Warehouse storage of lithium-ion batteries

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Contents

Abbreviations

AEGL	Acute exposure guideline level
AVD	Aqueous vermiculite dispersion
BMS	Battery management system
ESFR	Early suppression fast response
LCO	Lithium cobalt oxide
LFP	Lithium iron phosphate
Li-ion	Lithium ion
LMO	Lithium manganese oxide
NFPA	National Fire Protection Association
NMC	Lithium nickel manganese cobalt oxide
NCA	Lithium nickel cobalt aluminium oxide
PM2.5	Particulate matter less than 2.5 µm
PNEC	Predicted no-effect concentration
PPE	Personal protective equipment
SOC	State of charge

1. Introduction

Lithium-ion (Li-ion) batteries are embedded into every aspect of modern life – from powering mobile devices and electric vehicles to enabling large-scale energy storage systems, that support the transition to renewable electricity generation. As global demand surges, the transport and logistics sector has become crucial to a rapidly evolving supply chain, tasked with safely handling, storing and transporting these potentially high-risk goods.

This second white paper from TT Club builds on its commitment to supporting the industry in navigating the complex challenges posed by Li-ion battery logistics. The first white paper, published in November 2022, provided a general introduction to the hazards of Li-ion batteries for the transport and logistics sector.[1] This paper focuses on the contractual, physical, operational, safety and environmental risks of storing Li-ion batteries in warehouses.

The paper confirms that the risks are real and growing. Global demand for Li-ion batteries is expected to increase to 4.7 TWh by 2030, while the value of the battery value chain could exceed US$400 billion by 2030.[2] But thermal runaway events, resulting in toxic gas emissions, unique fire behaviour and potential vapour cloud explosion all demand a new level of vigilance and preparedness.

Warehouse contractual frameworks should clearly define liability and scope – especially when value-added services such as charging or co-packing are involved. Warehouses also need to be designed and operated with appropriate fire suppression, environmental controls and emergency protocols, and inventory management systems should ensure traceability and compliance. Operators need to engage with fire safety experts, local emergency (fire) services, train staff and clearly communicate with stakeholders and emergency responders.

The paper also explores the evolving regulatory landscape and highlights innovative technologies – from early detection systems to advanced firefighting agents – that offer promise in mitigating the risks in the future.

1 Lithium batteries whitepaper, TT Club, 2022
2 Capturing the battery value-chain opportunity, McKinsey & Company, 2022

2. Contractual risks of storing Li-ion batteries

Warehouse operators need to be aware that storing Li-ion batteries can present a complex range of contractual risks and liabilities. As discussed in this and the previous white paper, they can be classified as dangerous goods which can cause unpredictable and rapidly propagating fires and risk of vapour cloud explosion, potentially leading to significant damage to property, people and the environment.

Scope of warehousing services

Contractual risks increase further when operations extend beyond basic warehousing to include value-added services such as repacking or charging. These activities, while commercially attractive, can introduce significant scope creep – where the services provided exceed those originally agreed. This can expose the logistics operator to liabilities that may not be adequately covered by standard trading conditions or insurance. Examples include the handling and storage of defective or critically damaged Li-ion batteries, which present quite different risks.

Know-your-customer principles should be a primary risk management tool. Understanding who the customer is, the products they ship, the standards they keep and how they package their products are all examples of how risk can be mitigated.

A critical first step in managing the risk of storing Li-ion batteries is to define the scope of services in the contract. This includes not only what is being provided, but also what is explicitly excluded. For example, if battery charging is offered, the contract should specify equipment supply and maintenance, safety protocols, monitoring responsibilities and liability thresholds. Without such clarity, the operator may inadvertently assume responsibility for incidents such as thermal runaway or fire, which could lead to catastrophic loss.

Limiting liability

The risk of catastrophic loss is particularly acute with Li-ion batteries due to their potential volatility. A single incident can result in fire, structural damage and business interruption, with claims potentially exceeding standard liability limits. Therefore, it is essential to incorporate robust limitation-of-liability clauses, ideally aligned with compulsorily applicable national laws or international conventions. Operators should also ensure that any subcontractors involved – such as those handling, charging or co-packing – are contracted on back-to-back terms. This alignment ensures that liabilities passed on to subcontractors mirror those assumed by the operator, avoiding unrecoverable gaps in the event of a claim.

Inventory management

Inventory levels also play a pivotal role in risk exposure: high volumes or high energy densities of stored batteries increase the potential size of the loss. Contracts should therefore address maximum inventory thresholds and include provisions for periodic risk assessments. These assessments should weigh the commercial reward of holding large volumes against the increased exposure to loss and liability.

It is important to watch out for inventory that becomes stagnant in storage and risks being abandoned. Such situations can arise and escalate quickly for several commercial and regulatory reasons. The ability to identify affected cargo at an early stage and then hold a contractual lien over it can be critical in managing risk.

The longer such goods remain in storage, the greater the potential for deterioration, damage, or unnoticed hazardous conditions to develop, increasing exposure to fire, structural damage, and business interruption. It is therefore essential that operators maintain robust monitoring processes to detect when stock ceases to move and may be at risk of abandonment, enabling early intervention. Proactively identifying and addressing such cargo – whether through customer engagement, exercising contractual rights, or prioritising safe removal – supports stronger operational resilience and reduces the likelihood of avoidable incidents.
Incorporating standard trading conditions into all customer contracts is another cornerstone of risk mitigation. These conditions should include 'Himalaya clauses' to extend liability protections to subcontractors, time bars to limit the window for claims, a jurisdiction clause, and exclusions for indirect or consequential losses, such as loss of market or profit. Where enhanced liability is offered – such as full-value protection for stored goods – this must be declared to insurers and mirrored in subcontractor agreements to avoid uninsured exposures.

Finally, the risk-versus-reward equation must be continuously evaluated. While offering additional services can enhance customer value and revenue, they should be priced to reflect the increased risk and operational complexity. A legal review of all contracts is essential to ensure enforceability, particularly in jurisdictions that may not recognise distinctions between principal and agent roles.

Hierarchy of Controls

The hierarchy of controls provides a structured and widely recognised framework that helps warehouse operators strategically manage the risks associated with storing Li-ion batteries. By organising risk mitigation measures from most to least effective – Elimination, Substitution, Engineering Controls, Administrative Controls, and Personal Protective Equipment (PPE) – the hierarchy guides operators to prioritise interventions that remove or reduce hazards at their source rather than relying solely on procedural or behavioural safeguards.

In the context of Li-ion battery storage, this approach is especially valuable given the unique fire characteristics and thermal runaway risks these products present. Applying the hierarchy encourages operators first to consider whether certain high risk activities can be eliminated entirely, such as avoiding the storage of critically damaged or non compliant batteries. Where elimination is not possible, substitution may involve considering the battery chemistry and/or storage configurations. Engineering controls – such as compartmentalised storage zones, fire resistant construction, enhanced ventilation, and early detection systems – form the next essential layer of defence. Administrative controls then support consistent practice through staff training, handling protocols, inventory monitoring, and emergency planning. PPE serves as the final safeguard where residual risks cannot be designed out.

By adopting the hierarchy of controls as a strategic framework, operators can build a more robust, proportionate, and defensible approach to managing Li-ion battery risks in warehouse environments.

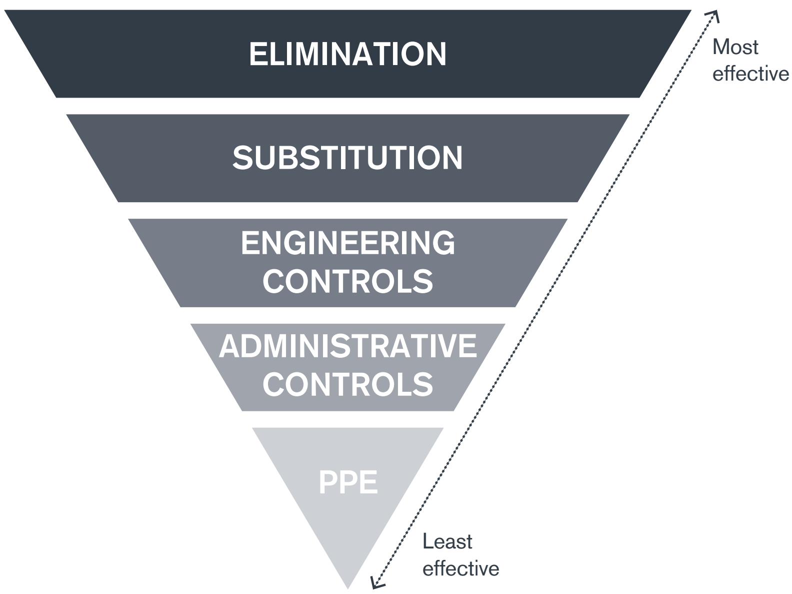


Figure 1 *– The Hierarchy of Controls*

3. Physical risks of storing Li-ion batteries

Defective, damaged or incorrectly handled, Li-ion batteries can fail and go into thermal runaway. This is a process in which chemical reactions are accelerated due to increases in temperature, which in turn results in more chemical reactions and further temperature increases, creating a self-accelerating reaction.

Thermal runaway events in Li-ion batteries are a concern during storage, especially when large quantities are kept close together in warehouses. There have been several Li-ion battery storage fire incidents over the last decade. Investigations into these accidents have found causes to be related to short circuits, spontaneous combustion, battery age and cell failures. While Li-ion batteries are generally considered to be safe, internal failures or an external abuse factor can result in instability within the battery that could lead to a fire.

Adjacency risks can arise when Li-ion batteries become involved in a fire that did not originate from them. Even if they are not the proximate cause, exposure to heat or flame can trigger the same hazardous failure modes – most notably thermal runaway, characterised by rapid temperature escalation, toxic gas release, and the potential for re-ignition. Once adjacent batteries are heated beyond critical thresholds, they may behave unpredictably and significantly intensify an incident, making suppression far more challenging. This escalation effect underscores the importance of spatial separation, strict segregation practices, and early detection and suppression measures to prevent secondary battery involvement in any warehouse fire scenario.

Li-ion battery fires behave differently to conventional fires in a few ways (see Figure 2). First, the time taken for a Li-ion battery fire to reach higher temperatures is much faster than a conventional fire. Li-ion fires also burn at much higher temperatures – up to 1,200 °C – and can be sustained at this level for a long time. Importantly, Li-ion battery fires are hard to put out, due in part to internal reactions that can release oxygen, meaning they are less dependent on external oxygen than conventional fires (see Figure 3). As such, conventional firefighting methods that rely on smothering the fire by removing oxygen are unsuitable. Li-ion battery fires can also reignite hours, days or even weeks after they have been initially extinguished.

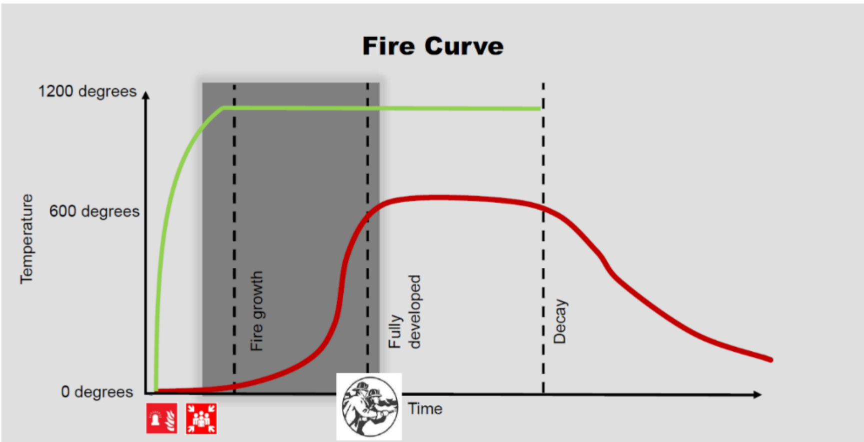


Figure 2 *– Indicative fire curves for conventional (red) and Li-ion batteries (green) (source: REACT Emergency Response B.V.)*

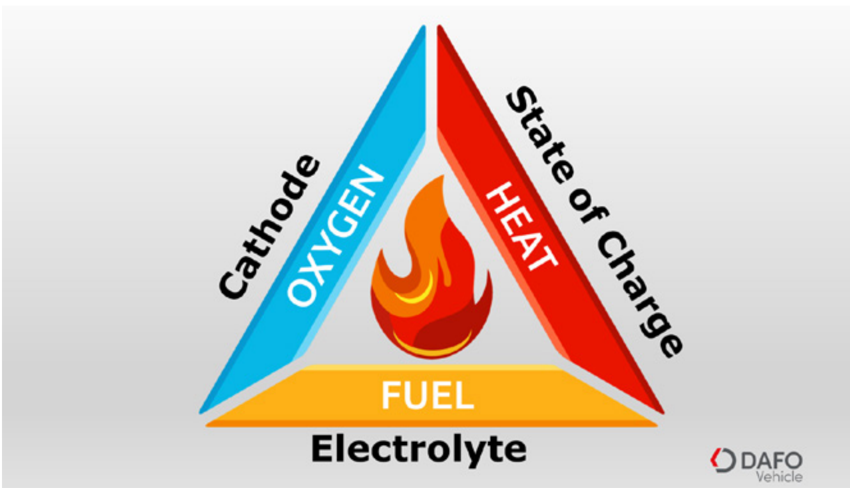


Figure 3 *– Chemical fires provide their own oxygen (source: DAFO)*

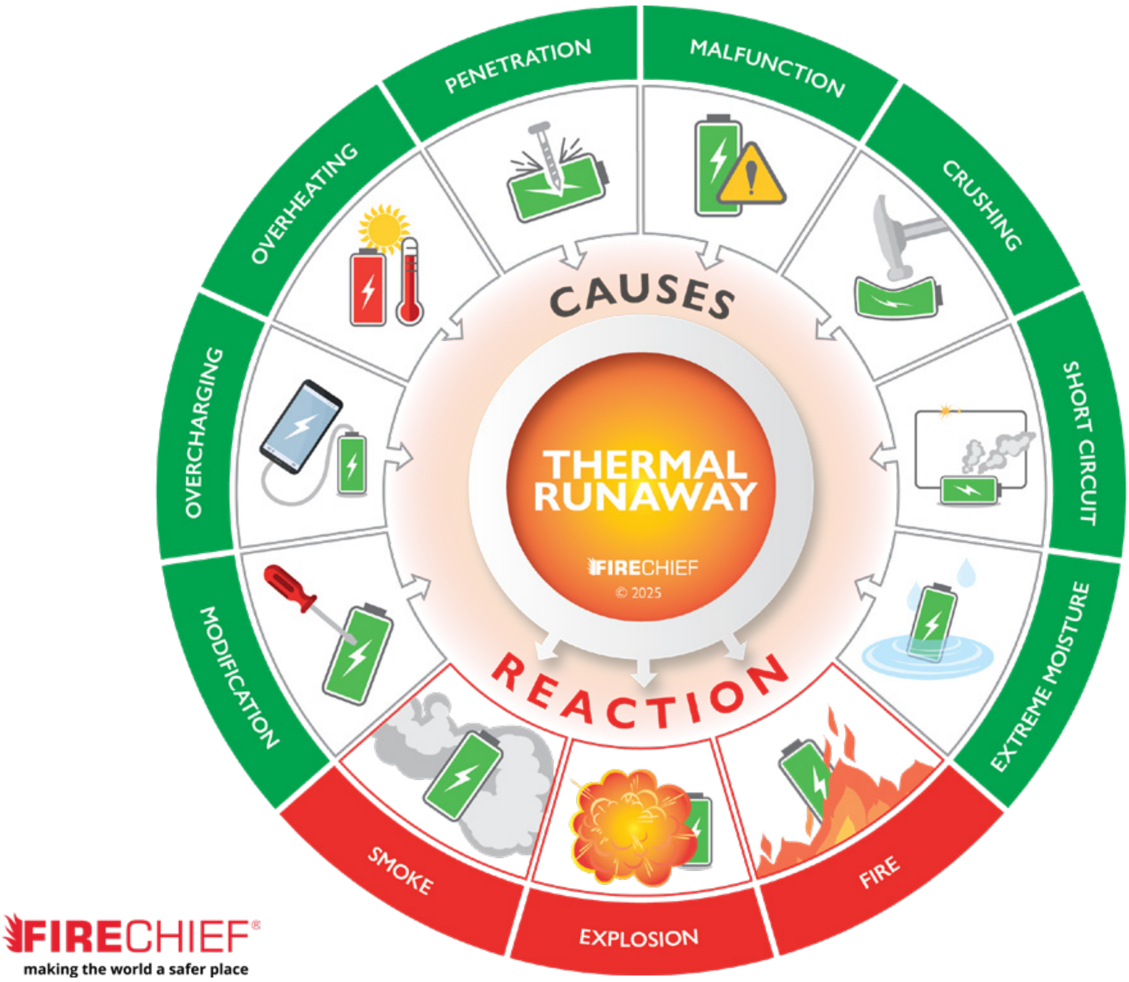
The severity of the fire risk posed by Li-ion battery storage depends on battery-related and warehouse-related factors. For the batteries, factors include the following:

- Type
- Chemistry
- State of charge (SOC)
- Quantity
- Energy capacity and density
- Energy rating
- Enclosure
- Packaging
- Storage period
- Whether cell terminals are disconnected or not

Warehouse factors include:

- Spacing between storage areas
- Temperature and humidity control
- Position in warehouse
- Racking solutions
- Segregation and compartmentalisation
- Ventilation
- Fire risk assessments, emergency procedures and staff training
- Fire, gas and smoke detection systems
- Firefighting options
- Awareness training for warehouse staff

The following sub-sections discuss battery type, chemistry and SOC in more detail, while the next main sections cover warehouse design and operating considerations.



Thermal runaway 2025 graphic (Credit: FireChief)

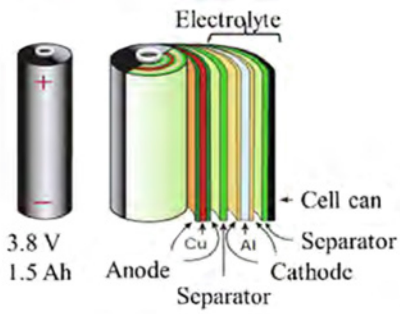
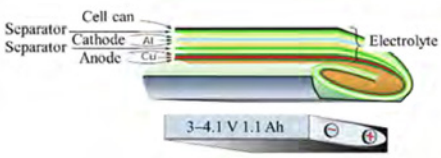
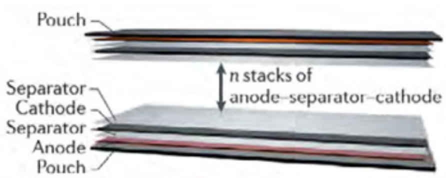
3.1 Battery type

The type of battery influences fire risk due to how susceptible it is to damage. Li-ion batteries can consist of a single cell and the three main types are cylindrical, prismatic and pouch cells. Both cylindrical and prismatic cells have a hard outer casing which offers improved protection from punctures, while pouch cells are in a soft casing which is more vulnerable to being pierced. Mechanical abuse resulting in punctured or pierced batteries can damage the separator, potentially causing internal short circuits and increasing the risk of thermal runaway.

While a Li-ion battery cell is the smallest unit capable of storing and releasing electrical energy, a battery typically refers to an assembly of multiple interconnected cells, often incorporating sophisticated electronic battery management systems (BMS). Cells can be connected in parallel to increase the current, in series to increase the voltage or a combination of the two. These connected cells are known as a module, which are incorporated with other components to form a battery pack.

The distinction between battery cells, modules and packs is critical in warehouse safety management. A single cell, if damaged, can overheat or enter thermal runaway, which – in isolation – may result in a localised fire or venting. But when many cells are tightly packed within a battery, the risk profile escalates: failure in one cell can propagate heat or fire to adjacent cells, compounding the hazard and potentially leading to a severe incident.

A BMS monitors the health, voltage, current and temperature of each cell within the battery. It acts as a safeguard, automatically disconnecting the battery when unsafe conditions are detected – such as overheating, overcharging or internal short circuits. In a warehouse, especially where large battery packs are stored, the BMS serves as the frontline defence against catastrophic failure, significantly reducing the likelihood of fire by spotting issues before they escalate. However, improper storage, physical damage or bypassed BMS functions can still result in serious incidents, underscoring the need for strict protocols and regular inspection.

Battery type	Physical characteristics	Picture	Typical uses
Cylindrical 	The separator and electrodes are wound into a tight cylinder and placed in the casing; the electrolyte is poured in and the battery is sealed. Battery packs of cylindrical cells are less space efficient, due to their shape, but are easier to cool.	 *[Journal of Energy Chemistry, 2021, 59, 83]*	E-bikes, medical devices, power tools, Electric vehicles.
Prismatic 	Made up of large sheets of electrodes that are sandwiched between separators and rolled up before flattening so that they fit into a cubic housing. They can also be assembled by stacking the electrodes in layers rather than rolling. Prismatic cells are thinner and more space efficient but have poor heat dissipation.	 *[Journal of Energy Chemistry, 2021, 59, 83]*	Mobile phones, tablets, and other lightweight electronic devices. They are also used in electric vehicles and scooters.
Pouch 	The electrodes and separators are stacked in the cell container, which is a sealed flexible foil, usually an aluminium plastic film. Pouch cells offer greater flexibility over cylindrical and prismatic cells for fitting the cell to a particular device shape but they can withstand less pressure than a metallic shell casing.	 *[Nature Reviews Materials, 2016, 1, 16013]*	Used in laptops, tablets and electric vehicles.

3.2 Battery chemistry

The battery chemistry refers to the different compounds that can be used within a Li-ion battery. These influence the properties of the battery, including their capacity (how much energy can be stored) and safety. The components that can have different chemistries are typically the cathode (positive electrode) and electrolyte.

Common Li-Ion cathode chemistries include:
- lithium nickel manganese cobalt oxide (NMC)
- lithium nickel cobalt aluminium oxide (NCA)
- lithium manganese oxide (LMO)
- lithium iron phosphate (LFP)
- lithium cobalt oxide (LCO)

For most available batteries on the market, the electrolyte consists of a flammable liquid. This is commonly made from lithium salt dissolved in organic solvents such as ethylene carbonate, dimethyl carbonate and diethyl carbonate. There are also solid-state electrolytes made from ceramics like lithium metal oxides and polymers.

3.3 Battery state of charge (SOC)

The SOC shows how much charge a Li-ion battery currently holds, with 100% being fully charged. Guidelines on the safe SOC for storage of Li-ion batteries will depend on the battery chemistry and the rate at which the batteries naturally discharge over time.

In a thermal runaway event, the SOC can influence both the onset temperature and the rate of heat generation. At higher SOC levels, thermal runaway may be triggered at lower temperatures and the heating rate can increase much more rapidly. Studies have shown that the SOC also has a great impact on the speed of fire and toxic gas spread following thermal runaway. A simulation of LMO Li-ion batteries with 50% SOC filled a 33.7 m x 13.6 m x 5.2 m warehouse with smoke and vapour in 120 seconds, while batteries with 100% SOC took just 30 seconds.[3]

Li-ion batteries will have different safe SOC levels depending on their battery chemistry and how it is manufactured. It is advisable to check the safe storage SOC for various Li-ion batteries with the manufacturer before storing them. Batteries with a very low SOC can also pose a safety concern, as over-discharging is another type of electrical abuse that can lead to failure.

TT Club's research highlights that battery SOC is a critical factor when assessing the risks associated with storing lithium-ion batteries in warehouse facilities. While reducing SOC generally lowers the amount of energy available to fuel a thermal runaway event, it does not eliminate the risk of fire, toxic gas release or vapour cloud explosion. Warehouses should therefore avoid assuming that low-SOC batteries are inherently safe.

3 Jun Xie, Jiapeng Li, Jinghong Wang, Juncheng Jiang, Fire protection design of a lithium-ion battery warehouse based on numerical simulation results, Journal of Loss Prevention in the Process Industries, Volume 80, 2022

4. Warehouse design considerations

For the storage of Li-ion batteries in warehouses, consideration should be given to the design of the warehouse and control of the atmosphere within it. The storage location for the Li-ion batteries as well as the storage conditions must also be considered.

It is good practice for safety, compliance and risk management to have a dedicated storage area or preferably a separate warehouse for Li-ion batteries. This should be cool, dry, sheltered and away from heat sources and direct sunlight. The ideal surfaces for storing Li-ion batteries are concrete, metals with high melting points, ceramics or other non-flammable materials. The storage area should be free from combustible material such as carpet, wood or fuel containers. The location of the Li-ion battery storage should also be away from evacuation points and directly under sprinklers.

4.1 Standards and guidance

Currently, there are no mandatory global standards for the storage of Li-ion batteries in warehouses. However, a variety of local guidance and standards are available. In the USA, Factory Mutual published FM Property Loss Prevention Data Sheet 7-211 - Lithium-ion Battery Manufacturing and Storage[4] in October 2024 and revised it in April 2025. For example, Table 2.4.5.1-1 provides guidance on fire protection of new or refurbished Li-ion cells, modules and batteries stored in solid-pile or palletised storage arrangements, and Table 2.4.5.1-2 covers open-frame rack storage arrangements (see Figure 4).

Table 2.4.5.1-1. Protection Guidelines for Lithium-Ion Cells/Modules/Batteries in Solid-Piled or Palletized Storage Arrangements

Maximum Lithium-ion Cell/Module State of Charge	*Maximum Ceiling Height*	*Storage Height*	*Packaging*	*Protection (QR Sprinklers only)*
60%	45 ft (13.5 m)	15 ft (4.5 m)	Wood crate, metal encased or corrugated carton with cellulosic and/or unexpanded plastic internal packaging only	CUP per Data Sheet 8-9 (Note 1)
			Corrugated carton with expanded plastic internal packaging	CEP per Data Sheet 8-9 (Note 1)
			Unexpanded Plastic external packaging	UUP per Data Sheet 8-9 (Note 1)
			Unexpanded Plastic external packaging with > 40% expanded plastic (by volume) inside	UEP per Data Sheet 8-9 (Note 1)

Note 1. Use the Data Sheet 8-9 protection table based upon the storage configuration (solid-pile or palletized) and the protection option based on the ceiling height.

Table 2.4.5.1-2. Protection Guidelines for Lithium-Ion Cells/Modules/Batteries in Open-Frame Rack Storage Arrangements

Lithium-ion Cell/Module State of Charge	*Maximum Ceiling Height*	*Maximum Storage Height*	*Packaging*	*Ceiling Protection (QR sprinklers only)*	*In-Rack Protection*
≤ 60%	45 ft (13.5 m)	15 ft (4.5 m) (Maximum of 3 tiers)	Wood crate, metal encased or corrugated carton with cellulosic and/or unexpanded plastic internal packaging only	CUP per Data Sheet 8-9 (Note 1)	NA
			Corrugated carton with expanded plastic internal packaging	CEP per Data Sheet 8-9 (Note 1)	NA
			Unexpanded plastic external packaging with ≤ 40% expanded plastic (by volume) inside	UUP per Data Sheet 8-9 (Note 1)	NA
			Unexpanded plastic external packaging with > 40% expanded plastic (by volume) inside; or expanded plastic external packaging	UEP per Data Sheet 8-9 (Note 1)	NA
			Uncartoned	Per surrounding occupancy	See Section 2.4.5.5 and 2.4.5.6
	> 45 ft (13.5 m)	NA	Cartoned or uncartoned	Per surrounding occupancySee	
> 60%	NA		Cartoned or uncartoned	Per surrounding occupancy	

Note 1. Use the Data Sheet 8-9 protection table based upon the storage configuration (open-frame rack, solid-pile or palletized) and the protection option based on the ceiling height.

Figure 4 *– Guidance for fire protection of stored Li-ion batteries (source: FM Property Loss Prevention Data Sheet 7-211 Tables 2.4.5.1-1 and 1-2).*

4 FM Property Loss Prevention Data Sheet 7-112 LITHIUM – ION BATTERY MANUFACTURING AND STORAGE, Factory Mutual Insurance Company, 2025

Also in the USA, the National Fire Protection Association (NFPA) has a general standard for shelf-spacing in NFPA 230, Standard for the Fire Protection of Storage (2003)[5], though this does not specifically cover storage of Li-ion batteries. Similarly NFPA 13, Standard for the Installation of Sprinkler Systems (2025)[6] does not specifically cover fire protection for Li-ion batteries. NFPA 855, Standard for the Installation for Stationery Energy Storage Systems (2026)[7] covers fire protection for Li-ion battery energy storage systems once installed, but not during storage.

In China, while no standards have been issued for Li-ion battery warehouses alone, the Code for Fire Protection Design of Buildings GB50016-2014 (2018)[8] states that single-storey Li-ion battery warehouses must be set up with automatic fire extinguishing systems if they are elevated warehouses or cover an area greater than 1,500 m^2. The standard also recommends automatic fire sprinkler systems. In October 2025, AQ 7017-2025 Safety Specification for Lithium-Ion Battery Production[9] became mandatory.

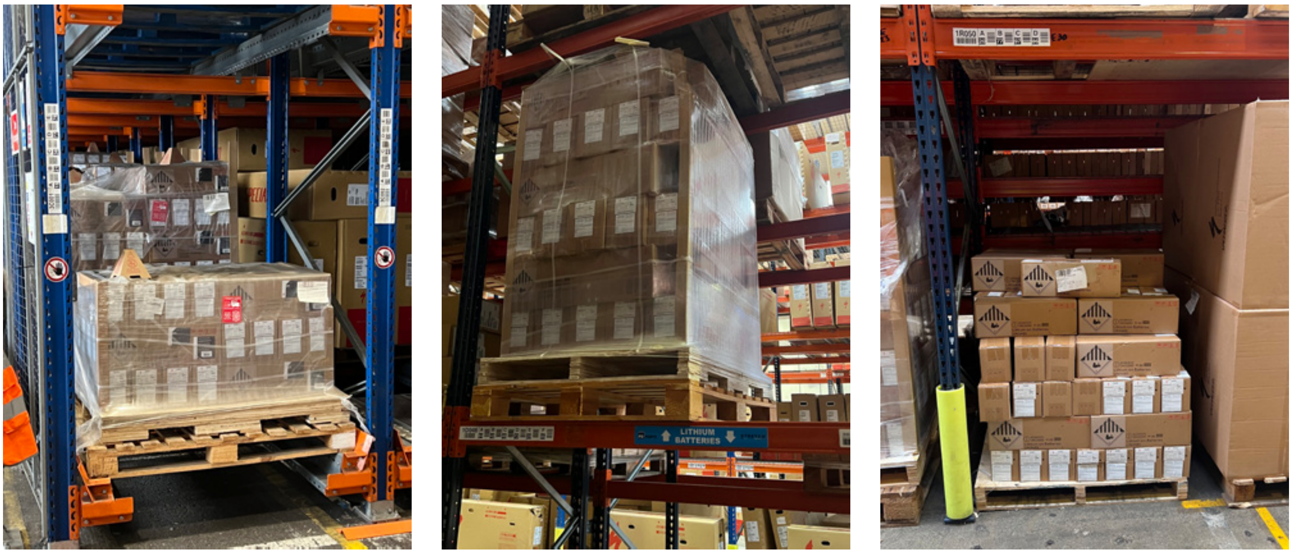
4.2 Racking systems

Broadly speaking, racking systems can be split into pallet racking and picking solutions. Many warehouses will use a pallet racking system to maximise the storage space (see Table 1).

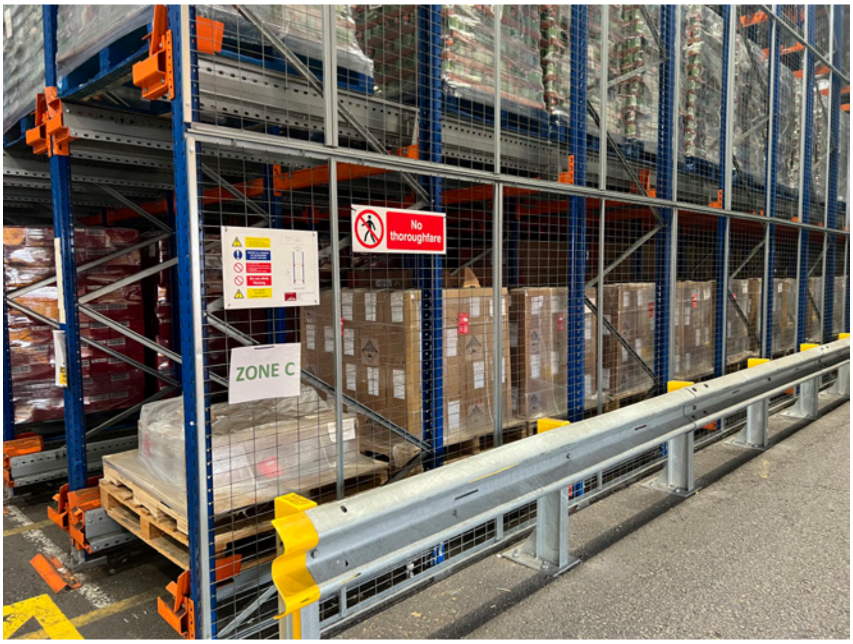
Racking system	Description	Suitability for Li-ion batteries
Adjustable pallet racking	Most-used pallet racking system. Aisles run parallel to the racking and forklifts have direct and immediate access to all loads stored.	OK.
Very narrow aisle racking	A compact version of adjustable pallet racking that increases storage capacity by reducing aisle widths to 1.5 m.	Increased risk of fire spread due to closer spacing.
Pallet flow (gravity flow) racking	Racks have a slight gradient, so pallets slide from one end to the other, with no access to pallets in between.	Restricted access for firefighting.
Drive-in racking	Compact racking system with reduced forklift aisles. Forklifts may not be able to access all pallets.	Increase risk of fire spread due to closer spacing and restricted access for firefighting. Increased risk of forklift collision and battery damage.
Double-deep pallet racking	Pallets stored at two depths, so forklifts may not be able to access the second row. Also need telescopic forks or similar to do so.	Increased risks of fire spread due to closer spacing and restricted access for firefighting. Increased risk of mishandling.
Push-back racking	Last-in/first-out racking, in which pallets loaded onto a sliding platform, so forklifts cannot access all pallets at any one time.	Restricted access for firefighting.
Mobile racking system	Racks are closer together but can be moved to create a forklift aisle.	Increased risk of fire spread due to closer spacing and restricted access for firefighting if mobile system fails.
Semi-automated shuttle system	Semi-automated racking with a motorised shuttle moving pallets horizontally for loading/unloading by forklift.	Increased risks of fire spread due to closer spacing and restricted access for firefighting, particularly if shuttle fails.
Pallet shuttle system	Automated racking system with motorised shuttles, powered by Li-ion batteries, moving pallets horizontally in high-density storage structures.	Increased risks of fire spread due to closer spacing and restricted access for firefighting, particularly if shuttle fails.
Multi-directional shuttles	Fully autonomous racking system that moves pallets horizontally and vertically in high-density storage structures.	Increased risks of fire spread due to closer spacing and restricted access for firefighting, particularly if shuttle fails.

Table 1 *– Typical warehouse racking systems and associated risks for Li-ion fires.*

5 NFPA 230, Standard for the Fire Protection of Storage, National Fire Protection Association (NFPA), 2003
6 NFPA 13, Standard for the Installation of Sprinkler Systems, National Fire Protection Association (NFPA), 2025
7 NFPA 855, Standard for the Installation of Stationary Energy Storage Systems, National Fire Protection Association (NFPA), 2026
8 GB 50016-2014 Code for Fire Protection Design of Buildings, National Standard of the People's Republic of China, 2018
9 AQ 7017-2025 Safety Code for Lithium-Ion Battery Production, Ministry of Emergency Management, China, 2025



Typical racking types (Adjustable pallet racking and Pallet shuttle system) (Credit: PD Ports)



Given the smaller distance between aisles in very narrow aisle racking, should a Li-ion battery or other fire break out, this will spread more easily from aisle to aisle. As Li-ion battery fires are extremely difficult to put out, having large numbers of batteries close together is not advisable to prevent rapid spread of the fire from battery to battery.

Pallet flow, drive-in, double-deep and push-back racking systems also have increased risks should a Li-ion battery fire break out as there is no readily available access to all pallets. To extinguish a Li-ion battery fire, firefighters and the firefighting medium must have direct access to the batteries to cool them to temperatures where the chemical reactions subside.

While mobile racking is very efficient for space, for most of the time the racks storing the Li-ion batteries will be close together. These systems pose two major potential challenges: firstly the close proximity of the Li-ion battery pallets will facilitate the faster spread of fires, and secondly, there is the potential for faults or short circuits to develop within the batteries powering the mobile system during a fire. Such incidents could prevent the aisles from separating where needed to allow firefighting to take place, such that the fire spreads more than if there been access to the origin of the fire.

In both semi-automated and automated shuttle systems, there is no need for aisle spacing between the racks. Again, given the space constraints and in the event of a fire, this could make the area difficult to access for Li-ion battery firefighting operations. Short circuits in the shuttle system could also hinder the removal of pallets of concern from the racking system.

4.3 Building design

Fire compartmentalisation

As discussed above, the risk of fire spread from a Li-ion battery fire to other areas is increased by having tightly packed aisles and pallets stacked on top of one another. According to a simulation carried out by Xie et al.,[10] the critical shelf spacing to prevent fire spread from NMC Li-ion batteries with a 100% SOC was 8.3 m, which is clearly impractical.

Fire compartmentalisation is therefore an important design consideration for storing Li-ion batteries in a warehouse. The purpose of fire compartmentalisation is to divide the warehouse into fire-resistant areas or 'compartments' that limit the spread of fire, smoke and toxic vapours from a potential fire incident. Fire compartments are considered a passive form of fire protection as they do not involve system activation. By preventing or delaying fire spread, they provide critical time for evacuation and help to avoid large-scale damage to the warehouse and goods.

Construction materials

The materials used within a Li-ion battery warehouse or storage area should be considered carefully. While conventional fires will burn at temperatures of around 600 °C, Li-ion battery fires can reach temperatures up to 1,200 °C. To put this in context, aluminium melts at 660 °C and polyether ether ketone, the plastic with the currently highest melting point, melts at 350 – 390 °C. Steel generally melts at around 1,370 – 1,530 °C depending on the carbon content and presence of other alloying elements. Therefore, if a Li-ion battery fire reaches its typical maximum temperatures, there will be large scale destruction of most warehouse components. To reduce the risk of collapse, racking needs be constructed from materials such as steel, which can handle the high temperatures anticipated in a Li-ion battery fire.

Storage height

Ideally warehouse designs should avoid storing Li-ion batteries at height to minimise the risk of damage if they fall. Examples of incidents that may mechanically damage a Li-ion battery include drops from a height of just 30 cm which may result in internal damage to the battery and/or being punctured by a sharp object. Mechnical damage that can lead to battery failure may not always be visible, the time it takes to reach thermal runaway can be anywhere from a few seconds to several hours or even days.

Temperature control

Given that temperature is a factor that can result in battery failure and thermal runaway, having the ability to control the temperature within the warehouse is an important factor to consider. Li-ion batteries should ideally be stored in an environment, which is inline with the OEM recommendations, which is typically between 18 to 25 °C and out of direct sunlight. Storing Li-ion batteries at too high a temperature can lead to capacity decay, in which the amount of energy the battery can store decreases. While this does not have safety implications, it is not desirable. Having climate-controlled storage facilities will help to ensure the Li-ion batteries are kept at consistent temperatures suitable for their storage. Exposure to too high temperatures (thermal abuse) will lead to exothermic reactions taking place, eventually leading to thermal runaway.

Humidity and ventilation control

Another design consideration regarding the warehouse environment is the humidity level. To avoid corrosion of battery components, which could result in battery malfunctions, the relative humidity of the air within the warehouse should be kept at levels as per the manufacturer's recommendations.

An important point regarding Li-ion battery failures is the complex mixture of explosive, flammable and toxic gases that are vented as multiple battery components decompose during a thermal runaway. Li-ion batteries will vent a white vapour cloud consisting of hydrogen, carbon monoxide and hydrogen fluoride, as well as various hydrocarbons and organic solvents. Automatic operating vents linked to the fire alarm system will help enable these gases to be directed out of the warehouse to reduce explosion and health risks.

10 Jun Xie, Jiapeng Li, Jinghong Wang, Juncheng Jiang, Fire protection design of a lithium-ion battery warehouse based on numerical simulation results, Journal of Loss Prevention in the Process Industries, Volume 80, 2022

4.4 Detection and monitoring systems

Detection and monitoring systems vary between warehouses and there are no unified guidelines for how stored Li-ion batteries should be monitored. Thermal runaway warning technology is critical for ensuring Li-ion battery safety, with effective warning systems capable of monitoring battery status in real time.

Early warning systems include those within devices that contain Li-ion batteries as well as within the warehouse. The key features such systems require are high sensitivity and the ability to detect real-time temperature rises, gas emissions and smoke, with warning systems that respond automatically at certain pre-determined thresholds. The sensors must also be heat and interference resistant.

Temperature monitoring

Having thermal detectors in the Li-ion battery storage area is strongly recommended. These thermal detectors should be capable of providing continuous live temperature readings of all boxes and pallets with Li-ion batteries. In an ideal system, the thermal readings should automatically be reviewed and any readings of concern flagged.

In addition to fixed position temperature measurements, it could be helpful to have drones fitted with cameras and thermal readers to take scans of the temperatures in any areas of concern. Using drones rather than warehouse personnel offers a safer way of checking the batteries.

Different temperature sensors are available, ranging from thermocouples, thermistors and infrared sensors to fibre-optic sensors. These sensors can all measure surface and internal battery temperatures through contact or non-contact methods, but each have their pros and cons.

During thermal runaway, there will initially be a temperature difference between the inside and outside of the battery, which can lead to delayed sensor responses. Fibre-optic systems are particularly suitable because they are resistant to electromagnetic interference (unlike thermocouples), are highly sensitive, have short response times and can achieve high-precision measurements in the range of ±0.1 to ±1 °C.

Gas detection

Early warnings can also be provided based on gas detection. As the components decompose during thermal runaway and generate gas, it causes the safety valve to activate or ruptures the casing. Both lead to flammable gases being released into the atmosphere.

Detectors should be installed for gases such as carbon monoxide and organic compounds such as methane. Specialist hydrogen fluoride detectors are also available. All these gases are indicative of battery failure.

Smoke detection

Smoke detectors are essential in any warehouse. However, given the speed that a Li-ion battery fire can develop, close attention should be given to their location. Smoke detectors in designated Li-ion battery storage areas need to be placed close to where smoke is likely to be released should the batteries fail. For warehouses with high ceilings, it may be helpful to have the detectors closer to, or attached to, the racks storing the batteries.

4.5 Firefighting systems

Traditional fire suppression and extinguishing systems that target fuel, oxygen or heat may not be as effective for Li-ion battery fires as the cells can produce their own oxygen. There are six different classes (A-F) of fires depending on the material involved, and Li-ion batteries fall into the first four classes.

Class A fires involve solid materials which ignite due to open flames or high temperatures; class B fires involve flammable liquids; class C fires involve flammable gases; and class D fires involve metals. The ideal firefighting medium for a Li-ion battery fire should be effective for all four classes but this has yet to be discovered.

Figure 5[11] summarises the existing firefighting agents that could be installed in a warehouse for fighting Li-ion battery fires and how they compare to one another. Each has its own strengths and weaknesses.

11 Zhang, L., Jin, K., Sun, J. et al. A Review of Fire-Extinguishing Agents and Fire Suppression Strategies for Lithium-Ion Batteries Fire. , Fire Technology, 2024

Fighting Li-ion batteries – fire fighting agents

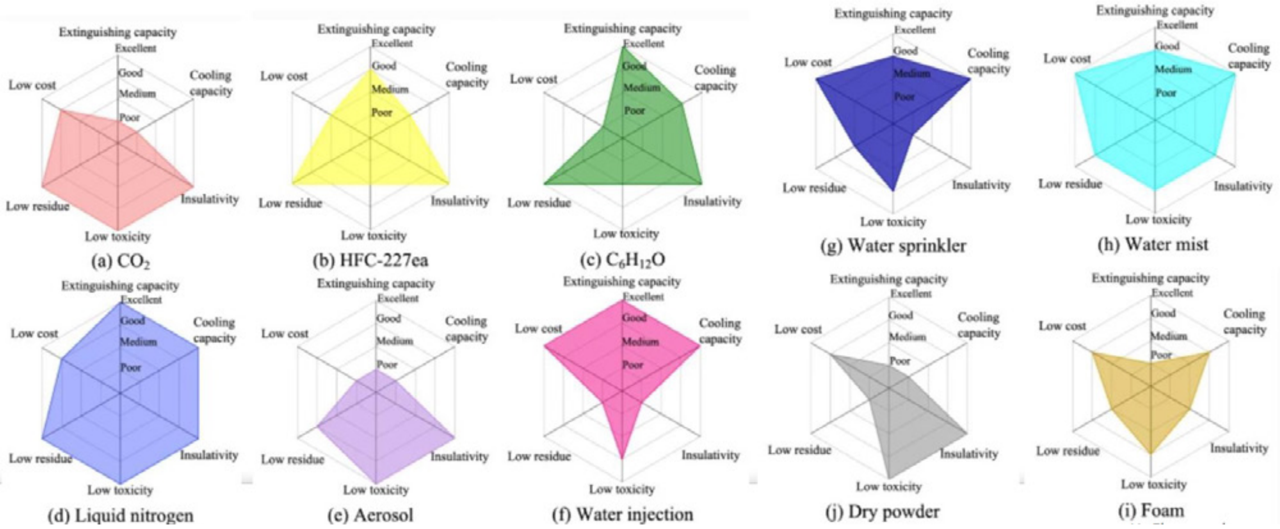


Figure 5 *– Firefighting agents for Li-ion batteries.*

Fire extinguishers

Warehouse operators should carefully evaluate the role of portable firefighting equipment in areas where Li-ion batteries are stored, charged, or handled. The provision of products marketed as "Li-ion extinguishers" should not be interpreted as an expectation that employees will approach a battery that is venting, overheating, or undergoing thermal runaway. Li-ion battery failures can escalate rapidly and may result in intense heat, fire propagation, toxic gas release, and explosion. As such, personnel safety must remain the primary consideration when developing emergency response procedures. Operators are strongly encouraged to seek guidance from their local fire and rescue service, insurers, and competent fire safety professionals to confirm that the proposed control measures are appropriate for the specific hazards present at the site. Engagement with local firefighting services can help ensure that emergency response plans are aligned with current operational practices and capabilities, while also avoiding the unintended consequence of encouraging personnel to undertake interventions that may place them at greater risk. Any decision to deploy specialist extinguishing equipment should be supported by a documented risk assessment, clear operating procedures, and suitable training that defines both the capabilities and limitations of the equipment.

Sprinkler systems

It is also recommended that automatic sprinkler systems are installed. There are many types of sprinkler systems (see Table 2) and it is critical to choose an appropriate system to deal with a Li-ion battery fire. This means dealing with a rapid temperature increase, high maximum temperatures of over 1,200 °C and fires that are difficult to put out. Having a sprinkler system that has direct access to the source of the fire is critical.

ESFR sprinkler systems are strongly recommended for dealing with Li-ion battery fires. They have much faster response times and higher sensitivity levels compared to conventional wet and dry pipe sprinkler systems, cooling the atmosphere and surface at an early fire development stage. They also have their own water supply, which is separate from the rest of the building's water supply, and the larger droplets can penetrate the fire plume without evaporating before they reach the fire source.

In-rack sprinkler systems can be effective for handling Li-ion battery fires. These systems are installed by fitting a network of water pipes within the racks, which can release water at a high velocity. The benefit of in-rack sprinkler systems are the sprinklers being as close to potential fire sources as possible and there are fewer or no obstacles (such as other pallets on higher levels) from blocking the water from reaching their destination. Usually, the sprinklers used here are like conventional wet-pipe sprinklers.

Dry pipe or deluge systems use sprinklers or nozzles that are always in the open position. The pipes to these sprinklers are empty under normal conditions. During a fire, the heat or smoke detection systems will be activated, which then automatically allows the pipes to fill with water, which will flow out from every sprinkler head in the system. Due to the large volumes of water released from deluge systems, they are highly effective at cooling and extinguishing large fires. However, the water released from these systems will not be localised on the area of fire alone, potentially resulting in water damage to stock away from the site of fire.

Whichever sprinkler system is selected, it should be noted that Li-ion battery fires usually require vast quantities of water to extinguish them. For example, for electric vehicles, the fire services will often submerge the entire vehicle in a skip filled with water for numerous days to put of the fire. Even then, the fire can re-ignite once the electric vehicle is removed from the water.

Sprinkler system	Description	Suitability for Li-ion battery fires
Wet pipe	Always water in the sprinkler pipes. Sprinkler heads have a glass bulb or fusible link, which breaks if temperatures get high enough, allowing water to flow freely from individual sprinklers. Designed to control the fire spread, not put it out.	Useful to control fire spread. But water could freeze in cold conditions and, if on the ceiling, could be slow to activate.
Dry pipe / deluge	Sprinkler pipes not filled with water until the glass or fusible link breaks.	Good at suppressing large fires but delay in acting and can cause widespread water damage.
Early suppression fast response (ESFR)	Faster reaction than conventional wet and dry pipe systems due to thinner and more sensitive thermal elements and own water supply. Also, sprinkler heads produce heavier and larger droplets that penetrate the fire plume without evaporating.	Strongly recommended, but widespread water damage.
In-rack	A network of wet water pipes within the storage racks, capable of releasing water at a high velocity. Sprinklers require cages to protect them from damage and need shielding from nearby sprinklers.	Can be effective for handling local Li-ion fires.

Table 2 *– Sprinkler systems and suitability for Li-ion battery fires*

In the 2020 battery energy storage system fire at Perles-et-Castelet in France, around 180 m^3 of water was used by the firefighters. In this instance, the storage capacity was 1,500 kWh, meaning that around 0.12 litres per Wh was used to extinguish the fire. This gives an example of the amount of water that can be involved. As such, warehouses storing Li-ion batteries should ensure their firefighting systems can release large volumes of water at high pressure.

Water mist systems

Water mist systems are also suitable for protecting Li-ion storage areas. These create water droplets less than 1,000 µm, much smaller than those from sprinklers, which gives them a larger surface-area-to-volume ratio and allows greater absorption of heat energy for the same water volume. The systems can also release larger droplets, which pass through the fire plume to cool and extinguish the burning matter, and can shield areas from a fire to prevent its spread.

Water mist systems such as HI-FOG have been shown in full-scale fire tests with various Li-ion battery manufacturers to be effective at suppressing fires by cooling batteries to prevent thermal runaway in adjacent battery modules and cooling the combusting materials and gases to reduce smoke and gas volumes.

Foaming agents

The fire-supressing capabilities of sprinklers and water mist systems can be enhanced with additives. These include high-expansion foaming agents which are combined with water in the pipes before it comes out of the sprinklers or mist system. This saves water and produces a large amount of foam in a short time to smother and cool the fire.

Encapsulating foaming agents, such as F-500, are stated to be effective against class A, B and D fires including Li-ion battery fires. When added to sprinkler systems they encapsulate fuels, preventing them from igniting, and can rapidly cool fires by absorbing free radicals and interrupting chemical chain reactions. They can be biodegradable and free from fluorine, perfluorooctanoic acid and perfluoroalkyl and polyfluoroalkyl substances, and can be dosed directly into existing sprinkler and mist systems.

Carbon dioxide

Carbon dioxide fire suppression systems release carbon dioxide gas to the site of a fire to displace oxygen. However, in comparative studies, the cooling and extinguishing capacity of carbon dioxide was found to be not as strong as water sprinklers and water mist. Also, it is less applicable for fighting Li-ion battery fires as during thermal runaway internal reactions can release oxygen, meaning they are less dependent on external oxygen than conventional fires.

5. Warehouse operating considerations

5.1 Risk management

Understanding the risk

Know your customer (KYC) principles must sit at the very core of any effective risk management strategy when handling and storing Li-ion batteries. These batteries present unique and often elevated hazards, meaning operators cannot rely solely on standard contractual or operational safeguards. A deep understanding of who the customer is, the nature and condition of the products they ship, the standards they uphold, and how those products are packaged is fundamental to mitigating exposure. This insight enables operators to identify potential elevated risks – such as defective, damaged, or misdeclared batteries – before they enter the warehouse environment. When applied rigorously, KYC provides the foundation for appropriate service scoping, safe handling procedures, and informed decision making, ensuring that risk is controlled from the very outset rather than merely managed once batteries are already in storage.

Prior to agreeing to store Li-ion batteries, warehouse management staff should carry out a detailed risk assessment to understand the potential risks associated with storing them at their facilities. The risk assessment should consider a range of factors, including the building design, the safest location for Li-ion batteries to be stored, provision of defective battery quarantine area, the nature of the goods stored near the batteries, and the firefighting systems and whether these are appropriate. It may be worth engaging a risk consultant to assess the warehouse facilities and spot any hidden risks that may have been overlooked.

Risk management strategies

Once the warehouse has been considered suitable for Li-ion battery storage, warehouse management will need to plan and develop strict procedures for quality control, Li-ion battery handling, daily checking schedules and safety. The warehouse staff will rely on these protocols to identify and segregate Li-ion batteries and products containing them. The batteries should first be quarantined and only allowed into the warehouse following visual inspections, temperature monitoring and checks for SOC.

Packages of Li-ion batteries should be checked for their integrity and any signs of damage. Any packages that are found to be at high temperature, visibly damaged, or dropped or impacted during operations should be segregated into a different area. Depending on warehouse policy, these packages should either be rejected or undergo a quality control evaluation before deciding where to store them. Pallets of Li-ion batteries should not be stacked on top of one another unless they are in a racking system.

Ideally Li-ion batteries should be monitored by continuous thermal monitoring systems in which sensors are integrated into the storage system to accurately measure temperatures over the required area (see previous section). Should these sensors detect a temperature anomaly that exceeds preset safe limits, an alert will be triggered. Alternatively, as a minimum, the warehouse should have daily temperature and visual inspections of the pallets of Li-ion batteries stored at their facilities. The temperature readings should be recorded and kept.

Operational Controls and Contingency Planning

All staff working at warehouses storing Li-ion batteries should undergo training to understand the safety (including toxicity) concerns with Li-ion batteries, the signs to look out for in the case of battery failure or damage, and what to do in these situations. Warehouses should have internal standard protocols in place for handling Li-ion batteries (including what to do if a Li-ion battery is dropped), their storage and firefighting measures.

A well considered contingency plan is essential when storing Li-ion batteries, particularly because real world operations do not always align with contractual expectations. Even where a contract expressly excludes critically damaged batteries, such items may still arrive unannounced, for example left behind by a carrier or mis declared by a customer. Critically damaged batteries present materially different and significantly higher risks, and operators may inadvertently assume responsibility if no predefined process exists. Effective contingency planning therefore requires clear internal protocols for immediate isolation, escalation, and communication, along with established decision pathways for rejection, safe quarantine, or return. Having these measures in place ensures operators can respond decisively to unforeseen variations, preventing ambiguity and reducing exposure to thermal runaway or liability related consequences.

Risk management framework

The FireChief HALO™ 8 step Battery Safety Plan provides a structured and practical framework that warehouse operators could adopt to strengthen their strategy for managing the operational risks associated with storing Li-ion batteries. Its value lies in combining proactive and reactive measures into a coherent cycle, ensuring that risk is addressed holistically rather than through isolated interventions.

The process begins with **Education** and **Assessment**, encouraging organisations to build internal awareness of Li-ion battery hazards and to systematically evaluate the risks present in their specific storage environments. By understanding battery types, conditions, and failure modes, warehouse managers can make informed decisions about storage zoning, infrastructure, and emergency preparedness.

The steps **Segregate** and **Control** highlight the importance of physical and procedural separation. By isolating batteries from incompatible or combustible materials and implementing robust control measures – such as environmental monitoring, safe handling protocols, and controlled charging areas – warehouses can significantly reduce the likelihood of a thermal runaway event.

The next phases, **Contain**, **Act**, and **Suppress**, focus on limiting escalation if an incident occurs. These steps emphasise timely intervention, early detection technologies, and the availability of appropriate suppression systems to slow or stop the spread of a fire. Given that Li-ion battery fires can be unpredictable and may reignite, a planned, trained response is crucial.

Finally, **Train** reinforces continual competency. Regular drills, scenario based exercises, and staff familiarisation ensure readiness and reduce response times.

Overall, the FireChief HALO™ plan offers a clear, sequential tool that warehouses can integrate into their operational risk strategy, supporting safer storage and more resilient responses to Li-ion battery incidents.

The FireChief® HALO™ 10 step battery safety plan

PROACTIVE ACTIONS

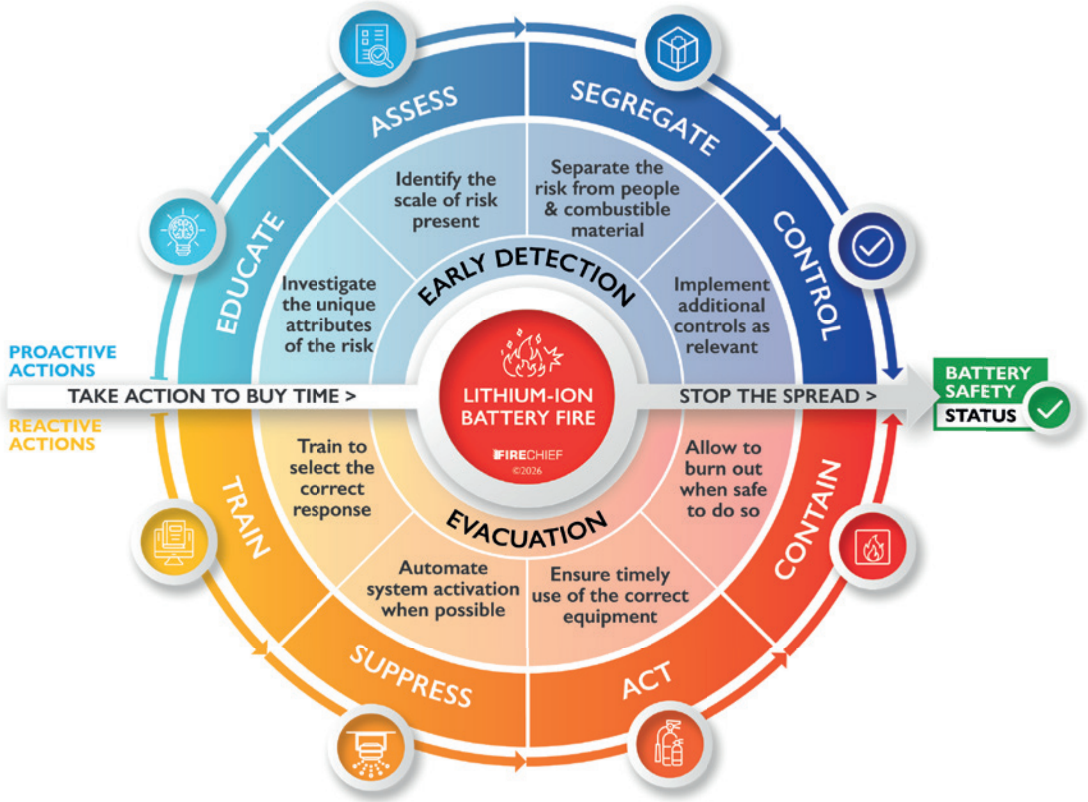
1 EDUCATE
Build awareness of lithium-ion battery risks and ensure everyone understands the correct procedures.

2. ASSESS
Carry out a competent lithium-ion battery risk assessment specific to your site.

3. SEGREGATE
Keep batteries away from people, escape routes and combustible materials wherever possible.

4. CONTROL
Implement practical controls to reduce risk and support safe behaviours.

5. EARLY DETECTION
Monitor for warning signs and detect overheating before thermal runaway occurs.



REACTIVE ACTIONS

6. TRAIN
Train staff to recognise hazards and respond safely to lithium-ion battery incidents.

7. SUPPRESS
Where appropriate, use automatic suppression systems designed for the identified risk.

8. ACT
Take prompt, informed action using the correct equipment and procedures.

9. CONTAIN
Contain the incident where safe to do so and prevent fire spread.

10. EVACUATION
Evacuate immediately and call the Fire & Rescue Service without delay.

FIRECHIEF®
making the world a safer place

Credit: FireChief

5.2 Personal protective equipment

The type of personal protective equipment (PPE) available in warehouses will depend on the work environment. The dangers posed to workers in the case of a Li-ion battery fire include extremely high temperatures, the potential for chemical burns due to the hazardous compounds in the smoke and vapour cloud, and specific toxicity issues related to hydrogen fluoride, carbon monoxide and hydrogen cyanide emissions.

Risk management framework

Hydrogen fluoride inhalation can be particularly dangerous and even fatal, depending on the dosage. The US National Institute for Occupational Safety and Health 'immediately dangerous to life or health' dosage for hydrogen fluoride is 25 mg/m^3, while the US Environmental Protection Agency 'acute exposure guideline level 3' (AEGL-3) – the threshold for life-threatening health effects or death – dosage is 139 mg/m^3. To put these figures into context, experiments have shown that Li-ion battery fires have the potential to release up to 200 g of hydrogen fluoride per kWh capacity.[12] Therefore, the total amount of hydrogen fluoride gas released will depend on the capacity of the batteries in storage and the number of batteries that undergo failure or thermal runaway.

The harmful effects of inhaling hydrogen fluoride may not become apparent until several hours following the incident. The gas can also be absorbed through the skin and cause skin burns, while high level absorption into the body can lead to fluorosis. This is a serious condition in which the calcium and magnesium within bones and tissues are displaced and, if not treated promptly, can cause cardiac arrhythmias and death.

High levels of carbon monoxide are released in the vapour cloud during thermal runaway. This poses a serious risk to health as it binds to the haemoglobin in blood, leading to hypoxia and death.

Hydrogen cyanide may also be present in the vapour cloud in a thermal runaway event, particularly if the battery has nitrogen components. Inhalation can result in respiratory failure and nausea, and even short-term exposure to high concentrations can be fatal.

Based on the dangerous and toxic gases involved in Li-ion battery fires and the high temperatures involved, the basic PPE commonly provided to warehouse workers will be inadequate. In any event, PPE should always be regarded as the 'last resort' in the hierarchy of safety measures and is intended to supplement, not replace, control measures to ensure there is a safe system in place. Warehouses should first implement the other measures already discussed, such as segregation and fire compartmentalisation, to reduce the likelihood and impact of a Li-ion battery fire. Only after these controls are in place should PPE be used to protect workers from any residual risk that cannot be eliminated by other means.

Recommendations

The recommended PPE for those needing to get close to a Li-ion battery fire consists of certified full-face self-contained breathing apparatus to prevent the inhalation of harmful gases, and a completely encapsulated chemical-resistant suit to protect from skin contact with compounds in the gas. Inner and outer chemical-resistant gloves and boots should also be worn. Even if warehouse staff have the correct PPE, it is recommended that only professional firefighters try to extinguish the fire.

Another consideration is removing the contaminants from Li-ion battery fires from the PPE following exposure. Conventional methods for cleaning PPE consist of washing them with a suitable detergent and multiple rinses.

5.3 First aid

It is recommended to have first-aid treatments readily available in the warehouse for anyone who has been potentially exposed to hydrogen fluoride gas. The first step is to decontaminate them with soap and water. First-aid kits should be equipped with quaternary ammonium compounds for compresses on areas of skin that may have contacted hydrogen fluoride. Alternatively, calcium gluconate or carbonate gels can be applied.

For instances in which hydrogen fluoride may have been inhaled, indigestion tablets are helpful to reverse the effects by replenishing the magnesium which may have been lost. In all cases, the person should seek medical treatment at a hospital if it is suspected that they came in contact with the gases from a Li-ion battery fire.

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12 Larsson, F., Andersson, P., Blomqvist, P. et al. Toxic fluoride gas emissions from lithium-ion battery fires. Scientific Reports, 2017

5.4 Emergency response

Proactive engagement with the local fire department is an essential component of safely managing Li-ion battery storage. Establishing early communication ensures that first responders are familiar with the site, understand that Li-ion batteries are present, and know exactly where and how they are stored. This foreknowledge significantly enhances the effectiveness of an emergency response, enabling firefighters to anticipate the unique hazards – such as toxic gases, rapid fire development, and potential re ignition – and to deploy appropriate tactics from the outset. Providing accessible floor plans and clear hazard information supports faster, safer decision making and reduces the likelihood of an incident escalating unnecessarily.

As soon as a Li-ion battery starts venting or smoking, often accompanied by clicking and popping sounds, all personnel should be evacuated from the area. Warehouse workers should also be made aware of the fact that the densities of the gases released from Li-ion batteries during thermal runaway and venting vary: toxic gases such as hydrogen chloride are denser than air and may gather along the floor. Therefore, the advice of keeping low during evacuation may not be appropriate in a Li-ion battery fire.

Should a fire break out, warehouse staff need to cooperate with firefighting services. The warehouse should have floor plans showing the storage location of the Li-ion batteries and any other hazardous goods, plus the locations of firefighting systems. The floor plans should be readily accessible in a location known by all staff so they can be provided to the firefighters as soon as they arrive on site.

Study on Li-ion fire plume

Lejon *et al.*[13] carried out retrospective simulations on a large-scale warehouse fire that took place in Morris, USA, in which around 60 tonne of Li-ion batteries caught on fire on 29 June 2021. The order to evacuate the area was made on 30 June due to toxicity concerns, with around 3,000 to 5,000 people being evacuated. At this point, the most intense part of the fire and most of the heat had been released but it took a further 2 weeks before the fire was declared extinguished.

The paper took existing data gathered from witnesses and firefighters to establish parameters for firefighting. The fire progression was not like a normal fire and popping sounds were heard by witnesses, corresponding to the venting and ignition of battery cells. Based on aerial photographs, the height of the plume was estimated to be around 600 m. Weak south-westerly winds of 2–4 m/s were present at the time of the incident.

The paper assessed the plume spread and the matter that may be in this by considering the levels of various gases released from Li-ion batteries and miscellaneous plastic based on literature data. The gases included hydrogen fluoride, nitrous oxides, sulphur dioxide and particulate matter less than 2.5 µm ($PM_{2.5}$). Action levels were also reported for hydrogen fluoride (0.2 ppm) and $PM_{2.5}$ (25 µg/m^3), while AEGL-1 30 minutes exposure[14] maximums were 1 ppm for hydrogen fluoride and 0.2 ppm for sulphur dioxide. This highlights that the health risk of sulphur dioxide should not be underestimated.

The simulation was carried out for an average source and an intense source. It was noted that for the average source, the ground concentration exceeded $PM_{2.5}$ action levels for distances of 10 km, with a maximum of 13 km, while hydrogen fluoride levels were close to the action level limit but did not exceed this. For the intense source simulation, the particulate matter concentrations exceeded the $PM_{2.5}$ action limits for an area covering several tens of square kilometres, with figures ten times higher than the limit found as far as 10 km from the warehouse. Hydrogen fluoride levels were noted only to be above action levels close to the fire source.

The above study showed that large areas had particulate matter that exceeded the PM2.5 action levels. First responders may therefore need to be more cautious with deciding how large an area needs to be evacuated.

13 Lejon, C., Vågberg, D., Schönfeldt, F. et al. Lagrangian plume rise and dispersion modelling of the large-scale lithium-ion battery fire in Morris, USA, 2021. Air Quality Atmosphere & Health, 2024

14 AEGL-1 30 minute exposure is the airborne concentration of a substance above which, it is predicted the general population could experience notable discomfort, irritation or certain asymptomatic non-sensory effects.

5.5 Environmental management

Warehouse staff should follow the fire service's recommendations on how to deal safely with the gases and particulate matter released into the surrounding environment.

After extinguishing a Li-ion battery fire, there are also likely to be large volumes of firefighting water contaminated with various environmentally harmful compounds from the batteries to deal with (see study below).

Study on Li-ion firefighting water run-off

An experimental study[15] assessing the run-off water from firefighting operations dealing with small quantities of NMC Li-ion batteries found it contained an array of different metals, carbonaceous species and undecomposed solvents used in the electrolytes. The metals included lithium, manganese, cobalt, nickel and aluminium. These were found mixed with other carbonaceous compounds and were present in nanometric or nanostructured clusters as well as in larger particle sizes.

Liquid compounds were also detected, including organic carbonates from the electrolyte depending on the temperature of the fire. Gases such as polycyclic aromatic hydrocarbons were also detected. The tests showed that the water could be either basic or acidic, depending on the components within the water, and the pH was outside safe levels.

The results from the experiments were extrapolated to understand the likely concentrations of the compounds detected and compared to the 'predicted no-effect concentration' (PNEC) for the substances, taken from the European Chemicals Agency website.[16] The comparison revealed that the concentration in the firefighting water was above the PNEC values for all substances discovered, except naphthalene. Cobalt and ethyl methyl carbonate were noted to have concentrations of 2,500 and 2,600 times greater than their PNEC values respectively.

The results from the study highlight that the water from firefighting has the potential to be hazardous to the environment depending on the thermal runaway situation. Given the environmental damage risks, careful consideration must be given when disposing of this water. Currently, there are no specific standards for this.

15 Bordes, A.; Papin, A.; Marlair, G.; Claude, T.; El-Masri, A.; Durussel, T.; Bertrand, J.-P.; Truchot, B.; Lecocq, A. Assessment of Run-Off Waters Resulting from Lithium-Ion Battery Fire-Fighting Operations, Batteries, 2024

16 European Chemicals Agency (ECHA), Homepage, accessed 2026.

6. Looking to the future

6.1 Safer batteries

One of the main research areas for Li-ion batteries is improving their safety. This includes changes to the electrolyte, which is the main flammable component, such as by moving to solid polymer electrolytes or non-flammable electrolytes.

Other research focuses on modifying other battery components, such as the separator that prevents the electrodes from contacting. Examples include creating heat-resistant organic separators and adding smart coatings to the electrodes, which can shut down the battery cell if temperatures get too high. Battery-level innovations are also being investigated to improve cooling system design, cell isolation and pressure-relief mechanisms.

The dangers associated with Li-ion batteries may therefore be eliminated in the future. However, in the interim period, the supply chain must be vigilant and have the necessary safety protections in place.

6.2 Improved early warning

Multiple gas detection

Studies carried out on LPF Li-ion batteries found that carbon dioxide and hydrogen were the main gases emitted during thermal runaway, with hydrogen being released earlier than other gases. Monitoring the concentration changes in multiple gases allows for more complex models to be used for fault detection, improving accuracy and reliability.

The electronic nose, which is an artificial sensor system that simulates the biological nose, has been investigated as a means of detecting mixed gases released during thermal runaway. It uses an array of gas sensors to convert odours into quantifiable signals, which can then be analysed to identify and quantify specific gas components. Different algorithms are used for classification and regression of the gas sensory data. As sensors can display cross-sensitivity to different types or concentrations of gases which are not the target gas, it can be difficult for one sensor to be precise. Therefore, a multi-sensor system with trained data-processing models can be used to identify gases accurately.

Ultrasound monitoring

Ultrasound is a non-destructive method that is emerging as a system for early detection for thermal runaway. Ultrasound can propagate in solids and liquids, so it can be used to find early signs of anomalies which could lead to thermal runaway. Research has found that prior to thermal runaway, the gas generated within the batteries alters their acoustic properties. If ultrasound sensors are used to monitor these changes in real time, this could offer the ability for warnings to be issued before thermal runaway, allowing for more time for mitigation measures.

Pressure monitoring

Another option for thermal runaway early warning systems is pressure monitoring. Researchers have used pressure sensors to monitor real-time changes to develop a model representing changes during early side reactions of thermal runaway. The information from such modelling can be used in conjunction with warning systems to provide alerts at preset pressure thresholds. Calibrating the monitoring thresholds is essential and each individual cell would have to be connected to the pressure sensors, so this technology may be more suited to niche applications.

Machine-learning systems

Research is being conducted on using machine-learning-based early warning systems. These systems analyse multidimensional data to provide real-time monitoring of a range of parameters. Such systems have been developed for the BMS to provide insight into how the battery behaves during charging and discharging cycles. This data is then used to find anomalies during operation. As Li-ion batteries should not be charged or discharged while they are stored in warehouses, this technology is not applicable, but it is useful to know that such developments exist.

Case Study: Leveraging Visual Machine Learning for Early Fire Hazard Detection in Li-ion Battery Warehousing[17]

The storage of Li-ion batteries presents a uniquely challenging risk profile, where early identification of abnormal conditions – such as overheating, unsafe equipment interactions, or hazardous behaviours – can be the critical factor in preventing catastrophic fires. Voxel's visual machine learning platform offers a transformative approach to managing these risks by converting existing CCTV infrastructure into a real time, intelligent hazard detection network. Through AI models fine tuned to each facility, Voxel continuously monitors people, vehicles, equipment and environmental conditions with **95%+ detection accuracy**, providing early warning of safety critical deviations.

In warehouse environments storing Li-ion batteries, the ability to detect precursor behaviours – such as improper handling, unauthorised access to storage zones, unsafe charging practices, or early signs of thermal events – provides operators with vital reaction time. The platform's real-time insights and automated workflows enable supervisors to intervene immediately, assign corrective tasks, and enforce risk reduction measures before conditions escalate.

For Li-ion battery storage, where thermal runaway can evolve rapidly and spread unpredictably, Voxel's AI powered site intelligence can offer a crucial defensive layer – detecting anomalies far earlier than human observation or conventional CCTV review would allow. By turning passive video feeds into proactive decision support tools, warehouse operators can not only enhance fire prevention capability but also build a more resilient, data driven risk management framework suited to the evolving hazards of modern energy storage logistics.

6.3 Novel firefighting agents

Hydrogels

Hydrogels are a three-dimensional network consisting of polymers and a large quantity of water. They are non-toxic, biodegradable, leave no residues following firefighting, physically cool and isolate burning material, and rapidly absorb heat. Research has shown that high-flow hydrogel extinguishers are able to prevent thermal runaway from spreading between individual battery cells.

Perfluorohexanone

Perfluorohexanone has been investigated as a fire extinguishing medium: it is an odourless, colourless and non-conductive liquid with low toxicity that physically and chemically inhibits flames. It evaporates and reacts with combustibles, thereby lowering the concentration of combustible gases.

Liquid nitrogen

Liquid nitrogen, which has a boiling point of -196 °C, is extremely effective at lowering ambient temperatures to inhibit flame spread by cooling the burning material to below its ignition point and diluting oxygen within the area. Studies have found that applying liquid nitrogen to batteries before they reach critical thermal runaway temperatures can prevent thermal runaway from taking place at various SOC without affecting battery cycle performance. While liquid nitrogen does not leave any residues nor has any environmental impacts, it requires specialised storage facilities and training to handle it safely. The costs associated with using liquid nitrogen could therefore be higher than other options.

17 European Chemicals Agency (ECHA), Homepage, accessed 2026.

7. Summary

Lithium-ion batteries are integral to modern life, powering everything from consumer electronics to electric vehicles and energy storage systems. With global demand projected to grow by 700% between 2022 and 2030, the logistics sector faces increasing pressure to safely handle and store these high-risk goods. This white paper outlines the operational, contractual and safety considerations for warehouse operators managing Li-ion battery cargo.

Contractual risk

Warehousing Li-ion batteries introduces complex contractual exposures, especially when value-added services like charging or co-packing are involved. Scope creep can lead to liabilities not covered by standard trading conditions or insurance. Operators must define service boundaries clearly, implement robust limitation-of-liability clauses and ensure subcontractors are bound by back-to-back terms.

Inventory levels and stagnation also influence risk. Contracts should address maximum thresholds and include provisions for abandoned or stagnant stock. Incorporating Himalaya clauses, time bars and jurisdictional protections into contracts is vital for mitigating exposure.

Physical risk

Thermal runaway is the key physical hazard, triggered by internal faults or external abuse. Li-ion battery fires differ from conventional fires – they burn hotter (up to 1,200°C), release toxic gases and are difficult to extinguish. Factors influencing fire risk include battery chemistry, SOC, packaging and warehouse layout. Simulations show that higher SOC levels accelerate fire spread and gas diffusion.

BMS play a critical role in monitoring cell health and preventing failures. However, improper storage or physical damage can bypass these safeguards, leading to catastrophic incidents.

Warehouse design

Warehouse design must prioritise robust risk assessment, fire compartmentalisation, spacing and use of fire-resistant materials. Racking systems should be chosen with fire suppression access in mind, avoiding high-density configurations that hinder firefighting.

Traditional fire suppression methods are often ineffective against Li-ion battery fires. Recommended systems include ESFR sprinklers, in-rack sprinklers and deluge systems with water additives like F-500 or AVD. Firefighting requires large volumes of water and specialised equipment.

Warehouse operations

Warehouse operations must include thorough inspections upon receipt, segregation of damaged units and use of non-combustible racking systems. Environmental controls such as temperature and humidity regulation are essential to prevent degradation and spontaneous ignition. Inventory tracking via warehouse management systems ensures traceability and compliance, especially when managing diverse battery types.

Staff should be trained to recognise signs of battery failure and evacuate promptly. PPE should be available but regarded as a last resort – segregation and system design are the primary defences. Li-ion battery fires release flammable, explosive and toxic gases including hydrogen fluoride, carbon monoxide and hydrogen cyanide. These pose serious health risks and require advanced detection systems.

Warehouses must engage with local fire departments, conduct drills and keep accessible floor plans. Post-fire, contaminated firefighting water contains harmful metals and solvents, needing careful disposal.

Innovative solutions

Emerging technologies aim to improve battery safety and early detection. These include solid-state electrolytes, smart coatings and advanced sensors for gas, pressure and ultrasound monitoring. Machine-learning models are being also developed to predict failures.

7.1 Key takeaways

- Li-ion batteries pose significant fire, health and environmental risks in storage.
- Warehouse design, inventory control and staff training are critical to safe operations.
- Contracts must clearly define scope and liability, especially for value-added services.
- Fire suppression systems must be tailored to Li-ion battery behaviour.
- Detection technologies and emergency protocols must be robust and proactive.
- Regulatory standards are evolving but remain inconsistent globally – operators must stay informed and vigilant.

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