euralarm

Guidance on

Integrated fire protection solutions for Lithium-Ion batteries

Change revision table

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DISCLAIMER

This document is intended for stakeholders in relation to fire protection of Lithium-Ion batteries. Whilst every effort has been made to ensure its accuracy, readers should not rely upon its completeness or correctness, nor rely on it as legal interpretation. Euralarm will not be liable for the provision of any incorrect or incomplete information.
Note: The English version of this document is the approved Euralarm reference document.

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1 INTRODUCTION

This Euralarm guidance paper provides information on the issues related to the use of Lithium-Ion batteries, how fires start in batteries and on how they may be detected, controlled, suppressed and extinguished. It also provides guidance on post fire management. Excluded from the scope are explosion and ventilation issues.

This paper is intended as guidance for all professionals dealing with fire safety, fire protection, extinguishing and fire suppression in connection with the use, storage or transport of Lithium-Ion batteries and their fire risks. Aspects of consumers products aren't covered in this guidance.

The paper is intended as general guidance and is not a substitute for detailed advice in specific circumstances. This document represents the current understanding of the industry and will be updated as more information becomes available.

2 MANAGEMENT SUMMARY / CONCLUSIONS

Lithium-Ion batteries have become the battery technology of choice in a variety of areas, including amongst others, power generation, communications, industrial, vehicles and many other applications. Active control of the energy being stored and extracted from Lithium-Ion batteries has been the foundation of their increasing popularity. The relatively low frequency of major incidents is testament to the effort and successful design applied to the critical aspect of using such high-density energy products. However, active control of the battery energy is not sufficient to prevent safety-critical situations and multiple levels of defence are needed to minimize the serious consequences of a failure in a Lithium-Ion battery.

The mere presence of Lithium-Ion batteries in a room represents a considerable risk of fire as Lithium-Ion batteries combine high energy materials with often flammable electrolytes. Any damage to the separator inside the batteries (caused either by mechanical damage or high temperatures) may lead to an internal short-circuit with a high probability of a thermal runaway. Once a cell has experienced thermal runaway it is very likely that the heat will propagate to adjacent cells leading to a chain reaction with often catastrophic consequences.

A cohesive strategy incorporating; risk avoidance, early detection, interventional actions, active extinguishing as well as physical separation, must always be taken to limit the likelihood and the consequences of a Lithium-ion battery fire.

The increasing number of Lithium-Ion batteries and an increasing amount of stored energy in different Energy Storage applications present a new type of fire hazard where Fire Protection is challenging. There are many technologies available for detecting developing fires in the different stages, however, very early detection plays a key role, providing an early opportunity to stop propagation of thermal runaway and significantly limits the overall damage. Detection of the off-gases which are released during the early stages of battery abuse/failure is an area of innovation and the approval of such systems is beginning to emerge. Detection systems for smoke and heat are also applicable for fire alarm purposes and triggering a fire protection system – in the event that early intervention is not successful.

Automatic fire protection systems either extinguish or prevent incipient fires in order to protect objects, rooms or entire buildings from fires and their consequences. The extinguishing agents used for this purpose include water- based agents, foams, powders, aerosols and gases. However, key issues in any fire protection system are the selection of the most appropriate agent for the specific hazard, system layout, the correct discharge of the extinguishing agent, as well as correct installation, the use of approved systems and constant maintenance by appropriately trained staff.

Each fire protection **application requires a specific solution, based on the use of approved systems, as there is no protection concept that is equally suitable for all applications.**

Before selecting the optimal concept, the objectives of the measures, the protection concept and the possible side effects of the technologies used must be considered. In addition to the technical options available on the market the whole environmental situation of the application has to be taken into account.

Finally, when a battery fire is extinguished a significant fire hazard may still remain as batteries involved in, and affected by the fire, are likely to be hot and still pose the potential to vent combustible and toxic gases and have the potential to reignite. It is therefore necessary that post fire management operations commence as soon as practicable by suitably equipped and trained personnel.

3 TECHNOLOGY and APPLICATIONS of Lithium-Ion-Batteries

Lithium-Ion batteries (also often referred to as Li-ion) are fast emerging as a power source and have become the battery of choice in many applications, due to their high-energy-to-weight ratio.

Lithium-Ion battery technology

Lithium-Ion batteries vary widely, and continue to evolve, in terms of their materials of construction, chemistry and configuration. They are rechargeable (as opposed to lithium batteries which are not) and contain lithium ions in a flammable electrolyte. They do not contain any free lithium metal, however, in most cases Lithium-Ion batteries combine high energy materials with highly flammable electrolytes.

Cell enclosures may typically be metal or polymer used to configure cylinders (jellyroll), pouch/polymers (squashed jelly roll/ books/sheets) or prismatic. Cathodes are an oxide coated lithium, such as lithium cobalt oxide with an anode, such as graphite, in an electrolyte with a poly film separator.

The batteries vary in size and configuration depending on their use and application. Larger batteries may be found in Energy Storage Systems (ESS) and vehicles whilst smaller batteries are used in laptops and mobile phones with lots of intermediate applications.

Batteries are arranged in series to increase voltage, and in parallel to increase capacity.

The figure below shows the expected battery chemistry development. It is expected that the technologies of today's batteries considered here will still be in wide use until the middle of the next decade.

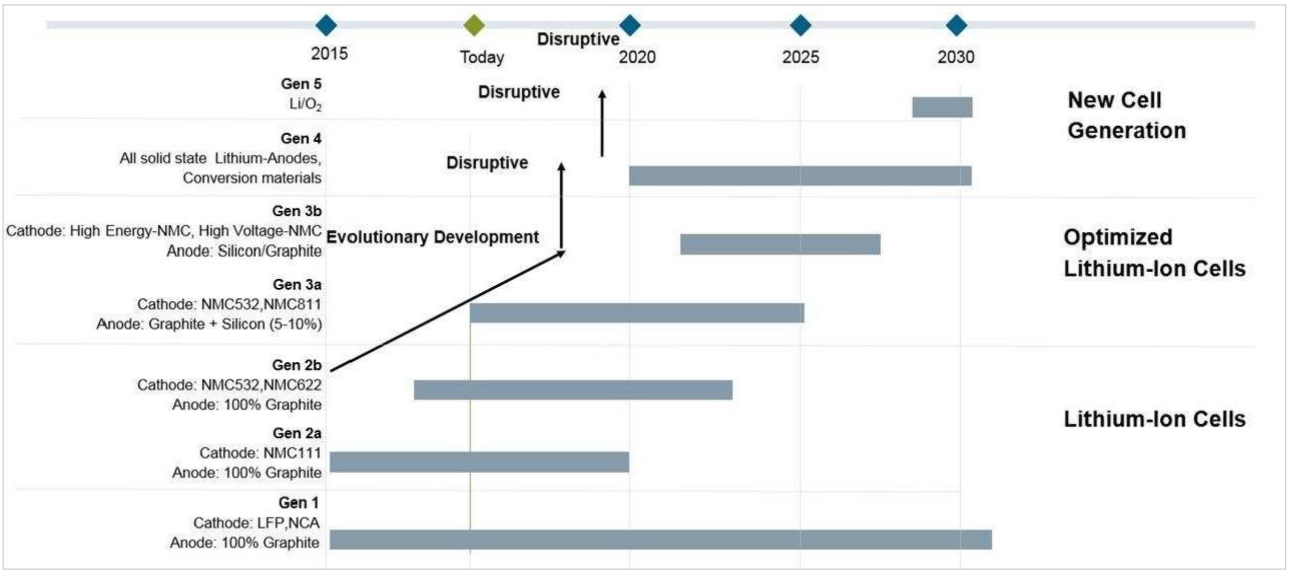

Figure 1: Lithium-Ion battery development in future

(Source: SIEMENS White Paper "Fire protection for Lithium-Ion battery energy storage systems" – May 2020)

3.1 Applications of Lithium-Ion batteries

Lithium-Ion batteries provide higher levels of capacity combined with reliable operation when compared to other forms of cell and battery technology including Nickel Cadmium (Ni-Cd) and Nickel Metal Hydride (NiMH). As a result of their characteristics, Lithium-Ion batteries have become the battery technology of choice in a variety of areas, including amongst others, power generation, communications, industrial, vehicles, military and aerospace applications.

In the following chapters there is a short description of the main uses (most popular applications) for rechargeable batteries and their typical batteries capacities in that application. In this context it is important to note that **in case of a fire, heat of combustion is directly linked to the battery power**.

Battery Management Systems

The most important electronic component of many Lithium-Ion battery applications is the battery management system (BMS) which, in addition to controlling and monitoring the state of charge at cell and system level, also performs temperature monitoring and management during charging and discharging cycles.

An efficient BMS will keep the cells in the intended safe operating range, so that over-charging and over-discharging are avoided.

3.1.1 Individual Small Rechargeable, Portable Devices and other commonly used electronic goods

The generic term "Portable Devices" covers a very wide range of applications for such batteries in consumer and professional use. It includes mobile phones, smartphones, laptops, tablets, e-readers, cameras and many other electronic gadgets powered by rechargeable batteries (e.g., power tools etc). These products are usually equipped with battery **capacities of 2 up to 30 Wh** (see table 1).

Device	*Capacity of Battery*
Cameras	2,5 - 9 Wh
Mobile Phones / Smartphones	7 – 10 Wh
Laptops / Tablets	15 – 27 Wh
Power Tools	3,6 – 18 Wh

***Table 1**: Batteries capacity of portable devices (Source: numbers from several manufacturers)*

3.1.2 Small Electric Mobility

Small Electric Mobility comprises of different types of smaller equipment/vehicles that facilitate the movement of one to two people and that are equipped with an electric motor in addition to the human drive. This draws its energy mostly from external rechargeable batteries. Batteries of such products varies **typically from 50 up to 1250 Wh** (see table 2).

Equipment/vehicle	*Capacity of Battery*
Vitality Electric Mobility	50 – 500 Wh
Electric bikes	500 -1250 Wh

***Table 2**: Batteries capacity in small electric mobility (Source: numbers from several manufacturers)*

3.1.3 Emergency Power System or UPS (Uninterruptible Power Supply)

An Emergency Power System is an independent source of electrical power that supports important electrical systems on loss of a normal power supply. A standby power system may include a standby generator, batteries and other apparatus. Emergency power systems are installed to protect life and property from the consequences of loss of the primary electric power supply. It is a type of continual power system. They find uses in a wide variety of settings from homes to hospitals, scientific laboratories, data centers, telecommunication equipment and ships. Batteries of such systems varies typically **from 1 up to 200 kWh** (see table 3).

	Capacity of Battery
Small	1 – 5 kWh
Medium	50 – 100 kWh
Large	100 – 200 kWh

***Table 3**: Batteries capacity in EPS / EPS (Source: numbers from several manufacturers of UPS)*

3.1.4 Electric Mobility and Electric Automotive (Vehicle Electrification)

Electric Mobility comprises all vehicles and boats that are powered by an electric motor and primarily get their energy from the power grid – in other words: can be recharged externally. This includes:

- purely Electric Vehicles (EV),
- vehicles with an electric motor and a small combustion engine (Range Extended Electric vehicles – REEV)
- hybrid vehicles that can be recharged via the power grid (Plug-in Hybrid Electric Vehicles – PHEV)
- electric buses
- electric boats/ships

Electrical Cars (EV) are currently available on the market with battery capacities in a range **between 25 – 100 kWh**, whilst other vehicles may go up to **2500 kWh** (see table 4).

Modell	*Battery*	
Fiat 500	24 – 42	kWh
Renault Zoe	41 – 52	kWh
Tesla Model 3	55 – 75	KWh
VW ID.4	62 – 82	KWh
Ford Mach-E	76 – 99	kWh
Porsche Taycan	79 – 93	kWh
Electric Buses	100 – 500	kWh
Electric boats	20 – 200	kWh
Electric ships	200 – 2500	kWh

Table 4: *Batteries capacity in vehicle electrification (Sources: ADAC - General German Automobile Club e.V. and Wikipedia)*

3.1.5 Energy Storage Systems (ESS)

Battery Energy Storage Systems (ESS) cover a large range of applications in the supply of electricity - from generation to consumption. They help to optimize asset performance by smoothing out power demands across the network; stabilizing frequency and voltage and balancing variations between supply and demand in industrial and domestic electricity supplies.

Some examples of ESS applications:

- electricity supply applications for grids and microgrids
- electricity supply for industry
- integration of renewable energy

Currently ESS's are available on the market with battery capacities **in a range between 5 – 500 kWh** and in very large applications with a capacity of several thousand kWh (see table 5). Because of the high energy stored, Lithium-Ion battery energy storage systems are an application with a clear need for comprehensive fire protection.

	Capacity of Battery
Residential	5 – 50 kWh
Medium	200 - 500 kWh
Large	➢ 4000 kWh

Table 5: *Batteries capacity in ESS (Source: numbers collected by editorial team)*

4 FIRE RISKS AND HAZARDS of Lithium-Ion batteries

Active control of the energy being stored and extracted from Lithium-Ion batteries has been the foundation of their increasing popularity. The relatively low frequency of major incidents is testament to the effort and successful design applied to this critical aspect of using such high-density energy products. However, incidents do occur and multiple levels of defence are needed to minimize the serious consequences of a failure in a Lithium-Ion battery.

4.1 Risks inherent in Lithium-Ion batteries

To understand the inherent fire risk of Lithium-Ion batteries it is important to understand the battery technology first.

At the heart of the battery system are the electrochemical battery cells. Each Lithium-Ion cell consists of two electrodes, the Anode (negative electrode) and the Cathode (positive electrode). These electrodes consist of a collector and an active material applied to it. In between the electrodes is the ion-conducting (typically flammable) electrolyte. This is a mixture of lithium salts dissolved in organic solvents with various additives which acts as a mediator of the processes of ion exchange within the cell. Finally, a separator that ensures the electrical separation of the electrodes while facilitating efficient ion exchange.

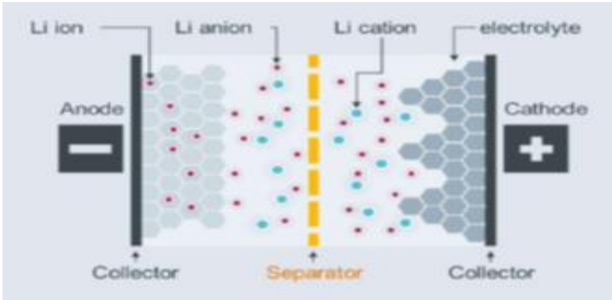

Figure 2: Li-Ion Battery structure

As Lithium-Ion batteries combine high energy materials with often flammable electrolytes, as they use organic solvents, such as Ethyl Carbonate mixed with higher volatility linear carbonates[1]), any damage to the separator (caused either mechanically or by high temperatures) will lead to an internal short-circuit with a high probability of **thermal runaway** (see chapter 4.5.1). Safety-critical situations are almost inevitable.

NOTE: *For certain industries and applications, battery cells are contained in IP-rated sealed battery packs. This may make it difficult or impossible to apply the fire protection agent to the battery cells. The construction methodology greatly impacts the risk and mitigation strategies.*

4.2 Causes of Failure of Lithium-Ion batteries

Failure of Lithium-Ion batteries and the resulting risk of overheating and / or self-ignition (see "thermal runaway) may result from one or more of the following causes:

- Internal manufacturing defects (material defects, contamination, assembly/construction faults)
- Physical damage (during assembly into finished goods, shipping, handling, waste disposal or during service; whether accidental or malicious)
- Separator defect due to dendrite formation (by undetected aging[2] and subsequent internal short-circuit
- Mechanical abuse (Crush / Penetration)
- Thermal abuse
  - exposure to high temperatures (i.e., non-climate-controlled storage)
  - exposure to flames
  - heat from adjacent/neighbouring cell(s)*
- Electrical abuse
  - overcharging / over - discharging,
  - short circuit

*): *Lithium-Ion batteries, for example those used to electric vehicles are in fact many hundreds, even thousands of individual cells. If a single cell overheats, catches fire or even explodes, the propagation of heat to adjacent cell can quickly lead to a catastrophic situation.*

[1] Examples are EMC (Ethyl Methyl carbonate), DEC (Di-ethyl-carbonate) and DMC (Di-methyl-carbonate)

[2] See study "Influence of Aging on the failing behavior of Automotive Lithium-Ion Batteries" published April 7th 2021 - available under https://www.mdpi.com/2313-0105/7/2/23

4.3 Stages of Lithium-Ion batteries failures

Lithium-Ion battery failures have four distinct stages, shown in the figure below:

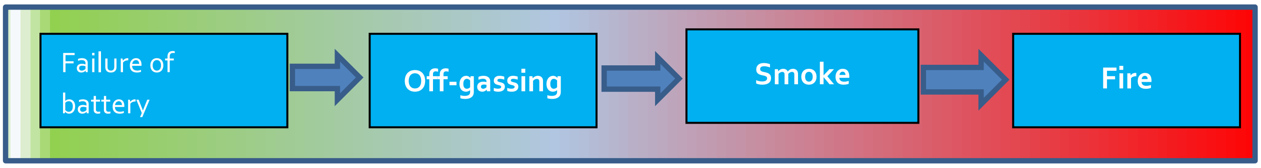

Figure 3: stages of Lithium-ion battery fire

4.3.1 Off-gassing

Off-gassing occurs prior to thermal runaway, during initial battery cell venting, then increases when thermal runaway occurs and continues thereafter. Typically, cylindrical and prismatic cells have pressure relief vents specifically designed to release the overpressure. Pouch cells typically do not have such pressure release mechanisms. Instead, the pouch can expand to a certain extent to accommodate some degree of off-gassing, but are designed to burst (often along a seam or deliberate weak spot) so that overpressure is relieved in a predictable manner/location. This initial off-gassing provides a good opportunity for early intervention, providing it can be detected.

4.3.2 Smoke

Where the temperatures generated by a failing battery start to exceed the design limits of the construction materials their decomposition will produce smoke – specifically formed by the particles of decomposition being carried on the thermal air currents that accompany the high temperatures. In some instances – such as when battery failure is instigated by external heat, smoke may be released before off-gassing occurs. Early smoke detection at this stage can and should be used to initiate intervention measures. Conversely, when heat is internally generated due to other failure modes (e.g., overcharging), smoke and high external temperatures are more likely to occur after off-gassing has occurred (as indicated in Figure 3 above).

4.3.3 Fire

With elevated temperatures, clouds of potentially flammable gases and increasing quantities of smoke, the transition to a fire condition and the development of flames is almost inevitable – particularly where thermal runaway is unchecked and propagates to adjacent cells with exponential temperature growth.

4.4 Risks

From the point that a fire is established and developing the task moves from fire prevention to suppression and containment. The mere presence of Lithium-Ion batteries in a room represents a considerable risk of fire - whether they are in storage or operational. Therefore, measures must always be taken to limit the spread of fire in case that occurs. Thus, containment is a fundamental consideration in relation to mitigating the risk and must take into account the serious consequences of a Lithium-Ion battery fire, including:

- release of toxic gases (HF, CO, CO_2, POF_3, etc.)
- heat release
- burning of flammable materials
- explosion risk

4.5 Thermal runaway and its hazards

4.5.1 What is a "thermal runaway"?

Lithium-Ion battery **thermal runaway** occurs when a single cell, or area within a cell, achieves elevated temperatures due to thermal failure, mechanical failure, internal/external short circuiting, over-discharging, over-charging or electrochemical abuse. When the internal temperature of the cell gets high enough to ignite the electrolyte, which is an organic liquid, the oxide material in the cathode will break down and release oxygen. Thus, in the damaged cell there are now fuel (liquid organic electrolyte) and oxygen (from the oxides in the cathode) ingredients for a fire that can generate its own oxygen, making it extremely difficult to extinguish.

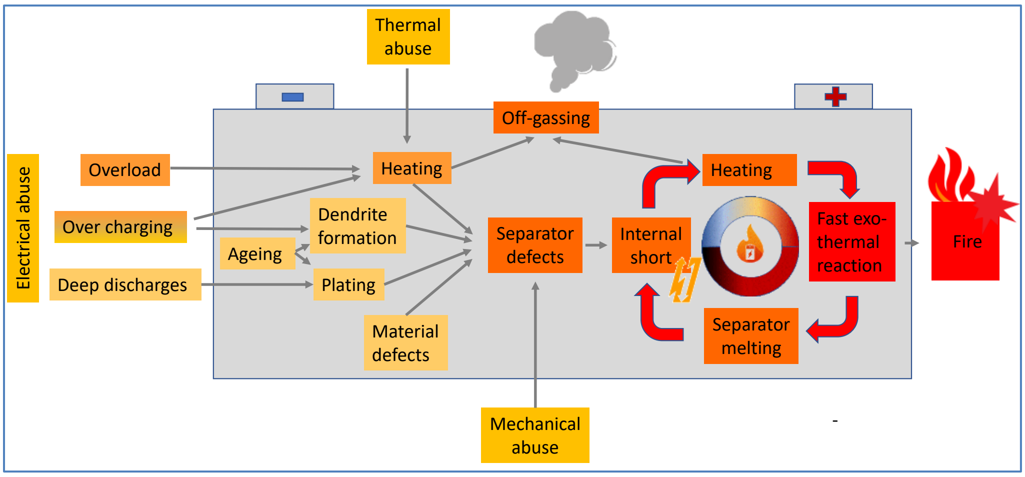

***Figure 4:** Cause/effect relationships leading to thermal runaway for liithium-ion cells*

At elevated temperatures (prior to thermal runaway), exothermic decomposition of the cell materials begins. As a consequence, the internal pressure within the cell will build up until electrolyte vapour is released initially via a relief valve or by the controlled fracture of the shell. Early detection of the vapours vented during the initial stages of off-gassing can offer an opportunity to intervene in the processes surrounding the battery – particularly the charging and cooling systems that support them. At this stage the dominant gases are the electrolytes solvents.

Eventually, the self-heating rate of the cell is greater than the rate at which heat can be dissipated to the surroundings, the cell temperature rises exponentially, stability is ultimately lost and thermal runaway ensues. At this stage the gases emitted are indicative of thermal decomposition and include CO, CO_2 and H_2. The loss in stability also results in all remaining thermal and electrochemical energy being released to the surroundings.

Thermal runaway typically starts in a single cell before thermal propagation creates a domino effect through the adjacent cells. In case such thermal runaway starts:

- **no technology has been proven to STOP thermal runaway in a cell**
- it doesn't need oxygen to develop
- initially it lasts some seconds only in a single cell – depending on number of cells in a battery system and by domino-effect it may last from hours up to several days in total.
- thus, it leads to high temperature (more than 600°C) in the materials, that may last many hours.

4.5.2 Causes of a Thermal Runaway

The complex and intricate design, the ever-increasing energy density and aging[3] of the battery are the causes of the danger. Defects and physical damage can also create internal short circuits leading to cell failure. Other events which could lead to cell failure arise external to the cells and so may be detected. The thermal runaway phase exhibits increasing temperature and heat release plus venting/gassing off of flammable/ toxic electrolyte. This accelerates as cell failure approaches. Without countermeasures, an explosive gas-air mixture will be generated: If then an ignition source is present an explosion may result. If the heating is not stopped, thermal runaway will occur.

> **Note:** *The potential for thermal runaway is influenced by the state of charge, operational conditions, battery electrode materials, electrolyte, and separator.*

[3] See study "Influence of Aging on the Failing behavior of Automotive Lithium-Ion Batteries" published April 7th 2021 Available under https://www.mdpi.com/2313-0105/7/2/23

5 OBJECTIVES and CHALLENGES of FIRE PROTECTION

The increasing number of Lithium-Ion batteries and an increasing amount of stored energy in different Energy Storage applications present a new type of fire hazard that is not fully understood in the market place. Fire Protection is a multi-level challenge, but for the purposes of this document it is split into three distinct aspects:

- Prevention (passive/preventative fire protection):
  - Any opportunity to prevent a threatening situation arising should be exploited
  - Correct choice of materials is essential
  - Appropriate compartmentalisation and separation of equipment is needed
  - Accurate energy management and monitoring of power during charging and discharge of the batteries is essential.
  - See chapter 6 for further details
- Fire detection:
  - Reliable detection of the first indications of a threatening event can provide time to intervene and avoid a threat escalating
  - Can provide a suitable signal for the initiation of a fire protection system if early intervention fails
  - See chapter 7 for further details
- Fire protection
  - Extinguish external flames, but flame extinguishment alone is not sufficient
  - Cooling is essential to reduce the high temperatures that occur
  - Cool throughout the thermal runaway process in the ignited module (design shall ensure that cooling is possible for a period long enough for the hazard to subside)
  - Stop thermal runaway propagating from ignited module to other modules
  - Control release of overpressure from battery module due to off-gassing, i.e., no projectiles etc.
  - See chapter 8 for further details

In all stages it is important to consider that there are different battery manufacturers, many battery types and chemistries on the market.

6 PASSIVE/PREVENTATIVE FIRE PROTECTION

Passive and/or preventative fire protection is defined as, "reducing the risk of fires" or "reducing damages in case of fires" by preventative measures. This can today be performed by:

6.1 Flame retardants added for battery thermal stability

The term flame retardants subsume a diverse group of chemicals which are added to manufactured materials, such as plastics and textiles, and surface finishes and coatings. Flame retardants are activated by the presence of an ignition source and are intended to prevent or slow the further development of ignition by a variety of different physical and chemical methods.

6.2 Fail-safe measures

Measures stopping and/or decreasing the damage caused by thermal runaway, including separator shutdown and cell venting.

6.3 Compartments (fire protected) as an additional housing for the batteries

One method of handling fires in Lithium-Ion batteries is to contain the battery and fire to prevent it spreading to other cells or materials. This can be a solution for small portable battery powered devices. At this time, e.g., most commercial airlines issue a fireproof bag to aircraft crews which have been successful in containing small battery fires on aircraft.

As the size of the battery increases, selecting the methods of containment become more complicated. For example, when looking at vehicle systems, containment will add weight to the vehicle which might not be the best solution, but protecting the battery pack from mechanical damage is being used as a compromise.

For large Energy Storage Systems, the use of fire walls between the cell packs and housing them in separate ISO containers can mitigate the spread of fire from one to another. Using fire rated containers (typically 90+ minutes fire resistance) with explosion relief can be used for large systems and even for vehicles after a crash. These containers can also be fitted with a suppression/extinguishing system.

6.4 Monitoring by Battery Management System (BMS)

A battery management system (BMS), when it is installed, can give early inputs for identification of unusual operating data of batteries. Parameters like cell temperature, voltage, currency, state of charge etc. may by monitored, controlled by BMS and, in case of abnormal data, an alarm or other control/action is activated.

Mitigating actions may include:

- partial or complete system shutdown
- increasing ventilation to reduce the possible build-up of explosive vapours
- increased cooling to extract as much heat as possible quickly

Fast shutdown and isolation of individual banks of batteries is essential to capitalize on the benefits provided by detection and extinguishing systems – which themselves are activated when events beyond the control of the BMS occur (or the BMS itself malfunctions)."

NOTE: *A project in the framework of Horizon 2020 – "**Electric Vehicle Enhanced Range, Lifetime and Safety Through INGenious battery management** (**EVERLASTING**)" - will develop innovative technologies to improve the reliability, lifetime and safety of Lithium-Ion batteries by developing more accurate, and standardized, battery monitoring and management systems. This allows predicting the battery behaviour in all circumstances and over its full lifetime and enables pro-active and effective management of the batteries, which leads to more reliability and safety which enables preventing issues rather than mitigating them. More details on this project are available on https://everlasting-project.eu/*

7 DETECTION Technologies

7.1 Introduction

In applications and equipment with Lithium-Ion batteries a (very) quick detection of cells/battery displaying abnormal signs is required to avoid thermal runaway. As such early and reliable fire detection is a must when designing fire protection systems for Lithium-Ion battery systems. However, the environment in which the batteries are normally used has a strong impact on the suitability of the various solutions, especially on mobile uses such as a bicycle or a car where most detection systems cannot be installed.

Furthermore, any embryonic fire, perhaps starting in an adjacent area must be quickly extinguished using automated, targeted extinguishing systems to prevent a large number of cells, batteries or battery modules incurring thermal runaway and catching fire (see following chapters).

Any fire in Lithium-Ion batteries, starts with the spreading of gas and particles. After this, in the next stages of fire development, smoke becomes visible with subsequent flame formation.

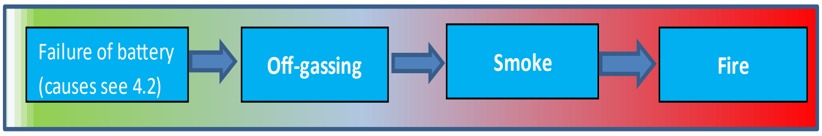

Figure 5: Stages of Lithium-ion battery fire

There are many technologies available for detecting such developing fires in the different stages, but before selecting a detection system, some basic principles are to be considered:

- **Very early fire detection based on gas or smoke is possible after the initial venting of a cell started**. After such a venting event, reliable detection may be performed with different types of technologies.
- **The detection system plays a key role**, as an early measure to stop propagation of thermal runaway and significantly limits the overall damage
- As different detection technologies and types of detectors have different characteristics, **a suitable solution must be selected case by case or according to applications/installations**.

7.2 Detection of Gases and Particles

Gas warning products/systems detect molecular concentrations of gases or vapours in the air. They may be sensitive to the typical products of thermal runaway such as hydrogen (H_2), carbon monoxide (CO) and carbon dioxide (CO_2) but systems that are sensitive to the organic solvents used as electrolytes have the potential to detect the off-gases which, as explained above can occur before thermal runaway sets in.

Where battery enclosures exist, gas detectors sensitive to H_2, CO or CO_2 may provide warnings and be linked to battery management and fire protection systems. Gas sensors are capable of detecting levels as low as 1 ppm, providing early warning.

Systems that can detect off-gases or particles given off during off-gassing in low concentrations can provide an early warning of an impending thermal runaway – and trigger shut down systems to electrically isolate the individual, or bank of, or rack of battery cells – and thus avoid thermal runaway occurring. Such systems generally rely on a degree of enclosure around the batteries, such as an ESS container or a room housing large banks of batteries. Typically, highly sensitive aspirating smoke detectors are used as particle detectors responding to the vapour clouds of the off-gases as they are vented rather that to individual gas/HC molecules.

For effective off-gas detection, the ventilation arrangements must be taken into account. However, it is often the case that air movement is used to keep batteries cool during normal charging operations. Hence, off-gassing event sensors need to be strategically positioned and sensitive enough to detect the first signs of the off-gas events before they become too diluted – or in the case of vapours have dispersed back to the gaseous state.

Moreover, strategically positioned off-gas event detection can provide situational awareness of the conditions within a facility; for example, providing information on where the incidence started to assist personnel responding to an event as well as more general information on any hazardous or toxic risks which may indicate that entering the facility is not appropriate.

There are currently no specific EN product standards for off-gas detectors.

7.3 Heat Detection

7.3.1 Point-type detectors

Heat detectors are equipped with a temperature sensitive element and are working as:

a) Fixed Temperature Detector

In these detectors, a maximum temperature is defined. Upon exceeding this temperature, the detector switches to alarm status. These detectors only react when a certain temperature is reached, independent of the smoke density and other characteristic values.

a) Rate-of-Rise Temperature Detector

With rate-of-rise temperature detectors, the temperature increases per unit of time required to trigger an alarm is defined (K/min). If the measured temperature increase per unit of time exceeds this threshold, an alarm is triggered. Rate-of-rise temperature detectors are usually based on the functional principle of a thermistor.

7.3.2 Linear heat detectors.

Linear heat detection systems consist of a line-type sensor and an evaluation unit. The sensor is either a cable with electrical or optical conductors, a cable with a number of sensors or a pipe. These evaluation units may be connected to higher-level systems, enabling the visualization of measured values and control/release of several other actions (e.g., fire protection).

7.3.3 IR-Cameras

A thermographic camera, also called an infrared camera (IR) or thermal imaging camera, is a device that creates an image using infrared radiation, similar to a common camera that forms an image using visible light. The practice of capturing and analysing the data they provide is called thermography.

The theory of operation is based on the fact, that all objects emit a certain amount of radiation as a function of their temperature. Generally speaking, the higher an object's temperature, the more infrared radiation is emitted. An IR-camera can detect this radiation in a similar way to how an ordinary camera detects visible light. It even works in total darkness because ambient light level does not matter. This makes it useful for any operation in applications without light and for use 24/7.

NOTE: *In most cases heat detection cannot be considered as an early detection especially for the application of this document. However, it is mentioned anyway for giving an overview and in case no other detection principle is applicable in a specific application.*

7.4 Detection of Smoke

Airborne particles show different types and ranges of particle sizes. The blue area shows a typical particle size distribution of smoke from a fire with a maximum particle count around 0.2 µm particle size. The red area shows a particle size distribution from dust particles with a maximum at 90 µm.

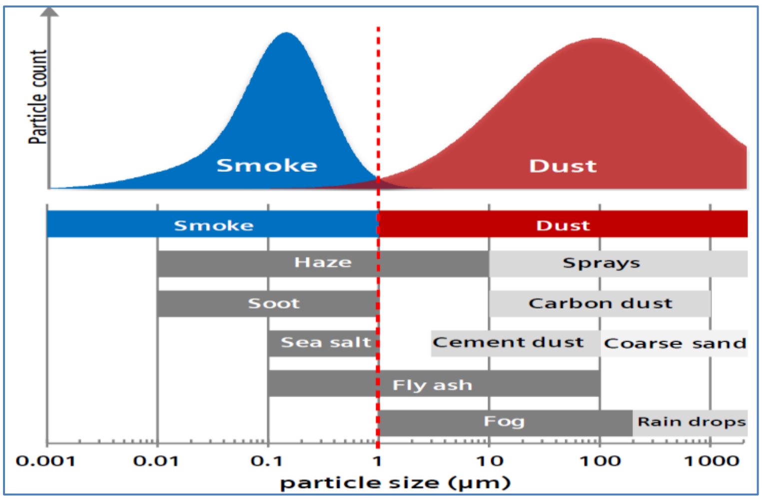

Figure 6: Particle size of smoke and dust

While figure 2 indicates that most smoke particles are under 1 µm particle size (blue area). and that deceptive phenomena like dust particles are generally larger than 1µm (red area) the distinction is not quite so distinct – particularly when smoke/vapour particles conglomerate or when dust is particularly fine. However, the principle can assist very sensitive smoke detectors to achieve some level of discrimination between smoke particles and potential nuisance alarms.

7.4.1 Point-type smoke and multi-sensor detectors

These are the most common detectors used in fire safety systems. They are used in areas where incipient, smoke-generating fires are to be expected and where little or no deceptive phenomena occur. Most frequently used are scattered light smoke detectors. They operate optically, by detecting the light scattered by smoke, though historically they used an ionization chamber. They are particularly suited to detect small smoke particles.

Increasingly, multisensory point-type detectors combining optical smoke detection and heat detection (and in some variants also CO) are increasingly common. Due to the intelligent interlinking of the sensor signals, such detectors are able to offer more reliable detection.

7.4.2 Linear (beam) smoke detectors

Linear (beam) smoke detectors work by measuring the light attenuation caused by smoke. Systems accommodating the emitter and receiver in the same housing use a remote reflector and have the advantage that they need to be wired in the detector line at one point only, and that maintenance is easier. In systems without a reflector, the emitter and receiver are separate. Both systems, however, work according to the same measuring principle.

Linear (beam) smoke detectors are used in areas in which smoke-generation is to be expected and where point-type smoke detectors cannot be used. Typical application areas for linear (beam) smoke detectors are:

- very high rooms (atriums, hangars)
- large halls in which the maintenance of point-type detectors would be more difficult or more expensive than that of linear smoke detectors
- historical buildings in which point detectors are unwanted for aesthetical reasons

NOTE: *In most cases linear (beam) smoke detection cannot be considered as an early detection technology, especially for the application of this document. However, it is mentioned anyway for giving an overview and in case no other detection principle is applicable in a specific application.*

7.4.3 Aspirating smoke detectors

Aspirating smoke detectors (also known as air sampling smoke detectors or ASD) operated by drawing air samples from the monitored area to the detection chamber via a pipe network by means of a suitable suction system/fan.

ASD typically incorporate filters to remove dust particles which may lead to unwanted alarm and may also incorporate technology to enable them to detect and to distinguish between smoke-like particles (~0.2 µm) and dust (>1 µm particle size). They are typically used wherever smoke must be detected as early as possible and point-type detectors are too insensitive or not sufficiently robust against soiling. High sensitivity aspirating smoke detectors are able to detect off-gassing events by detecting the mixture of gas and particles in the off gas from Lithium-Ion batteries by particle detection as early warning gas sensors.

7.5 Flame Detection

Flame detectors convert the electromagnetic radiation emitted by flames into an electric signal. To rule out faults and deception by sunlight, reflected light, lamps and other light sources as far as possible, the detection range of the detectors is shifted from the visible to the invisible range. Most flame detectors therefore operate in the ultraviolet or infrared range and also monitor for the characteristic flicker that flames produce.

Flame detectors are used in areas where open fires may occur very rapidly and where large open areas must be monitored.

7.6 Video Fire and Smoke Detection (VFD)

Video Fire and Smoke Detection is based on videos from cameras, combined with intelligent video analysis. It is used in many safety-/security-applications, particularly in challenging environments and large open areas.

VFDs have potential to minimize the detection time compared to the other techniques described above, in both indoors and outdoors applications, because cameras can monitor "volumes" and do not have to wait for the smoke to reach them. However, they are still an emerging technology and rely on complex algorithms to differentiate smoke/flame like situations from a real smoke or fire event.

8 FIRE PROTECTION SYSTEMS (SUPPRESSION and EXTINGUISHING)

Automatic extinguishing systems either extinguish or prevent incipient fires in order to protect objects, rooms or entire buildings from fires and their consequences.

The extinguishing agents used for this purpose are liquid (water), two-phase (foam), solid (powder), gaseous (gases) or aerosols. Depending on the extinguishing agent, heat and/or oxygen is displaced from the fire, which means separated from the fuel. The extinguishing or suppressive effect begins during the flooding time and ends after expiry of the holding time. Intervention and activation of the fire protection system must be harmonized accordingly.

Key issue in any fire protection system: Each system layout and especially the correct discharge of the extinguishing/suppressing agent under sufficient pressure is decisive for the correct functioning of the extinguishing/suppression system. Of course, not only layout and design of a system, but also correct installation, the use of approved systems[4] and constant maintenance by appropriately trained and certified staff[5] are key issues.

8.1 Automatic water systems

Water is the most frequently used and most widely distributed extinguishing agent. It is used in different sprinkler systems as well as in water spray and water fog systems. While the activation of sprinkler systems is mostly temperature sensitive, other systems generally require the activation by automatic fire detectors.

The main purpose of water-based systems is the protection of the building and spaces. For the protection of electrical equipment, the risks of equipment damage associated with water-based systems shall be considered.

The cooling effect from automatic water systems depends on battery configuration and it may be difficult to reach the area on fire ("*Spray-shadow*").

<u>Effectiveness:</u> Strong cooling effect, prevents fire spread to other objects

NOTE: *Water based agents are electrically conductive unless de-ionised water is used. De-ionised water will become electrically conductive when in the presence of compounds, such as salt, which may be present in the risk area.*

8.1.1 Sprinkler Systems

The most commonly used automatic system using water is the sprinkler system. These systems are employed in almost all fields of industry, larger business enterprises, department stores, garages, meeting places, schools, hospitals, hotels, airports, etc. They are consisting of special nozzles, held closed by heat sensitive frangible elements, mounted in steel pipework, at the ceiling/roof level, and connected to a dedicated water supply via control valves. The heat from a fire causes one or more sprinklers to open to discharge water onto the seat of the fire and adjacent combustibles. The amounts of water and the number of sprinklers expected to open will increase as the fire load density and fire growth rate increases.

Sprinklers are automatically activated individually when the temperature at the sprinkler head exceeds a critical value. As the activation automatically triggers the water supply, sprinkler systems also serve as fire detection systems and initiate an alarm.

<u>Effectiveness:</u> Strong cooling effect, prevents fire spread to other objects

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[4] See **Euralarm-Guidance on approved system versus approved components** – publicly available: see: https://euralarm.org/euralarm-publications/public-guidelines/guidance-on-gaseous-systems-approved-systems-versus-approved-components

[5] See Euralarm guidance paper on "**Maintenance of extinguishing systems/equipment**" – published Q4/2021

8.1.2 Water spray and Deluge systems

Deluge (also called "Water spray") systems are, in terms of setup, similar to sprinkler systems. The two most significant differences are, that the system is provided with open sprinkler heads or nozzles; the water spray heads have no heat-sensitive elements and to activate the water spray range valves, a separate fire detection system is required.

Water spray systems apply water through many spray heads. The deluge system has been developed for areas with a particularly high combustible load, such as fuel storage facilities where rapid ~~a~~ fire growth has to be expected. In such cases faster fire detection than provided by frangible bulbs is needed so that water can be applied earlier to attack the fire before it grows to overwhelm the system.
Due to the very large water volumes discharged, water spray systems require a high capacity of water supply.

Electronic detection enables a quicker water release compared to automatic sprinklers.

<u>Effectiveness:</u> Strong cooling effect, prevents fire spread to other objects

8.1.3 Water Mist/Water Fog Systems

Water mist systems use small water droplets to provide flame cooling and steam smothering of fires by rapid evaporation of water. In addition, water mist blocks radiant heat to protect the surroundings.

In contrast to the conventional sprinkler technology, these systems try to achieve a droplet spectrum with the smallest possible diameters by applying low- or high-pressure technologies (and specially designed nozzles). Small droplets have a larger surface area to water volume ratio, which leads to faster evaporation and more efficient cooling. In comparison to sprinkler systems, water mist technology aims to applying considerably lower water volumes, as tests and approvals have shown. Their design basis is always determined by full scale fire testing. Therefore, water mist should only be used for the protection of Lithium-Ion batteries where there is an established test protocol.

Electronic detection when employed enables a quicker water release compared to automatic sprinklers.

<u>Effectiveness:</u> Strong cooling effect, prevents fire spread to other objects

8.2 Gaseous Fire Extinguishing Systems

Gaseous extinguishing systems use either inert gases, CO_2 or synthetic extinguishing agents. Inert gases and CO_2 extinguish through oxygen displacement, synthetic extinguishing agents extinguish by heat absorption. They are designed to extinguish a fire in sensitive environments where water or other suppressing agents are not desired due to the risk of consequential damage.

Gaseous extinguishing agents are electrically non-conductive, volatile and gaseous when used as a fire extinguishant, that does not leave a residue upon evaporation. Gaseous extinguishing systems are often used where water as an extinguishing medium is not desirable or where the particular properties of a gas are more appropriate. Total flooding fire extinguishing systems using clean agents are used primarily to protect hazards that are in enclosures (to preserve agent concentration). As gas is 3-dimensional, gaseous extinguishing agents are highly effective in penetrating any void within the hazard.

Gaseous fire extinguishing systems are a very effective way to protect critical hazards and high value assets, when it is important to have no collateral damage caused by the extinguishant or residues. For any kind of electric risk (Data Centre, IT rooms, Control rooms, Switchgear rooms, etc.) or very sensitive/valuable assets or materials (Art, Antiques, Rare books, etc.), they are often the first choice. An additional factor is personal safety as many of these applications are occupied, either permanently or occasionally. They are suitable for total flooding and consist essentially of a source where the gas is stored under pressure in containers, and a piping system by which it is conveyed from the source to the points of discharge. Currently, blanketing inert gases, CO_2 and synthetic (halocarbon) extinguishing agents are available for gaseous extinguishing systems.

As the extinction is rapid, the equipment can be saved from unnecessary damage caused by the fire and smoke (contains breakdown products from the fuel and potentially from the extinguishing agent), there is very little cleaning up required after extinction. Since they are not electrically conductive, they are safe to use in this way.

For all gaseous agents, enclosure leakages may be compensated by using an extended discharge. However, a defined enclosure volume is required for any total flooding systems and a well sealed enclosure is generally preferred to any form of compensation for leakage.

NOTE: *For all gaseous agents, enclosure leakages may be compensated by using an extended discharge. However, a defined enclosure volume is required for any total flooding systems and a well-sealed enclosure is generally preferred to any form of compensation for leakage*

Some more details on features of different gaseous agents are described in following sub-chapters.

8.2.1 Inert Gas systems

Inert gas fire extinguishing systems utilize natural inert gases like Nitrogen, Argon, and/or mixture of the inert gases, including one blend containing CO_2. They extinguish fire by reducing the oxygen concentrations in the enclosure, and they are suitable to be used for Class A, B and C Fire Hazards.

Inert gases leave no residue and by-products when exposed to fire. Inert gases have zero GWP (Global Warming Potential), zero ODP (Ozone Depletion Potential) and are safe to be used in occupied areas.

Inert gas agents, have a density similar to air and are less sensitive to leakage from the protected enclosure. However, as they are stored as pressurized gases, the number of containers used in a system may be greater than with halocarbon agent systems. The high-pressure storage is very useful in allowing the designer to locate the containers a considerable distance from the protected enclosure.

Effectiveness:
- Potential to slow down thermal runaway by extinguishing the electrolyte
- Preventing explosive atmospheres in the enclosure
- Rapid distribution of the agent within the risk
- Ability to extinguish fires in nearby electrical equipment
- Ability to extinguish fire involving electrolytes
- Allows for longer hold times, when the enclosure is well sealed
- Allows for longer hold times in enclosures not hermetically sealed, by extended discharge

8.2.2 Halocarbon systems

Halocarbon extinguishing systems use a range of synthetic extinguishing agents. They extinguish fire predominately by means of heat absorption. They are suitable for Class A, B and C fire hazards.

The current generation of halocarbon gases are safe to be used in occupied areas and have zero ODP (Ozone Depletion Potential). Commonly used halocarbon agents have a GWP (Global Warming Potential) between 1 and 3500.

Halocarbon agents are stored as liquids, use relatively low extinguishing concentrations and as such need significantly less agent storage capacity. Generally, the containers need to be located closer to the protected area than with inert gas systems, but higher-pressure systems may address some of these limitations.

Effectiveness:
- Potential to slow down thermal runaway by extinguishing the electrolyte
- Ability to extinguish fires quickly
- Preventing explosive atmospheres in the enclosure
- Rapid distribution of the agent within the risk (10s)
- Ability to extinguish fires in nearby electrical equipment
- Ability to extinguish fire involving electrolytes
- Allows multiple discharges

8.2.3 Carbon dioxide systems

Carbon dioxide extinguishing systems utilize Carbon Dioxide (CO_2), which is a colourless, odourless, electrically non-conductive gas. It is highly efficient as a fire extinguishing agent primarily by displacing oxygen with some contribution by cooling.

Carbon dioxide gas has a high rate of expansion, which allows CO_2 fire-fighting systems to work fast. Since carbon dioxide is a gas, there is no clean-up needed following a CO_2 fire extinguishing system discharge.

CO_2 is stored as a liquid, like halocarbon, but uses significantly higher design concentrations and therefore does not achieve the same storage efficiencies.

While CO_2 fire extinguishing systems are highly effective at suppressing fires, the CO_2 agent also poses a **lethal risk** for people being in the area of exposure, at concentrations much lower than needed for fire extinguishing. For this reason, CO_2 fire extinguishing systems should only be used in non-occupied spaces.

Effectiveness:
- Potential to slow down thermal runaway by extinguishing the electrolyte
- Preventing explosive atmospheres in the enclosure
- Ability to extinguish fires in nearby electrical equipment
- Ability to extinguish fire involving electrolytes
- Allows for longer hold times in enclosures not hermetically sealed, by extended discharge

8.3 Foam & Water-based media systems

Foam & water-based media use additives proportioned into a water stream. Foams are generally formulated for use for blanketing and smothering flammable liquid fires.

They include Standard Class B foams, Class A foams and Wetting agents and dispersions.

NOTE: *Use of fluorinated fire-fighting foams will be restricted in the future, so it is advised to take that into consideration in the agent choice.*

8.3.1 Standard Class B foams

Class B foams are based on fluorinated or fluorine free chemistries and are divided into three classes distinguished on the basis of the air volume:

- **Low-expansion foam systems (Foam expansion ratio < 20)**
  Low expansion is commonly used on large hydrocarbon fires such as in tank storage, refineries, airports and ships.
- **Medium-expansion foam systems** (**Foam expansion ratio ≥ 20 to < 200)**
  Medium-expansion foam systems are intended to provide protection, either indoors or outdoors, against spills of flammable liquids where the foam can be applied gently close to the hazard, to build up rapidly and to give good vapour suppression.
- **High-expansion foam systems (Expansion ratio of foam ≥ 200)**
  High-expansion foam systems dispense foam from a number of high expansion foam generators to fill the volume within which fires (either class A or class B) might exist at various levels. They are suitable for large volumes, cable tunnels, refrigerated rooms, basement areas, etc. While predominantly suitable for indoor use, high-expansion foam can be used in outdoor areas, sheltered from the effects of the wind.

8.3.2 Class A foams

Class A foams are specifically formulated to fight fires containing Class A materials. Typical applications include wildland fires, waste fires.

8.3.3 Wetting agents / Aqueous dispersions

Wetting agents materially reduce the surface tension of plain water and increases its penetration and spreading ability. Similar to class A foams, typical applications include wildland fires and waste fires. The majority of wetting agents utilize natural plant-based material and nothing other than the environmental consideration of fluorinated foams has to be taken into account in using such system.

Aqueous dispersions can include an aqueous dispersion of chemically exfoliated vermiculite which is applied in the form of a mist. Vermiculite is the name given to a group of hydrated laminar aluminium-iron-magnesium silicates.

The chemical exfoliation of vermiculite produces microscopic, individual platelets that are freely suspended in water, which yields a stable aqueous dispersion of vermiculite. Vermiculite particles are deposited on the surface of the burning cell, creating a film over the surface. The film dries instantly and the vermiculite platelets overlap each other and bind together. This forms a non-flammable physical oxygen barrier between the fire source and the atmosphere. This process may have a cooling effect on the fire.

Wetting agents/aqueous agents can be used in fixed installations, portable extinguishers, mobile fire extinguishers and in backpack extinguishers.

<u>Effectiveness:</u> Dependent on the application method and fire types

8.4 Powder systems

Powder systems are highly effective at providing fire suppression capabilities. When discharged, powders act as a two-phase fluid, a solid suspended in a gas, which allows them to be highly effective where obstructions are present and do not suffer significant performance impacts from spray-shadow as with some other agent types. Powder agents can be used in unconfined spaces as well as confined enclosures.

The main mechanism by which most powders suppress fires is by inhibiting the chemical chain reaction. Powder agents are generally non-toxic.

There are different types of powder agents, each of which provide different levels of suppression capabilities.

Effectiveness:
- Rapid distribution of agent within the risk area
- Protected volumes do not have to be sealed to contain the agent
- Ability to slow down the propagation of thermal runaway to neighboring cells
- Ability to extinguish fires in nearby electrical equipment
- Ability to extinguish fires quickly

8.5 Condensed aerosol systems

Condensed aerosol systems use similar control and monitoring equipment to gaseous fire extinguishing systems. They also flood the room with a fire extinguishing agent, however, unlike gaseous fire extinguishing systems, condensed aerosol systems consist of a solid block compound stored in a non-pressurised container (or generator), which is mounted directly in the protected area.

The aerosol consists of micro or nano sized solid particles suspended in another substance such as gas without being dissolved into the gas. Fire is extinguished by inhibiting the chemical chain-reaction that is a fire.

While condensed aerosol systems are highly effective at suppressing fires, the agent may pose a health risk for people being in the area of exposure. Therefore, in occupiable areas, the system design should employ the safety precautions mentioned in the standards. Determination for use of an agent in spaces that are normally occupied, normally unoccupied, or unoccupiable shall be based on an evaluation of the adverse effects(s).

Since aerosol extinguishing systems can differ significantly in their composition, their suitability for extinguishing lithium-ion battery fires should be tested and proven on a case-by-case basis.

Effectiveness:
- No cooling effect
- Potential to slow down thermal runaway by extinguishing a fire involving the electrolyte
- Ability to extinguish fires quickly
- Rapid distribution of the agent within the risk
- Ability to extinguish fire involving electrolytes
- Ability to extinguish fires in nearby electrical equipment
- Allows for longer hold times in enclosures not hermetically sealed
- Preventing explosive atmospheres in the enclosure

8.6 Oxygen Reduction Systems

Oxygen reduction systems are typically designed to deliver either pure nitrogen, or air with a pre-mixed composition with increased nitrogen, into a protected enclosure in order to maintain an oxygen concentration of between 13% and 16%. When the oxygen concentration is reduced to around 13%, conditions are similar to the atmosphere created after the discharge of nitrogen gas by a system intended to extinguish surface fires.

An environment continuously maintained at the appropriate level of oxygen prevents the development of flaming combustion in materials that give rise to class A fires. Lower concentrations could be needed for some materials, particularly if there is a risk of deep-seated combustion (considerably lower concentrations are normally required to extinguish such fires) and for fuels that give rise to class B fires.

Although flaming combustion is likely to be suppressed under these circumstances, the presence of a heat source still gives rise to pyrolysis. The potential for smouldering and/or the generation of products of incomplete combustion under low oxygen conditions should be taken into account.

The design of oxygen reduction systems should be determined through fire testing but, to date specific test data has not been published in relation to Lithium-Ion battery fires. Oxygen Reduction Systems can prevent Flame Stacks but this can lead to excess toxic & flammable fumes leaving the enclosure which then need to be dealt with. Therefore, oxygen reduction systems should only be used for the protection of Lithium-Ion batteries where specific testing has first taken place.

<u>Effectiveness:</u> Decreases the risk of fire due to a flammable atmosphere after off-gases have been released

8.7 Portable Fire Extinguishers

Portable fire extinguishers should only be used on individual small rechargeable, portable devices and other commonly used electronic goods (such as laptops, mobile phones, e-cigarettes, power tools etc.) containing Lithium-Ion batteries which have been disconnected from mains power. Complete extinguishment may not be possible but use of a nearby water or water-based extinguisher should prevent the fire from spreading to other nearby materials, whilst the alarm is raised.

There are several kinds of agents used inside portable fire extinguishers (water-based, CO_2, powder, etc.), but water-based agents are the only ones being applicable to Lithium-Ion-battery fires.

Do not use portable fire extinguishers for high voltage or for batteries with higher capacities (like in EV, PHEV or ESS).

9 DESIGN OF FIRE DETECTION AND EXTINGUISHING SOLUTIONS IN DIFFERENT APPLICATIONS

9.1 Design Principles

Each application requires a specific solution, based on the use of approved systems[6], as there is no protection concept that is equally suitable for all applications.

Before selecting the optimal concept, the objectives of the measures, the protection concept and the possible side effects of the technologies used must be considered. In addition to the technical options available on the market (see Chapters 6 and 7) the whole environmental situation of the application has to be taken into account.

The concept should provide a holistic approach which should include consideration of:

- Risk assessment
- Protection goals and targets
- Passive/Preventative Fire Protection
- Prevent fire spread to adjacent batteries and areas
- Battery Management System (Detection of battery failure)
- Type of Fire/Smoke detection system
- Off-gas detection system
- Automatic inerting system
- Automatic extinguishing system
- Side effects
- Ventilation / Extraction
- Over-pressure release system
- Applicable standards
- National or regional fire department regulations

[6] See **Euralarm-Guidance on approved system versus approved components** – publicly available: see: https://euralarm.org/euralarm-publications/public-guidelines/guidance-on-gaseous-systems-approved-systems-versus-approved-components

9.2 Applications (Environmental situations of Lithium-Ion batteries)

In chapter 3.1 of this document there are 5 classes of Lithium-Ion battery applications mentioned:

I. Portable devices and other commonly used electronic goods
II. Small Electric Mobility
III. Emergency Power System or UPS
IV. Electric Mobility and Electric Automotive
V. Energy Storage Systems

This classification only relates to the respective battery capacities and thus to the various fire loads. For information on the applicability of certain fire protection technologies, however, it must be considered in which environments these products / systems equipped with Lithium-Ion batteries are located. This means that the respective product / system must be considered in its respective environment in order to be able to define the optimal solution for fire protection.

In the following, a number of currently known environmental situations are described with details of the detection and extinguishing concept:

9.2.1 Batteries in public transport

This means use cases where portable devices and other commonly used electronic goods, as well as small electric mobility vehicles (scooters etc.), equipped with Lithium-Ion batteries, are transported in public transport (Bus, Train, Aircraft, Ship, etc.) it also considers hybrid and fully electric powered public transport vehicles.

There are an increasing number of hybrid and fully electric buses used in public transport to meet environmental targets. UNECE R107 whilst providing a requirement for vehicle suppression systems doesn't specifically address battery fires. Furthermore, battery cells are usually enclosed within sealed battery packs which may make it impossible to apply the suppression agent directly to the cells.

Similarly, to meet IMO emission targets hybrid and fully electric powered ships and boats are becoming more common. There is a 62-meter, 453 tonne tanker being built in Japan which will be fully powered by 2 1740 kWh Lithium-ion battery ESS. A number of passenger ferries in Scandinavia are also fully battery powered, these range from 20m with 70 passengers and 180-400 kWh capacity to 140+m with 1000 kWh capacity. With this move to electric power, in 2017, RISE the Swedish test institute published a report on battery propulsion at sea[7] , which considers the fire protection challenges. In addition to propulsion, ships may also have their own ESS to provide electrical power which adds an additional risk. In aviation Airbus, Boeing and others are working on fully electric aircraft projects.

All of the above applications will also have crew and passengers bringing on board their own small battery powered devices.

The challenges for fire protection in these applications are varied and include protecting the power supply and also the devices brought on to the vehicles. Measures to be considered by providers/owners of public transport, by taking into account all of the points mentioned in chapter 9.1.
Provision of suitable compartmentation around the battery packs to limit the spread of any fire, this is probably much simpler in marine applications. Suitable Battery Management Systems linked to fire and gas detection systems to enable fast detection to allow for activation of fire protection systems and evacuation of passengers where applicable.

Total flooding applications such as gaseous extinguishing and water-based systems are logical solution in marine applications with the in-place compartmentation. Small fixed systems, to UNECE R107 are already in place on most buses and related vehicles although the design densities may need to be reviewed. Aircraft systems will need to take into account the weight considerations.

For the small devices, carried on board by passengers, provision of portable fire extinguishers and also containment should be considered. Also, some airlines limit what devices can be carried in the hold and in the cabin and all aircraft now carry one or more bags in which to place any small device that starts to show signs of thermal runaway.

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7 *Safe introduction of battery propulsion at sea - Petra Andersson, Johan Wikman, Magnus Arvidson, Fredrik Larsson, Ola Willstrand SP Rapport 2017:34*

9.2.2 Residential Applications (ESS in connection with Photovoltaic + Garages with EV's)

Residential Energy Storage Systems, also referred to as Powerpacks, mainly serve the purpose of power backup when the grid goes down. They also supplement renewable energy systems, such as solar, allowing for energy use when the natural source is not available. At the same time, they offer peak shaving and power load levelling with benefits extended to both the end-users as well as the Utility companies. The growth in renewable energy generation along with the increasing number of electric vehicles are factors contributing to the double-digit growth rates of the residential energy storage market.

Risk:
The small scale of these systems may suggest that the risk for thermal runaway and eventually a fire is minor. However, there are publicly available records on tens of thousands of Residential Energy Storage Systems that have been recalled due to potential fire risks. The records refer to systems overheating, releasing fumes and starting fires. Moreover, due to their large numbers and their installation in garages and places where fire safety is sometimes not a priority, the risk of a fire propagating to the room and the rest of the building is considerable.

The risk is associated with the generation and emission of gases from the battery-electrolyte. It is a twofold risk. On one hand the gases are highly flammable and on the other, depending on the chemistry of the batteries, the emitted gases can be toxic, containing, for example, hydrogen fluoride which can be threatening to life and health even in small concentrations.

Fire Protection:
The size of this application (small-sized cabinets), the fact that there are no safety regulations governing it and finally its users being households and individuals without fire-safety background, elevate the challenge of managing the associated risks.

Preventative good practices, such as the following, do help:

- avoid having combustible materials in close proximity to the Energy Storage System
- positioning the Energy Storage System outdoors or close to openings, to allow for dispersion of the flammable / toxic gases

The above can be communicated by the Authorities, the Utilities, the Insurance companies and also the Manufacturers and Vendors of the systems.

The relevant fire protection solutions for this application are the ones that are stand-alone, installed inside the Energy Storage System, are complete with detection and extinguishing, are resilient and have minimum maintenance requirements.

On the contrary, complex and maintenance-intensive, engineered solutions, either for off-gas detection, fire detection or fire extinguishing are not so practical to be implemented.

9.2.3 Electric mobility

9.2.3.1 Risk assessment

Electric vehicles have become an integral part of our streetscape and they also need to be parked and charged. The fire safety of indoor and underground car parks with capacity for electrically powered vehicles, as well as safety of charging stations, is therefore a topical issue.

Example: Severe electric car fire and explosion at a charging station – watch it in Youtube: https://insideevs.com/news/423581/severe-electric-car-fire-explosion-charging/

In assessing risks in applications/infrastructure with electric vehicles it has to be considered;

- Electric cars are at the greatest risk of fire when parking and charging[8] (see results of ALBERO-project: > 50% **of** all fire accidents with electric cars happened during charging or while parking)
- The risk of fire coming on an electric vehicle is no greater than the risk of fire on a gasoline or diesel vehicle. In fact, it appears to be less. However, battery fires are harder to extinguish. It's a matter of fact, that a fire in e-vehicles can spread much faster and is much more difficult to control.
- In the event of a burning electric car, it is not possible to extinguish the fire promptly. A reinforced concrete floor can withstand heat for a certain time, but if too much heat is applied, the concrete may burst and the iron melt, leading to the potential for collapse.
- Because of the reactive and sometimes highly toxic materials, battery fires in closed rooms or underground infrastructures present chemical dangers also. The released pollutants can concentrate in the air due to limited ventilation options and exceed critical threshold values for people more quickly than in the open air, where the smoke gases are more diluted. The escape or rescue options in such rooms make the situation even more difficult.

The goals of fire protection out of this risk assessment are finally leading to priorities on protecting the building and protecting people. Protecting a burning electric vehicle is on lower priority as long as there are no measures already integrated in such car.

Finally, fire protection has to concentrate on preventing fire spread to adjacent batteries and areas, and has to look for passive/preventative fire protection measures.

9.2.3.2 Passive/Preventative Fire Protection - Prevent fire spread to adjacent batteries and areas

a) **Architectural** measures:
   - add extra protection to the building structure near parking spaces with chargers.
   - charging stations fitted with collision protection, or place where collisions are not possible.
   - pay attention to how an electric vehicle can be moved to an outside area after a fire has been extinguished, e.g., for cooling it in a water tank.

b) **Installation** measures
   - enabling means to interrupt the current to all the chargers by means of a single action by those present.
   - consideration during the design process to the location of parking spaces for electric vehicles and charging stations/facilities relative to ventilation openings and escape routes.
   - the use of displacement ventilation/smoke and heat removal can help to increase the probability of a successful action.
   - exhaust ducts positioned to minimise the probability of any nuisance to the environment being caused by combustion products escaping from the indoor car park.

c) **Organisational** measures
   - e-cars should ideally be parked in fireproof individual parking spaces. In the event of a fire, these separate areas could then be flooded quickly and in a targeted manner with total flooding systems.
   - structural separation would also help to minimize the smoke in the underground car park in the event of a fire, because this is a significant hazard to people, along with the fire itself.

[8] **ALBERO** (Transport of alternatively powered vehicles on ro-ro ferries) – Project coordinated by Institute for Safety Technology/Ship Safety - 18119 Rostock-Warnemünde, Germany – sponsored by Germany Federal Ministry of Education and Research – Details see: *https://alberoprojekt.de)*

- instructions for the use of the indoor car park and its charging facilities (including maintenance) and informing drivers about what to do in the event of a fire and how to deal with error messages from the battery management system (BMS).
- option of not charging and/or parking any electric vehicles in the indoor car park. Whether it makes sense to offer charging options in underground garages should be discussed.

9.2.3.3 Fire/Smoke detection system

It goes without saying that an emerging fire in an e-vehicle would be most likely to be recognized by appropriate monitoring / detection and reporting systems in the car. However, since this has not yet been prescribed by law up to now, it cannot be assumed to be fundamentally available.

The detection methods to be recommended here therefore include all smoke and fire detection methods mentioned in the respective buildings by national legal regulations.

Usually there are no detection systems available for e-vehicles parked outdoors, unless some are built into charging stations, wall boxes, etc.

9.2.3.4 Extinguishing systems/agents

In underground car parks, the aim would be to extinguish the fire and limit the spread of the fire to other vehicles and the building structure. There is currently no evidence that fixed systems can have an impact on the cooling the battery pack in the vehicle.

The agent should be selected taking into account impact of compartmentation, smoke control, agent run off and possible contamination of water local water supplies and impact on persons who may or may not be present.

9.2.4 Warehousing (Storage of batteries or goods equipped with batteries)

The storage of batteries in warehouses can occur in the 3 different following contexts:

1. Stored goods integrating batteries
2. Batteries storage
3. Presence of equipment using batteries such as forklift trucks

9.2.4.1 Security measures

Specific attention needs to be given to employee's security as the fire will produce a high smoke density and spread due to batteries off-gas fire. A quick evacuation is required.

Awareness should be raised among people intervening on the fire about projections risk.

9.2.4.2 Stored goods integrating batteries

These goods can be of very different types and sizes: computers, mobile phones, portable tools, electric bikes, ...

Generally speaking, the state battery charge level of the stored good is typically low (<50%), but more than 10% in any case. Consequently, there is a risk of battery fire. In addition, the device is switched off in its box so that the BMS system is also off.

Goods are generally stored inside a packaging made of cardboard and plastics. Starting from a battery thermal runaway, the fire development is comparable to usual warehouses fires as it will propagate through the packaging.

Measures to prevent from a fire spread can be of several types:

- Passive solution: to store goods with regular separations between racks
- Preventative solutions: to lower the battery charge level to its minimum acceptable value
- Fire detection system: smoke detection systems are the most suitable in this environment
- Automatic fire fighting solutions: a design derived from standard rules of fire protection in warehouses, especially using sprinkler systems, should be preferred. However, the protection goal should be the non-propagation as the presence of batteries make the complete extinguishing of the fire difficult to ensure.
- Ventilation / Extraction systems should be designed and installed using national regulations.

9.2.4.3 Batteries storage

Batteries can be of very different types and sizes depending on their applications.

Generally speaking, the battery charge level is typically low (<50%), but more than 10% in any case. Consequently, there is a risk of battery fire. In addition, there is no BMS system in the battery itself. The level of risk depends on the batteries size and power.

In addition, the risk of battery fire propagation is directly linked to the storage density. As there is no packaging or only a light packaging, thermal radiations may generate a quick domino effect.

Measures to prevent from a fire spread can be of several types:

- Passive solution: decrease the storage density and store batteries with regular separations between racks
- Preventative solutions: lower the battery charge level to its minimum acceptable value
- Fire detection system: smoke and off-gas detection systems are the most suitable in this environment
- Automatic fire fighting solutions: the protection goal should be the non-propagation, using sprinkler or water-mist systems.
- Ventilation / Extraction systems should be designed and installed to national regulations.

9.2.4.4 Presence of equipment using batteries such as forklift trucks

A forklift truck fire may occur in the following situations:

- The truck is used by an employee when the fire starts: drivers should be trained to park the truck in an identified area where the propagation risk is limited. Then a manual intervention can be carried out.
- The truck battery is being charged in a charging station. This situation occurs especially out of working hours so that nobody is present. In addition, in large warehouses, several trucks are loaded at the same time in the same area.

In both cases, the BMS system is operating and decreases the risk. However, this second situation generates a much higher risk and requires automatic prevention and protection systems.

Measures to prevent from a fire spread can be of several types:

- Passive solution: to install physical separations between truck electric charging stations or to have enough space between charging stations
- Preventative solutions: not to leave trucks in charging state during a long time, especially during weekends
- Fire detection system: off-gas detection system will be the earliest detection technology in this environment
- Automatic fire fighting solutions: the protection goal should be the non-propagation from a truck to another or from a truck to its environment. Watermist and water-based systems covering the electric charging stations areas are suitable in this case.
- Ventilation / Extraction systems should be designed and installed to national regulations.

9.2.5 Energy Storage Systems (ESS)

9.2.5.1 Protection targets

The starting point for the design of all fire protection system is always the protection goal to be achieved. It follows directly: different protection targets lead to different protection concepts and ultimately to different solutions.

Within the framework of the individual risk analysis, suitable measures must be defined in order to find a suitable protection concept. The measures to achieve the protection targets for the protection of people and property and protection against business interruptions may differ.

In simplified form, protection goals describe the maximum extent of damage that may occur in the event of a fire. The minimum protection target is usually set by the authorities responsible for installation and operation, and is typically supplemented by the protection targets of the system operator.

- Acceptable extent of damage;
- Protection of the facility itself;
- Protection of the environment;
- Ensuring fast return to service.

In general, the relevant building codes and regulations introduced under building law must be complied with. All structural installations must be considered on a case-by-case basis.
In any case, the respective building permit including the fire protection concept/proof must be respected. The building owner or operator is responsible for ensuring that the conditions of the respective building permit are complied with.

The measures for personal protection, availability, protection of material assets and environmental protection depending on the risk level determined in each case

Typical scenarios and protection level targets:

Level 1: Fire from outside onto the battery storage (external fire event outside the ESS).
Protection goal: Ensure that a fire event cannot spread to the battery storage facility
Possible measures: structural separation with sufficient fire resistance, spatial separation or extinguishing systems.

Level 2: Fire event in the area of secondary electronics (power electronics, air conditioning unit ...). Fire event takes place outside the battery room, but has adequate fire barrier separation from the lithium-ion battery storage.
Protection goal: In the case of fires starting near the secondary electronics or lithium-ion batteries, reduce the effect in such a way that fire spread to the other room is prevented. Battery systems, modules and cells must be protected against external (electrical) fires.
Possible measures: Fire alarm system with automatic extinguishing system for electrical risks. The extinguishing agent should ensure zero residue to the protection of the installation.

Level 3: Fire impact on the lithium-ion battery storage (fire event takes place within the battery room) and a reliable differentiation whether it is a fire of the lithium-ion batteries or the power electronics is not given. In the case of incipient fires in the vicinity of the batteries (e.g., fire in the power electronics, etc.), reduce the impact in such a way as to ensure that fire spread to the batteries is prevented.
Possible measures: Fire alarm system with automatic extinguishing system for electrical risks. The extinguishing agent should ensure zero residue to the protection of the installation.

Level 4: Scenario: Fire within the lithium-ion battery storage system (fire or thermal reaction at "cell level").
Protection goal: In case of a cell runaway, prevent the spread to neighboring cells or the runaway of a module. Depending on the battery configuration, cell fires must be limited to individual cells or affected modules. Prevention of the propagation of thermal runaways beyond the affected and of secondary fires.
Possible measures: System for earliest possible fire and off-gassing detection in combination with automatic extinguishing system for residue-free extinguishing of electrical fires and long-lasting suppression of fires.

9.2.5.2 *Risk assessment*

Due to the comprehensive normative regulations and specifications for tests to be carried out as part of the certification of the battery cells, it can be assumed that the storage system itself can be classified as "relatively" safe. Therefore, it is first of all necessary to protect the storage systems from an external fire event in order to prevent cell breakdown processes initiated due to external combustion heat.

Electrical fire hazard

First and foremost, every litium-ion battery energy storage poses an electrical fire risk.
Statistics (GDV) show that in around 25% of all cases, electrical fires are the cause of major losses and the main cause of fires in industrial companies. These risks alone require both reliable detection and automatic extinguishing systems for safe operation. Electrical fires can be detected at an early stage and extinguished safely with automatic gaseous extinguishing systems.

Fire hazard thermal runaway

The filigree design, the ever increasing energy density and aging of the battery are the causes of the danger. If external mechanical forces are excluded, then a fire caused by battery cells themselves is always due to age-related damage to the separator and a subsequent internal short-circuit. The resulting temperature increase causes the (usually highly flammable) electrolyte to start evaporating. As a consequence, the internal pressure within the cell will continue to build up until electrolyte vapour is released either via a relief valve or by the bursting of the shell. Without countermeasures, an explosive gas-air mixture will be generated: only an ignition source is needed and the result will be an explosion. If the heating is not stopped, thermal runaway will occur.

9.2.5.3 *Exemplary fire protection concept - Protection concept to meet safety level 4*

A developing thermal runaway event must be recognized as early as possible by the detection of off-gasing and an adequate concentration of the extinguishing agent must be discharged before the separator of the first battery cell breaks down. The early information about the off-gassing of battery cells is to be used by the battery management system to carry out emergency shutdowns, which could possibly stop the development of a runaway by overcharging or overload.

Early discharge / flooding of the extinguishing agent to:

- prevent the formation of large quantities of explosive electrolyte-oxygen mixtures,
- reduce the extent and reaction speed of a first thermal runaway,
- inhibit the propagation of such runaways,
- prevent re-ignition and secondary fires and by means of a long lasting inerting.

Fire and off-gas detection:

Detectors are required which can reliably detect both electrical fires and off-gassing.

Extinguishing

As the fire sources may be hidden or covered, only total flooding extinguishing agents will be effective.

The selection of the extinguishing agent should take into account the following:

- it should not cause damage to assets
- if used in occupied spaces it should be safe for humans

Combination of fire detection, battery management system and extinguishing

The key to meet the formulated fire protection goals lies in the combination of the earliest possible fire detection with high performance detectors and suitable extinguishing systems and and the alarm transmission to the battery management system.

9.2.5.4 *Proof of effectiveness*

Evidence of effectiveness must be provided by practical fire and extinguishing tests and should be validated. The proof of effectiveness must be based on the protection goal or the corresponding scenario and must be carried out by an independent testing body.

10 CONCLUSION

Lithium-ion batteries incidents can develop into significant and unstoppable thermal runaway fires so carefully considered measures are required to address the hazards that these pose and the options available to manage such risks.

Incipient and pre-fire conditions in lithium-ion batteries can be detected by monitoring several phenomena such as emissions of mixture of solid and liquid suspended particles in an electrolyte gas and abnormal temperatures.

Evidence has shown that the key to successful fire protection of lithium-ion batteries is suppressing/extinguishing the fire, reducing of heat-transfer from cell to cell and then cooling the adjacent cells that make up the battery pack/module.

The fire hazard may remain after the operation of the fire protection system due to the likely damage to adjacent cells caused by the original failure; therefore, remedial actions may be required to prevent a re-escalation.

The use of lithium-ion batteries is widespread and in applications using cell quantities, both large and small. For this reason, consideration of any fire protection measures must take into account the particular circumstances and hazard configuration and whether any fire protection measures have been validated for the particular application.

In all cases, a risk assessment is required to determine the nature and extent of the fire challenges and the safety measures that should be put in place.

11 POST FIRE MANAGEMENT

11.1 Batteries

When a battery fire is extinguished a significant fire hazard may still remain; those batteries involved in and affected by the fire are likely to be hot and still pose the potential to vent combustible and toxic gases and also have the potential to reignite.

It is therefore necessary that post fire management operations commence as soon as practicable by suitably equipped and trained personnel. This may include:

- Ventilation
- Extraction
- Isolation
- Fire watch (e.g., by using thermal imaging cameras to monitor the temperature)
- Recovery

The level of post fire management of the battery will be dependent on battery size for single cell/pouch devices once the fire is extinguished and the risk of further fires is then minimized.

11.2 Media

Media should be disposed of via an environmentally suitable method. The design and installation standard for the various firefighting systems include information on the post discharge provisions.

Toxic gases dampened down by water-based systems can lead to contaminated run-off which will need to be contained.

ANNEXES

1 TERMS, ABBREVIATIONS and DEFINITIONS used in this document

Term/Abbreviation	Definition
Battery	a container consisting of one or more cells, in which chemical energy is converted into electricity and used as a source of power
BMS	**Battery Management System** - Electronic system that manages a rechargeable battery
Li-Ion **Li-ion**	**Lithium-Ion Battery** - rechargeable battery that uses lithium ions as the primary component of its electrolyte
ES	**Energy Storage** - the capture of energy produced at one time for use at a later time
ESS	**Energy Storage System** - collection of batteries used to store energy
EV	**Electric Vehicle -** vehicles with one or more electric motors for propulsion
GWP	**Global Warming Potential**
IR	**Infrared**
LOAEL	**Lowest Observed Adverse Effect Level** - lowest concentration of a substance that causes an adverse alteration of morphology, function, capacity, growth, development, or lifespan of a target organism distinguished from normal organisms of the same species
µm	**Micrometre**
PHEV	**Plug-in hybrid vehicles** - Hybrid vehicles being recharged via the power grid
REEV	**Range extended electric vehicles** - Vehicles with a combination of electric motor and a small combustion engine
SEI	**solid electrolyte interface** - is a passive boundary layer that forms in lithium-ion batteries the interface between the anode, which consists of carbon, and the electrolyte, which is formed by the electrolyte decomposes. The internal resistance of the battery increases due to the SEI layer.
SoC	**State of Charge** - Level of charge of an electric battery relative to its capacity. The units of SoC are percentage points (0% = empty; 100% = full).
Thermal Runaway	Exothermic chemical reaction generating more heat than is being dissipated, Note: *characterised by a self-heating rate of 10°C/min or greater.*
Thermal Propagation	In case a single battery cell thermal runaway spreads to neighbouring cells it's called "Thermal Propagation".
Fire Tetrahedron	elements required to sustain a fire - Fuel, Heat, Oxygen and a Chemical Chain Reaction
Off-gassing	venting of flammable/ toxic electrolyte vapours.
Wh	Watt-hour
kWh	**kilowatt-hour** = 1.000 Watt-hours

2 Fire types / Fire Classes

Fire class is a system of categorising fire with regard to the type of material and fuel for combustion. This is used to determine the type of extinguishing agent that can be used for that fire class.

Class letters are often assigned to the different types of fire, but these differ between territories. There are separate standards for the Europe, United States and Australia.

Image	Description	Europe (EN 2)	United States	Australia
	Combustible materials (wood, paper, fabric, refuse)	**Class A**	Class A	Class A
	Flammable liquids	**Class B**	Class B	Class B
	Flammable gases	**Class C**	Class B	Class C
	Flammable metals	**Class D**	Class D	Class D
	Electrical fire	**Not classified (formerly Class E)**	Class C	Class E
	Cooking oils and fats	**Class F**	Class K	Class F

Table 6: Fire classes in Europe, USA and Australia

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