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Review—Meta-Review of Fire Safety of Lithium-Ion Batteries: Industry Challenges and Research Contributions

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The Lithium-ion battery (LIB) is an important technology for the present and future of energy storage, transport, and consumer electronics. However, many LIB types display a tendency to ignite or release gases. Although statistically rare, LIB fires pose hazards which are significantly different to other fire hazards in terms of initiation route, rate of spread, duration, toxicity, and suppression. For the first time, this paper collects and analyses the safety challenges faced by LIB industries across sectors, and compares them to the research contributions found in all the review papers in the field. The comparison identifies knowledge gaps and opportunities going forward. Industry and research efforts agree on the importance of understanding thermal runaway at the component and cell scales, and on the importance of developing prevention technologies. But much less research attention has been given to safety at the module and pack scales, or to other fire protection layers, such as compartmentation, detection or suppression. In order to close the gaps found and accelerate the arrival of new LIB safety solutions, we recommend closer collaborations between the battery and fire safety communities, which, supported by the major industries, could drive improvements, integration and harmonization of LIB safety across sectors.
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Lithium-Ion Batteries and Fire Hazards

The Lithium-ion battery (LIB) is an important technology for the present and future of energy storage. Its high specific energy, high power, long cycle life and decreasing manufacturing costs make LIBs a key enabler of sustainable mobility and renewable energy supply.[1] Lithium ion is the electrochemical technology of choice for an increasing number of industries, ranging from small cells in consumer electronics to large scale packs in the electrification of road transport and smart grids. The combined LIB market is immense, for example, the global electric vehicle market alone is predicted to rise up to $93.1 billion by 2025.[2]

Although great success has been made on LIB commercialization, safety concerns have emerged because of unexpected fires. Some LIBs can display a tendency to ignite under abuse conditions and initiate fires or release toxic gases, thus creating a hazard. Moreover, as LIB technology moves to larger scales, from single cells to modules and packs, assuring their safety is an issue of growing severity and stakes. Exceeding the window of conditions in which LIBs operate safely can trigger thermal runaway (TR) and lead to fires (see Fig. 1). Thermal runaway is a state that occurs when the temperature of the LIB reaches a critical value such that the reaction rate of an exothermic reaction increases the temperature, which in turn leads to further acceleration of the reaction rate.[3] This positive feedback of temperature increase is a sign of ignition and creates the fire hazards. Once a cell fails, the large amount of heat generated could trigger the thermal runaway of adjacent cells, contributing to fire propagation. Fires on the module and pack scales can release large amounts of heat and toxic gases[4] and are difficult to suppress.

During the last two decades, fires of LIB-powered devices have captured the headlines several times, ranging from small consumer electronics to large power systems. The most notable fires are summarized in Table I. Initial concerns arouse in portable devices such as cell phones and laptops. The first major product recall due to fire safety took place in 2006, when Sony recalled more than 9.6 million LIB that powered notebooks of well-known computer manufacturers, with an estimated direct cost of $360 m.[5] Ten years later, in 2016, Samsung made one of the largest recalls in history: 2.5 million Note 7 smartphones, with an estimated direct cost of $5.3bn ($17bn including loss of profit).[6] Later concerns affected larger LIB assembled into modules and packs, for example in electric vehicles (EV), where fires of Chevy Volt and Tesla Model S hit the headlines.

Beyond media, official statistics collected by agencies in specific sectors show the impact of LIB fires. In China, the world's largest market of EVs, 31 LIB fires are recorded per year on average,[7–9] with the most common cause being sudden ignition (36.9%), followed by charging (26.2%).[7] In the USA, the National Transportation Safety Board (NTSB) has reported 17 Tesla and 3 BMWi3 LIB fires out of 350,000 and 100,000 vehicles respectively.[10] Large-scale LIBs have also led to safety problems during storage and transportation, before connection into a product. The USA Federal Aviation Administration (FAA) has recorded 252 air and airport fire incidents involving LIBs in cargo or baggage since 2006.[11] And the USA Consumer Product Safety Commission (CPSC) reported 25,000 fire incidents in more than 400 consumer products between 2012 and 2017.[12]

Although statistically rare, LIB fires are a concern because LIBs are ubiquitous in modern society, and also because LIB fires pose hazards which are significantly different to other fire hazards in terms of initiation, spread, duration, toxicity, and extinction. It has even led to the new concept of strained energy in reference to the persistent and intermittent burning behaviour observed in many EV fires. There are many technologies for increasing the level of safety of LIBs which can be organised into four main layers of fire protection (as shown in Fig. 2): prevention, compartmentation, detection and suppression. The concept of layers of protection is common in fire engineering but rarely applied before to LIB fires. It has the advantage of rational classification of different technologies according to aims. The prevention layer aims at avoiding thermal runaway; it is about the intrinsic safety of LIB design. Once prevention fails, ignition occurs and it leads to a fire. Compartmentation aims to hinder fire propagation and avoid a cascading failure. Early detection is key to allow time for the emergency response, evacuation and trigger suppression. Once activated, sprinklers or similar suppression systems could quench the

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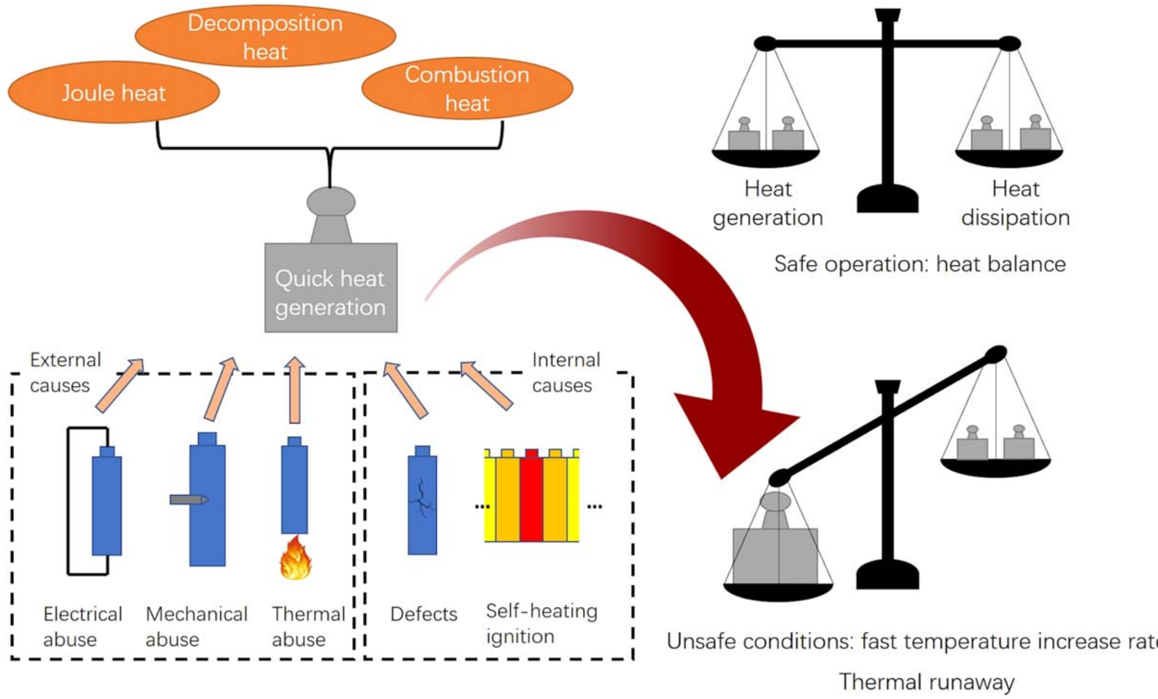

Figure 1. The 4 known abuse conditions that can lead to LIB thermal runaway and the imbalance between heat generation and heat dissipation.

Table I. Lithium-ion battery fires that received large media coverage in the last two decades. Incidents are arranged by application and then presented chronologically.

Application	Company	Year	Incident description
Cell phone	Nokia	2003–07	Sudden failure in batteries of mobile phones.
	Kyocera Wireless	2004	
	Samsung	2016	
Notebook	Sony	2006	Sudden failure of batteries powering notebooks.
Electric Vehicle	Chevrolet	2011	Chevy Volt on fire weeks after crash test.
	Tesla	2013	Model S on fire after hitting debris.
		2013	Model S on fire after crash.
		2016–19	Model S suddenly on fire while parked.
	Jaguar	2018	i-Pace suddenly on fire while parked.
Aerospace	Boeing	2013	Sudden failure in auxiliary units of Dreamliner 787.
Hoverboard	Various	2015–17	Sudden failure in many hoverboard's batteries.
Marine	Corvus Energy	2019	Hybrid-battery ferry on fire due to coolant leaking.
Stationary energy storage systems	Various	2017–19	Battery fires in large grid-connected systems

flames and cool the battery. Each layer of protection has a different role at each of the scales of LIB technology, which span from active materials to cell to pack (see Fig. 3). For example, the development of safer chemistries is typically conducted at the active materials scale, while techniques to avoid thermal runaway are studied at the cell scale, and fire propagation at the module and pack scales.

This paper collects and analyses the safety challenges faced by LIB industries across sectors, and compares them to the research contributions found in the field. We present the safety challenges faced by LIB industries and convert them into research questions then an analysis of the state of the art of LIB fire research structured into the layers of protection and scales. Finally, we compare the industry challenges with the research contributions to identify knowledge gaps and opportunities going forward.

This paper aims to bring together knowledge and experts from two different disciplines, i.e. battery and fire, to share knowledge and different approaches to LIB safety, which is an intrinsically interdisciplinary topic. Such an exchange should have a dramatic impact on the rate of finding successful solutions to the problems currently hindering a fuller uptake of LIBs. The successful integration of disciplines requires also bridging the terminologies. Battery experts and fire experts often prefer different terms to describe the same phenomena. In this paper, the term ignition includes thermal runaway initiation, and the term fire propagation includes the cascade of thermal runaway events among cells (also called thermal runaway propagation).

The Safety Challenges Faced by Industry

Many industry sectors are actively working to advance and improve the safety of LIB technology. Here we analyze the major safety challenges faced by different industries and their research needs to tackle LIB fires. We sent a survey to 12 LIB companies covering many industry sectors. We asked for their main safety concerns and research needs. 9 replied, providing their views and informing our analysis (6 companies agreed to be named in the acknowledgments). The industry sectors considered include manufacturing, consumer electronics, EVs, heavy-duty off-road vehicles, aerospace, drones, logistic,

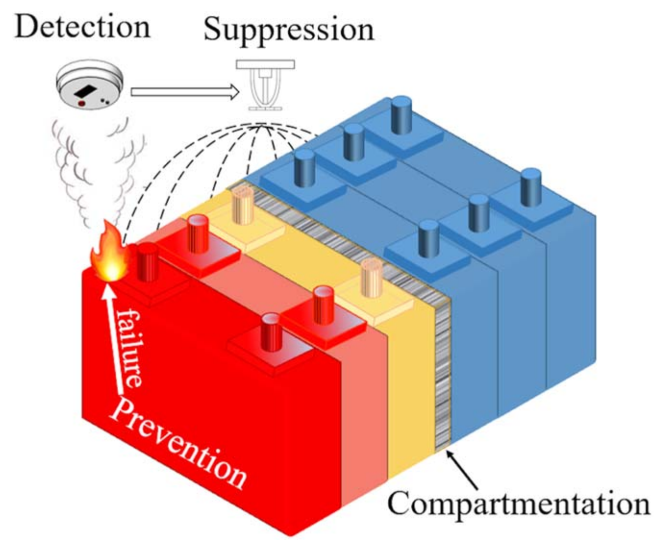

Figure 2. The four layers of fire protection present in LIB. Prevention includes safety components and safety devices. Once prevention fails, the detection layer can provide quick warning, triggering suppression and the emergency response. Compartmentation aims at delaying or stopping the propagation to other cells and modules.

grid, stationary energy storage, waste treatment and battery recycling. We have grouped all their concerns into five main challenges (see Fig. 4): Ignition and Propagation, Regulations and Standards, Detection and Reliability, Emergency Response, and Transport and End-of-life. These five challenges have been ranked by relevance, listing first the safety challenges most common to these companies.

Ignition and propagation challenges.—The major LIB safety challenge, as perceived across industries ranging from consumer electronics to stationary energy storage, is the possibility of thermal runaway initiation in one of the cells. Thermal runaway is perceived as the most safety-critical failure mode of a battery.[13] Its associated effects include cell overheating, overpressure, gas and particulate emissions, sparks, flames and even explosion.

There are several causes that can trigger thermal runaway, summarized in Fig. 1, which can be classified into external abuse (e.g. mechanical, thermal, electrical) or internal failure (e.g. defects, self-heating).[13] The abuse conditions are related to each other. The mechanical abuse, such as penetration or crushing, causes a short circuit, which is electrical abuse. The electrical abuse results in joule heating, which increases the cell temperature (thermal abuse) which can trigger thermal runaway. Internal failure can lead to spontaneous ignition. Most of the studies focus on abuse conditions, and only a small portion of the papers investigate spontaneous ignition. This is despite the statistics of EV safety showing that spontaneous ignition is the most frequent cause, accounting for 80% of the fire. Failures attributed to manufacturing defects are by far the most worrying as these are very difficult to detect, even with the extensive efforts carried out by battery manufacturers. Thus, internal cell defects and internal faults that develop inside individual cells over time, causing the initiation of thermal runaway, are a major concern for all industries which demand methods and tools to reliably identify them. Manufacturing defects can also be induced at the module and pack levels and these faults might not be detected until the unit is powered up and the battery management system (BMS) identifies a resistance issue (assuming a BMS with this capability). After a defect has been detected, re-manufacturing of modules where the bus bars have been welded onto cells is problematic, as re-working the weld can result in excessive heat build-up or internal cell damage that, in turn, can cause a short circuit. For this reason, the defected module as a whole may need to be scrapped. Pack manufacturers therefore demand research into early-detection methods of sub-standard welds (before the module assembly is completed and the BMS powered up) and into ways of safely reworking welds at both module and cell levels, thus avoiding the need to scrap them. One approach to avoid this problem is to develop new ways of attaching bus bars to cells.[14]

The link between the type of abuse and the time to ignition (also called incubation period) is another topic that has drawn significant interest, with a wide range of industries asking for further research. For example, heating the cell surface to 200 °C for 10 s does not lead to thermal runaway, but holding a cell at 110 °C for 1 h does.[13] Factors such as SOC, chemistry and SOH also influence time to ignition, in ways not sufficiently understood.[13] Furthermore, understanding crash-related fires is an issue of high importance in the

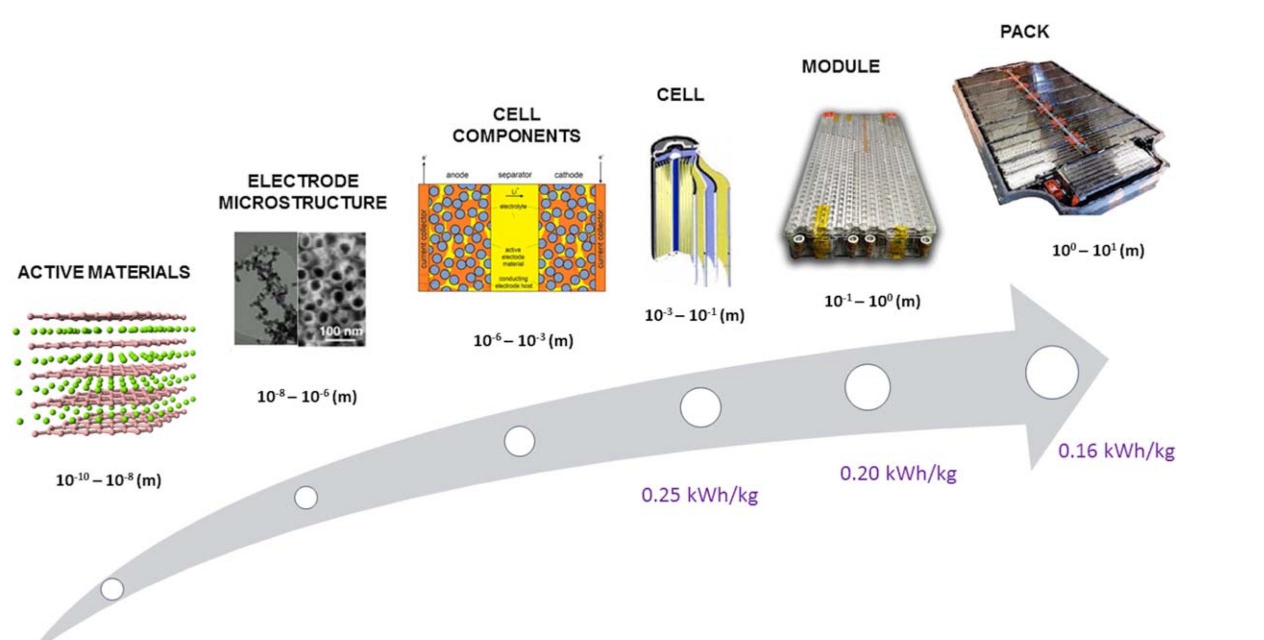

Figure 3. The different scales involved in LIB technology from active materials to cell to pack. At different scales, the fire hazard and the protection strategies are different.

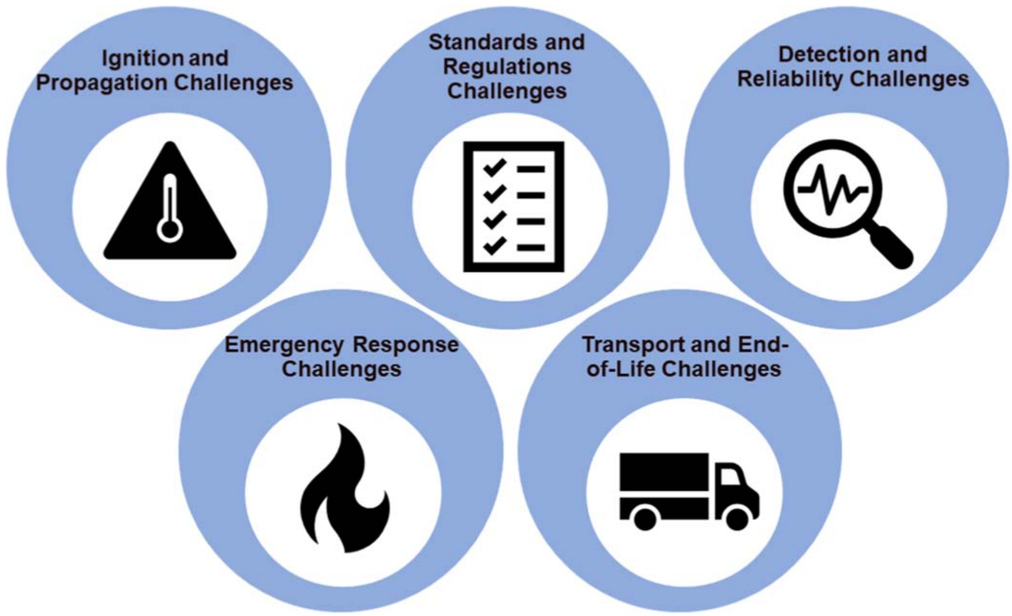

Figure 4. The top five safety challenges faced by Lithium-ion battery industries according to the data collected in this work.

automotive industry. The consequences of a battery being crushed in a vehicle, the likelihood of ignition and how to assess its safety, are major concerns for the EV and HV industries.

According to manufacturing, advanced engineering, automotive and aerospace industries, research should focus on control measures to detect battery failures through the fundamental understanding of cell limits. Three areas of research should be key to avoiding thermal runaway initiation; (i) developing methodologies to determine the maximum safe temperature (T_{safe}) for specific cells, (ii) evaluating the relationship between T_{safe} and the maximum allowed temperature by the BMS and (iii) understanding the variability of T_{safe} with SOC and ageing (SOH), and location within the module. This relates back to fundamental research on cell heat generation and its variation with SOC, ambient temperature, current and SOH understanding. Furthering understanding of the processes involved in cell heat rejection will reduce the risk of thermal runaway initiation.[15,16]

Fire propagation in LIB systems is a major issue for industries involved in large-scale batteries where the evacuation time of people can be long, such as automotive or stationary grid.[17] Cell to cell propagation depends on the thermal runaway characteristics and the balance between heat generation and heat dissipation (Fig. 1). One of the major concerns in this regard is the relationship between the mode of thermal runaway (type of abuse) and the fire severity, and therefore the propagation characteristics. This relationship has produced significant confusion, as the abuse methods included in regulations and standards are not always representative of real scenarios. The short circuit current is a fundamental parameter in the process. As of this date, no reliable method exists to create on-demand internal shorts in cells that lead to propagation and thus showing a response that is representative of the shorts originated by real failures.[13] Therefore, there is a need to develop a robust propagation test in addition to the single-cell thermal runaway test.

Fire propagation is also influenced by other contributing factors such as the initial temperature of the system, the thermal boundary conditions (e.g. heat conduction to adjacent cells, cooling strategies and cooling power of the module or pack), architecture and mechanical structure of the module, temperature inhomogeneity within the cells or among cells in a module leading to thermal gradients and accelerated localised degradation, etc. Aside from the total heat generated in a thermal runaway event, other important quantities for describing and predicting fire propagation are the heat generation rate, able with cell chemistry, SOC, current and SOH, and other external factors, such as presence of an ignition source, and availability of oxygen.

There are two specific approaches recommended by industry towards fire protection of batteries.[18] The first recommended approach is the development of safe battery chemistries or safe battery designs that do not result in thermal runaway or subsequent fire propagation. There is a consensus that some cathode chemistries are safer than others (e.g. LFP has higher thermal stability than LCO, LMO or NMC).[19,20] Other protection strategies are the use of modified separators (with ceramic coating or particles) that rise the thermal runaway trigger temperature or shutdown separators that stop the transport of Lithium ions once a set temperature has been reached. The use of modified electrolytes or non-flammable electrolytes would limit heat generation and potential further damage.[18,21] Solid state batteries are seen as the next game changers in terms of safety as they do not contain a flammable electrolyte.[21] Other candidates for future battery chemistries such as the LiS batteries present different risks related to the rapid reactions favoured at the surface of a Lithium anode. However, an overall safety assessment would be required to establish the safety effects of these choices at cell and module levels.

The second approach recommended by industry towards fire protection, most common in automotive, aerospace and advance engineering industries, assumes that thermal runaway will eventually occur and relies on the implementation of reliable, lightweight, low-volume safety features that centre on the detection, compartmentation and mitigation of cell to cell and module to module fire propagation. Having reliable detection and compartmentation measures would be advantageous, reducing battery weight, improving its performance and ultimately reducing its cost.[13] Thus, these industries demand specific research on protection strategies by battery design. Analytical studies of the impact of cell spacing distance, spacing materials, clearance above the cell burst disc, cell surface treatment, individual cell fusing, and cell holders designed to slow down fire propagation are some examples of research on design strategies needed at the cell and module levels. An example of adequate cell spacing is illustrated in Fig. 5, where a thermal runaway is induced in the cell located at the centre of the pack and no propagation occurs to the adjacent cells.

At the moment, no single approach has been identified to mitigate fire propagation and as a consequence a wide range of different safety strategies are combined to achieve a sufficient level of

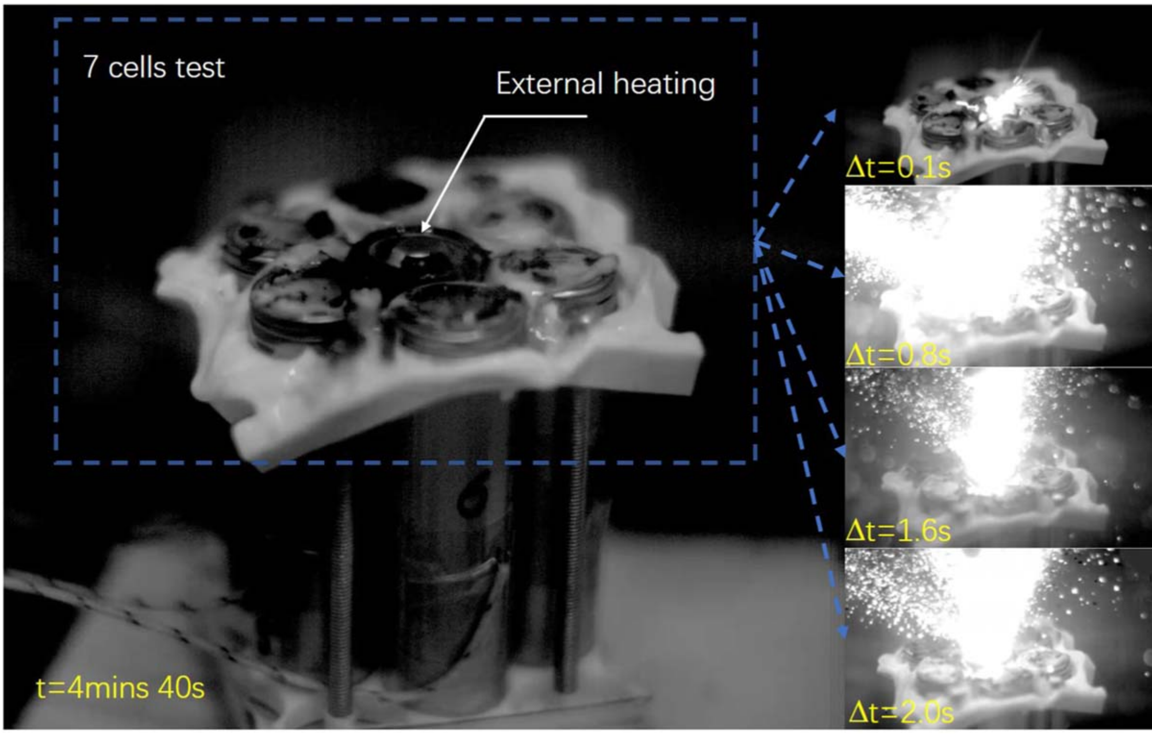

Figure 5. High-speed camera images showing ignition and evolution of the fire in the central cell of a 7-cell 18650 battery pack. External heating was applied to the central cell and ignition took place after 4 min and 40 s. Footage provided by Cognition Energy.

safety.[13] Shut-down separators, thermal fuses, temperature cut-off devices, positive temperature coefficient devices, current limiting fuses, current interrupt devices, vent disks or plugs and BMSs are incorporated into cell, module, and battery pack levels to protect against off-normal conditions.[13,19,20] However, containing any fire or explosion within the battery case during failure is still a challenge for most industries that operate with large format cells (e.g. EVs, HVs, aerospace, manufacturing or stationary grid). Specific research on what energy needs to be contained in the battery case, how to calculate it and thus what thickness of material to use for the case, is still required.

Another major challenge that it is relevant to these industries in the event of LIB failure is how to direct any vent gases safely away from passengers. Standards such as SAE J2289:2008[22] describe that material vented from the battery should not be directed towards the passenger compartment as it may pose a hazard. Research on this subject supported by modelling (e.g. accident case studies in different scenarios) is demanded by many transportation industries.

Battery developers, product designers and OEMs also demand more testing at module and pack level in order to improve the understanding of fire propagation. A holistic view of cell, module, pack and application is required to mitigate the risks of fire propagation, avoiding the subsystem optimisation trap that leads to a limited increase in safety at a higher cost.

Regulations and standards challenges.—LIBs must pass a series of safety tests to be certified for use in applications according to international and national standards and regulations. These safety tests have been developed based on research and pre-normative findings by regulatory bodies, industry and academia. While regulations are issued by governments and have legal enforcement, standards are voluntary documents defining industry consensus on minimum design and test requirements to achieve a desired level of safety or operation. As LIB technology is still evolving, there is not yet an industry consensus on system design and performance-based test methodologies.[19] However, the standards available provide a basis for sharing knowledge and experience, and allow a consistent level of safety to be established across industry.

In the case of the EV industry, a number of recognized international (SAE,[23,24] ISO,[25–27] IEC[28–30]) and national (e.g. US,[31–33] Korea,[34] India,[35] China[36]) standards are in place focusing on LIB safety testing at the system, pack, module and cell levels. LIB safety standards are also available for other industry types such as consumer electronics,[37] manufacturing and industrial applications,[38] aircraft installations[39] and stationary applications.[40,41] These standards may be referred to by battery regulations such as the UN/ECE-R100.02[42] or the GRT-EVS[17] in the case of the EV sector.

One of the major concerns across all these industries is that the standards available may not be representative of real-world scenarios. In the case of EV and HV, most standards and regulations impose test conditions derived from internal combustion engine vehicle regulations and therefore not representative of LIB field failures. Despite vehicle accidents being dynamic events, the testing described in the relevant standards is carried out at a component level using static assemblies (e.g. nail penetration test).[43] These industries demand more analysis and data evaluation specific to electrified powertrains and the addition of relevant tests such as low temperature hazards, flammability, toxicity, roll over, drop and immersion into future standards and regulations.[43]

Another concern raised by most industries is the need to further harmonization among standards in terminology, testing conditions, testing parameters and pass/fail criteria. For example, further harmonization is needed on the way batteries qualify against the risk of thermal runaway,[17,31] since various options appear in different standards.[13] Including details on temperature increase rate, occurrence of venting and fraction of energy released would be useful to establish thermal runaway sub-categories.[13]

Despite many standardisation efforts, current standards allow for very different initiation methods and test setups. There is currently no reliable method of driving cells into thermal runaway that is also representative of field failure modes.[13,44] The wide variability in testing conditions (e.g. SOC, temperature, charging/discharging rate) for abuse tests such as overcharge, short circuit or thermal shock hinders comparisons based on data obtained by using different standards.[43] Differences in test conditions might be intended to consider different scenarios but further harmonisation efforts are required in this regard. In addition, internal short circuit thermal runaway testing remains controversial as there is not a representative test that emulates a true internal short circuit characteristic of field failure in a testing environment.[13,43,45] Research is needed to gain further knowledge on the ways in which an internal short circuit develops within a battery. This would enhance the development and implementation of a representative test method. Industries also request a better understanding of the range of conditions that change the severity of the response to abuse; e.g. external short circuit testing at 60 °C is much closer to real life conditions in which thermal runaway will occur than testing at 25 °C. Additionally, they demand clear and unambiguous testing procedures as part of the test method along with a thorough description. For example, the thermal runaway event caused by nail penetration testing depends on nail size, penetration depth, tip shape, surface of the nail, and nail material composition.[46] Including detailed procedures for testing would improve the reproducibility of safety tests[47] in cases where the test set up has a significant impact on the test result.[13] Automotive, advanced engineering and manufacturing industries, among others, demand a reliable, repeatable, and practical method to create on-demand internal short circuits that produce a response that is relevant to the ones seen in field failures. This method should also account for variability in important factors such as the cell state of charge (SOC), chemistry, form factor and state of health (SOH). In response to this demand, the Electric Vehicle Safety Informal Working Group (EVS-IWG), established under the United Nations World Forum for Harmonization of Vehicle Regulations, has as one of their objectives to find such testing method demanded by industry.[47]

A significant variability in the criteria requirements in various standards has been identified.[13] For example, pass criteria for IEC 62619[38] and UL 1973[40] is "no fire outside the system," for VDE AR 2510-50[41] the criteria is "no fire, no explosion, no leakage" and for SAE J2464[23] there is no pass/fail criteria. Another example of controversy is the presence of a source of continuous sparks during thermal runaway testing as required by some standards[31,33] and not required by others.[27] This would directly affect the "no fire" pass/fail condition as it would be tested in different environments. While safety is application dependant, such that the pass/fail criteria can differ depending on the application being tested, there is a clear benefit to a consistent approach to classification of pass/fail criteria across standards.

Another important concern that most industries agree on is the importance of the scale at which the safety testing takes place (see Fig. 3). The tests performed at component level might not be comparable to the tests performed at system level. Most of the research on safety is performed on cells[46,48] or small modules, and similar data at pack and system is scarce. Because performing all tests at system level is prohibitive, studies on the comparability of testing results at cell, module and pack level are needed urgently.[43] Industries demand further pre-normative research to address this issue, and to provide guidelines to selecting the appropriate level at which each test should be performed. Such studies would have an immediate impact in providing representative results for assessing the safety of the application, and would minimise the complexity of standards and testing cost.[13]

Finally, a common concern for all industries approached is the effect of cell ageing on safety test results, a subject currently not covered by any standard. Differences have been observed in test outcomes between beginning of life (BOL) and end of life (EOL) cells.[49] However, the aging influence on safety characteristics is not yet understood in the scientific community. Further research on this topic is encouraged by all industries.

Harmonised approaches are easier to implement when international regulations apply, as, for example, in the case of transportation of hazardous goods (e.g. UN 38.3).[50] These regulations are developed and regularly updated every two years, at the United Nations level by appropriate committees of experts. In the EV sector major efforts have been put into the development of the Global Technical Regulation on the Electric Vehicle Safety previously mentioned[17] and established under the United Nations World Forum for Harmonization of Vehicle Regulations.

In the renewable energy sector, the safe introduction of battery-based energy storage is not yet internationally regulated. In the context of the revision of the 2006 battery EU Directive which will be published in October 2020.,[51,52] the EU has requested harmonised standards for performance evaluation and for sustainability assessment.

Detection and reliability challenges.—Automotive, aerospace and transport industries are concerned about failure detection since their products and applications need to ensure plenty of egress time for passengers.[17] A better understanding of the trade-off between shutting the battery pack down or continuing to provide power to mission critical systems (e.g. emergency landing/stop) is crucial in these applications.

LIB failure can occur very rapidly after a cell is damaged, or slowly over a long period of time, causing delayed failure long after the damage is initiated.[19] The time in between is usually referred to as the incubation period which can last from several hours to years, depending on the cause and failure mechanism (see Fig. 1). However, when a critical point is reached, usually governed by the balance between heat generation and heat dissipation from the cell and battery pack to the environment, the failure happens very fast.[20] Since LIB failure processes are time-dependent, early detection plus diagnostics could evaluate the cell failure mechanisms in real time. This could identify if the failure is an emergency requiring urgent action, or if action could be delayed because it is about mitigating long-term damage to the battery.

The BMS is currently the most widely used mechanism through which failure is detected in battery applications. A BMS relies on the built-in voltage and temperature sensors to monitor the state of a battery. However, many pack designers and manufacturing industries are concerned about the reliability of the BMS. For example, the internal cell temperature is the most direct measure of a cell entering thermal runaway, while not being an accessible measurement. Instead, temperature sensors must be located on the external surface of a cell. For many realistic scenarios a significant time lag can occur between temperature rising in the middle of the cell and temperature rising on the surface.[19] A surface sensor would show a statistically significant temperature rise when the rate of temperature rise is already too large, and thermal runaway is inevitable.[20] For this reason, key parameters relevant to detecting and controlling damage evolution are not currently measured but are inferred through models.[19] Pack designers and manufacturers therefore demand the implementation of additional protection strategies beyond the BMS (e.g. fuses, relays, current interrupt device, positive thermal coefficient, heat shields, ground fault detectors) to prevent failures due to external electric or thermal abuse.

Research on BMS design (e.g. adequate number of sensors, suitable sensor location, integration of model-based sensing, reduced sensor lag and synchronization error) is encouraged by EV, HV and aerospace industries to enable early failure detection and fast activation of control and mitigation measures. These industries also demand the development of novel in situ diagnostic techniques that can identify an incipient failure and take action early enough to prevent thermal runaway. Research on diagnostics, artificial intelligence (e.g. cloud-computing, big data)[53] and other data analysis techniques is encouraged by these industries, not only to prevent failure but also to provide sufficient energy and power for emergency stop or landing if the conditions for failure are detected. There is a significant body of research aiming to design improved detection methods, as discussed below.

Battery-powered transportation industries advocate the development of fault-tolerant battery systems (e.g. fail-soft and fail-safe systems).[54] This can be achieved not only through hardware (e.g. redundant design), but also through high-level (e.g. derating strategies) and low-level software (e.g. recovery blocks, N-version programming, self-checking software).[55]

The development of models for cell, module, and battery pack safety are also a priority for these industries since they will drive understanding and improvements in the safety of large battery packs. One of the major problems faced in this regard is the lack of transferability across scales. Large amount of literature has been dedicated to improved modelling, diagnosis and prognosis techniques at cell scale, using advanced lab equipment.[56,57] However, much of this knowledge is not easily transferable to commercial systems (e.g. Electrochemical Impedance Spectroscopy (EIS) based methods)[58] due to a lack in quality and quantity of measurements available in commercial systems, and a lack in processing power within the BMS or the system's control central unit. The latter issue could be solved through 5 G technology and cloud-computing,[53] although further research is required as it may be not a problem-free solution (e.g. emissions, costs, data privacy).

A more fundamental problem hindering developments in diagnostics is the difficulty of online parameter identification of complex battery models, due to the limited system observability.[59,60] The states of the battery model are cell-dependent, and can only be inferred from voltage, current, and limited surface temperature data. Adding to the problem, in most applications there is limited controllability of those variables. The integration of active balancing systems can provide more controllability, but it will increase the complexity of the system and may affect reliability.[61,62]

Emergency response challenges.—Due to the complexity involved in LIB fire safety, issues are not easy and simple, and there is a demand of sharing information, knowledge and understanding in all fields of application, e.g. EVs,[63,64] stationary grid storage,[65] or aerospace.[66]

For example, stakeholders require detailed knowledge of the various key factors influencing the heat release rate from a battery fire (the fire power), and the rate and toxicity of gases released.[63] While there are many studies focusing on cell and pack level fire safety,[67–70] there is little data published on system-level fire safety (e.g. stationary grid storage or EVs).[64,65] This gap in the literature could be explained by the higher cost of system-level destructive testing, and the consideration of these matters by stakeholders as industrial secrets because of technical reasons as well as due to reputation and brand image. While it is true that reasonable predictions of key factors could be made based on cell or pack level data, and the limited database of fire incidents in the field,[63] comprehensive and methodological system-level fire testing would shed light on these important issues like: fire test repeatability, sensitivity to test conditions, scalability with mass or SOC, and fire suppression systems.

Regarding the latter, there is not a unique approach to tackle LIB fires, and different extinguishing agents and forms of application are available. Common fire extinguishing agents available include water (pure or with additive agents), foam, dry chemical powder, wet chemical or inert gases, each one having advantages and disadvantages. There is little literature in the subject for large battery applications (e.g. stationary grid storage, EV, HV, aerospace)[64,65] and further research in this area is encouraged. However, it appears that water-based extinguishing agents are among the most effective on the basis of available evidence.[63] This is due to their cooling capabilities, although they are not a problem-free solution, as discussed below.

For instance, long extinguishing time and large volumes of water may be required to avoid glowing and re-ignition problems, which may arise even hours after the fire extinction, due to persistent electrical or thermal abuse.[63–65,71,72] Hence, risk of water supply issues may exist. In addition, the application of water to a large LIB may cause an electrical hazard. Indeed, water can damage both the battery system itself and other assets, shorting undamaged cells or modules, and resulting in total loss of the system. There is also a risk of electric current leakage. When using water suppression, the personal protection equipment and precautions should be taken and a clear distance should be observed.[64,65]

Extinguishing time, water volume, harmful gasses emissions, and risk of re-ignition due to water induced shorts are concerns that arise among most industries. However, these can be drastically reduced by: 1) design, through improved enclosure fire rating,[72] internal cascading protections or heat shields,[72–75] optimum cell spacing;[76,77] 2) using a small percentage of certain encapsulating additives;[78] or 3) more direct contact of water with damaged cells, through water lances, penetration hammers, and ad hoc system designs. Submersion of damaged batteries in ad hoc portable water-proof containers has also been proposed to avoid re-ignition, and to fully discharge large damaged batteries.[79]

Water or water-based agents can be applied through water mist or sprinkler systems, which have proven to be effective in large stationary grid storage applications and battery warehouses fires.[80,81] In this way a reduced volume of water is required, limiting water induced risks or damage in the battery system and other assets. Dielectric liquid agents have also been proposed, but they can be easily contaminated in the early stages of fire suppression, becoming conductive and as problematic as regular water. Foam agents have not proven better performance than water, showing a lower cooling capability and therefore not recommended for battery fires.[64,72]

In those cases where the use of water is a concern (e.g. stationary energy storage for data centres), inert gasses or dry powder may seem a preferred solution, although their effectiveness to suppress battery fires is limited, due to their inability to cool down the battery.[72] However, when used in combination with early prediction measures, ventilation and cooling systems, a battery fire in a module with adequate cascading protection could be suppressed with a gas agent. The risk of re-ignition would still be present due to the limited battery monitoring capability.[72] For these reasons, non-water-based agents have been proposed in staged extinguishing approaches, to put out the fire in initial stages of stationary storage fires. If the problem persists or further cooling is needed water-based solutions should follow.[72]

In the case of limited access to water supply and no further risks to public health and safety, or damage to valuable property, it has been recommended to let the battery burn as a practical self-extinguishing approach, even though the fire may be active for 24 h.[64,65,82] Such passive strategies are not viable in many indoor or underground battery fires,[64,65,83] or aerospace battery fires, which require particular fire suppression and containment strategies.[66]

Large emissions of toxic gases are expected as a result of a LIB fire, and containment or ventilation will be required. EV and HV industries demand further research on the amount and toxicity of the products (gases and residues) released from LIB fires. They also require new methodologies for containing and cleaning these gases in sensitive areas where ventilation is not possible. While there is not an exhaustive knowledge of toxic emissions of battery fires,[84] it seems that they do not differ significantly from those of plastic fires in the case of stationary grid storage applications,[72] or ICEV fires in the case of EVs.[64] However, enhancing further knowledge in this area is demanded by most industries and stakeholders.

Transport and end-of-life challenges.—Transportation of pristine LIBs poses a risk. In regular conditions, while the probability of a cell fire is low, the severity of the fire incident may be high if large quantities of cells are carried together.[66] This is particularly true in the case of air carriage, and explains why Lithium-ion cells or batteries have been prohibited as cargo on passenger aircrafts,[66] and are required to pass a number of tests defined in international regulations (e.g. UN 38.3)[50] and standards (e.g. IEC 62133)[37] to be shipped by cargo-aircrafts or other means.[85]

Nowadays, while IEC standards and UN regulations have been harmonized up to some extent, there are still many differences in battery transport regulations across countries and regions, which make logistics complex, time-consuming, and costly.[85] For instance, there are many differences in packaging, marking, and labelling.[85] Test requirements at cell, battery and system level should be unified too.[85] Regulations also differ depending on the mode of transportation, and tend to be easier for road, train or sea transportation, particularly for non-pristine cells.[85,86] Furthermore, logistic industries need regulations to address battery storage at transport logistic centres.[85] Pre-normative research is required on shipping and storing BOL cells, particularly on the likelihood of safety incidents as a function of SOC. Manufacturing, transportation, logistics and recycling industries demand further research on risk assessment and mitigation measures for transportation of cells that are damaged or defective, for disposal, recycling and second life purposes.

Re-using, recycling, or disposing of battery systems may create considerable electrical, thermal, chemical, and fire risks, and require significant manual labour for partial or complete disassembly. These problems can be mitigated if battery packs and systems are designed with these final product stages in mind. This is currently an uncommon practice. "Life-cycle" battery module design would enable an automated robotic disassembling and it would also increase the rate of battery re-use or material recovery. This will in turn improve battery sustainability and recyclability.[87,88]

The Safety Contributions in the Scientific Literature

Research efforts are helping to improve LIB fire safety. Here we conduct a meta-review of the 13 most relevant review papers associated with LIB fires to identify the current state of research. We highlight areas of research rather than the specific findings of any one study, and therefore we primarily refer to review papers rather than individual papers. To understand the importance of each research area, we count the numbers of papers that are included in each review for the causes of fire, scales and protection layers. These statistics are provided in Fig. 6.

We find that the number of studies focusing on the component and cell scales is much larger than the number of studies on module and pack scales. Indeed, improving component and cell safety is essential to protect from fires. However, the fire behaviour of large-scale LIB packs is different to that of an individual cell. The outcome of fire protection strategies also differs depending on the scale at which they are studied. As an example, for suppression of LIB fires, research at the cell level is not sufficient[89,90] and LIB fire experiments have to be conducted at the pack level.

As highlighted in the introduction, and shown in Fig. 2, all four layers of fire protection are important. We find that most research has focused on prevention, and only 5% of the research investigates other protection layers. Nearly all the current detection research is based on BMS, and only a few papers investigate the use of other sensors. Compartmentation studies focus on thermal barriers alone. Only a few papers investigate LIB fire suppression, with those existing putting the emphasis on sprinkler protection of storage spaces, and without agreement on what extinguishing agents are effective in avoiding re-ignition.

Therefore, more research should focus on the module and pack scales to better understand fire dynamics at large scale and to improve fire protection combining compartmentation, detection, suppression. Further findings for each layer are reported in the following.

Prevention research.—The prevention layer aims at avoiding LIB ignition. It is the first and most important layer of protection. To make effective preventions, the first step is to understand the fundamental mechanisms of LIB ignition, and then designing the corresponding strategies to avoid the triggers.

Many studies[91,92] have analysed the behaviour of LIBs and their components at elevated temperatures, and many reviews[3,68] have already presented in detail what is known about the mechanisms of LIB failure. Here, we summarize the main processes with a focus on fire safety. Based on the physics involved, we classified the processes of heat generation into three stages: Joule heating, decomposition, and combustion.

During the electrical cycles of LIBs, a part of the energy is released in the form of heat due to the cell impedance, known as Joule heating.[48] One extreme case is the creation of a short circuit, where a large portion of the energy stored could be released as heat, increasing the temperature of the battery quickly. Many studies on the development of electrochemical models to describe this phase have been published.[3]

When the temperature of LIB reaches a certain level, the reactive components of LIB start to release heat because of the chain of exothermic reactions promoted, i.e. solid electrolyte interphase (SEI) decomposition, electrode decomposition, and electrolyte decomposition, driving the temperature even higher.[68] This is the decomposition stage. The reactions in this stage occur between solid and liquid phases, generating various gaseous fuels[91] between 100 °C–200 °C. A number of experimental studies[68,93] have been conducted using adiabatic calorimetry, i.e. accelerating rate calorimetry (ARC) and differential scanning calorimetry (DSC), to investigate the thermal performance of an individual component or coupled components. It was found that the chain of exothermic reactions start from the decomposition of the SEI layer,[3] which is a thin passivating layer formed on the electrodes. The SEI layer decomposes at around 100 °C,[3] exposing the intercalated Lithium in the negative electrode to the electrolyte, promoting further reactions. The active materials of the positive electrode are also unstable and could decompose at high temperature releasing gases.[94] The electrolyte is also found to have several exothermic stages at elevated temperature.[91] A few chemical models have also been developed to analyse the decomposition stage.[95]

When the temperature rises even more, the overpressure due to gas generation can break the outer casing of the LIB thus mixing with oxygen outside and forming a flammable mixture.[96] When the mixture is ignited, it leads to the combustion stage which involves combustion reactions, flames and fire dynamics. This stage is mainly studied so far by means of experiments.[97] The fire behaviour of LIBs has been studied at both cell level and pack level.[96,98] One cell can burn with a jet flame or a buoyant flame, and its burning period is about 20 s.[98] A battery pack can have multiple jet flames[96] while the burning period is in the order of 300 s (or longer if re-ignition takes place). The SOC has significant influence on the fire behaviour;[99] cells with lower SOC burn for shorter times and with weaker flames.

There are some studies available that focus on the development of computational models to understand and predict thermal runaway. Hatchard et al.[100] and Kim et al.[95] are the pioneers developing the multi-step reaction scheme that is the center of many computational studies. Using this reaction scheme and associated kinetics parameters, the effects of cell geometry[101] and cathode material[102] on thermal runaway was investigated. Recently, Ren et al.[103] has proposed a new reaction scheme that considers the interaction between anode, cathode and electrolyte for a LIB at 100% SOC. Thermal runaway caused by mechanical abuse has been the subject of recent research using modelling approaches.[104] The effect of ageing was studied by Abada et al.,[105] who combining experiments and modelling, found that calendar ageing lowers the critical temperature for thermal runaway and delays the onset of self-heating.

To effectively prevent ignition, there are some strategies to control each of the stages described already, especially for the Joule heating and decomposition stages. These strategies can be divided into: control heat generation, or enhance heat dissipation. Controlling heat generation involves reducing Joule heat, decomposition heat and combustion heat. Joule heat can be controlled by avoiding short circuits. For example, using cushion or isolating materials for cell spacing to avoid mechanical or electrical abuse. Even if short-circuits occurred, the Joule heat could be reduced by internal safety design[106] such as PTC, redox shuttles, and shut down separators to reduce or cut off the current when temperature rises. The heat of decomposition can be controlled by using different materials. Moving towards lower voltage systems such as LMO/LTO or using more thermally stable

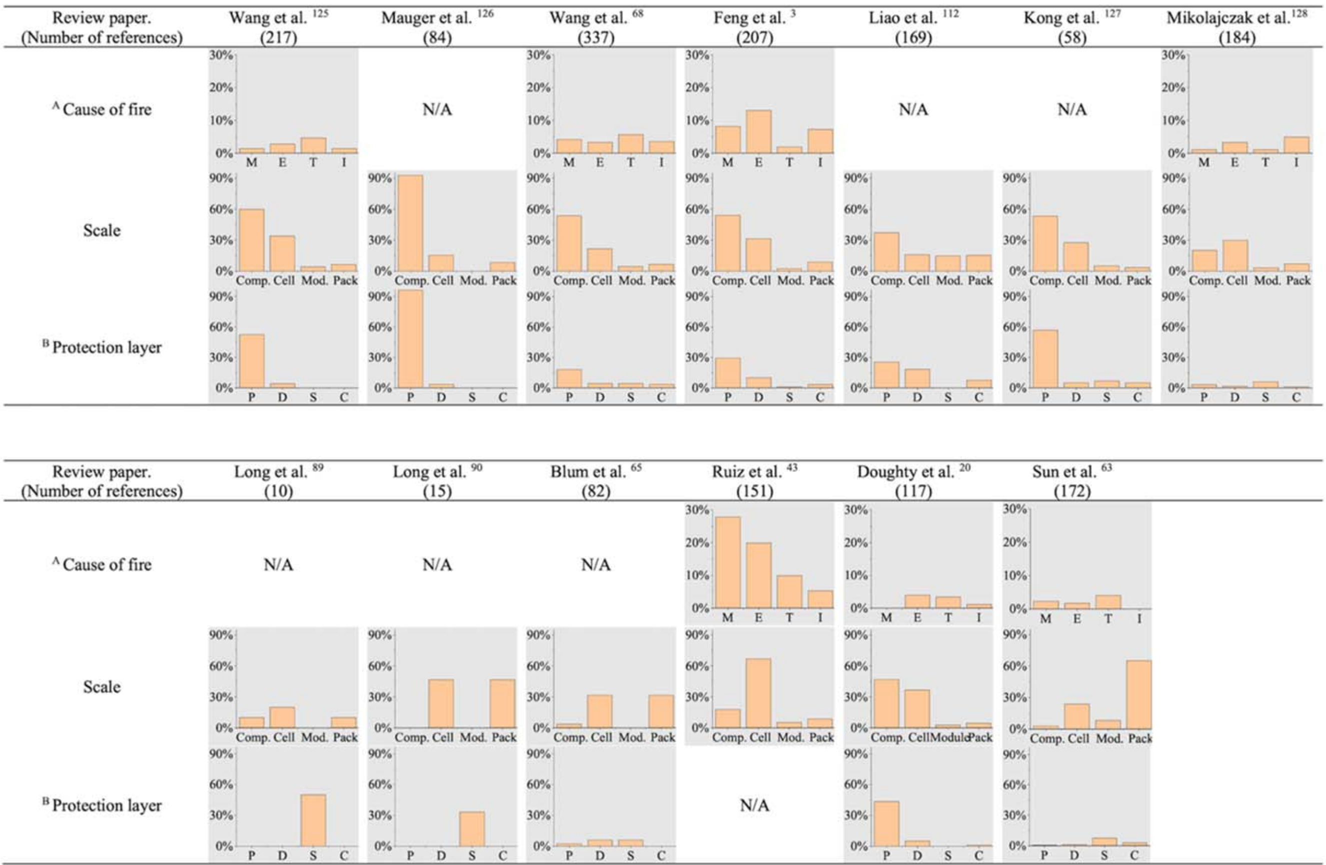

Figure 6. Meta-review of the most relevant 13 review papers found in the scientific literature. The causes of fire, scales and protection layers considered in each review paper are analysed. The value in each plot refers to the percentage of references in each review paper. [A] Causes of fire are: (M) mechanical abuse, (E) electrical abuse, (T) thermal abuse including self-heating, and (I) internal short circuit. [C] Protection layers are: (P) prevention, (D) detection, (S) suppression, and (C) compartmentation.

cathodes (e.g. LFP instead LCO) can improve safety at the expense of energy density and cost.[106] All-solid-state Lithium-ion batteries offer a wider operating temperature range in addition to improve safety and higher energy density. However, key challenges remain such as the volume change in the electrodes, interfacial charge transfer resistance, flexibility and cycling stability. Despite the advances on shape flexibility and contact with the electrodes achieved with solid polymer electrolytes,[21] these systems are limited in terms of electrochemical stability windows and ionic conductivity at room temperature.[107] If the materials for the main components cannot be changed due to the consumer's request, safety can also be improved by applying surface coating on the electrodes. Surface coating could prevent the electrodes from direct contact with electrolyte, improve structure stability and reduce side reactions.[3] Adding flame retardant additives into the electrolyte is also an effective way to improve material safety and reduce the decomposition heat.[108] This strategy also reduces the gases generated at high temperature and increases the onset temperature of the chain reactions.[68] The heat of combustion could be controlled by using safer materials with lower fire load. Safety vents can manage the internal pressure and control the direction of gas ejection during the failure, which helps to postpone combustion stage.

Another main strategy in LIB fire prevention is enhancing heat dissipation. It is mainly achieved by introducing active or passive methods that increase the heat transfer between the batteries and the environment. For EVs, the BMS is used to monitor the state of batteries and the environment.[68] BMS is usually equipped with a cooling system that ensures the temperature range for correct battery operation. One of the most commonly used methods is air cooling (forced convection). Liquids have a higher heat transfer coefficient and therefore a higher cooling efficiency. However, the weight addition from the liquid cooling system increases the load and costs. PCMs are an alternative method for thermal management. They usually have a large latent heat, allowing heat storage. For batteries with low energy density (consumer electronics), passive cooling is mainly used because of the restrict requirements on the weight of those portable devices. Natural air convection is mainly used in this case. Heat pipes could also be used for a slightly higher heat load.

Compartmentation research.—If the prevention layer fails, compartmentation is the key layer for protection against LIB fires, by containing or delaying fire propagation within a battery pack. This reduces damage, and provides more time for evacuation and for emergency response.

LIB fire propagation within a pack is dominated by heat transfer. There are three main heat transfer paths: heat conduction through cell surface, heat conduction through the pole connector (tabs), and heat radiation and convection from the flames.[68] Feng et al.[3] have found that the heat transferred through the cell surface is around 10 times larger than the heat transferred through the pole connector. Said et al.[74] have investigated the fire propagation in cell arrays in the air and the nitrogen atmosphere. The results show that the propagation rate in the air with flames is 9 times quicker than the propagation rate in the nitrogen without flames. In addition, the location of the cell that initiates the failure within a module,[109] the connections (series or parallel),[110] the cell factor[110] and the SOC[111] are important factors in fire propagation.

The strategies to restrict LIB fire propagation include hindering heat transfer paths to nearby cells and improving cell heat dissipation. To hinder the heat transfer, the simplest method is to increase the spacing between cells, which can slow down the propagation. A spacing distance of 2 mm is recommended by Lopez et al. for cylindrical cells.[112] Compartmentation can be achieved by dividing a battery pack into several compartments through the use of barriers between cells. Several strategies such as Tesla's multi-layer thermal barrier,[113] flame retardant plates,[114] metal plates,[114] heat-conducting plates[114] and PCMs[115] have been proposed. Hermann et al.[113] invented a multi-layer thermal barrier, made of a composite containing thermal insulation materials and electric materials. The barrier divides the battery pack into several compartments and reduces the heat transfer and the mechanical impact between compartments. Berdichevsky et al.[114] proposed the use of a non-combustible plate for compartmentation, such as a ceramic fibreboard, which has very low thermal conductivity. Another method to alleviate fire propagation is the use of a metal plate[114] as a heat sink between modules. The thermal mass of the plate and the thermal contact resistance between the cell and the plate are two important factors affecting the mitigation of fire propagation.[116] Lee et al.[117] studied the effect of double-layer stainless steel, intumescent material and ceramic fibreboard inserted in gaps between cells as physical barriers for fire propagation mitigation in a 9-cell compartment. The results showed that none of these physical barriers stop the fire propagation between compartments but slow down the propagation rate, with the ceramic fiberboard being the most effective. The use of phase change materials (PCM)[115] is another effective method to prevent fire propagation. A recent study[115] shows one case of fire propagation starting from a cell being stopped when the cells are surrounded by PCM. PCM, such as paraffin wax, have a high latent heat of fusion and can absorb heat when thermal runaway occurs. However, PCM can be combustible thus adding to the fire load, be costly and add significant mass to the pack.[118]

To improve heat dissipation away from cells, the basic technology is venting.[68] Feng et al.[3] and Liao et al.[108] have also proposed battery thermal management systems, such as air and liquid cooling and heat pipes, to be used to prevent fire propagation but none of these techniques have been studied for compartmentation. Compartmentation strategies during transportation are different from the compartmentation strategies used inside a battery pack to avoid fire propagation. The current compartmentation strategy during transportation is using a sealed fire compartment for LIBs. For example, a stainless steel box with walls 3 mm thick was used in the Boeing Dreamliner[119] for compartmentation. This ensures that even if there is a battery fire, it cannot spread to other compartments aboard the plane.

Detection research.—Early detection of failure, thermal runaway or fire is crucial. Batteries can quickly reach ignition, for example, in case of mechanical or electrical abuse. Detection methods can be summarised in five categories:[108] i) terminal voltage using the BMS; ii) unusual gases emitted; iii) internal battery temperature; iv) current variations as indication of short circuit; and v) mechanical deformation using strain gauge sensors.[120]

The most widely used method for detection is a mix of terminal voltage (i) and temperature (iii). The BMS of the batteries has built-in sensors which can be used to monitor the surface temperature and voltage of each cell within the battery. When any abnormal signal is detected, the BMS triggers a warning.[108] BMS can improve heat dissipation by thermal management, avoiding cell over-heating, and also locate a faulty cell within a battery pack. However, the BMS does not respond fast enough to detect the initial stages leading to thermal runaway. Internal temperatures measured via dedicated embedded sensors have a higher accuracy than the surface temperature measurements to predict thermal runaway, but they add a high cost as well as complexity to the pack.

Gas sensors can be used to detect the initialization of thermal runaway. They are faster than voltage or temperature methods as the build-up of initial gases often precedes any significant changes in the voltage or temperature signals. However, it adds complexity and cost, and faults could trigger false alarms. The use of heat, smoke or gas detectors is relevant for all battery industries. For example, gas detectors are recommended for stationary energy storage systems in enclosures so they give a warning before flammable gases build-up.[121]

Monitoring the creep of the batteries relies on the external mechanical structure of the battery to deform, and it might not reliably detect the onset of runaway.

Suppression research.—Suppression is a fundamental protection layer if the preventative measures fail. There are four suppression approaches for fires: smothering, cooling, chemical suppression, or isolating the fire.[68] Many reactions that lead fire in a battery do not require external oxygen supply as oxygen is present in its components. This makes the smothering approach not very effective. Cooling the battery with a continuous water mist is a promising approach for the suppression of LIB fires.[68] However, it can also have an impact on the integrity of the electrical circuits, as water can cause an external short circuits and further ignition or thermal runaway propagation. Conventional fire extinguishers are not suited to stop the thermal runaway reactions inside LIBs. They have only been proven effective to extinguish open flames external to the battery as the battery's surface temperature decreases. The addition of additives (i.e. C6F-ketone) has been shown to improve the fire suppression but when exposed to high temperatures these produce HF which is extremely toxic and corrosive, and therefore pose a danger to any emergency personnel.[68] Furthermore, it was also observed that the battery fire might re-ignite after initial suppression, due to the fact that the exothermic chemical processes inside the cells continue, and therefore suppressing agents would have to be reapplied even after first suppression.[68]

Research on suppression methods for battery fires is at an early stage and it is far from reaching an optimal solution to effectively and safely extinguish battery fires without the production of toxic gases, so further work is needed.[68]

Key protection technologies.—As overview, Table II shows the current key technologies used for different protection layers. Prevention technologies are comprehensive and well developed for improving cell safety. The cathode modification methods[68] to improve its thermal stability include surface coating, such as phosphate, fluoride, and solid oxide, and element substitution using Ni and Al to replace Co. Regarding anode modifications, the surface coating method[68] is also recommended, using an Al_2O_3 thin layer on the anode to serve as unstable SEI layer. Electrolyte additives have been reviewed by Feng et al.,[3] including solvent substitute additives, SEI supporting additives, flame-retardant additives, thermal shutdown additives, and overcharge protection additives. All these additives can help improve the intrinsic safety of cells.[122] Safety devices, such as the positive temperature coefficient device (PTC) and the safety vent, can protect from overcharge and overpressure, respectively.[68] The BMS is an excellent device for fire protection with roles in prevention, compartmentation and detection. The key roles of the BMS are the estimation of the state of cells, battery equalization, diagnostics, charge and discharge control, thermal management and battery safety control.[93] The thermal management system uses a cooling medium, either air, a liquid or a phase-change-material (PCM), to dissipate heat, depending on the pack design. Air cooling is the simplest cooling method but also the least efficient. While liquid cooling has a higher efficiency, its application can also create thermal gradients.[93] The thermal management system and the cell state estimation function help preventing failure. Regarding detection and compartmentation layers, the BMS can also help detecting failure at an early stage as it monitors temperature and voltage. It can also enhance heat dissipation to slow down fire propagation when the prevention measures have failed.

While prevention measures have received a lot of attention producing novel scientific breakthroughs in battery materials and components, compartmentation, detection and suppression technologies

Table II. Current key technologies used for different protection layers.[68] Prevention technologies are comprehensive and are developed for improving cell safety. Comparatively, compartmentation, detection and suppression technologies inspired by traditional fire technology are less effective for battery fires.

Protection layers	Scale	Key technologies
Prevention	Component, cell, module, pack	Cathode and anode modification, electrolyte additive, shut down or ceramic-coated separator, positive temperature coefficient device, vents, battery management system.
Compartmentation	Module, pack	Barriers, battery management system, sealed metal container.
Detection	Cell, module, pack	Battery management system (voltage, temperature, deformation), different detector (heat, smoke, off gassing).
Suppression	Cell, module, pack	Smothering, cooling, chemical suppression, isolating.

are inspired by traditional fire technologies, which are less efficient for LIB fires and need further study.

The Way Forward

Industry and research institutions share the common goal of producing safer batteries, but there are clear distinctions between their approaches. Industry embraces the top-down approach, with a focus on specific questions at larger scales, while research tends to follow the bottom-up approach, focussing on the fundamental understanding of phenomena with emphasis on the smaller scales. Bringing the two communities together sooner rather than later could prove crucial to solving LIB safety issues. Our conclusions are visually summarised in Fig. 7.

During safety testing and certification, industries perceive that there is a lack of harmonisation in the mode of abuse that leads to thermal runaway. There are no representative and repeatable methods for all relevant failure modes, and many test methods are not representative of field failures. There are multiple controversies around the best method to induce thermal runaway. While there are several recognised international standards for every industry that uses LIBs, a major concern shared by all industries is that the available standards are not always representative of real-world scenarios. Further controversy can be found in pass/fail criteria in various standards for thermal runaway. More research is needed to understand first how an internal short-circuit develops within a battery, before a method to reliably reproduce it can be defined. To prevent thermal runaway at the pack scale, the development of more fault tolerant, fail-safe or fail-soft systems is needed. Yet, there is no industry consensus on safe system designs and performance-based methodologies. Although this could be attributed to the wide range of applications that are covered by these standards, harmonisation is required. The regulations, standards and committees that do exist provide a valuable basis for sharing knowledge and experience across industries that use LIBs.

LIB fire standards and regulations have been harmonised to some extent for transport industries, but there are still significant differences between transport modes and across regions, which add costs and hinder innovation. No established regulations and standards exist for storage at logistics centres, which are especially needed for cells that are defective, possibly damaged, or aged.

Fire propagation between cells is a main concern. Two approaches are needed for fire compartmentation. Firstly, new battery chemistries or designs that do not result in thermal runaway and therefore would not require mitigation must be found. Secondly, assuming thermal runaway can occur, compartmentation technologies to prevent propagation, and adaptive control measures to detect thermal runaway must be developed. These techniques could be based upon a combination of voltage, current or temperature signals, i.e. measurements implemented in the BMS. Further research into the development of other detection methods, such as sensor for gases, heat or flames is also justified.

Another concern is the scales of most experiments. We find that the number of studies focusing on the component and cell scales is much larger than those studying the module and pack scales. Improving safety at the component and cell scales is essential but not sufficient because it is not possible to avoid completely the possibility of LIB accidental ignition. Lessons from studies performed at the component scale do not necessarily translate to the pack scale because fire dynamics are affected by scale (larger fires release more heat and propagate faster). More research is need on the pack and system scales to understand fire evolution at its highest intensities and to develop more robust protection layers. Further research into how the knowledge at each scale can be integrated is

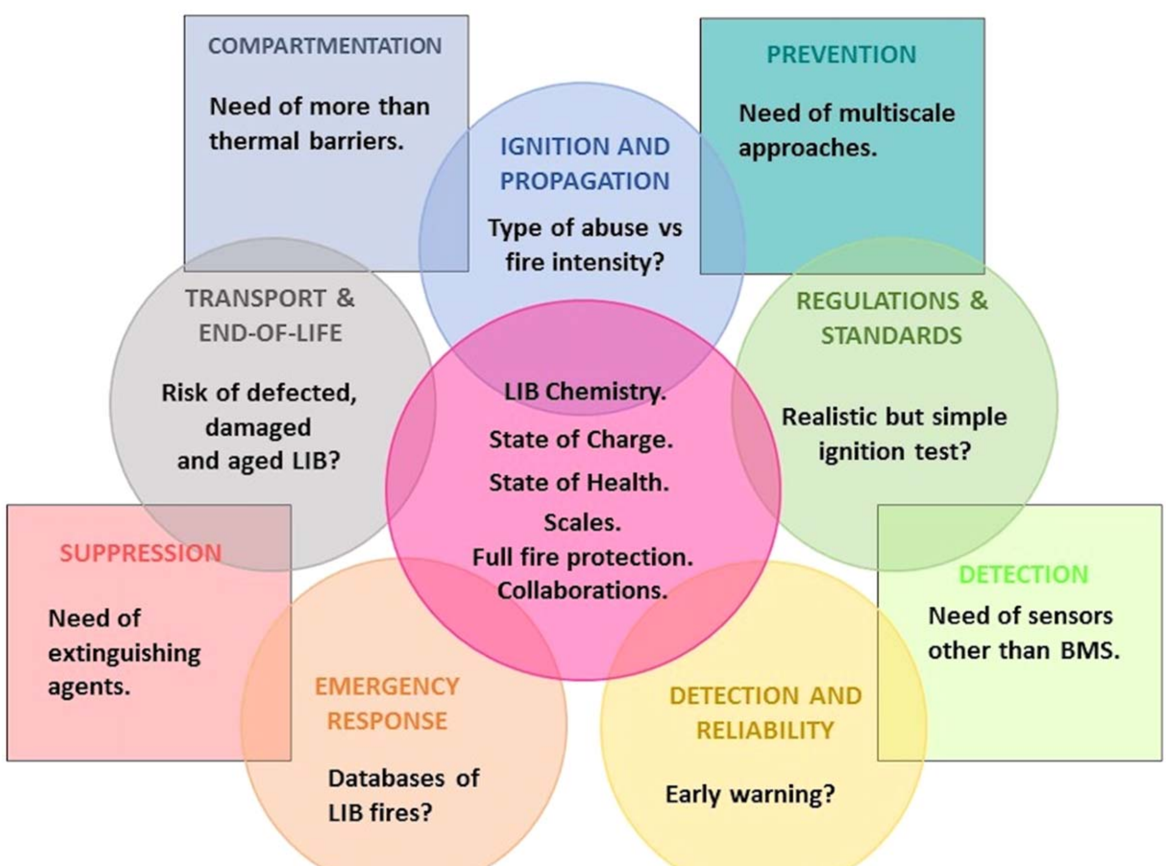

Figure 7. Summary of the conclusions of the meta-review in the form of a Venn diagram combining the five industrial challenges and research contributions to the four layers of protection.

justified. A multiscale research approach is needed as LIB fire safety involves many scales.

Further research in all four layers of fire safety is needed - prevention, detection, compartmentation and suppression. We find that most research has focused on prevention, and very little research investigates other protection layers. Nearly all the current detection research is based on BMS, and only a few papers investigate the other sensors. Compartmentation studies focus on thermal barriers alone. Just a few papers investigate LIB fire suppression, showing that there is no agreement on what extinguishing agents are effective for LIB fires. Given the current fire concerns of industry and stakeholders, early detection, robust compartmentation and effective suppression deserve more research attention. We strongly recommend that LIB industries embrace more comprehensive fire protection strategies that integrate all four layers. This way, LIB safety will surely improve.

Research studies would increase their immediate impact by using real-world data from industry as a baseline to develop new approaches to battery safety. The lack of fire statistics at the international level for LIB incidents could be mitigated by establishing a single international body, representing all the major industries that use LIBs, responsible for facilitating communication and harmonising standards and regulations across the multiple industries. International professional syndicates such as Recharge (industry association for advanced rechargeable Lithium batteries) in the EU and PRBA (Rechargeable Battery Association) in USA do exist to provide guidelines.

In order to close the gaps uncovered in this meta-review and accelerate the arrival of more LIB safety solutions, we recommend closer collaborations between the battery and fire safety communities, which, supported by the major industries, could drive improvements, integration and harmonization of fire safety across sectors.

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