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Key Learnings from Recent Lithium-ion Battery Incidents that have Impacted e-mobility and Energy Storage Fast Growing Market

Guy Marlair[a,*], Amandine Lecocq[a], Arnaud Bordes[a], Paul Christensen[b], Benjamin Truchot[a]

[a] Institut national de l'Environnement Industriel et des Risques (Ineris), Parc technologique Alata, BP2, 60550 Verneuil-en-Halatte (France)
[b] School of Engineering, Newcastle University, Newcastle upon Tyne, NEI 7RU, United Kingdom
guy.marlair@ineris.fr

Learning lessons from accidents has always been very instructive for developing inherently safer technologies and processes. This paper aims to show that lithium-ion rechargeable battery (LIB) technology is no exception, as the penetration of these devices into society has been accompanied by a number of significant fires and explosions. The relatively small incidents involving LIBs arose from their application in an ever wider and more varied range of portable electronic products in the mid 2000's, leading to, for example, repeated recalls of laptop computers. Later it became apparent that failures could and would occur in the full value chain of LIBs, starting from the manufacturing of cells up to end-of life issues and recycling. The true nature of the risks and hazards of LIBs has only started to become apparent with larger batteries, for example those associated with e-mobility (electric vehicles) and grid-scale battery energy storage systems, and hence this paper focusses on the lessons to be learnt from incidents involving these systems.

1. Introduction

Lithium-ion batteries (LIBs) were first put on the market by Sony in 1990 and have since become the dominant power system in many consumer products including laptops, smartphones and portable power tools. Concerns over climate change have opened up larger scale applications for these devices since c.a. the late 2000s, in terms of e-mobility and lithium-ion battery energy storage systems (LiBESS) to support national electricity grids and store energy from renewable energy generators. Battery electric vehicles (BEVs) are intended to progressively replace ICE vehicles, whilst LiBESS may store GWh's of energy and are already competing in terms of performance and cost with, for example, Sodium-Sulfur (Na-S) high temperature batteries.

The rapid and, since the late 2000's, major expansion of LiBs, particularly into applications utilising 10s to 1000s of kWh rather than 10s of Wh, demands a new paradigm in terms of the risk profile of these devices. The risk of Thermal Runway (TR), with the attendant hazards of toxic gas, fire and explosion, is new in battery technology, resulting from: (1) the replacement of an aqueous electrolyte by a flammable organic one and (2) the requirement to operate the battery in very narrow thermal and electrochemical windows, combined with (3) very high energy densities. Thermal runaway has replaced the easier-to-manage risk of hydrogen release during the charging of secondary batteries making use of aqueous electrolytes such as lead acid or Ni/Cd cells.

A very significant body of research has focussed on elucidating the processes that lead to TR following abuse (crush, penetration, heating, overcharge), but the chemical reactions that actually trigger TR, and even the definition of TR, remain controversial. However, only a limited research effort (Sun *et al*, 2020) has been focused on learning from actual fires and explosions involving LIBs, despite the significant, and often exaggerated, publicity such incidents attract. Past experience of other emerging technologies dictates that early monitoring and reporting of incidents and near misses may help to identify critical issues with respect to safety management and save time and money in developing appropriate risk management (Rivière et al, 2010).

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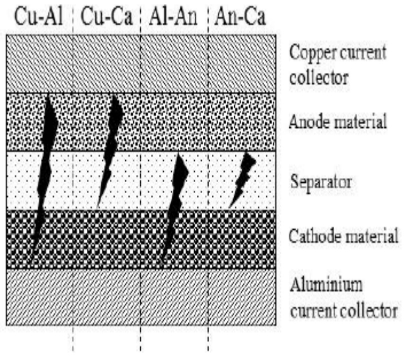
Therefore, this paper aims at presenting and discussing scientific sound knowledge acquired from incidents having so far been reported with LIBs and related applications, with a focus on yet non mature but fast developing markets such as e-mobility and BESS applications.

2. Historical learnings achieved from early use on LIBs based on incident records of consumer products.

As a matter of fact, according to LIB technology design, managing short-circuiting remains a complex issue since multiple types of internal shorts have to be taken into considerations (Figure 1) and internal shorts are not easily detectable. Basically, two major issues were identified from the significant recalls of consumer products incorporating LIBs prompted by fires and explosions of, for example, mobile phones and laptops:

- The presence of non-intentionally added substances (NIASs) during manufacture could lead to catastrophic internal short circuit at any time following manufacture, for example via perforation of the thin polyolefin separator. Examples of NIAS include airborne particles in manufacturing areas.
- Poor design/manufacturing also led to internal short circuit: for example, inappropriate LIB current collector mountings. Defects such as these caused the recall of the Nexus and Samsung Galaxy Note 7 smartphones.



Contact Situation	Cu-Al	Cu-Ca	Al-An	An-Ca
Expected resistance	~10 mΩ	>100 mΩ	~100 mΩ	>100 mΩ
Resistance	-	+	o	+
Heat conduction	+	o	-	-
Short power	-	+	o	+
Local temperature	o	+	-	+
Occurrence	+	o	o	-
Potential risk	o	+	−	+

Figure 1: (left) Scheme of the various short-circuit (SC) potential configurations in LIB; (right): Related criticality of outcomes according to SC configurations. Al-An: aluminium current collector vs. anode material; and An-Ca: anode material vs. cathode material; symbols used: – for high risk, o for medium risk, + for low risk (after Volck et al, 2016).

It is generally reported in the literature and in battery safety conferences that field failures due to manufacturing defects are of the order of 1 cell out of one to ten million (fault rate rated 10^{-7} to 10^{-6} for 18650 cylindrical cells only), as the cells are assembled in clean rooms. The semiconductor industry still experiences defects in semiconductor wafers due to airborne contamination despite production taking place in advanced cleanrooms (see: https://www.cassindustries.com/lithium-ion-battery-safety-failure-causes/). Despite the very low manufacturing failure rate in LiB manufacture, and insurance quality systems mandated by the Transportation of Dangerous Goods Model Regulation (United-Nations, 2019) for the transport of LIB cells and batteries under UN3480, it must be anticipated that field failures will still happen due to billions of such cells being placed on the global market.

Another key message that has to be kept in mind is that virtually all applications of LIBs in consumer products have experienced field failures leading to the venting of flammable and toxic gases, with or without fires due to thermal runaway: there have been regular media reports of incidents involving laptops, phones and smartphones, e-cigarettes, power tools, hoverboards, e-bikes and e-golf caddies). More recently e-scooters have been subject of alarming media reports. Given that LIBs have penetrated all levels in society, it is not surprising that insurances companies are presenting alarming statistics about recurrent fire events that are originating from careless managements of LIB and LIB-powered systems or related chargers (Sim, 2021): for example, the fatal fire in New York City due to the charging of nine e-bike batteries (King 2021).

3. Field failures lessons from last decade e-mobility development

3.1 overall field failure driven lessons

Many countries all over the world have e-mobility strategies to produce vehicles of all sorts from light e-mobility vehicles (LMV) including escooters and ebikes, to hybrid or full battery electric vehicles (HEVs, BEVs): the latter are now sold in significant quantities by nearly all car makers. Fleets of e-buses are also fast emerging in many large urban areas. Battery safety appears to be significantly lower on the agenda than range limitation ("range anxiety") and increasingly rapid charging, it is clearly important for the successful expansion of the EV market (Bordes, 2022) to understand why EVs are catching fire.

With the increase of power and size of EV's battery making use of LIB technology, as noticed by Christensen (2021), it is important to consider the LIB hazards over the complete life cycle of EVs, and to understand that the corresponding threats, also clearly revealed by EV incidents, may encompass risks to health, fire risks and risk to the natural ecosystem.

According to the survey performed on EV field incidents in this work, the main lessons learnt are as follows:

- Nearly all EV models (if not all) put on the market and powered with LIB have experienced (albeit infrequent) battery safety issues, often leading to fires.
- Safety considerations have led to stringent regulatory requirements (e.g.: R100 for vehicle homologation) and appropriate standards developed by IEC Committees TC21 and SC21A (see for instance IEC 62660 series and IEC 62660-3 in particular). However, the fervent quest for ever improved performance at static (if not reduced) costs makes ensuring that safety is adequately addressed ever more challenging, as reflected in the numerous recalls of EVs in the last two years following EV fires (Hyundai Kona, Chevy Bolt…).
- As illustrated by the details of > 60 Tesla vehicle fires listed in an open access database (www.tesla-fire.com), field failures can happen in any state of the vehicle life cycle (during cruise, at the garage or car park, during charging, after maintenance, at car store etc.).
- Incidents have no single root cause, hence fires may occur as a result of a crash, inappropriate repair, inadequate battery integration, shortcomings in design or operation of the Battery Thermal Management System (BTMS)) or in the Battery Management System (BMS) hardware or software. Water or liquid refrigerant cooling might progressively be preferred to air cooling in future more powerful EV for better BTMS (Edmonson et al, 2020) for reason of better cooling efficiency
- Metallic lithium plating on the anode due to overcharging, fast charging and charging at low temperature has been identified as potential critical safety issues, as well as the formation of dendrites (Bordes et al, 2022)
- Multiple charging points for EVs or e-buses in narrow and or confined spaces proved to be critical, as shown recently by destruction of e-buses and three bus depots in Germany or in China (Nedelea 2021)
- Fire-fighting an EV fire is not an easy task and need significant training of the fire-brigades and appropriate safety information from the EV car manufacturer
- Re-ignition of EVs after the first emergency response is quite frequent and may occur hours, days or even weeks later
- After a collision involving an EV, precautions need to be taken whatever action is taken subsequently (repair or recycling) as the integrity of the battery integrity may have been compromised and hence delayed ignition is possible.

3.2 Emerging statistical data from field failures leading to EV fires

Although no robust figures are yet made available in terms of EV fire statistics (Ahrens, 2020), there is no clear evidence that EV fire events occur more frequently than Internal Combustion Engine (ICE) cars, despite the impressions that may be obtained from sensational media reporting of EV fires and controversial claims (e.g. by the London Fire Brigade, reporting a failure rate of 0.1% for EVs, more than double that of ICE vehicles:(Garret, 2020):figures possibly biased due to the limited number of fire records considered).

A database recording Chinese EV fires (He, 2021) which covers the years 2018 to 2020, appears to show that EV fires occur more often in summer, which could possibly be linked to inappropriate sizing of the BTMS (Figure 2).

More recently, on the information collated on a publicly accessible online database www.teslafire.com (Unknown, 2021) and regularly updated, regarding fires involving Tesla Model 3, S and X vehicles, strongly suggests that the root cause of the fires involving these vehicles is crashes, see table 1. This observation is also consistent with statistics regarding vehicle fires in general (Ahrens, 2020). Fast charging only accounts for some 5% of overall fire records. However, apparent 'spontaneous ignition' accounts globally for nearly 30% which might have to be related to manufacturing defects or contaminants, potentially reflecting design or manufacturing issues that are not specific to Tesla Models. This conclusion is given added weight by the recent multiple recalls of EVs by several car manufacturers.

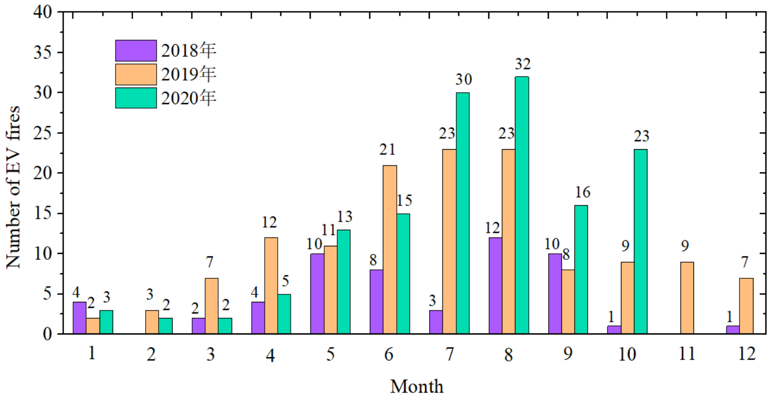


Figure 2: fluctuation of reported EV fires in China, after data reported at the 2nd China International Electric Vehicle Safety Technology Innovation Conference, 2020 (He 2021)

Table 1: distribution of Tesla model fires known records as a function of reported root causes (multiple EV fires in stores or car carrier excluded)

Fire root cause or circumstance	# EV fires (-)	Proportion of EV fires (%)
Post-crash or due to overturn	35	56.5
Spontaneous ignition at rest	11	17,7
Spontaneous ignition on the road	6	9.7
Normal or fast charging	4	6.5
Impact from projectile laid on the road	3	4.8
Unknown circumstance	3	4.8

4. Field failure regarding stationary applications (BESS)

The fast development of stationary application for storing renewable energy with BESS is the most recent market targeted and largely dominated by lithium-ion battery manufacturers and energy storage providers for domestic and industrial applications, including services to the grid. Originally dominated by lead acid (mostly UPS systems) and for application over the MW range by sodium-sulfur systems (the latter being developed and marketed by NGK from Japan) it is interesting to note that Li-ion technology had the opportunity to enter this market following a major fire that abruptly stopped the domination of Na-S batteries (NGK Insulators, 2011). Stationary applications, although at that time rather more expensive was considered safer option, until a series of incidents. However, the rapid market development of BESS (mostly in containerized modular systems) has led to a series of major fires and explosions across the world from 2012, with most occurring from 2017. For example: Belgium (Drogenbos, 2017), Australia (Brisbane 2020, Geelong 2021), United-Kingdom (Liverpool, 2019), France (Perles-et-Castelet, 2020), USA (Surprise, AZ, 2019, La Salle, IL 2021), China (Beijing, 2021), Germany (Neuhardenberg, 2021), and chiefly in South Korea, where a series of fires struck some 25 BESS, mostly in coastal and mountainous areas and in years 2017 to 2019.

4.1 Common lessons from well investigated fires outside South Korea

To date there are some 45 reported case studies of BESS (EPRI, 2021) that have experienced significant field failures, mostly leading to major fires and explosions with significant property loss. These have provided important lessons and have highlighted critical gaps in safety. Some of the underpinning field failures are summarised in table 2, highlighting the wide range of configurations in terms of capacity, application, age and status: as can be seen from table 2, critical situations may arise whatever the capacity, at any stage of the life cycle of the unit from construction to long term use, outdoor and indoor and any type of hosting site. The key information may be summarized as follows:

- Dealing with a BESS incident is a difficult and potentially risky operation for fire and rescue services: rendering the fire under control may take hours (Liverpool 2020, Korean fires 2017-2020) if not days (Australia Victoria 2020), and there is the explosion risk due to the vapour cloud vented by cells in cascading thermal runaway (Surprise 2019, Liverpool, 2020; Brisbane 2020)
- No chemistry, not even less reactive LFP li-ion chemistry, is exempt from thermal runaway

- Installing battery systems in on-top and side-by-side configurations, and in upper storeys of buildings should be avoided (Perles-de-Castelet, 2020; Moorabool 2021; Brisbane,2020)
- Remote operation, of such systems require well designed and resilient command and control and ICT systems (Liverpool, 2020)
- Detection and fire protection systems need to be optimised: so far no clean suppression (gaseous) agent has proven effective for controlling or stopping TR in containerized BESS
- The energy storage electrochemical subsystem may be not be the root cause of a fire event: BTMS and other key parts of a BESS may also be involved (for example, a (Goolagong, 2021) as evidenced by BESS of hybrid ships (Mrozik et al, 2021) and the SK fires
- A fail-safe approach with multi-layer protection barriers should be the future strategy, not just relying on the use of safer materials in the hope of negating the TR hazard

Table 2: a selection of reported BESS fires (adapted from EPRI battery failure database, 2021, and Mrozik et al 2021)

Location	Capacity (MWh-MW)	Application	installation	Event date	System age (y)	status
US, CA Moss Landing	1,200-300	Solar Integr. (SI)	Power Plant	09-4-2021	0.8	
Australia, Moorabool	450-300	Grid Stability (GS)	Rural	07-30-2021	0	Construction/ commissioning
Germany Neuhardenberg	5-5	SI/ frequency reg. (FR)	Indoor/ hangar	07-18-2021	5	
China, Beijing	25- ?	SI+ other services	Mall	04-16-2021		Construction/ commissioning
France Perles-de-Castelet, Arège	0.5-0.5	Local demand mgt	substation	12-1-2020	0	testing
UK, Liverpool	10-20	FR	substation	09-15-2020	1.5	
US AZ, Surprise	2-2	Volt Reg, PQ, SI		04-19-2019	2	
SK,N.Geyongsang, Chilgok	3.7-?	SI	Mountains	05-04-2019	2.2	Charged, inactive
Australia, Brisbane		SI	Indoor, elevated floor	03-17-2020	6.7	
Belgium, Drogenbos	6(1;5)-4(1)	Test Center	Gas power plant	11-11-2017	0	

4.2 Major learning as reported by the official investigation teams put in place by Korean government

From the 23 (out of the 30 BESS fires in Korea) that were officially investigated under a mandate from the local authorities, the conclusions were essentially:
-A particular battery chemistry, specific application, manufacturer (although LG Chem technology has been the focus of significant concern because of the Korean BESS fires as well as EV and domestic battery system recalls) or specific capacity in terms of energy or power could be singled out for serious concern re safety.
-14 out of the 23 incidents investigated occurred during the waiting state after full charge of the system, 6 took place during charge or discharge process and 6 occurred during construction or commissioning
-Globally, 4 categories of root reasons were evidenced, namely: i) insufficient protection against electrical shocks and short circuit, ii) underscored rating of criticality of local environmental conditions of BESS operations (e.g.: maritime and or mountainous geographical locations), iii) negligence/complacency in the implementation phase of the system and iv) inadequate command/control efficiency for the protection of the system.
Multiple actions were taken in response of these statements (MOTI, 2019), including the rapid development of safety standards, stakeholder training and the limitation of effective maximum charge in BESS as compared to nominal capacity. This latter measure was justified by the fact that most of incidents involved BESS that were fully charged in stand-by mode, waiting for power demand, which had led the authorities to request a maximum charge rated to 80% to 90% of nominal unit capacity.

5. Conclusions

In this paper, incidents that have paved the fast-growing and tremendously innovative markets of li-ion technology were reviewed with a focus on e-mobility and stationary applications, showing that developing fit-for-purpose energy storage systems for these markets keeps really challenging in terms of safety management.

It may be anticipated that in the context of ever reducing price market demand, emergence of LIB secondary life market and other circular economy driven aspects and eger demand for more powerful systems (e.g.: more energy-dense batteries), intrinsic safety of future LIBS will not progress significantly. Therefore, sustainable and safe further development on LIB applications in the future shall rely on a variety of initiatives such as i) better education of all stakeholders including all end-users, ii) an improved set of standards and certification schemes, iii) maintenance of financial support to energy storage safety-focused research, iv) and an overall control of efficiencies of all measures implemented from implementation and maintenance of consolidated battery failure databases allowing reliable exploitation in terms of safety performance statistics.

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