

Battery Thermal Runaway in eVTOL Aircraft: Risks, Mitigations, and Firefighting Strategies

CAP 3203

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CAA Introduction

Electric Take-Off and Landing aircraft (eVTOLs) are being developed by a mixture of start-ups and traditional aviators, testing the capabilities of battery technology for inter-city and regional flight. They promise to be quieter with potentially lower operational costs than traditional rotorcraft, bringing the opportunity to undertake significantly higher volumes of journeys, unlocking the economic and social benefits associated with improved connectivity. This futuristic model for aviation is known as Advanced Air Mobility.

Many members of the public will be aware of the hazard of carrying lithium-ion batteries on-board within Personal Electronic Devices, with most passengers familiar with the protocols regarding their carriage. The need for these protocols is to minimise the risk of batteries overheating to an uncontrollable extent, a process known as thermal runaway.

The significance of this hazard is now evolving with lithium-ion batteries forming part of the propulsion system for aircraft in development, meaning we need to understand and manage potential risks.

The United Kingdom is putting in place the regulatory framework to allow safe initial commercial piloted operations of eVTOL aircraft by the end of 2028, and as part of this the CAA is working to understand the key risks they face – including those potentially posed by lithium-ion batteries.

This thermal runaway research sits within a wider programme of eVTOL technical research that the CAA has investigated, including downwash and outwash assessments and modelling (CAP3075/2576), and a systems thinking analysis of eVTOL operations (CAP 3141).

UK Future of Flight Programme

The UK Future of Flight Programme encompasses the CAA's work to support the integration of novel aviation technologies, currently focussed on Uncrewed Aviation Systems (referred to informally as drones) and eVTOL aircraft. The programme is sponsored and funded by the Department for Transport, with the DfT's Minister of Aviation also chairing the Future of Flight Industry Group which brings together industry, government and the regulator to oversee the programme.

The funding provided by DfT allows the CAA to undertake research to ensure we implement effective regulation, including through this battery thermal runaway research.

Aims

The use of lithium-ion batteries as part of the propulsion system of aircraft and other electric vehicles poses hazards that need to be analysed, understood and where necessary mitigated. This requires an evidence base to assess the risks and the development of a regulatory solution to enable lithium-ion batteries to be used appropriately. There are also significant discussions taking place within the rescue and firefighting community regarding how best to deal with lithium-ion battery thermal runaway.

To that end, the objectives of this study were twofold:

1. To assess the key characteristics and circumstances that might lead to battery thermal runaway – age, state of charge, chemistry, and diagnostic techniques.
2. To obtain a full picture of the merits and limitations of various firefighting techniques for lithium-ion battery fires

Using the results of this research

The CAA will consider the findings of this independent research as part of our regulatory programme. Many of the report's recommendations have implications for the CAA's procedures, policies and regulations. Where regulatory changes are required, we will work to build these into the existing programme to develop the regulatory framework, in line with the government's objective of seeing initial eVTOL commercial operations from 2028.

Acknowledgements

The CAA would like to thank all who participated in the numerous workshops and technical sessions, both in-person and remotely. Without industry's contribution to this exercise, this exercise would have been rendered impossible.

We would also like to thank colleagues across the CAA who volunteered their time to share their views, helping to start a wider conversation about proactive approaches to safety.

Lastly, but by no means least, we wish to thank the researchers from the Energy Innovation Centre at WMG, who have undertaken a sterling effort to complete this exercise.

Battery Thermal Runaway in eVTOL Aircraft: Risks, Mitigations, and Firefighting Strategies

A report prepared by WMG, the University of Warwick for the UK CAA

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Executive Summary

Lithium-ion battery technology, while widely used and generally reliable, has inherent hazards that require careful management when considering its safe integration into eVTOL aircraft designs. There are no established and proven methods which can be effectively deployed for firefighting lithium-ion battery thermal runaway. Therefore, the knowledge and understanding of the risk, how to mitigate and how to manage that risk in the event of a fire is key to everyone engaged in the design, manufacture and use of eVTOL aircraft.

This report presents the Thermal Runaway (TR) risks associated with lithium-ion battery systems in electric Vertical Take-Off and Landing (eVTOL) aircraft, a critical concern for the UK and global aviation sector's transition towards net-zero emissions. The report aims to provide a foundation starting point to inform stakeholders, including eVTOL OEMs, regulators, Rescue and Fire Fighting Service (RFFS) providers at airports, local fire and rescue services, researchers and the public about the causes, consequences, and mitigation strategies for battery TR-related hazards in the emerging Urban Air Mobility (UAM) sector.

The report begins by explaining the fundamental mechanisms of thermal runaway, how these mechanisms are activated and manifest themselves to TR when different mechanical, electrical, and thermal triggers are present. Material and design factors such as anode-cathode chemistry, cell format, size, intrinsic safety device inclusion play a significant role in dictating the likelihood of TR initiation in a battery pack. Equally important are the operating conditions of the cell/pack in governing the onset and the severity of the ensuing hazard. Higher State of Charge (SoC) reduces the TR onset temperature and increases the maximum temperature during TR. High charge and discharge rates, particularly relevant for the operational requirements of eVTOL, increase the likelihood and severity of TR.

Once a cell is selected, the TR risk of an eVTOL aircraft battery pack/system largely depends on the design choices to mitigate cell TR propagation to neighbouring cells, and if propagation happens, containment. Current regulatory guidelines, i.e. RTCA DO-311A and EASA MOC VTOL.2440 emphasise stopping the cell TR propagation and containment of TR within the battery enclosure if cell TR propagates. Adhering strictly to these requirements, combined with regular monitoring and maintenance, is expected to minimise the probability of cell TR and its propagation. However, extreme scenarios resulting from conditions beyond the testing and certification envelope cannot be eliminated. Different abuse scenarios, such as a damaged battery enclosure and pack due to an uncontrolled landing, or fire originating from a non-battery component, may lead to an uncontained battery pack TR. In such a scenario, the Rescue and Fire Fighting Service (RFFS) personnel at an airport/vertiport need to respond and manage the incident.

The report explores lessons learnt from road EV battery TR incidents. It was found that the traditional methods of firefighting at incidents involving gasoline powered vehicles do not apply to EVs. There is no single method which can be applied for any EV battery thermal runaway; it depends on various factors. Current EV firefighting methods are effectively composed of two approaches: actively extinguishing the fire and managing the fire while allowing controlled burn. Immersion or flooding the battery packs with cooling media e.g. water to actively contain a TR event have been used. To avoid reignition and highly hazardous waste from the run-off, firefighters may consider using a controlled burn of the battery pack, while isolating the vehicle to prevent the fire from spreading to the surroundings. This approach has gained significant attention, as it offers the most efficient, quickest, and lowest impact on the environment. It also removes the reignition risk and less hazardous debris.

Following review of the TR risks, stress factors and lessons learnt from road EV incidents, this report presents a consolidated proposal for RFF of eVTOL aircraft battery TR. This was shaped through the engagement of different stakeholders, including eVTOL OEMs, airport RFFS providers, regional fire and rescue service providers, regulatory authorities, and other RTOs and insurance providers. The RFF is presented in three distinctive phases: Phase 1 being dedicated to evacuation and lifesaving, Phase 2 being containment and extinguishing, and Phase 3 concerns disposal and operational continuity. Details of these three phases can be found in the full report. Phase 1 is initiated upon the first report of a cell TR, flagged by the Battery Management System or an alarm raised by the pilot or ground crew. In this phase, RFF is mainly focused on creating a safe evacuation route and rapidly rescuing passengers and air crew. A simultaneous assessment of the severity of the TR may also be conducted.

Phase 2 focuses on containment and extinguishing. If TR is propagated and fire spreads outside a battery compartment or fire is initiated outside of the battery enclosure and propagated inside battery enclosure, then the fire should be controlled to stop it spreading to surroundings. If there is high likelihood of fire being spread to the surroundings, active suppression should commence. If fire does not propagate outside the battery compartment (except dedicated vent path) then an active intervention may not be required, aircraft can be quarantined for a predefined period, investigated, serviced or recycled.

Phase 3 concerns quarantine, safe disposal, operational continuity and infrastructure assessment following the fire being extinguished. If a controlled burn approach is taken for the battery, the level of damage to the rest of the aircraft is likely to be severe. eVTOL aircraft are predominantly made from composite materials, which are more vulnerable and prone to ignition than alloys. Following recent incidents involving aircraft manufactured with composite materials, it is known that fire is likely to spread to the aircraft structure rapidly and consume much of it. As with any firefighting activity, water runoff must be managed to avoid contamination of the water course or ground water.

The report ends with a list of gaps in current knowledge of how to develop robust methods for RFF of eVTOL aircraft. The key gap is that the methods discussed here are currently opinion-based, backed by individual experience and expertise, gained mainly from the road EV context. This needs to be reinforced by evidence-based understanding from eVTOL aircraft context. Another point is that standards and MOCs concerning eVTOL aircraft are at a nascent stage and require regular and frequent dialogue due to rapid development in this segment. Public funding is critical to address these gaps.

The report offers a foundational framework for understanding and managing battery TR in eVTOL aircraft. It combines fundamental theory, lessons learned from real-world EV incidents, and stakeholder insights to propose actionable strategies for RFFS preparedness for eVTOL aircraft operation. While not a regulatory guideline, it is expected to serve as a critical resource for shaping future standards and operational protocols in the UAM sector.

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List of Acronyms

AC	Alternating Current
ARC	Accelerating Rate Calorimetry
ATC	Air Traffic Control
BMS	Battery Management System
CAA	Civil Aviation Authority
CCTV	Closed-circuit television
CID	Current Interrupt Device
DEC	Diethyl Carbonate
DMC	Dimethyl Carbonate
DO	Document
EASA	European Union Aviation Safety Agency
EC	Ethylene Carbonate
EU	European Union
EUCAR	European Council for Automotive Research and Development
EV	Electric Vehicle
FATO	Final Approach and Take-off Area
FR	Flame Retardant
HSE	Health and Safety Executive
HV	High Voltage
IAFC	International Association of Fire Chiefs
ICE	Internal Combustion Engine
IP	Ingress Protection
IR	Infrared
LCO	Lithium Cobalt Oxide
LFL	Lower Flammability Limit
LFP	Lithium Iron Phosphate
LHR	London Heathrow Airport
LMO	Lithium Manganese Oxide
LTO	Lithium Titanate Oxide
MAN	Manchester Airport
MOC	Means of Compliance
MSD	Minimum Set of Data
NATS	National Air Traffic Services
NCA	Nickel Cobalt Aluminium Oxide
NIPV	<u>Netherlands Institute for Public Safety</u>
NMC	Nickel Manganese Cobalt
NTSB	National Transportation Safety Board
OBD	On-Board Diagnostics
OEM	Original Equipment Manufacturer
PC	Propylene Carbonate
PCM	Phase Change Material
PE	Polyethylene
PM	Particulate Matter
PMMA	Poly Methyl Methacrylate
PP	Polypropylene
PPE	Personal Protective Equipment

PTCR	Positive Temperature Coefficient of Resistivity
QR	Quick Response
RCM	Restraint Control Module
RFF	Rescue and Fire Fighting
RFFS	Rescue and Fire Fighting Services
RISE	Research Institutes of Sweden
RPE	Respiratory Protective Equipment
RTCA	Radio Technical Commission for Aeronautics
SC	Special Condition
SCBA	Self Contained Breathing Apparatus
SEI	Solid Electrolyte Interphase
SOC	State of Charge
SOS	Distress signal
TPFPB	Tris-Pentafluorophenyl-Borane
TR	Thermal Runaway
UAM	Urban Air Mobility
UHP	Ultra High Pressure
UK	United Kingdom
US	United States of America

1 Introduction to eVTOL aircraft battery safety

The UK government has set a target of net zero aviation by 2050, of which all domestic flights must achieve net zero by 2040. Lithium-ion battery-powered aircraft are expected to play a major role in achieving this, especially in urban and domestic aviation [1]. An electric propulsion system offers significantly lower noise and zero air pollution at the point of use. This technological change introduces novel Electric Vertical Take-Off and Landing (eVTOL) variants. Globally, several eVTOL aircraft have been certified, are in the process of certification, and are in the testing and development phase [2]. All current eVTOL aircraft use lithium-ion batteries, and in upcoming decades are likely to continue to use future lithium-ion battery variants. However, battery safety still poses a significant risk. This is largely because the mature international aerospace standards only address the use of lithium-ion batteries in small, auxiliary power systems. While RTCA DO-311a [3] can be used to certify propulsion battery packs for eVTOL aircraft, it was not primarily developed for eVTOL aircraft. Recently, EASA published the means of compliance “SC VTOL.2440 Propulsion Batteries Thermal Runaway” for OEMs to demonstrate the safe management of Thermal Runaway (TR) events of eVTOL aircraft propulsion battery packs [4]. This provides the most up-to-date guidelines for the battery pack requirements, which in turn dictate the pack and battery compartment design.

Battery cells used for eVTOL aircraft are similar to the ones used for road Electric Vehicles (EVs). While road EVs have mostly proven to be safer than their gasoline counterparts, battery thermal runaways do happen. Road accidents and charging are the two biggest reasons for it [5]. For eVTOL aircraft, with much stricter certification requirements, regular monitoring, and maintenance requirements, the probability of battery thermal runaway will be significantly lower. However, the likelihood of thermal runaway cannot be eliminated. Different scenarios, such as a damaged battery enclosure and pack due to a crash landing, or fire originating from a non-battery component, may lead to uncontained battery pack thermal runaway. In such a scenario, the Rescue and Fire Fighting Service (RFFS) personnel at an airport/vertiport need to respond and manage the incident.

RFFS response to an incident involving conventional aircraft powered by traditional fossil fuels is well established [6]. However, TR of a large propulsion lithium-ion battery pack introduces complex and distinct risks. The main hazards are smoke, fire, explosion, toxic gas, flammable gas and vapour cloud [7]. From EV battery thermal runaway incidents, it has already been established that the traditional means of firefighting will have little success in extinguishing such fires. This indicates RFFS response to an eVTOL emergency needs a fundamental reassessment and a new perspective to develop new or enhance existing methods. An effective and robust RFFS response to eVTOL emergencies is critical before commercial eVTOL operations commence.

Foreseeing the requirement for a bespoke RFFS approach and training, this report is a consolidated first effort towards understanding the risk of battery hazards and contextualising it from an eVTOL perspective. The report is the outcome of a six-month consultation program with national and international stakeholders from the eVTOL ecosystem including OEMs, regulatory bodies, airport managing authorities, fire and rescue services, battery fire research experts and insurance providers.

The report begins with a detailed description of the root causes of battery TR in Section 2. The purpose behind providing a deep discussion of the theory behind TR is to provide crucial foundations that are necessary for policymakers and RFFS to rise beyond popular battery misconceptions, such as “LFP batteries will never catch fire”. The scientific reasoning also answers practical questions such as the failure of conventional fire-extinguishing solutions for battery fires, which will enable RFFS personnel to make smart tactical and strategic choices. Thermal runaway theory is followed by Sections 3-6, covering individual and combined effects that battery design and conditions play in dictating the occurrence and eventual manifestation of thermal runaway for Li-ion battery. A multi-scale approach is used to discuss battery design, starting from material-level aspects such as Li-ion cell chemistry, material composition etc. up to cell and pack design options. Passive and active safety solutions are also described as the last line of defence against potential battery hazards. Battery conditions, which are known to influence battery properties and performance, are explained from an event-specific perspective, i.e. TR trigger alongside state and application-dependent factors including cell health, remaining charge and manufacturing quality.

After the causation analysis in Sections 2-6, the report shifts focus to addressing the ensuing hazards from battery TR. Section 7 is dedicated to re-ignition, a phenomenon unique to battery fires that has troubled primary and secondary responders significantly and resulted in bespoke protocols and training for EV fires. Section 8 discusses firefighting methods and their rationale for Li-ion battery TR. The section tries to summarise fire and rescue actions sequentially, starting from the emergency call all the way to disposal of battery/vehicle debris. Section 9 is an attempt at refining battery firefighting methods described in Section 8 for operational eVTOL aircraft, recognising additional challenges (and opportunities) that this sector may present. Section 10 combines a phased approach to eVTOL fire and rescue approaches developed through detailed discussions with stakeholders. Finally, the nascent nature of eVTOL has raised several unknowns pertaining to fire and rescue approach for the eVTOL sector. Addressing these uncertainties requires focused research activities to provide quantified answers. These unanswered questions and corresponding future work are summarised in Section 11.

Many current eVTOL aircraft use lithium-ion cells with high nickel content. This report will focus on these cells; other cell chemistries like LFP, LCO, LTO will not be discussed extensively.

This report in no way should be considered as a UK CAA guideline or recommendations. This report should be taken as information only and could be used by different eVTOL stakeholders.

2 Theory of Battery Thermal Runaway Mechanisms

The primary safety concern affecting all lithium-ion battery technology is a potentially catastrophic phenomenon known as Thermal Runaway (TR) [8], affecting batteries used in eVTOL aircraft, mobile phones, EVs or otherwise. This comes with all the hazards associated; flammable, toxic and corrosive gases and materials, high-temperature debris, explosions, and unexploded abused cells at greater risk of self-initiating runaway. The understanding of triggers and consequences of such an event is vital to improving the safety of lithium-ion technology.

In simplest terms, thermal runaway is a self-accelerating exothermic reaction. It is a positive feedback loop of rising temperatures that increases the rate of exothermic reactions, leading to more heat release, higher temperatures, and faster rates of exothermic reactions [9], see Figure 1. Additionally, heat generation can also come from other sources aside from exothermic reactions [10, 11]. For example, from surrounding components like other cells or busbars. Electric current through the cell, especially during high current charge/discharge, or even a short-circuit, leads to a rapid temperature increase. Further exothermic side reactions from materials introduced by the thermal breakdown of cell components can also occur. Most concerning is a propagating thermal runaway event, the heat and debris from one cell in thermal runaway can be in excess of 1000 °C, resulting in substantial heating of its surrounding environment [12].

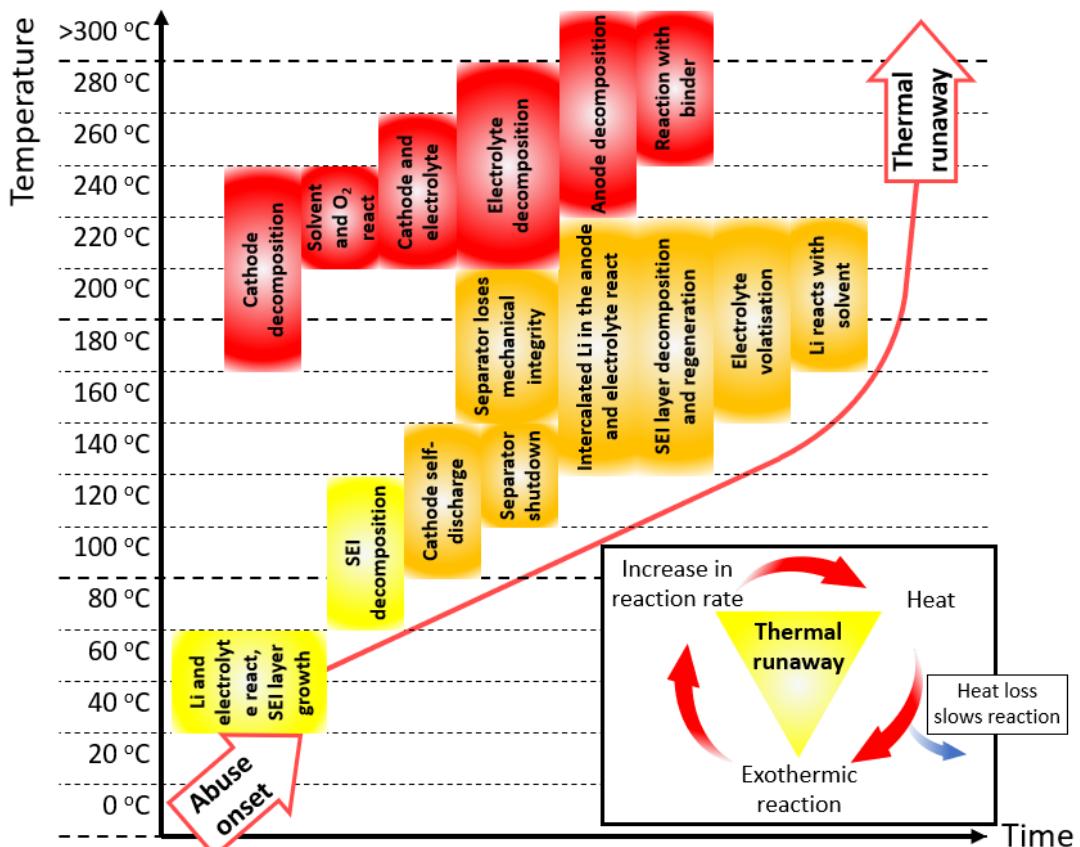


Figure 1: Representation of the behaviour against time for a lithium-ion cell undergoing thermal runaway. Superimposed are the chain reactions during thermal runaway as temperatures increase as well as a simplified thermal runaway positive feedback loop. Figure adapted from [9].

There are three distinct stages of heat generation often cited during the approach to lithium-ion thermal runaway [11, 13, 14, 15], with temperatures of each stage varying depending on literature source and cell chemistry. The first stage is a small heat release from 30 °C to 120 °C. The heat released from this stage is independent of the State of Charge (SoC) of the cell and is worsened by increasing cycle number. It has therefore been linked to the State of Health (SoH) of the cell. It has been theorised as a thermal decomposition of electrolyte in contact with a graphite anode, a reduction of carbonates by means of Li^+ and e^- , although this is unproven. Some sources dispute this [11] as the independence of the process from the SoC implies lithium is not required to be present and the process occurs at much lower temperatures than electrolyte decomposition typically would. The worsening with increasing cycles implies an accumulation with cycling. A safety vent can be triggered during this stage meaning gassing has occurred. Electrolyte decomposition produces hydrogen, which can then penetrate and accumulate within graphite anodes in its atomic form. This atomic hydrogen is released as temperature increases allowing for recombination reactions to occur. Gas measurements showed increasing amounts of hydrogen within a cell as cycle numbers increased, which was largely independent of SoC. Studies have shown that this effect is reproducible by artificially ageing a cell via cycling at 0 °C [11]. Heat released from this first stage matches recombination energy for the amounts of hydrogen; therefore, the first stage exothermic reactions may well be due to hydrogen recombination. The higher exothermic release by hydrogen recombination can then lead to the next two stages of thermal runaway. As the amount of hydrogen within the anode is increased, the activation energy decreases decreasing the initial temperature of the exothermic reaction of the thermal runaway. It must be noted that as this is an ageing process, the state of health of the cell is worsened. Thermal runaway is exacerbated by higher capacities and therefore, a thermal runaway event initiated by a stage 1 process would have a lower capacity and potentially a less violent event. This is because the energy released by the final stages is far higher than that released in the first.

The second stage, from 90 °C to 200 °C is characterised by decomposition and regeneration of the anode solid-electrolyte interphase (SEI), causing gassing and capacity fade. This SEI is a passivation layer formed on the surface of the graphite anode by the electrochemical reduction of the electrolyte during the first cycle. Lithium ions are consumed during this, reducing capacity. However, SEI layers are sensitive to increases in temperature, resulting in their decomposition and subsequent regeneration during any additional cycling, leading to further capacity loss. The electrolyte reduction during SEI formation is also a significant source of gassing (CO_2 and small hydrocarbons). Also, in this phase, the separator will melt (e.g. polyethylene at 130 °C and polypropylene at 170 °C) and collapse, allowing an internal short-circuit.

The final and most significant source of heat generation is the final stage above 200 °C. Oxygen species are released from the cathode via thermal decomposition, which go on to perform highly exothermic side reactions [14]. One such side reaction is the decomposition of the electrolyte at the cathode. Heat release is greater at higher SoC as cathode thermal stability falls and oxygen release rate increases. It is the oxygen that is the major source of heat, allowing significant exothermic reactions to occur. As such, reactions at the cathode are seen as the triggering mechanism for thermal runaway and are self-sustaining. Delithiated cathode materials release oxygen species (O_2^- , O^- , and O_2) at high temperature, which may go on to react immediately with the reductive electrolyte [14]. Both the heat released by the redox

reaction and the consumption of the oxygen species would accelerate the phase transformation of the cathode material allowing the release of further oxygen species. The thermally driven oxygen species release pathway strongly depends upon the surrounding electrolyte. The electrolyte negatively impacts the thermal stability of the cathode, which facilitates phase transformation and oxygen release.

Heat released can also be analysed by the materials present in the reaction. For a cell at 100 % charge [8, 13], the graphite anode decomposes above 250 °C. Electrolyte decomposes between 230 °C and 280 °C, depending upon materials used, leading to the release of small hydrocarbons, CO, CO₂, H₂O, and the decomposition of lithium salts to HF. As for the cathode, electrode composition plays a crucial role, NMC decomposing between 260 °C to 458 °C [16]. The anode can also show a broad and mild exothermic peak around 280 °C relating to the reaction between lithiated graphite and the binder. There is a reaction between the cathode and anode around 230 °C, an exothermic reaction between the oxygen released from the cathode and lithiated graphite. However, the addition of the electrolyte introduces a reaction that has been identified as the thermal runaway trigger [14], presenting a rapid increase in heat generated at around 215 °C. For a cell at 100 % SoC and no ageing, several reactions are shown in Table 1 [8, 13].

The material list in Table 1 is limited, and there is a vast range of chemistries at the cathode and anode, along with electrolyte materials and non-active components that add numerous complexities to the conditions for thermal runaway within lithium-ion cells [13]. Discussions around chemistries will, therefore, form around more common materials already in commercial use. Several standard materials decompose at characteristic temperatures with rapid heat release [8]. This allows thermal runaway to be interpreted as a series of reactions more succinctly. Note that as temperatures increase the thermal decomposition reaction become more exothermic, facilitating the self-accelerating thermal runaway event. Another popular and convenient method to quantify thermal runaway safety is shown in Figure 2. Three temperature values, T₁, T₂ and T₃, are identified during different stages of thermal runaway [17]. T₁ is the onset temperature associated with the first instance of self-heating. It is generally the point of SEI breakdown, as happens in the second stage. The thermal runaway trigger temperature, T₂, defines the point where self self-heating rate significantly exceeds the rate of cooling, resulting in a steep temperature rise. The third temperature, T₃, is the maximum temperature attained during thermal runaway. It is desirable for a battery to have a high T₁ and T₂ for delayed thermal runaway, while a low T₃ would limit the resulting damage. These three temperature values are typically determined using an Accelerating Rate Calorimetry (ARC) experiment and identifying transition points in the self-heating rate.

Under normal operating conditions the cell separator acts to prevent short-circuiting between the two electrodes. However, melt and collapse of the separator as temperatures climbs can lead to an internal short-circuit, which is often cited as critical to triggering the redox reaction of anode-cathode [13, 18], but this is not entirely accurate [19]. PE and PP are common separator materials with melting temperatures of 130 °C and 170 °C respectively. Onset temperature, i.e. T₁, for heat generation caused by the decomposition of SEI occurs below 100 °C [13]. Following this, the initial major heat source comes from the anode under 180 °C. The temperature gradient increases due to these anode reactions and is then joined by the cathode to release heat. Although a PE separator melts at 130 °C, major internal short-circuit will only occur after separator collapse at 192 °C, significantly increasing the heat generation. The rapid

anode-cathode reaction will not occur until 250 °C, i.e. T2, when thermal runaway is triggered. Thermal runaway is mainly determined by this rapid redox reaction rather than the internal short-circuit itself. Rather than initiating thermal runaway the short-circuit merely accelerates its occurrence. Overall:

1. The major heat source is the redox reaction of the anode-cathode.
2. The fire releases lots of heat, but most of the heat is not used to heat the cell itself.
3. The internal short-circuit is critical to trigger the redox reaction of the anode-cathode.
4. The internal short-circuit is not the major heat source that heats the cell to over 800 °C.
5. The redox reaction of anode-cathode is triggered when the initiation temperature reached.

Temperatures will easily climb above the melting point of metals within the lithium-ion cell, such as aluminium current collectors at 660 °C, which will be forcibly ejected along with flammable organic gases. These can easily heat and cause external short-circuits of adjacent cells to propagate thermal runaway. Several gases are produced throughout a thermal runaway event [20], which may pose a hazard to people in the vicinity when vented. This venting can initiate up to an hour prior to the thermal runaway event; this allows for such an event to be detected and managed before a catastrophic scenario initiates. The gaseous mixture is highly combustible and toxic due to the presence of aromatic species. Some of the gases that are released include: carbon dioxide, hydrogen, carbonates, carbonate breakdown products and various lighter hydrocarbons, metal and metal oxide particles (PM2.5 dust posing a carcinogen risk as well as risk to electronic and mechanical systems), HF, etc.

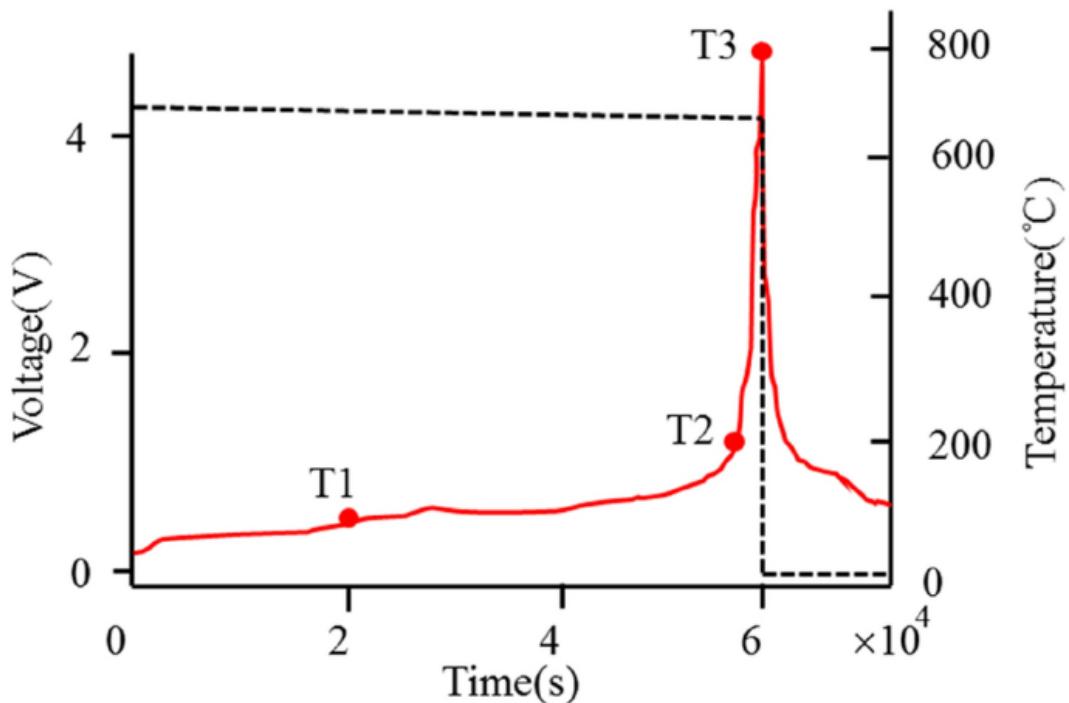


Figure 2 Three characteristic temperature identified during thermal runaway of a Li-ion cell. Figure from [17], licensed under CC BY 4.0.

Table 1: Examples and descriptions of reactions that occur for core materials present within a lithium-ion cell: anode, electrolyte, separator, and cathode. Temperature and heat transfer of reactions are given where possible.

Reactions at the anode	Decomposition and combustion of electrolyte	Separator melting	Reactions at the cathode
SEI decomposition, 90 °C to 120 °C. Some sources report temperatures as low as 60 °C [21]. Heat generated depends upon anode surface area.	The amount of electrolyte influences the heat released. 230 °C to 280 °C (dependent on materials), 210 J g ⁻¹ to 515 J g ⁻¹ (dependent on materials).	PE and PP, melting points at 130 °C and 170 °C respectively. Above these temperatures collapse is reached, electrodes contact and cause internal short-circuit.	LFP, 190 °C to 310 °C, 250 J g ⁻¹ to 290 J g ⁻¹ . (Delithiated LFP) 2Li _{0.5} FePO ₄ → Fe ₂ P ₂ O ₇ + (1/2)O ₂ LMO, 150 °C to 400 °C, 350 J g ⁻¹ to 450 J g ⁻¹ .
Assuming main SEI component is (CH ₂ OCO ₂ Li) ₂ , SEI decomposition is:	Small hydrocarbons (C ₂ H ₄) can be produced via carbonate solvent decomposition.		Li _{0.2} Mn ₂ O ₄ → 0.2LiMn ₂ O ₄ + 0.8Mn ₂ O ₄ • 3Mn ₂ O ₄ → 2Mn ₃ O ₄ + 2O ₂ • LiMn ₂ O ₄ → LiMn ₂ O _{4-y} + (y/2)O ₂ • LiMn ₂ O ₄ → LiMnO ₂ + (1/3)Mn ₃ O ₄ + (1/3)O ₂ Mn ₂ O ₄ → Mn ₂ O ₃ + (1/2)O ₂
(CH ₂ OCO ₂ Li) ₂ → Li ₂ CO ₃ + C ₂ H ₄ + CO ₂ + 0.5O ₂	Decomposition of lithium salt. Further reactions will generate HF. PF ₅ can go on to further reactions with carbonate solvents.		NMC, 260 °C to 275 °C, 325 °C to 458 °C (heavily dependent on ratio of NMC used), 160 J g ⁻¹ to 971.5 J g ⁻¹ (heavily dependent on ratio of NMC used).
SEI regeneration, 120 °C to 250 °C. Intercalated lithium within anode can contact electrolyte once SEI decomposition occurs. Within the stated temperature range, SEI decomposition and regeneration occur simultaneously. Average SEI thickness is stable.	LiPF ₆ ↔ LiF + PF ₅	Separator melting is endothermic, PE and PP -90 J g ⁻¹ and -190 J g ⁻¹ respectively.	Li _{0.35} (NiMnCo) _{1/3} O ₂ → Li _{0.35} (NiMn _{1/3} CoO _{2-y} + (y/2)O ₂
Graphite decomposition, >250 °C. Above 250 °C the balance of SEI decomposition and regeneration is broken when the graphite structure collapses.	Oxidation of carbonate solvents: 2.5O ₂ + C ₃ H ₄ O ₃ (EC) → 3CO ₂ + 2H ₂ O 6O ₂ + C ₅ H ₁₀ O ₃ (DEC) → 5CO ₂ + 5H ₂ O 3O ₂ + C ₃ H ₆ O ₃ (DMC) → 3CO ₂ + 3H ₂ O 4O ₂ + C ₄ H ₆ O ₃ (PC) → 4CO ₂ + 3H ₂ O		NCA, 160 °C, 850 J g ⁻¹ to 941 J g ⁻¹ .
			Li _{0.36} Ni _{0.8} Co _{0.15} Al _{0.05} O ₂ → Li ₂ O + 0.8NiO + 0.05Co ₃ O ₄ + 0.025Al ₂ O ₃ + 0.0372O ₂ 0.18

3 Triggers of Thermal Runaway and Their Impact

Thermal runaway (TR) triggers within lithium-ion cells are often termed ‘abuse conditions’ [8, 9, 10, 11]. Typically, these are categorised into mechanical, electrical, or thermal abuse, as shown in Figure 3. Mechanical abuse is physical strain or deformation leading to deformation or rupture of a cell. This can trigger a short-circuit, which is a common feature for electrical abuse. Short-circuits result in excessive currents. Due to ohmic and internal resistances of cells, excessive currents from short-circuits or over-currents during electrical abuse will generate heat and initiate thermal abuse. This leads to the positive feedback loop of TR. At this point, catastrophic failure can occur, e.g. an explosion at worst case, sending debris outward that can cause physical harm to persons or result in TR propagation of neighbouring cells. Similarly, flames can result, which can also cause physical harm or propagation. Should pressure be released safely, gas, vapour and smoke are released. However, these gases are still hazardous, containing toxic and corrosive materials such as HF acid and flammable hydrocarbons. Figure 3 additionally shows common experimental trigger methods for initiating thermal runaway, as well as the EUCAR hazard levels associated with TR [13, 22]. Trigger methods include:

- Mechanical abuse – nail penetration, crush
- Electrical abuse – metal particle (internal short-circuit defect), overcharge, overdischarge, external short-circuit, overcurrent
- Thermal abuse – external heating

Other ways for a controlled trigger to TR exist, such as internal short-circuit devices [23, 24, 25], but these are less common as they are areas of ongoing research or difficult to employ. Thermal runaway can even be triggered by the ageing of the cell. During ageing, components will degrade such as cracking or breakdown of the electrodes and damage to the separators, resulting in imbalanced internal resistances, unwanted side reactions, etc. This can lead to other abuse scenarios, e.g. gassing leading to high internal cell pressure and lithium dendrite formation.

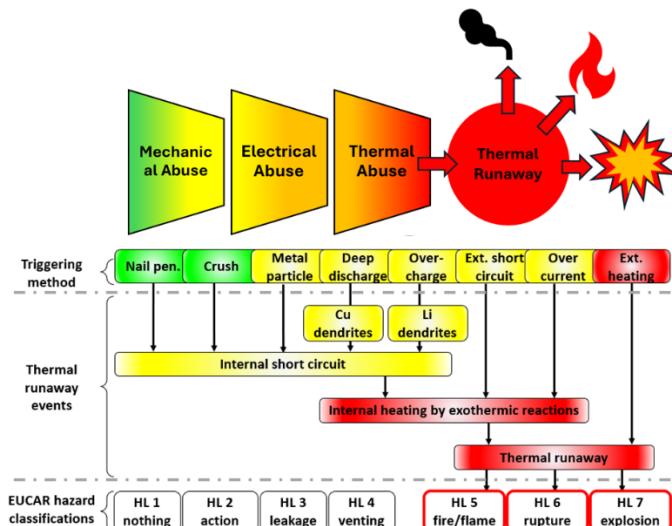


Figure 3: Two flow diagrams, above is a flow diagram of the relations between different abuse conditions that result in thermal runaway and the final consequences. Below is a flow diagram of common experimental triggering methods for thermal runaway, thermal runaway events, and the subsequent EUCAR hazard levels. Abuse conditions are coloured coded according to: mechanical = green, electrical = yellow, thermal = red. Figure adapted from [8, 10].

External trigger conditions, mechanical, electrical, and thermal, need consideration when designing battery packs and management systems. Certain triggers will prove more likely within certain sectors or scenarios, such as high-altitude aviation. Additionally, certain triggers cannot be prevented and will require fail-safes in place. As such, they will be discussed in brief.

3.1 Mechanical triggers

Mechanical refers to external stresses or pressures placed upon the battery pack casing [26]. Some scenarios include crushing, bending, and penetration [27]. These can result from a more impulsive event, from a crash of an eVTOL aircraft, or due to poor design. Loads applied to the casing are transferred to internal components, in turn deforming them. Contact between the separator, anode, cathode, and current collectors becomes possible with the resulting consequences of an internal short-circuit [28]. These mechanical modes of failure are greatly affected by the form factor of the cells, with cylindrical, prismatic, and pouch cells being the most common. As such, the likelihood of failure for mechanical modes can vary for each of the cell forms [29, 30]. Current eVTOL battery packs are mostly made with small cylindrical cells, in few occasions with pouch cells, which is in contrast to the road EVs. Therefore, most of the recent knowledge of abuse testing of prismatic cells as used by road EVs is likely not applicable to the eVTOL aircraft battery.

Battery monitoring systems (BMS) are unlikely to involve stress measurements and will be unable to react to rapid failures, such as in a crash, allowing little warning time for preventative action. Initial signs under a mechanical trigger would likely come from thermal or electrical measurements after cells have already failed, a short-circuit between cell internals measured as a drop in potential. Robust pack designs that can mitigate compression or penetration are key to preventing mechanical abuse, with appropriate fail-safes should this progress too far.

3.2 Electrical triggers

Electrical abuse modes are varied, but easier to detect than mechanical modes. Short-circuits are one example, which can be internal or external. Internally, this is caused by mechanical modes, internal defects, cell ageing, or dendrite formation within a single cell. Externally, failure of circuitry results in excessive power draw across one or more cells [27]. Both lead to rapid drops in voltage, large currents, and significant heat generation. A robust BMS can detect these failures and take actions to potentially prevent further failure of a battery pack.

Other electrical abuse scenarios arise from improper operation. These include overcharging, overdischarging, and overcurrent. The first two are largely failures due to electrochemical processes, whilst the latter is purely electrical. To summarise, when overcharging above 4.2 V, cathodes produce flammable and reactive gases that increase internal pressures [31]. Aluminium current collectors also corrode, leading to cell imbalances [32]. Overdischarging a cell to a very low voltage will cause copper dissolution as well as copper and lithium dendrites. This leads to poor cycle life, degradation of the electrodes, production of gases, and internal short-circuits [33]. Excessive currents cause overcurrent and are a major limiting factor preventing faster charging lithium-ion batteries. This is a significant source of heat generation [10, 11] and can additionally result in dendrite formation as the kinetics of lithium-ion intercalation within graphite anodes are limited. These electrical abuse scenarios can also be detected via a BMS measuring both electrical and thermal properties.

3.3 Thermal triggers

Lithium-ion cells are very susceptible to temperature and are best operated within a narrow range of $20\text{-}40 \pm 5$ °C [27] but can be safely charged and discharged from 0 °C to 50 °C depending upon chemistry with some risks to performance characteristics [34]. This necessitates suitable heat sinks to remove excess energy as well as cooling and heating methods. Lower temperatures reduce discharge energy and power density, and during charging can cause thermal runaway by exacerbating dendrite growth [35]. Higher temperatures, conversely, improve energy and power, but excessive heat generation will result in accelerated degradation. Exceeding the safe temperature limits initiates the sequence of decomposition reactions that lead to T1, T2, and all the way to TR, as discussed in the last section. Sources of temperature within a lithium-ion battery include [10, 11]:

- Lithium-ion battery electrochemical reactions,
- Side-reactions due to impurities or material decomposition,
- Overcurrents due to improper cell management or short-circuits,
- From surrounding cells, electrical components, engines within hybrid vehicles, etc.

4 Impact of battery chemistry on TR

Safety solutions for thermal runaway often consider fail-safes to contain the event. However, understanding the possible causes and mechanisms at the internal cell level can allow for preventative mitigation strategies that circumvent the possibility of runaway or reduce the severity of such an event [36]. Hence, it is valuable to discuss the mechanisms of failure within the cell and the breakdown of cell materials that lead to thermal runaway.

Materials within cells serve either an electrical or electrochemical purpose, see Figure 4. The anode and cathode provide active material for cell reactions whilst the electrolyte is a charge transfer medium between the two, these form the chemical basis of the cell. Separators electrically insulate the anode from the cathode, preventing an internal short-circuit during normal operation. Current collectors, typically copper on the anode side and aluminium on the cathode side, provide a path for electrons between the electrodes allowing electrical work to be performed by the cell. As each is made of different material their failure mechanisms will differ.

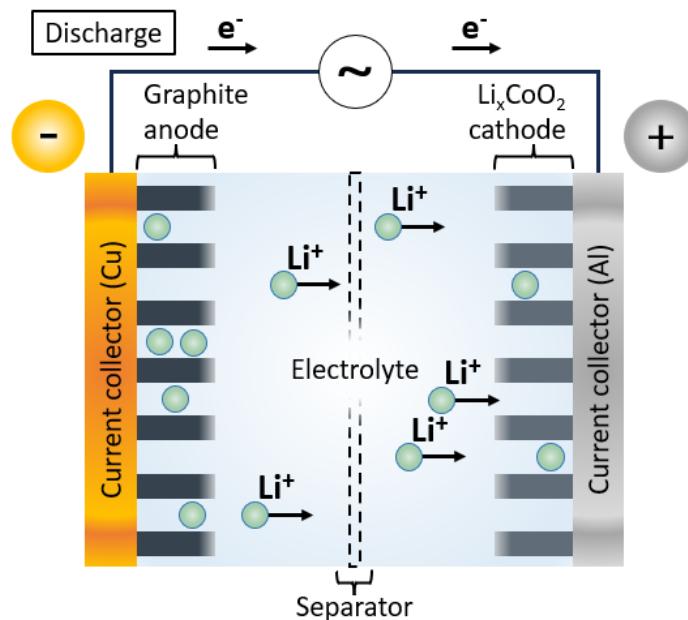


Figure 4: Transport of lithium ions for a typical battery discharge operation. Figure adapted from [9].

4.1 Impact of anode chemistry

The most studied and widely available lithium-ion anode material is graphite. It is therefore prudent to discuss how graphite anodes effect the conditions within the cells before comparing with potential future alternatives, see Table 2.

Graphite anode operates around 0.01 – 0.2 V, which makes it susceptible to reduction when combined with common electrolytes. During the first time cells are charged (formation cycle), common electrolyte will react with the graphite anode to form an SEI [37]. This layer protects the anode from further unwanted side reactions. However, SEI formation causes irreversible material loss leading to reduced capacity of the cell. The layer is also more resistive than the anode, although very thin, leading to internal resistance raise [38]. Losses due to SEI increase over time as both the electrode is permeable, leading to SEI growth, and the SEI may break down and regenerate, furthering material loss. This is typical ageing of the cell, leading to

higher resistances, higher operating temperatures, lower capacity, and faster discharging, all of which contribute to reduced cycle life.

The SEI will break down under thermal abuse but will regenerate quickly. When the SEI layer begins to decompose, the electrolyte reacts with the newly exposed lithiated anode surface forming a secondary SEI layer. Lithium-ions react with the electrolyte exothermically, producing gases such as CO_2 , O_2 , and hydrocarbons. This may repeat over the secondary and subsequent SEI layers, decomposing the SEI to expose the lithiated anode that reacts with the electrolyte to produce further gassing. Should abuse conditions persist, this process of SEI layer decomposition and regeneration will continue to repeat.

Should there be an excess of SEI decomposition and regeneration a pressure build-up of gases can occur, leading to crushing of the cell internals and potentially a short-circuit [39]. Cracks within the anode surface will also develop overtime, largely due to volume expansion of anodes during cycling or defects in the anode itself [40]. This is greatly exacerbated by rapid charging cycles, limiting lifetimes and power capabilities of batteries. Electrical abuse [27], such as rapid charging, and low operating temperature, typically below 20 °C, causes dendrite growth from the anode [35, 41]. During dendrite formation lithium within the lithium-ion cell deposits on the anode forming a dendrite. These dendrites, after sufficient growth, can pierce the separator and lead to a short-circuit [11, 42].

Graphite as an anode material is favoured due to long cycle life, low cost, and relative abundance [43]. However, there is a consistent drive for higher energy and power densities to better serve markets that have more specialist requirements, for instance aerospace. Alternative materials have been studied and in further development. Lithium titanate (LTO) is commonly seen as a safer alternative with much reduced risk of thermal runaway, although at a trade-off of energy capacity. One reason for increased safety is that the intercalation process of lithium-ions into the anode takes place at a higher potential (circa 1.55 V vs. Li/Li^+) than in graphite, minimising electrolyte decomposition, preventing lithium dendrite formation and avoiding SEI formation [44, 45]. It is also considered a zero-strain material, with only a 0.2 % change in volume of the unit cell during charging and discharging, prolonging the cycle life. Comparatively, graphite suffers a total volume expansion of 13.2 %. This is primarily because graphite intercalates lithium between layers of material whereas LTO undergoes a phase transformation, incorporating lithium within its crystal lattice. There are two main disadvantages, lower output in voltage compared with graphite, by about 1.5 V vs Li^+/Li^0 , and also lower theoretical capacity, 175 mAh/g to 372 mAh/g. This lower energy capacity is due to the spinel structure of LTO only accepting three additional Li^+ ions to obtain a rock-salt structure. LTOs long cycle life, high power capacity for fast charging, and inherent safety has seen the material make substantial commercial contributions to EVs, electric bikes, and especially electric bus fleets, with some exposure in other industries. However, with high battery energy density being critical for eVTOL aircraft, cells made with LTO anode has a limited potential for eVTOL propulsion battery pack.

Lithium metal anodes are also of interest to researchers. At present, they make up high performance batteries for non-rechargeable applications. This is because they bring an exceptional energy and power capacity. Energy capacity alone is ten times that of the common graphite anodes, 3860 mAh/g to 372 mAh/g [46]. There are, however, significant drawbacks in cycle life, resulting in limited adoption beyond primary battery applications. Lithium metal

anodes typically suffer from uncontrollable dendritic growth due to uneven lithium plating and limited Coulombic efficiency during lithium-ion cycling. The result is a poor cycle life despite a working mechanism with no volume expansion. Some technologies and materials have been developed to enable safer and more efficient operation over several cycles [47], including rechargeable Li–air batteries, Li–S batteries, and Li metal batteries, which utilise intercalation compounds as cathodes. Materials that encourage uniform lithium deposition and reduce dendrite growth are of significant interest [48]. However, certain advancements, such as polymer electrolytes, can be severely limited by lithium metal anodes as the materials will react, passivating the anode surface. Solid-state electrolytes known for their chemical stability may be the bridge to enable high cycle life of lithium electrodes and provide superior safety alongside the significant energy capacity [49]. Perhaps the most significant drawback to pure lithium metal anode technology is the limited abundance, resulting in excessive costs compared to graphite anodes.

A material of significant future potential is the silicon anode. These carry a significantly higher energy capacity of 4200 mAh/g [50]. The material itself is also relatively abundant and cheap to manufacture [51]. Despite this, there is limited to no commercial availability due to an exceptionally poor cycle life. The primary factor is a volume expansion up to 300 % resulting in the pulverisation and failure of the anode after relatively few cycles. This subsequently leads to loss of electrical contact, continuous formation of SEI, and cycle retention decay. Novel binders, electrolyte additives, and composite designs and many other pathways are in development to overcome this [52]. One variation that has seen commercial adoption is the silicon/graphite composite anode [53]. This combines some of the features of the two materials, bringing a higher cycle life than typical silicon anodes with an improved energy capacity over graphite anodes, although this is still lower than the respective pure materials. Typical studies have looked into varying silicon percentages from 5 % to 20 % by mass [54, 55].

Table 2: Common anode materials for lithium-ion cells

Material	Energy capacity (mAh/g)	Cycle life (number of cycles)	Cost (US\$/kg)	Additional notes
Graphite	372 [44]	>1,000 [56]	10 [57]	Common within lithium-ion cells, limited energy capacity
Lithium titanate	175 [44]	>10,000 [58]	50	Zero strain material, high thermal and chemical stability
Lithium metal	3860 [46]	>400 [47]	250	Suffers severe dendrite formation
Silicon	4200 [50]	>350 [59]	40 [51]	Suffers severe pulverisation

Among the three characteristic thermal runaway temperatures, T1 is affected the most by anode chemistry due to its association with SEI decomposition. Graphite, the most abundant anode material, forms an SEI that decomposes at a temperature between 85-120°C. On the other hand, LTO anodes that do not form an SEI pushing the onset temperature higher. In fact, T1 is virtually non-existent for LTO cells. Si-rich anode particles are a topic of ongoing research in this regard. The greater specific surface area and significant volume expansion leads to the

perception that Si would render poor SEI stability and hence lower T1. However, results in literature indicate similar or improved stability of Li_xS with caveats around parameters such as particle size, salt composition etc [60]. T2 could be lowered in the presence of anode materials that trigger mechanisms to cause additional heat release, e.g. plating on graphite anode could result in internal short circuit that increases the heat release rate and trigger thermal runaway. T3 is generally anode independent but can be increased by the presence of Li metal that reacts aggressively and increases T3.

4.2 Impact of cathode chemistry

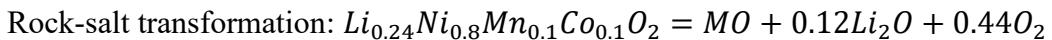
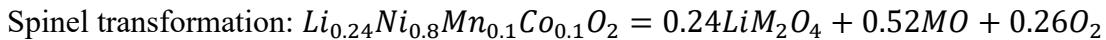
Anodes for commercial lithium-ion batteries are often graphite due to impressive performance in energy, power, cost, and lifespan; however, for cathodes there is a wider variety [61, 62, 63]. Lithium nickel manganese cobalt in a ratio of 8:1:1 (NMC-811) is a popular choice amongst electric vehicles, providing suitable energy and power densities [61, 64]. These are not suitable for all transport applications, with lithium iron phosphate (LFP) seeing greater use within electric buses due to improved safety in exchange for energy performance [62]. Requirements for aircraft applications involve high power and energy capacity and are, therefore, likely to make use of an NMC based chemistry or a cathode of similar performance [65]. Respective energy densities for NMC-811 and LFP are 220 mAh/g and 170 mAh/g. There are also a few alternative cathode chemistries that should be briefly discussed, see Table 3, along with an overview of how these materials behave under abuse conditions.

Cathode materials are susceptible to an electrical abuse scenario of overcharging where electric potentials exceed those expected for 100 % SoC [66, 67]. The potential value will vary for each cathode material used and will result in decomposition of the electrode generating gases that can be flammable and reactive, such as O_2 , CO_2 , CO , CH_4 , C_2H_4 , C_2H_6 , C_3H_6 , C_3H_8 , and $\text{C}_2\text{H}_5\text{F}$. Studies by Kong *et al.* [31] identified the composition of gas given off for three different cathode materials (LFP, LMO, and LCO) from 4.2 V to 5.0 V. They found the gas components were independent of cathode material, but the percentage of each gas would vary. Electrodes with higher oxidation ability produced more O_2 and CO_2 from 4.2 V to 5.0 V, making them less thermally stable. This results in larger amounts of gas, higher internal pressures, and large quantities of heat from exothermic reactions, which decrease battery safety. When charged to 4.5 V flammable hydrocarbons began to appear (C_2H_2) produced from exothermic reactions between the cathode and electrolyte, with larger amounts appearing for weaker oxidation ability cathode materials. It was found that the stability of the three cathodes from lowest oxidation ability to highest, or most to least stable) was LFP > LMO > LCO. Consequently, LFP is a cathode material highly stable under abuse conditions and hence favoured for thermal runaway resistant scenarios.

Electrolyte oxidation by the cathode directly, or by the thermally-induced oxygen from the cathode, triggers thermal runaway and releases more heat. Oxygen species released react with organic components in the electrolyte (ethylene carbonate) in further oxygen evolution reactions, an autogenous reaction occurring without ambient external oxygen. This accelerates the self-heating and furthers thermal runaway. Temperatures raise until the cathode-anode reaction dominates, a reaction that releases the most heat during runaway raising temperatures up to and above 1000 °C. Reaction between the cathode-anode is similarly governed by the migration of oxygen to the anode that reacts with the intercalated lithium of the anode. Because the required oxygen for the cathode-electrolyte and cathode-anode reactions is self-supported

during TR, isolating the battery from the environment does not stop the exothermic chemical reactions, making fire-fighting difficult.

NMC has a relatively strong oxidation ability [68], consequently producing a significant amount of oxygen as it decomposes [31]. This oxygen drives many of the thermal runaway reactions. Studies show that the evolution of oxygen is derived from a phase transformation of the layered oxide of NMC to a spinel structure and/or a rock-salt structure [68], occurring around 230 °C as temperatures rise, with the final products dependent upon cathode composition and temperature ($M = Ni, Mn, Co$):



NMC-811 is a typical mixture of the material, representing 80 % by mass nickel, 10 % manganese, and 10 % cobalt. The properties of NMC cathode can therefore be tailored by varying the material stoichiometry, something of interest to future developments of the technology [64, 69]. Nickel enhances the energy capacity of the electrode whilst manganese improves chemical stability and cycle life. Cobalt enhances both energy capacity and the stability of the cathode. Recent developments are moving towards an NMC with stoichiometry of 90:5:5, known as NMC-955 [70].

Cathode materials are not known to affect the onset temperature T1. T2 is moderately affected based on the onset of cathode-anode reactions after the separator collapses completely. Increase of T2 has been reported with reduced thermal stability of the cathode [71]. T1 and T2 are often difficult to distinguish for stable LFP. The main contribution of cathode materials is on T3 from the oxygen release that instigates further reactions as described above. These reactions raise the temperature beyond the auto-ignition point of the organic electrolyte resulting in additional fire hazard. Therefore, Ni and Co containing cathodes have greater T3 compared to LFP due to greater oxygen-phosphorous bond strength [71]. In NMC cathodes that are relevant for eVTOL applications, increasing Ni content is known to further increase T3.

Table 3: Common cathode materials for lithium-ion cells

Material	Energy capacity (mAh/g)	Cycle life (number of cycles)	Cost (US\$/kg)	Additional notes
LFP	170 [72]	>1000 [73]	15	High stability
LMO	148 [74]	>450 [75]	10	High power capacity
LCO	140 (practical) [76] 274 (theoretical)	>500 [77]	50	Cut-off voltage limits energy capacity
NMC-111	160 [70]	>1000 [78, 79]	30	Variable stoichiometry to alter properties such as
NMC-622	180 [70]	>1000 [78, 79]	28	energy capacity and
NMC-811	200 [70]	>1000 [78, 79]	25	stability
NMC-955	220 [70]	>1000 [78, 79]	15	

4.3 Impact of choice of electrolyte

Electrolyte choice is crucial to cell performance, and the proximity of the material to both cathode and anode has the potential to facilitate highly exothermic reactions. Organic liquid electrolytes with dissolved lithium salts are typically used within lithium-ion cells. These are highly efficient in ion transport, allowing high energy and power performance. However, they do possess notable drawbacks. Firstly, they are a main contributor to side reactions with the anode and cathode, leading to capacity and power fade. Secondly, they are highly inflammable and unstable unless operated within limited windows of temperature and voltage [80]. Operating outside these windows, for instance, at temperatures around 100 °C, they decompose, allowing the generation of gases and the resulting risk of thermal runaway. Additionally, when exposed to water and oxygen impurities during either manufacture, electrode gassing, or exposure to the environment after cell failure, the electrolyte will undergo side reactions that can produce HF acid. This is a major risk, with exposure limits set as low as 2 ppm for 8-hour long-term exposure and 4 ppm for 15-minute short-term exposure [81].

Several additives have been researched to improve the thermal runaway performance of liquid electrolytes. Maximum temperatures of thermal runaway can be reduced from around 750 °C to 650 °C by reducing highly reactive oxygen species that form oxygen gas within the electrolyte [14]. This decreases the reaction probability between cathode and electrolyte. It also alleviates the redox reaction between cathode and anode, the main heat source during thermal runaway. The cathode-anode reaction occurs when the anode reacts with the oxygen molecular species within the cathode structure. By introducing a reducing agent to the electrolyte, such as TPFPB, the oxygen gas could be induced to release at a lower temperature before thermal runaway [14]. TPFPB decreases the reaction rate between cathode and electrolyte, indicating that the exothermic reaction between cathode and electrolyte was initiated by the oxygen species rather than oxygen gas [14].

The thermal runaway onset temperature is governed by SEI decomposition. Therefore, electrolyte compositions that form stable SEI are expected to delay the onset. Salts such as lithium bis(oxalato) borate (LiBOB)-, and lithium difluoro(oxalate) borate (LiDFOB) improve the thermal stability of SEI, resulting in T1 above 110 °C [82]. However, such salts could result in performance loss due to lower ionic conductivity, greater toxicity etc. The other two temperatures, i.e. T2 and T3 are expected to reduce through the design of non-flammable electrolyte substitutes via combination of molecular and solvation strategies [82]. For instance, Wu et al. [83] reported a rise in T2 of 47°C alongside a 72°C reduction in T3. Salt alternatives that render the electrolyte non-flammable may come with exclusive fire hazards due to new exothermic reactions at the graphite-electrolyte interface and must be considered holistically [84].

Additional research has been performed on alternative forms of electrolyte, mainly polymer electrolytes and solid-state electrolytes. Polymer electrolytes facilitate ion transport through a polymeric material. These can be wetted to form a gel-polymer or exist without any liquid electrolyte to form a solid-polymer [85]. This has the potential to improve thermal stability, depending on the material chosen, and also reduces the amount of liquid used, decreasing the amount of a source of gassing within the cell. High ionic conductivity does limit the power capability of such cells, forming a significant barrier to commercial adoption. Polymeric materials do carry the risk of passivating lithium metal electrodes and so could limit future

material improvements of certain technologies. Inorganic solid-state electrolytes are also undergoing studies that have exceptional stability with lithium metal [86]. Indeed, long cycle life and thermal stability have been reported with certain solid-state materials and LFP; however, the same material against an NMC cathode gave rise to violent burning under an argon environment, as the NMC was not chemically stable in contact with the electrolyte [87, 88]. Therefore, depending on cell chemistry solid-state electrolyte could provide good thermal stability, long cycle life, as well as low cost, and low leakage.

4.4 Inactive components

Several components that do not play a role in the electrochemistry can still have an impact on the progression of thermal runaway. Mainly, the separator, which facilitates ion transport between the electrodes. They are a critical component to prevent direct contact and short-circuits between anode and cathode. However, separator damage can lead to direct contact and thermal runaway, typically from lithium dendrite growth or mechanical abuse during operation [89]. The materials used to form the separator also possess a temperature limit. For example, a polyethylene separator will melt at 130 °C leading to the ion transfer pores closing. This can potentially halt thermal runaway but will render the cell irreversibly inoperable, a shutdown effect [9, 90]. Should temperatures rise further due to other factors, the separator will shrink and collapse leading to electrode contact, short-circuit, and thermal runaway. Studies by Shi *et al.* [91] show that a temperature rise from 120 °C to 140 °C can result in a reduction of separator diameter of up to 80 % for polyethylene based separators, see Figure 5. A common method of introducing a separator with a shutdown effect is a tri-layer of PP-PE-PP. PP has a melt temperature of 170 °C, allowing outer layers of the separator to maintain their structure whilst the inner PE melts between 130 °C to 170 °C. This cuts the ion transfer preventing the runaway exothermic reactions and prevents a short-circuit. However, this has no impact on abuse conditions external to the cell and so cannot always prevent thermal runaway. Separators can also be damaged due to ageing, leading to uneven resistances and potentials within the cell [92, 93]. It is widely believed that separator collapse is the thermal runaway trigger due to the ensuing short circuit and hence should influence the characteristic temperature. However, actual thermal runaway trigger is the cathode-anode reactions that are merely facilitated by the separator collapse. Experimental [94] and modelling [95] work does show increased T2 and reduced T3 upon use of non-standard separator material (graphene-doped, ceramic-coated etc.), however, these results require further validation.

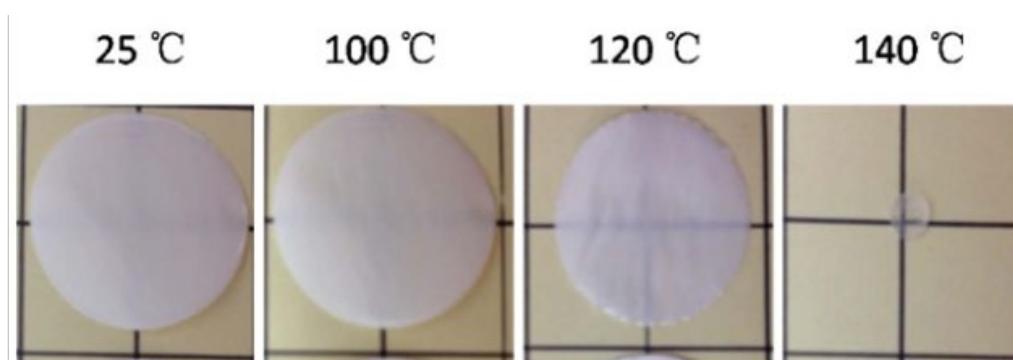


Figure 5: Shrinkage and collapse of a polyethylene-based separator from 25 °C to 140 °C. Melting temperature of polyethylene is 170 °C. At 140 °C it shrink to 20 % of the original diameter. Figure from: [91], licensed under CC BY 4.0.

More inactive components that contribute to thermal runaway under certain abuse conditions are the current collectors. Current collectors are typically formed from copper on the anode side and aluminium on the cathode side. These materials are chemically stable in their respective roles during operation; the anode will be used at lower potentials (0.005 V to 1.5 V vs Li/Li⁺) and the cathode at higher potentials (3.0 V to 4.5 V vs Li/Li⁺) [96]. However, at lower potentials, aluminium undergoes alloying and dealloying with lithium ions, whilst at higher potentials copper dissolution occurs.

Charging a cell beyond the upper safety limit to higher potentials results in an overcharge condition. This causes corrosion of aluminium current collectors [32, 97], leading to increased electrical resistance and an increase in self-discharge [32]. Slight overcharging may not lead to thermal runaway or performance degradation [27]. However, overcharging remains a severe safety concern indicative of a malfunction or inappropriate design of management systems, and most problematically capacity inconsistency between cells. This inconsistency can come from cell degradation or defects giving an inhomogeneous balance of voltages across a battery pack.

Overdischarge occurs when discharging beyond a lower safety limit [33]. Like overcharging it is caused by failure of management systems or abusive conditions [98]. A typical lithium-ion cell runs from 2.7 V to 4.2 V. Discharging below 2.7 V, down to 1.5 V will start the process of copper dissolution and formation of copper and lithium dendrites. All these result in short cycle life of cells. Deep overdischarge down to -0.5 V also exhibits disintegration of the cathode material caused by over-lithiation and instability of the SEI layer. Repeat breakdown and reformation of the SEI causes gassing and pressure build-up, resulting in even shorter cell life. Ultimately, contact between electrodes is made, and an internal short-circuit occurs [33].

5 Impact of cell conditions on TR

It has been briefly covered that conditions such as electrical abuse can trigger thermal runaway or exacerbate the instability of a lithium-ion cell. However, normal operating conditions can also have detrimental effects over extended periods of time. They can also create more violent thermal runaway events should an abuse condition manage to trigger one. This section will cover standard parameters that are inseparable from cell operation: SoC, SoH, charge profile, and manufacturing quality.

5.1 Impact of State of Charge (SoC)

SoC is simply represented as the percentage of energy held within a cell to the maximum possible capacity. Broadly speaking, higher SoC means more energy within the cell, therefore, more violent thermal runaway events [99, 100, 101, 102]. However, there are some additional considerations. For instance, thermal stability of the cathode material decreases at higher SoC [14]. Delithiated cathode materials release oxygen species, which are involved in highly exothermic reactions. Heat release accelerates, accelerating phase transformation of the cathode material allowing the release of further oxygen species. This also implies further degradation and gassing of materials [103]. The thermal stability of anode materials also reduces at high states of charge due to increased lithiation in anode, allowing more severe thermal runaway [104, 105]. It should be noted that a lower SoC also decreases surface temperature during runaway, decreasing the degradation of materials within the cell [106].

Studies also suggest a high SoC is required for a thermal runaway event to occur, typically around 70 to 100 % [106]. Above 50 % SoC is when the likelihood of cell rupture begins to greatly increase. This is because higher states of charge allow more heat and energy to be released from the cell during a thermal runaway event; this large amount of heat results in reduced case stiffness making a rupture more likely. When a rupture does occur, far more mass and ejecta are lost as a result, increasing the chances of a propagation in a neighbouring cell [107]. Below 10 % SoC likelihood of thermal runaway reduces significantly. In short, high SoC decreases the T1 and T2, and increases T3, irrespective of battery chemistry, SoH and ambient temperature.

5.2 Impact of State of Health (SoH)

State of health is the ratio of the current maximum practical charge of the cell to the original maximum charge when the cell was first produced. Over time and with use of the cell, the quality and performance will degrade, decreasing the state of health of the cell. This is an unavoidable process for lithium-ion batteries, reducing energy and power capacities. Further, ageing also affects both the likelihood and severity of thermal runaway. Typically, increasing the SoC of a battery will introduce more energy to the system and lead to a more severe thermal runaway [108]. However, the SoH will reduce with ageing, lowering the maximum possible capacity. As a result, the relationship with the degradation caused during battery operation and its safety can be complex.

Some of the effects of ageing include: growth of a cathode electrolyte interface, cathode particle cracking, transition metal dissolution, SEI growth [109]. All these changes, along with damages to the separator cause imbalances in internal resistances, producing heat during normal use [92, 93]. The consequence of this is a reduction in maximum power to manage heat generation. SEI growth is the main mechanism of capacity fading, reducing energy density

[110]. A consequence of the capacity fading is a reduction in the heat released during thermal runaway, reducing the maximum temperatures experienced [109, 110, 111]. However, this does not make aged batteries inherently safer. Aged batteries are less thermally stable, especially if aged under conditions that encourage lithium plating, resulting in more mass loss, faster propagation of thermal runaway, and faster increases in temperature [108, 109, 111]. An aged cell may experience failure and internal short-circuiting in shorter times at lower temperatures [42]. The aged lithium-ion cell can lower the T1 and T2 temperature, however, will also lower T3. Therefore, as the battery degrades, cells are more likely to go into thermal runaway, but the impact of the thermal runaway will be lower.

5.3 Impact of charge profile

The charge profile of eVTOL aircraft significantly differs from road EVs. Due to high power requirements for landing, and regulatory requirements for reserve, eVTOL aircraft will have a significantly high SoC when they land. This could be around 30-40% SoC. As a quick turnaround is essential, it is expected battery pack of eVTOL aircraft will be charged rapidly to a high SoC. As the maximum charge rate significantly reduces closer to 100% SoC, most of the charge may end around 90-95% SoC. Therefore, the requirement is to charge rapidly from 30-40% SoC to 90-95% SoC. This will be complicated by several factors, e.g. after landing, the battery pack temperature will be high due to high power discharge during landing, and the pack may have limited cooling capability during charge on the ground. This will significantly increase the likelihood of lithium plating, thermal abuse and T1 temperature may be reached in several cells. These are directly linked to accelerated degradation and safety. High temperature can initiate the exothermic process as discussed earlier. Plated lithium can create an internal short-circuit, which in turn can generate a large amount of heat, leading to localised temperature rise, reaching to T3 will initiate exothermic process and collapse of the separator. Accelerated degradation due to fast charge and high temperature directly impacts the graphite anode. This in turn, increases the likelihood of lithium plating as it degrades. In addition, as the battery degrades, its internal resistance increases, which will increase the heat generation linearly when the charge current is kept the same. Therefore, as eVTOL aircraft battery pack ages, the likelihood of lithium plating and thermal abuse will increase due to fast charging.

5.4 Impact of the manufacturing quality of the cell

The manufacturing quality of the cells themselves will not introduce a new abuse mechanism for thermal runaway. Instead, it increases the likelihood of other abuse conditions. For example, lithium dendrite growth, internal short-circuit and thermal abuse. Manufacturing quality refers to both cell-to-cell variation and the likelihood of producing a cell with an existing defect.

The cells used by the eVTOL aircraft OEMs are usually known for their good quality control and low tolerance, often leading to less than 1% cell-to-cell variations when they are new. In an eVTOL aircraft battery pack, several cells are usually connected in parallel first (cell block), then the cell blocks are connected in series to provide the desired pack voltage and maximum current capability. Adding cells in parallel will reduce the impact of cell-to-cell variation at the pack level in terms of voltage imbalance. However, within individual cell blocks, the cell-to-cell variation will persist. It has previously been shown that cells connected in parallel will experience different charge/discharge current distribution [112]. This leads to a temperature gradient, slight overcharge of few cells and a degradation gradient under low to moderate charge/discharge current (nominal EV operating condition). In addition to internal short circuit

and thermal abuse risk, slight overcharge can cause corrosion of aluminium current collectors [32, 97]. However, as the battery pack of an eVTOL aircraft will experience regular high current charge and discharge, the current distribution gradient and temperature within a cell block will be significantly amplified [113]. The likelihood of charge current being too high to initiate significant lithium plating and momentarily overcharging one or more cells in a cell block is high. This issue will worsen as the pack degrades, as there is no monitoring or control of individual cells in a parallel string.

The presence of a defective cell in a cell block will accelerate this failure mode. The presence of cells with existing manufacturing defects is rare but has been seen before [114]. Defects within anodes have been reported to impede the structural integrity of the cell electrode. Cracks within the anode surface will worsen overtime, largely due to volume expansion during cycling, and can be greatly exacerbated by defects in the anode itself [40]. This can result in excessive SEI decomposition and regeneration, leading to a build-up of gases and abuse [39]. As the automotive industry has shifted from small cylindrical cells to large format prismatic/pouch cells, this issue remains largely unexplored. However, the problem is significantly amplified for eVTOL aircraft battery packs compared to a road EV, therefore this needs further attention if eVTOL industry continues to use small cylindrical cells.

6 Impact of cell/module/pack safety solutions on TR probability and its character

The safety solutions to cell/module/pack TR are mainly categorised as prevention and mitigation. Prevention starts with the choice of cell components (e.g. anode active material, cathode active material, binder, separator etc.) and cell design; then extends to prognostics for TR. When single-cell TR occurs, mitigations are used. Mitigations include diagnostics for single cell failure/TR, and anti-propagation between cells, modules, packs and battery compartments within the aircraft. This multi-level approach is summarised in Figure 6.

The choice of cell components is not relevant for cells currently being used. However, it is very likely eVTOL industry will use future cells of similar size and shape, keeping their module/pack design mostly the same. Therefore, it is important to look into how the choice of cell component can affect the likelihood of cell thermal runaway and its characteristics. It is possible to alter intrinsic cell components such as chemistry, materials and design features to reduce the likelihood of TR and its impact. This can be hugely beneficial but requires unique manufacturing routes that may not be commercially available. For example, minimum separator thickness, electrode porosity, heat capacity of the cell stack, cell vents, and thicker cell walls [16].

Apart from cell components, fault prevention is key to TR from occurring at all. It has been touted before that cell thermal runaway can be forecasted minutes, hours, days even weeks ahead (except TR initiated by impulsive abuse conditions like penetration, crash) [115]. However, little has been seen in practical application.

Once single-cell TR occurs, mitigation should be the next line of defence. Several preventative measures can be applied to stop propagation, and containment if propagated [116]. The method which likely can be found in eVTOL aircraft battery pack will be driven by the certification requirement as outlined in the RTCA DO 311a and EASA MOC VTOL.2440. Some simple design considerations are standard practice for cells and battery arrangements [117]. Direct cell-to-cell contact is avoided to isolate each cell thermally from the other. Safety vents are present on the cell with venting pathways to carry effluents from the cell safely out of the battery pack. A consideration that is commonly considered is the mass and volume of any proposed solution, as the density of the battery pack is often a crucial metric for performance, especially in aerospace. In this section, a detailed review of all the methods that have been implemented or considered previously will be presented.

It must be noted that some of these safety solutions may have to be altered to account for lower air pressure environments and lower temperature whilst an aircraft is airborne. At lower air pressures, TR can occur at both shorter and longer than expected times [16]. Low pressures also present a significant challenge to cell venting of internal gases, posing a risk of uncontrolled explosions of gases and heat during venting. With the change of altitude and air pressure lower temperature might be experienced by the aircraft. However, as a large amount of internal heat will be produced from high power discharge, from the climb phase, the external low temperature is unlikely to reduce battery temperature significantly. In addition, for eVTOL, the service ceiling is going to be low, therefore, these issues may not be applicable for eVTOL aircraft and thus will not be discussed in greater detail.

Broadly, five main points to consider to design safety solutions for thermal runaway [102]:

1. Short-circuit protection at the cell and pack level.
 - Failing cells can become an external short-circuit to adjacent cells resulting in electrical abuse of the adjacent.
2. Provide adequate cell management (temperature, pressure, etc.).
 - Direct contact between cells without proper insulation or appropriate heat dissipation allows excess energy from failing cells to affect surrounding cells.
3. Reduce the risk of sidewall ruptures.
 - Weak cell walls without structural support are likely to experience sidewall ruptures and be at high risk of thermal runaway propagation.
4. Protect adjacent cells from thermal runaway cell ejecta (solids, liquids, and gasses).
 - Thermal runaway ejecta can be electrically conductive, causing short-circuits. Ejecta is also at high temperatures and can heat neighbouring cells.
5. Prevent flames and sparks from spreading and exiting the battery enclosure.
 - These can spread heat to nearby cells. Often this is achieved through tortuous gas paths before vent ports that are equipped with flame arresting features [117].

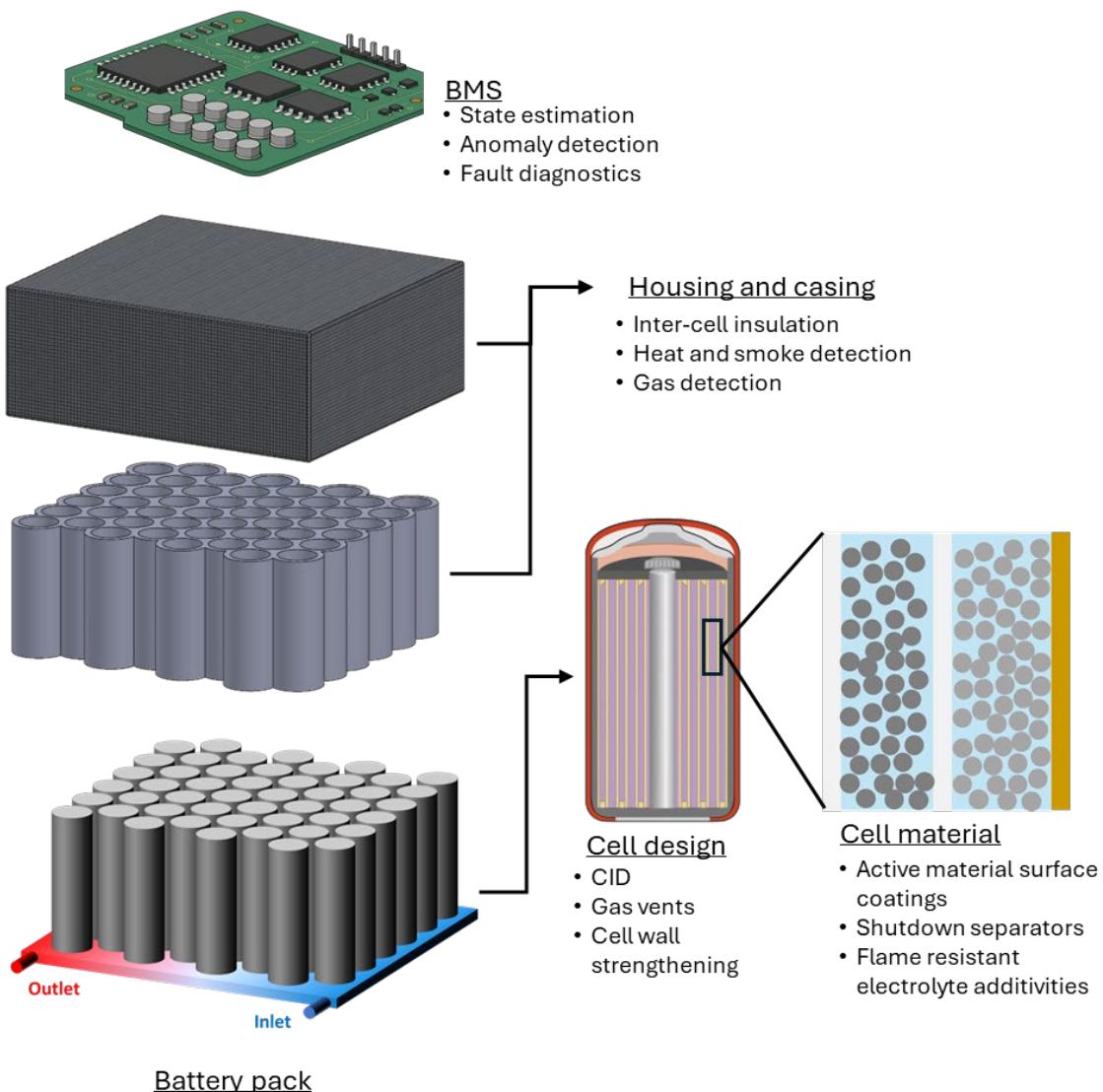


Figure 6: Groupings of several approaches for preventing and containing failures within lithium-ion battery packs.

6.1 Intrinsic cell materials

The design of lithium-ion cells is crucial to their safety. Other than the selection of bulk anode and cathode materials for more thermally stable alternatives, a range of other strategies are available. Atomic layer deposition is a popular method for anode surface coatings. A typical example is Al_2O_3 , which is often used to improve thermal stability and cycle performance [27]. Baginska *et al.* [118] studied a thermoresponsive polymer layer that melts in response to heat, preventing ionic transport and cell chemistry reactions. Silicon nanowires have also been reported to aid against mechanical loads [119]. Similarly, alterations to cathode material are possible. Surface coatings to improve thermal stability and cycling performance [8], for example: TiO_2 [120], MnSiO_4 [121], AlF_3 [122]. Cathode element substitution and doping are also effective for enhancing performance. Aluminium is an efficient doping agent for transition metals such as Co, Ni and Mn, increasing structural stability under thermal stress in exchange for gravimetric energy capacity. A combination of Al and Ni can be used to increase the electrochemical performance [123]. To either electrode, Positive Temperature Coefficient of Resistivity (PTCR) materials can be applied [116, 124, 125, 126, 127]. As is implied in the name, as the temperature of the material increases, so too does its resistivity, generally in response to a phase change. PTCR materials make effective devices for protecting against overcurrent. Unlike thermal fuses, these materials are present at the source of the electrochemical reaction within the cell, allowing for immediate responses to the temperatures within the cell and not those projected externally. Some examples include percolation binders and PTCR coatings [85].

Similar to PTCR materials on electrodes, separators may also be altered to have such functions, commonly known as shutdown separators [9, 102]. These are well developed and commercially available, with brands such as Celgard. A typical separator's primary purpose is to prevent short-circuiting between the anode and cathode whilst enabling passage of the electrolyte ions [116]. Separators with a shutdown effect go through a structural change, normally in response to temperature, that cuts the ionic pathways to prevent electrochemical reactions. Ideally, these shutdown separators require a suitable melt temperature to allow shutdown of ion transport and a suitable collapse temperature to avoid mechanical collapse that would lead to an internal short-circuit. By carefully selecting materials used temperatures of melting and collapse can be tailored to control the shutdown effect. For example, Celgard uses a PP-PE-PP trilayer where PP (polypropylene) has a melt temperature of 160 °C and provides mechanical support whilst PE (polyethylene) has a melt temperature of 130 °C and provides the shutdown effect. Ceramic coatings are also studied to enhance melting temperatures of separators [27]. A common method of preventing dendrite growth is to coat the separator with a thin conductive layer of copper, modulating deposition of lithium with a preferential surface [128].

The electrolyte is the last active material within the cell chemistry to consider. Alterations largely involve additives for overcharge protection and to improve flame resistance [27, 116, 129]. The electrolyte itself forms part of the interface with the electrodes, the major source of gas, especially flammable gases, during a thermal runaway event [116]. The composition and presence of different materials has direct implications for the formation and stability of the SEI layer as well as the thermal stability of the electrolyte, potentially providing a barrier to heat generation. In terms of overcharge protection [14, 116], decomposition of the cathode to oxygen during overcharge is strongly dependent upon the surrounding electrolyte. The electrolyte negatively impact thermal stability of cathode, which facilitates the phase

transformation and oxygen release. Certain additives can suppress the presence of reactive oxygen species and improve cathode stability. For example, redox shuttle additives are stable during normal operating potentials, but at overcharge potential, the shuttle additive oxidises on the cathode surface to form an active molecule. This active molecule will move through the separator, reduce at the anode, and then diffuse back to the cathode to repeat the process, consuming excess energy during overcharge. Another example is electrochemical polymerisation additives. During overcharge, monomers in the electrolyte oxidise to produce a free radical that deposits on the separator and cathode before being polymerised, passivating cathode, and preventing further reactions [130, 131].

Flame retardant electrolyte additives prevent flames following a thermal runaway event [116]. Additives increase the boiling and flash point of the electrolyte and can remove the highly reactive free radicals generated by combustion, inhibit the occurrence of chain reactions, stop continuous propagation of combustion, and mitigate the occurrence of thermal runaway. These are commonly phosphorous-based or halogen-based. Phosphorous-based additives cause rapid dehydration and charring of the combustible surface in the electrolyte. They also generate a non-volatile glassy material that forms a dense barrier layer that protects cell materials against flame. Halogen-based additives are flame-retardant efficient for low cost but carry the significant disadvantage of a toxic gas product that is unsuitable for release to the environment.

6.2 Safer intrinsic cell design

Cells can be designed with beneficial geometries, materials, and dedicated devices for improved safety, e.g. the current interrupt device (CID) [116]. This acts in response to the high pressures of gas released and high temperatures during a runaway. Electrical and thermal abuse can both result in the electrolyte decomposing to produce a variety of gases, increasing pressure within the cell. Subsequently, the CID experiences higher pressures. The solder joints welded to the pressure relief sheet circuit will decompose, the pressure relief sheet will flip over, and the battery will be disconnected internally [132, 133]. Effectively, the CID is a fuse that interrupts current in response to high gas pressure.

Another ubiquitous safety device is a safety vent. The vent will rupture if internal pressures of a cell reach a critical value higher than the CID activation point, allowing the safe release of gas and avoiding explosion [20]. This venting can delay and even prevent thermal runaway events [134]; this allows for such an event to be detected and managed before a catastrophic scenario initiates. The gaseous mixture released is highly combustible and toxic due to the presence of aromatic species and must be directed away safely from bystanders. Gas is vented at lower temperatures than the ignition points of the vapour, preventing fires. Venting also provides an avenue for hot gases to be removed from the cell and provides Joule-Thomson cooling, reducing cell temperatures. These vents are typically mounted at the end caps of cylindrical cells, made from a gasket and perforated membrane below several spikes. As pressure rises the gasket is forced upward allowing the spikes to penetrate the perforated membrane, releasing gas from the vent. This strategy is commonly the last barrier to thermal runaway as the cells reach the point of self-heating and irreversible damage prior to this. Some studies have identified that the introduction of additional vents on both the top and bottom of cylindrical cells is an effective method of mitigation [100, 103, 106]. One reason for this is that it reduces the risk of the gas paths out of the cell being blocked, damaged, or malfunctioning by introducing an additional path. The additional path also provides extra release, allowing

more heat to be dissipated from the cell. Application of safety vents in airborne vehicles needs further consideration. Environmental conditions differ significantly compared to ground-level applications, specifically ambient air pressure [16]. As a result, venting rates and effectiveness of safety vents can be greatly impacted.

Two uncommon methods due to the requirements of new cell manufacturing routes are strengthening of the cells walls and strengthening of the electrode windings. Stronger cell walls can be achieved by using stronger materials or by increasing the wall thickness. The often cited advantage is the reduced risk of rupture away from the vents during a thermal runaway event [106, 135, 136]. This can also provide additional support against an external mechanical load. Additionally, materials that have greater mechanical strength at higher temperatures, 100 °C to 300 °C would better resist rupturing. Lao *et al.* [136] reported that thicker cell walls with a 2.5 % increase in mass resulted in an increased tensile strength of 36 %; this was accompanied by a 1.5 % fall in energy density. In battery pack studies, no thermal runaway propagation was observed, and the heated cell did not rupture. Stronger cell windings reduce chances of the electrodes rupturing and short-circuiting during a thermal runaway. However, this can be difficult to implement as alternative strong and electrically conductive materials are likely to be more expensive and thickening the windings would result in a marked reduction of the volume available for active material. Therefore, thicker cell walls are a more practical approach.

6.3 Fault diagnostics and prognostics

Fault detection is paramount to the safety and long life of battery packs. This is chiefly performed using a battery management system (BMS). A BMS is a control system that manages a rechargeable battery to ensure safe and efficient operation. Monitoring of key parameters is required of the individual cells as well as the larger battery pack, with collected data informing decisions performed by the BMS [27], represented by the flow diagram in Figure 7. Some of this data includes voltage, current and temperature [16, 116]. This data is monitored, logged, and used to balance the system as well as predict and flag any potential fault.

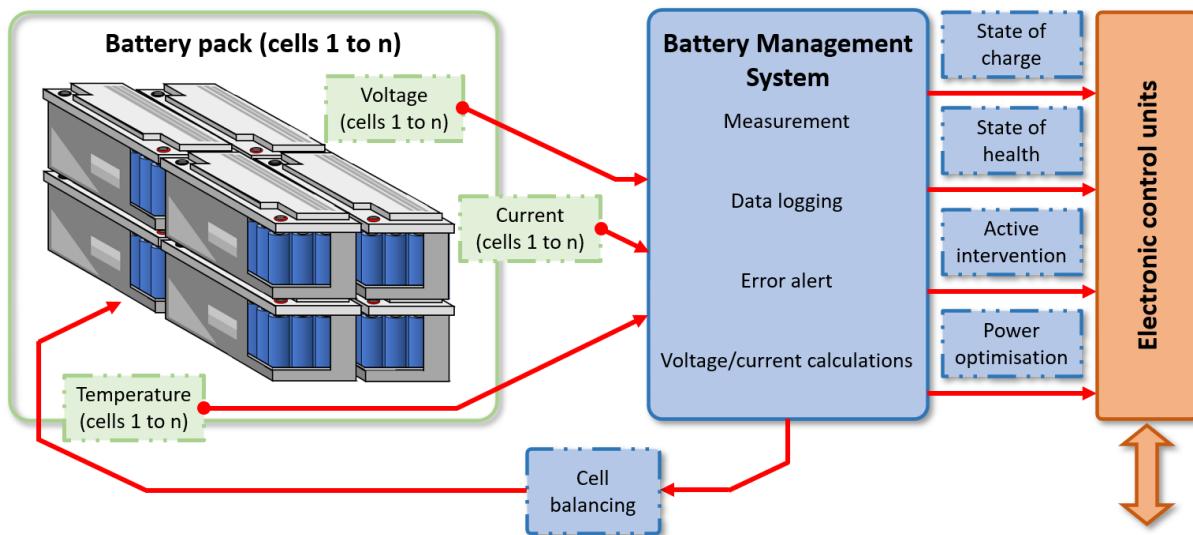


Figure 7: Flow diagram of the operation of a battery management system and the interactions involved with the battery pack and electronic control units.

The BMS will communicate with electronic control units (ECUs) to control rates of charging and discharging allowing power output to be optimised to meet differing applications and duty cycles as required [65]. This is complemented by predictive calculations performed by the BMS on the SoC and state of health of each individual cells, facilitating energy is provided for the required duration of use.

With the data gathered, a BMS can also address most abuse scenarios experienced by a battery pack. Cells and modules may be electrically isolated in the event of short-circuits to prevent overcurrent. Monitoring SoC and SoH during normal operation prevents overcharge and overdischarge of cells by enforcing limits on the electrical properties of the cells. This monitoring is accurate enough to avoid unequal potentials between individual cells, which will limit energy and power of the battery pack. These potentials can be matched using passive and active cell balancing procedures. In the event of a fault of the sensing equipment where voltage and current data may be inaccurate or unavailable, predictive algorithms that calculate what cell values should be can detect errors and issue warnings. This enables potential hazards to be avoided, errors addressed, and damage prevented.

Temperature measurements available to BMS systems can be used to engage active cooling or heating. This is performed during normal operation to maintain efficient operation, heat from battery components or extreme environmental conditions are addressed preventing cells from operating under too cold or too hot conditions. Peak lithium-ion battery performance occurs within a specific range of temperatures, $20-40 \pm 5$ °C [27], making lithium-ion technology susceptible to these environmental factors and sources of heat generation. Abnormal temperature fluctuations can be managed by the implementation of these active techniques or emergency procedures implemented should severe hazards be detected. Other intervention methods can also be activated by a BMS, allowing a robust response to any failure scenario. Predictive calculations by the BMS may identify faults before they result in TR.

Outside a BMS, additional monitoring equipment can be employed to monitor the environment surrounding the battery pack. Gas detectors are commonplace when working with lithium-ion technology, specifically to monitor HF levels but other gases such as CO and CO₂ can be monitored [31, 80]. These are indicators of cell failure as cell contents need to be vented to the external environment for abnormal levels to be detected. Pressure sensors and strain gauges can also detect cell swelling due to gassing within a cell.

6.4 Inter-cell and inter-module TR propagation barrier

Once a cell has failed, current regulatory guidelines require a system that has sufficient precautions in place to contain and prevent propagation [16]. Containing the spread of fire is also critical. Surrounding individual cells with functional foam materials is common practice. These foams provide insulation and separation between cells allowing individual heat to be dissipated preventing propagation of high local temperatures. Foams carry the obvious advantage of cushioning the volume change of cells and protecting against mechanical abuse. The inclusion of additives can enhance or introduce new properties. For instance, Yang *et al.* [137] created several variations on a well-known polyurethane foam, a material which has seen use as compressible pads within batteries, through additives and hybridisation. These included filling or coating with flame-retardant materials, one additive with better burn performance and a coating with intumescent properties. It was reported that thermal runaway was considerably delayed by polyurethane foams incorporating flame-retardant additives or coatings and

complete prevention of cascading failure was achieved with dense polyurethane foams with multilayered coatings of fire wall and intumescent materials. It was identified that key parameters for preventing thermal propagation with foam materials were high-temperature stability and sufficient thermal insulation. Similarly, Mei *et al.* [138] performed a study comparing the performance of different passive thermal runaway retardation materials that surrounded a battery within a tube. However, materials used within this study focused on heat absorption and removal to prevent failure spreading from one cell to adjacent cells.

6.5 Other battery pack TR preventatives

Preventative measures to circumvent the occurrence of thermal runaway can be both passive, acting without any input from external systems, or active, action is initiated by an external system such as a BMS [116]. A passive system acts without any external energy being consumed, providing advantages such as long life, simple construction, and low cost. Conversely, active systems require an energy input but can be far more effective. Both categories aim to avoid failure occurring or to delay any failure to allow fail-safes more time to be effective.

Thermal management is one of the most crucial considerations. As well as passive or active, these can be further categorised into internal or external, and direct or indirect. Further still, the three most common types of thermal management are air cooling, liquid cooling, and Phase Change Material (PCM) cooling. Air cooling is popular for smaller battery packs where there is a low heat generation [27]. They are typically low cost, lighter, and have simple designs. Natural air convection is a passive approach where air circulates via natural currents, forced air convection is the active alternative where air is circulated via a fan. Forced convection is typically used when larger amounts of heat need to be removed or when there is no duct present for air passage from the atmosphere. These currents will either pass directly over the cell surface, direct cooling, or over a heat sink, indirect cooling, carrying heat away via convection [117, 135]. The amount of heat removed is dependent on heat transfer coefficient of the air and material surface, as well as the surface area being cooled. This latter variable is where heat sinks provide potential benefits. Heat sinks conduct heat away from the cell surface and dissipate it over a larger surface area, where convection then acts to remove heat from the system. Typically, they will be formed as fins or larger surface area shapes to facilitate this.

Liquid cooling also acts via convection, but their higher thermal conductivity and specific heat make it a more effective alternative for larger battery packs. Liquid cooling also helps to reduce cell-to-cell propagation during a thermal runaway event [136]. However, obvious disadvantages include adding additional weight to the system, requiring energy to circulate the liquid, and a risk of leakage that may trigger an external short-circuit if a conductive liquid is used as the coolant. The selection of coolant is critical to performance, with major coolants including water, oil, nano-fluids, and liquid metals. The major factors to consider are specific heat capacity, thermal conductivity, and viscosity. Liquid cooling can be applied internally within the battery pack or externally where the liquid is passed along the outer periphery of the battery pack. Internal cooling is often more efficient, but external cooling is safer as it evades direct contact between coolant and the battery surface [27]. The use of liquid cooling while aircraft is on the ground, charging, but draining the coolant to reduce weight before flight has been considered by eVTOL OEMs. It is an interesting way to manage the risk.

Not all cooling systems rely on convection, PCM cooling operates using the latent heat of a material, the heat input required to transition the bulk of a material from one state to another during which temperatures do not increase. PCMs have the advantage of simple structures, reusability, low prices, ease of recycling and disposal, and no requirement for an external power supply [139]. They have been widely used in scenarios such as electric vehicle batteries, solar collectors, food storage and transportation, and building space heating/cooling. An advantage of a PCM system is that it can maintain the battery pack at a temperature just above ambient even as the battery is releasing heat for a significant time, this higher temperature can in turn improve the battery cycling efficiency. Convection is then often employed to remove the excess heat from the PCM and battery pack [140]. Careful consideration of volume expansion, PCM melting point and thermal conductivity are key to the designs of PCM-based temperature management [141]. Common PCM materials are paraffin, fatty acids, and molten salts. In automotive applications, PCM materials are often combined with an aluminium foam, a graphite matrix, or a copper foam to optimise heat conduction. However, their main drawback for eVTOL application is the weight.

Moving away from cooling systems, thermal fuses are a widely used preventative measure [116]. It is a non-recoverable one-time protection element that cuts the external circuit in response to abnormal operation. It operates based on the heat generated by the current flowing through the component; when current flowing through the thermal fuse is greater than the rated current, the heat generated reaches the melting point of the thermal fuse and the power supply is cut automatically. Thermal fuses are especially important for external circuits, as a thermal runaway cell can form an external short-circuit, producing massive currents through parallel cells and potentially propagating thermal runaway [135]. It is therefore good practice to employ fuses between adjacent cells.

Example mechanical solutions involve protecting cells or battery modules from potential external mechanical stresses that may induce crushing or penetration failures. For instance, Jia *et al.* [142] investigated a carbon fibre reinforced polymer sleeve that would surround the sidewall of an individual cell casing. These can protect cells from external stresses and contain a failure event should one occur. Much more common is to optimise battery casing designs with protective cross sections between double layers of sheets, example shown in Figure 8 [143]. The cross sections protect cells by absorbing and distributing mechanical stresses, making them useful for shielding batteries against impacts.

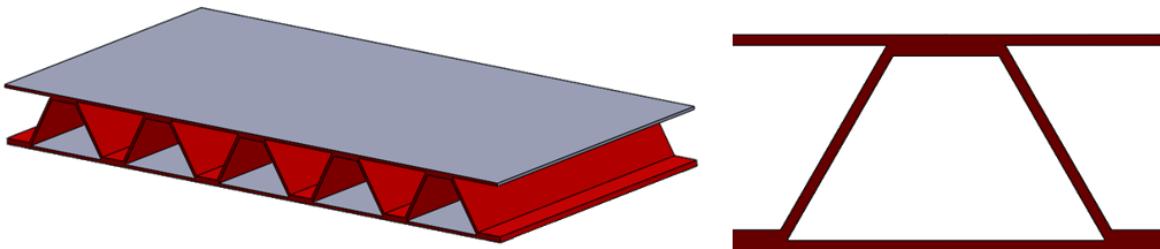


Figure 8: Profile view and cross-section of a NavTruss sandwich structure.

7 Parameters affecting re-ignition probability and its character

A battery fire resulting from cell TR is not safe after immediate suppression. Being a self-sustained source of heat, the battery could re-ignite because of the remaining unspent energy, i.e. stranded energy. Previous research on road EVs reported re-ignition in 13% cases [144]. Batteries subjected to undesirable conditions without immediately entering thermal runaway may still cause hazardous events later, i.e. delayed ignition. This section discusses such secondary ignitions that are non-trivially hazardous and potentially pose a risk similar to or greater than the primary event. The first sub-section discusses important lessons from road EV incidents recorded globally. Based on the lessons, a comprehensive list of considerations for the risk of delayed/re-ignition is provided in the second sub-section, discussing probable links between the parameters and hazard risk.

7.1 Lessons learned from road-EV incidents

References [145, 146] provide non-exhaustive but extensive list of road EV incidents. Detailed reports of several EV fire incidents are accessible from government repositories such as the National Transportation Safety Board (NTSB) accident dockets [147, 148, 149, 150]. These reports indicate that re-ignition is common across majority of reported road EV hazardous events. Numerous incidents also recorded more than one re-ignition event. Re-ignition events have been observed within minutes of initial fire suppression, as well as days or even months afterward. Re-ignition therefore was not limited to the site of initial event but was reported on the towing vehicle and storage yards to which the vehicle was carried. Such examples highlight the complex and non-deterministic nature of battery hazards.

In the incidents studied in this report, re-ignition was particularly common for vehicles that had undergone high-speed collisions. No records of re-ignition were found where the thermal runaway initiated during charging. Therefore, contrary to the onset of a thermal runaway, charging is less likely to result in re-ignition. This is intuitive as the charging process affects the entire battery pack, therefore, TR is likely to be initiated in all cells during the first incident. Similarly, cases of thermal runaway due to flooding were not followed by re-ignition as the entire battery pack may have shorted by the conductive path established due to the liquid. Partially flooding may lead to a delayed short-circuit, therefore delayed TR. In contrast to charging and flooding, a crash may only damage a few cells and modules and initiate a local thermal runaway. The remainder of the modules and cells are likely to be electrically isolated and remain at their pre-crash SoC. These set the scene for reignition.

Re-ignition is either thermal or electrical. *Thermal re-ignition* occurs when part of the battery that underwent thermal runaway is cooled insufficiently. Being a self-sustained heat source, the thermal runaway can reinitiate when external cooling stops prematurely, within seconds of water application ending by fire services, for instance. The thermal runaway could also propagate to undamaged portion of the battery through external heating. Periodic hissing and smoke release observed in previous incidents correspond to the sequential ignition of individual cells. *Electrical re-ignition* involves short circuits within the battery pack caused by undesirable electrical connections. Generally, this occurs when a structurally compromised pack is moved (e.g. during loading, towing or offloading), resulting in twisting or bending to create electrical contact that rapidly discharges and increases its temperature. Rare incidents of foreign objects such as chains used for towing have also been reported to create a short in damaged battery pack with exposed leads.

The principal objective of the RFFS is to save lives, then control a fire (allow the source of a fire to burn whilst being monitored) before looking to extinguish it. Once the visible fire has been extinguished, a close inspection of the battery for a few minutes to few hours (this will depend on the manufacturer's guidelines) is performed before it is deemed safe for towing. Despite this approach, stranded energy remains in the battery that may cause re-ignition. Post-incident reports have revealed that, despite multiple re-ignition events, on different occasions, more than 80% of the EV battery cells can remain intact [147]. Therefore, while the intensity of the initial fire may appear to consume the entire battery pack, they may only have resulted from local thermal runaway in a few modules. At this point, for most of the incidents, BMS become inoperative, therefore cannot inform the status of the cells and modules. Therefore, unless reliable electrical measurements are taken (which has proven difficult in the past incidents), the battery should be considered as a live high voltage source with significant stranded energy.

7.2 Factors affecting risk of reignition

From road EV incidents, the risk of reignition/delayed ignition can be related to multiple factors. Based on academic literature and understanding of battery operation, the risk can be tied to the state of the battery, expressed using measurements from sensors such as voltage, SoC, temperature, gas composition etc. In real-life thermal runaway scenarios, such measurements are often not available due to lack of equipment, damage to battery terminals and restricted access to the battery. Therefore, here the risk is correlated with causes and actions related to the primary thermal runaway event and original battery design. Each factor is discussed with its potential contribution to both electrical and thermal reignition.

7.2.1 Cause of primary event

7.2.1.1 Collision/crash

Evidence from road EV fires indicates that crash/collision related incidents are more prone to reignition. This is attributed to the localised damage that the battery pack sustains, leaving significant amounts of stranded energy. The initial thermal runaway is limited to the immediately damaged cells, but heat propagation could raise the temperature in neighbouring cells/modules, albeit at a slower rate compared to the primary thermal runaway. Once the initial extinguishing action is halted, insufficient cooling would elevate the temperature of the neighbouring cells beyond the point of no return, resulting in thermal runaway via thermal reignition.

The electrical insulation of a collision-damaged pack can be compromised through intrusion of metallic chassis members, damaged high voltage connections, exposed leads etc. This lack of insulation is a potential outlet for the energy remaining in the cells/modules, which were thermally unaffected by the initial event. Movement during lifting or towing could cause shorts or arcing, triggering a thermal runaway. A collision could also result in a slow fluid leak(s), which may end up causing a short and a delayed ignition [151].

7.2.1.2 Charging/post-charging

Charging-initiated thermal runaway is more likely to affect each cell in a battery pack. While rare, overcharging caused by faulty algorithm/equipment could overcharge the majority of the cells in the battery pack. High SoC makes each cell more susceptible to rapid initiation. Therefore, it is highly likely that almost all cells will be consumed through thermal

propagation. Consequently, the primary event likely will be more hazardous and difficult to contain. The likelihood of reignition is low, as supported through incident reports. However, this cannot be eliminated for eVTOL aircraft. In contrast to road EVs, eVTOL aircraft have multiple packs, all of which may not be charged at the same time, which likely to reduce this risk.

7.2.2 Primary response to initial event

7.2.2.1 Extinguishing medium

The next section of the report discusses extinguishing media in detail. Media such as CO₂, that work on the principle of smothering fires, are effective in rapidly extinguishing the initial battery fire. However, their limited cooling effect is unable to prevent propagation, leaving the battery susceptible to thermal reignition. Extinguishing media with greater cooling ability, such as water, liquid nitrogen etc. may reduce the heat flow from the initial thermal runaway to neighbouring cells, thus reducing reignition probability.

7.2.2.2 Application of extinguishing media

Battery packs are designed to stringent Ingress Protection (IP) standards, often rendering extinguishing media ineffective as they are unable to reach the cells. This is partly responsible for EV fire requiring greater water compared to Internal Combustion Engine (ICE) vehicle fires.

Recent developments in fire extinguishing technology have investigated intrusive firefighting methods, such as the ultra high pressure water jet system that can penetrate the battery casing and reach the cells would ensure that the battery is effectively cooled and reduce reignition risk.

7.2.2.3 Allowed to burn out

Fire rescue services may consider allowing road-EV fires to burn out to exhaust all combustible substances. Overlooking the social and environmental concerns, this is an effective strategy for battery fires as the risk of thermal reignition is minimised.

7.2.2.4 High voltage deactivation

EVs have an inbuilt mechanism for disabling the high voltage bus in the event of an emergency. Referred to as an Electrical cut loop, the mechanism involves cutting an externally accessible part of the low voltage bus, deactivating the high voltage circuit. It is noteworthy that the disconnect mechanism was often found inaccessible in real-life battery fire incidents. Details of the location and deactivation mechanism are provided by the manufacturer in the emergency rescue data sheets of the vehicle, which are available online [152]. EVs also have in-built Restraint Control Modules (RCM) that fire a pyrotechnic fuse in the event of a crash that disable the HV system [148]. Deactivation of the high voltage circuit, either automatically or by the rescue services, reduces the risk of an electrical reignition.

7.2.2.5 Battery discharge

Reducing the battery SOC is a known method to reduce the risk of thermal runaway or reignition. Previous road EV incidents have recorded attempts by OEM representatives to discharge the compromised battery using bespoke equipment. Practical implementation of such discharge mechanism might be complex: the initial battery fire could damage battery leads and render any discharging mechanisms ineffective.

7.2.3 Battery pack design

7.2.3.1 Anti-propagation measures in battery pack

Battery packs could have compartmentalised modules, separated by anti-propagation material. Section 6.3 provided an overview of the different types of inter-cell and inter-module propagation barriers that have been proven to effectively contain thermal runaway. The presence of such measures would minimise the risk of heat transfer between cells and hence minimise the risk of propagation during the initial thermal runaway as well as thermal reignition.

7.2.3.2 Distribution of battery pack

Road EV batteries are constructed to be compact and housed in a single casing. Thermal runaway reignition, both thermal and electrical, are probable for such battery packs. For large scale applications such as trucks, aerospace etc. the pack could be separated into sub-packs. It is feasible to have these sub-packs physically isolated by having individual housing, distributed locations and potential to electrically isolate them in case of an event. Risk of reignition would be negligible for (sub)packs that are not compromised in the initial thermal runaway event.

Figure 9 qualitatively summarises the links between reignition risk and parameters discussed above. Electrical and thermal reignition risks have been segregated as they may not be directly correlated in all scenarios. Using this chart, the risk of re-ignition can be approximated, and suitable prevention strategies can be devised.

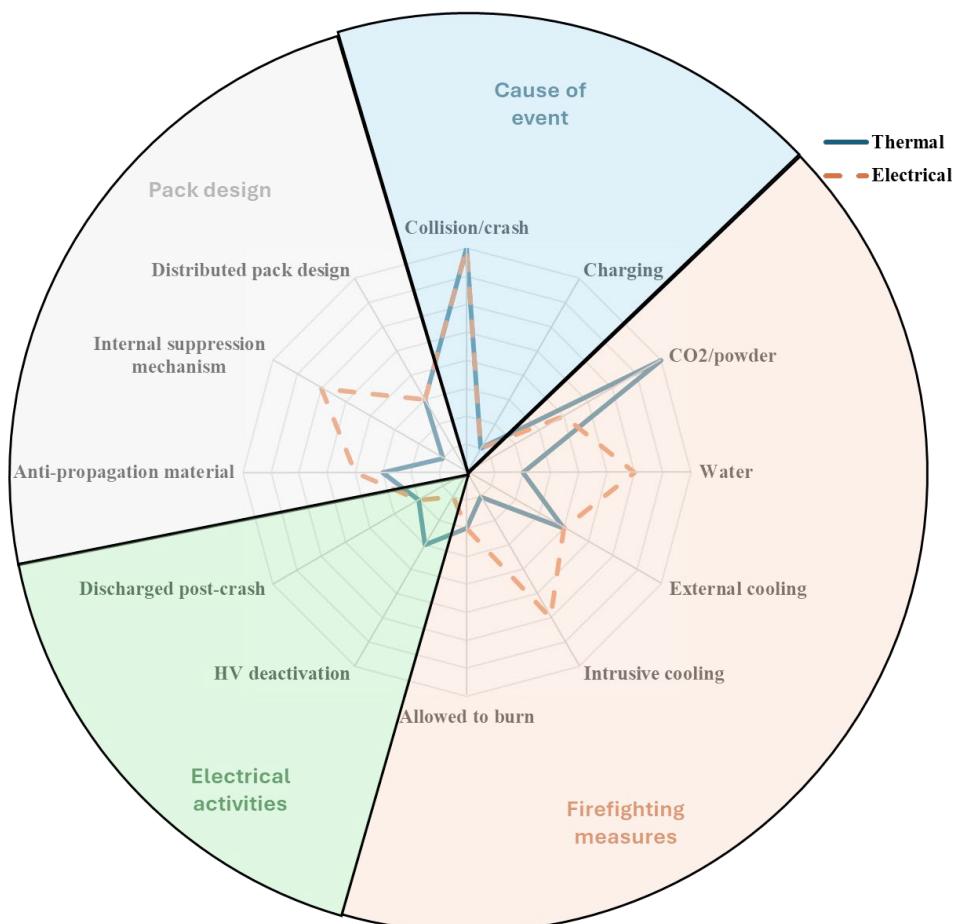


Figure 9 Risk of electrical and thermal re-ignition based on four critical parameters.

8 A review of firefighting methods for EV battery pack thermal runaway

Reviewing the firefighting method for road EVs provides a baseline understanding for eVTOL aircraft. Addressing a fire involving a road EV involves four stages [7], shown in Figure 10. The process begins with the identification of the vehicle involved, followed by an assessment of the root cause of the fire and selection of a suitable sequence of actions. After the immediate risks to life and property are addressed, multiple activities are conducted to eliminate residual risks, including environmental hazards. This section discusses the existing knowledge pertaining to each stage.

8.1 Identification and assessment

Once RFFS team is notified of a vehicle fire, they aim to identify whether the vehicle is an EV or an ICE vehicle. Many countries in the world use distinctive number plates for EVs, such as green stripes in the UK, green plates in India, but these markings may not be universally implemented. Visual cues such as the absence of exhaust pipes and fuel ports may be used. If the license plate is visible, online registration databases can be used to retrieve vehicle information. Modern regulations mandate the presence of an emergency eCall systems in new vehicles to automatically alert the rescue authorities in the event of a crash [153]. There are also recommendations for transmitting a Minimum Set of Data (MSD) automatically when onboard sensors detect a severe incident [154]. This data includes key vehicle information, helping to save valuable time.

Upon identifying the vehicle as an EV, the RFFS team retrieve the vehicle's Emergency Responder Guides, which contain details such as battery location and access points. Emergency Responder Guides, available from OEMs, can be accessed through tools like the Crash Recovery System [155], and in some cases via Quick Response (QR) codes placed on the vehicle body [156]. Critical information includes instructions for high-voltage (HV) system deactivation to reduce electrocution risk. The assessment of the event commences once the RFFS are on site. If there is no fire, vapour or smoke, a visual and acoustic inspection is conducted to check for signs of battery damage. External damage indicators include cracks, protrusions, or fluid leaks (electrolyte or coolant). Acoustic cues such as hissing or creaking suggest the battery may be venting or close to thermal runaway. It must be noted that EV battery packs are often encased in the underbody, making direct visual inspection difficult. If no signs of damage are found, the vehicle is observed for a stipulated duration before secondary actions can begin. Efforts could be made to take measurements from the battery to evaluate its status. In case of impact damage, the HV system is deactivated automatically through the activation of the RCM but damaged battery leads can still pose a hazard. Trained personnel with insulated tools and PPE take charge at this stage. Secondary action commences if no damage is identified. If damage is identified, the battery pack is prophylactically cooled. The uncertainty with the battery status is resolvable through the availability of BMS data to the RFFS, given the BMS is still operational. Currently, BMS data is not accessible using On-Board Diagnostics (OBD) ports. Efforts are underway in Europe to mandate a minimal set of BMS data to be shared with RFFS team in an emergency [157]. Such data sharing is already implemented in several EV fleets across China under non-emergency circumstances, which provides an example to push for remote real-time access to BMS data access [158, 159].

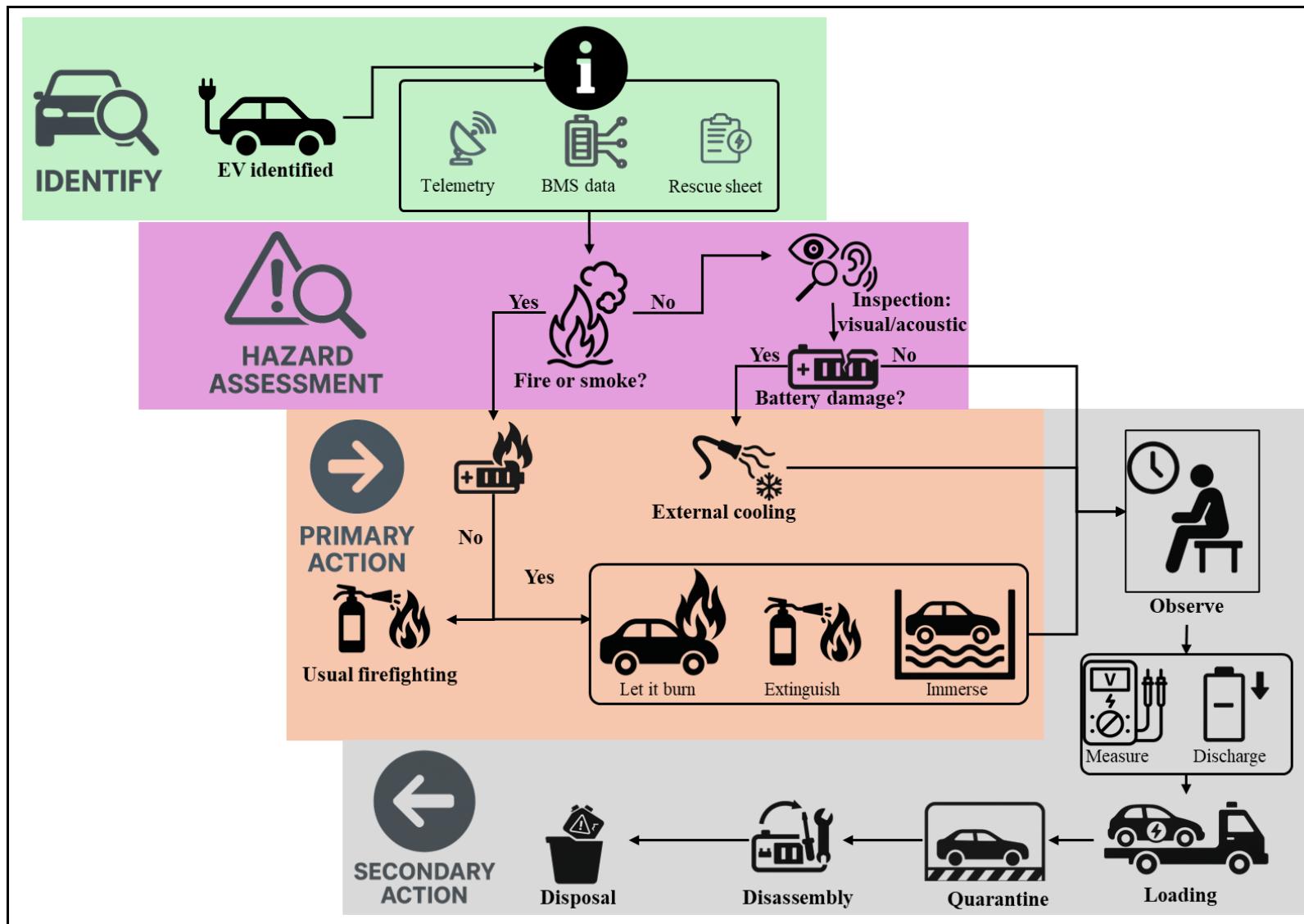


Figure 10 Electric vehicle firefighting sequence.

If smoke or fire is directly observed, an assessment is made to determine if the battery is the source. Crude assessment methods include monitoring the colour of the smoke or vapour, e.g. white or light-coloured vapour/smoke often is linked with Lithium-ion battery. Advanced methods do exist, such as sensing the gas composition and using a thermal camera to identify a heat signature; however, these methods have their own limitations. If the battery is confirmed not to be on fire, HV system can be made safe and standard firefighting methods can be used for the vehicle. At any point, if signs of battery thermal runaway are confirmed, cooling the pack and controlling the fire becomes the priority over preventing a short circuit.

8.2 Primary response

8.2.1 Controlled burn for battery pack

Once the risk to life is eliminated, a prominent strategy in tackling road EV fires involves securing the surrounding area, containing the fire and then allowing the battery pack to burn itself out. This is especially useful in the absence of any structure or vehicle in a close proximity to the compromised EV [160]. Given the large amount of water needed to extinguish battery fires, letting the fire burn out is considered a viable approach by firefighters and recommended by some OEMs. It is perceived that a sustained flame consumes flammable vapours, reducing the risk of an explosion: *“If it’s burning, there is less explosion hazard”* [161]. Allowing the battery to burn is expected to consume all the cells in the battery pack, thus minimising remaining energy or stranded energy in the pack. This reduction of stranded energy in turn minimises the risk of reignition in the future, simplifying post-incident handling of the vehicle involved.

Note that a controlled burn may involve the selective application of extinguishing agent. This may involve the activation of the site’s engineered fire protection system, which serves to prewet the aircraft structure in order to prevent exterior fire spread during the controlled burn. Secondary benefits to this approach involve cooling the landing deck surface and prewetting any adjacent combustible materials that are at risk of thermal damage or ignition.

Despite the perceived advantages, letting an EV burn in a public place is not always practical. EV accidents may result in extensive burn times depending on the firefighting strategy used, which can render public infrastructure such as motorways and car parks inaccessible, extensively disrupting normal life. Given the nascent nature of EV technology, the spectacle of an EV burning for hours could hamper public perception and affect the long-term goal of electrifying transport.

8.2.2 Battery firefighting

8.2.2.1 Extinguishing media

Fire is distributed into six categories based on the source as shown in Table 4 [162].

Table 4 Categories of fire based on original source [162].

Fire Class	Source/fuel
Class A	Solid combustibles e.g. wood, paper etc.
Class B	Flammable liquids e.g. petrol, diesel etc.
Class C	Flammable gases e.g. butane, propane etc.
Class D	Combustible metals e.g. Magnesium, Lithium etc.
Electrical fires	Electrical equipment
Class F	Cooking fats found in kitchen

Due to the composition of Li-ion batteries, a battery fire encompasses five among these six categories (A, B, C, D and electrical), which highlights the difficulty in extinguishing a battery fire. Several reviews [163, 164, 165, 166, 167] list the available fire extinguishing agents and compare their abilities to control or suppress battery fires. Fire extinguishing agents suppress a fire through physical mechanisms including smothering and cooling, and chemical mechanisms that involve interrupting the reaction chain causing the fire. Crucial properties desirable in extinguishing agents include:

- High heat capacity to cool batteries
- Electrically insulating
- High wettability and low viscosity to penetrate pack
- Environmentally friendly
- Have smoke reduction abilities

Among these, cooling property is the most important as suppression through isolation and suffocation are only temporary solutions against a battery fire because of self-production of oxygen. Detailed information on these agents is available in the references. While other gaseous and powder-based agents may exhibit greater flame suppression properties, reignition is highly likely with these suppressants. Flooding the battery with water remains the preferred option due to its higher cooling property and easy availability, although concerns regarding HV hazards have been raised. Water could be deployed as a jet, sprinkler or mists to make it more effective. Among these three, water mist was identified to be most effective due to lower water consumption, greater wettability and oxygen dilution via steam. Water mist also reduced toxicity by encapsulation of fumes and HF in smoke [168]. Moreover, additives such as F-500 are known to synergistically enhance suppression properties of water. F-500 was reported to reduce the viscosity of water thus improving its wettability and chemically deactivate flammable hydrocarbons, thus adding a chemical suppression mechanism [169].

Case studies from the field show that a typical EV fire requires larger amount of water compared to an ICE vehicle [170]. However, this is primarily due to limited access to the battery pack. In addition, there are criticisms of using water associated with its conductivity and greater HF production. Water is a conductor and may prematurely short-circuit cells, contributing to thermal runaway. Therefore, water is used when the battery is visibly burning as the electrical shorting may be a low-priority risk [171]. Using de-ionised water is another option to rule out the risk of shorting. Water does react with the fluoride salts in electrolyte to produce HF. This is the primary reason behind battery manufacturing being conducted in a dry environment. Nevertheless, despite the initial rise in rate of HF production, the overall HF content was reported to be identical in the absence of water as a suppressant [172].

Some intrinsic fire extinguishing solutions are also available. Flame retardants (FR), micro encapsulated in a polymethyl methacrylate (PMMA) shell, integrated into the battery electrolyte and/or coated on the separator are effective in self-suppression of Li-ion cell fires [173]. When the cell reaches a critical temperature, the liquid FR evaporates while the PMMA capsule wall weakens so that the FR is released into the cell. The FR causes the cell temperature to decrease, preventing thermal runaway and extinguishing the fire. The micro capsules do not inhibit the electrochemical performance of the cells and can be selected based on cell chemistry. Challenges regarding cost and rising temperature during charging remain to be solved.

8.2.2.2 Delivery of media

The large amount of water needed to extinguish EV fires is attributed to the lack of access to the source of fire, i.e. the Li-ion cells. Battery packs are manufactured to stringent Ingress Protection standards [174] restricting the water to outer surface of the burning packs. Recognising that the battery packs are stored in the underbody, firefighters have turned the vehicles on their sides for ease of monitoring as well as access [175], albeit this does not aid in penetrating the outer casing of the pack.

Improved access to the cells has been achieved through smart pack design. Renault developed a thermally actuated port in the car body [176]. Located under the rear passenger seat, this plastic portion would melt during a fire and create a route for the firefighters to direct water into the vent ports of the battery pack, thus flooding the cells. Formula-E battery packs are designed with dedicated ports, called “dousing ports” [177]. In the event of an incident, the ports can be used to douse the battery with water, thus cooling the cells and preventing reignition. RISE demonstrated a unique strategy of fixed fire suppression systems installed inside the pack [167]. The internal water release systems were demonstrated to reduce peak temperatures and also prevent module-to-module propagation. In the absence of inherent suppression systems in the pack, cracks in damaged packs could be used as entry locations for insulated lances to deliver water into the pack [168]. Puncturing the battery pack is also considered if the RFFS team have sufficient knowledge of the vehicle or details of appropriate locations for such activity are mentioned in the rescue data sheet.

Use of ultra-high pressure (UHP) water jet with abrasives has been recently investigated in Europe [178] [179]. The high-pressure stream of abrasives was shown to puncture battery packs, followed by delivery of an atomised stream of water directly to the cells. The portability, reduced water consumption and effectiveness in controlling battery fires from road EVs were verified through bespoke experiments as well as field deployment in the Netherlands and Czech Republic. However, concerns have been raised about their effectiveness as well as the high level of training required given the safety risks to the individuals using the UHP system. If not applied directly to the location where TR initiated, it may initiate TR to a new location and make the incident worse before any improvement. A method for correctly identifying the location of TR live in a real-world incident is yet to be developed.

8.2.3 Immersion

Immersing an EV in a large container filled with extinguishing media such as water or foam is an acceptable strategy in several countries for cooling the battery and reducing the risk of reignition. Partial immersion by placing the EV in a pit followed by water filling has also been implemented to rapidly cool a battery [175]. In the Netherlands, a liquid-tight container, referred to as a salvage container, is used for the recovery of EVs [180]. The container must be transported to the site of the incident and full immersion of the battery is difficult to ensure. In France, two immersion techniques have been considered: liquid-tight immersion tanks and temporary immersion baths [181]. The immersion baths are created by establishing watertight barriers around the vehicle and filling them with water. The bath has added advantages of easy transport to the vehicle and possibility to combine with external extinguishing agents to have a synergistic benefit. Bespoke containers have also been developed in Denmark with additional nozzles to circulate extra water for cooling [182]. In the UK, commercial EV submersion units are available [183], however, immersion is not included in the regulatory guidelines.

While the method of immersion holds promise, it relies heavily on the ability of water to infiltrate the battery pack. It also poses the additional logistic challenge of transporting a large

heavy container to the incident site. Appropriate disposal of the contaminated water is also a crucial post-incident consideration. Further work is needed to weigh the pros and cons of immersion as a firefighting or recovery method.

8.2.4 Smoke and explosion risks

Lithium-ion battery thermal runaway releases vapour and gases produced during uncontrolled chemical reactions inside the cells. The emitted gas volume and composition have been correlated with battery properties such as cell chemistry, SoC etc. However, these correlations are non-trivial in nature with several conflicting results in existing literature. It is important to appreciate that the assessment of gas composition of battery fire emissions is difficult. The off-gas is composed of dozens of by-products in a high-temperature environment (> 600 degrees), with multiple corrosive constituents that pose limitations on the sensors deployed. Some constituents are known to be short-lived, e.g. gaseous HF binds to available surfaces rapidly, thus leaving minimal traces in the gas samples being measured [184]. Therefore, understanding of gas emissions has been an area of deep interest and is constantly evolving.

Bugryniec et al. [185] provided a detailed review of gases emitted from battery fires. CO₂, CO, H₂ and hydrocarbons are the main gases emitted with toxic components HF, HCl, HCN, NO_x, and SO₂. The off-gas is known to have Lower Flammability Limit (LFL) of 6 to 11% [171] and can ignite from the self heating of the battery cells. These ignitions often manifest in the form of jet flames with temperatures in excess of 800 degrees. Direct exposure to such flames can cause severe burns [178]. Table 2 in [185] lists the major risks involved with exposure limits for each toxic or flammable gas. Among these, HF risk is deemed the most severe and captured in risk assessments and literature. In fact, between EVs and ICE vehicles, HF is the main differentiator in off-gas composition, with EVs producing at least twice as much [172, 186, 187]. Moreover, HF gas production is reported to increase as the fire proceeds. Despite the heavy risks, until March 2025, there are no confirmed cases of HF inhalation injuries from Li-ion battery fires [188]. Similar conclusions were drawn through the experience of medical and poison control authorities in Sweden and Norway, with no cases of HF inhalation despite the large number of EVs in these countries [184]. In contrast, symptoms of HCN poisoning were found in some victims. The data from these studies has raised the consciousness of RFFS teams and highlighted the importance of carrying provisions for rapid oxygenation of the victims' cells, bronchodilation and anti-inflammatory drugs as well as have HCN and HF antidotes, i.e. sodium thiosulphate and Calcium Gluconate solutions.

In addition to combustible and toxic products, the emissions could also contain electrolytes in the form of vapour. The solvent in the electrolyte, generally organic carbonates, have additional flammability, irritability and toxicity hazards. The existence of this highly flammable substance in the form of a “vapour cloud” is a result of incomplete combustion due to lack of oxygen. Being heavier than air, the solvent vapour should settle on the ground, however its properties are heavily dependent on the ambient conditions. The vapour cloud accumulation poses a severe explosion risk upon delayed ignition. Vapour cloud explosions are generally associated with confined spaces and poor ventilation [189] suggesting that large open spaces are safer for extinguishing and containment activities compared to confined spaces such as car parks or tunnels.

8.3 Secondary response

8.3.1 Monitoring

In the absence of smoke or fire and obvious damage to the battery, it is recommended the vehicles are monitored for 15-60 minutes to a few hours, at least two in Germany[168], to ensure their safety. The surrounding area is cleared to prevent collateral damage in case of a delayed ignition. Upon completion of the waiting period, the HV isolation of the battery is ensured by severing the HV rescue loop followed by insulation tests. Such monitoring activities may also benefit from the availability of BMS data as discussed in Section 2.1. OEMs have bespoke equipment to discharge their EV batteries externally. If such equipment is available, the battery is discharged in the absence of any signs of fire, smoke or damage by trained personnel with appropriate PPE.

Passive monitoring remains a part of the operating procedure even if smoke or fire was addressed during primary response. Monitoring is possible through visual and acoustic inspections from a safe distance. Gas sensors and Infrared (IR) cameras could also be used to provide detailed assessment. The Netherlands Institute for Public Safety (NIPV) recommends a waiting period of 15 to 30 minutes without any temperature rise monitored via thermal imaging cameras [178]. However, longer waiting periods are also advised by OEMs. If possible, an on-site assessment of remaining energy in the battery pack is recommended, followed by a discharge using OEM devices, if possible. Access to BMS data would be beneficial even for fire damaged packs. However, real life battery fire damage often damages battery leads as well as BMS [147], limiting the options to discharge or monitor battery data.

8.3.2 Moving an Electric vehicle (EV)

Moving an EV after an incident significantly increases the likelihood of immediate or delayed re-ignition. The compromised structural integrity of the battery can cause bending or twisting resulting in short circuits via unwanted electrical contact [147]. Use of conductive tools such as chains and belts to lift the vehicle during loading operations could further cause external short circuits. While these incidents have been recorded previously, it is expected that with time and experience, such hazards are easily preventable.

Towing EVs on their wheels is to be avoided, as wheel rotation may generate current and re-energise parts of the battery system [190]. UK, US and EU guidelines recommend the usage of flatbeds or trailers [160, 190, 191, 192]. It is prudent to avoid busy/populated routes and tunnels to minimise damage in case of an ignition. Monitoring activities could also be continued during towing via IR cameras. As for firefighting, submerging a vehicle in a large water tank is also a strategy when considering moving the vehicle, although this approach has practical constraints as discussed in Section 2.2.3. Fire blankets may be used covering the vehicle during transport [168]. These are made from materials that release fire-suppressing gases when heated. However, fire blankets are not a complete solution—vapour cloud build-up beneath the blanket can present an explosion risk when exposed to air. In addition, water mist systems have been added to a few flatbed or trailers designed to carry stranded EVs. It can cool under the vehicle and reduce the likelihood of the spread to the surrounding area in case TR is initiated while moving.

8.3.3 Quarantine

Quarantine areas are often used to store an EV with a compromised battery pack while considering a further course of action. Quarantine areas are located at tow yards, repair workshops, recycling facilities etc. for post-incident safety. The specific guidelines for

quarantine differ across countries with a general similarity in approach [160, 190, 191, 192]. Assuming a high probability of re-ignition (or delayed ignition), vehicles should be placed at a safe distance from surrounding objects, including other vehicles. The safe distance is 15 m as per UK and US guidelines, while EU mandates recommend a 5 m distance. Immobility of the vehicles during storage is ensured by tying them down to prevent any movement that might result in accidental shorting or collisions. Each set of guidelines recommends open-air storage with adequate ventilation to prevent flammable vapour cloud build-up, risking explosion hazards. Depending on the weather, rain covers may be employed to prevent rainwater ingress.

During quarantine, the vehicle monitoring continues with active preparedness for firefighting: Firefighting gear and extinguishing agents must be readily available to contain fire in the event of an ignition. EU guidelines also recommend non-combustible flooring as well as appropriate water containment facilities to prevent discharge of leaked fluids or water used for secondary firefighting [192]. Monitoring periods of 24-48 hours are recommended before the battery is considered fully cooled and safe for further activities.

The quarantine area may be used for conducting further assessment and disassembly to prepare adequately for disposal or recycling, thus requiring insulated tools and devices adequate for high voltage. If possible, devices for passive discharging of cells/modules with stranded energy can be deployed in consultation with the respective OEM. Appropriate PPE and RPE must be available for protection against electrical and chemical hazards. UK regulations recommend a set of PPE and RPE based on individual standards (Table 1 in [190]). The International Association of Fire Chiefs (IAFC) recommends usage of Self-Contained Breathing Apparatus (SCBA) [191].

While the vehicle is in quarantine, standard housekeeping practices are mandatory, such as restricted access to the facility using barriers and signage displaying the safety levels of each vehicle using colour-coded labels. Closed-circuit television (CCTV) cameras could be deployed to facilitate remote monitoring over extended periods. Local agencies including fire and rescue service, medical services and law enforcement and OEMs must be informed and regularly updated.

9 Addressing eVTOL battery Thermal Runaway: A consolidated position for RFF

eVTOL aircraft are the backbone of the future UAM ecosystem. After raising $> \$12$ billion investment and received ~ 7000 pre-orders by 2021, several OEMs are on the route to manufacture air-worthy aircraft [193]. By 2030, predictions estimate a \$3 billion global market with 20,000 flights per day [194]. The promising eVTOL trajectory is fraught with looming uncertainty of production delays and funding crunch [195]. Ensuring fire safety and minimising risk to life and property is therefore critical to the survival of the UAM dream.

Compared to road EVs, eVTOLs have unique aspects that may or may not contribute to the risk of a battery thermal runaway. An eVTOL aircraft could weight more than twice a medium-sized car while its footprint may outsize a road EV by a factor of 100. Vertical flight requires the battery pack to provide high power resulting in a larger battery pack and higher voltage. Nevertheless, OEMs have chosen to distribute the battery pack into multiple sub-packs that can be isolated physically and electrically, providing opportunities for localised firefighting. Stringent weight constraints also imply that liquid cooling systems and dedicated isolation materials may be sacrificed in first generation eVTOL batteries. The air-cooling during flight may be supplemented with forced high-pressure air cooling while the batteries get charged on the ground, through detachable units that plug into the batteries. Liquid coolant pumped to the aircraft during charging but drained at the end of charging is an interesting compromise for eVTOL aircrafts. Considering the nuances of eVTOL, this section presents a consolidated position regarding the sequence of steps to be followed for passenger rescue and containment of fire. The process was developed through engagement with different stakeholders, including eVTOL OEMs, airport RFFS providers, regional fire and rescue service providers, regulatory authorities, RTOs and other organisations. The procedure is divided into three distinct phases: Phase 1 being dedicated to evacuation and lifesaving, Phase 2 being containment and extinguishing, Phase 3 concerns disposal and operational continuity. Each phase is presented as a flowchart and discussed in detail to guide the future development of Standard Operating Procedures and guidelines for eVTOL industry.

9.1 Phase 1: Evacuation and life saving

Figure 11 summarises actions during Phase-1. Response actions commence with initial assessment of the situation followed by a set of decisions concerning the appropriate strategy for passenger rescue based on the chronology of events leading to the incident. Three possible scenarios are considered:

1. Aircraft emergency during flight, with pilot and passengers on board
 - a. Emergency related to the battery pack, aircraft performs an uncontrolled landing
 - b. Emergency related to the battery pack, aircraft performs a controlled landing
 - c. Emergency related to non-battery issues, aircraft performs an uncontrolled landing
 - d. Emergency related to non-battery issues, aircraft performs a controlled landing
2. Aircraft emergency on ground while/following charging, no pilot/passengers inside
3. Aircraft emergency on ground, just before take-off, pilot and passengers on board

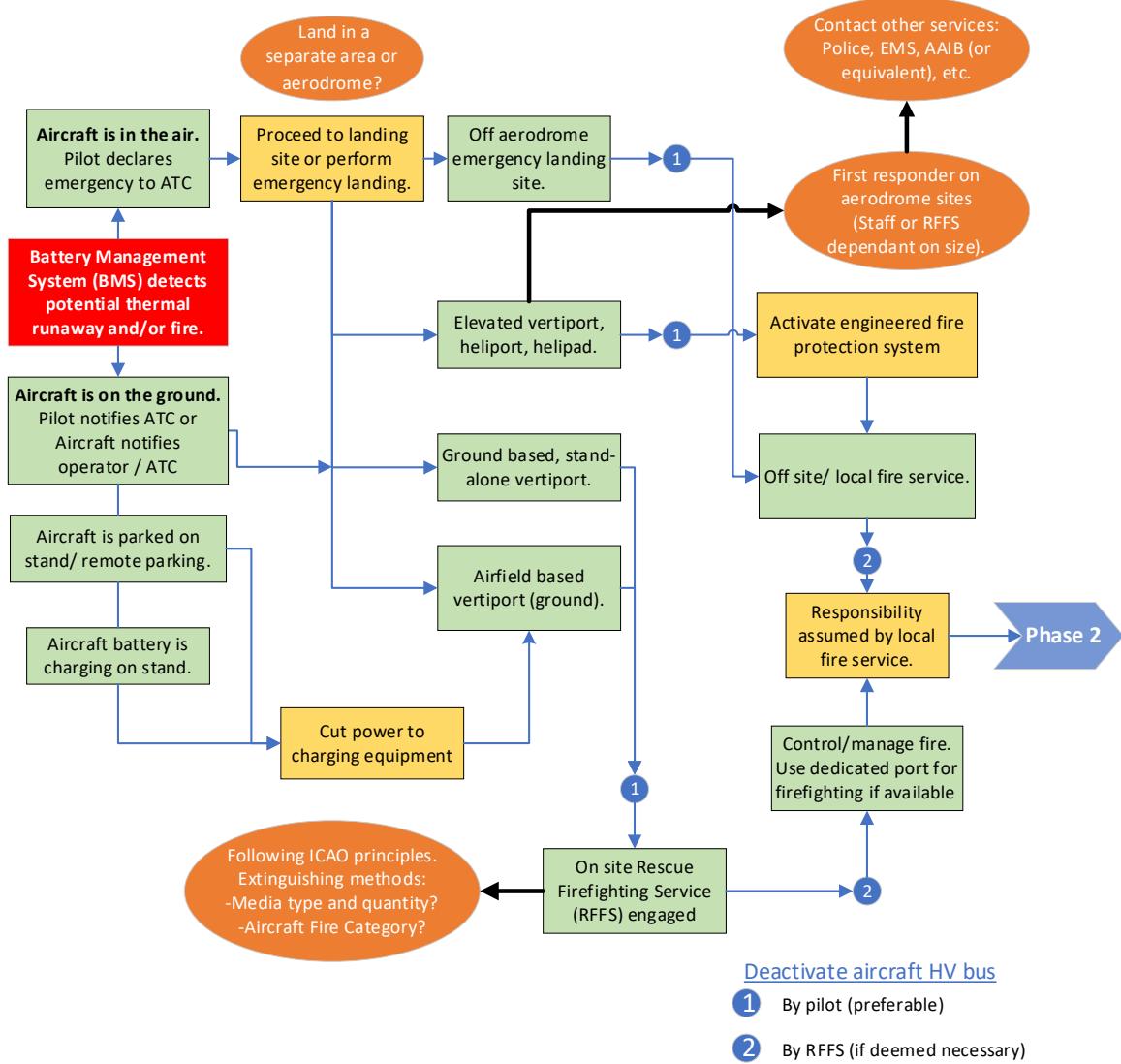


Figure 11 Phase 1 of RFF procedure detailing steps involved in evacuation and life saving.

If the aircraft is in the air, the pilot should declare an emergency and proceed to land. Ideally, the pilot should aim to land at a designated Final Approach and Take-off Area (FATO), which could be at an elevated vertiport, or ground-based standalone vertiport or within a large airfield. If time allows, the safest option is to land at a ground-level FATO with a high level of RFFS provision. An off-aerodrome emergency landing may be necessary if the pilot considers it unsafe to fly further, for example, if flames, vapour or smoke are visible. At large airfields and ground-based standalone vertiports, onsite RFFS should be engaged. They should manage the incident to create a safe evacuation route. If the aircraft is on the ground, then it may be unoccupied, in which case proceed to Phase 2. If occupied, it is likely that evacuation of an eVTOL will be rapid and straightforward, since there are few occupants and good provision of exits. However, in the case of a rapidly developing thermal runaway, it is possible that passengers will face risks from smoke/vapour or heat and that RFFS action may mitigate this.

If circumstances permit, the high voltage bus should be deactivated before commencing rescue operations. However, RFFS should refer to the instructions on the aircraft crash card for

appropriate interaction with the high voltage distribution system. The deactivation might be achieved in two possible ways: manual deactivation by pilot through manual switch in cockpit and deactivation by RFFS team using deactivation system detailed in the crash card. It is theoretically possible to have remote deactivation but may require regulatory push, OEM compliance and communication systems in working condition that is not guaranteed in the event of a crash.

Once initial rescue/evacuation is completed, the responsibility to manage and extinguish the fire can be conducted in conjunction with the local fire service. For the elevated vertiports and other sites where no onsite RFFS is available, any automated firefighting system should be deployed (e.g. deck integrated firefighting system for elevated vertiports/helipads), and local fire service should be engaged. It must be noted that existing automated firefighting systems were designed to fight hydrocarbon fuel pool fires, it is considered unlikely that they will be particularly effective against battery fires. They might be effective to delay or stop the spread of fire to the composite surface of the aircraft and surrounding. If the aircraft performs an off-aerodrome emergency landing, the local fire service should assume responsibility.

The importance of timely and efficient exchange of information in Phase 1 is noteworthy. Figure 12 shows the ideal communication chain through the important stakeholders involved corresponding to each scenario. If the pilot or aircraft autonomous monitoring system detects an emergency (scenarios 1 and 3), notification of the incident would generally come from the pilot's mayday call to Air Traffic Control (ATC). On the other hand, if the aircraft catches fire while charging on the ground without the pilot present, notifications may originate from the ground operations team or aircraft's autonomous monitoring system.

Each stakeholder has a designated responsibility: airport RFFS are tasked to create a safe evacuation route for passengers, crew and anyone else affected while the responsibility of supporting the RFFS response lies with the local fire services. Based on the respective roles and priorities, the information can be streamlined for each team. The critical information for each team is detailed in Table 5. Assessing the crash-card, and based on the nature of the emergency, the aircraft may be guided to a suitable location at the airport. If the aircraft catches fire on the ground, early access to the crash card will aid in developing an optimal rescue strategy while the RFFS are on their way to the event site, saving vital seconds.

The advantages of having access to real-time battery data for RFFS were previously discussed in Section 7. The inclusion of battery data within MSD for EVs in Europe and UK was highlighted. For eVTOL and the wider aerospace industry, telemetry is already being employed to transmit data from the BMS in test flights by OEMs. With the technology developed and tested by the OEMs, it will be viable to implement battery data exchange via telemetry for production aircraft. However, concerns regarding data sharing may remain as the majority of the information is proprietary. A feasible middle ground is needed: in an emergency, sharing of limited data that does not concern the OEMs but is sufficient to provide the RFFS with critical information that can guide them in selecting the appropriate course of action. Future regulations would define the requirements for the limited data that satisfies the RFFS requirements. The information would itself answer queries that delay firefighting response for road EVs including:

1. Is the battery the source of the fire?
2. Is the electrical insulation of the battery compromised?
3. Which sub-pack is likely to undergo thermal runaway?

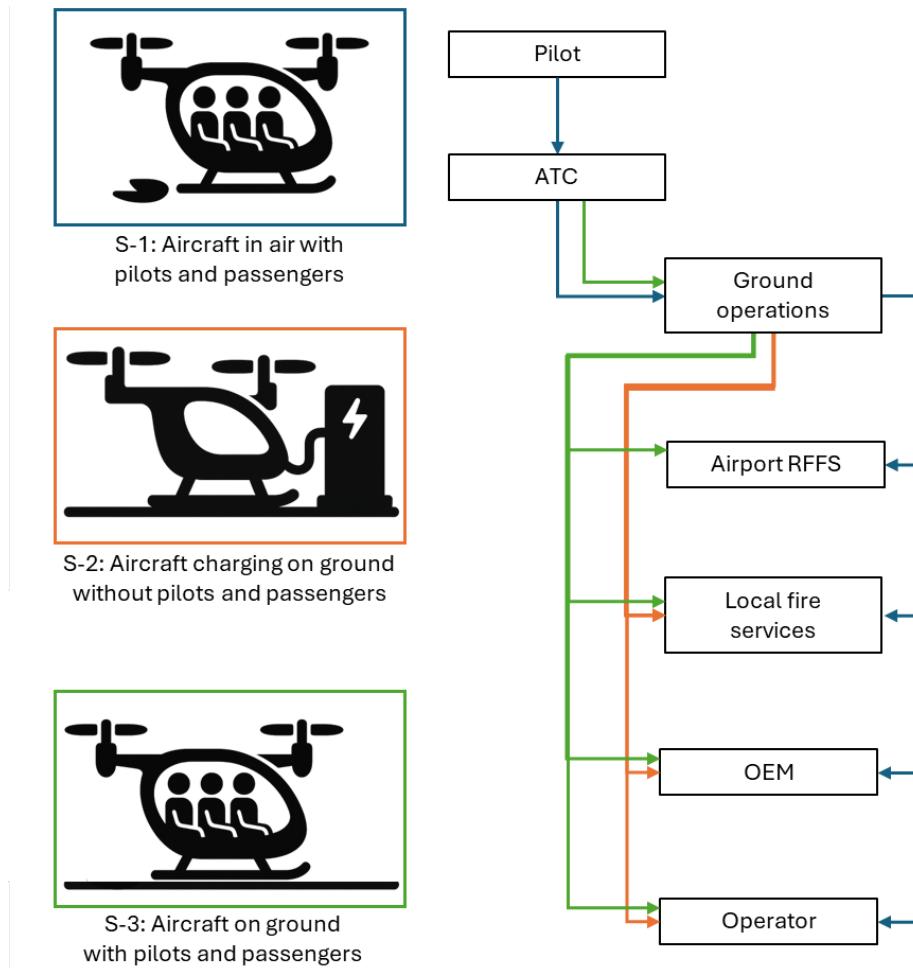


Figure 12 Standard communication chain in an emergency, ATC to airport RFFS, to local fire service, to operator/OEM [6].

Table 5 Critical information required by each team during eVTOL hazard.

	Aircraft/vertiport information	BMS/battery data
Air Traffic Control	• Sortie routine to determine future journeys that may be affected	
Ground operations	• Vertiport schedule	
Airport RFFS	• Number of passengers on board • Specific mobility requirements • Potential rescue points in aircraft structure • Location of vent ports to avoid inhaling harmful gases • Location and procedure of HV disconnect	• Location of sub-pack undergoing thermal runaway, if any • Insulation resistance of each sub-pack
Local fire service	• Presence and Location of dousing ports or firefighter's access for water ingress • Location of aerodrome water supplies	

9.2 Phase 2: Fire containment and extinguishing

Following evacuation and lifesaving, Phase 2 focuses on containment and extinguishing any fire, as depicted in Figure 13. As BMS has detected potential thermal runaway and/or fire, RFFS personnel should look for signs of thermal runaway propagation. The common signs include fire, smoke or vapour coming out through the dedicated exhaust vent designed for the battery thermal runaway events. Other signs include audible noise (for example hissing, or pops/bangs noise) and high temperature near the battery compartment. If any of these signs are observed, the firefighting process should be initiated. The RFFS personnel involved in

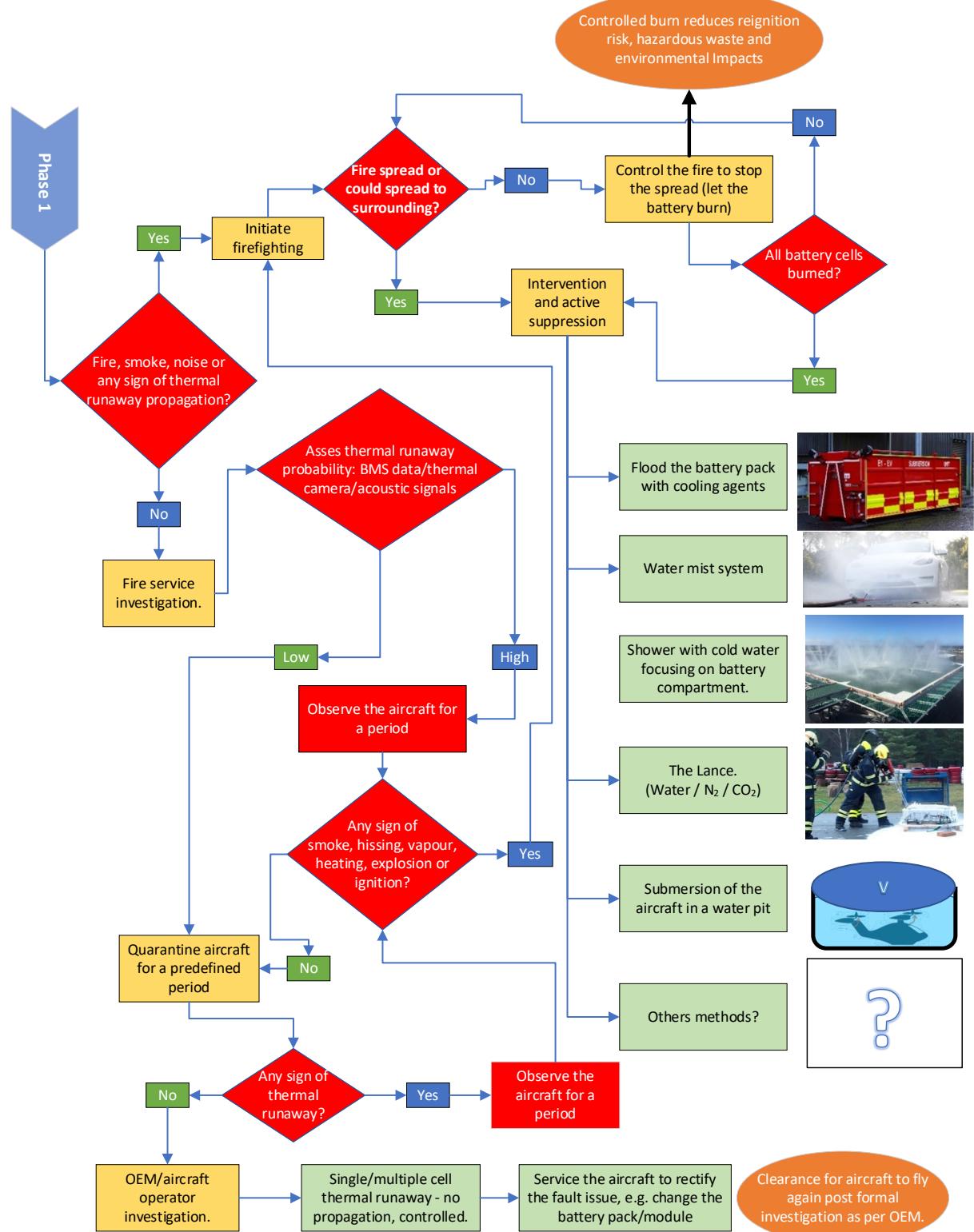


Figure 13 Phase 2 of RFF procedure with sequential actions and options for fire containment and extinguishing.

The firefighting process starts with identification of the source of the fire. If the available information through BMS data and observations confirm that the battery is safe despite smoke and fire, normal firefighting measures can be adopted. Battery pack design regulations, such as

RTCA DO-311A [3] and EASA SC-VTOL-02 [] ensure that the pack casing is able to contain thermal runaway without releasing smoke or fire except designated vent path for long enough to address the fire. If the battery is confirmed as the source, an assessment of the location of the incident must be conducted to determine if the fire could be spread to the surrounding area, e.g. any building, aircraft, vehicle etc. in close proximity. If the likelihood of the fire spreading to the surrounding area is low then the fire should be controlled while thermal runaway propagates through all the cells and all cell active materials are consumed by the fire. As discussed earlier, this controlled burn reduces the reignition risk, hazardous waste and environmental impact. An important consideration in this is that the battery pack casing is designed to contain any internal fire and release flames and smoke through a vent port. Therefore, it is reasonable to allow the cells to burn out while intervening as necessary to prevent damage to the surroundings and flame spread to other parts of the aircraft.

While the controlled burn is happening, a continuous assessment of the likelihood of fire spreading to the surroundings should be carried out. At any point of controlled burn, if the risk of fire spreading to the surroundings is found to be high, then active suppression targeting the burning lithium-ion batteries should be used. Otherwise, once thermal runaway has propagated through all the cells, if an ordinary combustible fire is still burning on any portion of the aircraft (including the battery pack or modules), use an appropriate method for extinguishing this fire.

For active suppression, different methods can be used, all offering certain advantages and limitations. Flooding the battery pack with cooling agent could be an effective option to remove heat from the battery pack and therefore suppressing and potentially extinguishing the fire. Current designs do not include an injection point for cooling agents but it may be possible to use the vent for this purpose. A more extreme version of this approach is submersion of the aircraft in a water bath. This would be effective in quickly containing the fire but does require substantial investment in infrastructure, which can only be effective at that location. Additionally, this might be logistically challenging considering most eVTOL aircraft have significant wingspans, and batteries might be hundreds of centimetres above the ground. Therefore, requiring thousands of litres of water to fill an extremely large immersion tank in a short period. Secondary issues with these methods include the potentially contaminated waste water.

Use of a UHP lance to cut into the aircraft and directly inject the cooling agent to the source of fire is an option. However, this is a destructive technique and reliable identification of the exact location of the source of fire may be very difficult. If applied to an unaffected battery module/pack, this could trigger a second thermal runaway event and worsen the scenario. Also, the risk of reignition and contaminated waste water remains.

Water spray or jets, focusing on the battery compartment, can be used to cool the pack externally. However, the effectiveness of this method is limited by the fact that battery packs are themselves waterproof and are enclosed within the aircraft structure. It, however, can be deployed for controlling the fire during the ‘controlled burn’ phase for the battery as it can be used to cool other parts of the airframe and the surroundings. It will also create a large volume of potentially contaminated water, which may need to be treated before releasing it to the local environment.

A water mist system may be effective in controlling the fire, as they are efficient at absorbing heat and thereby limiting damage from radiated heat. However, their effectiveness for active suppression is yet to be proven for large battery systems. A significant benefit is that a water mist system creates less contaminated runoff. Another method which might be useful for the

controlled burn phase is the use of a fire blanket(s). Covering a complete aircraft with fire blankets is not practical, however they can be used to shield surfaces to limit or slow flame spread to other areas.

At the beginning of the Phase 2, if there is no sign of thermal runaway propagation, then the RFFS should investigate the available data from BMS, heat signature and the physical condition of the eVTOL aircraft. If there is a chance of thermal runaway propagation, then the aircraft should be monitored for a certain period. However, this duration is not deterministic and may also hamper commencement of regular operations at the vertiport, causing additional financial losses. A straightforward approach to negate the risk of reignition is to discharge the battery. Car OEMs have been known to have bespoke equipment to discharge EV batteries externally. Discharging a battery externally after a crash or fire has faced challenges such as damage of battery leads, difficulty in accessing the battery etc. For eVTOL, the electrical isolation of sub-packs could enable this route: sub-packs that have survived the initial fire could be discharged individually through external leads detailed in the crash cards. OEMs yet to share plans about including such a provision in their designs and would need detailed assessment of available methods and personnel safety before it can be covered in regulations.

During the monitoring period, if there is any sign of fire, smoke, vapour, audible hissing or accelerated temperature rise near the battery compartment, then firefighting process should be initiated. If no sign of thermal runaway propagation is observed during the monitoring period, then aircraft should be quarantined for a predefined duration. Ensuring safe movement of the aircraft to quarantine might be challenging, particularly for aircraft with structural damage from a hard landing. External discharge is ideal but may not be possible in extreme circumstances. Smaller fire-blankets may be used to cover critical areas for ground transport of the aircraft. The provision of bigger and more reliable vent ports unlike automotive battery packs render the risk of vapour cloud explosions negligible if the blankets do not directly block these ports. A rather extreme idea would be to physically detach potentially risky battery sub-packs before moving the remaining aircraft. It may appear infeasible however eVTOL business is expected to push batteries to their performance limits and require packs to be replaced during an aircraft's lifetime. Therefore, ease of disassembly built into the design for battery replacement may be exploited for optimal secondary response to thermal runaway. This approach of physical detachment may also enable the usage of submersion containers for safe handling of the risky sub-packs. However, this approach can be extremely dangerous and should only be undertaken under direct from the OEM or their dedicated emergency response representative. If any sign of thermal runaway develops during the quarantine period, firefighting should be initiated. However, if there is no sign of thermal runaway propagation then the OEM or aircraft operator should investigate the incident. If a single cell or multicell thermal runaway without any propagation triggered the BMS to raise thermal runaway flag then the aircraft could be serviced, e.g. change the battery module/pack, and put back in operation.

9.3 Phase 3: Disposal and operational continuity

Phase 3 concerns safe disposal, operational continuity and infrastructure assessment following the fire being extinguished, as shown in Figure 14. If a controlled burn approach is taken for the battery, the level of damage to the rest of the aircraft will depend on the effectiveness of the battery pack enclosure in containing the fire. eVTOL aircraft are predominantly made from composite materials, which likely be more vulnerable and prone to ignition than alloys. Following recent incidents involving aircraft manufactured with composite materials, it is known that fire is likely to spread to the aircraft structure rapidly and consume much of it.

The pragmatic approach suggested is that once the fire in the battery pack has consumed all the cells then active firefighting is used to preserve the airframe as much as possible. One important consideration is that some designs have multiple battery packs that are in separate parts of the aircraft, limiting the fire to a single pack is an important target for both the aircraft designers and firefighters. Once the active battery fire in the first pack is over then conventional fire fighting techniques will be effective on the air frame.

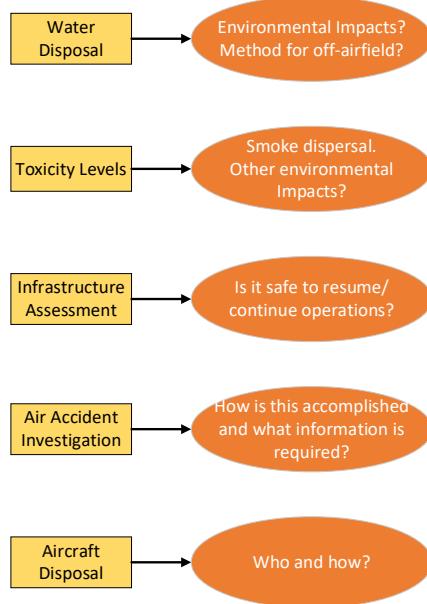


Figure 14 Phase 3 of RFF procedure with actions for disposal and operational continuity.

The safe disposal of material from the fire may be divided into battery materials, contaminated water and other airframe materials (which are outside the scope of this report). Battery materials can be further divided into those that are still thought to be active cells, that contain stored energy, and those that have been destroyed. Sub-packs that are found to have even a single cell vented, abnormal voltage or impedance readings, bus bar distortion (from excessive heating or physical damage for example) should be marked for disposal. Destroyed cells can be handled and disposed of as hazardous waste. The main concern with cells that are thought to be active is that having been through this incident, they may be damaged and may later go into thermal runaway themselves and cause reignition. Therefore, any remaining cells must be treated as a high risk and must be quarantined in a suitable location to control that risk. If possible, the risk can be reduced by discharging these cells, for example by immersion in a water bath. Ultimately, the cells must be disposed of through an approved battery disposal contractor. It is possible that battery packs separate from the pack involved in the thermal runaway incident may remain undamaged and safe. This will require inspection and a judgement to be made by the OEM.

As with any firefighting activity, water run off must be managed to avoid contamination of water courses or ground water. It must be assumed that water runoff is hazardous and should be intercepted and held for testing wherever possible. It may be necessary to collect the water and remove it for treatment. In practice this is no different from normal procedure, although the type of contamination may be different.

9.4 Potential regulatory additions

The discussion regarding RFFS response for eVTOL battery thermal runaway has raised ideas for technical inclusions that may improve firefighting response. Five such technical inclusions have been listed in Table 6 with markers indicating the relevant stakeholders. It must be noted that ease of implementation for these inclusions may vary based on the design, size and architecture of the aircraft. Therefore, regulators may choose to include them in MOC/guidelines instead of strict standards.

Table 6 Potential technical inclusions for improved eVTOL hazard response preparedness

	Additional technical/design inclusions	Additional cost	Potential for regulatory enforcement	Additional support from airport authorities/operators	Additional pilot/ground staff/RFFS training
Real-time battery data sharing via telemetry	Minimal	Moderate	High	High	Moderate
Remote HV disconnect	Moderate	Moderate	Moderate/high	Minimal	Minimal
Firefighting port	High	High	High	Moderate	Moderate
External discharging mechanism/equipment	High	High	Moderate	High	High
Simple detachment of battery sub-pack	High	High	Low	High	High

For firefighting, there also remain critical decisions that should not be left purely to the experience and instincts of the RFFS team on ground. Three such decisions are listed below:

1. Should the aircraft be allowed to burn out without any intervention?
2. How long should the aircraft be monitored before moving it to quarantine area?
3. How should the risk of moving a compromised aircraft be weighed against the delay in resuming normal operations?

Focused activities are needed to generate evidence and information that can provide specific answers to these questions and improve preparedness towards potential incidents and save lives in the future. In the interim, an operating site and flight path specific fire risk assessment may be used to inform RFFS for eVTOL landing locations and on the flightpath.

10 Future research

Several future work requirements were highlighted during the discussions with stakeholders and identified from the literature. These are to understand the risk profile of the eVTOL battery thermal runaway, the performance of certain methods for firefighting, and specific functionality requirements for eVTOL aircraft. These are discussed below; order does not reflect priority:

1. Practical, evidence-based understanding of active extinguishing vs controlled burn of eVTOL battery fire needs to be developed. This has not been comprehensively investigated, even for EVs. This needs to be benchmarked against other active extinguishing methods, e.g. use of UHP water lances. This can present a comparative analysis for technical risk mitigation, operational impact to aerodrome, environmental impact and public perception.
2. eVTOL aircraft implement modern telemetry methods, capable of live transmission of the different data to the operator's/OEM's technical team. However, in an emergency how much of that data can be shared with the RFFS providers, how it can be shared rapidly, and how that can help the RFFS providers is yet to be understood.
3. Another topic for future work is the safe handling of potentially hazardous battery modules following an emergency or BMS flagging potential issues with a battery cell/module/pack. RFFS requirements for safe removal of that type of battery packs from the aircraft, transport and storage, ideally in a quarantine area, need to be understood. In addition to these, there are a few other future requirements which were mentioned by the different stakeholders and authors of published work.
4. Although a dedicated port to flood the battery pack has been discussed, and a number of eVTOL OEMs have considered this, the performance of such a method needs to be better understood and validated. There are certain benefits of having this type of port and using water to flood the pack. There are concerns regarding using water for this purpose, e.g. electric shock, electrolysis. The risk of using water needs to be fully understood. If water poses a high risk, then other options could be liquid CO₂, or liquid Nitrogen, anything that can cool the pack rapidly and make it safe for a certain period, allowing relocation, dismantle and risk mitigation. Another point is how diverse requirements for the port and flow rate required for different eVTOL aircraft can be met by a standardised port connector design. Also access to such port(s) in an emergency needs to be investigated.
5. Performance of current eVTOL standards and MOCs to identify and mitigate thermal runaway risks have been up for debate. As the eVTOL industry is at a very early stage of technical maturity, the MOC and standards should be consistently debated and updated. This will need closer collaboration of stakeholders e.g. EUROCAE WG 112.
6. Performance evaluations of firefighting methods/materials discussed here are mostly using results from real world road EV incidents, research performed with a focus on road EV RFF, and the expert knowledge gained from these. However, the battery module and pack design and their integration in an eVTOL aircraft is fundamentally different than an EV. Therefore, a fresh insight dedicated for eVTOL aircraft battery pack is needed.
7. Low to mid TRL research demonstrated that diagnostics and prognostics techniques can detect/predict thermal runaway seconds, minutes, hours, even days in advance. Therefore, they should be investigated for deployment to reduce the number of thermal runaways within the eVTOL aircraft fleet. When thermal runaway is inevitable, it can provide valuable minutes to mitigate hazards posed by thermal runaway. If mandated this technology may significantly reduce the likelihood of eVTOL battery thermal runaway, reduce number of RFFS responses, save lives and aircraft loss.

11 Summary

This report categorically discussed the thermal runaway (TR) risk of large lithium-ion battery systems. It reviewed the current knowledge of how different battery parameters e.g. chemistry, SoC, SoH, and operating conditions e.g. charge rate impact the likelihood of TR and its character. It was identified, due to different usages pattern of the eVTOL aircraft than the road EVs e.g. operating SoC window, high power discharge for take off and landing, and regular fast charging. The strain these will put to an eVTOL aircraft battery is different than a road EV, which will lead to increased likelihood of thermal runaway and its character.

Following this, the lesson learned from road EV thermal runaway and associated RFF has been presented. It provided a fundamental understanding of different methods that have been used or considered for road EVs. A few methods e.g. submersion in a water tank, controlled burn of the battery pack were found to be effective and practical. A few methods have conflicting expert views e.g. use of fire blanket, use of an ultra-high-pressure water jet, for their effectiveness. When a large volume of water is used, contaminated water needs to be treated. A controlled burn of the battery, if it poses limited risk to the surrounding area was found to be widely accepted to reduce the environmental pollution and reduction of downstream risk e.g. reignition.

This provided a solid baseline understanding to develop a robust RFFS response in an eVTOL aircraft emergency. Some options however are not appropriate due to practical limitations, e.g. use of water tank, use of fire blankets. Controlled burn of a battery, if thermal runaway propagated through the battery remains as a practical option. This however is not well understood for an eVTOL context. Including this, several other future workstreams have been highlighted, which are the logical next steps following this work.

This report in no way should be considered as CAA recommendations. This report provides an in-depth understanding of eVTOL battery thermal runaway risks and possible methods for RFF. This should serve as a baseline for responsible organisations to develop robust RFF methods.

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