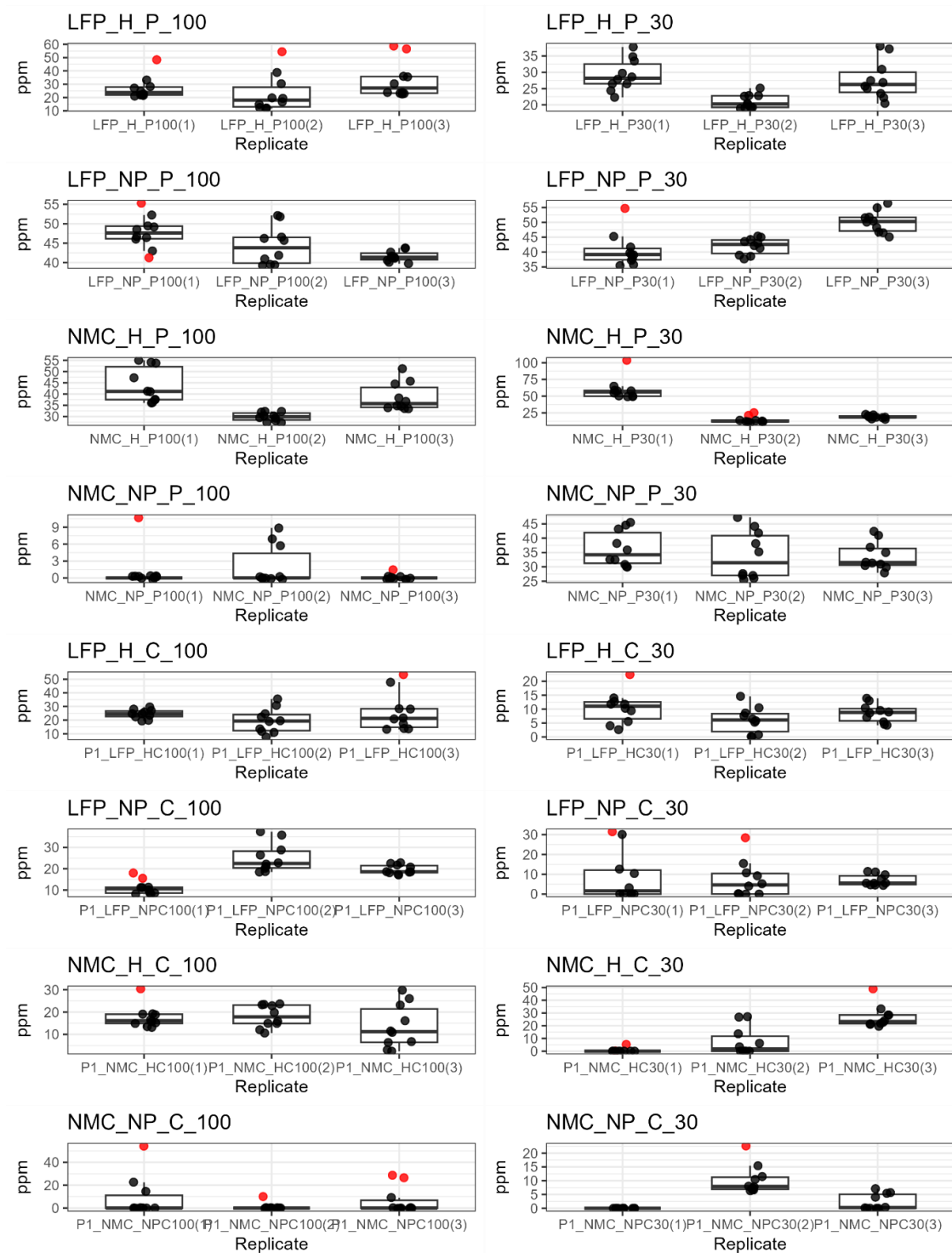


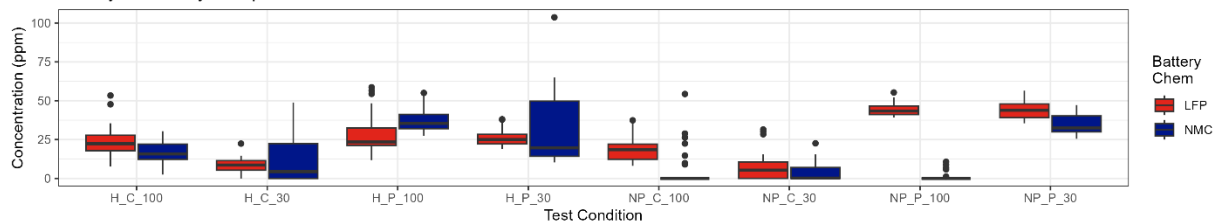
Figure A-15. A boxplot with the top 10 highest peaks of chlorobenzene per test condition. Each plot is a test condition. Y-axis represents chlorobenzene ppm and the X-axis is the three test replicates for each test condition. Red dots indicate any potential outliers within that test replicate.

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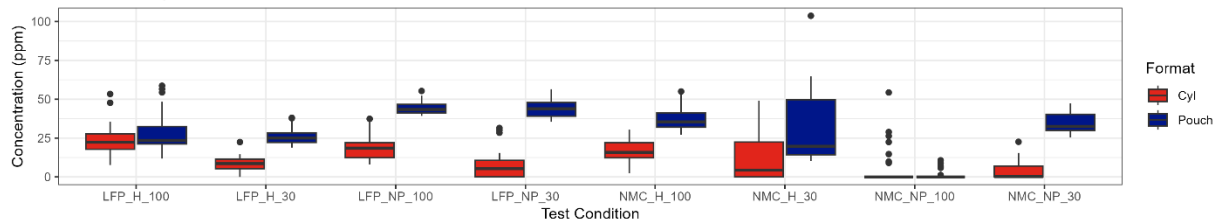
Table A-9. Highest 30 peaks of chlorobenzene per test condition. Mean, Min, Q1, Median, Q3, and Max all in ppm.

Test Scenario	Chem	Abuse	Format	SoC (%)	Mean	sd	Min	Q1	Median	Q3	Max	n
1	LFP	H	C	100	23.30	9.91	7.68	17.81	22.33	27.77	53.37	30
2	LFP	H	C	30	8.34	4.90	0.00	5.33	8.61	11.47	22.43	30
3	LFP	H	P	100	27.83	12.67	11.83	21.24	23.47	32.47	58.68	30
4	LFP	H	P	30	25.99	5.73	18.90	22.24	25.06	28.39	38.08	30
5	LFP	NP	C	100	18.61	7.36	8.10	12.38	18.50	22.07	37.39	30
6	LFP	NP	C	30	7.71	8.80	0.00	0.05	5.35	10.66	31.50	30
7	LFP	NP	P	100	44.59	4.49	39.24	41.15	43.37	46.65	55.31	30
8	LFP	NP	P	30	44.25	5.93	35.49	39.12	43.89	47.92	56.45	30
9	NMC	H	C	100	16.46	7.04	2.45	12.33	15.79	22.07	30.40	30
10	NMC	H	C	30	11.74	13.83	0.00	0.00	4.37	22.45	48.95	30
11	NMC	H	P	100	37.51	8.21	27.25	32.03	35.40	41.20	55.01	30
12	NMC	H	P	30	30.99	22.81	10.30	14.27	19.72	49.70	103.69	30
13	NMC	NP	C	100	5.52	12.41	0.00	0.00	0.00	0.00	54.33	30
14	NMC	NP	C	30	4.19	5.58	0.00	0.00	0.25	7.01	22.60	30
15	NMC	NP	P	100	1.12	2.87	0.00	0.00	0.00	0.00	10.73	30
16	NMC	NP	P	30	34.67	6.52	25.49	29.95	32.49	40.28	47.24	30

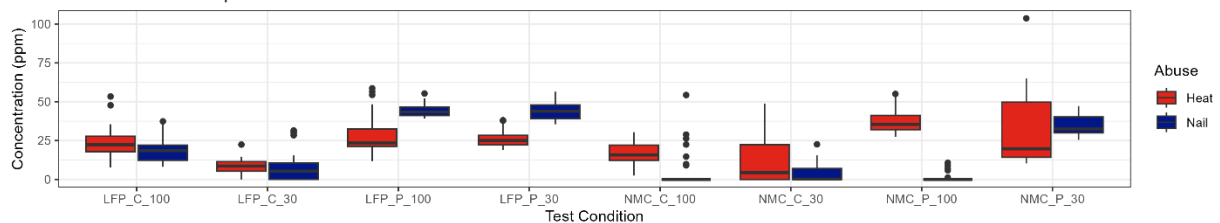
A Battery Chemistry Comparison - Chlorobenzene



B Format Comparison - Chlorobenzene



C Abuse Method Comparison - Chlorobenzene



D Battery SoC Comparison - Chlorobenzene

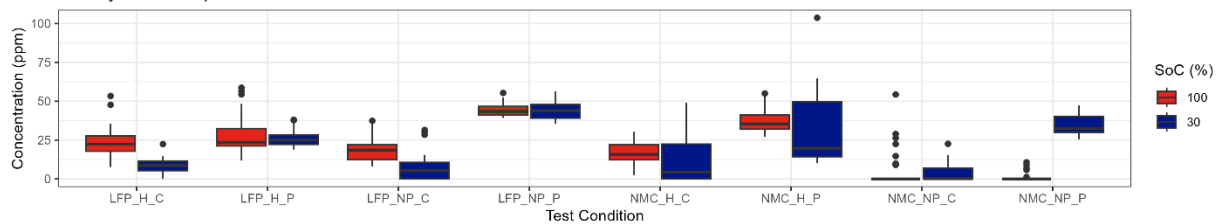


Figure A-16. Boxplot with all test conditions broken up into test scenarios. Y-axis represents chlorobenzene ppm and the X-axis is the test scenario. (a) battery chemistry, (b) cell format (c) abuse type, and (d) battery state of charge.

A.3.9 Diethyl carbonate

Top 10 Peak Distribution per Replicate Compound: Diethyl carbonate

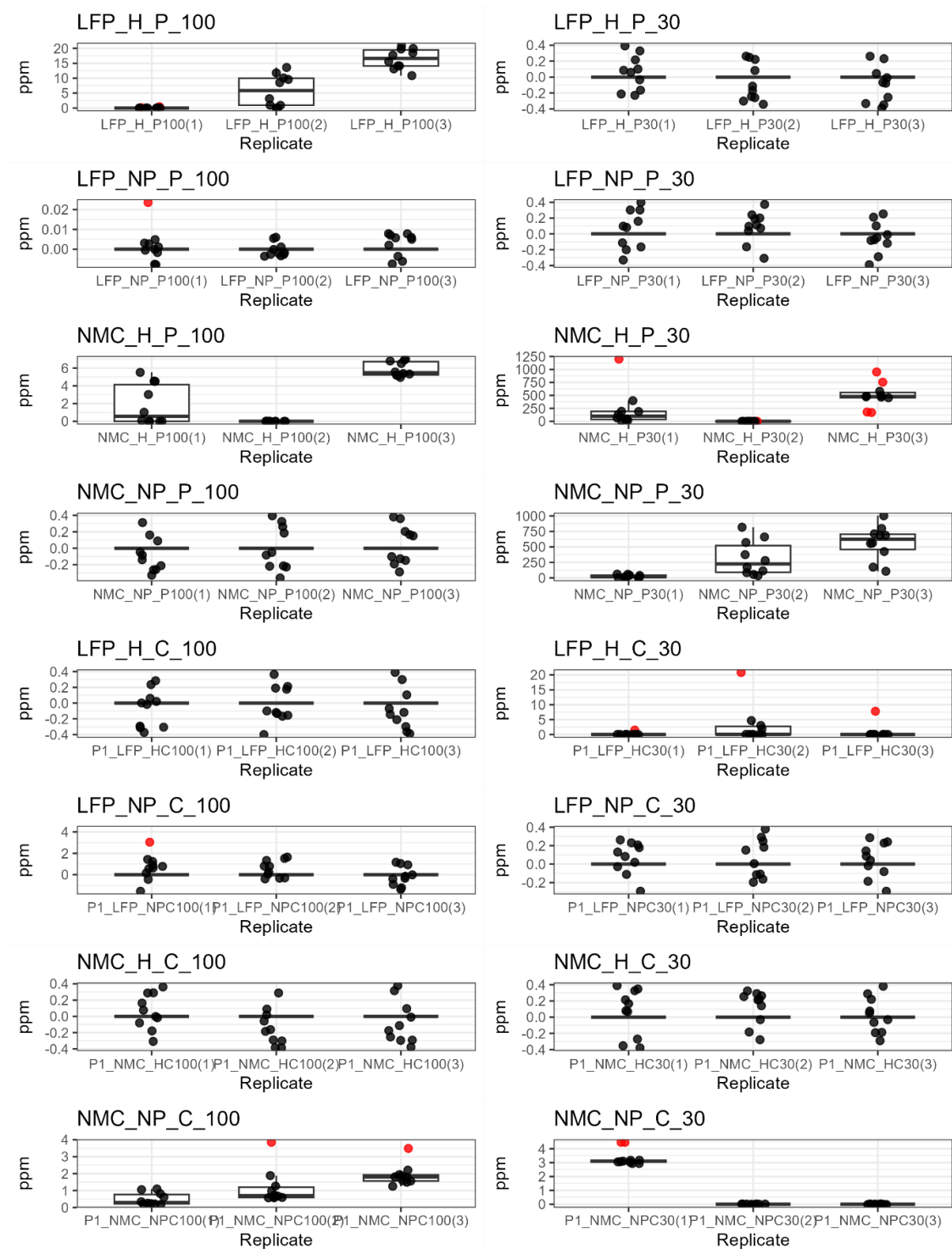


Figure A-17. A boxplot with the top 10 highest peaks of diethyl carbonate per test condition. Each plot is a test condition. Y-axis represents diethyl carbonate ppm and the X-axis is the three test replicates for each test condition. Red dots indicate any potential outliers within that test replicate.

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Table A-10. Highest 30 peaks of diethyl carbonate per test condition. Mean, Min, Q1, Median, Q3, and Max all in ppm.

Test Scenario	Chem	Abuse	Format	SoC (%)	Mean	sd	Min	Q1	Median	Q3	Max	n
1	LFP	H	C	100	0.00	0.00	0.00	0.00	0.00	0.00	0.00	30
2	LFP	H	C	30	1.33	4.07	0.00	0.00	0.00	0.00	20.84	30
3	LFP	H	P	100	7.46	7.75	0.00	0.00	5.83	13.99	20.82	30
4	LFP	H	P	30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	30
5	LFP	NP	C	100	0.14	0.78	0.00	0.00	0.00	0.00	4.27	30
6	LFP	NP	C	30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	30
7	LFP	NP	P	100	0.00	0.00	0.00	0.00	0.00	0.00	0.02	30
8	LFP	NP	P	30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	30
9	NMC	H	C	100	0.00	0.00	0.00	0.00	0.00	0.00	0.00	30
10	NMC	H	C	30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	30
11	NMC	H	P	100	2.58	2.84	0.00	0.00	0.55	5.30	7.01	30
12	NMC	H	P	30	242.98	316.98	0.00	0.43	99.06	462.76	1197.91	30
13	NMC	NP	C	100	1.19	0.91	0.18	0.58	1.01	1.74	3.85	30
14	NMC	NP	C	30	1.11	1.63	0.00	0.00	0.00	3.01	4.45	30
15	NMC	NP	P	100	0.00	0.00	0.00	0.00	0.00	0.00	0.00	30
16	NMC	NP	P	30	305.25	314.36	0.00	40.92	143.67	569.15	1002.56	30

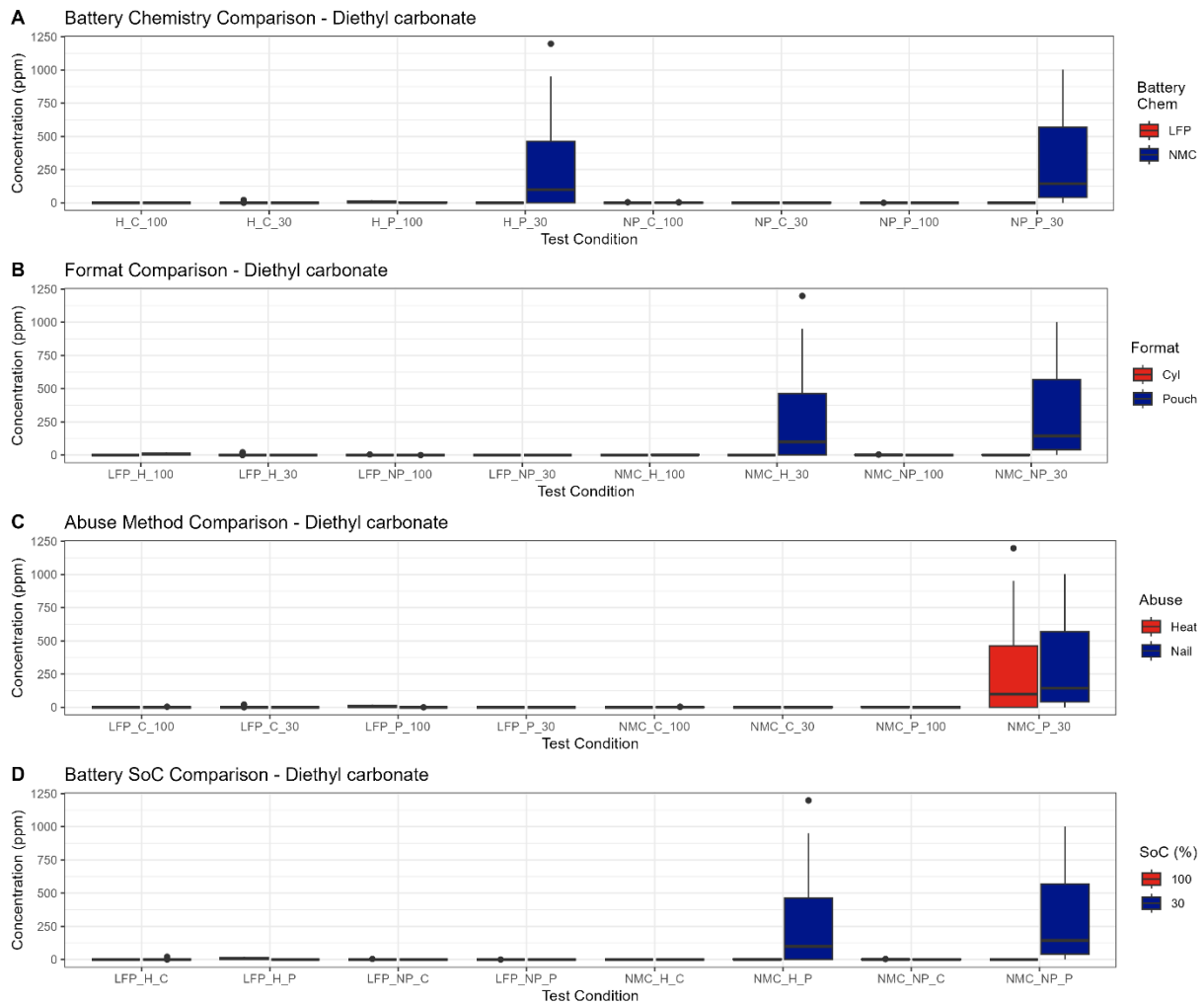


Figure A-18. Boxplot with all test conditions broken up into test scenarios. Y-axis represents diethyl carbonate ppm and the X-axis is the test scenario. (a) battery chemistry, (b) cell format (c) abuse type, and (d) battery state of charge.

A.3.10 Dimethyl carbonate

Top 10 Peak Distribution per Replicate Compound: Dimethyl carbonate

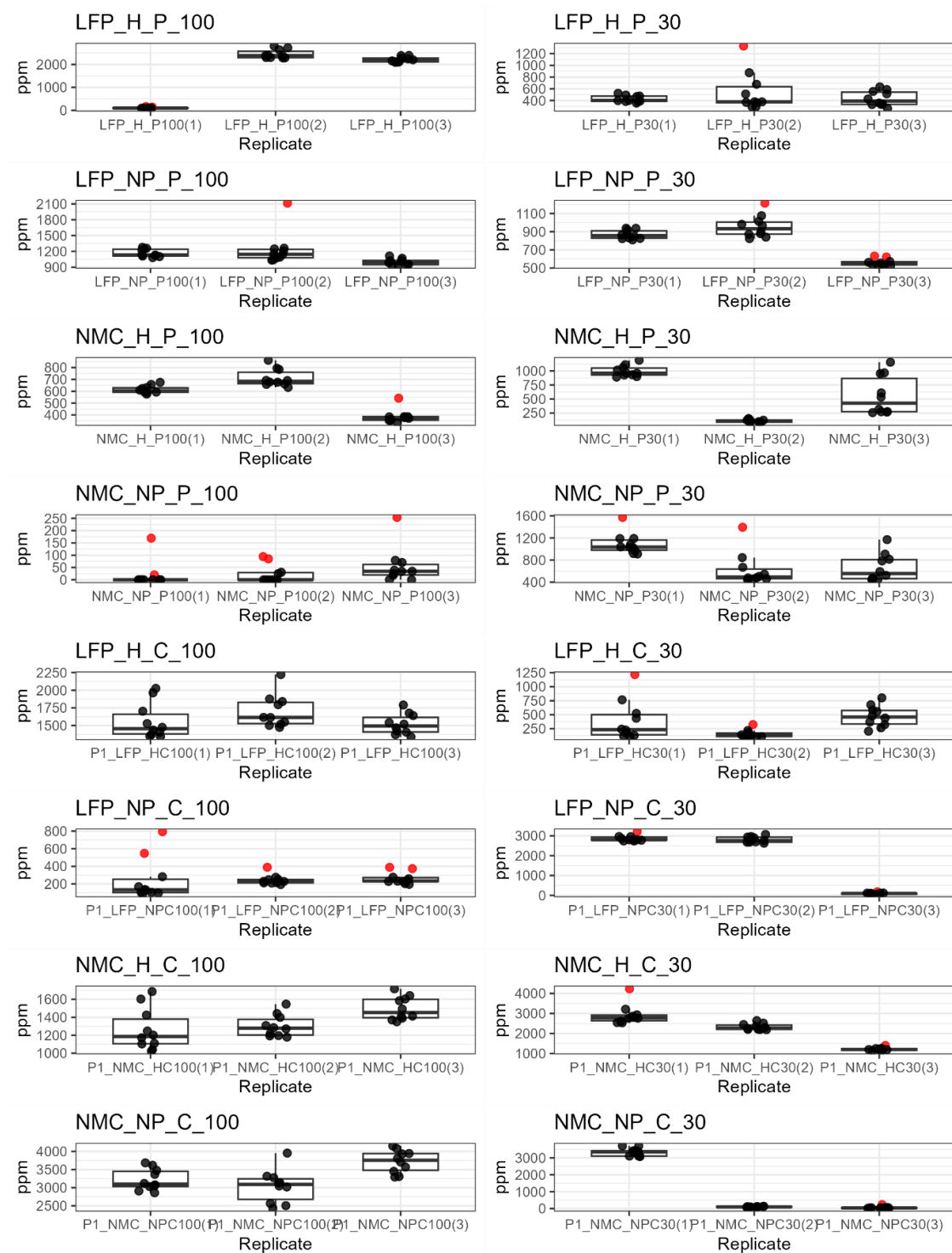


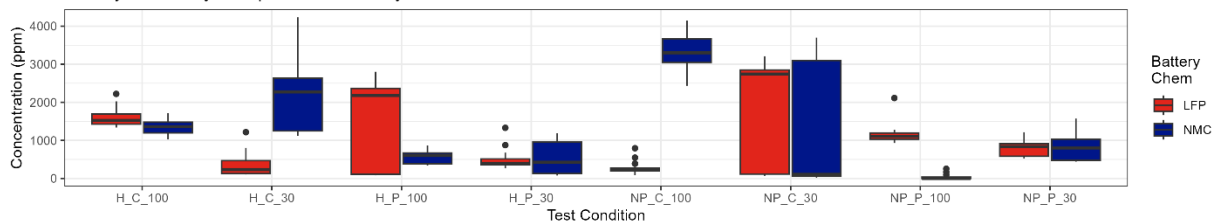
Figure A-19. A boxplot with the top 10 highest peaks of dimethyl carbonate per test condition. Each plot is a test condition. Y-axis represents dimethyl carbonate ppm and the X-axis is the three test replicates for each test condition. Red dots indicate any potential outliers within that test replicate.

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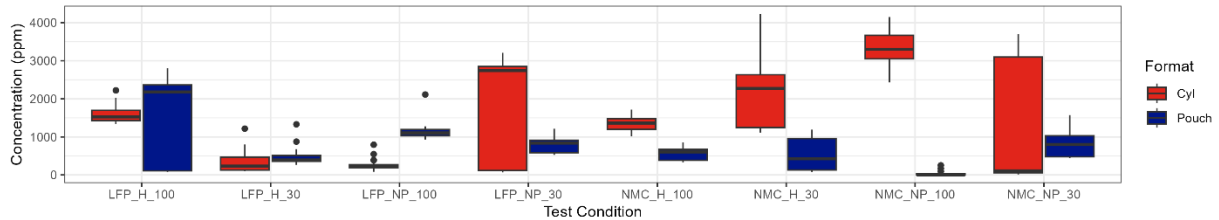
Table A-11. Highest 30 peaks of dimethyl carbonate per test condition. Mean, Min, Q1, Median, Q3, and Max all in ppm.

Test Scenario	Chem	Abuse	Format	SoC (%)	Mean	sd	Min	Q1	Median	Q3	Max	n
1	LFP	H	C	100	1592.87	223.11	1338.51	1427.03	1524.01	1696.22	2221.70	30
2	LFP	H	C	30	339.49	266.43	102.16	128.25	232.57	468.03	1216.70	30
3	LFP	H	P	100	1588.45	1080.43	82.20	109.10	2178.99	2364.99	2802.71	30
4	LFP	H	P	30	469.53	208.26	265.25	358.26	394.39	513.26	1330.21	30
5	LFP	NP	C	100	250.48	141.87	84.68	193.43	228.07	271.44	793.50	30
6	LFP	NP	C	30	1925.60	1317.58	67.50	115.03	2741.56	2848.60	3208.77	30
7	LFP	NP	P	100	1134.65	211.29	931.07	1030.47	1105.49	1193.49	2113.38	30
8	LFP	NP	P	30	794.63	188.17	526.95	583.60	835.63	913.72	1213.38	30
9	NMC	H	C	100	1353.83	193.87	1022.93	1197.71	1359.78	1479.27	1716.15	30
10	NMC	H	C	30	2155.89	781.39	1113.56	1247.76	2272.57	2633.33	4233.50	30
11	NMC	H	P	100	570.78	150.20	334.84	385.79	603.50	671.93	861.45	30
12	NMC	H	P	30	555.42	418.91	78.04	130.18	425.27	956.92	1189.52	30
13	NMC	NP	C	100	3327.85	455.81	2432.38	3049.09	3301.30	3667.37	4149.23	30
14	NMC	NP	C	30	1162.98	1564.45	13.84	57.44	107.60	3097.81	3700.03	30
15	NMC	NP	P	100	32.61	57.33	0.00	0.00	0.00	34.62	253.64	30
16	NMC	NP	P	30	793.49	322.96	442.15	477.15	799.86	1030.03	1571.96	30

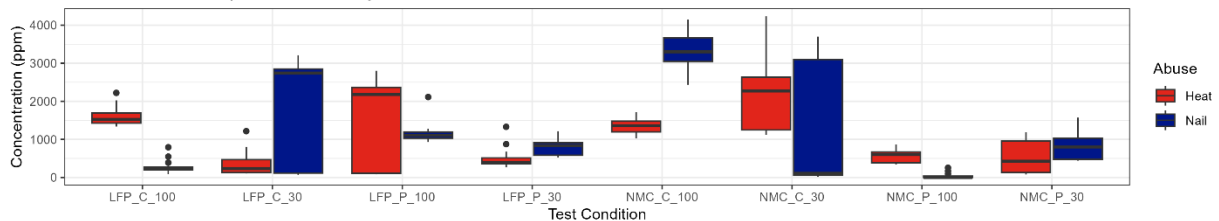
A Battery Chemistry Comparison - Dimethyl carbonate



B Format Comparison - Dimethyl carbonate



C Abuse Method Comparison - Dimethyl carbonate



D Battery SoC Comparison - Dimethyl carbonate

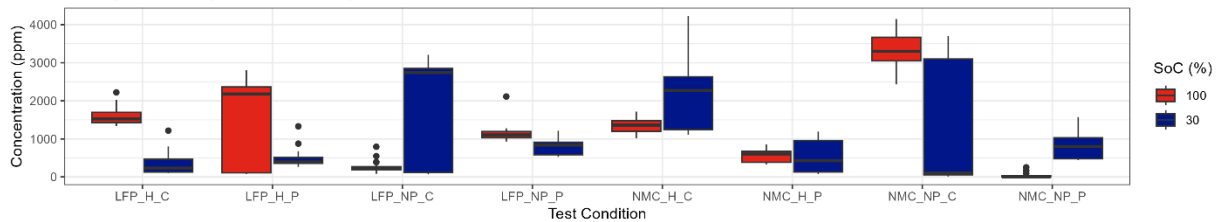


Figure A-20. Boxplot with all test conditions broken up into test scenarios. Y-axis represents dimethyl carbonate ppm and the X-axis is the test scenario. (a) battery chemistry, (b) cell format (c) abuse type, and (d) battery state of charge.

A.3.11 Ethyl methyl carbonate

Top 10 Peak Distribution per Replicate Compound: Ethyl methyl carbonate

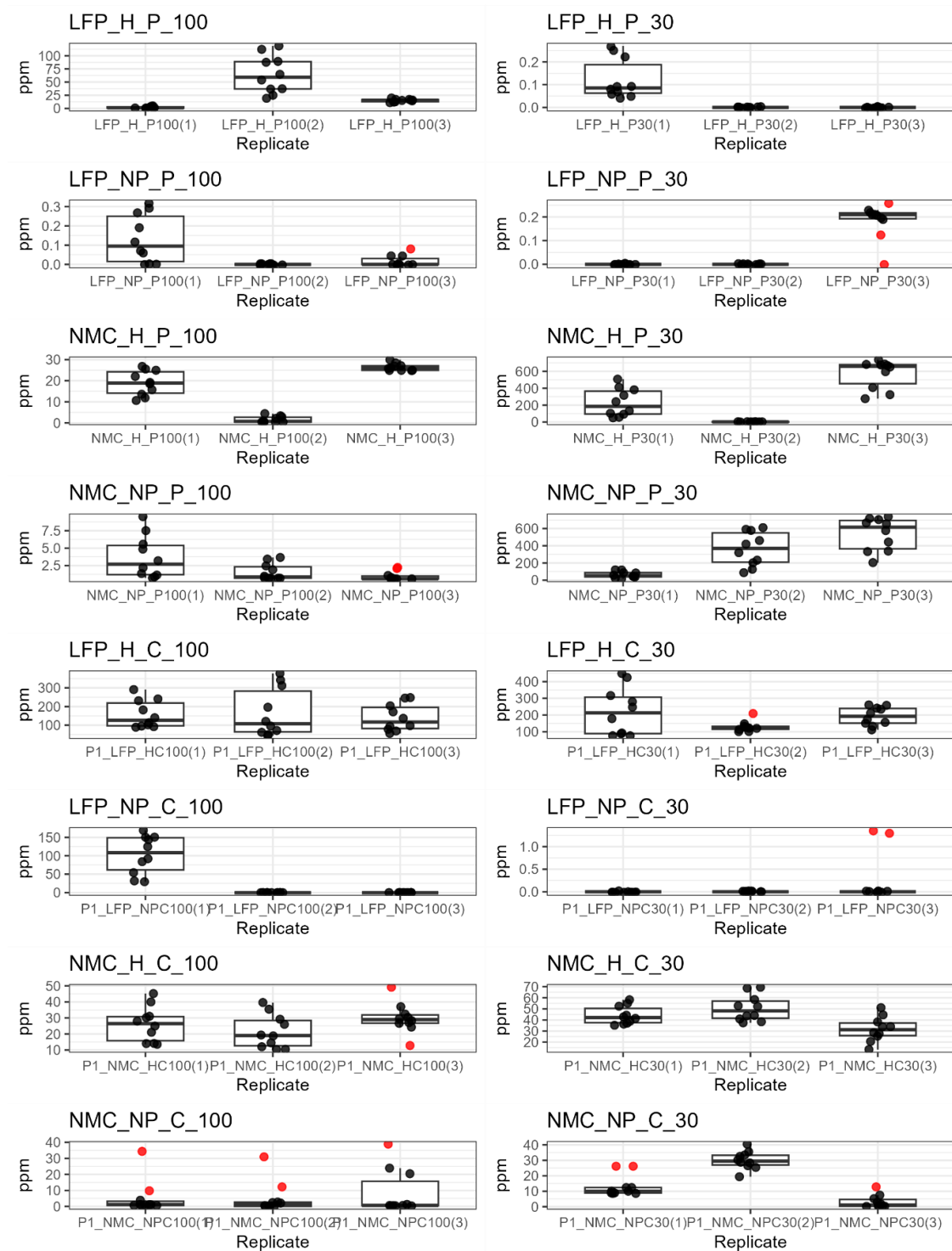


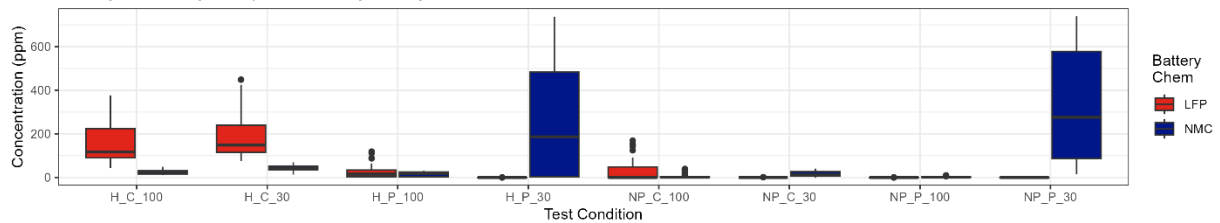
Figure A-21. A boxplot with the top 10 highest peaks of ethyl methyl carbonate per test condition. Each plot is a test condition. Y-axis represents ethyl methyl carbonate ppm and the X-axis is the three test replicates for each test condition. Red dots indicate any potential outliers within that test replicate.

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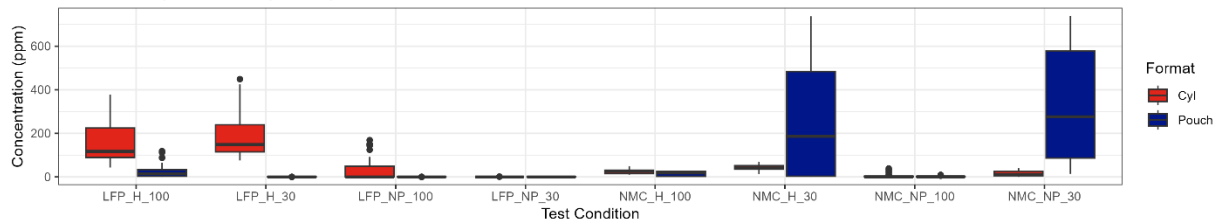
Table A-12. Highest 30 peaks of ethyl methyl carbonate per test condition. Mean, Min, Q1, Median, Q3, and Max all in ppm.

Test Scenario	Chem	Abuse	Format	SoC (%)	Mean	sd	Min	Q1	Median	Q3	Max	n
1	LFP	H	C	100	154.90	93.55	43.39	89.94	116.98	224.58	377.24	30
2	LFP	H	C	30	181.87	95.70	75.73	115.07	148.91	239.55	448.81	30
3	LFP	H	P	100	27.13	33.97	0.32	3.42	15.44	33.83	118.64	30
4	LFP	H	P	30	0.04	0.08	0.00	0.00	0.00	0.06	0.27	30
5	LFP	NP	C	100	34.32	57.24	0.00	0.00	0.00	48.46	168.83	30
6	LFP	NP	C	30	0.09	0.34	0.00	0.00	0.00	0.00	1.36	30
7	LFP	NP	P	100	0.05	0.09	0.00	0.00	0.00	0.06	0.32	30
8	LFP	NP	P	30	0.06	0.10	0.00	0.00	0.00	0.17	0.26	30
9	NMC	H	C	100	25.84	10.48	10.29	15.57	26.85	30.84	49.13	30
10	NMC	H	C	30	42.15	12.93	13.31	35.44	41.19	51.89	69.49	30
11	NMC	H	P	100	15.63	11.12	0.43	3.01	18.87	25.40	29.96	30
12	NMC	H	P	30	267.27	271.76	0.36	3.44	186.39	483.52	737.52	30
13	NMC	NP	C	100	6.39	11.29	0.00	0.46	0.88	3.58	38.89	30
14	NMC	NP	C	30	15.48	12.58	0.17	5.76	11.19	26.40	40.45	30
15	NMC	NP	P	100	2.09	2.21	0.59	0.69	1.02	2.40	9.52	30
16	NMC	NP	P	30	321.24	252.63	14.65	86.72	276.29	578.05	739.48	30

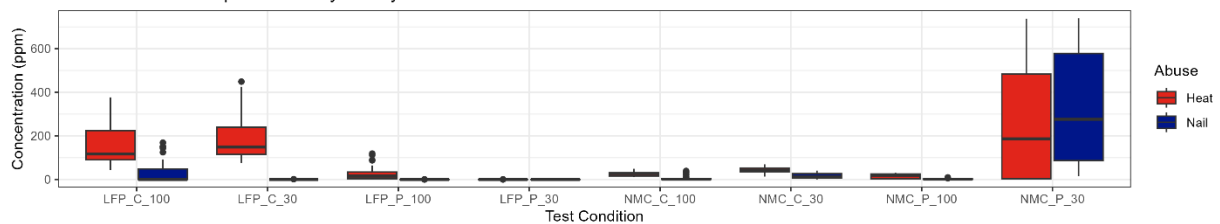
A Battery Chemistry Comparison - Ethyl methyl carbonate



B Format Comparison - Ethyl methyl carbonate



C Abuse Method Comparison - Ethyl methyl carbonate



D Battery SoC Comparison - Ethyl methyl carbonate

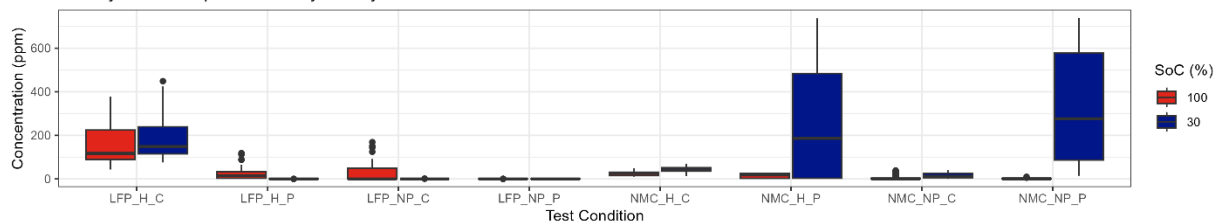


Figure A-22. Boxplot with all test conditions broken up into test scenarios. Y-axis represents ethyl methyl carbonate ppm and the X-axis is the test scenario. (a) battery chemistry, (b) cell format (c) abuse type, and (d) battery state of charge.

A.3.12 Ethylene

Top 10 Peak Distribution per Replicate Compound: Ethylene

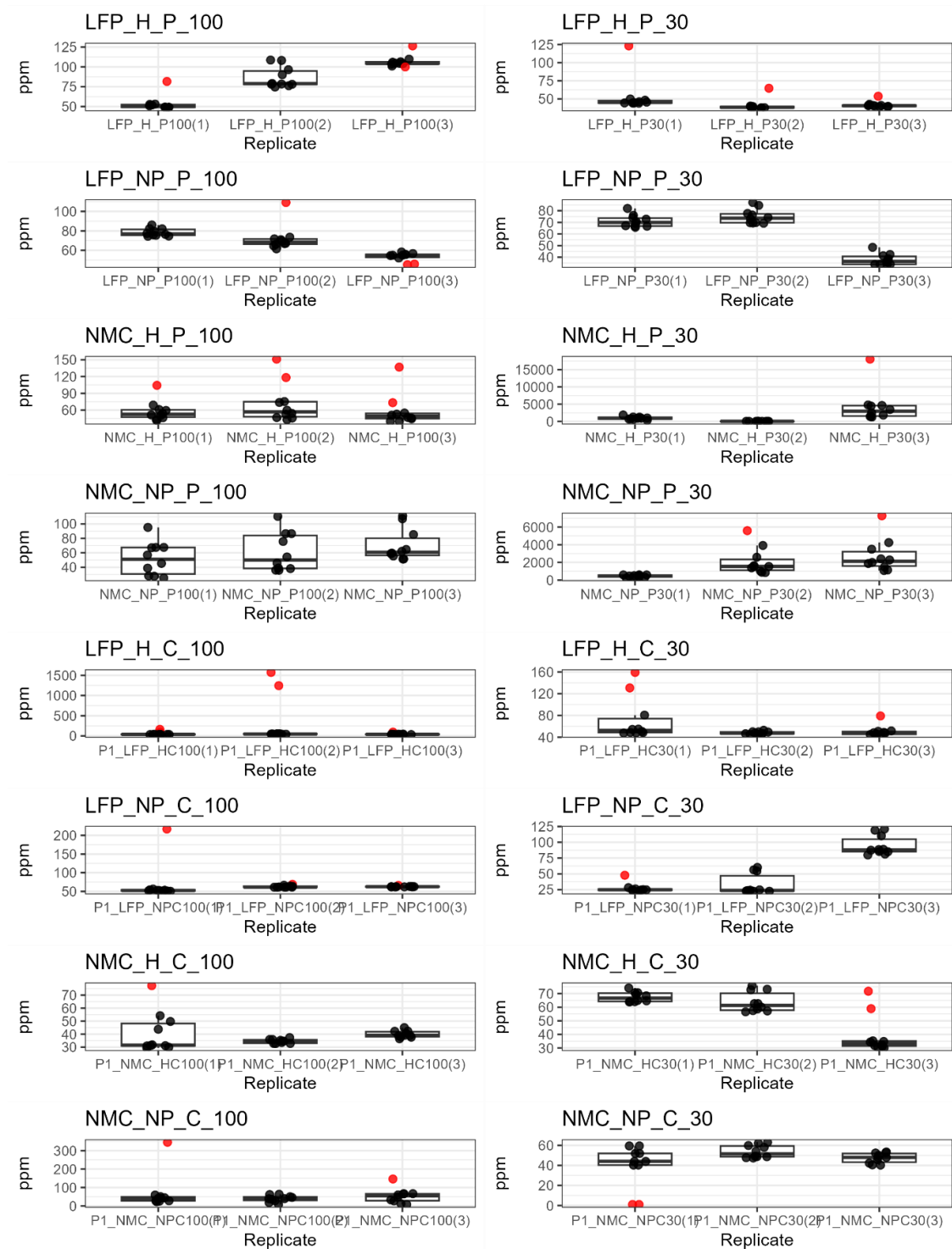


Figure A-23. A boxplot with the top 10 highest peaks of ethylene per test condition. Each plot is a test condition. Y-axis represents ethylene ppm and the X-axis is the three test replicates for each test condition. Red dots indicate any potential outliers within that test replicate.

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Table A-13. Highest 30 peaks of ethylene per test condition. Mean, Min, Q1, Median, Q3, and Max all in ppm.

Test Scenario	Chem	Abuse	Format	SoC (%)	Mean	sd	Min	Q1	Median	Q3	Max	n
1	LFP	H	C	100	139.27	348.58	33.15	35.04	42.89	47.07	1572.05	30
2	LFP	H	C	30	57.02	25.61	44.79	46.73	48.57	51.38	159.28	30
3	LFP	H	P	100	82.20	24.52	47.99	52.72	80.31	104.13	126.41	30
4	LFP	H	P	30	45.48	15.73	37.36	39.39	40.96	44.72	123.12	30
5	LFP	NP	C	100	64.94	29.18	50.38	54.69	61.85	62.88	216.99	30
6	LFP	NP	C	30	51.79	33.64	22.58	23.94	27.23	84.10	120.86	30
7	LFP	NP	P	100	68.01	13.57	45.24	56.07	68.41	75.75	109.17	30
8	LFP	NP	P	30	61.37	17.80	33.57	41.56	69.33	73.81	87.10	30
9	NMC	H	C	100	38.49	9.31	29.49	32.87	36.20	40.33	77.21	30
10	NMC	H	C	30	56.78	15.74	30.10	40.61	62.68	69.19	75.83	30
11	NMC	H	P	100	62.88	28.36	39.97	45.94	52.72	67.00	151.09	30
12	NMC	H	P	30	1800.99	3381.74	32.00	38.68	943.86	1750.98	18060.95	30
13	NMC	NP	C	100	53.52	60.93	7.65	27.57	41.18	59.63	345.31	30
14	NMC	NP	C	30	46.82	14.06	1.06	43.97	48.68	53.18	62.99	30
15	NMC	NP	P	100	61.14	24.57	25.18	40.54	57.86	73.64	111.24	30
16	NMC	NP	P	30	1757.02	1671.72	239.24	585.23	1260.21	2205.74	7276.14	30

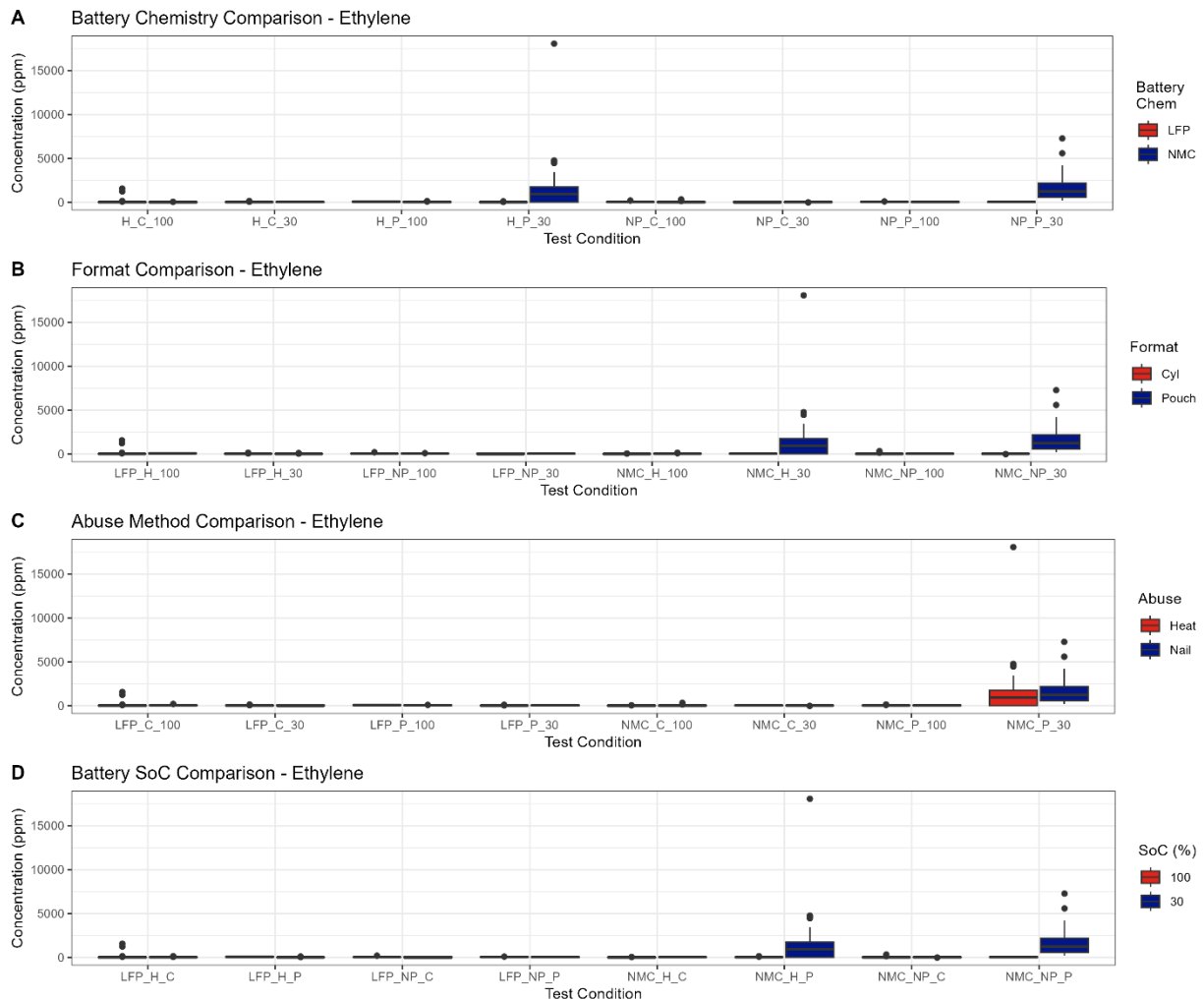


Figure A-24. Boxplot with all test conditions broken up into test scenarios. Y-axis represents ethylene ppm and the X-axis is the test scenario. (a) battery chemistry, (b) cell format (c) abuse type, and (d) battery state of charge.

A.3.13 Ethylene carbonate

Top 10 Peak Distribution per Replicate Compound: Ethylene carbonate

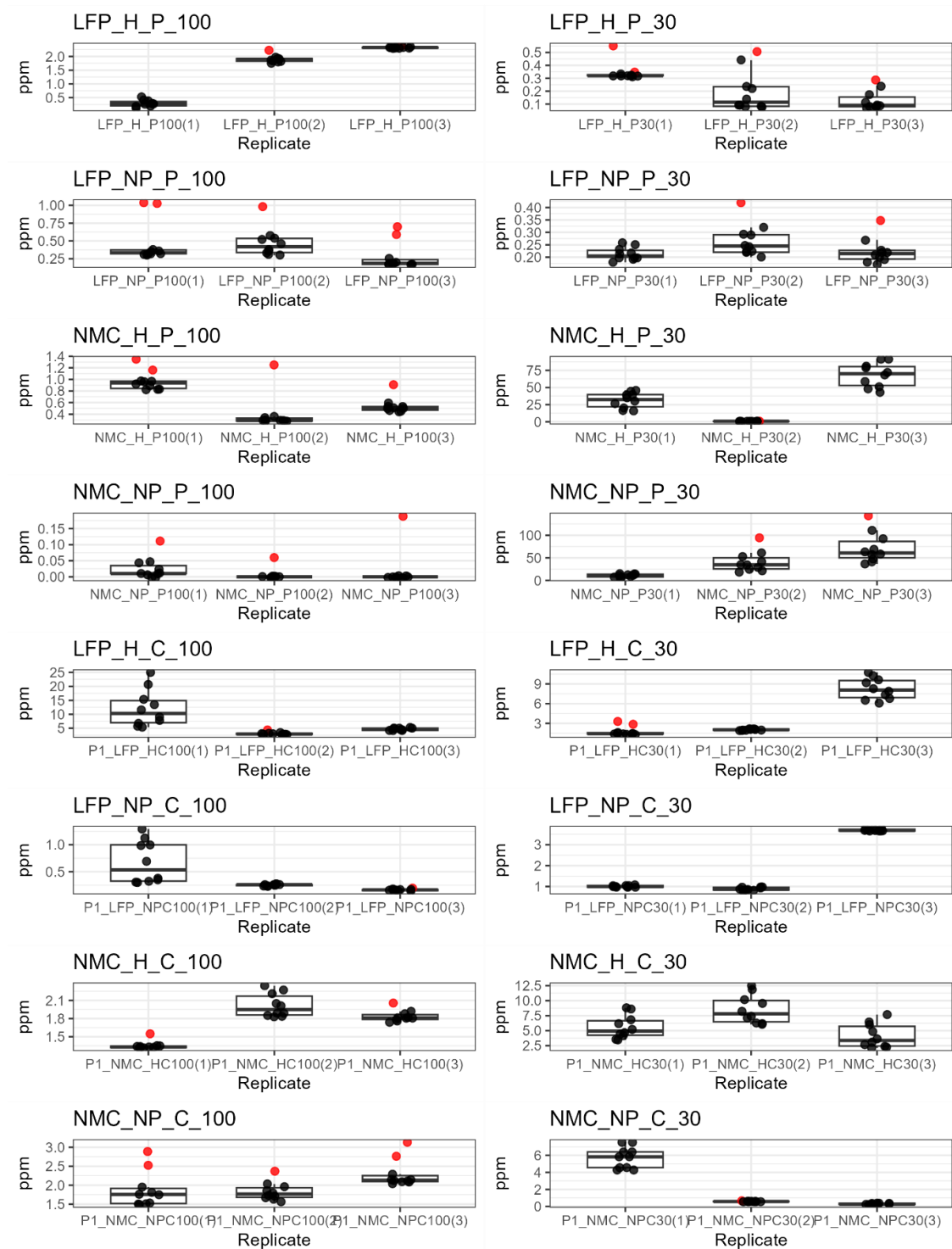


Figure A-25. A boxplot with the top 10 highest peaks of ethylene carbonate per test condition. Each plot is a test condition. Y-axis represents ethylene carbonate ppm and the X-axis is the three test replicates for each test condition. Red dots indicate any potential outliers within that test replicate.

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Table A-14. Highest 30 peaks of ethylene carbonate per test condition. Mean, Min, Q1, Median, Q3, and Max all in ppm.

Test Scenario	Chem	Abuse	Format	SoC (%)	Mean	sd	Min	Q1	Median	Q3	Max	n
1	LFP	H	C	100	6.61	5.44	2.72	3.24	4.63	6.48	24.99	30
2	LFP	H	C	30	4.02	3.21	1.30	1.68	2.12	6.71	10.74	30
3	LFP	H	P	100	1.51	0.90	0.12	0.39	1.89	2.30	2.38	30
4	LFP	H	P	30	0.22	0.14	0.07	0.09	0.23	0.32	0.55	30
5	LFP	NP	C	100	0.36	0.31	0.14	0.17	0.26	0.32	1.29	30
6	LFP	NP	C	30	1.87	1.32	0.78	0.97	1.00	3.66	3.75	30
7	LFP	NP	P	100	0.41	0.25	0.17	0.26	0.33	0.51	1.04	30
8	LFP	NP	P	30	0.24	0.06	0.17	0.20	0.22	0.25	0.42	30
9	NMC	H	C	100	1.74	0.31	1.32	1.35	1.81	1.89	2.34	30
10	NMC	H	C	30	6.08	2.77	2.14	3.77	6.12	7.61	12.50	30
11	NMC	H	P	100	0.64	0.32	0.28	0.35	0.52	0.91	1.35	30
12	NMC	H	P	30	33.43	30.43	0.63	0.71	32.54	50.25	91.31	30
13	NMC	NP	C	100	2.00	0.42	1.49	1.72	1.96	2.14	3.13	30
14	NMC	NP	C	30	2.20	2.63	0.23	0.36	0.58	4.49	7.53	30
15	NMC	NP	P	100	0.02	0.04	0.00	0.00	0.00	0.01	0.19	30
16	NMC	NP	P	30	41.29	34.18	5.54	14.31	34.72	58.16	143.03	30

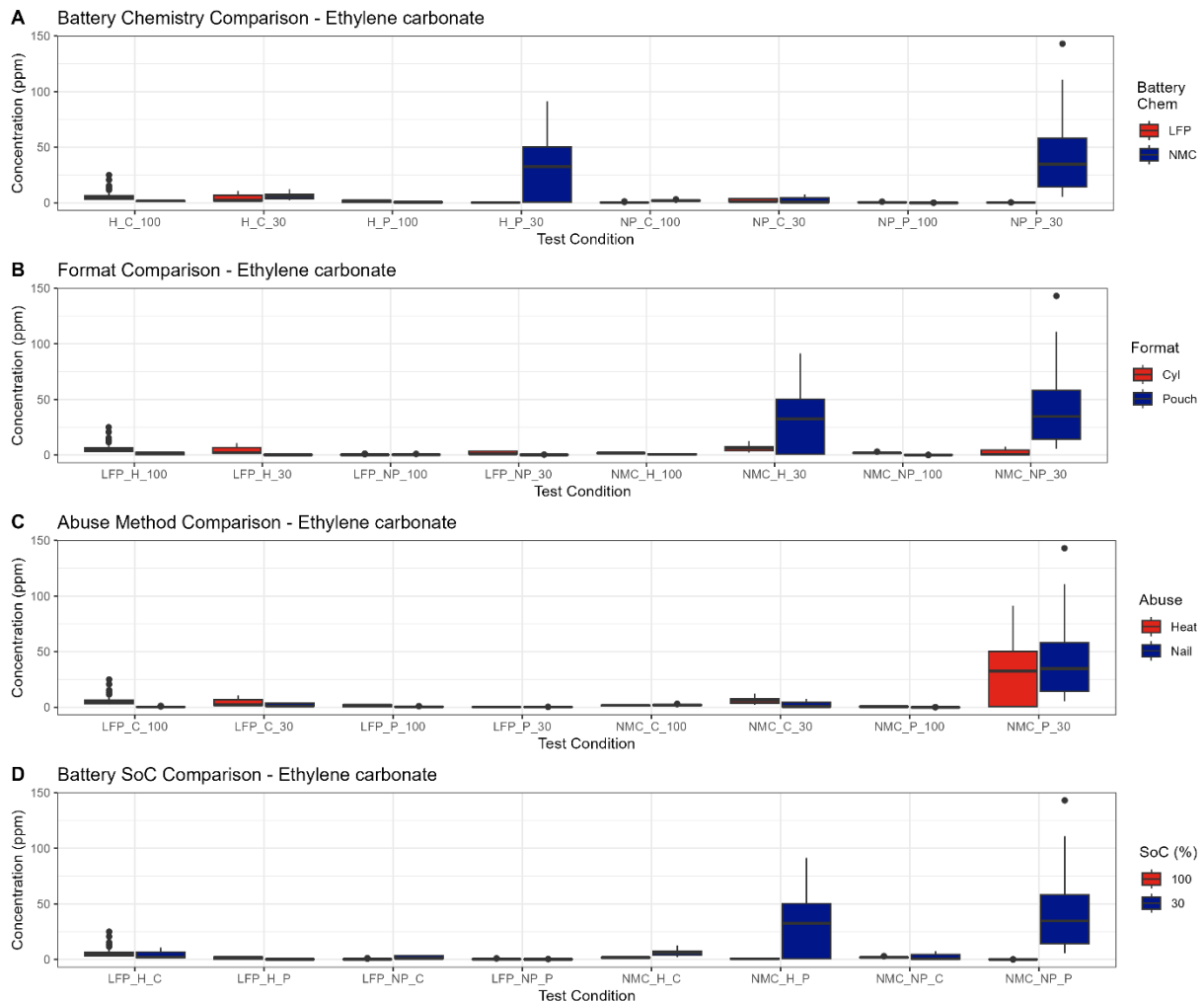


Figure A-26. Boxplot with all test conditions broken up into test scenarios. Y-axis represents ethylene carbonate ppm and the X-axis is the test scenario. (a) battery chemistry, (b) cell format (c) abuse type, and (d) battery state of charge.

A.3.14 Hexane

Top 10 Peak Distribution per Replicate Compound: Hexane

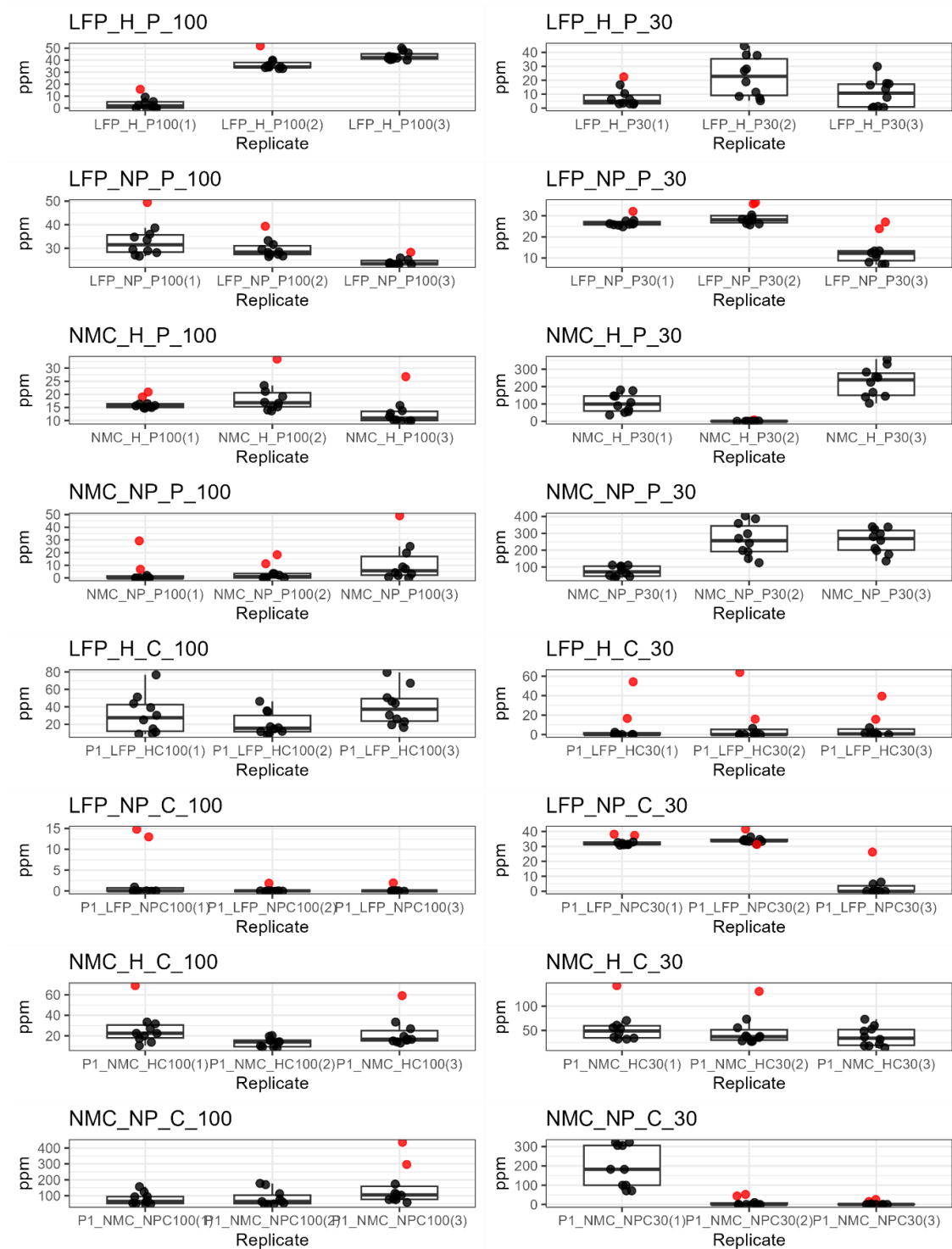


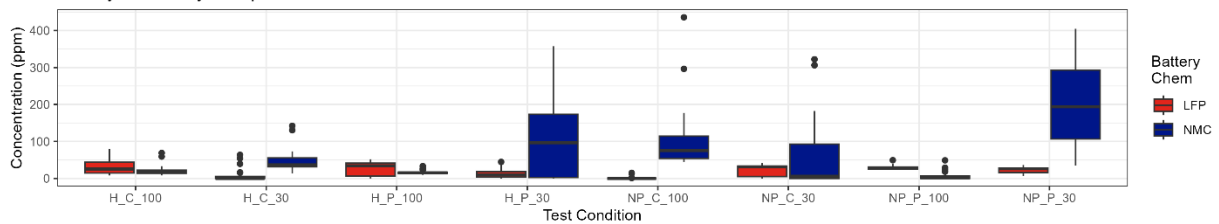
Figure A-27. A boxplot with the top 10 highest peaks of hexane per test condition. Each plot is a test condition. Y-axis represents hexane ppm and the X-axis is the three test replicates for each test condition. Red dots indicate any potential outliers within that test replicate.

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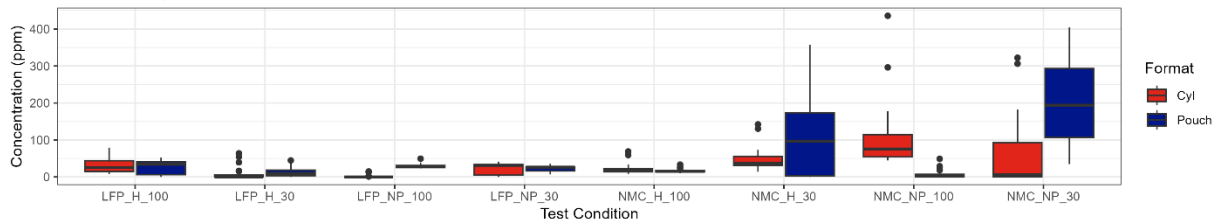
Table A-15. Highest 30 peaks of hexane per test condition. Mean, Min, Q1, Median, Q3, and Max all in ppm.

Test Scenario	Chem	Abuse	Format	SoC (%)	Mean	sd	Min	Q1	Median	Q3	Max	n
1	LFP	H	C	100	30.60	20.28	8.19	14.79	25.60	44.02	79.46	30
2	LFP	H	C	30	7.53	16.34	0.00	0.00	0.00	5.42	63.89	30
3	LFP	H	P	100	28.10	18.28	0.00	6.32	34.34	41.33	51.99	30
4	LFP	H	P	30	13.67	12.46	0.00	3.44	9.42	18.58	44.74	30
5	LFP	NP	C	100	1.09	3.54	0.00	0.00	0.00	0.00	14.88	30
6	LFP	NP	C	30	23.67	15.24	0.00	5.14	31.33	33.50	41.60	30
7	LFP	NP	P	100	29.08	5.96	22.98	25.28	27.75	31.05	49.44	30
8	LFP	NP	P	30	23.23	8.39	6.83	16.03	26.20	27.82	36.30	30
9	NMC	H	C	100	21.12	13.60	8.27	13.94	16.70	22.45	68.93	30
10	NMC	H	C	30	47.45	29.12	13.86	31.53	36.94	55.57	142.26	30
11	NMC	H	P	100	16.11	5.16	9.73	13.71	15.25	16.91	33.41	30
12	NMC	H	P	30	110.88	108.68	0.00	2.79	96.67	173.46	357.41	30
13	NMC	NP	C	100	105.46	83.31	44.65	54.21	75.49	114.43	435.73	30
14	NMC	NP	C	30	70.42	109.63	0.00	0.00	5.95	92.73	322.15	30
15	NMC	NP	P	100	6.53	11.27	0.00	0.00	1.92	7.11	49.03	30
16	NMC	NP	P	30	197.51	113.04	34.80	106.92	193.82	292.96	404.51	30

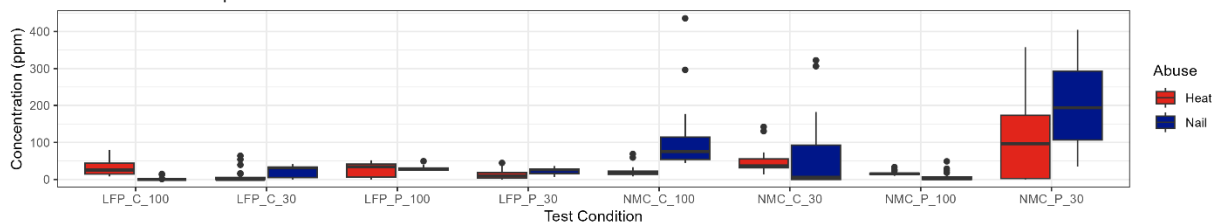
A Battery Chemistry Comparison - Hexane



B Format Comparison - Hexane



C Abuse Method Comparison - Hexane



D Battery SoC Comparison - Hexane

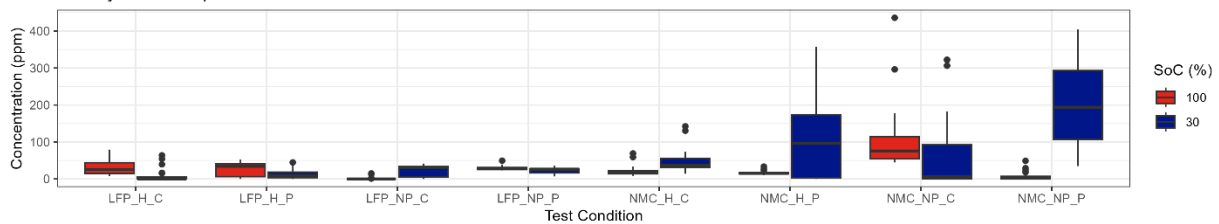


Figure A-28. Boxplot with all test conditions broken up into test scenarios. y-axis represents hexane ppm and the x-axis is the test scenario. (a) battery chemistry, (b) cell format (c) abuse type, and (d) battery state of charge.

A.3.15 Hydrogen cyanide

Top 10 Peak Distribution per Replicate Compound: Hydrogen cyanide

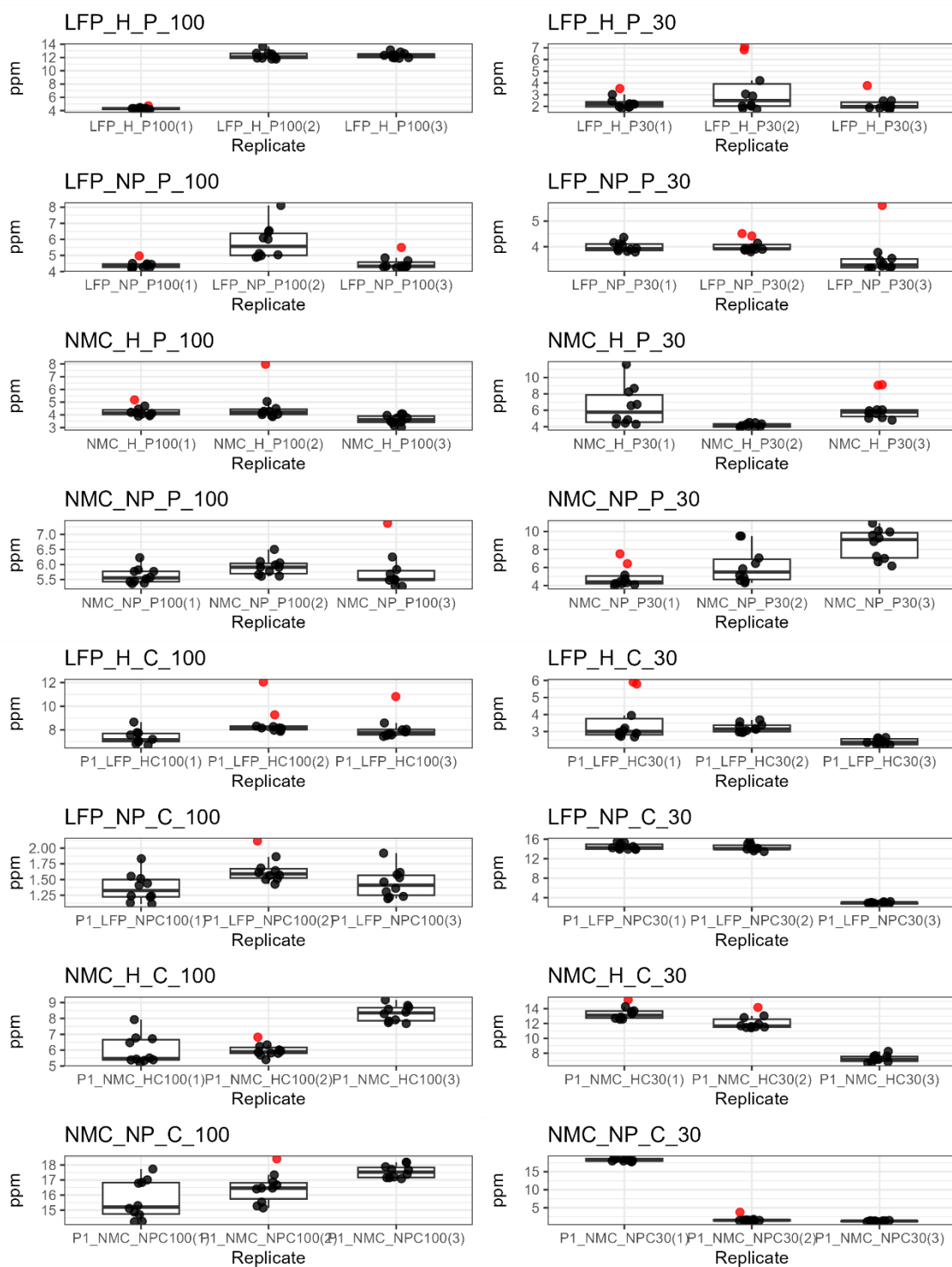


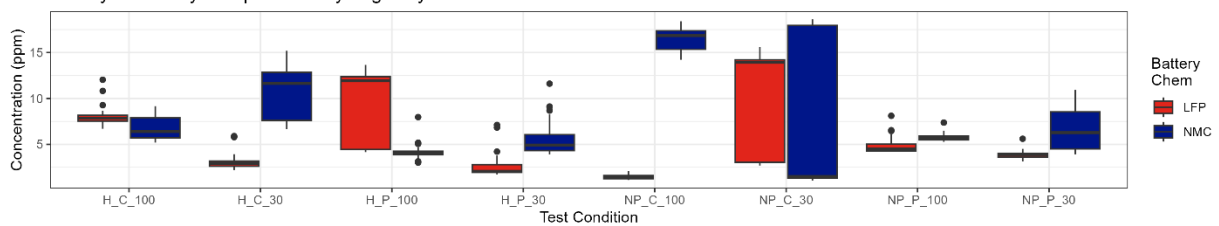
Figure A-29. A boxplot with the top 10 highest peaks of hydrogen cyanide per test condition. Each plot is a test condition. Y-axis represents hydrogen cyanide ppm and the X-axis is the three test replicates for each test condition. Red dots indicate any potential outliers within that test replicate.

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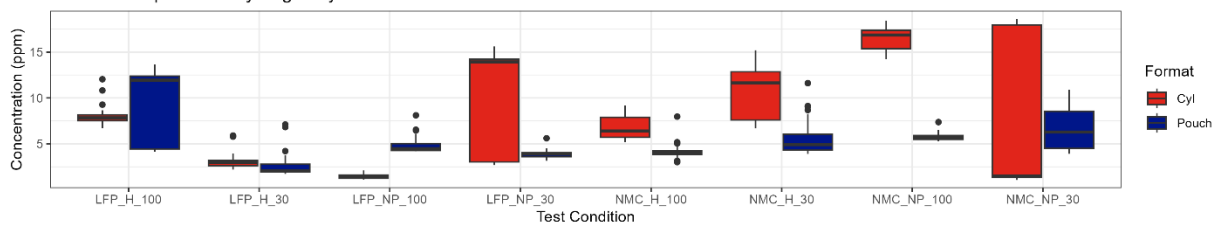
Table A-16. Highest 30 peaks of hydrogen cyanide per test condition. Mean, Min, Q1, Median, Q3, and Max all in ppm.

Test Scenario	Chem	Abuse	Format	SoC (%)	Mean	sd	Min	Q1	Median	Q3	Max	n
1	LFP	H	C	100	8.03	1.10	6.70	7.53	7.85	8.16	12.04	30
2	LFP	H	C	30	3.07	0.88	2.20	2.62	2.95	3.19	5.90	30
3	LFP	H	P	100	9.66	3.85	4.15	4.44	11.93	12.37	13.65	30
4	LFP	H	P	30	2.64	1.33	1.73	1.95	2.07	2.79	7.11	30
5	LFP	NP	C	100	1.49	0.24	1.11	1.26	1.51	1.60	2.11	30
6	LFP	NP	C	30	10.55	5.51	2.69	3.04	13.93	14.21	15.61	30
7	LFP	NP	P	100	4.91	0.91	4.19	4.28	4.49	5.03	8.11	30
8	LFP	NP	P	30	3.86	0.50	3.15	3.60	3.90	4.04	5.61	30
9	NMC	H	C	100	6.77	1.27	5.19	5.72	6.40	7.89	9.17	30
10	NMC	H	C	30	10.92	2.78	6.68	7.61	11.64	12.85	15.19	30
11	NMC	H	P	100	4.16	0.86	3.01	3.87	4.06	4.25	7.97	30
12	NMC	H	P	30	5.63	1.93	3.91	4.33	4.92	6.06	11.61	30
13	NMC	NP	C	100	16.57	1.22	14.22	15.36	16.85	17.37	18.41	30
14	NMC	NP	C	30	7.08	8.05	1.07	1.35	1.50	17.95	18.62	30
15	NMC	NP	P	100	5.77	0.43	5.28	5.49	5.68	5.91	7.37	30
16	NMC	NP	P	30	6.55	2.21	3.92	4.51	6.29	8.54	10.91	30

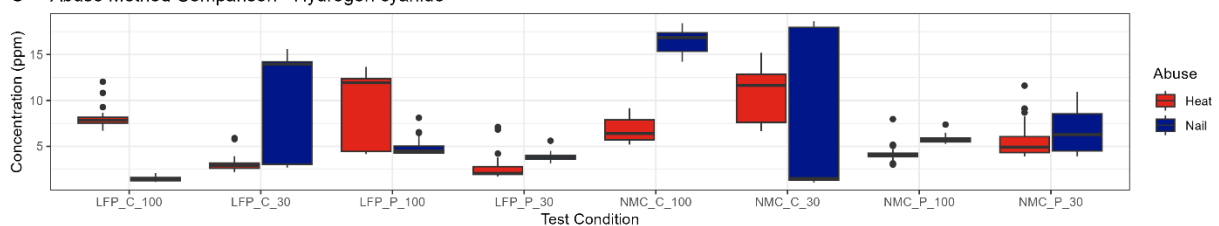
A Battery Chemistry Comparison - Hydrogen cyanide



B Format Comparison - Hydrogen cyanide



C Abuse Method Comparison - Hydrogen cyanide



D Battery SoC Comparison - Hydrogen cyanide

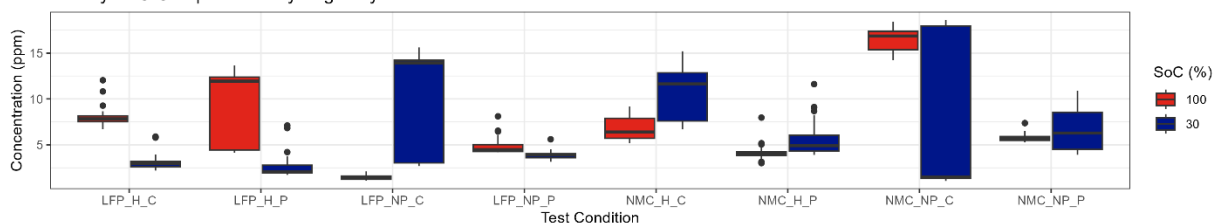


Figure A-30. Boxplot with all test conditions broken up into test scenarios. Y-axis represents hydrogen cyanide ppm and the X-axis is the test scenario. (a) battery chemistry, (b) cell format (c) abuse type, and (d) battery state of charge.

A.3.16 Hydrogen chloride

Top 10 Peak Distribution per Replicate Compound: Hydrogen chloride

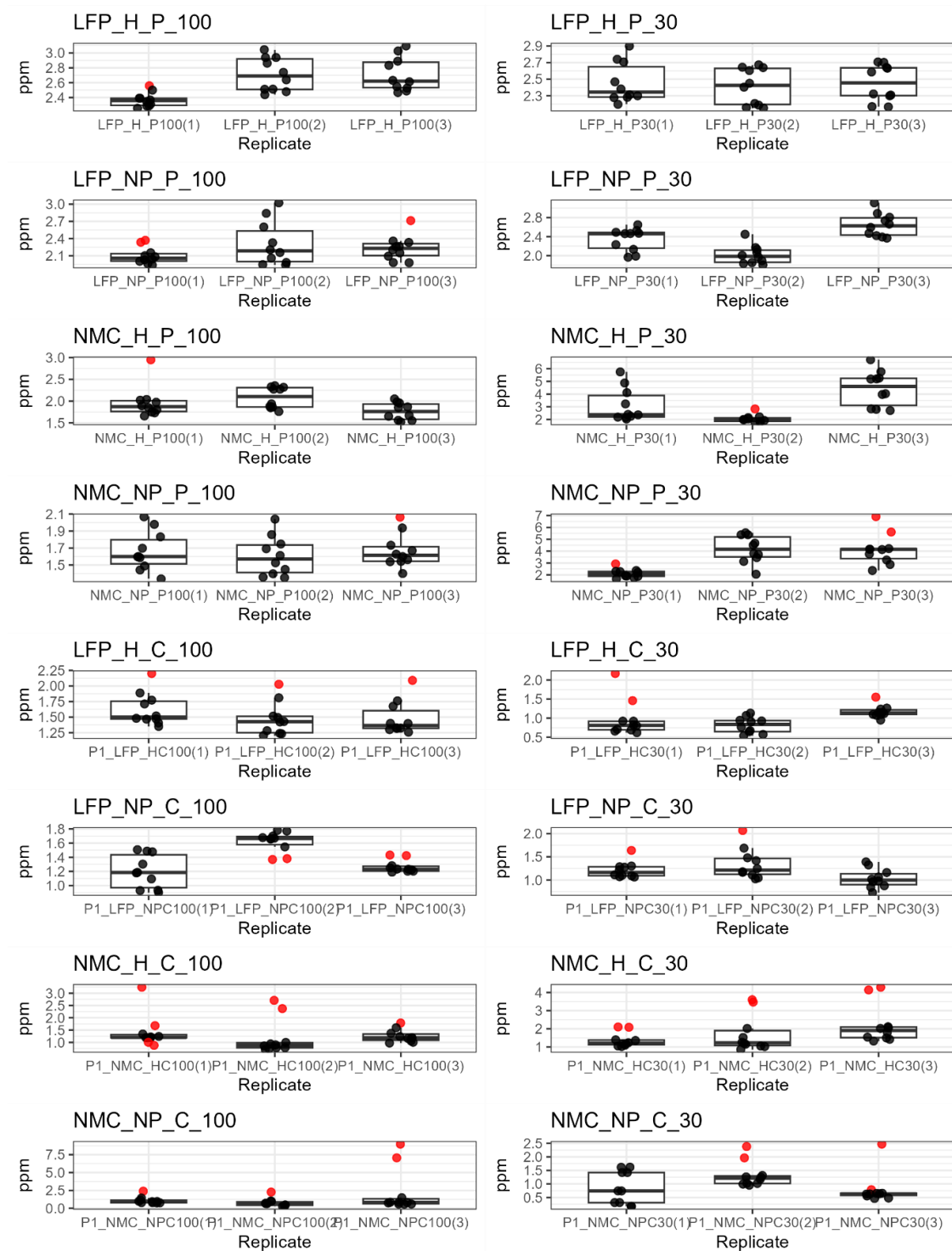


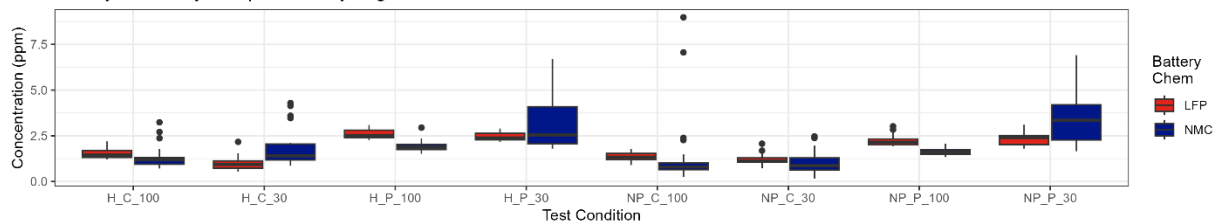
Figure A-31. A boxplot with the top 10 highest peaks of hydrogen chloride per test condition. Each plot is a test condition. Y-axis represents hydrogen chloride ppm and the X-axis is the three test replicates for each test condition. Red dots indicate any potential outliers within that test replicate.

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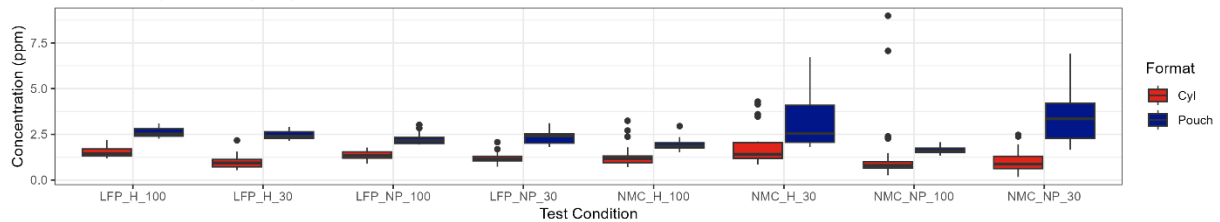
Table A-17. Highest 30 peaks of hydrogen chloride per test condition. Mean, Min, Q1, Median, Q3, and Max all in ppm.

Test Scenario	Chem	Abuse	Format	SoC (%)	Mean	sd	Min	Q1	Median	Q3	Max	n
1	LFP	H	C	100	1.53	0.27	1.20	1.32	1.45	1.70	2.20	30
2	LFP	H	C	30	0.99	0.34	0.54	0.73	0.94	1.13	2.17	30
3	LFP	H	P	100	2.60	0.25	2.26	2.40	2.52	2.81	3.09	30
4	LFP	H	P	30	2.44	0.22	2.15	2.28	2.39	2.64	2.90	30
5	LFP	NP	C	100	1.36	0.25	0.90	1.20	1.34	1.54	1.78	30
6	LFP	NP	C	30	1.20	0.27	0.73	1.06	1.14	1.30	2.07	30
7	LFP	NP	P	100	2.21	0.27	1.94	2.01	2.15	2.33	3.02	30
8	LFP	NP	P	30	2.33	0.34	1.80	2.02	2.41	2.52	3.11	30
9	NMC	H	C	100	1.28	0.58	0.71	0.95	1.19	1.32	3.24	30
10	NMC	H	C	30	1.77	0.93	0.86	1.18	1.41	2.05	4.29	30
11	NMC	H	P	100	1.94	0.30	1.52	1.75	1.88	2.04	2.95	30
12	NMC	H	P	30	3.21	1.47	1.80	2.07	2.55	4.09	6.71	30
13	NMC	NP	C	100	1.37	1.89	0.26	0.65	0.80	1.01	8.98	30
14	NMC	NP	C	30	0.99	0.60	0.17	0.63	0.87	1.30	2.47	30
15	NMC	NP	P	100	1.65	0.22	1.34	1.50	1.60	1.75	2.07	30
16	NMC	NP	P	30	3.47	1.39	1.66	2.28	3.35	4.20	6.91	30

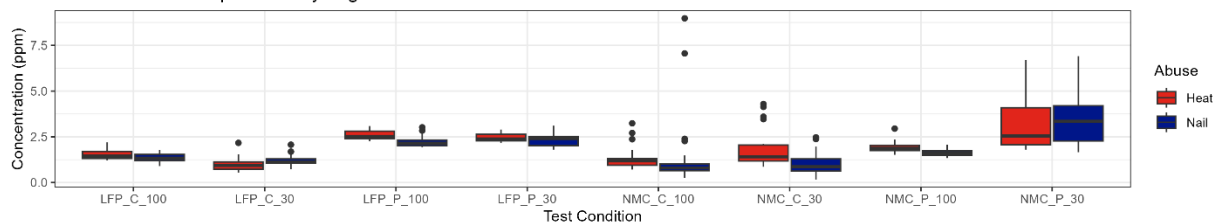
A Battery Chemistry Comparison - Hydrogen chloride



B Format Comparison - Hydrogen chloride



C Abuse Method Comparison - Hydrogen chloride



D Battery SoC Comparison - Hydrogen chloride

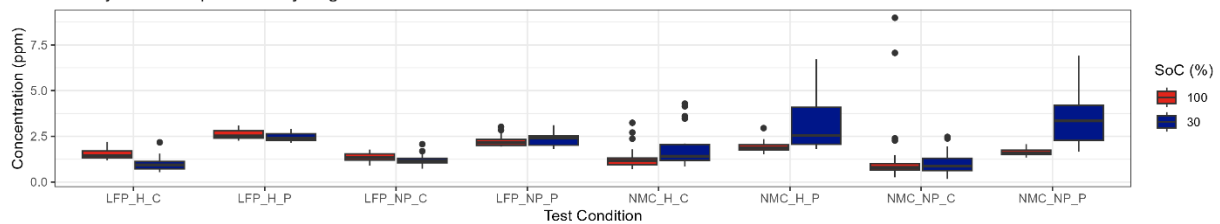


Figure A-32. Boxplot with all test conditions broken up into test scenarios. Y-axis represents hydrogen chloride ppm and the X-axis is the test scenario. (a) battery chemistry, (b) cell format (c) abuse type, and (d) battery state of charge.

A.3.17 Hydrogen fluoride

Top 10 Peak Distribution per Replicate Compound: Hydrogen fluoride

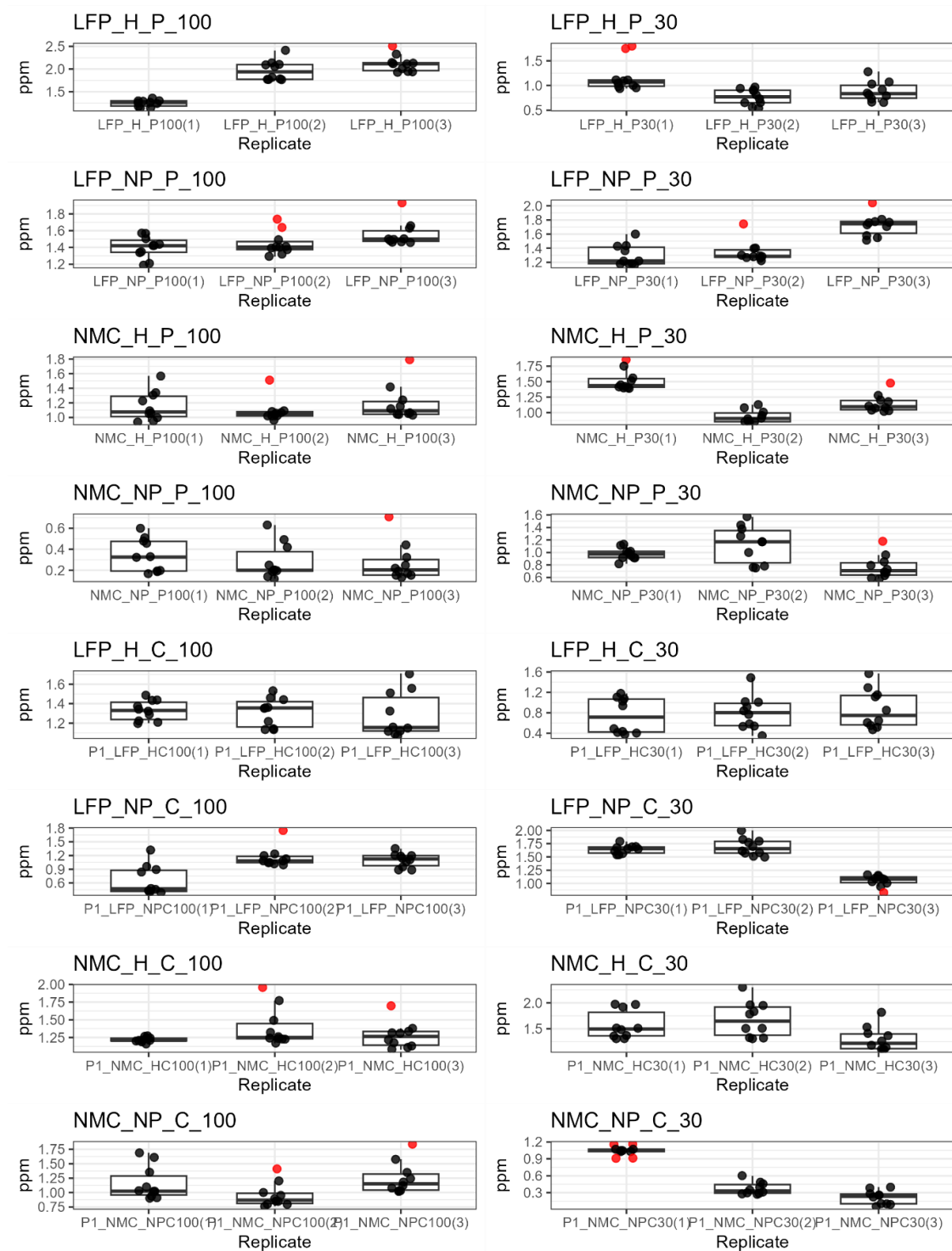


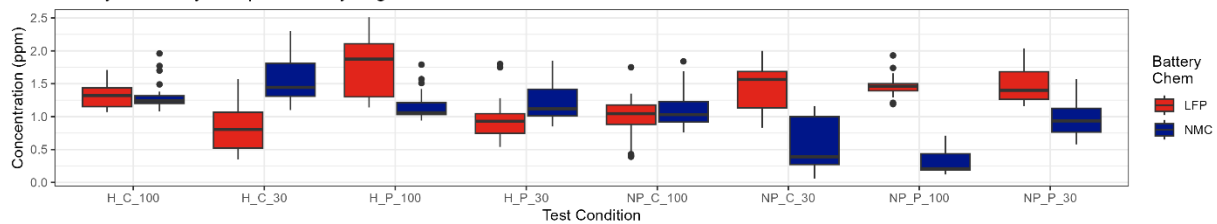
Figure A-33. A boxplot with the top 10 highest peaks of hydrogen fluoride per test condition. Each plot is a test condition. Y-axis represents hydrogen fluoride ppm and the X-axis is the three test replicates for each test condition. Red dots indicate any potential outliers within that test replicate.

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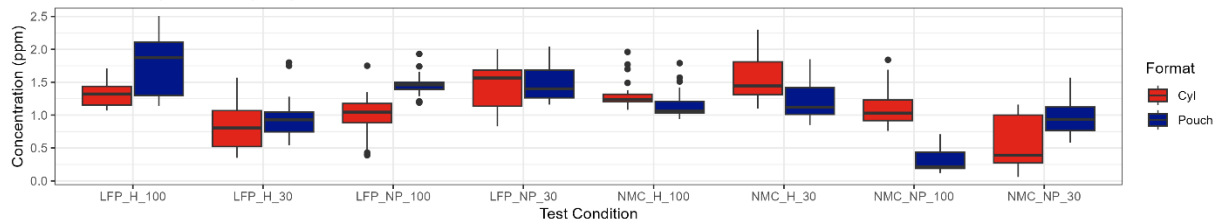
Table A-18. Highest 30 peaks of hydrogen fluoride per test condition. Mean, Min, Q1, Median, Q3, and Max all in ppm.

Test Scenario	Chem	Abuse	Format	SoC (%)	Mean	sd	Min	Q1	Median	Q3	Max	n
1	LFP	H	C	100	1.31	0.16	1.07	1.15	1.32	1.44	1.71	30
2	LFP	H	C	30	0.81	0.34	0.35	0.52	0.81	1.07	1.57	30
3	LFP	H	P	100	1.78	0.42	1.14	1.30	1.88	2.11	2.51	30
4	LFP	H	P	30	0.94	0.29	0.54	0.75	0.93	1.05	1.80	30
5	LFP	NP	C	100	0.97	0.33	0.39	0.88	1.05	1.18	1.75	30
6	LFP	NP	C	30	1.46	0.32	0.83	1.14	1.57	1.69	2.00	30
7	LFP	NP	P	100	1.47	0.15	1.19	1.39	1.46	1.50	1.93	30
8	LFP	NP	P	30	1.46	0.24	1.16	1.26	1.40	1.68	2.04	30
9	NMC	H	C	100	1.30	0.20	1.08	1.20	1.24	1.32	1.96	30
10	NMC	H	C	30	1.52	0.32	1.10	1.31	1.45	1.81	2.30	30
11	NMC	H	P	100	1.15	0.20	0.94	1.03	1.06	1.21	1.79	30
12	NMC	H	P	30	1.20	0.28	0.85	1.01	1.12	1.42	1.85	30
13	NMC	NP	C	100	1.12	0.28	0.76	0.92	1.03	1.23	1.84	30
14	NMC	NP	C	30	0.55	0.38	0.06	0.27	0.39	1.00	1.16	30
15	NMC	NP	P	100	0.30	0.17	0.12	0.19	0.21	0.44	0.71	30
16	NMC	NP	P	30	0.96	0.25	0.58	0.77	0.94	1.13	1.57	30

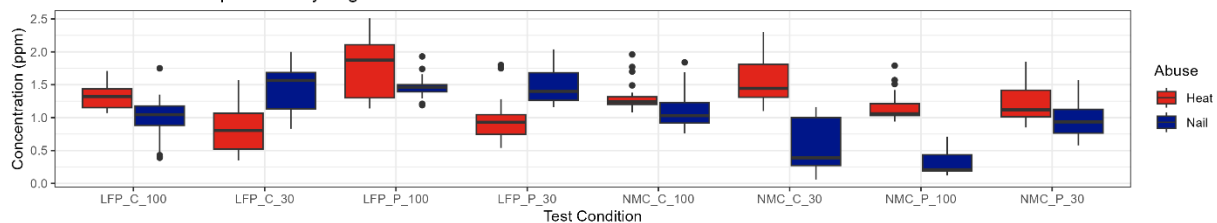
A Battery Chemistry Comparison - Hydrogen fluoride



B Format Comparison - Hydrogen fluoride



C Abuse Method Comparison - Hydrogen fluoride



D Battery SoC Comparison - Hydrogen fluoride

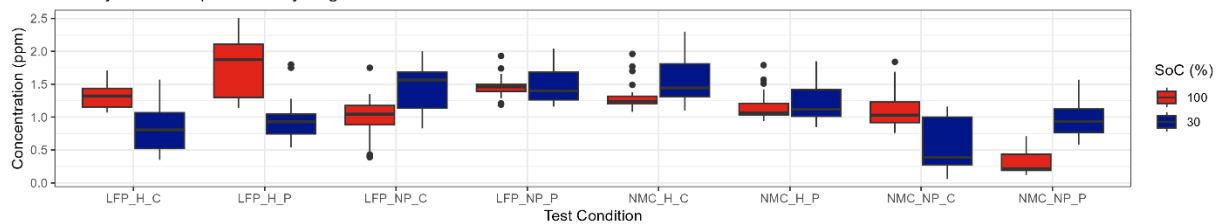


Figure A-34. Boxplot with all test conditions broken up into test scenarios. Y-axis represents hydrogen fluoride ppm and the X-axis is the test scenario. (a) battery chemistry, (b) cell format (c) abuse type, and (d) battery state of charge.

A.3.18 Methane

Top 10 Peak Distribution per Replicate Compound: Methane

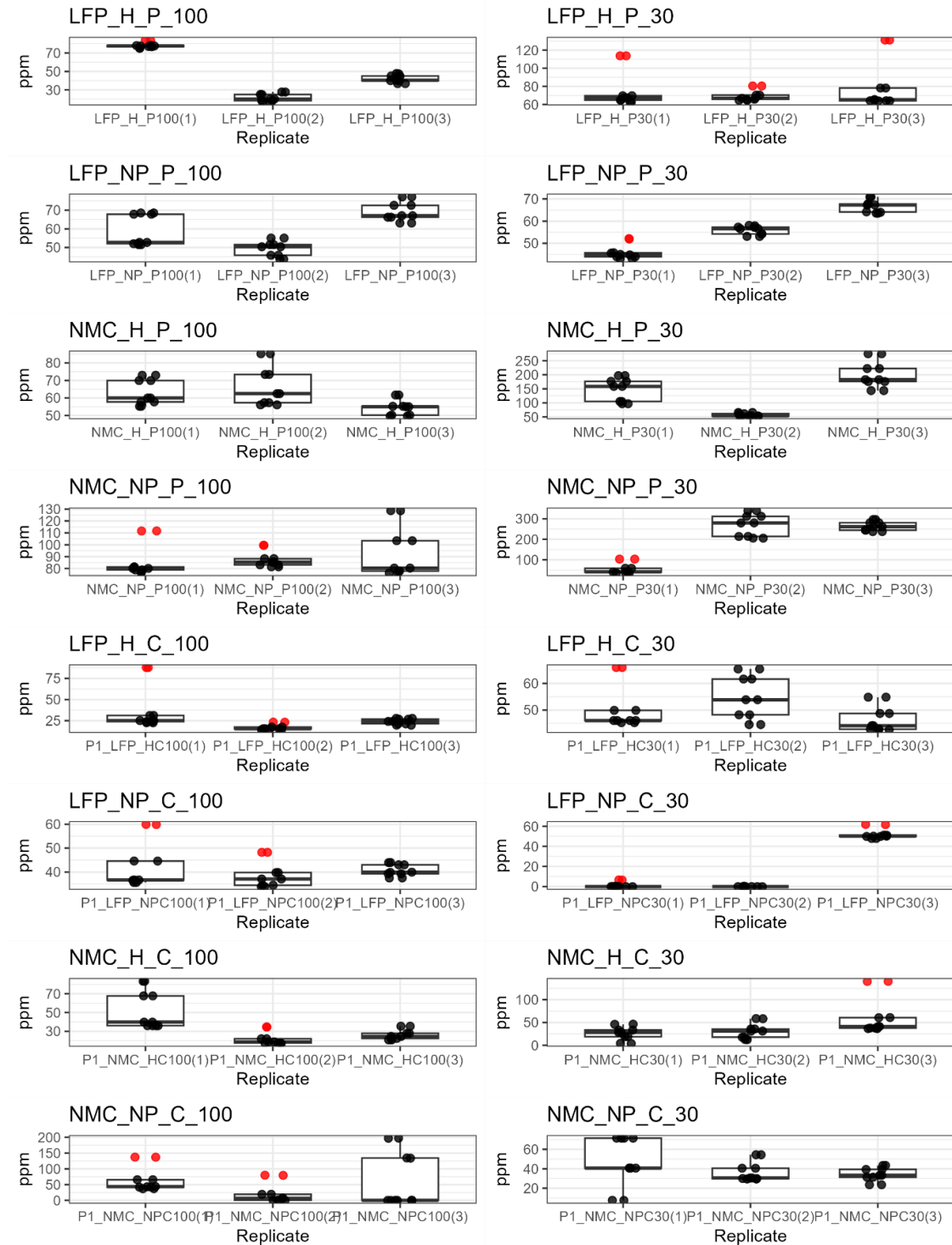


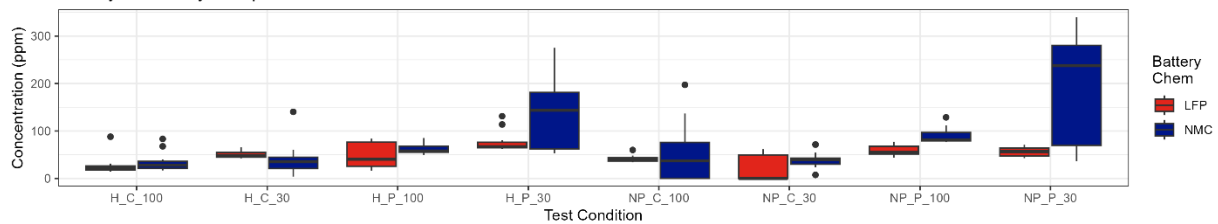
Figure A-35. A boxplot with the top 10 highest peaks of methane per test condition. Each plot is a test condition. Y-axis represents methane ppm and the X-axis is the three test replicates for each test condition. Red dots indicate any potential outliers within that test replicate.

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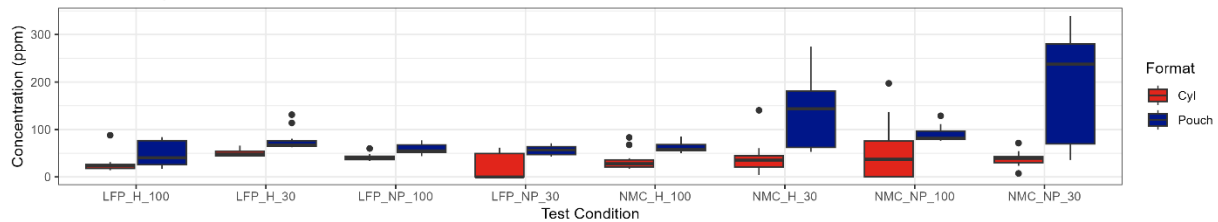
Table A-19. Highest 30 peaks of methane per test condition. Mean, Min, Q1, Median, Q3, and Max all in ppm.

Test Scenario	Chem	Abuse	Format	SoC (%)	Mean	sd	Min	Q1	Median	Q3	Max	n
1	LFP	H	C	100	26.39	17.42	14.18	17.97	23.23	26.30	87.97	30
2	LFP	H	C	30	50.66	7.82	42.59	44.73	48.21	54.58	65.94	30
3	LFP	H	P	100	47.32	24.16	16.75	25.72	40.45	76.52	83.93	30
4	LFP	H	P	30	75.29	19.76	62.47	64.68	66.95	76.27	131.21	30
5	LFP	NP	C	100	40.70	6.58	33.90	36.59	39.32	43.73	59.91	30
6	LFP	NP	C	30	17.83	24.92	0.00	0.00	0.00	49.37	61.74	30
7	LFP	NP	P	100	59.03	10.21	43.76	51.51	55.06	67.66	77.14	30
8	LFP	NP	P	30	56.16	9.07	42.86	47.28	56.60	63.99	70.94	30
9	NMC	H	C	100	33.57	18.54	16.95	21.12	27.85	35.97	83.30	30
10	NMC	H	C	30	40.12	31.28	3.97	20.99	35.40	44.75	140.46	30
11	NMC	H	P	100	61.49	9.68	49.70	55.27	57.78	68.06	85.22	30
12	NMC	H	P	30	134.68	69.52	52.94	62.24	143.74	181.28	274.99	30
13	NMC	NP	C	100	50.80	60.41	0.00	0.22	37.10	75.89	197.19	30
14	NMC	NP	C	30	39.18	16.50	7.47	30.07	39.35	42.78	71.48	30
15	NMC	NP	P	100	88.91	14.99	76.35	79.25	81.46	96.77	128.73	30
16	NMC	NP	P	30	196.70	107.79	36.11	69.74	237.75	280.27	339.55	30

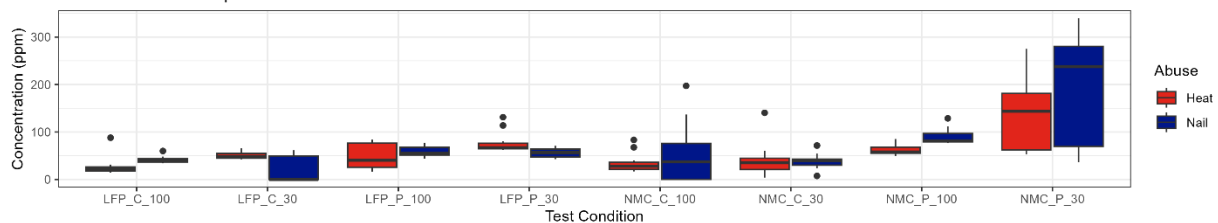
A Battery Chemistry Comparison - Methane



B Format Comparison - Methane



C Abuse Method Comparison - Methane



D Battery SoC Comparison - Methane

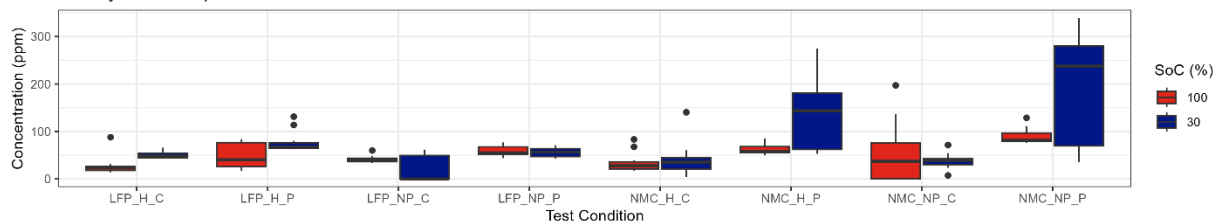


Figure A-36. Boxplot with all test conditions broken up into test scenarios. Y-axis represents methane ppm and the X-axis is the test scenario. (a) battery chemistry, (b) cell format (c) abuse type, and (d) battery state of charge.

A.3.19 Propylene carbonate

Top 10 Peak Distribution per Replicate Compound: Propylene carbonate

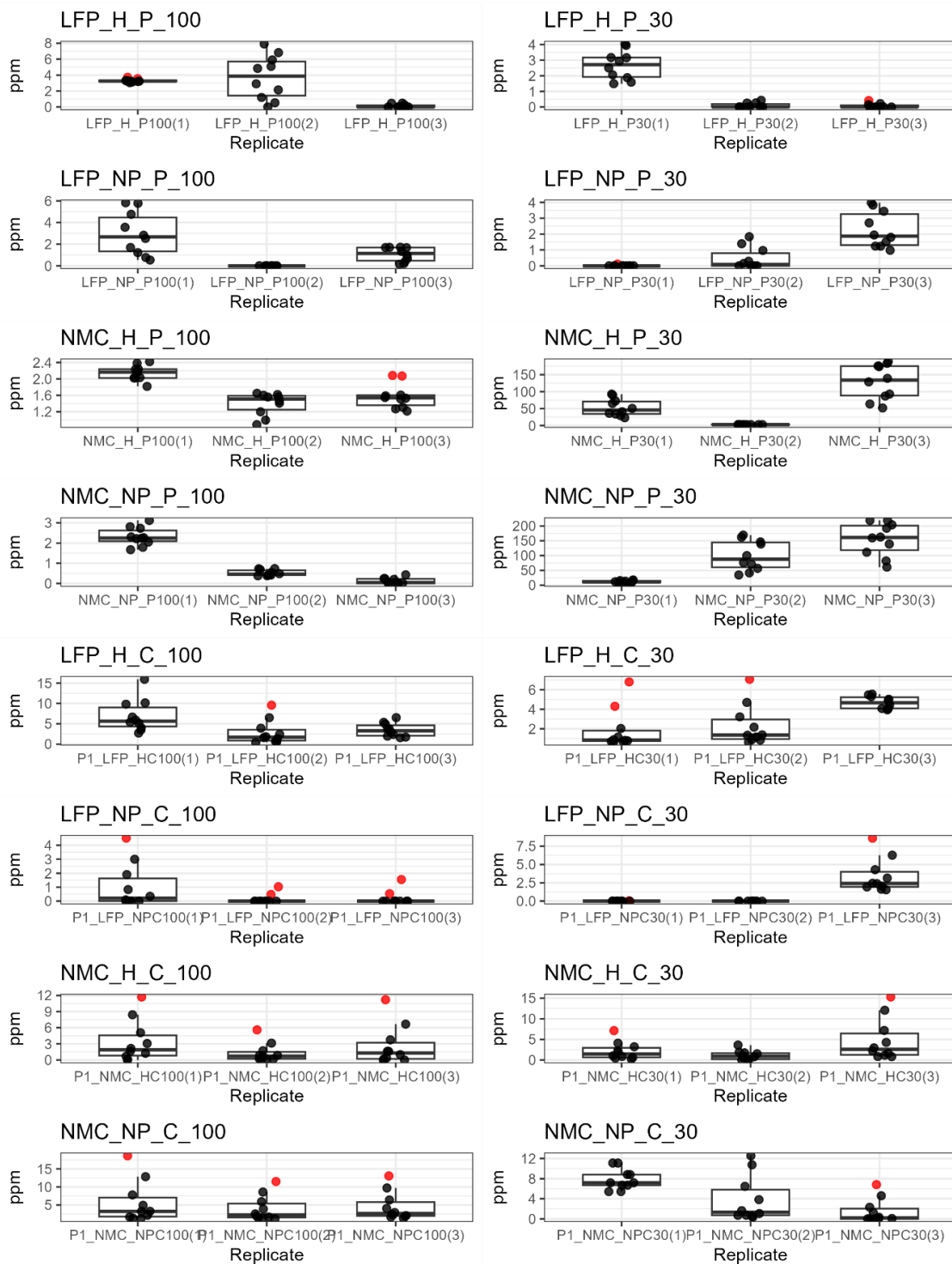


Figure A-37. A boxplot with the top 10 highest peaks of propylene carbonate per test condition. Each plot is a test condition. Y-axis represents propylene carbonate ppm and the X-axis is the three test replicates for each test condition. Red dots indicate any potential outliers within that test replicate.

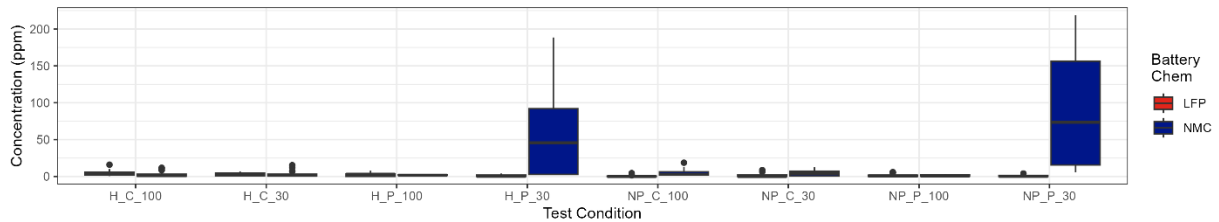
Quantification and comparison of lithium-ion battery fire hazards for emergency responders:

Recommendations for risk management and response

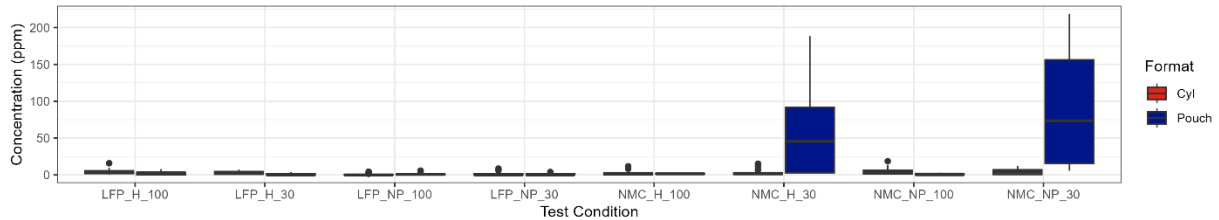
Table A-20. Highest 30 peaks of propylene carbonate per test condition. Mean, Min, Q1, Median, Q3, and Max all in ppm.

Test Scenario	Chem	Abuse	Format	SoC (%)	Mean	sd	Min	Q1	Median	Q3	Max	n
1	LFP	H	C	100	4.43	3.45	0.44	1.86	3.72	5.76	15.94	30
2	LFP	H	C	30	2.96	2.10	0.60	0.87	2.69	4.64	7.08	30
3	LFP	H	P	100	2.39	2.25	0.00	0.07	2.98	3.32	7.91	30
4	LFP	H	P	30	0.95	1.35	0.00	0.00	0.18	1.81	4.04	30
5	LFP	NP	C	100	0.48	1.03	0.00	0.00	0.00	0.45	4.51	30
6	LFP	NP	C	30	1.14	2.09	0.00	0.00	0.00	1.86	8.61	30
7	LFP	NP	P	100	1.33	1.70	0.00	0.00	0.72	1.71	5.82	30
8	LFP	NP	P	30	0.91	1.24	0.00	0.00	0.13	1.47	3.97	30
9	NMC	H	C	100	2.47	3.26	0.00	0.23	1.13	3.13	11.72	30
10	NMC	H	C	30	2.72	3.52	0.00	0.79	1.56	3.15	15.28	30
11	NMC	H	P	100	1.71	0.41	0.89	1.47	1.61	2.06	2.42	30
12	NMC	H	P	30	61.45	61.54	2.51	2.82	45.65	91.85	188.48	30
13	NMC	NP	C	100	4.76	4.45	1.16	1.67	2.73	6.27	18.64	30
14	NMC	NP	C	30	4.41	4.06	0.00	0.58	4.21	7.09	12.55	30
15	NMC	NP	P	100	0.99	1.01	0.00	0.24	0.46	1.99	3.12	30
16	NMC	NP	P	30	88.70	73.33	5.69	15.63	73.51	156.29	218.62	30

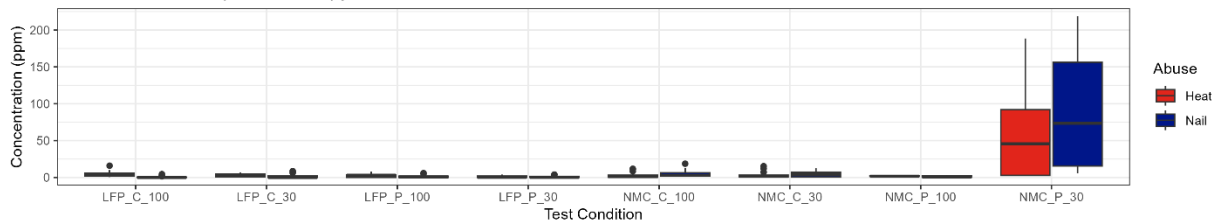
A Battery Chemistry Comparison - Propylene carbonate



B Format Comparison - Propylene carbonate



C Abuse Method Comparison - Propylene carbonate



D Battery SoC Comparison - Propylene carbonate

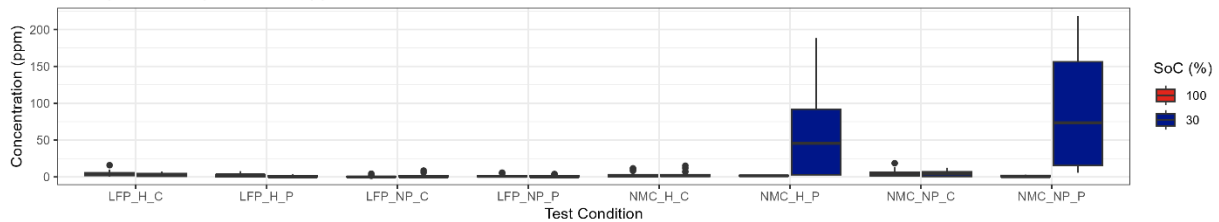


Figure A-38. Boxplot with all test conditions broken up into test scenarios. Y-axis represents propylene carbonate ppm and the X-axis is the test scenario. (a) battery chemistry, (b) cell format (c) abuse type, and (d) battery state of charge.

A.3.20 Styrene

Top 10 Peak Distribution per Replicate Compound: Styrene

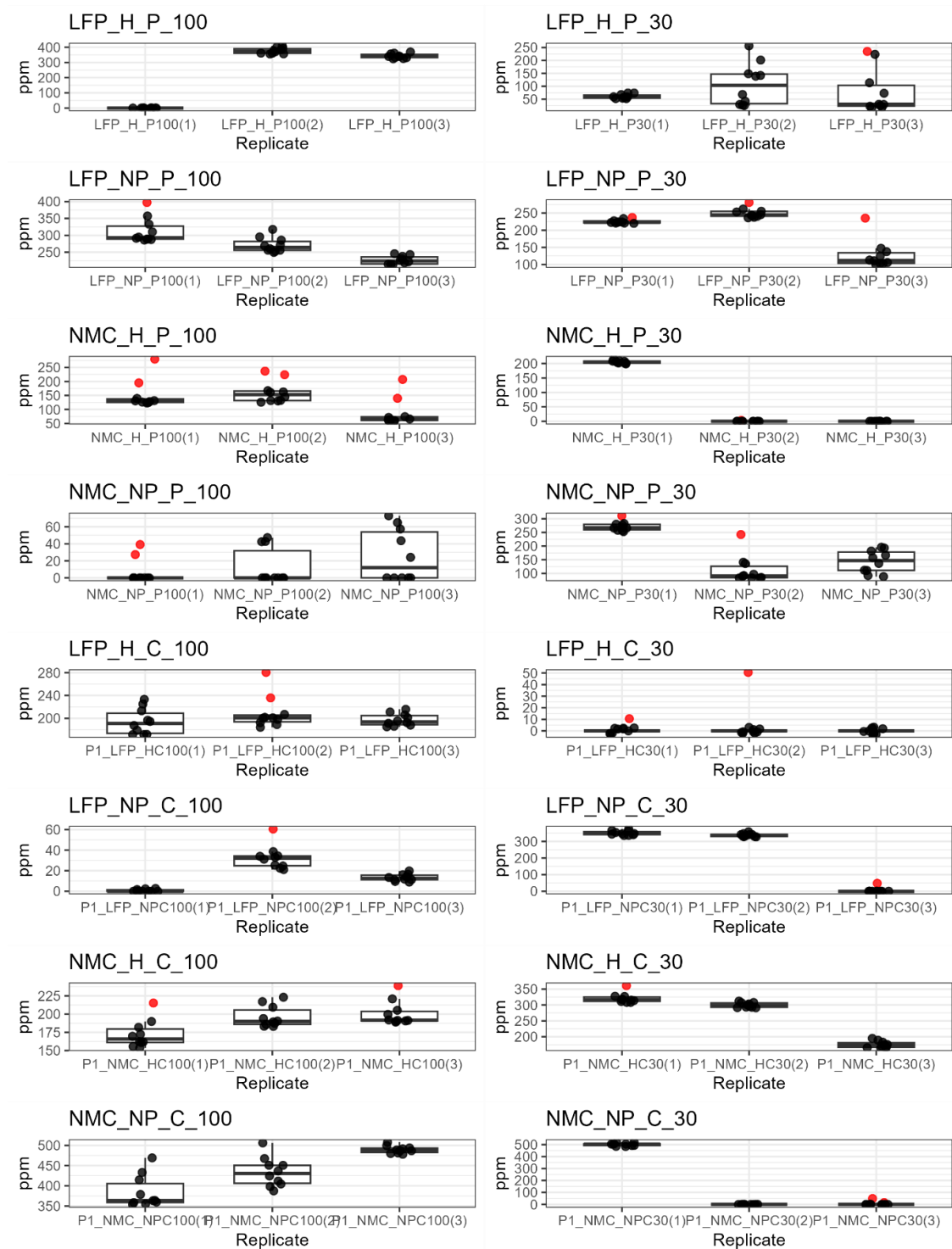


Figure A-39. A boxplot with the top 10 highest peaks of styrene per test condition. Each plot is a test condition. Y-axis represents styrene ppm and the X-axis is the three test replicates for each test condition. Red dots indicate any potential outliers within that test replicate.

Quantification and comparison of lithium-ion battery fire hazards for emergency responders:
Recommendations for risk management and response

Table A-21. Highest 30 peaks of styrene per test condition. Mean, Min, Q1, Median, Q3, and Max all in ppm.

Test Scenario	Chem	Abuse	Format	SoC (%)	Mean	sd	Min	Q1	Median	Q3	Max	n
1	LFP	H	C	100	200.21	22.20	171.50	187.60	196.04	206.69	280.40	30
2	LFP	H	C	30	1.95	9.17	0.00	0.00	0.00	0.00	49.77	30
3	LFP	H	P	100	239.69	173.53	0.00	0.00	339.63	361.31	409.12	30
4	LFP	H	P	30	82.61	68.61	15.86	30.00	58.90	103.75	256.28	30
5	LFP	NP	C	100	15.47	14.91	0.00	1.76	12.56	24.01	60.55	30
6	LFP	NP	C	30	231.33	163.50	0.00	0.00	334.91	346.21	375.03	30
7	LFP	NP	P	100	270.46	44.09	213.08	239.14	264.62	290.82	397.22	30
8	LFP	NP	P	30	200.86	58.79	99.35	139.72	224.00	239.85	280.71	30
9	NMC	H	C	100	189.83	20.60	153.78	182.18	189.95	198.19	238.86	30
10	NMC	H	C	30	265.17	66.14	165.20	184.40	297.95	311.92	360.67	30
11	NMC	H	P	100	132.76	55.96	57.68	86.61	130.62	157.00	279.47	30
12	NMC	H	P	30	68.60	98.46	0.00	0.00	0.00	201.48	215.16	30
13	NMC	NP	C	100	436.05	53.07	353.72	390.14	443.68	485.36	507.68	30
14	NMC	NP	C	30	169.15	238.93	0.00	0.00	0.00	490.64	518.85	30
15	NMC	NP	P	100	15.39	23.73	0.00	0.00	0.00	36.24	72.80	30
16	NMC	NP	P	30	176.18	79.14	83.39	93.33	161.96	257.36	310.80	30

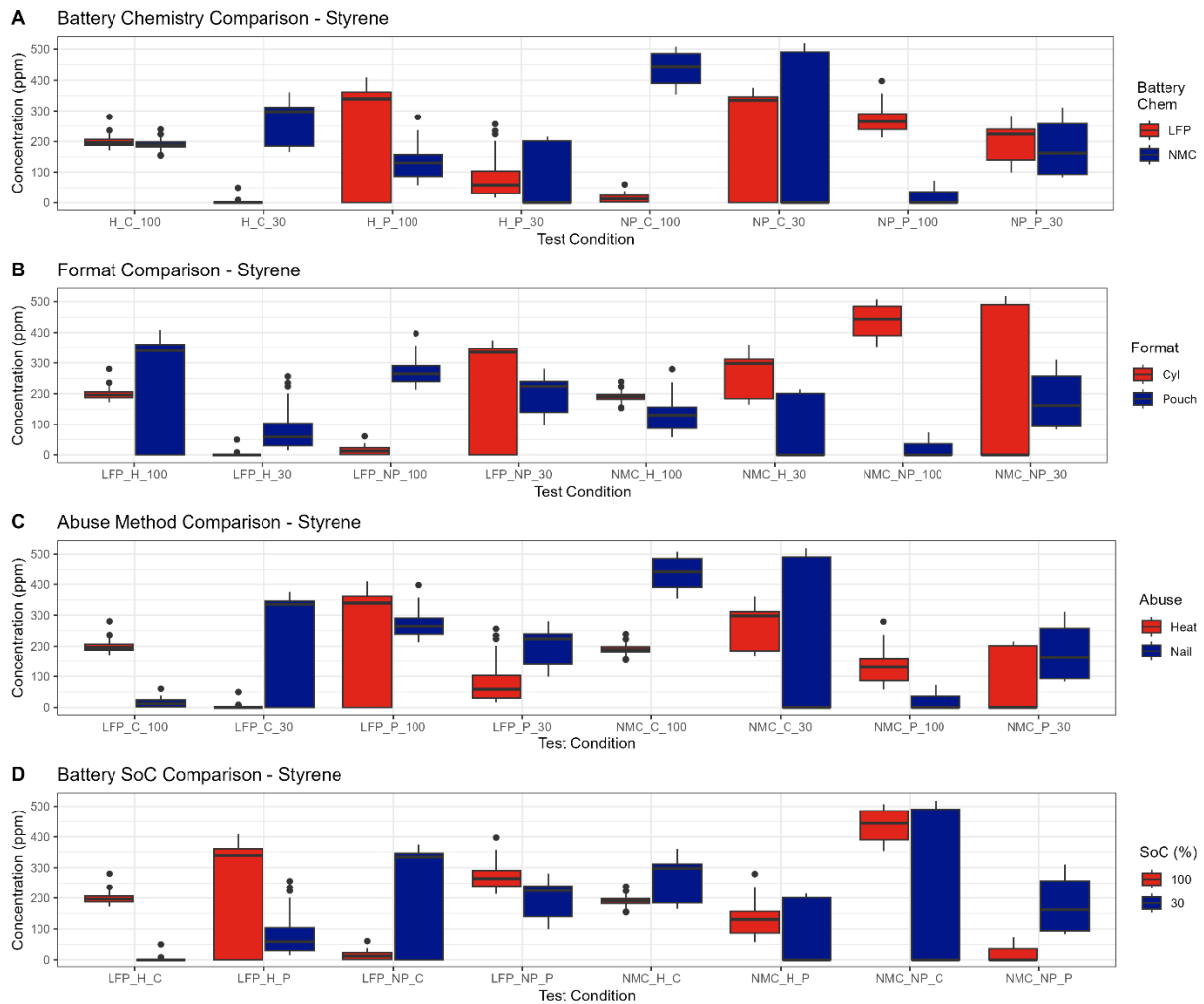


Figure A-40. Boxplot with all test conditions broken up into test scenarios. Y-axis represents styrene ppm and the X-axis is the test scenario. (a) battery chemistry, (b) cell format (c) abuse type, and (d) battery state of charge.

A.3.21 Toluene

Top 10 Peak Distribution per Replicate Compound: Toluene

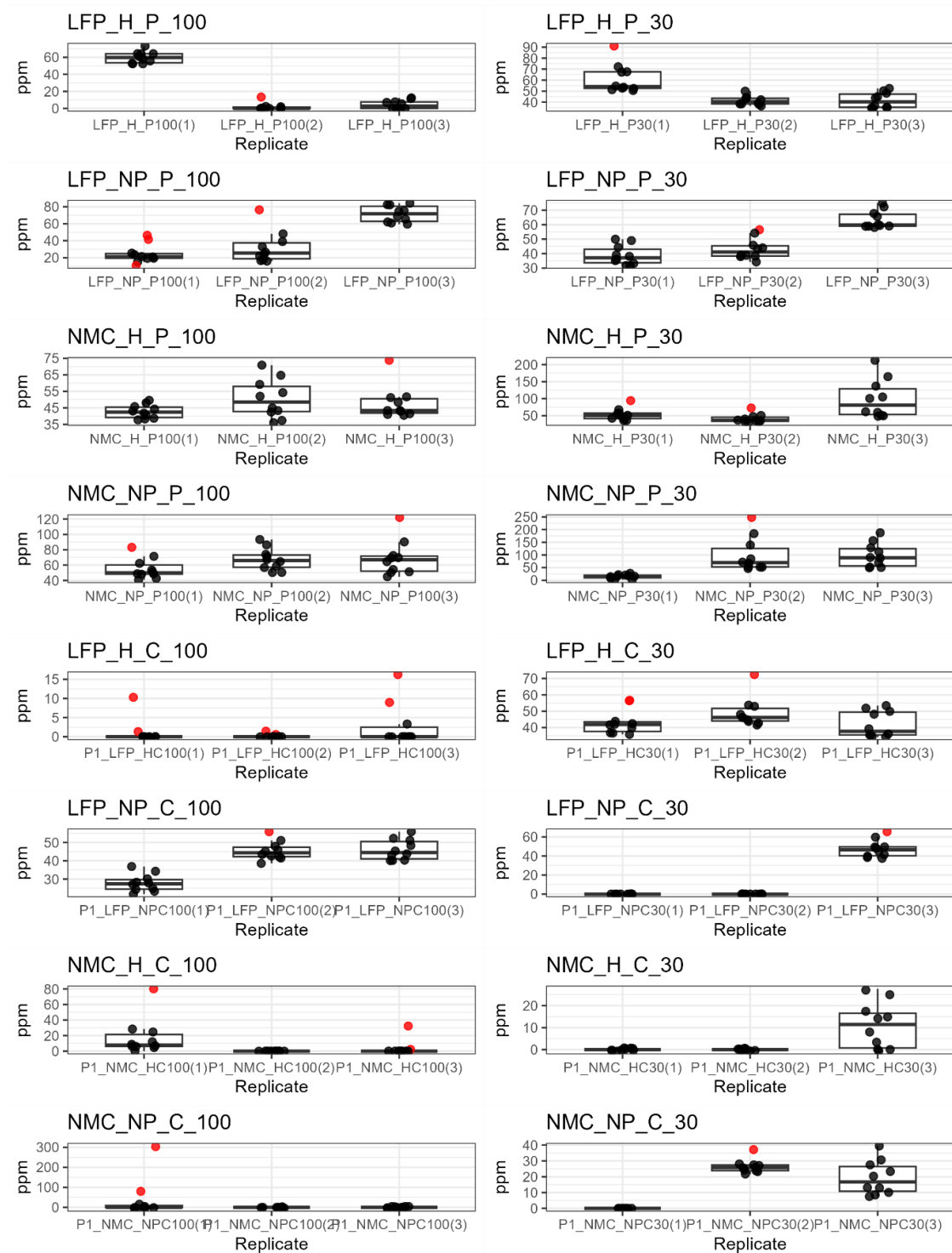


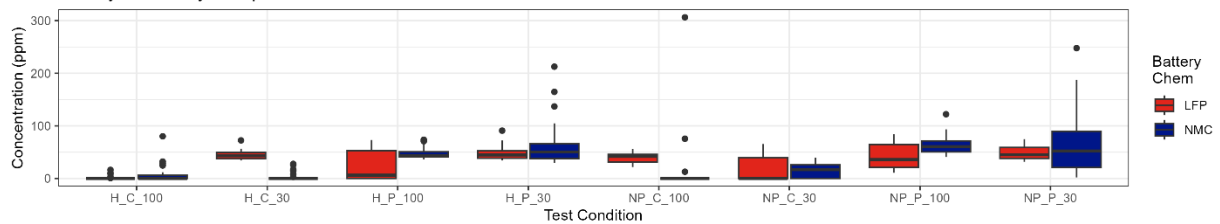
Figure A-41. A boxplot with the top 10 highest peaks of toluene per test condition. Each plot is a test condition. Y-axis represents toluene ppm and the X-axis is the three test replicates for each test condition. Red dots indicate any potential outliers within that test replicate.

Quantification and comparison of lithium-ion battery fire hazards for emergency responders:
Recommendations for risk management and response

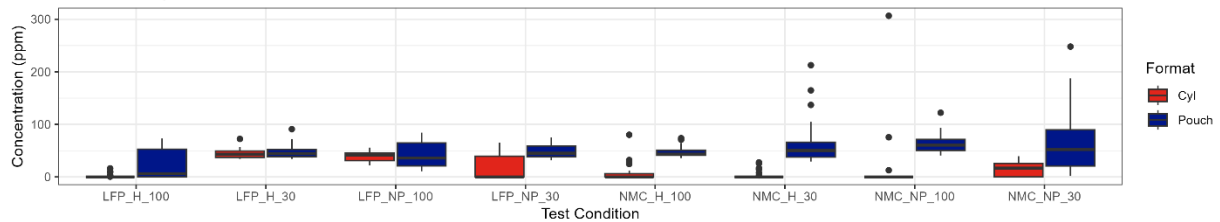
Table A-22. Highest 30 peaks of toluene per test condition. Mean, Min, Q1, Median, Q3, and Max all in ppm.

Test Scenario	Chem	Abuse	Format	SoC (%)	Mean	sd	Min	Q1	Median	Q3	Max	n
1	LFP	H	C	100	1.40	3.74	0.00	0.00	0.00	0.00	16.24	30
2	LFP	H	C	30	44.74	8.57	34.24	37.37	43.20	49.44	72.40	30
3	LFP	H	P	100	22.02	27.75	0.00	0.00	6.30	52.72	73.23	30
4	LFP	H	P	30	48.11	12.82	34.32	38.44	44.69	52.46	90.97	30
5	LFP	NP	C	100	39.81	9.93	21.80	31.18	41.83	45.85	55.93	30
6	LFP	NP	C	30	15.80	23.30	0.00	0.00	0.00	39.47	65.45	30
7	LFP	NP	P	100	42.64	24.88	10.79	21.04	36.00	64.59	84.24	30
8	LFP	NP	P	30	48.51	12.73	31.74	38.14	45.07	58.93	74.87	30
9	NMC	H	C	100	7.07	16.35	0.00	0.00	0.00	6.19	80.20	30
10	NMC	H	C	30	3.70	7.91	0.00	0.00	0.00	0.00	27.65	30
11	NMC	H	P	100	47.02	9.47	36.03	41.14	43.38	50.79	73.78	30
12	NMC	H	P	30	64.53	42.27	29.42	37.75	50.42	66.05	212.67	30
13	NMC	NP	C	100	13.16	57.13	0.00	0.00	0.00	0.00	306.58	30
14	NMC	NP	C	30	15.26	13.06	0.00	0.00	16.75	25.86	39.46	30
15	NMC	NP	P	100	63.77	18.00	40.85	50.41	60.47	71.35	122.18	30
16	NMC	NP	P	30	71.18	61.62	1.96	20.86	52.21	89.67	247.96	30

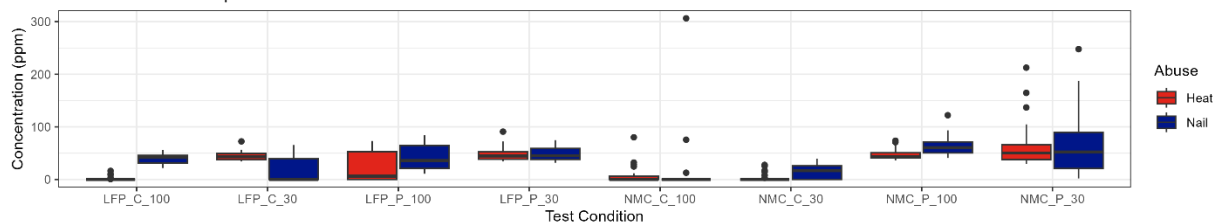
A Battery Chemistry Comparison - Toluene



B Format Comparison - Toluene



C Abuse Method Comparison - Toluene



D Battery SoC Comparison - Toluene

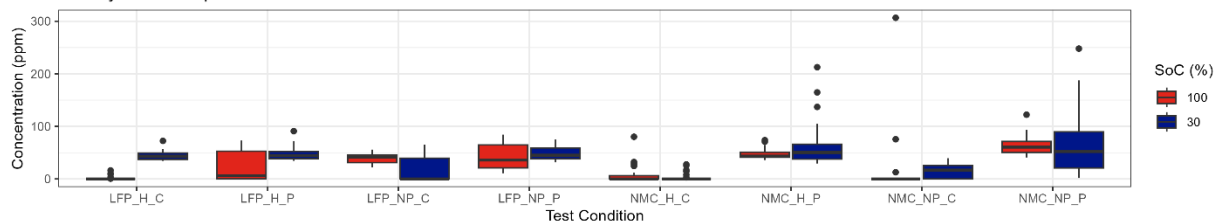


Figure A-42. Boxplot with all test conditions broken up into test scenarios. Y-axis represents toluene ppm and the X-axis is the test scenario. (a) battery chemistry, (b) cell format (c) abuse type, and (d) battery state of charge.

Appendix B Supplementary suppression analysis materials

B.1 Equations used in analysis

B.1.1 Pooled standard deviation

$$s_p = \sqrt{\frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n_1 + n_2 - 2}}$$

Where:

n is the sample size for each group, and

s is the standard deviation of each group.

B.1.2 Cohen's d

$$d = \frac{M_1 - M_2}{S_p}$$

Where:

M is the sample mean for each group, and

S_p is the pooled standard deviation.

B.1.3 Hedges' correction factor (J)

$$J = 1 - \frac{3}{4df - 1}$$

Where:

df is degrees of freedom.

B.1.4 Hedges' g

$$g = J \times d$$

Where:

J is Hedges' correction factor, and

d is Cohen's d .

B.1.5 Coefficient of variation

$$CV = \left(\frac{\sigma}{\mu}\right) \times 100\%$$

B.1.6 Newtonian cooling equation

$$T_t = T_a a + (T_0 - T_a)e^{-kt}$$

Where:

T_t is temperature at a point in time (t),

T_a is the temperature of the surrounding environment,

T_0 is the temperature of the object, and

k is a cooling constant for the object.

B.2 Supplementary analysis results

B.2.1 Analysis of thermal volatility

Table B-23. Thermal volatility of each extinguishment agent.

	Fire Blanket (σ of dT/dt)	LiB Blanket (σ of dT/dt)	Water (σ of dT/dt)	Encapsulating Agent (σ of dT/dt)	Control (σ of dT/dt)
Mean	20.0190	16.1527	26.1724	10.1930	53.8188
Standard Error	7.0696	4.5895	14.7507	4.5858	6.7534
Median	3.7000	9.5000	10.1374	8.5075	46.8000
Standard Deviation	29.1487	16.5478	46.6457	7.9428	39.9539
Sample Variance	849.6456	273.8286	2175.8224	63.0875	1596.3114
Kurtosis	5.6521	2.1180	8.4243	-	5.6770
Skewness	2.2485	1.4876	2.8387	0.9119	2.0302
Range	111.2476	55.9987	153.8935	15.6150	198.7629
Minimum	0.4521	1.6000	1.1000	3.2282	7.2000
Maximum	111.6998	57.5987	154.9935	18.8432	205.9629
Sum	340.3231	209.9850	261.7242	30.5789	1883.6575
Count	17.0000	13.0000	10.0000	3.0000	35.0000
Confidence Level(95.0%)	14.9869	9.9997	33.3683	19.7309	13.7246

B.2.2 Peak temperatures analysis

Table B-24. Summary of peak temperature analysis.

Groups	Count	Sum	Average	Variance
Control	36	38353.3	1065.4	21200.5
Water	36	31007.7	861.3	79831.4
Encapsulating Agent	36	21932.0	609.2	223709.5
Blanket	28	28035.6	1001.3	28900.6
LiB Blanket	32	32967.0	1030.2	29613.7

Table B-25. ANOVA analysis of peak temperatures.

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	4904858.589	4	1226214.647	15.299	1.21E-10	2.42712
Within Groups	13064289.3	163	80149.01414			
Total	17969147.89	167				

Table B-26. Hedges *g* analysis of peak temperatures.

	Control	Water	Encapsulating Agent	Blanket	LiB Blanket
Test Mean	1065.3693	861.3246	609.2217	1001.2725	1030.2184
Test SD	145.6038	282.5445	472.9794	170.0019	172.0862
Test <i>n</i>	36	36	36	28	32
Pooled SD		224.7575	349.9357	156.6964	158.5942
Cohen's <i>d</i> Raw Effect Size		-0.9078	-1.3035	-0.4091	-0.2216
J factor		0.9892	0.9892	0.9879	0.9886
Hedges' <i>g</i>		-0.8981	-1.2895	-0.4041	-0.2191

B.2.3 Analysis of individual segment TR times

Table B-27. Hedges' *g* analysis of battery pack segment TR times.

Case	Analysis	Control	Blanket	LiB Blanket	Encapsulating Agent	Water
Aluminium	Mean TR duration (s)	384.7	189.7	314.3	191.0	116.4
	Standard Deviation (s)	342.9	133.1	161.4	138.2	104.2
	Test number <i>n</i>	12	11	8	6	11
	Pooled Standard Deviation		264.6	286.3	294.6	258.4
	Cohen's <i>d</i> (Raw Effect Size)		-0.7	-0.2	-0.7	-1.0
	J factor		1.0	1.0	1.0	1.0
	Hedges' <i>g</i>		-0.71	-0.24	-0.63	-1.00
Steel	Mean TR duration (s)	154.5	219.3	108.3	136.2	89.1
	Standard Deviation (s)	107.0	133.7	101.4	94.0	228.4
	Test number <i>n</i>	12	12	12	10	12
	Pooled Standard Deviation	107.0	121.1	104.3	101.4	178.3
	Cohen's <i>d</i> (Raw Effect Size)		0.5	-0.4	-0.2	-0.4
	J factor		1.0	1.0	1.0	1.0
	Hedges' <i>g</i>		0.52	-0.43	-0.17	-0.35
Shrink Wrap	Mean TR duration (s)	426.7	276.3	339.4	148.2	170.3
	Standard Deviation (s)	188.9	125.4	285.0	143.9	79.1
	Test number <i>n</i>	12	4	12	5	10
	Pooled Standard Deviation		177.3	241.8	178.0	149.8
	Cohen's <i>d</i> (Raw Effect Size)		-0.8	-0.4	-1.6	-1.7
	J factor		0.9	1.0	0.9	1.0
	Hedges' <i>g</i>		-0.80	-0.35	-1.48	-1.65

B.2.4 Analysis of liquid suppression used

Table B-28. Details of liquid suppression used.

	Encapsulating Agent	Water
Mean	21.50	29.38
Standard Error	3.50	5.96
Median	20.88	33.00
Standard Deviation	10.50	15.77
Sample Variance	110.25	248.81
Kurtosis	-0.78	-1.46
Skewness	0.33	-0.58
Range	32	39
Minimum	7	7
Maximum	39	46
Sum	193.49	205.63
Count	9	7
Confidence Level (95.0%)	8.07	14.59

Quantification and comparison of lithium-ion battery fire hazards for emergency responders:

Recommendations for risk management and response

B.2.5 Effect size of suppression methods

Table B-29. Analysis of effect size of suppression methods tested.

Case	Analysis	Control	Blanket	LiB Blanket	Encapsulating Agent	Water
Aluminium	Mean TR duration (s)	384.7	189.7	314.3	191.0	116.4
	Standard Deviation (s)	342.9	133.1	161.4	138.2	104.2
	Test number <i>n</i>	12	11	8	6	11
	Pooled Standard Deviation		264.6	286.3	294.6	258.4
	Cohen's <i>d</i> (Raw Effect Size)		-0.7	-0.2	-0.7	-1.0
	J factor		1.0	1.0	1.0	1.0
	Hedges' <i>g</i>		-0.71	-0.24	-0.63	-1.00
Steel	Mean TR duration (s)	154.5	219.3	108.3	136.2	89.1
	Standard Deviation (s)	107.0	133.7	101.4	94.0	228.4
	Test number <i>n</i>	12	12	12	10	12
	Pooled Standard Deviation	107.0	121.1	104.3	101.4	178.3
	Cohen's <i>d</i> (Raw Effect Size)		0.5	-0.4	-0.2	-0.4
	J factor		1.0	1.0	1.0	1.0
	Hedges' <i>g</i>		0.52	-0.43	-0.17	-0.35
Shrink Wrap	Mean TR duration (s)	426.7	276.3	339.4	148.2	170.3
	Standard Deviation (s)	188.9	125.4	285.0	143.9	79.1
	Test number <i>n</i>	12	4	12	5	10
	Pooled Standard Deviation		177.3	241.8	178.0	149.8
	Cohen's <i>d</i> (Raw Effect Size)		-0.8	-0.4	-1.6	-1.7
	J factor		0.9	1.0	0.9	1.0
	Hedges' <i>g</i>		-0.80	-0.35	-1.48	-1.65

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