FIRE + RESCUE

Management of lithium-ion battery safety risks: A literature review of current knowledge and best practices

SARET Research Program

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Contents

1 Introduction

Fire and Rescue New South Wales (FRNSW) conducts research that informs the development of doctrine and training to prepare our firefighters for new and emerging risks in the community. It also provides an evidence-base from which we can minimise the potential consequences of fires and other emergencies by ensuring that fire safety measures are commensurate with identified risks. This is achieved by offering technical advice, assessment, and consultancy services to the building and fire safety industries, and providing guidance to regulatory authorities and government agencies.

FRNSW is highly supportive of the Australian Government's commitment to achieving net zero emissions by 2050, and supporting the safe integration of renewable and low emission technologies, including clean hydrogen, carbon capture, energy storage, and solar power (Australian Government Department of Industry, Science, Energy, and Resources, 2021). Batteries have an essential role in the energy transition (Accenture, 2021).

Lithium-ion batteries (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 electric scooters (e-scooters), electric bikes (e-bikes), electric vehicles (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 (Ghafari et al. 2023; Miao et al. 2019; Li et al. 2017). Over the past decade, LiBs have proliferated – with the global battery market forecast to grow to US$133 - 151 billion by 2030 (Accenture, 2021). 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). These estimates are largely based on the projected rise in demand for LiBs for use in EVs and BESS.

The rapid uptake of new technologies is often associated with new risks and challenges to public safety. The growth in LiB technology use has seen a comparable increase in reported LiB-related fires and casualties. 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, 2024a). Tragically, FRNSW also recorded the first deaths in a fire caused by a LiB, with 2 in 2024 and 1 in 2025.

For emergency responders, LiB-related fires pose several challenges related to the intensity of thermal runaway (TR) events, exposure to toxic gases, explosion risk in confined environments, stranded electrical energy risks from high-voltage systems, difficult and protracted extinguishment and cooling, risks of reignitions, and containment of potentially contaminated firewater.

Several industry and government stakeholders have contacted FRNSW to assist in acquiring test data and making specific recommendations. While there is an expansive body of research and literature to draw upon, knowledge gaps have been identified that limit FRNSWs ability to apply research outcomes to emergency response procedures and fire safety advice.

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. 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.

The SARET program, is divided into four project themes, each addressing a specific aspect of LiB safety and fire and emergency service response. These include:

Project 1: **Fire service response to LiB fires**

Project 1 focusses on safe and effective fire service response to LiB-related incidents. This includes assessing the efficacy of various extinguishing agents, delivery systems and methods, specialty tools and equipment, an assessment of personal protective clothing (PPC) and equipment (PPE) requirements for emergency responders to protect from hazards associated with LiB fires and incidents, and providing best practice recommendations on operational response and procedures.

Project 2: **End-of-life LiB hazard management**

Project 2 aims to assess solutions to mitigate LiB-related fire and explosion risk in battery waste collection, handling, storage, and transportation, including handling of damaged LiBs and battery systems from all applications.

Project 3: **Electric vehicle fires in structures**

Project 3 aims to characterise EV fire behaviour in parking garages, including assessing building systems responses and fire service intervention procedures and tactics to minimise risk to occupants, property, and emergency responders.

Project 4: **Fire propagation in stationary energy storage systems**

Project 4 aims to characterise fires involving BESS in buildings, including assessing fire propagation under different scenarios, and assessing building systems responses and fire service intervention procedures and tactics to minimise risk to occupants, property, the environment, and emergency responders.

This review examines a wide range of available literature to inform the development of the SARET program and highlight key areas in which this research will assist within the Australian context.

The review describes the main componentry, forms, designs, and functions of LiB cells. After examining the LiB cells, the associated risks and hazards are discussed, highlighting the limits of current knowledge and the areas in which current emergency response practices can be improved. The current fire test standards for LiBs, as well as different experimental test methods used by other researchers, are also discussed for both individual cell and pack level testing. Finally, the review explains how the SARET program aims to address the gaps in current knowledge.

The SARET program has been developed in conjunction with industry partners, government, other research institutions and fire agencies to ensure that the projects provide positive information to assist in the safe integration of LiBs.

2 Scope and limitations

A review of current literature was conducted with a view to creating a firm foundation for knowledge advancement and facilitating development for the SARET program. Review findings will inform the program's testing scope and define physical LiB testing requirements. Additionally, the identification of any potential environmental LiB hazards will determine required environmental controls for SARET LiB testing.

The review was based primarily on peer-reviewed scientific journal articles, with some grey literature considered where appropriate.

The objectives of this review were to:

(1) build working knowledge of LiBs, their components and chemistries, their potential hazards, and their basic failure mechanics.

(2) examine the risks and hazards of LiB incidents in a range of applications and scenarios.

(3) identify and assess effectiveness of available extinguishment agents, tools, and equipment that may be made available to firefighters during emergency response at LiB-related fires and incidents.

(4) identify LiB contamination and health risk to the community, the environment, and firefighters.

(5) assess the available safety standards and literature on experimental LiB research

(6) determine the gaps in research that can be addressed through research and testing programs

(7) determine the most suitable methods for, and experimental variables and measurement parameters to include in, LiB research and testing.

The following limitations of the review are noted:

(1) The review was limited to literature available to the SARET researchers at the time of writing and, as such, is not a complete review of all available and existing literature on these topics. Additional research papers were requisitioned where necessary and appropriate for the limited resource allocation to the SARET program.

(2) The review was limited to literature relating to LiB and their hazards within an emergency service response context. Research detailing LiB experimentation to characterise or assess LiBs, their hazards, and their failures for product research and development were not included, unless the results presented had a specific relevance to emergency service response to LiB-related fires. Standard test methods to assess the safety or compliance of LiB products were considered but not assessed within this review.

(3) The review does not assess the environmental and human toxicity of LiB-related fires and failures. While the review identifies potential environmental and human health hazards and toxicants, it does not project toxicity effects to impacted receptors.

3 Lithium-ion batteries

A LiB is a type of secondary (i.e. rechargeable) battery that operates by moving lithium ions between a positive (i.e. cathode) and negative (i.e. anode) electrode through a conductive electrolyte.

LiBs have higher energy densities when compared with other secondary battery chemistries such as lead-acid, nickel-cadmium, and nickel-metal hydride. Additionally, the improvements in manufacturing efficiencies and costs in the past two decades have established LiB chemistries as the preferred choice for secondary battery applications where reduced size and weight, increased portability, and high energy capacity are essential (National Academies of Sciences, Engineering, and Medicine, 2020; Nzereogu *et al.*, 2022).

In this section the basic construction, form, function, and components of LiBs are described. The complexity of LiBs is also discussed, with variability in components and differences between original equipment manufacturers (OEMs) and applications highlighted. It is inherently difficult to directly assess and compare LiBs owing to inconsistent disclosure by OEMs of the precise chemical composition of electrodes and electrolytes.

Furthermore, the primary mechanisms of cell failure within a LiB are discussed, an overview of the TR process is provided, and some of the key factors emergency responders are required to consider during a LiB incident are introduced.

3.1 Cell formats

The battery cell format, or form factor, refers to the shape of a battery's packaging or housing. There are three main LiB cell formats available – cylindrical, pouch, and prismatic (see Figure 1).

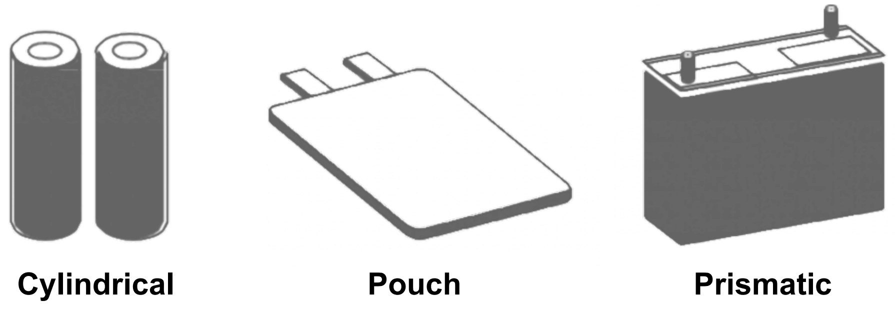


Figure 1. Main LiB form factors (from DJA, 2020).

Cylindrical cells are a popular form factor due to their early development, cost effectiveness, versatility, and resemblance to everyday alkaline batteries. They are used individually in small handheld and portable devices, or multiple cells can be connected in series and parallel into modules or packs that power larger devices such as e-micromobility devices (e.g. e-bikes, e-scooters), EVs and BESS. Cylindrical cells come in standard sizes (e.g. 14650, 18650, 21700, 30700, 38120, and 4680, where the first two digits denote the diameter in mm, and the following digits denote the length in mm or 1/10th mm) (International Electrotechnical Commission, 2017), although these naming conventions can vary between manufacturers.

Cylindrical cells have a rigid metal casing and can be built with overpressure valves and other safety features (Best *et al.*, 2023).

Pouch cells are a flexible form factor that loosely resemble a foil pillow or pouch. Pouch cells have a similar use case as cylindrical cells and can be used individually or in multiples – with their application extending from small handheld and portable devices up to large EV battery packs. Pouch cells can be built in a variety of sizes to suit the application and, due to their design flexibility and energy density, have become one of the most used cell formats (Link *et al.*, 2022).

Prismatic cells are typically rectangular-shaped, with rigid casings. Like cylindrical cells, prismatic LiBs are often built with overpressure valves (Link *et al.*, 2022). Prismatic cells are commonly used in larger devices and BESS and can be built in a variety of sizes to suit the application. Due to their larger size, prismatic cells often have better heat dissipation within the cell (Link *et al.*, 2022). A distinctive example of a prismatic battery is the Blade battery used in some EVs (BYD Australia, 2024).

The smallest form of LiBs are coin cells, which have compact cylindrical shape. Coin cells are used in small electronic devices such as hearing aids and watches, or are utilised in academic environments for experimental purposes (Lewis *et al.*, 2021). Due to their small size, small capacity and proliferation into the market, the risks associated with coin cells are quite low and hence they fall outside of the scope of this literature review.

3.2 Cell construction

All LiBs, regardless of their form factor, contain the same basic components required for an electrochemical cell. These components include the anode, cathode, separator, binders, electrolyte fluid, and cell casings. The materials and chemical combinations that make up LiBs determine their characteristics and performance and often vary between manufacturers. The differences in these components can also have effects on TR and the risks associated with LiB failure.

3.2.1 Anode

The anode is the negative electrode of a battery. It is chemically oxidised during discharge, releasing lithium ions (Li^+) into the electrolyte. Graphite is commonly used as the anode material due to its high negative potential (Ghiji *et al.*, 2020). Some alternative anode materials include lithium-metal, silicon, and lithium-titanate oxide ($Li_4Ti_5O_{12}$). Lithium-titanate oxide is considered the most promising anode material as it has a combination of longer cycle life, fast charge and discharge rates, and greater tolerance to thermal abuse (H. Zhang *et al.*, 2022). The anode material is usually coated on a copper foil current collector.

3.2.2 Cathode

The cathode is the positive electrode of a battery. It is chemically reduced during discharge, absorbing lithium ions from the electrolyte in a process referred to as intercalation. A lithium-ion transition metal oxide is commonly used as a LiB cathode material. The cathode material is usually coated on an aluminium current collector (Ghiji *et al.*, 2020).

The cathode chemistry is the defining parameter for LiB cells' electrical characteristics. Specific cathode composition is often proprietary information and thus are not disclosed to the community. Generic nomenclature is sometimes included on labelling or safety data sheets to denote nominal chemical composition. Some commonly available LiB chemistries are presented in Appendix A.

It is important to note that for each nominal chemistry cathode, variations in the proportion of active materials exist. For example, while ternary nickel manganese cobalt (NMC) cathodes typically combine these components in a 1:1:1 ratio ($LiNi_{0.33}Mn_{0.33}Co_{0.33}O_2$), some commercial variations include NMC_{532} ($LiNi_{0.5}Mn_{0.3}Co_{0.2}O_2$), NMC_{622} ($LiNi_{0.6}Mn_{0.2}Co_{0.2}O_2$), and NMC_{811} ($LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$), which vary in electrochemical performance (Loghavi *et al.*, 2022).

3.2.3 Binders

Chemical binders are used to bind the active electrode materials to the foil current collectors (Kaya, 2022). Binders help preserve the structural integrity of the electrodes and are critical in achieving reliable and consistent cycling performance in the electrode structure (Lee *et al.*, 2023).

Polyvinylidene fluoride (PVDF) is the most widely used binder for both the anode and cathode due to its electrochemical stability and flexibility. Some alternative binder materials are detailed in Appendix A.

3.2.4 Separator

The separator is a thin, porous membrane that acts as a physical barrier between the anode and cathode to electrically isolate the two electrodes, while also allowing for the transfer of ions during charge and discharge (Clean Energy Institute, 2022). Common separator materials are polyethylene (PE) and polypropylene (PP), which have melting points of 130 °C and 170 °C, respectively (Lai *et al.*, 2021).

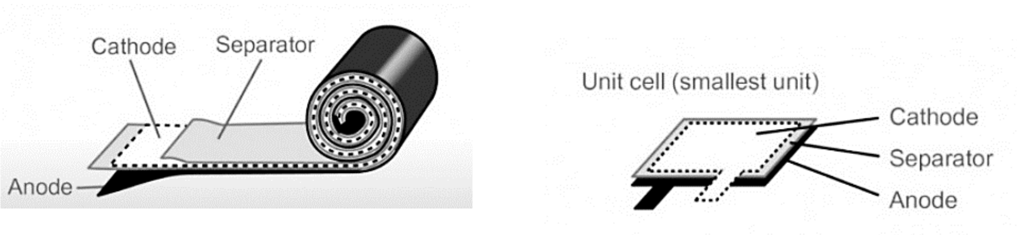
3.2.5 Cell assembly

Battery components (anode, cathode, and separator) can be packed in different ways to accommodate for different form factors and applications. The cell assembly is directly informed by the cell format and the application that the cell will be used for.

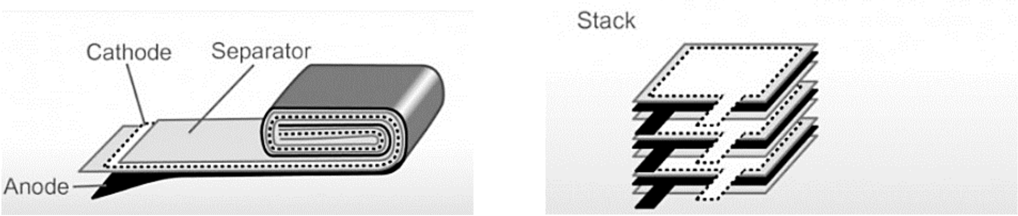
All styles of cell assembly follow the same basic principle of layering the anode and cathode, with the separator in between to prevent them from contacting. Contact between the electrodes will result in a short circuit.

There are two common cell assemblies which are utilised. The first method involves rolling the three layers into a cylindrical or elliptical coil, often referred to as a 'jelly roll', and is found in cylindrical cells formats. The second method involves stacking the three layers on top of each other, which is known as a 'stacked' format, which is often found in pouch cell formats. Prismatic cells can use either the elliptical coil or the stacked format for their cell assembly. Figure 2 visually presents these different cell assemblies.

Once the assembled jelly roll or stack is placed within the outer cell casing, a liquid electrolyte is then injected, before the casing is hermetically sealed.



Cylindrical 'jelly roll'



Elliptical 'jelly roll'

Stacked

Figure 2. LiB electrode arrangements for different LiB formats (from Korthauer, 2018).

3.2.6 Electrolyte

The electrolyte facilitates the movement of lithium ions between the electrodes (i.e. anode and cathode) in a LiB cell.

Liquid electrolytes are commonly used in LiBs, consisting of a lithium salt (Li-salt) and organic solvent mixture, but vary in composition based on OEMs and the materials used in other cell componentry. The Li-salts used in the electrolyte are the source of lithium ions within the battery, as typically no lithium metal is used within these lithium-ion cells. This mixture has high electrical conductivity to facilitate the rapid transfer of lithium ions through the separator. As most solvents used are organic, electrolytes are flammable and should be kept away from ignition sources or high temperatures (Blum and Long, 2016; Ghiji *et al.*, 2020).

The region where lithium ions in the electrolyte react with the electrode materials is known as the solid electrolyte interface (SEI) or SEI layer. The SEI layer is permeable to lithium ions but not to the electrons, and the stability of this layer is important for preventing degradation of the electrodes, cell safety, and cell longevity (Ghiji *et al.*, 2020; Schomburg *et al.*, 2023).

OEMs develop electrolytes with different salts, solvents, and other additives to enhance the performance of their batteries for competitive advantage. Like cathode chemistries, these formulations are rarely disclosed and considered commercially sensitive. Under normal operating conditions, the electrolyte is predominantly absorbed into the anode and cathode material, with no liquid electrolyte free within the cell. During normal use and cell conditions, LiBs should not produce any vapour, however, if subjected to abuse, vaporisation of the electrolyte can occur (Blum and Long, 2016). While liquid electrolytes are common, alternatives such as polymer gel and solid electrolytes can also be used. Some common electrolyte salts and solvents used in LiBs can be found in Appendix A.

3.2.7 Cell casing materials

LiB cell casings are usually made from hard nickel-plated steel, stainless steel, or aluminium of differing thicknesses (Bree, Horstman and Low, 2023). In pouch cell batteries, a soft aluminium-plastic composite film forms the outer casing, with internal electrodes connected to conductive tabs that protrude from the pouch. (Huang *et al.*, 2019). The metal casings are usually crimped or fused and welded for a hermetic seal. This seal is important for preventing contaminants entering the cell, interfering with normal usage, and chemical and vapour leaking from the cell.

3.2.8 Additional safety features

There are a number of safety mechanisms that can be built into LiBs to monitor and manage hazardous battery conditions that lead to TR. One such mechanism that is utilised in most LiBs is safety valves or vents which allow for the release internal cell pressure during failure events (Best *et al.*, 2023). During TR a large amount of gas can be generated within the LiB cell leading to dangerous pressure build up and the risk of further reactions. Effective venting of the cell during gas production can slow TR, minimise risk of projectiles, and act as an early warning signal that a cell is entering TR (Sun *et al.*, 2020; Link *et al.*, 2022; Dai and Panahi, 2025).

A battery management system (BMS) is installed in most modern LiB packs to control and monitor critical aspects of battery operation. While these can vary in complexity, the main function of a BMS is to manage the performance, efficiency, and safety of the battery system by monitoring state-of-charge (SoC), balancing the charge and discharge between cells within a module, disconnecting the battery from the load or charger if currents exceed safe limits, and providing performance data (Ghiji *et al.*, 2020; Best *et al.*, 2023).

Other protection devices such as a current interrupting device (CID) and positive thermal coefficient (PTC) are found to be employed in cylindrical cells (Link *et al.*, 2022). These devices serve to reduce or stop the current when the cell experiences elevated pressure (via the CID) or temperatures (via the PTC) (Link *et al.*, 2022). For larger packs, the use of a thermal management system can also be employed to assist in maintaining an optimum operating temperature for cells (Ghiji *et al.*, 2020).

While it is known that these systems are widely utilised to improve LiB safety and the benefits of these systems cannot be understated, they are not infallible and are prone to failure, bypass in modified systems, or may not be installed in ‘do-it-yourself’ systems. Therefore, it is important to understand and manage catastrophic LiB failures and mitigate the associated risks.

3.2.9 Example LiB cell

Any combination of the above formats, construction, and anode, cathode and electrolyte chemistries can be used in LiBs. An example combination is presented by Jia *et al.* (2022), who detailed the constituents of a commercial 18650 cell used in their testing; illustrated in Figure 3 and detailed below.

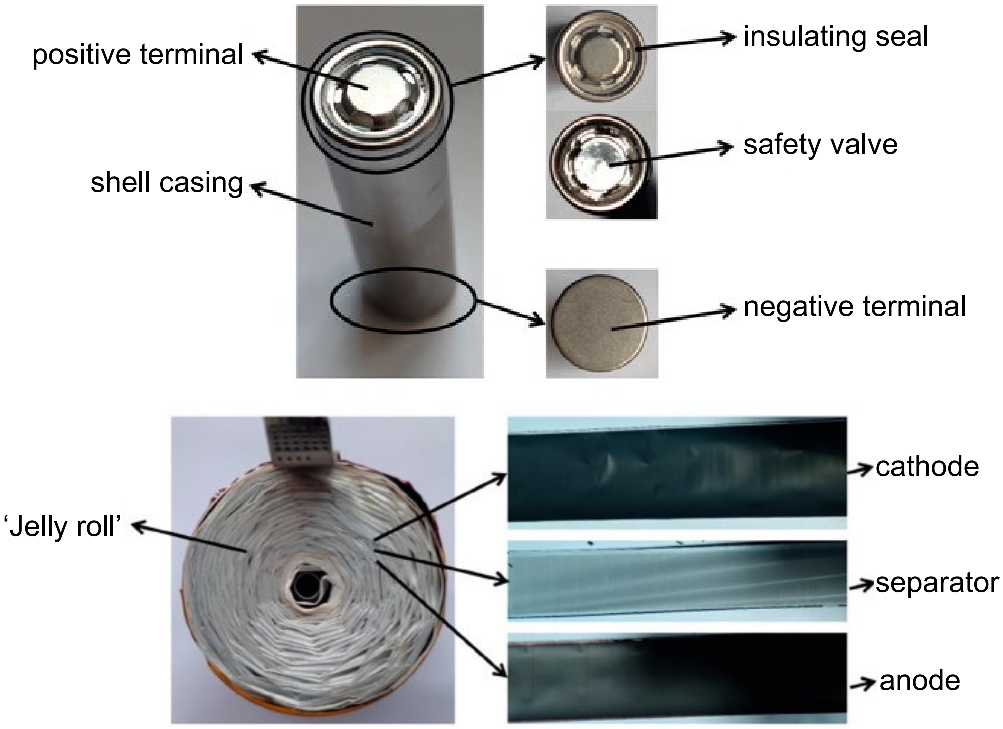


Figure 3. Example LiB cell construction (from Jia *et al.*, 2022).

Table 1. Anode, cathode, separator, and electrolyte chemistries of an example NCM$_{811}$ LiB (from Jia *et al.*, 2022).

Anode	Graphite
Cathode	$Li(Ni_{0.8}Co_{0.1}Mn_{0.1})O_2$
Separator	PP/PE/PP (three layers)
Electrolyte	$LiPF_6$/DMC:EMC:EC = 1:1:1
Rated capacity	2.9 Ah
Operating voltage	2.5–4.2 V
Weight	47–48 g

3.3 Cell function

LiBs operate through the movement of lithium ions between the anode and cathode during the charge and discharge process (Schultz *et al.*, 2016; Y. Chen *et al.*, 2021). During charging, electrons are removed from lithium atoms by an external electrical source, creating lithium ions (Li^+). The electrons (e^-) move through the external circuit towards the anode, while lithium ions move through the electrolyte from the cathode, through the separator, to the anode to maintain cell balance. The lithium ions embed into the anode through a process known as intercalation and are then re-bonded to the free electrons.

During the discharge process, this cycle is reversed. When connected to an external circuit (i.e. the device that the battery will power) lithium atoms at the anode are separated from their electrons, forming ions which then pass through the separator towards the cathode. The free electrons move through the external circuit, providing power to the connected device. Once the electrons arrive at the cathode, they bond with the intercalated lithium ions. During normal operation, LiBs produce heat which is typically dissipated safely. Failure to dissipate this heat effectively can lead to a variety of problems, and eventually TR. An overview of the charge/discharge process is shown in Figure 4.

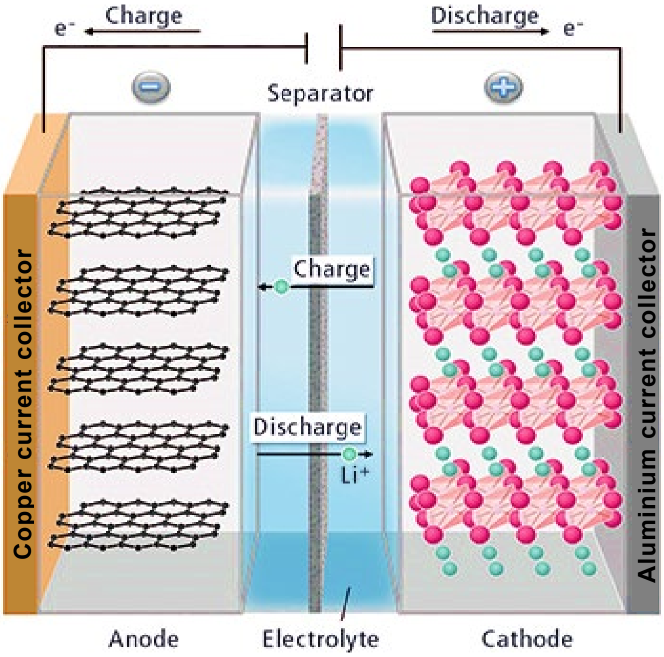


Figure 4. Schematic representation of LiB cell function (from Schultz *et al.*, 2016).

3.4 Pack assembly and arrangement

LiB cells can be assembled in a variety of ways depending upon the application they will be used in. Individual LiB cells can be used singularly to power small devices. Alternatively, an individual LiB cell can be combined and electrically connected (in series or parallel) with other LiB cells to form different LiB module or pack arrangements. When LiB cells are electrically connected, they are known as a ‘module’. LiB modules are thus electrically connected to create a battery ‘pack’ (Figure 5). LiB modules are considered a ‘pack’ when they provide a unified power supply to a device. The casings and connections between LiB cells and modules can be constructed from different packaging materials, dependent on the manufacturer and device, and in any number of different arrangements. Arranging LiB cells in this manner consolidates the overall assembly voltage and current (Blum and Long, 2016), allowing custom LiBs to be manufactured for individual applications, devices, and energy needs.

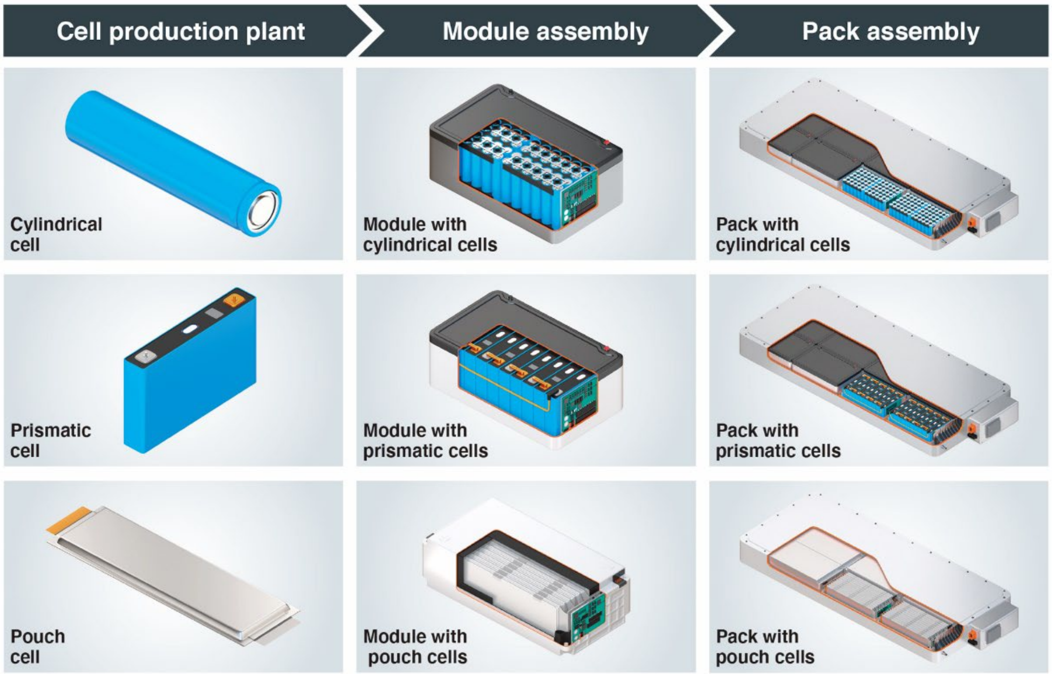


Figure 5. LiB cell to pack arrangement (from Hioki E.E. Corporation, 2021).

The variety of chemistries, packing arrangements and materials, and restricted information from OEMs contribute to the complexity of understanding and identifying LiBs. Differences in LiB characteristics, energy capacity, size and shape determine their safety. Understanding these details is important when assessing how and why LiBs fail and the hazards they may present in an emergency context. Often it is not possible to discern these details during an emergency, which contributes to the difficulties faced by emergency responders.

3.5 Applications and uses

As highlighted above, LiBs come in a variety of different arrangements. These arrangements are a critical factor in the application of LiBs.

Single cells are widely used in small portable devices which do not have high power requirements, or where reduced size and weight are required features. For example, single LiB cells can be found in devices such as e-cigarettes (cylindrical cell) and mobile phones (pouch cell) ("Single-Cell vs. Dual-Cell Batteries: What's the Difference?", 2023).

LiB packs (which consist of a varying number of modules depending upon application requirements) have a much wider array of applications due to the ability to increase size, battery capacity, voltage, and current based on the number of cells used. In some cases, singular modules are used in small or mid-size devices, which can also be referred to as a ‘pack’, such as laptops and power tools (approximately 6 - 12 cells depending on voltage required (Ureno, 2015)). Packs can also increase in size by connecting multiple modules together to power larger devices such as e-micromobility vehicles (e.g. e-bikes). Packs used in e-micromobility vehicles vary greatly depending on the size of battery chosen and the specific capacities of the cells that are used. An example 36 V 8.7 Ah battery may contain 30 individual cylindrical cells, while a 48 V 13 Ah battery may contain 65 cells.

Even larger LiB packs are used in applications such as BESS or EVs. EVs can range in pack size depending on the type of EV, with hybrid and plug-in hybrid electric vehicles (HEV or PHEV, respectively) requiring smaller packs than battery electric vehicles (BEV). The form factor of the cell used also dictates the number of cells required for an EV and can range from up to 9000 cylindrical cells, to a few hundred pouch cells or even fewer prismatic cells (Melancon, 2022). BESS can vary in size from small residential systems used for solar power storage utilising 5 - 6 modules within a pack, to large commercial BESS for grid-scale applications utilising large modules to create a single shipping container-sized pack (Stanley, 2018). With all LiB packs, as the number of cells increase, the difficulties and risks associated with battery failures events also increase.

4 Considerations for response to LiB incidents

4.1 Thermal runaway in LiBs

While LiBs are an extremely useful technology, they have the potential to pose a significant life safety risk. LiBs are an energy-dense power source; when that energy is released in unexpected or uncontrolled ways, there can be significant consequences.

The hazards associated with LiBs are dependent on several factors. Varying electrode chemistries, electrolytes, form factors, pack design, capacity, manufacturing quality, SoC, and state of health (SoH) all contribute to how LiBs respond to abuse and failure (Tapesh *et al.*, 2020). LiB abuse can lead to TR, with the resultant hazards a consequence of the battery design and abuse method (Guo *et al.*, 2017; Chen *et al.*, 2019; Huang *et al.*, 2019; Wang *et al.*, 2021; Yuan *et al.*, 2021).

TR is an uncontrolled increase in internal cell temperature caused by exothermic reactions leading to catastrophic cell failure (Quintiere and et al, 2016; Chen *et al.*, 2020; Ghiji *et al.*, 2020; Shahid and Agelin-Chaab, 2022). Under normal operating conditions, cells will produce heat that is able to be effectively dissipated through cell design, cell distribution or battery cooling systems before any adverse effects occur (Lammer, Konigseder and Hacker, 2017; Chen *et al.*, 2020; Link *et al.*, 2022). When cells cannot dissipate heat faster than it is being generated, a self-sustaining reaction is triggered; with rising heat levels increasing the rate of reaction (Dai and Panahi, 2025). The reactions occurring within the LiB cell produce large amounts of gas, increasing the internal pressure of the cell, which can lead to rupturing and venting of these gases into the atmosphere (Chen *et al.*, 2020; Ghiji *et al.*, 2020; Shahid and Agelin-Chaab, 2022). The self-sustaining, exothermic chemical reaction that starts within a single compromised cell can propagate to adjacent cells, cascading through a LiB pack (Feng *et al.*, 2014; Spinner *et al.*, 2015; Huang *et al.*, 2019).

Upon TR, LiB cells fulfil all aspects of the fire tetrahedron (heat, oxygen, fuel, and chemical reaction) and therefore presents a significant fire risk and unique challenges for hazard management. Based on different types of abuse that a LiB cell may face, there are several potential triggers for cell failure.

4.1.1 Causes of LiB thermal runaway

The processes which lead to TR are complex, varied and can be attributed to several factors, often with one form of abuse having cascading effects within the cell. The TR chemical chain reaction can be initiated by three types of abuse events: mechanical, electrical, or thermal (Chen *et al.*, 2020; Ghiji *et al.*, 2020; Dai and Panahi, 2025).

When the temperature within the battery cell heats to the melting point of the separator, the separator’s material melts to close the pores of the separator, preventing ion transfer (Dai and Panahi, 2025). As the temperature continues to increase, the separator can fail through shrinkage or collapse. Alternatively, mechanical abuse such as tearing or piercing (Ghiji *et al.*, 2020; Shahid and Agelin-Chaab, 2022) can also rupture the separator. This can cause the anode and cathode material to come into contact, leading to an internal short circuit (ISC).

ISC is an exothermic process, where electrical energy stored within the cell is released in the form of heat at the location of the short circuit, due to the low resistance, resulting in a high electrical current path (joule heating). Prolonged ISC will increase local temperatures within the cell. ISC does not inherently cause TR, although the associated elevated cell temperatures in conjunction with other abuse events can lead to electrolyte decomposition, rapid release of stored energy, and/or separator melting and shrinking. These factors cumulatively increase the likelihood of TR within a cell (Maleki and Howard, 2009; Feng *et al.*, 2018; Chen *et al.*, 2020).

Figure 6 provides a visual representation of how each abuse type leads to TR.

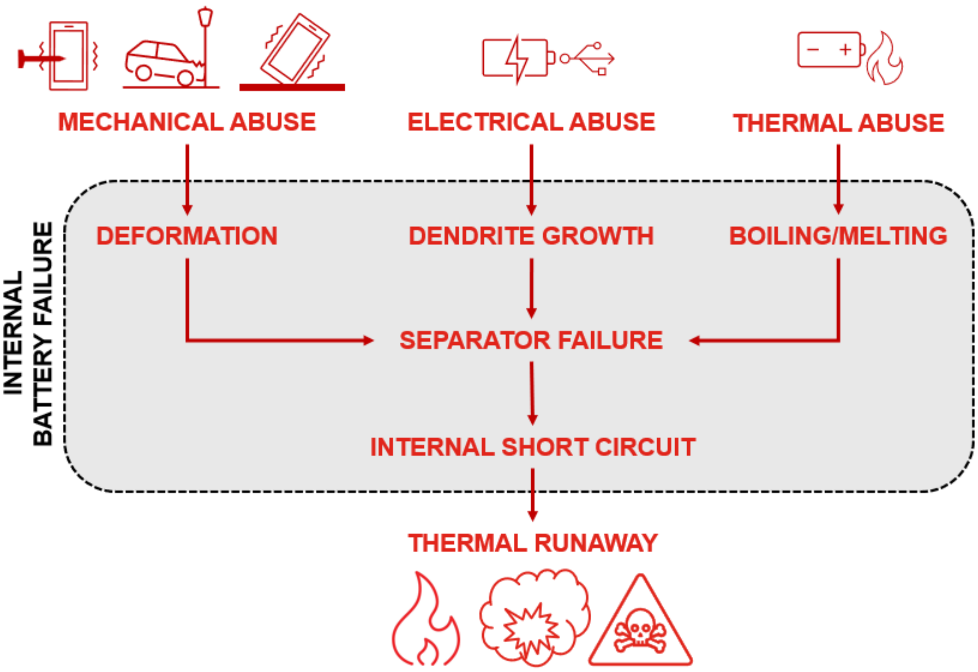


Figure 6. LiB abuse mechanisms leading to LiB TR.

LiB failure mechanisms have been studied and documented by a range of researchers (Spotnitz and Franklin, 2003; Larsson, Andersson, Blomqvist, Lorén, *et al.*, 2014; Lei *et al.*, 2017; Mier *et al.*, 2017; Q. Wang *et al.*, 2019; Snyder and Theis, 2022) and are summarised below.

4.1.1.1 Mechanical abuse

Mechanical abuse refers to physical damage or deformation from impact, compression, bending or penetration. Mechanical damage to a LiB cell leads to rupturing of the separator, causing the electrode materials to come into contact and triggering ISC (Shahid and Agelin-Chaab, 2022).

4.1.1.2 Electrochemical abuse

Electrical or electrochemical abuse is the over-discharge or overcharge of the LiB beyond its operating voltage and capacity (Jana and García, 2017; Ouyang *et al.*, 2019). Factors such as the battery cell ageing (Jana and García, 2017; Ouyang *et al.*, 2019), water ingress/submersion (Z. Wang et al., 2019), or external short circuits (ESC) (Maleki and Howard, 2009) may be considered electrochemical abuse.

Operating and charging batteries outside their normal range can lead to dendrite growth (Zhang *et al.*, 2021). Dendrites are heterogenous structures that can grow from lithium or copper deposits on the current collector. Dendrites eventually grow to pierce the separator, causing ISC (Zhang *et al.*, 2021).

4.1.1.3 Thermal abuse

Thermal abuse involves exposure of the battery cell to elevated temperatures, which raise the internal cell temperatures above normal operating limits. Thermal abuse can arise from within the battery pack or externally (Chavan *et al.*, 2024), with elevated temperatures accelerating the rate of reactions within the cell and progressing the TR process (Madani, Ziebert and Marzband, 2023; Dai and Panahi, 2025). Thermal abuse may result from increases in temperature from reactions within the cell, excessive charging/discharging producing joule heating, ISC, improper connections between batteries, adjacent cells in TR, or an external fire source (Chen *et al.*, 2020; Shahid and Agelin-Chaab, 2022; Mallick and Gayen, 2023; Dai and Panahi, 2025).

4.1.1.4 Other causes

Manufacturer faults may lead to TR through mechanical or electrochemical abuse. There are several types of manufacturer fault, with some of the most common being inclusions or impurities, cracked electrodes, creases in the separator or electrodes, poor alignment of electrode sheets or warping, and burred edges on electrodes (Chen *et al.*, 2024). These types of manufacturer faults have the potential to cause ISC and thereby lead to TR (Maleki and Howard, 2009; Ghiji *et al.*, 2020).

SoH can be generally described as a measure of a battery's capacity compared to its rated capacity (i.e. its minimum expected capacity when new) (Kularatna and Gunawardane, 2021; Wei *et al.*, 2023). Calculating a battery's SoH is complex due to the range of factors which can affect battery health. As LiBs undergo charge/discharge cycles through their lifetime, are exposed to abuse conditions, or age (calendar aging), they slowly deplete their SoH. Batteries with a decreased SoH have a decreased energy capacity and runtime, and are more prone to safety issues (Wei *et al.*, 2023; Zhang, Ji and Wang, 2024). Typically, degradation of the SoH in EVs is linear initially, and when packs reach approximately 80% SoH they are considered by OEMs to be at the end-of-life (EoL) (Best *et al.*, 2023; Christensen, Mrozik and Wise, 2023; Nuroldayeva *et al.*, 2023).

Although considered at EoL, cells from these packs can still be used (after testing and grading) (Geng *et al.*, 2022; Chen *et al.*, 2023) in applications with lower cycling rates and less demanding current draw, such as in BESS (Zhao *et al.*, 2021; Best *et al.*, 2023; Christensen, Mrozik and Wise, 2023). Continual use of the LiB cell will lead to a point at which the SoH begins to rapidly decline, which can occur from 50% - 60% SoH. At this point, cells should no longer be used due to an increased chance of failure (Christensen, Mrozik and Wise, 2023).

While recycling and second-life use of LiBs offer both environmental and potential economic benefits (Zhao *et al.*, 2021), the repurposing and re-use of LiBs salvaged from the original device with an unknown history can increase the risk of TR and cell failure (Christensen, Mrozik and Wise, 2023). Christensen *et al.* (2023) noted that salvage of LiB packs might occur in an effort to reduce waste through recycling, re-manufacturing, re-use, or repurposing seemingly 'healthy' LiB modules and cells.

Christensen *et al.* (2023) provide an example, where LiB packs can be removed from applications such as EVs, detailed in Figure 7. This process involves testing packs to see if they can be immediately re-used or if they must be opened and modules/cells tested individually. When tested individually, if only a single cell or module has a low SoH, it is removed and replaced with a module of similar SoH to the existing modules and the pack can be remanufactured for EVs. Conversely, if multiple cells or modules are unhealthy, they are removed and recycled while the healthy modules are removed and repurposed into other applications. It should be noted that when LiB packs are remanufactured, all cells must be at the same SoH to avoid dependence on healthier cells. Additionally, any re-use, remanufacturing, or repurposing may lead to issues due a decreased SoH of the cells.

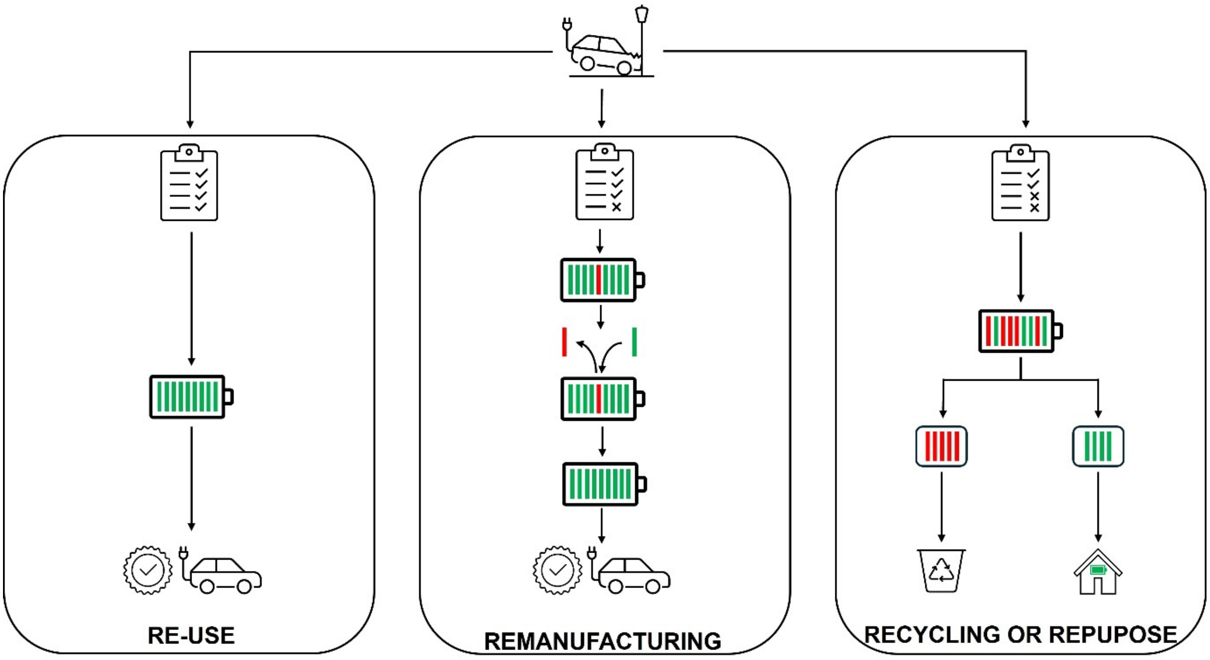


Figure 7. Example life- and second-life cycle of an EV LiB pack (adapted from Christensen, Mrozik and Wise, 2023).

Furthermore, the unregulated installation and manufacture of LiB packs using LiB cells and modules purchased from unregulated suppliers increases the risk of failure and TR (Christensen *et al.*, 2021). The increased prevalence risks associated with LiBs have prompted a push to increase safety regulations regarding installation, transport, storage, and manufacture to mitigate some of the associated hazards (Y. Chen *et al.*, 2021; Best *et al.*, 2023; NSW Fair Trading, 2024).

4.1.2 Thermal runaway at cell level

The response of a battery to different abuse methods has been found to result in different fire behaviours (Fu *et al.*, 2015; Ping *et al.*, 2015; Larsson, Andersson and Mellander, 2016). To this end, the onset of TR is a function of the type and magnitude of the abuse the LiB receives, while also influenced by the format, packaging, and chemical makeup of the LiB. It is worth noting that abuse events do not typically occur in solidarity, with one abuse event typically cascading and leading to others. An example is a cell which is punctured (mechanically abuse). This can lead to a short circuit occurring (electrical abuse), which in turn leads to localised heating (thermal abuse), and progresses to TR (Wang *et al.*, 2023; Dai and Panahi, 2025).

TR within a single LiB cell occurs as a series of events triggered by increasing cell temperature (Liu *et al.*, 2018), described by Lammer et al. (2017) as a heating ramp rate of at least 2 °C/min. During this process, a range of reactions occur as the individual cell components interact change, and decay. Factors such as cell chemistry, form, SoH, internal safety measures, and cell arrangement, which all influence internal transference of excess heat, make the onset of TR challenging to define. While the key steps of TR in LiBs have been described by various studies, the exact stages vary publication to publication. Onset temperatures for TR are variable, with many factors including cell chemistry, cell design, environmental factors, and the ability of cells to effectively dissipate heat potentially affecting the point at which a cell will enter TR. The sequence of events identified in Table 2 provide an overview of the key pathway a LiB follows as it enters TR and is representative of most TR reactions.

4.1.3 Thermal runaway at pack level

Significant efforts have been made to measure and understand the mechanism of heat transfer between a single cell in TR and its adjoining cells. Studies have examined cylindrical (Lamb and Orendorff, 2014; Spinner *et al.*, 2015; Lamb *et al.*, 2018; Huang *et al.*, 2019; Said *et al.*, 2019), pouch (Lamb and Orendorff, 2014; Feng *et al.*, 2015; Huang *et al.*, 2019), and prismatic cells (Feng *et al.*, 2014, 2015; Huang *et al.*, 2019; Lai *et al.*, 2021), utilising different arrangements, different cell chemistries, and different methods of inducing TR.

The results of these studies all show that TR in a single LiB cell will typically lead to the cascading failure of the entire LiB module/pack. The extreme levels of heat produced by a cell in TR is sufficient to trigger TR in adjacent cells, initiating a positive feedback loop as more cells enter TR within the pack. LiB cell format has also been demonstrated to affect the propagation of TR through a pack, due to the thermal conductivity cells touching each other and airflow (Lamb *et al.*, 2018).

Table 2. Overview of key reactions during TR.

Step	Events
Step 1: Overheating of the cell	Due to either internal or external causes, abuse to the cell generates heat beyond its capacity to effectively dissipate this heat (Rappsilber *et al.*, 2023). As temperatures increase, reaction begins to occur at the anode at ~90 °C (Lisbona and Snee, 2011).
Step 2: Heat accumulation and breakdown of SEI	As heat within the cell begins to accumulate, several reactions are triggered. Depending upon cell chemistry, the SEI layer will begin to decompose, typically above 100 °C. Unwanted reactions begin at the anode, with intercalated material reacting with the electrolyte exothermically. These exothermic reactions lead to further cell heating, and the generation of flammable gases and oxygen (Lisbona and Snee, 2011; Liu *et al.*, 2018).
Step 3: Separator breakdown	As exothermic reactions from SEI decomposition drive the cell internal temperature over 120 °C, the separator begins to melt and breakdown (Lisbona and Snee, 2011; Liu *et al.*, 2018; Rappsilber *et al.*, 2023) Breakdown of the separator can cause the anode and cathode materials to contact, creating an ISC which further raises the temperature (Liu *et al.*, 2018; Rappsilber *et al.*, 2023). Ghiji *et al.* (2020) highlight that although the separator and electrolyte have low mass within the cell, they react violently as they decompose, accounting for almost 80% of heat release in a LiB fire.
Step 4: Cathode decomposition	Once above ~180 °C, the cathode material begins to decompose exothermically, releasing large amounts oxygen (Liu *et al.*, 2018; Rappsilber *et al.*, 2023). Cathode decomposition is highly exothermic, resulting in temperature increases of up to 100 °C/min (Lisbona and Snee, 2011). The heat released caused by each of these reactions works to speed up the reactions and processes occurring within the cell.
Step 5: Combustion and/or explosion	Due to the build-up of heat, pressure, and flammable gases, LiB cells can rupture, releasing these gases into the atmosphere (Lisbona and Snee, 2011). Many cylindrical and prismatic cells have a pressure relief valve or burst disc, to avoid uncontrolled cell rupture. Due to the organic nature of the electrolyte, and the gases produced in the above steps, vented gases are also likely to combust or explode when exposed to the right conditions (Liu *et al.*, 2018; Chen *et al.*, 2020). Explosion can occur either when the vented gases are mixed with sufficient ambient oxygen in the air to create a mixture in the explosive range and an ignition source is introduced (Bugryniec *et al.*, 2024), or when the volume of vented gases results in a fuel-rich atmosphere and oxygen is introduced by a change in ventilation conditions (such as a door being opened) in combination with an ignition source (DNV GL, 2020).

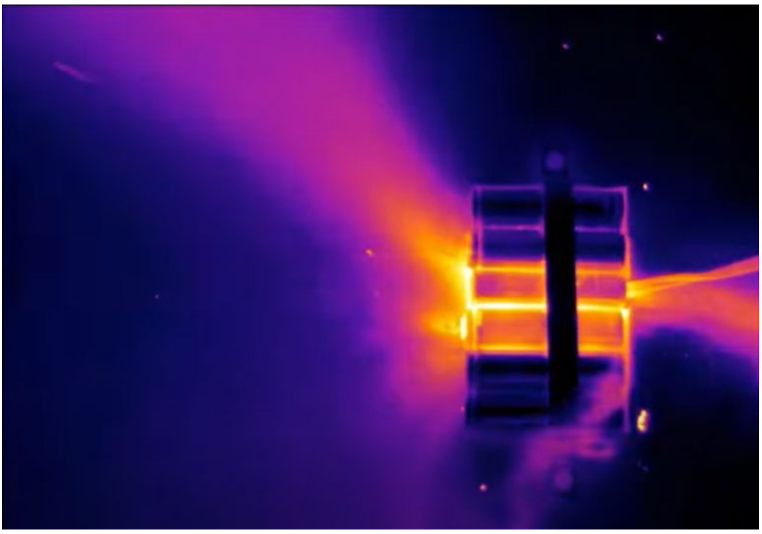


Figure 8. Thermal image demonstrating TR propagation from cell to cell within a LiB pack (from *Thermal imaging Li-ion cells in Thermal Runaway*, 2017).

4.1.4 Factors affecting thermal runaway in LiBs

Snyder and Theis (2022) summarise the hazards associated with LiBs for emergency response agencies, identifying fire, vapour clouds, deflagration, and explosion as key concerns for emergency response personnel.

It is important to note that many variables affect the severity of a LiB event, and it is important to be aware of these hazards when attending emergency incidents involving compromised LiBs (Mier *et al.*, 2017; Li *et al.*, 2019). It is not always possible to identify LiBs and potential hazardous behaviours before they occur. The wide array of design factors dictated by manufacturers and applications can affect the onset and hazards of TR.

4.1.4.1 State-of-Health and State-of-Charge

Despite declining SoH being known to increase the potential for cell failure, it is not well reported in studies whilst SoC generally is. SoC studies are being undertaken to understand the impact of SoH on TR (Ufine, 2024).

SoC is a measure of the maximum capacity of a cell, when it is fully charged. The SoC is also dependent on the LiBs SoH (i.e. a cell with 100% SoH and SoC will have higher stored electrical energy than a cell at 60% SoH and 100% SoC). The amount of stored energy within the cell is important as it can have significant effect on the cells behaviour during TR.

Studies have found that SoC is complex and a highly influential aspect in LiB fires. Generally, at higher SoC the results from TR are more catastrophic, with higher heat release rates (HRR) and increased vapour production, while at lower SoC the vapour produced may not ignite due to lower stored energy or the resultant fires may not be as severe (Chen *et al.*, 2018; Christensen *et al.*, 2021; Zhang *et al.*, 2021; Wang *et al.*, 2023).

4.1.4.2 Cell chemistry

Cathode chemistries have been found to dictate, to a large degree, the thermal stability and respective safety of LiBs (Jiang and Dahn, 2004; Ghiji *et al.*, 2020). Significant research continues to be conducted on new cathode and anode materials to enhance electrical performance and LiB safety (Martha *et al.*, 2011; Nitta *et al.*, 2015; Roy and Srivastava, 2015; Nayak *et al.*, 2018; Shi *et al.*, 2018).

Table 3 describes common cathode chemistries and their decomposition products. Note the contribution of flammable and combustion contributing by-products generated during decomposition, namely oxygen (O_2). The oxygen production due to the decomposition of cathode materials contributes to TR propagation.

Table 3. Common LiB cathode chemistry decomposition pathways.

Common name	Chemical formula	Decomposition products	Reference
Lithium Cobalt Oxide (LCO)	$LiCoO_2$	$Li_xCoO_2 \rightarrow xLiCoO_2 + \frac{1}{3}(1-x)Co_3O_4 + \boldsymbol{\frac{1}{3}(1-x)O_2}$ $Co_3O_4 \rightarrow 3CoO + \boldsymbol{0.5O_2}$ $CoO \rightarrow Co + \boldsymbol{0.5O_2}$	Z. Wang *et al.*, 2019; Chombo and Laoonual, 2022b
Lithium Iron Phosphate (LFP)	$LiFePO_4$	$2Li_0FePO_4 \rightarrow Fe_2P_2O_7 + \boldsymbol{0.5O_2}$	Q. Wang *et al.*, 2019; Sun *et al.*, 2023
Lithium Manganese Oxide (LMO)	$LiMn_2O_4$	$Mn_2O_4 \rightarrow Mn_2O_3 + \boldsymbol{0.5O_2}$ $Li_{0.2}Mn_2O_4 \rightarrow 0.2LiMn_2O_4 + 0.8Mn_2O_4$ $3MN_2O_4 \rightarrow 2Mn_3O_4 + \boldsymbol{2O_2}$ $LiMn_2O_4 \rightarrow LiMn_2O_{4-y} + \boldsymbol{y/2O_2}$ $LiMn_2O_4 \rightarrow LiMnO_2 + 1/3Mn_3O_4 + \boldsymbol{1/3O_2}$	Lei *et al.*, 2017; Z. Wang *et al.*, 2019
Nickel Cobalt Oxide (NCA)	$LiNiCoAlO_2$	$Li_x(Ni_{0.8}Co_{0.15}Al_{0.05})O_2 \rightarrow \frac{1+x}{3}\left[Li_{\frac{3x}{1+x}}(Ni_{0.8}Co_{0.15}Al_{0.05})_{\frac{3}{1+x}}O_4\right] + \boldsymbol{\frac{1+2x}{3}O_2}$ $Li_x(Ni_{0.8}Co_{0.15}Al_{0.05})O_{\frac{4(1+x)}{3}} \rightarrow Li_x(Ni_{0.8}Co_{0.15}Al_{0.05})O_{1+x} + \boldsymbol{\frac{1+x}{6}O_2}$	Z. Wang *et al.*, 2019; Chombo and Laoonual, 2022b
Nickel Manganese Cobalt (NMC)	$LiNiMnCoO_2$	$NCM \xrightarrow{\Delta T, solv.} (Mn, Ni)O + CoO + Ni + \boldsymbol{O_2}$	Q. Wang et al., 2019

Note: Highlighted in red are flammable or combustion contributing by-products.

As previously highlighted, cathode chemistries play a vital role in a LiB's functioning and is a determining factor for a cell's voltage and energy density. While the chemistries of components such as separators, binders, or electrolytes also influence TR, the cathode material is of most interest and, as such, many studies have examined how different cathode chemistries affect TR. It is known that cell chemistries containing nickel content promote higher energy densities but have lower thermal stability, while LFP cell chemistries demonstrate the inverse.

Yuan *et al* (2024) conducted testing on four commonly used cathode materials (LFP, LCO, NMC_{811}, and NCA), utilising accelerating rate calorimetry (ARC) and isothermal battery testing calorimetry. They found that the cathode chemistries with higher percentages of nickel and cobalt (e.g. NMC and NCA) had higher capacities but were more thermally unstable, presenting higher risks, while LFP was the most stable cathode due to the strong phosphate bond.

Yuan *et al* (2024) ranked the tested chemistries in terms of TR danger level as follows, LCO>NCA>NCM_{811}>LFP, based on the maximum temperature and maximum heating-rate. Similarly, Wei *et al.* 2023 compared LFP and NMC chemistries, finding that the maximum temperature of NMC cells during TR ranged from 555 – 1066 °C, while LFP cells had a maximum temperature range between 357 – 525 °C.

Additionally, when comparing temperature rise rate, they found that LFP cells had a minimum of 3.2 °C/s and a maximum of 24.3 °C/s. NMC cells, however, had a minimum of temperature rise rate of 24.9 °C/s and a maximum of 143.7 °C/s, highlighting a more violent TR event. They concluded from this that cells with increased nickel content were less thermally stable and had increased dangers associated with TR.

To further highlight this, Schöberl *et al.* (2024) found that the TR reaction speed regarding cell energy was nine times faster for NMC cells when compared to LFP cathode chemistries. Both Schöberl *et al.* (2024) and Wei *et al* (2023) state that cells with higher nickel content chemistries demonstrated more significant levels of ablation around vent locations and overall cell destruction.

Bugryniec *et al.* (2024) completed a meta-analysis of 60 papers investigating off-gassing, finding that NMC and LFP cells typically are the most studied. They found that there is conflicting information regarding the gas production and its relation to cell chemistries. Overall, they found that several studies had found a correlation between cell capacity and gas volume – that at 100% SoC, LFP cells generate lower gas volumes than other cell chemistries (LCO, NMC, LMO). They also found that NMC cells typically generate more gas than other cell chemistries, with higher nickel content cells producing higher gas volumes. Bugryniec *et al.* (2024) also highlighted that although LFP cells produce less gas, they are significantly more toxic than NMC.

Additionally, Wei *et al.* (2023) and Schöberl *et al.* (2024) highlight that at lower surface cell temperatures, gas is vented earlier by LFP cells. This earlier venting may result in the vented gases being less likely to combust, as the cell temperatures are lower when compared to NMC cells.

Cui *et al.* (2023) also demonstrated that under slow heating conditions gas release preceded fire ejection in LFP cells by approximately 987 seconds, while it was approximately 1585 seconds for NMC cells. They also highlighted that LFP cells produced more hydrogen (H_2) than NMC cells, which produced higher levels of carbon monoxide (CO). Cui *et al.* (2023) highlighted that H_2 has a much lower explosion threshold than CO, resulting in an elevated explosion risk with LFP based cells when compared with NMC.

Cell separators play a critical role in the safety of LiBs by preventing contact between the anode and cathode. Physical contact between the electrodes leads to an ISC, in turn initiating TR. The PP and PE separators commonly used in LiBs have low melting points, becoming damaged or distorted at temperatures above 120 °C, leading to ISC and TR. These separator materials are also highly flammable and contribute to the fuel load in LiB fires.

Another large contributor to the fuel load in LiB fires is the electrolyte. The low boiling point of most electrolyte solvents contributes a significant portion of combustible products during TR.

Table 4 describes common electrolyte solvents and their decomposition products. Note the contribution of combustible contributing by-products generated during decomposition, including CO, methane (CH_4), ethene (C_2H_4), ethane (C_2H_6), and propylene (C_3H_6).

Table 4. Common LiB electrolyte solvent boiling points (PubChem, 2023) and decomposition pathways (Q. Wang *et al.*, 2019).

Common name	Chemical formula	Boiling point (°C)	Decomposition products
DEC	$C_5H_{10}O_3$	126	$C_5H_{10}O_3 + 2Li^+ + 2e^- \rightarrow 2CH_3CH_2OLi + \mathbf{CO}$ $C_5H_{10}O_3 + 2Li^+ + 2e^- + H_2 \rightarrow 2Li_2CO_3 + \mathbf{2C_2H_6}$ $C_5H_{10}O_3 + 2Li^+ + 2e^- + H_2 \rightarrow CH_3CH_2CO_2OLi + \mathbf{C_2H_6}$
DMC	$C_3H_6O_3$	90	$2Li + C_3H_6O_3 \rightarrow Li_2CO_3 + \mathbf{C_2H_6}$ $C_3H_6O_3 + 2Li^+ + 2e^- \rightarrow 2CH_3OLi + \mathbf{CO}$ $C_3H_6O_3 + 2Li^+ + 2e^- + H_2 \rightarrow Li_2CO_3 + \mathbf{2CH_4}$ $C_3H_6O_3 + Li^+ + e^- + 1/2H_2 \rightarrow CH_3OCO_2Li + \mathbf{CH_4}$ $2Li + C_3H_6O_3 \rightarrow Li_2CO_3 + \mathbf{C_2H_6}$
EC	$C_3H_4O_3$	248	$2Li + C_3H_4O_3 \rightarrow Li_2CO_3 + \mathbf{C_2H_4}$ $C_3H_4O_3 + 2Li^+ + 2e^- \rightarrow (CH_2OLi)_2 + \mathbf{CO}$ $2Li + C_3H_4O_3 \rightarrow Li_2CO_3 + \mathbf{C_2H_4}$ $2Li + 2(C_3H_4O_3) \rightarrow (CH_2OCO_2Li)_2 + \mathbf{C_2H_4}$ $2Li + (CH_2OCO_2Li)_2 \rightarrow 2Li_2CO_3 + \mathbf{2C_2H_4}$
PC	$C_4H_6O_3$	241	$2Li + C_4H_6O_3 \rightarrow Li_2CO_3 + \mathbf{C_3H_6}$

Note: Highlighted in red are combustible by-products.

Li-salts used in the electrolyte also contribute to the thermal instability of LiBs. The melting points and initial decomposition temperatures of some common Li-salts as determined by both thermogravimetric analysis (TGA) can be found in Appendix A (Younesi *et al.*, 2015).

Combustible by-products from the decomposition of the electrolyte, including the solvents and salts, and the electrode materials, rapidly build within the enclosed LiB cell and account for a range of different hazards during TR (Larsson, Andersson, Blomqvist, Loren, *et al.*, 2014; Christensen, Mrozik and Wise, 2023).

Non-flammable electrolytes and additives are being developed to mitigate the fire risks without compromising electrical performance (Gond *et al.*, 2021). Zhang, Li and Lu (2021) reviewed batteries with non-flammable electrolytes and found that most of these types of batteries to have inferior electrical capacity and/or far higher costs and are therefore not ready for mass adoption. The designs of battery chemistries, combined with physical design factors such as form factor, cell arrangement, and cell assembly, can heavily influence the behaviour of a LiB during TR. The complexity is further increased when considering the relationship of these factors and the variety of real-life scenarios. Understanding these factors and their interactions within the Australian context is crucial to developing safe and effective risk and hazard management systems.

4.1.4.1 Form factor

Current literature has predominately focused on investigating cylindrical cells (Rappsilber *et al.*, 2023), however as the applications of LiBs increase, further understanding is needed on how different form factors may influence TR. All form factors offer benefits and disadvantages and should be selected depending upon the suitability for the specific application. Overall, it is difficult to objectively state the safety of different forms factors without considering the contextual factors which can influence the cell during TR. The role of different chemistries, abuse types, SoC, and inclusion of BMS all play pivotal roles in how a cell behaves during TR. However, this section highlights some overarching features of the different form factors which should be considered.

Chen *et al.* (2020) completed a review on LiB safety, highlighting several key aspects for consideration with respect to LiB cell safety. During their review, they stated that safety risks increase from cylindrical to pouch, with prismatic cells having the highest risk. Cylindrical cells have lower energy storage, as well as the benefits of a hard casing. The metallic casing can withstand more internal pressure than the aluminium foil pouch casing, while also having manufactured safety vents. Prismatic cells share this metallic casing, as well as having the best heat dissipation among the form factors. Chen *et al.* (2020) stated that although pouch cells offer the most flexibility with respect to design and shape, their casing cannot withstand large amounts of internal pressure – typically bulging or swelling during internal safety issues.

Much of this work is echoed by Ruiz *et al.* (2018) who reviewed international abuse testing standards. They also concluded that cylindrical cells promote good mechanical stability, good energy density, dedicated safety vents but poor packing efficiency. They also highlight that when pressure builds, there is the possibility of expulsion of the jelly roll. Additionally, they highlight that prismatic cells offer high packing efficiency, mechanical stability, and dedicated safety vents, but they do have slightly lower energy densities. Furthermore, they state although pouch cells have the highest energy densities, they are prone to swelling during operation and they do not have dedicated safety valves. The lack of a venting mechanisms instead forces the pressure to all the sealing points of a pouch cell, and the release of gas can occur from lower energy build-up than other cell designs. Additionally, the soft nature of pouch cells requires additional manufacturing to provide protection for the cells.

While looking at development perspectives for LiB cell formats, Link *et al.* (2022) highlight that prismatic cells have the highest heat dissipation and pouch cells have the lowest. They state that the energy density for cells can generally be categorised as the highest for cylindrical, followed by pouch and then prismatic, however they do note that pouch cells can compete with cylindrical cells in terms of energy density. They also identify the advantages of cylindrical and prismatic cells regarding the inclusion of hard casing and dedicated venting mechanisms, which parallel the statements by Ruiz *et al.* (2018) and Chen *et al.* (2020). They also highlight that harmful heat generation first occurs near the core of cylindrical cells, and at the tabs of pouch and prismatic cells. Link *et al.* (2022) contend that safety risks increase in all form factors as energy densities increase, and that safety features at different levels (e.g. cell chemistry, BMS, housing) may not prevent TR but do play a role in significantly reducing risks.

TR in large-format prismatic LiBs was studied by Feng *et al.* (2015). These form factors were also found to ignite via a cascading cell to cell mechanism following TR in one cell (Feng *et al.*, 2014). Lamb *et al.* (2018) studied the failure propagation of multi-cell LiB packs and compared LiB packs containing either pouch or cylindrical cells with the same cathode chemistry. Lamb *et al.* (2015) concluded that pouch cells demonstrated a faster fire spread than cylindrical cells, due to strong heat transfer between the pouches. The rate of heat transfer between the pouches was found to be a function of their geometry and packing arrangement.

Huang *et al.* (2019) also studied the TR of pouch and prismatic cells. Huang *et al.* (2019) studied LiB packs with the same cathode chemistry and found that prismatic LiB cells with a safety valve provided early indication of TR and a reduced likelihood of exhibiting significant deformation in comparison to pouch cells. Huang *et al.* (2019) also studied the effect of arranging cylindrical LiB cells in different patterns and found that the packing arrangement of the cylindrical cells resulted in slightly different TR times when heated with an external heater.

4.1.4.1 Abuse type

Investigations into LiB responses to abuse types has been widely examined in current literature. Given that TR occurs in response to mechanical, electrochemical, or thermal abuse, typical trigger methods adopted in testing include overcharging, overheating, or penetration. However, even when a trigger method is adopted in testing, there are no standards detailing how to enact that trigger method and researchers are left to devise or develop their own method.

Several different test methods have been utilised by different researchers when inducing TR within LiBs. Willstrand, Pushp, Andersson, *et al.* (2023) applied six different trigger methods, highlighting some of the more commonly used methods among researchers. In their study, they use nail penetration, overcharging, and four different methods for thermal abuse on large format prismatic NMC cells. They demonstrated that the trigger methods had effects on the maximum temperature achieved, mass loss, and the gas production rate. They found that trigger methods which preheat the cell, such as thermal abuse methods with slow temperature ramps, will result in higher gas production rates. They also found that trigger methods with higher input energy result in higher mass loss and that the maximum temperature at 100% SoC could vary as much as 400 °C depending on the trigger method.

Thermal abuse can vary in how it is applied. Any method of applying external heat to a cell can be used as thermal abuse. Some studies conduct ambient heating, by placing a cell within an oven or furnace apparatus or exposing it to a radiant heater (Quintiere and et al, 2016; Lammer, Konigseder and Hacker, 2017; Tao *et al.*, 2020; Chombo and Laoonual, 2022; F. Liu *et al.*, 2022). Another method involves applying current to a resistance wire wrapped around the cell to provide direct heating (Quintiere and et al, 2016; Shelkea *et al.*, 2022; Allen, Jones and Marco, 2025). Lamb and Orendorff (2014) highlight several mechanical abuse methods including compression, blunt rod deformation, flat crushing, three-point bend tests, and the popular nail penetration test. Within their paper they highlight that some issues exist as mechanical abuse has also been used as a supplement for ISC testing, however they may not accurately re-create ISC situations which occur in real-life scenarios. Electrical abuse methods may include overcharging, over-discharging, or exposing the cell to an ESC. Lalinde *et al.* (2024) highlight that overcharging is considered one of the most dangerous abuse types due to the excess energy that is stored within the cell and can be expelled during TR.

Many studies have looked at what effect the SoC has on different aspects of TR. Cells with a higher SoC have higher amounts of electrical energy stored, which can lead to different effects on the cell as it begins TR. Lai *et al.* (2021) investigated the TR propagation characteristics of LiB modules under different trigger modes. Lai *et al.* (2021) used prismatic cells to conduct their testing and used a combination of nail penetration, overcharging, and overheating to induce TR. Lai *et al.* (2021) found that nail penetration testing induced TR the most quickly, however it was noted that TR could be achieved more rapidly by increasing the heat or voltage in the overheating and overcharging tests, respectively.

Several studies have explored the effect of cell form factor when examining TR propagation throughout a pack. Lamb *et al.* (2018) studied the effects of initiating TR within a single cell to assess its propagation throughout a ten cell pack on both cylindrical and pouch cells using nail penetration. They found that cylindrical cells were less prone to cell-to-cell TR propagation when compared to pouch cells, which could most likely be attributed to the increased spacing between cylindrical cells reducing heat transfer. In cylindrical packs, heat transfer wasn’t as strong in series connections, while, alternatively, parallel connections exhibited excess heat generation due to electrical shorting and discharging leading to complete TR propagation. Lamb *et al.* (2018) also found that pouch cells progressed to complete TR propagation throughout the entire pack within 60 - 80 seconds.

Feng *et al.* (2015) examined propagation in pouch cells when initiated with nail penetration, using a pack which consisted of six electrically connected modules made of two cells, for a total of twelve individual cells. In this test they found that most of the heat transfer between cells was conducted through the battery container. Interestingly, they stated that external fire impingement had little effect on the propagation of TR throughout the pack but did cause significant damage on the accessories within the pack.

Kutschenreuter *et al.* (2020) examined fire safety in used EV battery packs, including both cylindrical (12 cells per module) and prismatic (132 cells per module). The authors utilised both penetration and overcharging in two separate test series to investigate the factors that may influence the burning behaviour of battery modules and packs and used common commercial detection systems and suppression agents to minimise the risks caused by LiB failure. Water based extinguishing agents provided sufficient cooling, but gas-based agents were also able to inhibit propagation. Kutschenreuter *et al.* (2020) determined that firefighting systems should be tailored to each specific incident.

Fransson *et al.* (2024) utilised 21700 cylindrical cells in both series and parallel, however each module only contained two cells. They initiated TR through nail penetration (6 mm/s) in a single cell (trigger cell), with TR propagation occurring in 56% of tests. They highlighted that there was no statistically significant trend in the frequency of propagation that could be attributed to the cell chemistry or electrical connection. However, the study highlighted that these factors could influence the TR propagation behaviour and severity. Fransson *et al.* (2024) found that propagation times were consistently shorter for NMC cells, independent of the electrical connection used. NCA cells connected in series were found to experience higher temperatures in the trigger cell, and sidewall ruptures were only observed in these cells.

Generally, they found the cells connected in series experienced higher average temperatures in the trigger cell and the propagation cell than modules connected in parallel. The authors reasoned that due to the rapid decrease in resistance in parallel connections, neighbouring cells could discharge through the cell where TR was initiated, leading to a large loss of electrical energy. In series connections, there is no electrical loss of energy and there is an increase in internal resistance. Energy can only be lost thermally in these cells, which leads to higher temperatures. This was highlighted as the cells connected in parallel had a lower TR onset temperature, and shorter propagation times between cells, while cells connected in series had a longer time until propagation but reached higher average temperatures. They also found that the heat transfer through the pole connectors accounted for approximately 1/10th of the heat transferred through the battery shell.

Jia *et al.* (2022) looked at the effects of heating LiB packs (consisting of five cells) with LFP and NMC chemistries under low altitude conditions by using a 300 W heating rod. Generally, they found that decreased atmospheric pressure resulted in less severe TR behaviour indicated by decreased average maximum temperatures across both chemistries, with combustion only occurring in NMC modules at 95 kPa. They also found that NMC cells at lower atmospheric pressure had decreased TR propagation speeds, but conversely, propagation speeds increased for LFP cells at these lower pressures. However, NMC cells recorder higher peak temperatures than LFP based chemistries.

Alternatively, Schöberl *et al.* (2024) studied NMC and LFP modules which are used in EV applications under regular atmospheric pressure using a heating pad on a module of five cells which were not electrically connected. They found that although there was propagation in both cell chemistries, there was reduced thermal stability, higher levels of cell destruction, material ejection, and side wall ruptures, as well as higher and faster heat release results for NMC cell chemistries. These results mirror findings at the cell level.

Lopez, Jeevarajan and Mukherjee (2015) also thermally abused packs containing nine electrically connected cells by wrapping a single cell with a flexible heater to understand the effects of cell spacing and thermal insulation on TR. They found that there was no TR propagation in cylindrical cells connected in parallel, which is contradictory to Lamb *et al.* (2018) findings. Lopez, Jeevarajan and Mukherjee (2015) recommend a cell spacing of at least 2 mm to help prevent heat damage and voltage loss to neighbouring cells. They found that thermal insulation, particularly intumescent material (which expands significantly when exposed to heat) in prismatic cells which had side vents, can help prevent propagation while also providing fire protection, with only a single additional cell undergoing TR in their testing when using insulation.

Ouyang *et al.* (2018) exposed a pack of three NMC cells, which were connected in parallel, to an electric heater to investigate the effects of SoC and charging or discharging treatment. Overall, they found that SoC had an influence on the fire behaviour, with modules at a higher SoC having a more violent TR reaction, most likely due to the additional O_2 generation. They also found that combination of higher heating and being charged resulted in more violent TR, due to additional input of energy to the cells, with earlier ignition and ejections being noted in both cases.

Juarez-Robles *et al.* (2021) looked at the differences between new and aged modules when overcharged. The study utilised modules consisting of twenty-four 18650 cells electrically connected and supplied with a 9 A current. They found that aged modules were overcharged quicker than fresh modules, however almost all fresh modules (seven out of eight tested) experienced complete TR, while aged cells did not. They highlight that the degradation during aging may lead to benign CID activation, inhibiting the TR process, and they also note that overcharging aged cells exacerbated the cathode degradation.

Sun *et al.* (2020) looked at the effects of overcharging LFP modules, considering the safety of implementing BESS. They highlight heat dissipation of a module is poor when compared to individual cells, and this allows for heat to be easily accumulated during the TR process. Interestingly, in one series of tests, they stopped the overcharging after the first safety vent was opened and waited two hours, finding that these modules had a reduced ability to withstand overcharge.

Kutschenreuter *et al.* (2020) employed overcharging when assessing fire behaviours of LiB modules. Although they didn't describe specifics of the overcharge method, they highlighted that they were able to initiate TR within the first cell within a range of 45 - 80 seconds. While the study focused on fire behaviour and the firefighting response, they stated that, regardless of the ignition method, it was likely that TR would propagate through the cells and modules.

F. Liu *et al.* (2022) looked at the effects of thermal insulation in protecting cells during overcharging. They utilised a module consisting of five electrically connected pouch cells, with a 3 °C overcharge condition. They found that without thermal insulation, it took approximately 62 s for TR propagation from the triggered cell to the final cell in the module. Using insulation was beneficial for preventing heat spread between cells, maintaining the temperature of the cell adjacent to the triggered cell below 200 °C. They highlight the beneficial properties of aerogel materials, which have better thermal spread suppression effects than nanofiber materials, specifically highlighting the benefits of pre-oxidised silk aerogel.

Said *et al.* (2019) conducted testing on arrangements of cylindrical 18650 LCO LiBs containing twelve to eighteen cells and induced TR in a single cell through a side heating arrangement. Said *et al.* (2019) found that TR in a single cell invariably caused a cascading failure and ignition of the entire LiB module. Said *et al.* (2019) conducted testing in both air and nitrogen environments and found the nitrogen environment slowed the rate of the cascading failure slightly. Spinner *et al.* (2015) also showed that TR of a single cell in a LiB module will typically lead to the cascading failure of the entire LiB module. Spinner *et al.* (2015) conducted similar experiments on LCO 18650 batteries to achieve comparable results to Said *et al.* (2019).

4.2 LiB-related risks and hazards

Ranging in scale from portable and e-micromobility devices, to EVs, residential BESS, data centres, and grid scale installations, a growing number of products and applications are utilising LiB technology. Emergency responders face a complex challenge in determining how LiB incidents should be handled given LiBs are manufactured in wide variety of battery pack designs, chemistries, formats, capacities, configurations, and their use spans both domestic residences and industrial sites. Determining best practice measures to support and protect both emergency responders and the community during and after a LiB incident is becoming increasingly time sensitive as more LiB-related incidents are reported globally.

Fire and emergency service organisations need awareness of, and evidence-based procedures, equipment, and training for high consequence incidents involving LiBs. The known risks associated with LiB incidents include extreme fire behaviour related to TR, the production of large volumes of flammable and toxic vapours and gases, the risk of vapour cloud explosions, electrical hazards from exposure to high voltage (HV) components and stranded electrical energy, contaminated fire water run-off, and risk of reignitions. These risks can pose both short and long-term threats to responders, the community, and the environment.

Currently, best practice procedures and response protocols are predominantly based on international standards and research. However, it will be critical to develop and understand what the risks and hazards of LiB incidents are in an Australian context.

The targeted research in SARET will allow the development of appropriate and considered input to Australian codes and standards, inform and provide evidence for important improvements in protocol, procedures, and equipment for first responders, and provide support for educational materials for first responders, industry and the community.

4.2.1 Fire

LiBs in TR are a fire hazard (Russo *et al.*, 2018), with injuries sustained as a result of flame burns from small to medium-size LiBs such as vapes, portable battery packs, e-bicycles, and e-scooters being the most common LiB-related injury necessitating hospital presentation (Seitz and Kabir, 2018; Duff *et al.*, 2024; Hu *et al.*, 2024; van de Warenburg *et al.*, 2025). Thermal radiation hazards due to the intense heat from LiB fires can also lead to major burns, with Mao *et al.* (2024) finding that in large LiB incidents such as EV fires, first-degree burns could result from a 20 second exposure to radiant heat when standing less than one metre away. Radiant heat from flames may also lead to further fire risk as flammable materials adjacent to the LiB incident are ignited or, in the case of large-scale battery incidents, heat radiation levels exceed survivable levels (Kang, 2024). Particularly in an underground carpark or enclosed/semi-enclosed spaces, Kang (2024) found that vehicles or charging equipment near an EV fire were at a high risk of spontaneous ignition.

TR in LiBs produce fires that are considered extreme in behaviour, as they are fast developing and can produce jet-like flames from vented gases that are released under pressure (Mao *et al.*, 2024). Jet fire during TR is concerning as it can be unpredictable, highly directional, and can propagate the spread of flames rapidly. In full-scale EV fire testing, jet flames of up to 2.5 m in length were measured and contributed to further fire spread to the rear of the vehicle (Zhao *et al.*, 2024). Flames can ignite nearby combustible materials or trigger adjacent cells to fail which can exacerbate the size, complexity, and intensity of the initial incident (Quintiere and et al, 2016).

Fire hazards can also occur after the initial incident due to the reignition potential of LiBs. Reignition can occur immediately after fire suppression efforts are reduced due to inadequate cooling, or may occur hours, days, or even weeks after an incident due to cells not being fully consumed or due to adjacent cells sustaining damage during or after the initial incident (Smith, 2012, p. 3; Finegan *et al.*, 2018; Liao *et al.*, 2020; Jiaqiang *et al.*, 2024).

4.2.2 Explosion

TR research has shown that the 'smoke' observed from a LiB in TR is a vapour cloud of toxic and flammable gases that are vented from within the battery (Christensen *et al.*, 2022; Goupil *et al.*, 2022; Snyder and Theis, 2022). When the liquid electrolyte atomises, it expands causing internal pressure to build up within the sealed LiB packaging, resulting in a vapour cloud release with explosive potential. As these vapour clouds have similar visual attributes to smoke plumes, there is a risk that these vapour clouds could be mistaken for conventional fire smoke in the initial stages of a LiB incident due to the lighter gases that behave similarly to a smoke plume. Unidentified or delayed identification of LiBs in TR, due to the similarities between their vapour cloud and a smoke cloud, presents a clear hazard to first responders and the community with the potential for explosions to occur. Explosive LiB incidents are most likely to occur when the vented gas mixture is confined and accumulates until it reaches its explosive limit (Wang *et al.*, 2012, 2023; Finegan *et al.*, 2018).

When gas pressure builds inside a confined space, ignition of the vapour cloud can result in an explosion, flames, heat, and molten projectiles such as battery parts or casing materials (Finegan *et al.*, 2018; Sauer, Gaudet and Barowy, 2024). Finegan *et al.* (2018) found that hot projectiles and molten materials can be released as part of the explosion as a result of pressure relief valves becoming blocked. Projectiles can lead to a greater dispersal of the flames or effluents and cause injury to nearby persons. Hazards posed by explosive events from LiB incidents can have fatal consequences (Beining, Thogmartin and Kurz, 2020; DNV GL, 2020; McKinnon, DeCrane and Kerber, 2020). The explosion risk of LiBs in confined spaces was realised in 2019 during the McMicken BESS facility explosion in Surprise, Arizona, where four firefighters were severely injured in a deflagration event (DNV GL, 2020; McKinnon, DeCrane and Kerber, 2020). In 2021, a 25 MWh LFP installation on top of a Beijing shopping mall exploded, killing two firefighters and injuring another (CTIF, 2022). Explosions can also compromise the structural integrity of buildings or rooms with Sauer, Gaudet and Barowy (2024) reporting that when enough gas pressure builds up, the resulting explosion can dislodge a garage door, potentially injuring persons outside of the structure. Explosive damage can be hazardous even with smaller LiB devices such as e-cigarettes, portable power packs, and e-micromobility, through the projection of molten debris and flame propagation (Seitz and Kabir, 2018; Diab *et al.*, 2021; Duff *et al.*, 2024).

The volume of vent gases and type of vapours produced during TR varies with LiB cell chemistry, cell format, SoC, and failure mechanism. LiB vent gas is primarily made up of H_2,

CO_2, CO, and some hydrocarbons (such as CH_4, C_2H_4, C_2H_6, and C_3H_6) (Golubkov *et al.*, 2014; Willstrand, Pushp, Ingason, *et al.*, 2023). The composition of the off-gassing compounds influences a battery's reactivity. Reactivity is measured through characterisation of the volume fraction of fuel required to create a flammable/explosive environment (lower flammability limit (LFL)), flame propagation rate through a non-turbulent gas mix (peak laminar flame speed (PLFS)), and the highest pressure generated during a combustion or explosion event relative to the atmospheric pressure (maximum over pressure (MOP)) (Baird *et al.*, 2020). LFL, PLFS, and MOP are currently used to assess the volatility of battery cells in TR, with Baird *et al.* (2020) finding that NCA and LCO cells to be more volatile compared to LFP. This is due to LCO batteries producing a higher amount of CO and hydrocarbons by volume compared to LFP, and NCA cells producing a higher volume of H_2 and less CO compared to LFP and LCO batteries. The greater the measured values of LFL, PLFS, and MOP, the greater the hazard potential is for explosive potential (Baird *et al.*, 2020). While the results from Baird *et al*. (2020) are useful in collating research on explosivity of LiBs of different chemistries, as the studies used within the paper test under different atmospheric conditions, future works would benefit from analysing how the variation in testing atmosphere may impact explosivity potential.

SoC can influence the timing and size of the explosive activity (Larsson, Andersson, Blomqvist, Lorén, *et al.*, 2014; Bravo Diaz *et al.*, 2020; Wang *et al.*, 2022, 2023). Liao *et al.* (2020) provides an extensive summary of the type of gases released during LiB TR based on SoC, finding that the higher the SoC, the greater the number of species of gases released. As SoC increases in a LiB, CO_2 production begins to decrease. As an inert gas, CO_2 helps dilute the volatility of the gas mixture produced during off-gassing (Golubkov *et al.*, 2015; Willstrand, Pushp, Ingason, *et al.*, 2023). A higher SoC has increased kinetic energy and a faster transition from an oxygen-rich to an oxygen-lean environment, increasing H_2 and CO production (Golubkov *et al.*, 2015). The faster the transition from an oxygen-rich to an oxygen-lean environment, the more severe the potential explosive event (Willstrand *et al.*, 2023). When SoC is also included in understanding the explosivity of LiBs in TR, Baird *et al.* (2020) found that in LCO cells there was a significant reduction in flammable gases (<25%/v) when the battery was below 40% SoC. These results complement findings from the US Federal Aviation Administration, who found that total hydrocarbon, H_2, and CO volume increased with increasing SoC (Maloney, 2015), with a sharp increase in H_2 and CO volume in cells greater than 40 - 50% SoC.

For first responders, it is important to understand the explosive potential of LiBs as it can impact incident management strategies. For example, Lee *et al.* (2024) studied the implications of different extinguishing methods and found that when an EV was covered in a fire blanket, while the flames were suppressed, the fire blanket also trapped vented gas which impacted explosion behaviour of the battery in comparison to when venting was able to occur freely. With greater uptake of LiB appliances in both industrial and home settings, continued research into the ways first responders can better identify and minimise potential risks and hazards from potentially explosive incidents will be critical in protecting first responders and consumers.

4.2.3 Toxicant exposure

LiBs release highly toxic and corrosive compounds due to the chemistry of the electrolytes, solvents, and binding agents used in LiBs. When a LiB goes into TR, highly toxic compounds of concern such as fluoride compounds are emitted (Andersson *et al.*, 2016; Lebedeva and

Boon-Brett, 2016) alongside typical combustion gases such as CO and hydrogen cyanide (HCN).

Lithium hexafluorophosphate ($LiPF_6$) has been the most commonly used Li-salt in commercial LiB electrolytes (Larsson *et al.*, 2017; Mauger *et al.*, 2018). When $LiPF_6$ decomposes, it forms phosphorous pentafluoride (PF_5) – a colourless, poisonous, non-flammable gas with a pungent odour that is extremely irritating to skin, eyes and mucous membranes (PubChem, 2025b). Inhalation of PF_5 is acutely toxic and can cause pulmonary oedema (PubChem, 2025b). On exposure to water or steam, both $LiPF_6$ and PF_5 will decompose to hydrogen fluoride (HF) and phosphorus oxyfluoride (or phosphoryl fluoride, POF_3) (Larsson *et al.*, 2017). While the toxicity of POF_3 is not known, the compound readily hydrolyses to form additional HF, which is known to be highly toxic and corrosive (PubChem, 2025a).

Table 5. Decomposition of LPF electrolyte salt.

Common name	Chemical formula	Decomposition products	Reference
LPF	$LiPF_6$	$LiPF_6 \rightarrow LiF + PF_5$ $PF_5 + H_2O \rightarrow POF_3 + \mathbf{2HF}$ $2POF_3 + 3H_2O \rightarrow P_2O_5 + \mathbf{6HF}$ $LiPF_6 + H_2O \rightarrow LiF + POF_3 + \mathbf{2HF}$	Wang *et al.*, 2012; Lebedeva and Brett, 2016; Chombo and Laoonual, 2022b

Note: HF produced highlighted in red.

HF is a colourless, fuming liquid or gas with a strong, irritating odour and is highly corrosive to metals and tissue (PubChem, 2025a). It is highly toxic by ingestion and inhalation, and exposure to fumes or liquid may cause severe burns, deep-seated ulceration, and severe and rapid hypocalcaemia (PubChem, 2025a).

SafeWork Australia (2025) advises a Time-Weighted Average (TWA) (8 hrs/day, 5 days/week) of 0.5 ppm or 0.4 mg/m^3 for HF, or a peak limitation of 2 ppm or 1.6 mg/m^3. Additionally, the CDC (2019) set an Immediately Dangerous to Life or Health (IDHL) exposure limit of 30 ppm for HF which is the maximum level of exposure for a person, above which only reliable breathing apparatus can provide workers protection and an ability to escape the contaminated environment.

Mass lost is the total weight of a battery that is lost during a fire event, with higher mass lost indicative of higher potential toxic byproduct production from the battery (Bugryniec *et al.*, 2024). Higher levels of HF production in LiBs were also seen when comparing EVs and ICEVs, with Lecocq *et al.* (2012) finding that total volume of HF produced during a full-scale BEV test to be 5.3 - 7.3 mg/g of mass lost compared to ICEV calculated to be 3 - 3.2 mg/g of mass lost. Based on experimental values, Andersson *et al.* (2013) calculated a potential total of 400 - 1200 g of HF could be released from a PHEV TR and fire (Andersson, Blomqvist and Lorén, 2013).

It is important to note that while LiBs have been shown to produce HF above safe exposure levels, HF levels can vary between battery types due to the range of cell formats and cell chemistries. Lecocq *et al.* (2012) highlighted that further testing must be completed as results should not be extrapolated to other vehicle or battery types. Additionally, when examining a LiB SoC, it is crucial to understand that HF concentrations increase inversely with the LiB SoC (Larsson, Andersson, Blomqvist, Lorén, *et al.*, 2014; Lecocq *et al.*, 2016). Lecocq *et al.* (2016) theorised that prolonged fire propagation in lower SoC batteries challenges the onset of the decomposition of the salts within the electrolyte, thereby allowing for more favourable HF production. Casings, packaging, and fuel load of the device the LiB is powering can further add to the emission profile of a LiB fire. For example, an EV can have similar contaminant exposure as an ICEV, with the addition of the above toxicants contributed by the LiB (Lecocq *et al.* 2012).

Hazards associated with toxicant exposure during a LiB incident can occur at any point during battery failure. Prior to ignition, venting from a damaged cell generates toxic gases which form a vapour cloud. Throughout the combustion phase of TR, smoke and vapours emit a range of toxic compounds, with firefighting intervention also influencing the formation of toxicants from a LiB failure. Q. Zhang *et al.* (2022) measured the effect of water spray on gas production during extinguishment and found that the application of water led to increased proportions of CO, H_2, and HF, while CO_2 decreased. This could have potential implications for managing LiB incidents in enclosed spaces, or choice of extinguishing agent used to ensure firefighters are kept safe.

Persistent off-gassing of a LiB post-incident can still contain highly toxic airborne compounds. Hill (2017) found that after extinguishment, LiB off-gassing was persistent enough to trigger firefighters' CO threshold alarms. These persistent emissions may be more hazardous to first responders due to PPE complacency (Hill, 2017).

Toxic effluent can present a hazard in the clean-up and site management of a LiB incident. Once a LiB has been extinguished or submerged, the leeched chemicals from the battery can contaminate water runoff or the water that the battery is submerged in (Held *et al.*, 2022). Where firefighting run-off water was tested, high levels of heavy metals such as nickel, cobalt, manganese, and lithium were detected over safe thresholds (Held *et al.*, 2022; Szmytke *et al.*, 2022). It will be vital to understand the level of contamination firefighters PPE and PPC might have and how effective current laundering procedures are in managing these high levels of toxic contaminant.

4.2.4 Electrical

The risks associated with electrical hazards from LiBs are relatively low in comparison to fire or explosion risk, with Diab *et al.* (2021) reporting that within NSW between 2005 and 2019, only 8% (n = 2 cases) of LiB-related burns admissions were the result of an electrical injury. However, incorrect handling of damaged LiBs or exposure to HV cables or devices can still occur when responding to LiB incidents and therefore need to be accounted for among the risks associated with LiB incidents.

A damaged LiB at 0% SoC can hold residual electrical charge referred to as 'stranded energy' (Blum and Long, 2016). Stranded energy presents electrical shock hazards to persons accidently coming into contact with battery terminals and closing open electrical circuits on the battery pack (Blum and Long, 2016; Hill, 2017). Hill (2017) found that standard firefighting turnout gear was adequate in protecting against LiB shocks but acknowledged HV DC could penetrate through where PPC is compromised.

As larger scale LiBs such as residential BESS, commercial BESS, and EVs are being more commonly integrated into our day-to-day life, there is an increasing likelihood of incidents occurring that will involve these larger battery systems. Higher capacity LiBs present a higher electrical risk (Long *et al.*, 2013; Blum and Long, 2016; Hill, 2017; Stave and Carlson, 2017; Wöhrl *et al.*, 2021; Snyder and Theis, 2022; Wilkens Flecknoe-Brown and Runefors, 2024). HV LiB systems can complicate incident site management, extinguishing efforts, as well as salvage, overhaul, and post-fire procedures (Long *et al.*, 2013; Hill, 2017). These larger LiBs tend to have strong safety features built in to help manage electrical risk. EV's HV cabling, for example, is isolated from the car's chassis and easily identifiable during rescue incidents due to its bright orange covering (Linja-aho, 2020). Vehicle rescue sheets are also required for every car model and year to allow safe access to cars when responding to incidents (Wöhrl *et al.*, 2021). In cases where an EV incident has occurred and airbags are deployed, an emergency disconnect system disengages the EV's contactors from the battery, isolating the battery's power and rendering the vehicle chassis electrically safe (Wöhrl *et al.*, 2021). In some EV models there is also a manual switch that can be used to disconnect the HV system, however this may not be a feasible tool during an incident if the manual switch is inside the car or inaccessible to first responders (Wöhrl *et al.*, 2021). In these scenarios, while the battery still holds energy, the use of some or all of these safety features can allow safer access to the vehicle (NTSB, 2020). During rescue or recovery operations however, there are still risks that first responders may come into contact with battery terminals which may inadvertently close the electrical circuit and lead to electric shock or arcing (Wöhrl *et al.*, 2021). Emergency disconnection of the HV system may not be successful in the event of substantial damage to the vehicle during an incident, impacting the identification of manual disconnect points (NTSB, 2020).

For a compromised BESS, Hill (2017) found that while electrical currents from the battery were not transferred up the firefighting hose stream during extinguishment, when the BESS was disturbed by metal tools, arcing and sparks were observed. When a battery has not been fully consumed by TR and post-extinguishment operations commence, any live cells could contain stranded energy which may pose a shock or arcing risk if incorrectly handled (Hill, 2017).

4.2.5 Waste management and end-of-life risks

As LiB uptake continues to increase both in Australia and globally, LiB waste generation within Australia is predicted to reach between 100,000 and 188,000 tonnes by 2036, up from 3,300 tonnes in 2016 (Randell, 2016; King and Boxall, 2019). Australia's lack of appropriate LiB collection and transfer infrastructure is posing a hazard for waste management and first responders alike. The Pragmatic Research & Advisory (2024) released results from a survey of waste and resource recovery collection and processing facilities across Australia which found that there could be as many as 12,000 battery-related fires a year across Australia. While this report should be interpreted with caution due to the assumptions made during analysis, should the report be taken as indicative of the growing risks of LiB fires in waste streams, this increase could have major financial, social, and environmental implications for Australian waste and recycling facilities.

Inappropriate disposal of LiBs can lead them to inadvertently entering crushers and shredders that cause mechanical damage, leading to TR (Gausden and Cerik, 2024; Terazono *et al.*, 2024) and rapid flame propagation that is magnified due to the mixed nature of waste and recycling streams (Zhao *et al.*, 2021). LiB-related issues in Australia's waste streams may stem, in part, from a lack of education and resources for the community to engage with to make more informed choices when disposing of their LiB-powered devices. While there may be a general awareness around the hazards of improper disposal of LiBs within the community, Islam *et al*. (2022) found that this awareness does not necessarily translate into appropriate disposal practices of waste batteries. A lack of accessibility and knowledge of safe waste battery disposal practices and collection points, along with a perceived inconvenience, factored heavily into the disposal habits of the community (Islam *et al.*, 2022).

The consequence of fire propagation and facility damage during waste treatment can vary based on a battery's SoC, size, and storage. For devices entering the waste stream, Nigl *et al.* (2021) determined that, of 980 waste battery cells tested, approximately 12% had at least 50% residual SoC, and a further 24% had at least 25% residual SoC. Batteries stored at a higher SoC can lead to more volatile TR (Xie *et al.*, 2022). While Gausden and Cerik (2024) found that smaller devices such as single-use e-cigarettes tended to have short-lived heating events which generated insufficient heat to ignite waste or recycling materials, even at 50% SoC, the impact of larger LiB packs or LiB cells stored together could exacerbate overheating and TR incidents even at lower SoC (Liu *et al.*, 2020; Xie *et al.*, 2022).

Damaged LiBs add an additional layer of complexity in the handling and disposal of cells as they have a high risk of reignition, leaking toxic effluent, and contaminating soils (Zhao *et al.*, 2021). After exposure to abuse or TR events, LiBs continue to be at risk of reignition if they have not been completely consumed or destroyed during the initial event, particularly modules where not all cells may have been involved. These secondary events can re-ignite from the previous abuse event, or stem from subsequent abuse due to mechanical damage, water ingress, or ESC during handling, transportation, disposal or recycling (Mikolajczak *et al.*, 2011; Hill, 2017; Bisschop, Willstrand and Rosengren, 2020; Bravo Diaz *et al.*, 2020; Terazono *et al.*, 2024). In consultation with vested stakeholders, Zhao *et al.* (2021) identified that further technical solutions are needed to address battery recycling and waste management issues within Australia, citing a need for fit-for-purpose containers that will minimise fire risks during transportation and storage (Zhao *et al.*, 2021).

Incorrect disposal, handling, and storage of LiBs can be dangerous, presenting hazards to first responders, the community, and businesses alike. Developing a clearer understanding of LiB end-of-life behaviour such as ignition risk, or propagation risks during transport will enable waste management businesses and first responders to better handle LiBs within the waste management system. Complementary to that, as new suppression and transportation products become available for use, comparative assessments on the efficacy and safety of these products will enable clearer guidance and education materials to be developed around the use of these products.

4.3 Management of LiB-related hazards

Whilst the individual hazards described above are not unique to LiBs, their character, consequence, and co-occurrence are inimitable of LiB failures, and therefore require bespoke hazard management strategies. The scale of LiBs is an important factor to consider when discussing the management of LiB hazards and associated risks. Small-scale, handheld LiBs such as portable devices and light vehicles (i.e. e-scooters and e-bikes) do not present a significant extinguishment challenge to emergency responders as water immersion has been demonstrated to be a practical and accessible solution at this scale (FRNSW, 2023). With adequate risk mitigation measures to prevent exposure to off-gassing and stranded electrical energy from submerged LiBs and appropriate wastewater disposal procedures, this approach can be readily deployed (FRNSW, 2023). At larger scales, from light and passenger EVs to BESS installations, extinguishment becomes more problematic due to the size and weight of these larger LiB packs. Access for extinguishment is often complex at these incidents due to the nature of their use in underground carparks, tunnels, and installation of large industrial-scale BESS (FRNSW, 2024b). Determining appropriate methods and tools for first responders to use when managing LiB incidents is an important step in protecting emergency responders.

4.3.1 Fire

Traditional firefighting strategies involve either cooling the heat source, separating the fire from the fuel, depriving the fire of oxygen, or interrupting the chemical chain reaction involved in combustion (*NFPA 921: guide for fire and explosion investigations*. 2021 edition, 2020). Ideal extinguishment agents are both thermally conductive and electrically insulating (Hill, 2017; L. Zhang *et al.*, 2022), inexpensive, non-toxic, leaving little to no residue, and able to absorb or neutralise toxic gases and effluents (L. Zhang *et al.*, 2022; Majeed *et al.*, 2024). The application of these principles to LiB hazard management is challenging.

Finding suitable extinguishing agents for LiB fires is highly complex due to the fuel load contained within LiBs, the limited access due to housings and sealed design, and the self-sustaining nature of exothermic TR reactions. To effectively manage LiB fires, an extinguishing medium, agent, or tool must effectively remove the heat in the system and provide sufficient, sustained cooling to slow and stop the TR reaction within the affected cells, while also preventing further ignition of surrounding cells.

While different extinguishment mediums and agents have their advantages and limitations, the six main types of portable and fixed extinguishing agents used include water, foam, dry chemical powder (DCP), CO_2, wet chemicals, and vaporising liquids (Mawhinney, 2013; Fire Protection Association Australia, 2016; Rajput, 2018; Aamodt *et al.*, 2020).

4.3.1.1 Water extinguishing

Water is the most common firefighting medium. Water is effective to reduce temperatures below that required for sustained combustion. Standard water suppression, water mist systems, and water submersion are three primary forms of water extinguishment that are currently being used to manage LiB fires (Hill, 2017; Ghiji *et al.*, 2020; Liu, Tao and Wang, 2020; L. Zhang *et al.*, 2022).

Standard water suppression

Water as an extinguishing medium is both a thermally conductive (~0.59 W/m·K at 20 °C) (Huber *et al.*, 2012; Thermtest Instruments, 2021) and cost-effective option for managing fire. Water has been successfully tested on experimental LiB fires at various scales (Yuan *et al.*, 2021; L. Zhang *et al.*, 2022), and is currently a widely recommended extinguishing medium for first responders attending LiB incidents (Ghiji *et al.*, 2020). A number of review articles have surmised that water is an effective option as it has the ability to both extinguish a LiB fire and cool damaged cells to a safe level (Tero, 2019; Ghiji *et al.*, 2020; Geertsema, Jansen and Liempd, 2022). While batteries with a higher SoC can have more extreme TR tendencies, water has been shown to be able to effectively cool and extinguish both cell and module level LiB fires at varying SoC (Tero, 2019; Ghiji *et al.*, 2020). Water is also an effective extinguishing medium for LiBs of different sizes, with testing by Andersson, Arvidson and Evergren (2018) demonstrating that water can provide rapid cooling and fire extinguishment in a purpose-built test BESS module fire. While other extinguishing mediums can help control and extinguish LiB fires, Liu *et al.* (2018) found that water provided the most effective cooling to the LiB in comparison to other tested agents.

A drawback of standard water suppression, however, is the volume needed to maintain a cooling effect on the battery to ensure it does not continue TR. Current recommendations to use ‘copious amounts of water’ to extinguish LiB fires (Paine *et al.*, 2012; National Fire Protection Association, 2018; Yuan *et al.*, 2021) can prove problematic for fire services where water pressure or supply might be limited. The volume of water needed to cool and extinguish a LiB fire is dependent on the efficacy of the water contact, the size of the battery, and its SoC (Hill, 2017; NTSB, 2020).

Long *et al.* (2013) conducted the full-scale fire and suppression test of a 4.4 kWh battery pack and a 16 kWh battery pack both used in different types of EVs. In one test, after initial water extinguishment had resulted in stabilisation of the battery temperature, the pack reignited 22 h after returning to ambient temperatures. During the suppression tests conducted by Long *et al.* (2013), the firefighters applied an average of 592 gal (2,241 L) and 1,853 gal (7,014 L) of water on the 4.4 kWh battery pack and 16 kWh battery pack, respectively.

Liu, Tao and Wang (2020) also conducted full battery pack testing within a car shell chassis. They highlight that large quantities of water can be used to effectively suppress EV vehicle fires; however, they also note that, due to the cover over the modules, water cannot directly act to cool the internal cells and prevent TR propagation through the module.

In July 2021 at a site housing a 450 MWh BESS installation in Victoria, Australia, a fire occurred in a Tesla Megapack which lead to fire propagation in a second unit. Extinguishing this incident required a significant quantity of water. Following the prolonged extinguishment and cooling of the Megapacks, 900,000 L of water was emptied from the catchment pond at the site and disposed of as hazardous waste. This figure does not include water that soaked into the ground or evaporated from the fire. It is estimated that over 1,000,000 L of water was used during the incident, most of which was transported in by bulk water tankers due to the remote location of the site (Blum *et al.*, 2022). Therefore, alternative application methods have been developed and tested to alleviate some of the issues identified during extinguishment testing.

Water mist systems

The use of water mist systems as an alternative or complementary application of water to TR incidents can have benefits over standard firefighting water delivery methods. Water mist was shown to be capable of cooling LiB cells in TR when applied for an appropriate amount of time, typically a few minutes, and demonstrated a cooling rate that exceeded 100 K/s (Liu, Tao and Wang, 2020). Water mist has also been shown to inhibit TR propagation in tests using single cylindrical cells bundled together (Liu *et al.*, 2021; Zhang *et al.*, 2023). The small droplet size created during water mist application can provide endothermic cooling of the battery surface which can help protect neighbouring objects from thermal heat radiation and reduce the volume of water needed in some instances (Cui and Liu, 2021). When comparing the performance of standard water extinguishment to water mist, water mist can extinguish a LiB fire whilst using less volume than is traditionally required for standard water extinguishment (Ghiji *et al.*, 2020; Yuan *et al.*, 2021). However, it was noted that reignition of a LiB fire can occur relatively rapidly after application of the water mist has stopped if there was insufficient cooling of the LiB pack (Juarez *et al.*, 2013).

Whilst water mist has been demonstrated to be effective against small-scale LiB fires such as single cell and small test modules, there is limited evidence on its use in larger-scale fires with L. Zhang *et al.* (2022) highlighting that water mist may not be able to penetrate fires where flame buoyancy is high, with higher heat release rates (L. Zhang *et al.*, 2022), and when batteries are encased in a cover or obstructed by objects. During testing conducted by Zhao *et al.* (2024), water mist was applied at a pressure of 10 MPa at 20 L/min and was found to extinguish flaming and reduce temperature (with a cooling rate of 3.1 °C/s on average) – although in this case, the fine water mist may have initially intensified combustion due to an aeration effect in the flame zone. Temperatures in the passenger compartment reached up to 800 °C during water mist application.

A drawback of water mist in extinguishing LiB fires is that the smaller droplet size vapourises more rapidly compared to the larger droplets produced during a standard fire suppression method which would also limit the ability for water mist to directly settle and cool on the battery surface. (Cui and Liu, 2021). Larger droplets can better penetrate flames and therefore will be more effective in knocking back flames. However, water mist may be of particular use when applied before TR process escalates to reduce the surface heat of the LiB, or in the later stages of extinguishment when flames are under control or when water resource are limited (Cui and Liu, 2021).

Water submersion

An alternative battery cooling method, water submersion, involves the full immersion of a LiB pack in TR in a water bath (National Fire Protection Association, 2018). Water submersion has been widely adopted to help mitigate small to moderate-size LiB fires involving portable devices to some light vehicles (i.e. e-scooters and e-bikes). However, battery submersion also introduces additional challenges.

Submersion containers for large LiBs, such as those found within EVs, have been developed and marketed over recent years – ranging from large containers requiring heavy vehicle transport (EmergencyOne, 2022; Fire Containers, 2022) to small, portable units that can be connected together to create a bund around the EV (Aspil Safety, 2023). Small, lightweight containers or bunds can be carried on any vehicle, easily deployed, and filled with water to create a temporary submersion pool. Other larger manufactured containers have a ‘dipping’ or drive-in option that can be filled with water as required. These heavy-duty options can have additional fire safety measure installed, such as fire suppression systems, cranes, winches, and other on-board cooling options.

Cui *et al.* (2022) found that submerging an EV battery within water was effective in reducing the temperature within the battery to 30 °C and to 50 °C at the location of initial TR. An examination of these dipping containers and possible alternatives was conducted by Hessles and Geertsema (2023). Hessels and Geertsema (2023) documented all the EV fire incidents where dipping containers were used in the Netherlands. The containers were used at EV incidents when it was determined that an ongoing risk of TR in an EV was present. It is important to note that filling of the dipping containers with water was seen as a last resort. Typically, the dipping containers were escorted to a storage area in convoy with a fire brigade pumping appliance. If reignition of the fire was observed on the way to the storage area, the fire brigade would extinguish with minimal water so that the dipping containers could be transported with as little water in them as possible. In extreme reignitions, the dipping container was to be unloaded on the side of the road and filled with water.

With adequate risk mitigation and disposal measures in place, this approach can be readily employed for smaller devices. However, for larger scale batteries, such as those found in light EVs, passenger EVs and BESS installations, submersion methods may not be a feasible solution due to the size, pack configuration, weight, and potential location (e.g. underground garages, tunnels, etc.) of these larger LiBs. Submersion during an ongoing incident may not be feasible, as manoeuvring large devices at risk of, or actively involved in, a TR event is possibly more hazardous than letting it burn out. However, post-incident submersion may enable the continued cooling of a large LiB system while being moved (Välisalo, 2019).

Other risks that need to be considered include persistent off-gassing occurring under water, leading to an increase in pH levels in addition to other contaminants leeching into the water (Hill, 2017). Testing by DNV GL demonstrated that while this method provides adequate cooling, it was not capable of neutralising voltage (Hill, 2017) which could in turn lead to risk of electrocution. Saltwater submersion of a damaged LiB has an additional benefit of removing residual energy from LiBs, reducing the hazard of stranded energy (Waller, Carter and Love, 2022).

Determining appropriate methods and tools for first responders to use when managing LiB incidents is an important step in protecting emergency workers. Water submersion is an effective tool, however it also requires additional safety considerations as well as appropriate disposal of alkaline and contaminated water (Hill, 2017).

4.3.1.2 Foam extinguishing agents

Foam is used primarily to suppress Class B fires involving flammable liquids by blanketing the fire and cutting off the oxygen supply. The two main types of foam agents are aqueous film-forming foam (AFFF) and alcohol-resistant aqueous film-forming foams (AR-AFFF) (or alcohol type concentrate, ATC). AFFF is used in fires involving petrol or oil, while AR-AFFF is used on solvents that readily mix with water. Firefighting foams are designed to extinguish fires by smothering and inhibiting atmospheric O_2.

Zhao *et al.* (2024) tested a compressed air Class A foam system deployed on an EV in TR after 3,910 s. The system was operated with a pressure of 0.75 MPa, flow of 3 L/s, and expansion rate ≥ 6. While the foam effectively extinguished the fire, with an average cooling rate of 9.8 °C/s, the battery continued to emit white vapour, necessitating additional water extinguishment for an 'extended' period, noting the exact time period was not specified in the study. It should be noted that several extinguishment techniques were used in sequence for this study (i.e. fire blanket, then water mist, then class A foams, and further water), and further research should be completed to examine the performance of each of these techniques individually or in isolation.

Similarly, Cui *et al.* (2022) reported that foam was found to not be as effective as water in controlling and cooling packs in TR, with the consumption of each agent being calculated as 0.628 m^3/kWh and 0.743 m^3/kWh for water and foam, respectively. Hill, 2017 found water to be more effective, as the foam blanket does not conduct heat away from the LiB fire. As such, foams have been found to be less suitable for LiB fires as they produce their own oxidiser during TR.

There are innovative foam extinguishing agent chemistries that are being developed which may be suitable for use on LiB fires, as well as Class A, B, D, and F fires (Intelagard, 2021; EMME, 2025). However, continued testing is required to assess their efficacy and suitability. It should be noted that there is currently no applicable standard for the testing and compliance of LiB-specific extinguishing agents (CSIRO, 2023).

4.3.1.3 Dry powder extinguishing agents

DCP extinguishing agents are used to interrupt the combustion chemical reaction by absorbing fuel molecules, and work by interrupting the fuel flame interface but do not act to actively cool the fire. DCP agents are normally discharged from a portable extinguisher via compressed air. Class ABE powders are usually based on monoammonium phosphate, while Class BE powders usually consist of sodium bicarbonate or potassium bicarbonate. Special powders are also available for flammable metal fires (Class D).

A number of research groups reviewed the effectiveness of DCP in extinguishing LiB fires and concluded that DCP was effective at initial fire extinguishment and knockdown but provided inadequate cooling (Liu *et al.*, 2018; Russo *et al.*, 2018; Ghiji *et al.*, 2020; Yuan *et al.*, 2021; L. Zhang *et al.*, 2022). Reignition was frequent in battery packs, with researchers concluding that DCP was not suitable for use on LiBs larger than a single cell (Yuan *et al.*, 2021; Tang *et al.*, 2023). Teubler (2017) tested DCP fire extinguishers on LiB fires while monitoring the associated changes in LiB temperature and concluded that the extinguishment performance was poor, recommending that these extinguishing mediums should not be used for LiB fires. (Ghiji *et al.*, 2020) reported that of sixteen LiB manufacturers, 75% recommended DCP for extinguishment of their product – including two that recommended the use of DCP over water.

While these extinguishing agents can aid in initial knockdown of flames, there is a potential for the misalignment of experimental results with consumer information or expectation. The risks associated with this potential discrepancy make full and transparent disclosure regarding product expectation and safe usage a pressing area of focus for both future research and communication efforts.

4.3.1.4 Gaseous and aerosol extinguishing agents

There are a range of existing gaseous and aerosol suppression agents that have been tested for use on LiB fires. These agents include:

- carbon dioxide (CO_2) (Russo *et al.*, 2018; Yuan *et al.*, 2021; L. Zhang *et al.*, 2022)
- Novec™1230 (dodecafluoro-2-methylpentan-3-one or $C_6F_{12}O$) (Yuan *et al.*, 2021; L. Zhang *et al.*, 2022)
- FM-200 or HFC-227ea (heptafluoropropane, C_3HF_7) (Yuan *et al.*, 2021; L. Zhang *et al.*, 2022)
- INERGEN®, typically a mixture of nitrogen (52%), argon (40%) and carbon dioxide (8%) (Bisschop *et al.*, 2021)
- liquid nitrogen (LN_2) (L. Zhang *et al.*, 2022).

CO_2 extinguishing methods displace air and oxygen to effectively smother fires, and are typically used in Class B and C fires where water is not suitable. Due to their low specific heat capacity and poor capacity to cool a LiB to a safe level, gaseous extinguishing media were dismissed in review articles by Andersson, Arvidson and Evergren (2018) and (Ghiji *et al.* (2020), as well as papers by Russo *et al.*, (2018) and L. Zhang *et al.* (2022).

Water typically absorbs four times more heat per kilogram of extinguishing agent used compared to gaseous extinguishing agents. This is due to gaseous extinguishing agents having a lower specific heat capacity of around 1 kJ/kg°C, as compared to water extinguishing agents with a higher specific heat capacity of 4.18 kJ/kg°C) and good latent heat of vaporization (~2253 kJ/kg) (Ha, Shin and Lee, 2021). The low specific heat capacity of gases as compared to water, and therefore gaseous extinguishing media, was seen as the main cause of the inability of these agents to effectively cool a LiB fire to a safe temperature (Ha, Shin and Lee, 2021). Table 6 below shows the specific heat capacity of some gaseous extinguishing agents versus water.

Despite the limited cooling capacity of gaseous extinguishment, it may prove beneficial in certain LiB installations such as BESS, where excessive use of water or other liquid agents could cause additional damage to uninvolved LiB packs, particularly in the early stages of a fire (Hill, 2017). Russo (2018) compared several extinguishing agents, finding that CO_2 along with dry powder were the least effective at safely bringing a LiB fire under control.

Along with CO_2, Novec™1230 and HFC-227ea are gaseous extinguishing agents that have been tested for their use on LiB fire, but also had limited extinguishing potential (Yuan *et al.*, 2021; L. Zhang *et al.*, 2022). Novec™1230 has a heptafluoropropane concentration of 4 – 6%, and its fire extinguishing efficiency is reportedly close to that of Halon 1301 – a now banned extinguishment agent, due to their contribution to ozone layer depletion (United Nations, 1987).

Studies by (Wang *et al.*, 2018; Y. Liu *et al.*, 2022) found Novec™1230 was somewhat effective at initial knockdown of LiB fires, however the agent provided minimal cooling which is a critical component in the timely and effective management of such fires. HFC-227ea, or heptafluoropropane, is a clean agent fire extinguishing system that works by rapidly cooling the fire through a gaseous discharge. The effectiveness of HFC-227ea in supressing lithium titanate LiB fires was reviewed by Wang *et al.* (2016) where initial extinguishment of a large single cell was promising; however, the agent did not cool the cell to a safe level and ongoing TR was observed. Si, Liu and Xue (2018) also reported on the effectiveness of HFC-227ea and found similar results, where if constant application of HFC-227ea did not occur across the length of the TR event, reignition occurred. This reignition was likely due to inability of the HFC-227ea agent to cool the battery to a point where the internal chemical reactions stopped as well. Si, Liu and Xue (2018) also reported that after being sprayed with HFC-227ea, the LiB ejected projectiles to an approximate distance of 4 m.

Nitrogen gas extinguishers produce an inert gas that deplete oxygen from the fire and are effective on flammable liquid fires, electrical fires, and Class A fires (Andersson, Arvidson and Evergren, 2018). Andersson, Arvidson and Evergren (2018) tested a nitrogen gas extinguishing agent and found that while it was able to achieve initial flame extinguishment, it was less effective at cooling than water and was not able to cool the simulated adjacent cells adequately to halt thermal propagation. Andersson, Arvidson and Evergren (2018) did however highlight that with an appropriately designed system, and enough extinguishing medium to provide pro-longed or sequential discharges over a long enough period, nitrogen gas extinguishers could provide adequate extinguishing capacity.

Although nitrogen's specific heat capacity is approximately 25% that of water, it can both smother and cool a fire owing to liquid nitrogens boiling point of -196 ^{o}C (L. Zhang *et al.*, 2022). However, the reasons for liquid nitrogen's low uptake as an extinguishing agent stem from the associated expense, its susceptibility to application issues due to ice formation blocking the extinguishing nozzle, in addition to transportation and storage problems (L. Zhang *et al.*, 2022).

Alternative to gaseous extinguishment, aerosol extinguishers have been explored for their LiB extinguishment potential as they can be placed in high-risk or confined areas. Aerosol extinguishers produce particles with a large surface area and a uniformed dispersion, creating a more efficient fire-extinguishing system (L. Zhang *et al.*, 2022). However, aerosol extinguishers experience similar problems to gaseous extinguishment as they have a limited capacity to cool a LiB in TR to a safe temperature to prevent further TR activity (Yuan *et al.*, 2021; Geertsema, Jansen and Liempd, 2022; L. Zhang *et al.*, 2022).

In the above literature, gaseous and aerosol extinguishing agents were found to be relatively effective at knocking down flaming combustion from LiB fires. However, they were ineffective at cooling LiBs to a safe temperature to prevent further TR or reignition. When early suppression of fires in ancillary systems, such as BESS, could prevent battery involvement, these extinguishing agents may provide a necessary alternative for fire mitigation measures when water suppression is problematic or unavailable.

Table 6. Specific heat capacity of gaseous extinguishing media (M.J. Hurley, 2016; preproom, no date).

Extinguishing medium	Specific heat capacity (J/kg·K)
Carbon dioxide	858
Nitrogen	1040
Argon	520
Water	4182

4.3.1.5 Specialist LiB fire extinguishing agents

There is a pressing need to understand the efficacy and applicability of specialist LiB fire extinguishing agents, for both the community and firefighting agencies in Australia.

At the time of publication, there are no Australian standards or guidelines for testing the efficacy of commercially available LiB fire extinguishing agents. Despite this, there are several extinguishing agents advertised as suitable and effective against LiB fires. Examples of commercially available extinguishing agents marketed for application on LiB fires are described in Table 7.

Hill (2017) reported testing of three water-based extinguishing agents, namely F-500 EA®, FireIce®, and Pyrocool®, along with an aerosol agent and water, in fire tests involving pouch and prismatic LiB cells and modules. At a cell level, all agents tested by Hill (2017) proved slightly less effective than water at cooling. At a module level, there was no evidence to suggest the agents tested performed any better than water. The aerosol tested was able to knockdown the fire, but was significantly less effective at cooling the fire compared to water. While the three water-based extinguishing agents were able to provide an initial knockdown of the fire, none were as effective as water at cooling a LiB fire.

Yuan *et al.* (2022) compared the extinguishing effectiveness and cooling capacity of 3% F-500 EA® and water mist in experiments involving TR of LFP modules and found that 3% F-500 EA® exhibited three times the cooling capacity of water mist. A limited experiment conducted by Tang *et al.* (2023) in which F-500 EA® was compared with water mist, F-500 EA® extinguishment experienced a sharper drop in LiB temperature than the test involving water mist. However, the tests conducted by Tang *et al.* (2023) were not repeated, and some anomalies could be observed in the reported thermocouple data, impacting the reliability of these results.

Table 7. Examples of extinguishing agents marketed for application on LiB fires.

Agent	Trade name(s)	Description	Associated website
Aqueous Vermiculite Dispersion (AVD)	AVD-Li or Lith-Ex	Hydrated laminar aluminium-iron-magnesium silicates	https://www.avdfire.com/
Micelle encapsulator agent	F-500 EA®	Encapsulating agent for use on multiple classes of fires. Advertised to absorb 6 - 10 times more heat than plain water and ability to ‘capture’ fuel and vapour in a molecular level.	https://hct-world.com/products/chemical-agents/f-500-encapsulator-agent/
Polyacrylate polymer gel	FireIce®	Water additive for enhanced fire suppression and retardant. Claims to interrupt fire triangle through suffocation and heat removal. Advertised as eco-friendly.	https://geltechsolutions.com/fireice/ https://fireicesolutions.com/
Hydrogel BM 048	Anogas Hydrogel, ASAPs Hydrogel	Hydrogel BM 048, a thermo-responsive gel with a clay additive for Class A, B, F fires and LiB fires	https://anogas.com/
Multiclass foam	Pyrocool®, Pyrocool® Green	0.4% or 1% foam, for use on multiple classes of fire. Advertised as environmentally safe, with excellent cooling properties. Suitable for use on Class A, B, D, pressurized 3D fires, EV fires.	https://www.pyrocooltech.com/ https://intelagard.com/firefighter-and-first-responder/

4.3.1.6 Efficacy of existing and new extinguishing agents

There are some competing and nuanced outcomes regarding the use of specialist extinguishing agents on LiB fires. Tests comparing the cooling effect of water, water mist, foam, and other extinguishing media by Russo *et al*. (2018) concluded that water and foam agents were most effective at cooling LiB fires. Hill (2017) however did not recommend using foaming agents, highlighting the risks of using an encapsulating agent such as foam due to the way it blankets the fire inhibiting heat removal. A review by Ghiji *et al.* (2020) also dismissed the use of foams as an extinguishing agent due to its inability to smother a LiB fire and the likelihood of LiB jet flames penetrating a foam blanket. While extinguishing agents with less heat capacity, such as high-expansion foam, still achieved extinguishment, they were found to provide reduced cooling compared to water based agents (Andersson, Arvidson and Evergren, 2018).

An important distinction was found as agents such as water and low-expansion foam, with a high heat capacity, provided rapid cooling and fire extinguishment in testing conducted by Andersson *et al*. (2018), and reduced water surface tension associated with low-expansion foam may have improved the possibilities for water penetration in these scenarios (Geertsema, Jansen and Liempd, 2022).

A combination of extinguishment techniques that incorporate specialist extinguishing agents have been flagged as potential forms of mitigation and management for LiB fires. Staged extinguishing practices may be valuable with Hill (2017) highlighting, that due to water and water-based agents potentially short circuiting undamaged or neighbouring cells, combining gaseous extinguishing agents in the initial phase of fire suppression, followed by a water-based suppression system, may help reduce the risk of further cells going into TR. Additionally, extinguishing agents or additives mixed in with water can reduce the amount of water needed for extinguishment (Egelhaaf *et al.*, 2013), making it a viable option in circumstances where large volumes of water are not available or advisable for extinguishment.

While many of these agents can knockdown LiB fires initially, their capacity to cool the battery to a safe level was less consistent, with failure to cool leading to a risk of additional cell damage and the potential for further TR events. As more specialist extinguishing agents are brought to market, developing a working understanding of their extinguishment method, their interactions with LiB fires, and efficacy of their fire mitigation and control potential, is critical to ensure that consumers of these products can make well informed decisions. Effective communication regarding, and regulation of, these products and their use will be pivotal in protecting and effectively managing LiB fires for both firefighters and the community.

4.3.1.7 Specialist LiB fire extinguishing tools and equipment

Along with specialist LiB extinguishing agents discussed in Section 4.2.1, specialist fire extinguishing tools and equipment are also being developed and commercially sold for use on LiB fires. There are a wide range of tools including EV fire blankets, undercar nozzles, piercing nozzles, and high-pressure extinguishing lances such as the Rosenbauer ‘Battery Extinguishing System Technology’ and Murer® ‘E-Extinguishing lance’®. To effectively support safe and successful fire management in LiB incidents, for both firefighters and the public, rigorous testing must be undertaken to provide reasonable recommendations and evidence for the effectiveness and safety of the product under different scenarios.

EV fire blankets

Large fire blankets have been designed to contain EV fires without the need for prior extinguishment. These blankets are usually made from fibreglass and are designed to be deployed over an active fire, to smother and contain the fire to the vehicle of origin. The blanket can remain in place until the battery has sufficiently cooled or the fire has self-extinguished (PT Rescue, 2023). As the fire blanket must be placed over the vehicle, it does require first responders to be in close proximity to the involved vehicle and therefore in potential danger of injury.

Preliminary tests by Zhao *et al.* (2024) have shown that fire blankets can provide initial flame and external heat suppression from the vehicle. However, due to the blanket trapping gas vapours produced from the battery during TR, when the blanket was removed the car quickly reignited and the temperature and volatility of the flames was reported to be much more intense. Lee *et al.* (2024) also found similar outcomes with regard to the volatility of gas build up when using a fire blanket, with the resulting explosion large enough to lift the blanket.

Fire blankets have also been tested in combination with other extinguishing methods. While using an extinguishing lance with seawater, Lee *et al.* (2024) applied a fire blanket to the vehicle and found that while the use of the lance allowed for a more controlled gas accumulation under the blanket, the outcome was still a considerable explosive reaction from the gas buildup. Lee *et al.* (2024) also measured HRR, with the blanket resulting in the highest HRR of 899.74 kW.

EV fire blankets may be of use where access to large volumes of water required for extinguishment is limited, or in locations where sensitive environmental receptors are located to reduce the spread of contaminated firefighting water runoff. However, appropriate safety measures would need to be in place to ensure that first responders were protected from any potential explosion or reignition risks due to heat and gas trapping. Further research needs to be done to determine how or if fire blankets can be effectively deployed in LiB fire events, and what firefighting practices and safety measures need to be adopted to mitigate the hazards posed by the toxic off-gassing and potential explosive event.

Figure 9. EV fire blanket deployed on a vehicle (from Hessels and Geertsema, 2023).

Zhao *et al*. (2024) deployed the fire blanket after 132 seconds, which they acknowledged was a quicker deployment than that noted in other literature, although they found that it effectively extinguished flames. However, the temperature inside the car suddenly increased as the fire blanket was deployed as a result of the fire blanket preventing the hot smoke from venting. The maximum temperature inside the vehicle was recorded at ~600 °C, with the temperature dropping after the blanket was removed. Fifty-seven seconds after the blanket removal, reignition occurred as the flammable gases and air mixed, noting that the flames were more intense than before the use of the fire blanket.

Undercar cooling nozzles, piercing nozzles, high-pressure extinguishing lances, and e-extinguishing lances

A simple innovation marketed for use in EV fires is the undercar cooling nozzle, or 'pancake' nozzle, that is designed to connect to an attack hose and be slid beneath an EV between the wheels. The design provides a dispersed spray pattern directed upwards towards the undercarriage to directly cool the surface of the HV battery in EVs. Unlike piercing or lancing devices, the undercar nozzle does not penetrate the LiB module or pack; rather, it acts as an external coolant to the battery casing.

Figure 10. Spray pattern from an undercar cooling nozzle (from Turtle^{TM} Fire Systems, 2023).

Unlike the undercar cooling nozzle, a number of piercing and lancing devices have been designed to deliver water directly into a LiB module or pack undergoing TR. Tools such as the Cold Cut Cobra's 'Cold Cut Cobra system', Rosenbauer's 'Battery Extinguishing System Technology', and Murer's® 'E-extinguishing lance'® aim to breach the LiB casing and directly apply extinguishing agents to the cells within the casing unit. This method of direct extinguishing medium application can allow for better access to the compromised cell, and for some tools enables the application of large volumes of extinguishing medium directly to the compromised cells.

The Cold Cut Cobra C 330 system, for example, is an ultra-high-pressure water mist lance designed to penetrate through construction material that operates at 300 bar and uses 28 L/min of water (Cold Cut Systems, 2023). The device operates with the assistance of an abrasive to cut through LiB batteries and their casings at high pressure, allowing for better access to the compromised LiB cells for extinguishment and cooling. The device can be mounted on light vehicles and firefighting appliances.

The primary benefit of penetrating through a LiB pack is greater extinguishment and cooling efficiency, therefore potentially reducing the total time required at each LiB incident. However, penetrating through a LiB pack also increases the risk of penetrating undamaged cells, leading to further TR and, in some instances, has been shown to lead to the ejection/explosion of individual cells inside a LiB (Hessels and Geertsema, 2023).

Rosenbauer have produced an extinguishing system solely for underslung batteries on electric vehicles. The 'Battery Extinguishing System Technology' has a piercing stinger which is driven through the external casing and LiB pack from underneath the vehicle to pierce holes into which water can be directly injected. The system then delivers water into the LiB pack at 8 gal/min, or approximately 30 L/min, at 100 psi and can be deployed at a distance of 25 ft, or approximately 7.62 m (Rosenbauer, 2022). The additional risks that the Rosenbauer system introduces are similar to those of other penetrative extinguishment systems, such as the Cold Cut Cobra.

Another LiB penetration system is the Murer® 'E-extinguishing lance'®. The 'E-extinguishing lance'® is driven into the LiB pack to deliver low pressure water flow directly into the LiB. After initial fire knockdown, the lance can be driven into the battery pack using a sledgehammer or similar tool from any location around the vehicle, usually through the footwell, but can be customised to an individual vehicle manufacturer's emergency response guide/data sheet. Once the tip of the lance has been driven into the battery pack, water or other extinguishing agents can be directly injected through the nozzle into the battery pack until sufficient extinguishment and battery cooling has been achieved. Use of the device was reviewed by (Egelhaaf, Ruecker and Heyne, 2021) and demonstrated that the 'E-extinguishing lance'® was effective on crashed EVs, however the tip of the device dulled and melted after multiple uses and would therefore require an ongoing consumables cost. The authors also noted that the installation of the 'E-extinguishing lance'® system could be improved to reduce manual strain and injury (Egelhaaf, Ruecker and Heyne, 2021).

The development of tools to improve the efficiency and safety of managing a LiB incident shows some promising applications, particularly in the EV space. At the time of publication, however, limited peer-reviewed testing had been undertaken to comparatively assess the consistency, effectiveness, and safety of these tools for first responders. To consider incorporating speciality equipment into firefighting doctrine, comparative testing of the different tools and equipment will need to be undertaken to assess their efficacy. If fit for purpose, this data can then be used to develop appropriate doctrine, standards, and protocols for first responders, to ensure the safe and effective deployment of these tools.

Fireproof bags, storage containers and other equipment

To manage potential hazards, speciality equipment such as battery racks, storage containers, fire blankets, and sleeves have been developed (CellBlock FCS, 2023) and promoted to the community and industry as protective equipment that is able to suppress fires and halt propagation of a LiB fire.

While these products may provide potential options for safer storage and hazard management of LiBs, independent testing should be a priority to establish whether these products meet relevant standard requirements. This will enable appropriate safety, training, and educational materials to be developed and distributed.

4.3.2 Explosion

While LiB explosions present a clear hazard to the welfare of first responders and the community, preliminary research has suggested that effective testing of gas levels might improve first responders' capacity to safely assess and manage risk, both during and after a LiB incident.

Atmospheric monitoring using multi-head gas detectors can assist in the management of incidents involving flammable gases. Standard detectors currently used by fire services detect the concentration of flammable gases as a percentage of the lower explosive limit (LEL) using a catalytic sensor, oxygen content of the atmosphere in per cent volume of atmosphere (%vol), CO in ppm, and hydrogen sulphide in ppm. LiB off-gassing, however, produces a wide range of gas types that can vary depending on LiB chemistry and SoC (Liao *et al.*, 2020). It will be important to experimentally test the suitability of current atmospheric monitoring equipment and, as part of that assessment, determine whether additional gas testing equipment might provide valuable reference levels to help protect first responders from explosive hazards in LiB incidents.

4.3.3 Toxicant exposure

Highly toxic, flammable, corrosive, and irritant substances are produced during LiB TR (Szmytke *et al.*, 2022). Toxicants present a hazard in both the immediate situation with skin irritants and vapour inhalation, but also long-term due to exposure to carcinogens. PPE and PPC must protect from the physical impacts of fire, explosion, and electrical hazards, but also acute and prolonged harm from chemical and toxicant exposure (Szmytke *et al.*, 2022). Polycyclic aromatic hydrocarbons (PAHs), along with HF, are of particular concern due to their carcinogenic properties (Stec *et al.*, 2018; Held *et al.*, 2022).

Due to the quantity of PAHs, HF, and hydrogen chloride (HCl) produced by LiB fires, VTT Technical Research Centre of Finland recommended the use of conventional PPE including self-contained breathing apparatus (SCBA), with consideration to use of suits with a higher water vapour resistance level, of Z21 in compliance with EN 469:2005, to ‘prevent the fumes entering through the skin’ (Välisalo, 2019).

A study by Kent *et al* (2013), however, found that PPC was penetrated, likely through skin on the neck which was the least protected area, leading to skin exposure to toxicants. Contaminated turnout gear released chemicals such as benzene into the air 25 minutes or more after firefighting had ceased. Additionally, PAHs including benzene, toluene, xylene, and styrene were released into the air from firefighters’ breath at a higher rate just after firefighting than just before.

In tests conducted by Held *et al.* (2022), firefighter PPC was exposed to smoke from an EV module fire where TR smoke was determined to contain metals and fluorine. After conventional laundering processes were used, PPC was adequately washed of the contaminants (Held *et al.*, 2022). As the types and quantities of toxicants from a LiB incident vary from other fire types, decontamination procedures and laundering of PPC and effectiveness of PPE may need to be reassessed for Australian firefighters to ensure both acute and longer-term exposure risk is known and is managed to safe levels. This testing will need to be completed for a range of chemicals including PAHs and HF using compliant Australian PPE and PPC to ensure that toxicant levels are measured and determined against Australian Standards.

With regards to different extinguishing methods, VTT Technical Research Centre of Finland considered the toxicity of emissions and run off from LiB fires and found that water typically resulted in the ‘cleanest’ run off, in comparison with other extinguishment agents tested, with a pH towards the alkaline (Välisalo, 2019).

As large-scale LiBs continue to proliferate, the implementation of specialist hazardous materials (HAZMAT) capabilities for LiB incidents warrants consideration.

4.3.4 Electrical

To manage the hazards and risks of electrical injury during a LiB incident, appropriate PPE and PPC should be worn when responding to a LiB incident, particularly BESS or EV incidents involving potentially larger batteries. While the risk of electrical shocks from a LiB incident are relatively low compared to the risks of fire or explosion, firefighter PPC and PPE can provide some shock protection (Hill, 2017). Care should be taken when handling fire-affected larger battery packs, due to the risk of electric shock or electrocution from stranded energy. It is not recommended that batteries are handled, opened or otherwise dismantled, or accessed within small enclosures (i.e. cabinets and containers) without adequate visual inspection of possible exposed battery terminals or cells (Blum and Long, 2016; Hill, 2017), regardless of whether alternating current (AC) power has been isolated from the incident site. Non-contact DC voltage detectors have been developed (G.L McGavin, 2023) as a potential solution to stranded energy electrocution risk.

Risk of electrocution from damaged HV batteries must be mitigated at all LiB incidents. Traditional voltage detectors typically require close proximity or contact with the electrified object to test for voltage, while non-contact DC voltage detectors aid in mitigating risk by testing for voltage from a distance.

When managing the electrical risks of LiBs, new products and techniques are being explored for the safe discharge of stranded energy (Rask *et al.*, 2020). However, there are currently limited options for emergency service personnel to handle stranded energy discharge during or post-incident. Immersion of the damaged battery in water or salt solution is currently the recommended course of action. Submerging in salt water has been shown to improve discharge rates for damaged LiBs with residual charge (Torabian, Jafari and Bazargan, 2022). This is a cost effective and simple method of rendering a battery safe with minimal intervention (NTSB, 2020). Alternatively, a trained and authorised specialist can be called to assist in attending the site of the incident to isolate, dismantle, or discharge the battery and render safe.

4.3.5 Waste management and end-of-life

To avoid cells short circuiting during transport, cell electrodes and battery terminals should be covered with insulating tape with appropriate transport containers and labelling (Phung, 2020). Additionally, packing materials and specialty containers can also aid in the safe transportation of LiBs.

With a number of options for packing media available to provide cushioning during transportation of damaged LiBs for recycling or disposal, some specialist materials have been developed that claim to be not only fire resistant, but also able to absorb the heat and toxic gases during thermal events involving LiBs (Radcliffe *et al.*, 2022). CellBlockEX, for example, uses porous glass spheres that have a reported thermal conductivity of 0.06 W/m·K and a ‘softening’ point of 700 °C (CellBlock FCS, 2021). Extover® by Poraver® melts at high temperature, absorbing heat and forming a hard casing to encapsulate the LiB (Poraver, 2024). Speciality fire suppression media such as these can provide potential alternatives to help manage the risks of reignition and TR in LiBs during the waste and end-of-life management processes.

The efficacy and benefits of different packing materials were compared by Pan *et al.* (2014) who looked at the functional properties of five packing materials – sand, vermiculite, Sorbix™, absorbent, and PyroBubbles®. Pan *et al.* (2014) found that there were significant differences in the effectiveness of the different packing media, with sand exhibiting the lowest thermal diffusivity and highest thermal conductivity, slowing a LiBs ignition while also maintaining the lowest temperature once the battery was in TR. Importantly, as new technologies and products continue to be developed, assessing their effectiveness and how they may be used to reduce the risks posed by LiB incidents will be important to ensure best practices can be maintained and implemented for first responders.

Additionally, education around appropriate disposal of LiB devices and easy-to-access drop-off points may reduce the rate of potential LiB-induced incidents seen within the waste stream across Australia. In Japan, Terazono *et al.* (2024) found that 80 - 90% of incidents could be attributed to LiB devices being crushed or shredded during the waste process, and proposed that a separate collection category be integrated into the waste management plan to help reduce the number of LiBs disposed of in non-combustible waste.

5 Considerations for design of LiB experiments

Designing valid, reliable, and appropriate solutions to manage LiB incidents requires an understanding of the range of scenarios, products, and potential hazards that can be encountered. Such solutions require comprehensive risk minimisation and mitigation strategies. Tests designed to compare and evaluate the impact of LiB incidents, hazards, and solutions need to be representative, realistic, and reproducible.

While in recent years there has been a large amount of LiB TR research undertaken, a lack of standardised methodologies and conditions – including diverse trigger methods, varied measurement apparatus, inconsistent parameters and conditions, varied cell chemistries and form-factors, and often small numbers of experiments – creates a fragmented and disparate body of work.

Comparison of the results, specifically on fire behaviour, vent gas emissions and composition, and additional hazards can be difficult. As such, the development of appropriate hazard management solutions is challenging.

5.1 Safety standards for LiBs

The standard and regulatory landscape within Australia is complex and ever-changing. Currently, the Australian Competition and Consumer Commission sets mandatory, legislated product standards, while other organisations, such as Standards Australia, develop voluntary standards. There are no legal repercussions for selling products which do not meet voluntary standards.

There are a wide array of safety standards worldwide which focus on the safety of LiBs, their operation, and their response during abuse events. These standards provide useful insight into industry level testing and expectations for the safety of LiBs. While some standards relate directly to installation, transport, or implementation of LiBs, many standards also include compliance criteria to different abuse types that LiBs may be subject to during their use.

Some common abuse methods include ESC, overcharge and forced discharge, crush, penetration, impact, and heating or fire exposure. These abuse methods are typically mirrored in the literature, however the methods used to apply these abuse types can vary greatly between studies. Other abuse methods described within LiB test standards include altitude, vibration, temperature cycling, or projectile, which are not as commonly seen throughout the literature.

While these standards attempt to bring a consensus performance and design of LiBs, there needs to be greater harmonisation of terminology, testing conditions, testing parameters, and pass/fail criteria within the industries, and greater harmonisation of abuse testing that reflect real-world applications and scenarios (Bravo Diaz *et al.*, 2020). Several key standards applicable to LiB safety and testing are discussed below.

5.1.1 Australian Standards and legislation

Standards Australia publish standards for Australian industries and organisations to achieve best practice regarding a wide range of products and services. Several of the standards they publish are adoptions of international standards that have been adapted to better reflect the Australian climate and market. Some relevant standards include:

- AS 15194:2016 *Cycles – Electrically power assisted cycles – EPAC bicycles (also known as pedelecs) (EN 15194:2009, MOD)* (for e-bikes with a maximum continuous rated output not exceeding 500 W)
- AS/NZS 60335.2.114:2023 *Household and similar electrical appliances – Safety Part 2.114: Particular requirements for Personal-e-Transporters (IEC 60335-2-114 Ed 2, MOD)*
- AS/NZS 5139:2019 *Electrical installations – Safety of battery management systems for use with power conversion equipment*

AS/NZS 5139 specifies requirements for general installation and safety requirements for BESS. This may become more important as the implementation of BESS becomes more common in both commercial and residential settings.

It is noted, within the NSW regulatory landscape, that the *Fair Trading Amendment Regulation 2025* (NSW) amending the *Fair Trading Regulation 2019* (NSW) commenced on 19 February 2025. The amendments require identifying information such as serial numbers, external approval, maximum speed and power rating, and information for electrical and fire safety to be displayed on e-micromobility devices within NSW.

5.1.2 UN and ADG Code requirements

The United Nations (UN) issues recommendations for the transport of dangerous goods in their UN Recommendations on the Transport of Dangerous Goods Model Regulations (UN Model Regulations) (United Nations, 2023b), which are adopted worldwide.

The *Australian Dangerous Goods Code* (ADG Code) (NTC, 2024) provides consistent technical requirements for the land transport of dangerous goods across Australia, and adopts the structure, format, definitions, and concepts of the UN Model Regulations. Both documents refer to the safety test criteria and test methods defined in the UN Manual of Tests and Criteria (United Nations, 2023a), specially under Part III Subsection 38.3 (commonly referred to as UN 38.3).

UN 38.3 is a self-certify standard and independent third-party certification is not required for compliance. However, the manufacturer must comply with the requirements of UN 38.3 where the LiB is intended to be transported by road or air in Australia.

The tests required for LiB cells and batteries in UN 38.3 include altitude simulation, thermal stability, vibration, shock, ESC, and overcharge pass criteria. These standards are a test of what can be reasonably expected during normal transportation and LiBs must pass without cell failure or entering TR. It should be noted that UN 38.3 does not test drop, projectile, penetration, ISC, crush, or fire exposure abuse methods, which might be reasonably expected in the event of a transportation accident.

5.1.3 ISO/IEC standards

International standards are developed by the International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC) and are adopted worldwide for a variety for applications. ISO/IEC have developed several standards addressing LiB safety, although most are not mandatory within Australia. Relevant standards for LiB safety include:

- IEC 62133 *Secondary cells and batteries containing alkaline or other non-acid electrolytes – Safety requirements for portable sealed secondary cells, and for batteries made from them, for use in portable applications*
- IEC 61960 *Secondary cells and batteries containing alkaline or other non-acid electrolytes – Secondary lithium cells and batteries for portable applications*
- IEC 62133-2 *Secondary cells and batteries containing alkaline or other non-acid electrolytes – Safety requirements for portable sealed secondary cells, and for batteries made from them, for use in portable applications – Part 2: Lithium systems*
- IEC 62485-5 *Safety requirements for secondary batteries and battery installations – Part 5: Safe operation of stationary lithium-ion batteries*
- IEC 62619 *Secondary cells and batteries containing alkaline or other non-acid electrolytes – Safety requirements for secondary lithium cells and batteries, for use in industrial applications*
- IEC 62660 *Secondary lithium-ion cells for the propulsion of electric road vehicles – Part 1: Performance testing, Part 2: Reliability and abuse testing, Part 3 – Safety requirements*
- IEC 62281 *Safety of primary and secondary lithium cells and batteries during transport*

Note: IEC 62281 is similar to UN 38.3.

5.1.4 UL standards

Underwriters Laboratories (UL) provide independent product safety certification in the USA which, in conjunction with other organizations and industry experts, publishes consensus-based safety standards. For lithium batteries, key standards are:

- UL 1642 *Lithium Batteries*
- UL 2054 *Household and Commercial Batteries*

Note: UL 2054 defers all component cell level testing to UL 1642.

- UL 2271 *Batteries for Use in Light Electric Vehicles (LEV) Applications*
- UL 2272 *Electrical Systems for Personal E-Mobility Devices*
- UL 2580 *Batteries for Use in Electric Vehicles*

- UL 2849 *Electrical Systems for eBikes*
- UL 62133-2 *Secondary Cells and Batteries Containing Alkaline or Other Non-Acid Electrolytes - Safety Requirements for Portable Sealed Secondary Cells, and for Batteries Made from Them, for Use in Portable Applications - Part 2: Lithium Systems*
- UL 9540 *Energy Storage Systems and Equipment*
- UL 9540A *Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems*

5.1.5 EN Standards

European standards are developed collaboratively by three standard organisations – the European Committee for Standardization (CEN), European Committee for Electrotechnical Standardization (CENELEC), and European Telecommunication Standards Institute (ETSI). The relevant LiB standards include:

- EN 15194:2017+A1:2023 *Cycles – Electrically power assisted cycles – EPAC bicycles*
- EN 50604-1:2016/A2:2025 *Secondary lithium batteries for light EV (electric vehicle) applications – Part 1: General safety requirements and test methods*
- EN 17128 *Light motorized vehicles for the transportation of persons and goods and related facilities and not subject to type-approval for on-road-use – Personal light electric vehicles (PLEV) - Requirements and test methods*
- EN 61960-3:2017 *Secondary cells and batteries containing alkaline or other non-acid electrolytes – Secondary lithium cells and batteries for portable applications – Part 3: Prismatic and cylindrical lithium secondary cells, and batteries made from them*
- EN 61959:2004 *Secondary cells and batteries containing alkaline or other non-acid electrolytes – Mechanical tests for sealed portable secondary cells and batteries*
- EN 62133-2:2017/A1:2021/AC:2022-01 *Secondary cells and batteries containing alkaline or other non-acid electrolytes – Safety requirements for portable sealed secondary cells and batteries made from them, for use in portable application – Part 2: Lithium systems*
- EN 62620:2015/A1:2023 *Secondary cells and batteries containing alkaline or other non-acid electrolytes – Secondary lithium cells and batteries for use in industrial applications*

5.1.6 NFPA Standards

The National Fire Protection Association (NFPA) also produce various fire safety and building codes. Currently, the only published standards relating to LiBs are:

- NFPA 855 *Standards for the Installation of Stationary Energy Storage Systems*

- NFPA 110 *Standard for Emergency and Standby Power Systems*
- NFPA 111 *Standard on Stored Electrical Energy Emergency and Standby Power Systems*

The NFPA is also currently in the process of developing a new standard, NFPA 800, which will provide uniform minimum requirements to provide protection from battery hazards – proposed as the *Battery Safety Code*.

5.2 Thermal runaway initiation methods

Single cell LiB experimental research has been thoroughly established since LiBs were introduced in the 1990s. Although LiBs have proliferated through the global market, there is limited understanding of the hazards and risks that are associated with their uptake, which is further compounded by the fact that methods and techniques used to research their safety are disparate between studies, and that a number of these studies are not easily applicable to real-world, emergency response conditions.

As LiB applications increase in size and energy density, understanding how to safely implement battery modules is critical. The way that these packs respond to different abuse conditions and their behaviour during TR is essential for improving safety outcomes for the community and first responders.

5.2.1 LiB single cell abuse testing

Currently, a wide range of literature exists examining different abuse methods and the responses from LiBs. Most literature has focused on cylindrical cells (Rappsilber *et al.*, 2023), which have a prolific market share. Additionally, recent focus has shifted towards EV safety, with research on how to optimise, protect, and enhance LiBs for use within these products which has become critically important as EVs begin to grow within the market. While current studies examine the safety of LiB cells, the majority of the literature identified here is conducted in controlled laboratory settings which, although useful for characterising LiB failures, may not fully consider the interactions that may be present in the human environment (Bravo Diaz *et al.*, 2020). Additionally, firefighting perspectives encompassing matters such as PPE and PPC suitability, extinguishing methods, and after-incident procedures including clean up and disposal are not widely examined throughout the literature.

Design of LiB experiments requires targeting various LiB components or OEM design features, all aspects influencing LiB reaction to TR. All factors, such as LiB chemistry, form factor, SoC, SoH, and abuse method, are important of the safety of a cell and they are widely variable in real-world incidents. Additionally, testing which explores LiBs in TR does not consistently report all these factors. As per the existing standards, abuse methods are already used as a way of assessing LiB safety, regardless of their form factor, chemistry, or other variables in their design. When studying TR, introducing an artificial abuse is needed to force a LiB into TR under controlled conditions.

There are three predominant abuse types, namely mechanical, electrical, and thermal abuse. Currently, there is no standardised method for carrying out these abuse methods under experimental conditions nor a standard method for measuring the outputs from these tests. A comprehensive literature review is critical in determining successful and reliable initiation methods and in making an assessment of where improvements may be made, particularly where existing research involves varied methodologies and sensing techniques and bespoke designs for individual applications.

5.2.1.1 Mechanical abuse

Mechanical abuse involves physical deformation to a LiB cell, triggering ISC through separator deformation and contact between electrodes. Currently, there are several reported methods for mechanically abusing a LiB, with an increase in cell temperature and voltage drop being utilised to signify an ISC event. Many of these methods are identified and explained within the relevant standards (Best *et al.*, 2023).

Indentation is a commonly used method, which uses a blunt metal rod to indent the surface of a LiB, compressing the electrode layers within the cell (Lamb and Orendorff, 2014). The rate at which the rod compresses is slow, with a velocity of 2 mm/min used by Lamb and Orendorff (2014) and 1 mm/min used by Sahraei, Campbell and Wierzbicki (2012). This method has been found to be successful for cylindrical cells, but fracturing of the cell housing often occurs in prismatic cells (Wang *et al.*, 2016).

Crush tests can also be used, which may take different forms. One method used by Sahraei, Campbell and Wierzbicki (2012) involved using a hemispherical punch 12.7 mm in diameter to apply compressive stress to the cell. Ruiz *et al.* (2018) highlight crush tests which use a textured or ribbed plate which is pressed into the cell.

Nail penetration tests are commonly used by researchers. Nail penetration tests are typically conducted at faster speeds than indentation tests, with Ruiz *et al.* (2018) citing a general speed of 8 cm/s, Xu *et al.* (2023) using a speed of 1 cm/s, and Lamb and Orendorff (2014) using a speed of 2 cm/s, while other authors use compressed air to rapidly inject the nail (Essl, Golubkov and Fuchs, 2020; Willstrand, Pushp, Andersson, *et al.*, 2023). There are also variations in how far the nail penetrates the cell. Some concerns have been raised, however, that nail penetration may not be representative of situations which are encountered in real-life scenarios (Lamb and Orendorff, 2014; Wang *et al.*, 2016; Ruiz *et al.*, 2018). As TR can be highly influenced and aggravated by factors such as SoC, nail speed, and nail diameter, this method is not representative of mechanical abuse and ISC which may be caused by such real-life abuse (Lamb and Orendorff, 2014; Wang *et al.*, 2016; Ruiz *et al.*, 2018). Nevertheless, nail penetration is still utilised as by many researchers as a method to initiate TR within a LiB cell, as it does not require the input of any additional electrical or thermal energy into the cell (Lamb *et al.*, 2018).

Some novel tests are discussed by Wang *et al.* (2016) and are highlighted for being impractical, including one developed by the Battery Association of Japan that involved disassembling a charged cell, removing the jelly roll to implant a small defect, and subsequently reassembling the cell – presenting an inherent safety risk. The second method used in this novel test is known as the implanted instigators test (Keyser *et al.*, 2015) which relies on a manufacturer purposefully placing small designed defects within a cell's jelly roll that melt at low temperature causing an ISC. This test is impractical to develop for large-scale testing and may promote difficulties in that conflicts of interest with manufacturers may arise. Wang *et al.* (2016) highlights that the impracticality of these testing methods makes them unsuitable for widespread research. Although utilised in various standards, tests such as vibration, drop, and projectile abuse do not have widespread use or reporting within the literature.

5.2.1.2 Thermal abuse

Thermal abuse involves heating a cell to initiate TR and is widely studied throughout current literature. Primarily, studies adopt the external heating of cells – although the means and methodologies vary between researchers. The rate at which a cell is heated can affect the TR reaction, with a slow heating rate resulting in uniform and complete heating throughout a cell, and fast thermal ramps initiating TR quicker but with less uniform heating throughout the cell.

Thermal ramp rates vary between studies, with temperatures ranging from 0.5 °C/min (Lammer, Konigseder and Hacker, 2017), 1 °C/min (Willstrand, Pushp, Andersson, *et al.*, 2023; Chavan *et al.*, 2024), 2 °C/min (Essl, Golubkov and Fuchs, 2020), 5 °C/min (Cui *et al.*, 2023), up to 20 °C/min (Willstrand, Pushp, Andersson, *et al.*, 2023). Additionally, Willstrand, Pushp, Andersson, *et al.* (2023) also utilised a patented TR inducing device which heated the cell at 50 °C/sec, resulting in rapid TR initiation within 20 seconds. Willstrand, Pushp, Andersson, *et al.* (2023) did include several different heating ramps as mentioned above. They found that increased cell heating before the onset of TR (e.g. with slower heating ramps) resulted in higher characteristic gas production rates. Additionally, they also found that the increases in heat input energy corresponded with increases in cell mass loss, but the different initiation methods did not influence the onset temperature of TR.

There are several different ways to thermally abuse a LiB, which can be generally classified as ambient heating or direct surface heating. Ambient heating has been achieved by way of ovens/furnaces (Larsson, Andersson, Blomqvist, Lorén, *et al.*, 2014; Lammer, Konigseder and Hacker, 2017; Cui *et al.*, 2023; W. Xu *et al.*, 2023), cone calorimetry (Quintiere *et al.*, 2016), or external heaters (He *et al.*, 2022). Ambient heating requires the control of surrounding atmospheric temperature within a closed set-up and longer experimental times. Cone calorimetry, utilised by Quintiere *et al.* (2016), uses a conical heater that is placed directly above the sample, to both apply radiant heat to the sample and to direct the effluents which are released. He *et al.* (2022) utilised surrounding heaters to apply ambient heating to cells at 5 °C intervals within an ARC chamber, which also raised the ambient air temperature to match the cell. Using ARC provides an enclosed system which has been commonly used with the heat-wait-seek (HWS) method. The HWS method involves heating the chamber and sample by a determined temperature. After the temperature within the chamber increases, the system waits – allowing for the temperature to stabilise. Once the temperature is stable, the system enters search mode, which monitors for any exothermic reactions or temperature increases within the sample. If no sample self-heating is found, the ARC system will repeat the process. As the testing is completed under adiabatic conditions, the outputs from TR can be accurately measured. By using ARC, studies can monitor for an extremely sensitive self-heating rate – however, testing can often take prolonged periods of time (i.e. >24 hrs).

Direct cell heating methods are varied between studies and are often described by the power output in watts. Cui *et al.* (2023) utilised electric heating plates that matched the dimensions of the prismatic cell used, with an output of 300 W. The cell was secured within a rig that ensured direct contact with the electric heating plate, providing direct heating to one side of the cell. Similar methods have been employed by Willstrand, Pushp, Andersson, *et al.* (2023) in which their heating ramps were developed by placing cells between aluminium plates with embedded cartridge heaters, Essl, Golubkov and Fuchs (2020) who used 500 W heating stripes on the top and bottom of cells, C. Xu *et al.* (2023) who applied side heating through a 300 W or 720 W electric heater to ensure even heating and power density between different cell formats, and Zhu *et al.* (2023) who utilised a ceramic heating plate with a power setting of 1,140 W.

While direct cell heating may be a faster way to initiate TR, depending upon the set-up, heating plates may result in uneven heat distribution where applied to only one side of the cell. Additionally, the increased speed of heating provided by heating plates may not allow for adequate heat dissipation throughout the cell. The use of direct side heating may not be applicable to cylindrical cells due to their form, and is much more suitable to pouch and prismatic cells. Chavan *et al.* (2024) were able to apply side heating to a cylindrical cell by using flexible heating strips (60 mm x 45 mm) on 21700 cells, which did not completely wrap around the cylindrical cell but could supply heating directly to one side.

Direct heating can also be applied by wrapping a cell surface with a flexible heating element or a resistance wire, providing heating to the entire surface, which is a more suitable method for cylindrical cells. Quintiere *et al.*, (2016) utilised nickel-chromium (nichrome) wire by wrapping it around cells, measuring the voltage and current to determine the power being delivered to the cell. This provides a relatively easy and practical method for applying direct heat to a cell with a variable power output. Use of resistance wires has also been reported by H. Chen *et al.* (2021), who used nichrome wire for validation testing of a developed mathematical model on 21700 cylindrical cells, and Shelkea *et al.* (2022), who utilised Kanthal® resistance wire made of an iron-chromium-aluminium alloy to also validate a developed model on 21700 cells. Wei *et al.* (2023) also utilised heating wire to apply direct heating to the examined pouch and prismatic cells while studying TR within adiabatic environments.

It is difficult to directly compare studies to determine the effects of thermal ramp rates on LiB behaviour as other experimental variables differ between each study.

5.2.1.3 Electrical abuse

Electrical abuse to LiB cells can be achieved by overcharging cells, over-discharging cells, or by applying ESC. Ouyang *et al.* (2018) explains overcharge as an excess current being supplied to a cell that extracts lithium ions from the cathode and transfers them to the anode. Continual overcharging results in thickening of the SEI layer, and the lithium ions also begin to oxidise to their metallic form, leading to lithium plating at the anode. The increase of metallic lithium within the cell leads to the formation of metallic dendrites, which contribute to ISC and the initiation of TR. Alternatively, during over-discharging, the lithium ions are moved from the anode towards the cathode. Continual over-discharging oxidises the copper current collector, with the copper ions transferring towards the cathode as well. As the SEI layer decomposes at the anode, excess lithium and copper ions travel towards the cathode and this build up begins to form metallic dendrites, leading to ISC.

Overcharging is most common within the literature, where a charge rating (C-rate) is typically described. Essl, Golubkov and Fuchs (2020) describe using a 1 C-rate which refers to the cell being fully charged (or discharged) to its rated capacity in one hour. Alternatively, a 2 C-rate, means a cell can be fully charged in 30 minutes. This rate is variable, depending upon the cell capacity, but is proportional and scalable to the battery being tested.

Ouyang *et al.* (2018) used C-rates of 1, 2, 3, and 4 for overcharge and over-discharge. They found that the temperature increased, however cells had to be exposed to an electric heater to trigger TR. When exposed to external heating, overcharged cells exhibited decreased time to failure – corresponding to increased charging rate and more violent TR reactions, including explosions, which could be attributed to the excess energy being stored within the cell. These results, when compared with cells which had been over-discharged in the same study, show that over-discharging cells resulted in less severe TR reactions.

Wei *et al.* (2023) explored the effects of micro-overcharging a cell (0.05 V over the manufacturer's recommendation) prior to thermal abuse. They found that the micro-overcharge resulted in a decrease in total stored energy within the cell, leading to decreased TR hazards but decreased TR onset temperatures in NMC cells. Similarly, Golubkov *et al.* (2015) exposed cells to overcharging processes prior to thermally abusing cells, increasing a cell's SoC up to 140%. As the cell's SoC increased, TR severity also increased, with the onset temperature for TR in overcharged cells dropping from 140 °C to as low as 65 °C and maximum temperatures reaching >1,000 °C.

Larsson, *et al.* (2014) utilised a 10 C- and 2 C-rate, depending upon the battery application. They highlighted that cells overcharged with a 10 C-rate did not enter TR, however they did swell after overcharging – ranging from 350 – 850% of the initial thickness. Interestingly, only a single cell overcharged with a 2 C-rate resulted in TR and fire, which they reasoned could be due to manufacturer defects. They also highlighted that for cells to be overcharged, failure of the BMS (if present) must also occur, and while this may not result in TR, the input of electrical or heat energy may result in a more severe TR process.

Larsson, *et al.* (2014) also attempted to electrically abuse cells using an ESC. This method does not add any additional energy into the cell and can be completed at various SoC. Under their testing, they found that one cell type began to swell and vent quickly, with a peak measured current of 900 A (equivalent to discharge of 128 C-rate). Another cell type (optimised for energy) experienced 1,100 A or a 24 C-rate, which resulted in the positive tab terminal being burnt off, stopping the short circuit. Neither cell type underwent TR, however the cells did experience a rapid increase in temperature.

Overcharging can be used to force a cell into TR, as demonstrated by Willstrand, Pushp, Andersson, *et al.* (2023). In their study, they utilised a 13 A constant current (equivalent to a 0.08 C-rate) to supply current to two cells until TR occurred. They found overcharging cells resulted in an increase in total gas production and higher characteristic gas production rates, however they do note it is difficult to determine whether these differences are caused by higher SoC or by the impact of overcharge cell degradation.

W. Xu *et al.* (2023) used a 0.5 C-rate to force pouch and prismatic cells into TR, noting that the venting behaviour was more violent than nail penetration or side heating. They also reported that overcharging resulted in the most severe damage to cell structure and, like Willstrand, Pushp, Andersson, *et al.* (2023), they found the highest amount of gas production occurred while overcharging cells.

Essl, Golubkov and Fuchs (2020) also forced cells into TR via overcharging with a 1 C-rate. Echoing the work of Larsson, Andersson, Blomqvist, Lorén, *et al.* (2014), Essl, Golubkov and Fuchs (2020) stated that to successfully overcharge the test cells, they had to block the safety devices. In their study, Essl, Golubkov and Fuchs (2020) were able to overcharge cells up to ~146% SoC before TR occurred, which is similar to the reported values of Willstrand, Pushp, Andersson, *et al.* (2023) and Golubkov *et al.* (2015). They concluded that overcharged cells had higher percentage mass loss, produced larger volume of vent gas, and vent gases produced consistently higher percent per volume of flammable, explosive, and toxic compounds.

5.2.2 LiB module and pack abuse testing

With increases in the use of packs and modules in everyday applications, safety testing of LiB modules and packs has also been carried out.

Blum and Long (2016) highlighted that there is limited public fire test data for large format battery packs, no public fire test data demonstrating fire behaviour of BESS, and no data to illustrate hazards to first responders and inform best practice. High costs, rigorous safety protocols, and the need for numerous trials to ensure probative outcomes are key factors contributing to the scarcity of large-scale research with respect to this application. Scaling up experiments from controlled, small-scale conditions to full-scale operations is a complex and expensive undertaking, requiring substantial resources, meticulous safety measures to protect both researchers and the environment, and repeated testing to confirm findings under realistic conditions. Mid-scale testing of modules and packs utilised in EV applications has been utilised as an alternative to large-scale research.

Below highlights some examples of trigger methods used in large-scale abuse testing, ranging from modules to full-scale EVs.

5.2.2.1 Mechanical abuse

Lamb *et al.* (2018) utilised nail penetration on cylindrical and pouch cell packs. These packs consisted of ten cells electrically connected in either series or parallel, and then securely constrained. Based on their previous work in 2014, Lamb *et al.* (2018) used nail penetration at 2 cm/s, to a depth of 20 mm, in specific locations of cylindrical and pouch cells. In cylindrical cells, the indentation was made into the central cell and parallel to the axis of cylindrical cells, whilst in pouch cells the indentation was made into the central or edge cell and parallel to the side. Both modules were electrically connected using 0.005 x 0.200” nickel ribbon.

Feng *et al.* (2015) also utilised nail penetration on a pack, which consisted of six modules, with each module containing two pouch cells. These cells were electrically connected in series for two of three tests, and insulation was used between the cells and the steel constraint to avoid heat transfer. An 8 mm diameter nail was inserted at a speed of 10 mm/s into the outermost cell on the side the pack.

Fransson *et al.* (2024) explored TR propagation in 21700 cylindrical cells, using nail penetration as the abuse method. The modules used consisted of two cells connected in either parallel or series, with a single ‘trigger’ cell penetrated with a speed of 6mm/s, approximately 1 – 3 mm deep. Interestingly, they used black carbon paint to cover all the cells used in testing, to improve the thermal imaging quality and decrease reflectivity.

While Lamb *et al.* (2018) initiated TR in the centre of the pack, Feng *et al.* (2015) initiated TR within the first battery in the module, which led to TR propagation through a single cell at a time rather than heating of multiple cells at once. The abuse location, namely the first cell within the module, was found to lower the TR onset temperature as compared to uniform heating when using ARC.

Kutschenreuter *et al.* (2020) examined fire safety in used EV battery packs, consisting of either cylindrical (12 cells per module) or prismatic (132 cells per module) form factors. Instead of typical nail penetration, Kutschenreuter *et al.* (2020) used mechanical drilling to trigger TR in a cell, however they do not provide specific details on the application their method. In a separate series of tests, Kutschenreuter *et al.* (2020) also used overcharging abuse to initiate TR, discussed in Section 5.2.2.3 below. The outcomes of this study highlight the variability in LiB fires based on cell format regardless of ignition method. Prismatic cells were reported to have longer burning times when compared to cylindrical cells, with battery fire development and speed of propagation dependent on ventilation conditions – where lower O_2 concentrations led to slower burning rates.

5.2.2.2 Thermal abuse

Jia *et al.* (2022) examined TR propagation in 18650 cylindrical cell modules consisting of either NMC or LFP cathodes at low pressure. In this study, they utilised a pack which consisted of five cells that were not electrically connected and a 300 W heating rod with dimensions replicating the cells under test. Insulation panels were used to wrap the entire module to avoid heat transfer between the cells and the environment. The heating rod was placed in the corner of the module, providing direct heating to two adjacent cells, and was turned off once TR was triggered in an adjacent cell.

Lopez, Jeevarajan and Mukherjee (2015) thermally abused packs containing either nine 18650 cylindrical or four prismatic cells electrically connected in either series or parallel. Depending on the test, the cylindrical cells were connected with either 1, 2 or 4 mm of spacing between each cell. A 18650 cell central within the module had a 2” square of heating tape applied, which was supplied with 20 W to increase the temperature in the central cell above 140 °C, in order to observe TR. In prismatic cell tests, the prismatic cells used had side-facing vents on their vertical walls, adjacent to neighbouring cells. Different forms of insulation were used to assess their effectiveness in limiting thermal propagation.

Ouyang *et al.* (2018) also utilised 18650 NMC cells to examine fire behaviour in modules. They constructed a module consisting of three cells connected in parallel, which were placed inside a cone calorimeter and exposed to an electric heater with a maximum power of 2 kW that was placed with a 1 cm gap below the module. Ouyang *et al.* (2018) carried out three series of tests – the first looking at the effects of SoC, using the maximum heating power of 2 kW; the second examining the effects of external heating on fire behaviour, using a 1 kW and 1.5 kW heating power; and finally, the application of external heating (2 kW) while charging or discharging the pack.

Schöberl *et al.* (2024) also used prismatic NMC and LFP based packs to assess TR propagation in cells used in EV applications. Five cells were assembled into modules. These cells were not electrically connected, and the modules were enclosed between two stainless steel plates with insulation on either end. An adapted heater covered the entire side of each cell type and, unlike other studies, a uniform heating power density of 6.2 W/cm^2 was used. This resulted in a heating power of 600 W for the NMC cells and 1200 W for the LFP cells, allowing for a uniform heating density – although noting that the dimensions of the cell were different.

Lam *et al.* (2016) conducted full-scale fire testing on seven vehicles including EVs, ICEV, and PHEVs. In their testing, a 2.4 m x 1.2 m propane sand burner with an output of 2 kW was used to thermally abuse each of the vehicles. The flame temperature produced by the burner was approximately 800 °C, which was similar to measured temperatures of a gasoline pool fire. A sandbox burner was used as a repeatable and controllable substitute to simulate a gasoline pool fire. In their testing, the vehicles were placed centrally above the burner, with all doors and windows fully closed, and the engines turned off. The EVs were stated to have 'large' battery capacity, and the PHEVs a 'small' or 'medium' capacity, although it is noted that the battery capacity was not explicitly stated. The EV and PHEV batteries were charged to either 100% or 85%, and the ICEVs were tested with a 'full' (volume unspecified) tank of fuel.

Kang (2024) also completed a full-scale test on an EV containing NMC pouch cells in a 72.6 kWh pack within a simulated underground carpark. A single pouch cell was forced into TR by a 575 W electric heating sheet attached to the cell within the pack. Thermocouple trees and heat flux meters were distributed within the simulated carpark, including adjacent parked vehicles and structural elements. In their testing, the front windows of the vehicle were opened to assess internal fire dynamics and the vehicle was fully charged.

Lecocq *et al.* (2012) conducted four full-scale vehicle tests including both EV and ICEVs. For the testing, they utilised a 6 kW gas burner to set fire to the front passenger side of the vehicles, with the windows down and the passenger seat lacerated to ensure that a sustained fire would occur within the vehicle.

In 2020, Willstrand *et al.* completed three full-scale fire tests to investigate the toxic gases produced from fires in EVs. They utilised two EVs charged to 80% and one ICEV which had an 80% full tank of diesel. The EV used in the second test had a 40 kWh battery pack which utilised pouch NMC cells, while the EV used in the third test had a 24 kWh battery pack which utilised prismatic NMC cells. To achieve worst-case scenario fires, the EVs had a 30 kW propane burner placed directly under the battery pack and remained active for the entire test duration, while the ICEV had half of its fuel placed on a pan underneath the fuel tank and set alight.

Long *et al.* (2013) conducted full-scale fire tests of large-format LiB using a 400 kW burner to develop the technical basis for emergency response procedures in EV fire incidents. The test included two types of batteries, a 4.4 kWh battery pack and a 16 kWh battery pack both used in different types of EVs. Three tests were undertaken for each battery – two with battery pack only, and the third a simulated full-scale test with representative passenger vehicle interior finishes and upholstery.

Bisschop *et al.* (2019) examined the differences in both external and internal application of commercially available suppression systems for heavy vehicles, using limited quantities of suppressant. By initiating TR with a gas burner on a single cell, they found that applying suppressant to the outside of the pack was not effective in reducing internal temperatures or preventing TR propagation.

Zhao *et al.* (2024) investigated response strategies to BEV fires caused by TR of the battery pack. Zhao *et al.* (2024) conducted a full-scale (38.1 kWh) EV fire test by thermally initiating TR through the attachment of a 400 W electric heating pad to one side of one of the modules in outdoor setting. The TR of batteries was allowed to propagate before suppression measures were applied.

Cui *et al.* (2022) undertook a full-scale EV fire experiment to evaluate fire extinguishing efficiency using an on-site assembled EV fire enclosure. The enclosure was injected with either water or compressed air foam to submerge the battery pack, instead of a water tank.

Blum and Long (2016) conducted full-scale testing on two 100 kWh BESS, comparing external and internal ignition. The BESS systems were installed outdoors to simulate typical commercial installation. For external heating, the BESS was exposed to a 400 kW propane burner for at least 60 minutes and once twenty cells were confirmed to be in TR the burner was turned off. For internal heating, cartridge heaters were placed between cells to internally heat the BESS system. It was found that external heating was able to induce the BESS into TR, however there were no violent projectiles or explosions, and the flames were mostly confined to the BESS. Internal temperatures raised to over 1000 °C, however the external temperature was found to be less than 240 °C. It was reported that the HF was generated to levels above 100 ppm. Internal heating induced multiple cells into TR, but not modules located away from the heat source (i.e. outside the module containing the cartridge heater). During testing, there were no flames, projectiles, or explosions observed, and the HF levels only reached 26 ppm. The maximum recorded external temperature only reached 82 °C, however the module which contained the cartridge heaters reached temperatures over 1100 °C. Unlike external heating, adjacent modules temperature stayed below 200 °C. Blum and Long (2016) highlights that flame spread would be unlikely if manufacturer recommendations for clearance are followed, but this could be affected by wind speeds. They do highlight that the recommended vertical clearance may not be sufficient if combustibles are above the BESS.

5.2.2.3 Electrical abuse

Sun *et al.* (2020) looked at the effects of overcharging LFP modules within the context of safety in implementing BESS. The testing was conducted within a prefabricated cabin (12 m x 2.4 m x 2.8 m) to simulate modules within a real BESS. The pack used consisted of eight modules connected in series with four batteries connected in parallel in each module, totalling 32 cells. The final module had a rated power of 8.8 kWh, with a voltage of 25.6 V. The initial tests involved directly overcharging, using a 0.5 C-rate, until TR occurred. The second test involved using the same 0.5 C-rate, however the current was immediately cut-off once the first safety vent opened. Once the safety vent opened, the module was allowed to stand for 2 hours and, after this period, it was overcharged again at a 0.5 C-rate until TR occurred.

In their 2020 study, Kutschenreuter *et al.* also employed overcharging as an abuse method, but do not provide any details on their methodology. F. Liu *et al.* (2022) examined the effects of thermal insulation in protecting cells during overcharging in a module consisting of five LCO pouch cells, which were held in place with a steel fixture. Different insulation materials were placed between each cell, depending on the test. The examined modules were abused using a 3 C-rate overcharge condition, as they had found this was more severe than 1 or 2 C-rates.

Li *et al.* (2020) completed testing using full-scale battery packs inside an EV vehicle chassis to investigate fire hazards. In their study, they initiated TR through overcharging by a 1 C-rate. Funk *et al.* (2023) undertook an experimental assessment on firefighting techniques and fire dynamics of EVs in an open-sided enclosure and aimed to find efficient suppression methods on vehicle fires at sea. Funk *et al.* (2023) conducted a total of nine full-scale tests using three different types of EVs. The EVs were surrounded by eight ICEVs, with ignition initially induced by short circuit of the battery and then external fuel if initial ignition methods failed.

5.3 Measurement methods

The ways in which live fire tests are measured, and their subsequent results are reported, are also not standardised. With different researchers employing different methods for different objectives, attempting to conduct a fair and accurate comparison between experimental results and outcomes proves challenging.

Rappsilber *et al.* (2023) completed a meta-analysis of 76 experimental research papers looking at the effects of LiBs in TR. During this review it was noted that current literature utilises a variety of test methods to measure peak heat release rate (pHRR), total heat release (THR), and smoke-gas emissions (SGE). Table 8 highlights the methods found to be the most commonly used.

Table 8. Rappsliber *et al*. (2023) review of commonly used TR measurement and reporting methods.

Commonly used test measurement methods	Measured value	Number of references
Combustion apparatus + oxygen consumption (Comb. App)	HRR and THR	12
Accelerated rate calorimetry (ARC)	HRR and THR	5
Cone calorimetry	HRR and THR	4
Fourier transform infrared spectroscopy (FTIR)	SGE	14
Gas chromatography – mass spectrometry (GC-MS)	SGE	10
Multi-gas analyser (MGA)	SGE	6
Nondispersive infrared sensor (NDIR)	SGE	6

5.4 Difficulties assessing LiB standards and research

Currently, there is no shortage of LiB research, with studies delving into the safety, applications, and optimisation of LiBs in society. There is a relatively strong existing database of knowledge surrounding TR and, although the focus is primarily on individual cells, there has been a push towards the EV and BESS space.

As demonstrated above, significant efforts have been made to measure and understand the mechanism of heat transfer between a single cell in TR and its adjoining cells (Feng *et al.*, 2015; Lamb *et al.*, 2018). When understanding TR in a LiB cell, some of the areas that have been identified to have a critical influence on LiB safety and the TR process include cell chemistry, form factor, abuse type, and SoC (refer to Section 4.1.4). Additional challenges arise when considering TR research as there are such a wide range of factors which can influence this process, and a change in any of these variables can have significant effects on a cell's behaviour and the TR process.

While oxygen consumption calorimetry (OCC) as a method for determining HRR (including pHRR and THR) has been widely used in the studies discussed above to compare the thermal properties of TR (Lam *et al.*, 2016; Kang, 2024), this method may underestimate the contribution from the stored energy in battery cells during cell failure (Voigt *et al.*, 2021; Willstrand *et al.*, 2024).

Quintiere *et al*. (2016) combined two techniques to measure the total energy released by a LiB by using the battery as a calorimeter to measure the internal energy and assessing combustion of the ejected gases using a cone calorimeter. They found that the rapid release of energy called for a new technique using a bomb calorimeter with nitrogen to measure the energy of the exothermic reaction and an analysis of the ejected gases to measure the combustion enthalpy.

Voigt *et al.* (2021) compared the sensible enthalpy rise approach (SERA) and OCC and found large discrepancies of 20 - 40%. Willstrand *et al.* (2024) reported that typical methods, such as OCC, can underestimate the THR from external flaming LiB cells by up to 10%. OCC has historically been used as a standard method of measuring HRR in large fires (as in ISO 5660-1 and AS/NZS 3837). However, as LiB cells in TR exhibit behaviours that differ from fires involving common fuels in that LiB fires generate their own oxygen within the cell, OCC is yet to be demonstrated as an appropriate HRR calculation method (Willstrand *et al.*, 2024).

Further, many researchers are required to develop their own bespoke apparatus for trigger methods or for calorimetry, given there is not yet an accepted or conventional method to initiate TR and measure LiB failure.

While this review is primarily focused on TR research, as this is the most pertinent when investigating the safety of LiBs, one of the key difficulties regarding LiB research is the disparate nature of the testing completed, making it difficult to directly compare the results. As varying methods and parameters can influence outcomes, it is difficult to meaningfully compare and extrapolate useful information from the literature.

This problem is further heightened when considering the both the Australian context and the dynamic reality of firefighting. The availability of studies which consider Australian firefighting practices, effects of Australian built environment standards and regulation, the Australian climate, and Australian consumer trends is sparse. It is important to ensure that research is conducted within the intended climate to which it would be employed, therefore it is becoming increasingly necessary that LiB research that directly considers the Australian context is conducted.

Both the Fire Protection Association Australia (FPAA) and the Commonwealth Scientific and Industrial Research Organisation (CSIRO) have released advisory notices to clarify that no applicable standards exist in Australia for portable LiB fire extinguishers (CSIRO, 2023; Fire Protection Association Australia, 2023). Similarly, the Australasian Fire and Emergency Service Authorities Council (AFAC) has circulated an advisory note to reinforce this message, including fire blankets marketed for LiB and EV fires (AFAC, 2024).

Without the necessary certification and independent testing in Australia to evidence and compare product efficacy and safety in the context of local fire and emergency service requirements, agencies are unable to make appropriate evidence-based decisions. The acquisition of new equipment requires a rigorous selection process that not only includes an assessment of the products’ efficacy and efficiency against like and existing equipment and procedures, but extends to the consideration of factors such as ongoing costs, logistics, stowage, shelf-life, maintenance, safety of deployment, disposal, in addition to any required changes to procedures, doctrine, and training.

6 Future research needs

Over the past decade, LiBs have proliferated to become a +US$117 (+AUD$182) billion a year industry (BCC Research, 2025). LiBs are now integrated into many household items and industry appliances. As the cost of the technology decreases or stabilises in many markets, the uptake of larger scale applications, including EVs, residential, and commercial energy storage continues to increase (Stanley, 2018; Ralls *et al.*, 2023).

The rapid uptake of new technologies is often associated with new risks and challenges to public safety (Best *et al.*, 2023). LiBs offer a multitude of benefits as an alternative energy technology due to their high energy density and longer life cycles.

Despite their advantages, the full extent to which LiB technologies pose risk to our community, our firefighters, and our built environment is largely unknown. It is essential that all risks and hazards associated with any new technology are thoroughly researched and understood to ensure safe and sustainable implementation. It is necessary to investigate how LiB's may fail, the consequence of their failure modes, and how we can best mitigate these consequences.

To this end, FRNSW have developed the SARET Research program. While there are valuable sources of research and published data to draw upon, there are gaps within the research that have been identified in the Australian landscape, as discussed in this review.

The myriad of risks and consequences associated with TR in LiBs was addressed in Section 4.2. Between the unusual fire behaviour, propensity for explosion, and the highly noxious emissions contained within a highly energy-dense electrical storage item, emergency responders are presented with a new and unique risk profile during incident response and management.

While emergency responders have the capabilities to manage traditional fire types and behaviours, as discussed throughout this review, these capabilities may not necessarily apply to effective TR intervention and extinguishment.

Toward this objective, the SARET program developed Project 1 to address the research gaps around the efficacy and safety of extinguishing agents and methods, specialty tools and equipment, and first responder personal protective clothing and equipment in LiB-related fire incidents. The primary objectives of SARET Project 1 are to quantify and compare the hazards associated with LiB fires with respect to cell chemistry, format, configuration, state of charge, to understand the efficacy and safety of new and existing extinguishing agents, tools, and equipment for use on LiB-related fires. Project 1 also aims to determine the efficacy and safety of personal protective clothing and equipment for use in LiB-related fires, and to provide recommendations for updates to operational procedures and guidelines, and materials for training of first responders in managing LiB-related fires.

With the continuing demand for LiB-powered consumer goods and appliances, and with the upsizing of these batteries, there is a need to establish effective LiB waste management practices within Australia. Due to the rapid uptake of LiB devices, waste and recycling streams are not adequately prepared to manage the increasing volumes of electronic waste, as discussed in Section 4.2.5. In addition, typical waste and recycling processes introduce opportunities for incidental abuse to disposed LiBs, leading to an increase in waste fires due to inappropriately disposed LiBs.

Therefore, it is necessary to understand the risk and impact of LiB fires within the waste industry. SARET Project 2 will look at fire and explosion risks related to end-of-life or damaged LiBs – considering a battery's SoC, the effectiveness of LiB containment systems in relation to fire propagation behaviour, and incident response measures for first responders to potentially implement during a LiB incident. The aim of this project will be to provide information that can be incorporated into recommendations for improving the practice of safe collection, transport, storage, processing, and enable risk mitigation measures to be developed to better protect first responders and waste facility staff.

While propagation and module-sized tests play a critical role in understanding how TR may progress through EVs, full-scale testing can provide additional insights on TR, fire behaviour, and gas composition – however, this field is still being developed. Knowledge of how an entire EV and BESS fire behaves is important as these applications become more prevalent throughout society. An understanding of how these fires progress and behave under different circumstances is needed.

SARET Project 3 will aim to contribute to the body of knowledge using full-scale EV tests. In Project 3, HRR, toxic and combustible gases released from different arrangements of ICEV and EVs will be measured, fire behaviour and spread between EV to EV, ICEV to EV and EV to ICEV will be examined as free-burns and with sprinkler protection, and the efficacy of various extinguishing agents and methods on ICEV and EV fires will be tested in order to inform emergency response procedures for vehicle fires involving LiBs within enclosed carparks.

Similarly, it has been highlighted that there is limited public fire test data for large-format LiBs, no public fire test data demonstrating fire behaviour of BESS, and no data to illustrate hazards to first responders and best practices as discussed in Section 5.2.2.

As Australia transitions towards renewable and alternative energies, appropriate storage facilities are required to ensure adequate energy is stored to meet peak demands on the energy grid. BESS are a viable and much needed asset being installed at both a residential and industrial scale. With the rapid uptake fuelled by incentivisation programs being delivered by both the State Government and Federal Government, it is critical that the hazards around fire propagation within and between BESS are studied, and that appropriate fire safety requirements are put in place to reduce not only the risk of ignition events but also fire spread.

Therefore, SARET Project 4 will also aim to contribute to the existing body of knowledge and address uncertainty around fire hazards using real-world scenarios to understand fire propagation behaviour in these stationary systems, and the efficacy of extinguishing methods that can be used for developing building and installation policy and first responder doctrine.

Through this literature review, gaps in current knowledge have been identified and promising research has been highlighted – allowing for the development of research questions that need to be answered to better protect better the community and first responders.

Moving forward, research on LiBs must continue to test real-world scenarios to enable results to be transferred from laboratory testing to doctrine, policy and procedural documents. The SARET program will therefore provide the necessary research and data to inform evidence-based decision making for built environment legislation and regulations, for emergency responders within the Australian climate, and to the community to help them safely adopt this prolific alternative energy source.

7 References

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8 Glossary

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

The following definitions apply in this review:

<table>
<tr><th>Term</th><th colspan="2">Definition</th></tr>
<tr><td>Class A fires</td><td colspan="2">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.</td></tr>
<tr><td>Class B fires</td><td colspan="2">Fires involving flammable liquids like gasoline, oil, and other similar substances. Water should not be used to extinguish Class B fires as it can spread the fire. Instead, dry powder, foam, or CO_2 extinguishers are recommended.</td></tr>
<tr><td>Class D fires</td><td colspan="2">Fires involving combustible metals like magnesium, sodium, potassium, and aluminium shavings. These types of fires require specialized extinguishing agents because common methods like water can worsen them.</td></tr>
<tr><td>Class F fires</td><td colspan="2">Fires involving cooking oils and fats, like vegetable oil, animal fats, and grease.</td></tr>
<tr><td>C-rate</td><td colspan="2">The charge/discharge current divided by the nominally rated battery capacity.</td></tr>
<tr><td>e-micromobility</td><td colspan="2">A range of small, lightweight vehicles, driven by users personally. Micromobility devices include, e-bikes, e-scooters, e-skateboards, e-balance/hoverboards, and similar transport devices.</td></tr>
<tr><td>First responder</td><td colspan="2">An individual who is among the first to arrive at the scene of an emergency and provide initial assistance, often involving basic first aid or emergency care.</td></tr>
<tr><td>Flammable/explosive range</td><td>Vapour cloud/air mixture increasing above LEL/LFL but below UEL/UFL
Explosion can occur when the vented gases are mixed with sufficient ambient oxygen in the air, to create a mixture in the explosive range, and an ignition source is introduced (Bugryniec <i>et al.</i>, 2024).</td><td>Vapour cloud/air mixture decreasing below UEL/UFL but above LEL/LFL
Explosion can occur when the volume of vented gases results in a fuel-rich atmosphere and oxygen is introduced by a change in ventilation conditions (such as a door being opened), in combination with an ignition source (DNV GL, 2020).</td></tr>
<tr><td>Heat release rate (HRR)</td><td colspan="2">The rate at which the chemical energy of the fuel is released during the combustion process.</td></tr>
<tr><td>Heat-Wait-Seek (HSW)</td><td colspan="2">A testing method used to assess the thermal safety of batteries. It involves a three-step process – heating the battery, waiting for thermal equilibrium, and then seeking an exothermic reaction.</td></tr>
<tr><td>Internal short circuit (ISC)</td><td colspan="2">Occurs in a battery when the anode and cathode are unexpectedly connected internally, bypassing the normal charging and discharging pathways.</td></tr>
</table>

Term	Definition
OCC	The method for measuring the oxygen consumed in a combustion system to determine the net heat released.
Peak heat release rate (PHHR)	The maximum amount of thermal energy released per unit time by a material during a combustion process.
Peak laminar flame speed	The fastest rate at which a flame can propagate through a premixed, unburned mixture in a laminar flow.
Primary cell/battery	A battery (galvanic cell) that is designed to be used once and discarded.
Positive temperature coefficient (PTC)	The kind of protective device whose resistivity increases with temperature.
Secondary cell/battery	A battery (galvanic cell) that is designed to be recharged and used multiple times.
Secondary or second responder	A broader term for anyone who supports first responders and assists in the recovery process following an emergency or event, including those who manage resources, cleanup sites, and help restore services.
Sensible enthalpy rise approach (SERA)	A method used to measure heat release rate. Heat release rate is calculated from the temperature rise (temperature of combustion products leaving the control volume T_e > temperature of the air entering the combustion zone T_a) of the gases flowing through a calorimeter.
State-of-Charge (SoC)	The actual amount of charge available in a battery compared to its maximum capacity, expressed as a percentage.
State-of-Health (SoH)	The remaining usable capacity and performance of a battery compared to its original specifications.
Stranded energy	The energy remaining in a cell after efforts to safely discharge the stored energy in damaged lithium-ion cells.

Appendix A Common LiB cell chemistries

Table 9. Some common LiB cathode chemistries (modified from Ianniciello, Biwolé and Achard, 2018).

	Lithium cobalt oxide (LCO)	Lithium iron phosphate (LFP)	Lithium manganese oxide (LMO)	Lithium nickel cobalt aluminium oxide (NCA)	Lithium nickel manganese cobalt oxide (NMC)	Lithium titanate oxide (LTO)
Available since	1991	1993	1996	1999	2008	2008
Cathode	$LiCoO_2$	$LiFePO_4$	$LiMn_2O_4$	$LiNiCoAlO_2$	$LiNiMnCoO_2$	Varies
Anode	Graphite	Graphite	Graphite	Graphite	Graphite	$Li_4Ti_5O_{12}$
Nominal voltage (V)	3.60	3.20, 3.30	3.70	3.60	3.60, 3.70	2.40
Specific energy (Wh/kg)	150–200	90–120	100–150	200–260	150–220	70–80
Charge rate (C)	0.7–1	1	0.7–1	0.7	0.7–1	1
Discharge rate (C)	1	1	1	1	1	10
Lifespan (cycles)	500–1000	1000–2000	300–700	500	1000–2000	3000–7000
Applications	Mobile phones, laptops, cameras	Portable or stationary applications with high charge rate	Medical devices, electric drive units	Medical devices, electric drive units	Electric bikes, medical devices, electric vehicles	Electric drive units
Characteristics	High specific energy, limited specific power, Cobalt expensive	Flat discharge curve, secure but low capacity and high auto discharge	High power and higher security than LCO but low capacity	Similar to LCO	High capacity and high power	Long lifespan, fast charge, secure but low specific energy and expensive

Table 10. Some LiB binder materials (Kaya, 2022; Lee *et al.*, 2023).

Common name	Chemical name	Chemical formula
PVDF	Polyvinylidene fluoride	$(C_2H_2F_2)_n$
PTFE	Polytetrafluoroethylene	$(C_2F_4)_n$
PAN	Polyacrylonitrile	$(CH_2CHCN)_n$
AMMA	Poly(acrylonitrile-methyl methacrylate)	$[CH_2CH(CN)]_x[CH_2CH(CO_2CH_3)]_y$
CMC	Carboxymethyl cellulose	$[C_6H_7O(OH)_3-x(OCH_2COOH)_x]_n$
PAA	Poly(acrylic acid)	$(C_3H_4O_2)_n$
PHT	Poly(3-n-hexylthiophene)	$(C_{10}H_{16}S)_n$
SBR	Styrene butadiene rubber	$C_{12}H_{14}$
LA132	Polyacrylonitrile multiple copolymer	$(-[-R_1-R_2-CH_2-CH(CN)]_n^-)$

Table 11. Some LiB electrolyte salts (Younesi *et al.*, 2015).

Common name	Chemical name	Chemical formula
LiPF	Lithium hexafluorophosphate	$LiPF_6$
LiBF	Lithium tetrafluoroborate	$LiBF_4$
LiFSI	Lithium bis(fluorosulfonyl)imide	$LiF_2NO_4S_2$
LiTf	Lithium trifluoromethanesulfonate	$LiCF_3SO_3$
LiTFSI	Lithium bis(trifluoromethanesulfonyl)imide	$LiC_2F_6NO_4S_2$
LiBOB	Lithium bis(oxalate)borate	$LiB(C_2O_4)_2$
LiDFOB	Lithium difluoro(oxalato)borate	$LiBF_2(C_2O_4)$
LiClO	Lithium perchlorate	$LiClO_4$

Table 12. Common LiB electrolyte solvents (Harris, Timmons, and Pitz 2009; Nagasubramanian and Orendorff 2011).

Common name	Chemical name	Chemical formula
DEC	Diethylene carbonate	$(CH_2O)_2CO$
DMC	Dimethyl carbonate	$C_3H_6O_3$
EC	Ethylene carbonate	$C_3H_4O_3$
PC	Propylene carbonate	$C_4H_6O_3$
EMC	Methyl ethyl carbonate	$C_4H_8O_3$

Table 13. Melting points and initial decomposition temperatures of Li-salts as measured by TGA (Younesi *et al.*, 2015).

Common name	Chemical formula	Melting point (°C)	Initial decomposition temperature (°C)
LiPF	$LiPF_6$	200	125
LiBF	$LiBF_4$	293-300	175
LiFSI	$LiF_2NO_4S_2$	135	200
LiTf	$LiCF_3SO_3$	~420	-
LiTFSI	$LiC_2F_6NO_4S_2$	234	360
LiBOB	$LiB(C_2O_4)_2$	>300	275
LiDFOB	$LiBF_2(C_2O_4)$	265-271	200
LiClO	$LiClO_4$	236	-

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