Battery Warehouses – the Major Accident Challenge

Pat Swords, Principal Process and EH&S Consultant, PM Group, Killakee Houe, Belgard Square, Tallaght, Dublin 24, Ireland.

Abstract: While lithium ion batteries are rapidly gaining in popularity, including for such large-scale usage as in vehicle traction, they are prone to spontaneous ignition, leading to intense fire and release of toxic gases. The terminology of a 'battery warehouse' could equally comprise the storage of battery units prior to dispatch or a Battery Energy Storage System (BESS). The consequences being the same if a fire occurs, the potential loss of the whole 'battery warehouse'. Indeed, the recent fire and sinking of the car carrier 'Felicity Ace' also falls within the context of a 'battery warehouse'. This paper therefore demonstrates the successful application of the established principles of risk management to a new context, one that presents particular challenges due to its energy density, but also familiar concepts related to fire and toxic releases

Keywords: Lithium ion batteries, storage, loss of control, fire, explosion, COMAH.

1.0 Background

Lithium ion batteries combine high energy density with relatively low weight and are in increasing use ranging from cell phones to vehicles. However, they have inherent hazards and unlike older lead acid and nickel metal hydride batteries with their aqueous electrolytes, the electrolytes in lithium ion batteries are flammable organic solvents. Self-ignition is a known occurrence for which the causes, leading to internal short circuit, are termed 'abuse'. Physical abuse occurs from penetration or mechanical impact, electrical abuse from such as overcharging or manufacturing defects, while thermal abuse from external overheating or similar leads also to an exothermic runaway reaction.

The scientific literature reports failure rates of ranging from 1 in 10 million to 1 in 40 million for lithium ion battery cells (Doughty and Roth, 2012); while a large 100 kWh battery for an electric vehicle can comprise over 8,000 cells. It is a numbers game and as more and more of these cells are manufactured, so too will the number of incidents of self-ignition. While such self-ignition originates in one cell, it will rapidly spread to adjoining cells, resulting in the loss of the whole battery unit. This domino effect continues if there are adjoining batteries, such as in a warehouse or large-scale energy storage system. Hence the terminology used in this article of a 'battery warehouse', which could equally comprise the storage of battery units prior to dispatch or a Battery Energy Storage System (BESS). The consequences being the same if a fire occurs, the potential loss of the whole 'battery warehouse'.

Such accidents are happening, for example on 16 April 2021, a 25 MWh lithium-ion energy storage system connected to a solar panel installation on the roof of a shopping mall in Beijing went on fire. Regretfully when the unit subsequently exploded, two fire fighters lost their lives. On 29 June 2021, a massive fire broke out at an old paper mill warehouse in Morris, Illinois. The toxic fumes formed resulted in the evacuation of over 1,000 homes for several days. Final extinguishment of the lithium ion batteries stored in the mill, ranging from phone size to car sized, was by smothering them with 28 tonnes of cement. In February 2022 a bulk car carrier, the Felicity Ace caught fire in mid-Atlantic with some 4,000 VW Group vehicles on board, the electric ones contributing to the intensity of the fire, which eventually sank the ship.

A knee jerk reaction to the above would be to seek to limit the development of this new technology sector. However, this ignores that the early years of the petroleum sector in the beginning of the 20th Century were characterised by a spate of major accidents. However, the principles of process safety were developed and adhered to and such accidents, while they still occur, are rare. After all as Trevor Kletz, recognised as one of the founders of process safety, put it succinctly: "*If you think safety is expensive, try an accident*". Indeed, after the massive fire and explosion in 2005 at the fuel depot in Buncefield, North of London, the UK Health and Safety Executive (HSE) successfully prosecuted the five operators of the terminal. Their then Director of Hazardous Installations issuing a challenge to high hazard industries:

- *Do we understand what can go wrong?*
- *Do we know what our systems are to prevent this happening?*
- *Do we have information to assure us they are working effectively?*

These questions strip the complexity of process safety to its core concepts and are equally applicable to the context of 'battery warehouses'. A safe facility is one in which the answers to the above are known. However, in many respects the situation currently applicable in mid-2022 is the classic case of which comes first, the chicken or the egg. Namely is it appropriate for a widespread roll out a new technology in the form of lithium ion batteries, in the absence of a regulatory and risk management structure. With this structure left for later development, as the accident situation becomes clearer or alternatively, should there be integration of this new technology, with some tweaks as necessary, into existing regulatory and risk management structures.

2.0 Risk Management

The ambition of all process safety professionals is 'zero harm' and a hazard is the potential to do harm, yet the concept of 'zero risk' is an ideal, which is unobtainable. Safety is therefore defined by ISO guidance (ISO, 2014) as "*Freedom from risk which is not tolerable*", while a tolerable risk is the "*Level of risk that is accepted in a given context based on the current values of society*". There is always some residual risk and risk is inherently related to reward. For example, if we want the benefit of vehicles, then as regards their fuels or batteries, an acceptance of some residual risk has to occur. However, it is how we manage this risk, which is critical. If we don't, as more and more lithium ion batteries are manufactured, the number of serious fires in 'battery warehouses' will inevitably increase and society will not accept this.

The worst way to manage risk is as a 'knee jerk' to unfolding events, while on the opposite spectrum ISO 31000:2018" Risk management — Guidelines" provides good guidance on the structured process to manage risk. This requires in particular the identification of the scope, context and criteria for the subsequent risk management, the scope in this case being 'battery warehouses'. The context is multi-faceted with internal and external drivers, such as regulatory, economic, environmental, reputational, and insurance related. The risk criteria is essentially the 'appetite' for risk. For example, a start-up company will have different criteria than an established company, which has brand share to lose.

Risk in a technological sense is the combination of the likelihood of such incidents and the subsequent consequences. Risk assessment identifies the sources of risk and then analyses them to comprehend their characteristics by consideration of the scenarios, likelihoods, consequences, uncertainties, etc. The final step of the assessment is the risk evaluation, which compares the acceptability of the residual risk with the previously determined context and criteria. Either the residual risk is accepted, the objectives reconsidered or a degree of additional risk treatment pursued. For example, a redesign to reduce residual risk by either reducing the likelihood of occurrence or the consequences which occur or a combination of both. It's an iterative process and just like vehicles on the road, there is no 'one size fits all'.

3.0 Regulatory Context

Regardless of jurisdiction, the regulatory context exists as a pyramid structure, with the apex comprising of overarching mandatory legislative requirements, whose interpretation is supported by the non-mandatory guidance and technical standards below. The latter representing the 'state of the art', which is constantly evolving. At the apex of the EU's environmental legislation is Article 191 of the Treaty for the Functioning of the European Union (TFEU) i.e. the Lisbon Treaty. This establishes that, "*Union policy on the environment shall aim at a high level of protection, taking into account the diversity of situations in the various regions of the Union. It shall be based on the precautionary principle and on the principles that preventive action should be taken, that environmental damage should as a priority be rectified at source and that the polluter should pay"*.

With the exceedance of defined thresholds of dangerous substances, the EU's Directive on Control of Major Accidents Hazards (COMAH) involving dangerous substances becomes applicable. This specifying an obligation *"to take all necessary measures to prevent major accidents and to limit their consequences for human health and the environment"*. How one goes about this is a risk based process in the individual case. This 2012/18/EU Directive, also commonly referred to as Seveso III, being the current version of legislation, originally adopted after a loss of control incident in 1976 at a chemical plant in Seveso, Italy, caused a major dioxin release. The thresholds of dangerous substances specified for its application specifically including those, "*which it is reasonable to foresee may be generated during loss of control of the processes*".

Additionally, and in circumstances where such thresholds for dangerous substances are not exceeded, Directive 2004/35/EC "*on environmental liability with regard to the prevention and remedying of environmental damage*" (ELD) establishes a framework based on the polluter pays principle to prevent and remedy environmental damage. Where such "environmental damage" is defined as damage to protected species and natural habitats, damage to water and damage to soil.

The above secondary EU legislation precedes BREXIT and therefore is applicable in both the UK and the Member States.

4.0 Loss of Control

While the EU Commission does not prescriptively define loss of control accidents, its DG Environment has published a FAQ on Seveso III in relation to Article 3(11) – "Presence of dangerous substances" this asks:

- *"Does this notion aim to cover establishments where dangerous substances may be generated as a result of loss of control of the processes in quantities exceeding the qualifying thresholds in Annex I, even if such establishment would not normally fall under the scope of the Seveso Directive, for reason of the actual or anticipated presence of dangerous substances in quantities above the qualifying thresholds?"*

To which there is provision of a lengthy answer concluding with:

- *"Therefore, if it is reasonable to believe that, in case of an incident, dangerous substances could be created in quantities exceeding the qualifying thresholds, then the operator of the establishment where non-Seveso substances are present or where Seveso-substances are present but below the qualifying quantities, should notify its activities as if it were a Seveso establishment"*.

However, the somewhat thorny interpretation of a 'loss of control incident', to which this legislation is applicable, is left for the individual Member States. Germany has the most Seveso III designated sites in the EU, it is also a Federal structure with the permitting, etc. occurring at the level of the 16 provinces. Although, there is also a Kommission für Anlagensicherheit,, in effect an advisory group on process safety at the Federal Ministry of Environment, which produces both guidance documents and technical regulations. Of particular relevance is KAS-43 Empfehlungen zur Ermittlung der Mengen gefährlicher Stoffe bei außer Kontrolle geratenen Prozessen [Recommendations for evaluating the quantity of dangerous substances with processes, which have run out of control].

Section 3 of this is entitled: *Concretisation "...for which it is reasonably foreseeable (...)"* [unofficial translation by the author]. There being no definition of 'reasonably foreseeable, but it does equate to the term 'reasonably cannot be excluded, given that *whether or not it is reasonably foreseeable that a hazardous substance may be produced in an out-of-control process may also depend, inter alia, on measures to prevent or limit accidents*". The guidance then referring to how "*in the presence of at least two independent engineered protective measures or one inherently safe engineered protective measure, it may be concluded that the generation of hazardous substances in out-of-control processes is not reasonably foreseeable*".

The following example is provided: "*In a warehouse, if the containers for the storage of acids and alkalis are located in in different, structurally separate areas in a warehouse or if the filler necks are technically designed in such a way as to exclude the possibility of confusing substances, and if the containers are also equipped with a pH-value measurement, the formation of hazardous substances due to an accidental mixing of acids and alkalis is not reasonably foreseeable, because it is only possible intentionally".*

It is also further elaborated: *"With regard to the determination of quantities, technical and constructional measures that can effectively limit the quantity of hazardous substances that may be produced can be taken into account. Example: If a warehouse has appropriate structural and defensive fire protection (fire compartments separated by F90 or fire walls, automatic extinguishing systems with VdS certification, etc.), the formation of hazardous substances is effectively limited".*

If we consider the UK Health and Safety Executive's L111 "A guide to the Control of Major Accident Hazards Regulations (COMAH) 2015"

- *8 Even if there are no threshold quantities of dangerous substances present at a site, it may still be subject to the Regulations, e.g. if specified dangerous substances could be produced in threshold quantities as a result of loss of control of a process – this is what happened in the accident at Seveso, referred to in Background, below.*
- *57 The definition is not intended to bring into scope premises which do not manufacture, use or store dangerous substances, solely because of dangerous substances being generated in an accident. For example, a warehouse holding non-dangerous substances is not in scope of the Regulations solely because a fire might generate dangerous substances above threshold quantities.*

The final paragraph 57 does seem in some manner to contradict the previous paragraph 8 and the regulation itself, unless interprets it that the probability of a fire has to be very low given the structural and active fire protection measures at the warehouse.

5.0 Relevance of Loss of Control to Major Accident Scenarios

Fundamentally, for the Seveso III legislation to have some applicability for battery warehouses, the above concept has two distinct elements, both of which need to be fulfilled. Firstly is a loss of control scenario reasonably foreseeable and in this regard a lithium ion battery is composed of multiple cells, which facilitate a chemical process changing as the cell charges and discharges and for which there is a known failure rate. Electronic systems monitor the cells, known to go unstable at temperatures as low as 60 ºC – 70 ˚C and reach auto thermal conditions by 120 ºC. These regulate the temperature and charging / discharging rate to prevent 'abuse' of the cell. However, as discussed previously, such abuse and subsequent failures do occur and referring back to KAS-43, such a control system does not suffice as an inherently safe protective measure. Propagation is the next element requiring consideration; does the loss of a single cell rapidly lead to a subsequent loss of adjacent cells? In general, with a limited exception the whole battery is lost, with a potential for spread to adjacent batteries.

In August 2017 Swedish researchers funded by the Swedish Energy Agency, published a paper entitled "Toxic fluoride gas emissions from lithium-ion battery fires" (Larsson, 2017). As its abstract highlights, it presented "*quantitative measurements of heat release and fluoride gas emissions during battery fires for seven different types of commercial lithium-ion batteries. The results have been validated using two independent measurement techniques and show that large amounts of hydrogen fluoride (HF) may be generated, ranging between 20 and 200 mg/Wh of nominal battery energy capacity. In addition, 15–22 mg/Wh of another potentially toxic gas, phosphoryl fluoride (POF_3), was measured in some of the fire tests".*

Hydrogen fluoride's GHS classification is a very toxic gas. While phosphoryl fluoride is an extremely reactive and hence unstable chemical, which the European Chemical Agency (ECHA) has not formally classified. It rapidly hydrolyses in the presence of water, which would be the circumstances of a fire, to give monofluorophosphoric acid, phosphoric acid and hydrogen fluoride. The relevant threshold in Annex I of Seveso IIII for very toxic compounds is 5 tonnes. Each fire situation would have to be evaluated individually, as there are additive rules applicable where a range of dangerous substances can be present. However, the above would indicate that 17 MWh of battery storage in a fire situation could produce a health hazard falling under the terms of the Seveso III Directive.

Vapour cloud explosions, such as the previously mentioned accident in Beijing, have also occurred with this technology, due to the rapid evolution of hydrocarbon vapours and carbon monoxide from incomplete combustion. However, it is unlikely that an exceedance of the Seveso III limit of 10 tonnes for explosive gases would occur, before ignition. However, it is also necessary to consider the metals used in the battery, particularly for the anode and cathode. The Karlsruher Institut für Technologie (KIT) Forschungsstelle für Brandschutztechnik [Research Centre for Fire Protection Technology] has produced a number of reports on lithium ion battery fires. KIT Report 175 (Kunkelmann, 2015) concluded, as to how the thermal release of energy from a lithium ion battery in a failure situation, can be circa six to ten times the electrical energy stored. Copious amounts of extinguishing water are thus required, while for substances and mixtures dangerous to the environment, the thresholds applicable in Seveso III are in excess of 100 tonnes.

However, the firefighting associated with lithium ion batteries generates such large quantities of contaminated firewater. For example, cobalt (II) oxide is found in batteries, for which the harmonised classification assigns an Acute Category 1 environmental hazard to a solution of 2.5% cobalt (II) oxide in water. Is it realistic in a large battery fire that 100 tonnes of such a solution occurs in a firefighting operation?

For certain batteries containing Nickel Manganese Cobalt (NMC) there is the potential for release of "Nickel compounds in inhalable powder form", for which the upper tier threshold set in the legislation is one tonne.

6.0 Applicability of COMAH Legislation

It is accepted that there is considerable uncertainty with all of the above, which can be traced back to a reluctance of the industry to complete appropriate large scale fire testing. In the EU Regulation (EC) No 1272/2008 on classification, labelling and packaging (CLP) of substances and mixtures (as amended), implements the UN's Globally Harmonised System of Classification and Labelling of Chemicals. It defines:

- *'article' means an object which during production is given a special shape, surface or design which determines its function to a greater degree than does its chemical composition.*

While further elaboration on this point does not occur in the CLP Regulation, ECHA has prepared considerable guidance documentation in relation to the implementation of the EU's REACH legislation on registration, evaluation, authorisation and restriction of chemicals, including a "Guidance on requirements for substances in articles" June 2017 Version 4.0. This lists a battery as an "*article with an integral substance / mixture*", although it is not clear, as to what size the battery under consideration is. While it is true that the Seveso III Directive utilises "Hazard categories in accordance with Regulation (EC) No 1272/2008", i.e. the CLP regulation, its concept of dangerous substances is very broad, including both explosives and explosive articles, while clarifying:

- *"In the case of dangerous substances which are not covered by Regulation (EC) No 1272/2008, including waste, but which nevertheless are present, or are likely to be present, in an establishment and which possess or are likely to possess, under the conditions found at the establishment, equivalent properties in terms of major-accident potential, these shall be provisionally assigned to the most analogous category or named dangerous substance falling within the scope of this Directive*".

Therefore, that certain batteries may be considered as articles in certain contexts, does not detract from their inclusion, where relevant', as dangerous substances for the purpose of COMAH assessments. Furthermore, battery chemistry does vary, so the number of batteries relevant for a threshold in the Seveso III Directive to be exceeded is, given the lack of firm data above, subject to interpretation. This of course predisposing that an initial fire in one battery module rapidly spreads to others adjoining it, the available controls to prevent this occurring being ineffective. This being an appropriate occasion to discuss what are the known controls to contain such a lithium ion fire, which as the next Sections describe, are somewhat underdeveloped.

7.0 Available Control Measures – Fire Triangle

Any fire scenario follows the principles of the fire triangle, namely sources of fuel, oxygen and ignition are required, while elimination of any of these prevents / stops the fire. The chemistry of lithium ion batteries utilises electrolytes, which are flammable and hence is very different to nickel metal hydride and lead acid batteries with their aqueous electrolytes. Indeed, an external fire can lead to a violent release and ignition of the stored flammable electrolyte. Given that 'fuel' is inherent to this sector, the next option for consideration is the possibility of eliminating oxygen. In this regard, a technology gaining traction in Europe is the utilisation of reduced oxygen atmospheres for the storage of special materials, such as data servers, critical document archives, chemicals with a significant environmental hazard, etc. Namely, the warehouse is airtight and the oxygen content reduced by addition of nitrogen.

Typically, such systems operate at 15% oxygen, in which if any fire occurs, it will be a smouldering and slow burning fire, while smoke detectors can be utilised to alarm and reduce the oxygen level even further. However, such systems do not operate below 13%, as at that point the risk for human entry without breathing apparatus is too great, hypoxia being the medical terminology describing the circumstances where the body tissues are starved of oxygen. The Karlsruher Institut für Technologie (KIT) Forschungsstelle für Brandschutztechnik [Research Centre for Fire Protection Technology] has produced a number of reports on lithium ion battery fires. Their Report 192 (Kunkelmann, 2017) investigated the use of nitrogen and argon enriched atmospheres for fire extinguishment.

As it points out, VdS 3527:2018, the German Insurance Association's 'Guidelines for Fire Protection Systems - Oxygen Reduction Systems', specifies that ignition limits for flammable liquids lie between 11% and 14.7% oxygen. The KIT report 192 provides a detailed description of experimental fire testing of small lithium batteries with nitrogen reduced atmospheres down to 8% and for argon reduced down to 7%. While this reduced atmosphere had an influence on the combustion by-products formed, increasing some and decreasing others, it did not stop the thermal runway reaction. A contribution factor to this being that battery combustion is associated with the generation of its own oxygen.

Furthermore, the reduced oxygen atmosphere did not prevent the spraying of sparks or the explosive energy releases associated with such battery fires. While the authors considered that the technique had applicability to storage of small scale batteries, where a reduction in the speed at which fire spread was achievable, it's applicability to larger scale battery fires was unknown. In practice, accident history has shown that gas suppression systems have not been effective for larger battery fires, such as in grid storage systems. The fires have been simply too intense and even if initially suppressed have reignited, which is not unexpected given that such gas suppression systems are also not recommended for fighting flammable liquid fires, where the energy release is also considerable. While another KIT Report 175 concluded, as to how the thermal release of energy from a lithium ion battery in a failure situation, can be circa six to ten times the electrical energy stored.

With respect to the fire triangle, this leaves the control of ignition sources as the only viable remaining option and as highlighted previously, the control of the charging and discharging rates is critical in this regard. Furthermore, if ignition does occur, the initial smouldering phase leads to the formation of hazardous off-gases, which are detectable by gas monitoring systems, providing an early indication of a developing fire scenario.

8.0 Available Control Measures – Active and Passive Fire Protection

A successful fire protection strategy has to be based on a combination of both active and passive fire protection measures. Active measures are those which come into action on detection of fire, such as sprinklers or foam extinguishing systems, while passive provisions relate to the fire defence provided by such as the fabric and construction of a building, the fire compartmentalisation, etc. Naturally, within the concept of inherent safety, passive fire protection measures should be prioritised over equivalent active measures.

In simple terms a lithium ion battery fire will be intense, which dictates that the building fabric has to have a significant fire resistance to prevent collapse during firefighting. As to how many minutes or hours this fire resistance has to be, is really a function of the intensity and duration of the applicable fire scenario. Equally, the extent of fire compartmentalisation, which segregates one storage compartment from another, is dependent on the applicable fire scenario and as to how far the fire spreads before it is successfully extinguished, if at all.

Experience has shown that foam extinguishing systems are particularly effective with hydrocarbon liquid fires, as they provide low densities and large surface areas, which allow them to exclude oxygen from the burning surfaces and extinguish such hydrocarbon-based fires. Water on the other hand sinks through the burning hydrocarbon surface due to its higher density, although it is useful for cooling adjoining infrastructure and preventing fire spread. The design of such foam extinguishing systems has evolved from large scale testing and if the foam application can be both quick and effective, then a large tank farm fire can be put out in minutes.

Unfortunately, this success has not transferred to larger lithium ion battery fires. As the literature (M Ghiji, 2020) reports: "*To be effective the foam must fully encapsulate the cell which is a challenging task as LiBs* [lithium ion batteries] *are considered to have multi-stage jet fires, presenting high-velocity flammable gas venting*". It also being concluded that: "*Water is identified as an efficient cooling and suppressing agent and water mist is considered the most promising technique to extinguish LiB fires*". While the whole area of extinguishing lithium ion battery fires is a very active area of research, such fires are characterised by long duration, high temperature, large water consumption and significant release of toxic fumes. A further problem is that the cost of larger sized batteries, such as utilised for vehicle propulsion, is considerable. Hence, to date fire testing simulating storage facilities containing such large batteries has been extremely limited.

Some fire testing has been completed on smaller batteries, such by the German Insurance Association VdS in their 2015 Forschungsbericht: Sprinklerkonzepte für Lager mit Li-Ionen Batterien [Research Report: Sprinkler concepts for warehouses with lithium ion batteries]. They utilised typical batteries for electric bikes, with between 46.3 kWh and 124.4 kWh of batteries combusted in each test, which is in the range of one to three vehicle sized batteries. The sprinkler system design was to the European insurance industry's code VdS CEA 401 for racked storage. Naturally, the test with the larger number of batteries showed a significantly faster development of the fire. It was also found that the water based sprinklers did reduce the spread of the fire and that the earliest possible triggering, complete wetting and cooling of the fire load led to a significantly slower reaction of the batteries and thus also a slower development of the fire. This lead to the conclusion that a quick-acting sprinkler system with a high level of water exposure can therefore be a possible measure to reduce the damage. However, "*precise dimensioning parameters must also be matched to the materials and storage situations*".

FM Global has also published in 2016 a White Paper on "Increased use of lithium-ion batteries". FM Global are continuing to complete research work with the National Fire Protection Agency (NFPA) on sprinkler effectiveness for the storage of intermediate size batteries. Likewise, this has demonstrated that as the cell capacity increases, so too does the relative hazard, larger format batteries being a higher fire risk. It is also appropriate to conclude from this and similar test programmes, that a reasonable level of knowledge exists in relation to sprinkler design for racked storage of small scale consumer batteries, but not for larger vehicle type batteries. Although some basic principles are common to both, in that the fire risk does increase with increasing racked storage height.

9.0 Available Control Measures – Firewater Retention

The storage of significant quantities of lithium ion batteries has the potential in a fire scenario to lead to the generation of considerable quantities of contaminated firewater, whose direct release into the environment is an area of concern. While requirements for firewater retention vary between jurisdictions, such retention is a general consideration of effective risk management for all battery warehouses. In terms of control measures, it is certainly possible to construct the floors and lower sidewalls of the storage compartment in a water impermeable finish. While the entry and exit doors can be fitted with an automatic barrier which drop into place when the fire alarm is activated. The lower level of the warehouse then becomes a compartment to retain the firewater.

10. Some Conclusions

Lithium ion batteries have won wide scale acceptance by the public despite the significant safety issues associated with their use. As regards their regulation, the EU and its Member States limit their legislative efforts to matters of public interest, such as public safety or environmental damage. Material damage, such as to property or business disruption, is a matter for the loss prevention insurers. Making predictions is difficult, particularly about the future. However, given the intense heat of a lithium ion battery fire and the damage it can do to adjoining structures, it is likely that some insurance restrictions will apply in the future, such as is currently utilised for transformers. However, these cannot be determined without first completing extensive fire testing. For example, (VdS 3103en, 2019) concludes for lithium batteries of high capacity, that they do not have "*any reliable information about adequate safeguards for batteries of high capacity.*" Possible measures include:

- *"Separation and limitation of quantity*
- *Storage in areas separated in a fire resistant manner or with safe distances [Spatial separation of 5 m].*
- *Automatic extinguishing system".*

Note, to reiterate, these are possible measures only, reliable measures are not yet developed. Therefore, the default position is to keep them outdoors with plenty of spatial separation to sensitive infrastructure. Not unlike how in days past, explosives were manufactured in separate bunkers, but this time dispensing with the man with the one legged stool. A failure of a battery cell in such circumstances should then only lead to the loss of the immediate battery, without propagating to adjoining batteries and leading potentially to a major accident scenario.

One can question is this extreme and in this regard, it is important to consider once again that the chemistry of lithium batteries varies greatly. The majority burn with an intense release of heat and flames. However, there is evidence that some batteries, based on lithium iron phosphate chemistry, which are less efficient in terms of energy density, will on loss of a single cell, not propagate the resulting fire to the adjoining cells in the battery unit. For these therefore such spatial separation is not necessary, but for other more volatile chemistries, with known flame propagation between cells, until actual fire testing proves otherwise, such spatial separation or fire walls are necessary and should be informed by actual fire testing.

References

Doughty DH, Roth EP. A general discussion of Li ion battery safety. Electrochem Soc Interface 2012; 21:37–44.

FM Global 2016: "Increased use of lithium-ion batteries". "Description of Hazards and Related Protection Schemes Proposed by FM Global for the Storage of Lithium-ion Batteries"

ISO/IEC Guide 51:2014 "Safety aspects - Guidelines for their inclusion in standards".

Karlsruher Institut für Technologie (KIT) Forschungsstelle für Brandschutztechnik 175: Jürgen Kunkelmann, 2015: Untersuchung des Brandverhaltens von Lithium-Ionen- und Lithium-Metall-Batterien in verschiedenen Anwendungen und Ableitung einsatztaktischer Empfehlungen [Investigation of the fire behaviour of lithium ion and lithium metal batteries in various uses and derivation of operational recommendations].

Karlsruher Institut für Technologie (KIT) Forschungsstelle für Brandschutztechnik 192: Jürgen Kunkelmann, 2017: Studie zur Brandbekämpfung von Lithium-Ionen-Batterien (Akkus) und Lithium-Metall-Batterien [Study for firefighting of lithium ion batteries and lithium metal batteries}.

Larsson F, Andersson P, Blomqvist P, Mellander BE. Toxic fluoride gas emissions from lithium-ion battery fires. Sci Rep. 2017 Aug 30;7(1):10018. doi: 10.1038/s41598-017-09784-z. Erratum in: Sci Rep. 2018 Mar 22;8(1):5265. PMID: 28855553; PMCID: PMC5577247.

M Ghiji et al. "A Review of Lithium-Ion Battery Fire Suppression". Energies 2020, 13, 5117.

VdS 3103en, 2019 Lithium Batteries – Publication by the German Insurers [GDV.e.V.] on the issue of loss prevention.