White Paper

on the Safety of lithium-ion battery applications in data centres

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1. Introduction

Data centres are a critical part of the digital infrastructure. As a new infrastructure, new data centres aggregate diverse data resources, use environmentally efficient and low-carbon technologies, provide secure and reliable capabilities, deliver efficient computing services, and enable applications across multiple industries. Traditional data centres are rapidly converging with networks and cloud computing, and evolving into a new generation of data centres.

Lithium-ion batteries, as the mainstream electrochemical energy storage devices, are widely deployed in data centres to support their stable operation. However, despite their high energy density and efficiency, lithium-ion batteries pose significant safety risks due to their tendency to continue reacting after thermal runaway, releasing high-temperature, toxic, combustible and explosive gases. These hazards create a high risk of fire and explosion, posing a great threat to the safe operation of data centres and drawing increasing concern from the industry. In fact, the indirect loss due to data centre accidents caused by lithium-ion battery fires is far greater than the direct economic loss caused by battery fires. Recent accidents highlight that the fire hazard associated with lithium-ion batteries in data centres cannot be underestimated.

Improving the fire safety conditions of lithium-ion batteries for power backup and power supply in data centres, upgrading the fire safety management level, and enhancing the fire extinguishing and rescue capabilities are critical measures to ensure the overall reliability of data centres and service systems, which is one of the key safety factors essential for ensuring the sustainable development of the entire lithium-ion battery industry chain.

In this context, this White paper on the Safety of lithium-ion battery applications in data centres, based on extensive research, in-depth analysis, and collective discussion and review, aims to encourage stakeholders to implement effective fire safety measures. It also seeks to promote technological breakthroughs in the intrinsic safety of lithium-ion batteries, minimizing the fire risks and hazards associated with them. The goal is to ensure the safe and stable operation of data centres, while fostering a secure fire-safety environment. This will support the development of an intelligent computing ecosystem centred around evolving data centres.

2. Terminology and abbreviation

2.1 Terms

Emergency power-off (EPO)

A button or switch, which, when activated, immediately disconnects the input and output of all power supplies in the battery room except the fire extinguishing system power supply.

Green data centre

A green or sustainable data centre can be defined as a repository for the storage, management and dissemination of data in which the mechanical, lighting, electrical and computer systems are designed for maximum energy efficiency and minimum environmental impact. (Recommendation ITU-T L.1300)

Lithium-ion battery cabinet

A cabinet in which multiple lithium-ion battery modules are connected in series, in parallel, or both. It is a primary backup power source and consists of the battery management system (BMS), monitoring and protection circuits, and communications ports.

Lithium-ion battery cell

A basic unit for converting mutually between chemical energy and electric energy, and for storing energy, it consists of electrodes, a separator, electrolytes, a shell, and terminals. It may also refer to a minimum unit that includes one battery cell, or several battery cells connected in parallel.

Lithium-ion battery module

A battery assembly that consists of multiple lithium-ion battery cells connected in series, parallel, or both. It has a pair of positive and negative output terminals, and is designed with a shell and management and protection devices.

Lithium-ion battery rack

A minimum system-level discharge unit that consists of multiple lithium-ion battery modules connected in series. It must also include components such as the BMS, monitoring and protection circuits, and electrical and communications ports.

Lithium-ion battery room

A room dedicated to the placement of lithium-ion batteries in a data centre.

Lithium-ion battery system

A battery assembly that consists of lithium-ion battery cabinets connected in parallel. It operates independently after being connected to a switch cabinet or a junction device.

Remote deployment

A method of separating the lithium-ion battery system from the building in which the data hall is located.

Skid-mounted lithium-ion battery system

A lithium-ion battery system with an enclosure structure such as a container, in a data centre.

Note: Recommendation ITU-T L.1221 "Innovative energy storage technology for stationary use - Part 2: Battery" contains more detailed technical definitions related to battery in line with IEC.

2.2. Abbreviations

ABC: fire extiguire for A, B and C class

BCU: Battery control Unit

BMS: Battery management system

CCTV: Closed-Circuit Television

DC: Direct current

DCR: Direct current resistance 33

EPO: Emergency Power Off

ESD: electrostatic discharge

FFU: Fan filter unit

FPY: first pass yield

GPS: Global Positioning System

HVDC: High Voltage Direct Current

LCD: Liquid Crystal Display

LCO: Lithium Cobalt Oxide

LEL: Lower Explosive limit

LFL: lower flammability limit

LFP: lithium iron phosphate

LMO : Lithium manganese oxide

MSDS: Material Safety Data Sheet

NCA: Nickel cobalt Aluminum

NCM: Nickel cobalt manganese

NMS: network management system

O&M: operation and maintenance

PDB: power distribution box

PFMEA: process failure mode and effect analysis

PPE: Personal protective equipment

SEI: Solid electrolyte interphase

SOC: State of charge

SST: Solid state transformer

UPS: Uninterruptible Power Supply

3. Overview of data centre lithium-ion batteries

3.1. Working principle

The charging and discharging process of a lithium-ion battery is designed to convert electric energy and chemical energy into one another. The working principle, as shown in Figure 1, is as follows:

Charge: When an external power supply applies a voltage, lithium ions and electrons in the cathode material are released from the transition metal in the cathode material and flow to the negative electrode through an external circuit. At the same time, positively charged lithium ions enter the electrolyte and move toward the negative electrode. The lithium ions gain electrons on the surface of the negative electrode and intercalate between layers of the anode material (usually graphite). When the lithium ions de-intercalated from the positive electrode are fully intercalated into the negative electrode, the battery is fully charged and the negative electrode is in a lithium-rich state.

Discharge: When a battery is connected to a load, the battery discharges. Because there is a potential difference between the positive and negative electrodes, lithium ions de-intercalate from the negative electrode, pass through the electrolyte and separator, and return to the positive electrode to recombine with the cathode material. In addition, electrons at the negative electrode also flow through an external circuit to the positive electrode to form a current and provide electric energy for the load.

In this process, lithium ions swing back and forth between the positive and negative electrodes, which is why lithium-ion batteries are often referred to as rocking chair batteries. The separator plays an important role in the entire charging and discharging process. It separates the positive electrode from the negative electrode of the battery to prevent internal short circuits. In addition, the separator allows the lithium ions in the electrolyte to pass freely, ensuring a normal current loop within the battery.

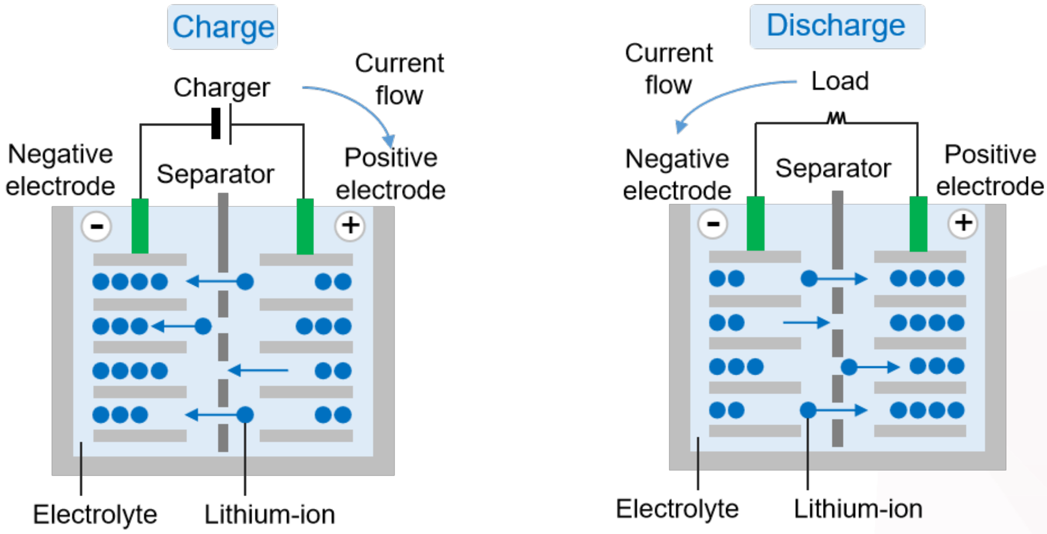

Figure 1: Charge and Discharge of lithium batteries

3.2. Battery classification

In general, lithium-ion batteries are classified based on the cathode material and the packaging mode.

3.2.1. By cathode material

Currently, by cathode material, there are mainly lithium iron phosphate (LFP), ternary lithium (NCM or NCA), lithium manganese oxide (LMO), and lithium cobalt oxide (LCO) batteries.

(1) Lithium Iron Phosphate Battery (LFP)

Advantages: LFP batteries feature high energy density, excellent performance at normal and high temperatures, environmental friendliness, and high reliability. The LFP material has good cycle stability and thermal stability, so that the cycle life of batteries can reach more than 10 000 times. Currently, LFP batteries are used widely in new-energy passenger vehicles, commercial vehicles and energy storage markets. It is also the main battery material used in data centres.

Disadvantages: The LFP cathode material has small granularity and low compaction, and the battery energy density is slightly lower than that of high-nickel ternary lithium batteries.

(2) NCM or NCA Battery

Advantages: NCM or NCA batteries feature high operating voltage, high energy density and good power performance, so meeting the requirements of electric vehicles in respect of battery life and power performance. Compared to pure lithium nickelate oxide and lithium manganate oxide, the high-nickel ternary structure has better stability and a higher capacity per gram.

Disadvantages: Compared to LFP, its safety performance is poor. The thermal stability of the structure is relatively poor, and thermal runaway occurs easily in the case of high temperature, overcharge, or overdischarge. The cobalt element is expensive and causes pollution. The cost of nickel is high, and a high proportion of nickel increases the cost of the cathode material. It is seldom used in data centres.

(3) LMO Battery

Advantages: With relatively abundant manganese as a raw material, the LMO battery has a low cost and is environment-friendly. It has good charge and discharge performance at high and low temperatures, and is used in cost-sensitive fields that do not require high energy density such as electric tools, low-speed electric vehicles, and medical equipment.

Disadvantages: Its energy density and cycle life are relatively low, and the stability of cycle performance at high temperatures is poor. During use, the Jahn-Teller effect will cause structural damage due to the dissolution of manganese, resulting in rapid degradation of battery performance. It is seldom used in data centres.

(4) LCO Battery

Advantages: The LCO battery features high discharge voltage, stable performance and easy synthesis. As the first commercial lithium-ion battery, it is used widely in consumer electronic devices that require a small battery size such as cell phones and laptops. It can provide high energy density and stable voltage output.

Disadvantages: Cobalt resources are scarce and expensive. In addition, the cobalt element is toxic and causes environmental pollution. It suffers from poor reliability and is prone to safety accidents when overcharged. In general, it is not used in data centres.

definitions related to battery in line with IEC.

3.2.2. By packaging mode

Nowadays, by packaging mode in the industry, batteries can be classified primarily into prismatic, cylindrical and pouch batteries.

Prismatic battery cylindrical battery pouch batteries

Figure 2: Picture of different batteries

(1) Prismatic battery

A prismatic battery is a battery characterized by a rectangular shape. The battery consists of stacked electrode materials packaged in a square shell usually made of aluminum or other lightweight materials.

Advantages:

- **Space optimization.** The prismatic battery uses a flat, rectangular design for excellent space efficiency.
- **Higher combination efficiency.** The stacked electrode material in the compact bag structure facilitates efficient packaging within the battery module and optimizes space utilization in large battery strings (such as those used in electric vehicles or energy storage systems).
- **Easy to manufacture.** The manufacturing process of a prismatic battery involves the uniform stacking of layers, which helps simplify the production line, thereby potentially reducing manufacturing complexity and costs.

Disadvantages:

- **Limited shape flexibility.** The fixed, rigid shape of the prismatic battery can be a challenge to adapt to irregular or custom-shaped spaces within the device, limiting its use in certain product designs.
- **Lack of standardization.** As there are many types of prismatic battery, standardization is a challenge.

(2) Cylindrical battery

A cylindrical battery is a battery characterized by its cylindrical shape. Its exterior is a cylindrical shell made of aluminum or steel, and its interior is an electrode material wound in a spiral structure that maximizes the use of internal space.

Advantages:

- **Mature process and low cost.** Cylindrical batteries are mature in process, resulting in high production efficiency.
- **High energy density.** Cylindrical batteries have high energy density.
- **Robust and durable structure.** The cylindrical shell provides structural integrity, making the battery more resistant to physical shock.

Disadvantages:

- **Limited shape and size.** The cylindrical shape may not be suitable for certain device designs that require flexibility or specific dimensions. This limitation can be a challenge in applications where space limitations or custom shapes are critical.
- **Susceptible to mechanical stress.** In some cases, the winding structure in a cylindrical battery may be susceptible to mechanical stress or deformation.
- **Limited capacity.** The radial thermal conductivity of the cylindrical battery limits the number of winding layers, resulting in a small capacity of a single battery.

(3) Pouch battery

Without a rigid shell, a pouch battery consists of stacked electrode materials and is encapsulated in a flexible package made of materials such as aluminum and polymer laminates.

Advantages:

- **Customizable shape and dimensions.** The pouch battery has excellent adaptability and can be customized to meet various shape and size requirements. This feature makes it ideal for scenarios in which space optimization and unique design are critical.
- **Enhanced reliability.** The pouch battery is packaged with aluminum-plastic composite film, which can effectively reduce the possibility of explosion compared to the rigid shell used in other types of batteries.
- **High energy density.** Compared to traditional batteries, the pouch battery is lighter and takes up less space. It is 40 per cent lighter than steel-shell batteries and 20 per cent lighter than aluminum-shell batteries of the same capacity, offering a higher energy density.

Disadvantages:

- **Limited structural support.** The absence of a rigid shell reduces the structural support of the pouch battery, and places higher technical demands on manufacturing and assembly process control.
- **Standardization and cost challenges.** The pouch battery faces difficulties in standardization, resulting in higher costs.

3.3. Battery selection

The lithium-ion battery system in a data centre is mainly used to provide backup power for power supply equipment (such as Uninterruptable Power Supply (UPS), High Voltage Direct Current (HVDC), and Solid State Transformer (SST)) to ensure power continuity and reliability for the data centre and the continuous operation of electrical devices such as servers, storage devices and network devices, so preventing data loss and service interruption caused by power failures.

In addition to basic requirements such as the backup power, backup time, operating temperature, and temperature rise, the selection of battery cells must meet the following requirements.

3.3.1. By cathode material

Data centres have high safety requirements. If a major accident occurs, the loss can be difficult to estimate and the impact can be widespread. Therefore, safety is the priority when selecting batteries.

Compared to other cathode materials of lithium-ion batteries such as nickel cobalt manganese (NCM), LFP has higher safety and longer cycle life, and has better stability at high temperatures. It has an olivine structure, and the phosphate (PO43–) in its crystal structure can provide strong structural stability, ensuring that severe structural changes such as lattice collapse are unlikely to occur. Its high-temperature decomposition starting temperature is 200°C higher than that of NCM. In addition, LFP is not prone to violent oxidation-reduction at high temperatures, generates less heat, and has a lower risk of thermal runaway. Other cathode materials such as ternary lithium contain a large number of transition metal elements and have a high reaction activity at high temperatures, generating a large amount of heat and gas and resulting in poor safety. Therefore, LFP is the preferred cathode material for data centre lithium-ion batteries.

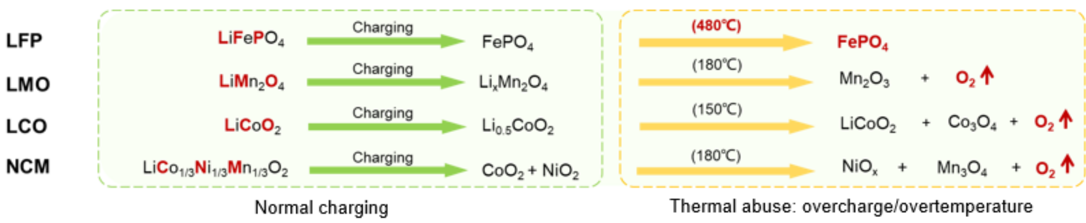

Figure 3: Comparison of Batteries' chemical reactions during Normal Charging and Thermal Abuse

* The data centre lithium-ion batteries mentioned in the following text are LFP batteries.

3.3.2. By packaging mode

In addition to safety and protection, battery selection must meet the following requirements: good heat dissipation performance; easy combination and manufacturing; and high space utilization.

(1) High Safety

According to the thermal runaway mechanism of lithium ion battery for electric vehicles, as explained in a review by Xuning Feng, Minggao Ouyang, Xiang Liu, Languang Lu, Yong Xia and Xiangming He, the thermal runaway of lithium-ion batteries can be illustrated by a chain reaction in the following figure 4. When an abuse condition such as a short circuit occurs, the battery temperature rises, causing side reactions. For example, in a complete thermal runaway process, side reactions such as temperature rise, electrolyte gasification and volatilization, solid electrolyte interphase (SEI) decomposition, negative electrode-electrolyte reaction, electrolyte decomposition and heat release, positive electrode-electrolyte reaction, and binder decomposition occur sequentially as the temperature rises. In addition, the above side reactions release more heat, forming a self-heating cycle. As a result, the temperature keeps rising, and eventually the battery experiences thermal runaway. Therefore, the thermal stability of the battery material system and separator is the key factor that affects the starting temperature of the battery thermal runaway reaction. In addition, by optimizing the battery shell structure, through-current design, N/P ratio, consistency and manufacturing process, the internal defects of batteries can be effectively controlled to reduce the battery failure rate.

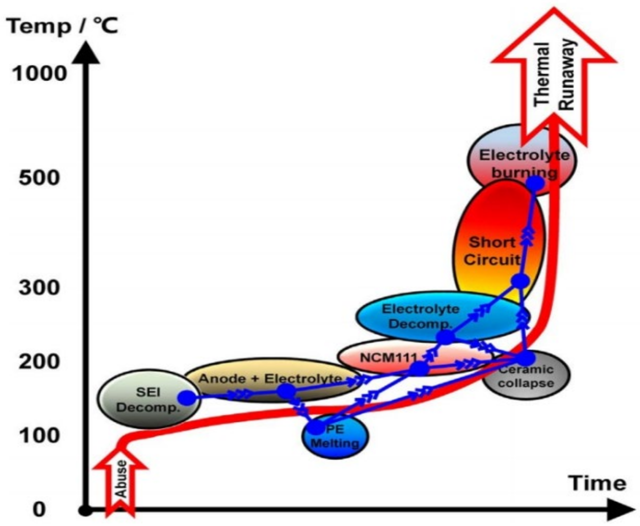

Figure 4: Progression from SEI Decomposition to Thermal Runaway during Battery Thermal Abuse

(2) Good Heat Dissipation Performance

The prismatic and pouch batteries have a large surface area, which provides a favorable condition for heat dissipation. During battery charging and discharging, heat generated by the battery can be transferred to the external environment more quickly through the shell, thereby reducing the internal temperature of the battery effectively, ensuring that the battery operates within an appropriate temperature range, and improving battery performance and prolonging battery life. This is beneficial to high-power scenarios. Due to the smaller surface area of the cylindrical battery shell, the temperature rises sharply in high-power applications. Currently, technologies such as the full-tab battery are being used to reduce the joule heat of high-rate charge and discharge.

(3) High Space Utilization

The prismatic and pouch designs enable a more efficient use of internal space of batteries, and can better accommodate components such as electrode materials. Considering the thermal diffusion and insulation protection of batteries in packs, insulating materials must be added when batteries are combined, which to some extent affects the volumetric energy density of battery strings. Cylindrical batteries meet the insulation and thermal protection requirements due to the gap between the cells during assembly. For safety purposes, the volumetric energy densities of batteries in three packages are not significantly different after combination.

(4) Easy Assembly and Integration

As the aluminum-shell prismatic battery and the pouch battery have a regular shape, they have advantages in the process of assembling and integrating battery modules, and can be more conveniently arranged and combined to save space and improve the space utilization of battery modules. In a data centre lithium-ion battery application scenario, the regular shape helps achieve efficient space layout and convenient connection. Generally, the positive and negative electrodes of a battery are located on the same side or two opposite sides of the battery, which facilitates electrode connection and wiring, reduces the difficulty and cost of battery module assembly, and improves production efficiency. In addition, the mechanical strength of the insulating film is low, making it susceptible to puncturing during assembly. Therefore, foreign object control during assembly and welding is a priority.

(5) Mature Manufacturing Process

After years of development and optimization, the manufacturing process of the aluminum-shell prismatic battery has become mature and stable. Throughout the manufacturing process such as battery cell production, shell processing, and packaging, complete technologies and equipment are available to ensure consistent battery quality and performance.

4. Intrinsic safety requirements for data centre lithium-ion battery systems

Implementing a robust safety design of lithium-ion battery systems in data centres can significantly enhance their intrinsic safety. Therefore, various safety risks must be fully identified during design, and the safety and reliability of lithium-ion batteries used in data centres must be maximized in terms of battery cell, battery module, and battery system design.

4.1. Battery failure analysis

The failure modes of lithium-ion batteries can be divided into two types:

- **Performance failure:** the performance of lithium-ion batteries cannot meet the requirements of use, including fast capacity attenuation, internal resistance increase, and large self-discharge.

- **Safety failure:** safety risks are caused by improper use or abuse of lithium-ion batteries, including insulation failure, bulging, valve opening, and thermal runaway.

This section describes safety failure modes.

(1) Insulation failure

Insulation failure occurs after the battery cell shell is damaged and the energized aluminum shell is connected to the pack metal shell. One of the main causes of battery cell insulation failure is that the external insulation medium is damaged. For example, the lugs or terminals are connected to the cover, or the blue film of the battery cell is damaged. Moreover, electrolyte leakage of the battery cell may also cause insulation failure. Electrolyte leakage may occur due to defective cell manufacturing or damaged shell. As a result, the insulation between the cell and the shell may fail and the cell may be short-circuited during operation, causing battery damage or fire in the event of thermal runaway.

(2) Abnormal bulging

When the internal pressure of the battery is too high, the surface of the battery cell shell bulges abnormally. The direct cause is that under some abnormal conditions, the electrolyte is oxidized and decomposed, and gas is generated inside the sealed battery. As a result, the battery may bulge and the valve of the bulging battery may open, creating a risk of explosion.

(3) Valve opening

Under abuse conditions, the electrolyte is oxidized and decomposed or vaporized by heat, producing a large amount of gas. The internal pressure continues to rise. When the pressure exceeds the threshold, the safety valve opens automatically to release gas or vaporized electrolyte. In this case, visible smoke is emitted and generally there is no open flame.

(4) Thermal runaway

Abnormal battery temperature rise causes a series of self-heating side reactions. As a result, the battery temperature rises sharply, and the battery catches fire or even explodes. The causes of battery thermal runaway are classified into electrical abuse, thermal abuse, mechanical abuse, and internal cell failure.

(a) Electrical abuse

External short circuit: External short circuit is a major cause of battery thermal runaway. Due to deformation caused by foreign object intrusion and insulation failure, the positive and negative electrodes of a battery are short-circuited. As a result, a large amount of heat is released in a short period of time, causing thermal runaway.

Internal short circuit: A battery cell may have defects such as metal impurities, burrs and separator holes during manufacturing, or may be bumped or crushed by external forces during use. As a result, the positive and negative electrodes are short-circuited. The short-circuit point generates a large amount of heat, causing thermal runaway. The growth of the lithium dendrite can also cause an internal short circuit. During charging, lithium ions are deposited unevenly on the surface of the negative electrode to form a dendritic lithium metal crystal. The dendrite may penetrate the separator and cause a short circuit between the positive and negative electrodes.

Overcharge: During overcharge, lithium ions in the cathode material are excessively de-intercalated. As a result, the structure becomes unstable and the decomposition reaction may occur. In addition, lithium ions may excessively intercalate into the anode material to form lithium metal deposits, increasing the risk of short circuits. Overcharge generates a large amount of heat, which may cause thermal runaway.

(b) Thermal abuse

Thermal abuse includes overheating, thermal shock and fire exposure. The optimal operating temperature range for batteries is 20–30°C. When the temperature is too high, the chemical reaction inside the batteries accelerates and side reactions increase, releasing a large amount of heat. If the heat release rate is greater than the heat dissipation rate, heat will continuously accumulate and the separator will melt, causing an internal short circuit. The internal self-heating reaction releases a large amount of heat, causing thermal runaway. (c) Mechanical Abuse

Mechanical abuse includes crush, collision, puncture, and bending. Mechanical abuse usually causes battery deformation, resulting in internal structural changes. In severe cases, the separator is punctured, and the external positive and negative electrodes are connected. As a result, a large amount of heat is generated due to internal and external short circuits, causing side reactions of battery materials, gas production, and eventually thermal runaway. Based on the safety failure analysis of lithium-ion batteries, safety design requirements must be imposed on battery cells, battery modules, and battery systems.

(c) Mechanical abuse

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4.2. Safety requirements for battery cells

4.2.1. Product safety requirements

The safety design of lithium-ion batteries must meet the system, manufacturing, transportation and application requirements that determine the safety of lithium-ion batteries. According to the preceding failure analysis, common safety-related failures include insulation failure, abnormal bulging, valve opening, thermal runaway. Therefore, the safety design of battery cells must be considered in terms of material selection, capacity selection, electrode plate design, structural design, and application restrictions. Basic safety requirement for battery are present in IEC 62619.[1]

(1) Material selection

Material selection includes the cathode, anode, separator, and insulating film. The cathode material shall be LFP with better thermal stability. The anode material shall be graphite with better dynamics and less rebound. The separator shall have high puncture resistance and good thermal shrinkage, and ceramic coating shall be added to the PE-based separator. The temperature aging resistance of the insulating film material shall meet the battery life requirements, and the material shall pass the 150°C/0.5 h test.

(2) Capacity selection

Select battery cells with appropriate capacity to optimize the power supply reliability, energy efficiency, and Operation & Maintenance cost for data centres. As cell technologies continue to improve and iterate, it is recommended that the cell capacity selection strategy be fully evaluated when safety conditions are met.

(3) Electrode plate design

The design includes the electrode plate size, active material surface density and compaction density. After being rolled, the electrode plates shall occupy less space than the space reserved for the internal mechanical parts of the battery cell. Otherwise, the rolls may be deformed due to interference, which may lead to lithium plating or internal short circuit. The design of active material surface density shall meet the charging capability of the battery cell. Otherwise, the active lithium ion may precipitate and cause an internal short circuit.

(4) Structural design

The structural design includes the dimensions and structure of the bare battery cell, the dimensions of the insulating films, the insulation resistance between the terminals and the shell, the through-current capacity of the connecting plates and the terminals/lugs, and the pressure relief structure.

A winding structure or a laminated structure can be selected for a bare battery cell. The length, width, and thickness of the bare battery cell shall be designed according to the internal space of the cell, the rebound capability of the electrode plate, and the manufacturing capability. The dimensions of the insulating films include those of the internal and external insulating films of a battery cell. The design of the internal insulating film must consider the dimensions of a bare battery cell to ensure full coverage and prevent the electrode plates from contacting the shell. The external insulating film of a battery cell must meet the requirements for the insulation and dielectric strength and the puncture resistance. This prevents corrosion and electrolyte leakage caused by battery shell short circuits.

The plastic of the negative terminal shall be insulated, and the plastic of the positive terminal shall

[1] IEC 62619 "Secondary cells and batteries containing alkaline or other non-acid electrolytes - Safety requirements for secondary lithium cells and batteries, for use in industrial applications".

be insulated or be of high resistance. A high-resistance positive terminal is used to prevent corrosion of the aluminum shell.

The dimensions of the connecting plates, terminals, and tabs mainly take into account the overcurrent capability at a high rate. The backup power capability of a data centre for five to 10 minutes is equivalent to the discharge of a single battery at 6C to 12C.[2] In the case of high current, the connecting plates and terminals must be kept at a low temperature to avoid burning the separator and the insulating plastic.

The pressure relief structure is selected based on the gas production volume and the failure-related gas production rate of the battery cell throughout the lifecycle.

(5) Application Restrictions

Application restrictions are defined in the system and product to support the electrical performance and safety performance of battery cells. They must be defined clearly. For example, the maximum expansion force supported by the restriction structure must be specified, and the pre-tightening force range supported by the larger surface of battery cells must be defined.

4.2.2. Manufacturing safety requirements

From design to a finished product, a battery cell shall be manufactured through high-quality process control. To avoid the preceding safety failure modes, every single parameter in each process of battery manufacturing must be

properly defined and strictly controlled from five dimensions: person, machine, material, method and environment. In the development process, the process failure mode and effect analysis (PFMEA) must be completed for battery cells

A battery's C-rate, which determines the rate of charging and discharging, changes how quickly a battery can charge or discharge. A higher C-rate means faster charging and discharging; for example, a C-rate of 6C means a battery can charge or discharge six times faster than its rated capacity, while 12C means it can do so twelve times faster.

in the C-sample phase. The PFMEA must cover all potential failure risks that can be identified during battery cell manufacturing to support manufacturing engineers to define and optimize the process flow and process parameters.

Before battery cells are sealed, the cleanliness in the large environment must be better than Class 100 000: for fully sealed equipment, the cleanliness can be Class 1 000 000 or better; and for key processes, a small environment shall be set for the equipment and a fan filter unit (FFU) shall be installed to raise the cleanliness to Class 10 000.

The manufacturing of battery cells is divided into three stages according to form and function.

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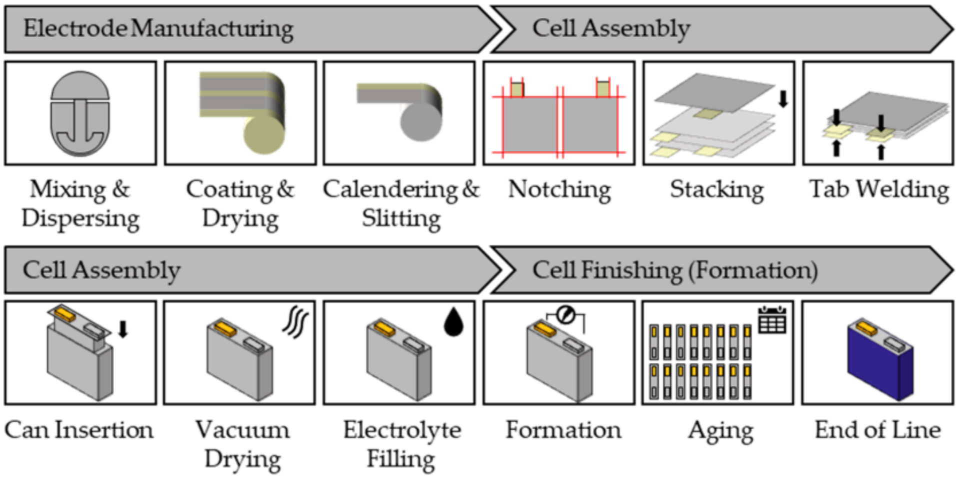


Figure 5: Production steps in lithium-ion battery cell manufacturing

(1) Early stage - electrode plate

This stage includes processes such as material mixing, coating, roll pressing, and cutting, and focuses on the mixing evenness, coating evenness and thickness consistency of materials. The key parameters for manufacturing control include the magnetic material content and burr dimensions to avoid defective products. Common serious failures are the low surface density of the negative electrode thinning area and lithium plating of the negative electrode at full charge.

(2) Middle stage – assembly

This stage includes processes such as winding, shaping, ultrasonic welding, and laser welding. It focuses on the assembly of components and relies on high-precision equipment. The stage focuses on controlling parameters such as cutting position burr, insulation resistance, welding stain area, welding depth and width, tape covering effect, and welding flanging height to avoid defective products. A common serious failure is that during welding, there is a gap between the top cover and the aluminum shell. As a result, the laser passes through the gap and damages the roll, causing the internal insulating film to fail and resulting in corrosion and leakage.

(3) Later stage – test

This stage includes processes such as baking, electrolyte injection, formation, aging, capacity grading, and self-discharge. It focuses on controlling parameters such as water content, formation capacity, grading capacity, and self-discharge rate to intercept defective products. A common serious failure is that the negative lug is not covered and the exposed part is connected to the aluminum shell, causing electrolyte leakage. By checking the voltage of the negative shell during the test, this failure can be identified.

4.3. Safety requirements for battery modules

4.3.1. Product safety requirements

The safety design of the battery module shall consider failure scenarios throughout the lifecycle, including manufacturing, transportation, storage, installation, operation, maintenance, and recycling. The design shall address mechanical, electrical, and thermal issues to prevent fires caused by combustibles, combustible aids, and ignition sources. This ensures product safety during normal use or foreseeable, reasonable abuse to prevent fire, explosion, personal injury or property damage.

(1)Manufacturing

The safety design of the battery module shall meet the requirements of the automatic production line; that is, to reserve working space for mechanical arms and to provide visual positioning marks. This avoids uncontrollable quality of manual operations during production and prevents damage to product safety features.

Automatic laser welding shall be used for the series and parallel connection of battery cells. The welding shall be reliable, in order to prevent loose connections. The welding area between the busbar and the battery terminals shall meet the through-current requirements.

(2)Transportation and storage

The battery module or package shall adapt to extreme environments during transportation and storage. It shall be protected from rain, electrostatic discharge (ESD), shock and vibration, and condensation. Desiccants may be used or exception detection labels such as tilt indicators may be attached to prevent product damage or to warn customers not to use products that may be damaged.

(3)Installation

The safety design of the battery module shall take into account the weight of the module. It should be designed with handles to facilitate movement and transportation, in order to avoid personal injury or internal battery damage caused by falling. In addition, safety warning labels shall be attached to warn of the risks of open flames or heat sources, stepping, rain, rolling, collision, falling, upside-down placement, personal injury caused by scalds or electric shocks, and other maloperations during installation and O&M. The battery module shall be able to withstand the short-circuit fault current or adopt the anti-short-circuit design. Short circuits may occur during installation, O&M, and commissioning. The I2T curve of the fuse shall be within the short-circuit safety boundary of a battery cell, and the rated breaking capacity shall be greater than the maximum fault current in the circuit. In this way, fast breaking can be implemented to avoid short-circuit fire of the battery module or fuse explosion due to breaking failure.

(4)Operation

Inside the battery module, sufficient safety clearance shall be provided between cells, between cells and other metal parts such as end plates and the shell, and between cells and circuit boards including power and monitoring boards. Insulation materials with high temperature resistance, puncture resistance, and fire retardancy shall be used or separate compartments shall be designed to prevent short circuits, insulation failure, and board arcing caused by foreign objects, condensation, and electrolyte leakage.

The battery module shall use heat-resistant and insulated sampling cables or use integrated busbars with heat-resistant and arc-proof fuses for temperature and voltage sampling to prevent battery short circuits caused by insulation failures of sampling cables or cable contact. The temperatures of each battery cell and the total positive and negative power copper bars shall be measured directly. If an exception occurs, the temperatures are reported to the system in a timely manner so that countermeasures can be taken to ensure that the battery cells are operating within a safe range, or the isolation device is started to prevent the failure from spreading.

The battery module design needs to consider the measures suppress local fires caused by sporadic cell failures. Local fire extinguishing submodules can be configured in the module to quickly and automatically extinguish open flames in the event of sporadic cell failures, preventing the fire from spreading to the entire system. The high protection and oxygen isolation design of the battery module can also be used to isolate oxygen from the source after cell failures.

The flame-retardant rating of plastic mechanical parts inside the battery module shall meet the requirements of UL94-V0 , and the cable sheaths inside the battery module shall meet the requirements of UL94-VW-1.[3]

(5) Maintenance

The battery module shall be configured with one or more charge devices, and a battery charge reminder shall be attached to remind operators to charge batteries in a timely manner after batteries are stored for a long time or have completed a discharge session. This prevents electrolyte leakage and safety issues caused by overdischarge.

(6) Recycling

The battery module shall be designed with an end-of-life management reminder or current limiting solution, which must be stated explicitly in the product documentation. This ensures that users are reminded to replace aging batteries and avoid safety issues such as lithium plating and electrolyte leakage caused by battery expiration. Additional guidance on proper end-of-life management of batteries is available in Recommendation ITU-T L.1035[4] .

4.3.2. Manufacturing safety requirements

The manufacturing safety design of the battery module shall consider incoming materials, storage, manufacturing, turnover, assembly, testing, shipping, repair, scrapping, and other scenarios. It should also analyse the five major factors that affect product quality: personnel, equipment, materials, solutions, and environment, and improve the first pass yield (FPY) of mass production. This helps intercept products that pose safety risks, ensure product safety during normal use or foreseeable reasonable abuse, prevent fire and explosion, and avoid or reduce personal injury and property loss.

(1) Incoming materials

During battery module manufacturing, key safety specifications of incoming materials shall be verified, including temperature resistance, voltage resistance, I2T fuse curve, and battery cell safety boundary. Non-destructive testing shall be performed comprehensively, and destructive testing shall be performed by sampling to ensure that incoming materials meet the product safety design requirements and avoid risks at the source.

[3] UL 94, Tests for Flammability of Plastic Materials for Parts in Devices and Appliances"
[4] Sustainable management of batteries

(2) Storage

During battery module manufacturing, storage and production environment control equipment must be configured to control key parameters such as temperature, humidity and cleanliness. This prevents high and low temperatures, condensation and dust from affecting the safety design of battery cells in terms of terminal area, insulation and dielectric strength, impedance, and so on.

(3) Manufacturing

During battery module manufacturing, environmental factors that may affect battery modules must be strictly controlled, including corrosive or organic substances, sunlight, fire sources, heat sources, and power supplies. Fire extinguishing equipment must be configured to prevent the external environment from affecting battery modules.

(4) Turnover/Assembly/Testing

During manufacturing turnover, assembly and testing of battery modules, automatic tools and devices shall be used, including mechanical arms, automatic stacking/assembly equipment, welding machines, intelligent electric screwdrivers, and insulation and dielectric strength testing/integrated performance testing equipment. Key process parameters shall be controlled and fed back to ensure production quality stability and reduce problems caused by manual operations. At least three guardrails or containers shall be designed to prevent product falling and collision.

(5) Shipping

Before battery modules are shipped, key safety specifications must be verified, including testing for insulation and dielectric strength, aging and temperature rise at high rate of discharge, and DC resistance (DCR). Non-destructive testing must be performed comprehensively, and destructive testing must be performed by sampling to ensure that the shipment quality meets product safety design requirements.

(6) Repair

The repair of returned defective battery modules must be separated from the repair of normal battery modules and be recorded. Tooling must be configured to ensure that no foreign objects are introduced during the repair. In addition, all returned battery modules must pass manufacturing testing.

(7) Scrapping

Defective battery modules must be scrapped as soon as possible. If battery cells or defective products that are deformed due to stress, or if they fail the aging test, and are thus deemed to be fire hazards after verification, they must be stored in a separate room equipped with fire-extinguishing equipment.

4.4. Safety requirements for battery systems

The safety design of battery cells and battery modules is the key to ensuring the intrinsic safety of batteries. However, during the operation of the lithium-ion battery system, battery thermal runaway or even fire may occur due to improper application. Therefore, the lithium-ion battery system shall also have safety design constraints to ensure the safety of the battery system.

(a) The lithium-ion battery system shall have a built-in battery management system (BMS) to monitor the voltage and temperature of each battery cell in the system and the charge and discharge current status of the battery rack. The BMS shall manage the battery system by layers and levels in a unified way. It shall monitor the voltage, current, temperature, and state of charge (SOC) of the batteries (cell, module and system) in real time based on the characteristics of each layer, and perform optimization control and comprehensive management to ensure the safe and stable operation of the battery system. The BMS shall consist of three levels: the first level is the battery module monitoring unit; the second level is the battery cabinet management system; and the third level is the management system for parallel battery cabinets. See IEC 62619[5] for minimum safety requirements for BMS.

(b) The battery system shall be able to independently connect to the network management system (NMS) and the cloud management system. The BMS on the device side shall be able to communicate and interact with the upper-layer system such as the NMS or cloud management system, to form a higher-level BMS that maintains battery safety, analyses long-term failures, and identifies potential battery cell risks in advance.

(c) When overvoltage, undervoltage, overcurrent, short circuit, high temperature, or low temperature occurs in the battery system, the battery charge and discharge loop shall be cut off quickly to isolate the fault point. In addition, alarm signals shall be reported to the monitoring system and UPS.

(d) Protective devices in the battery system shall include circuit breakers and fuses. If a short circuit occurs in the battery system, dual protection shall be implemented to protect the BMS system and battery cells from damage, including arcing, deformation, electrolyte leakage, smoke, fire, or explosion.

(e) The battery system shall ensure that the voltage and current of each battery cell, module, and rack do not exceed the design specifications. For example, a power control unit can be configured for each battery rack to accurately control the charge and discharge voltage and current of each battery rack.

(f) The lithium-ion battery cabinet shall provide protection against reverse power cable connections, that is, reverse power cable connections shall not cause battery damage. If reverse power cable connections are detected, an alarm shall be generated and the battery cabinet switch shall not be allowed to turn on.

(g) The top of the lithium-ion battery cabinet shall be waterproof to prevent water from entering the cabinet and damaging batteries. It is recommended that the lithium-ion battery cabinet be designed and certified to at least IP20 See IEC 60529. [6]

[5] IEC 62619 “Secondary cells and batteries containing alkaline or other non-acid electrolytes - Safety requirements for secondary lithium cells and batteries, for use in industrial applications”.

[6] IEC 60529:1989/AMD2:2013/COR1:2019, Degrees of protection provided by enclosures (IP Code).IPCode)

(h) The battery system shall be configured with an emergency power-off (EPO) dry contact and an EPO button in a safe area outside the battery room. In extreme scenarios such as lithium-ion battery valve opening, smoke, and fire, the battery system can be shut down remotely to prevent the failure from spreading. Before starting the water fire extinguishing system, the EPO shall be implemented to shut down the battery system. The lithium-ion battery cabinet should be configured with a fire detector and fire extinguishing equipment to control the fire in the early stage in case of thermal runaway.

(i) The customer wiring power terminal/copper bar of the battery cabinet shall have the temperature measurement and overtemperature protection functions to monitor, report, and protect against abnormal conditions, preventing overtemperature and fire caused by improper cable connections.

(j) The battery cabinet shall be equipped with a system-to-ground insulation monitoring circuit. Before the battery cabinet power-on switch is turned on and the battery system is connected to the power supply system, the system-to-ground insulation inside the battery system shall be detected. If the insulation resistance is low, an alarm shall be generated, indicating that the battery cabinet switch must not be turned on to prevent arcing and fire in the battery system due to insulation failure to the ground.

(k)The battery cabinet should be able to detect insulation failures in real time when the system is running. For example, a leakage current detector can be configured to detect the leakage current of the system in real time. When the leakage current is greater than the preset threshold, an alarm shall be generated to trigger protection (switch tripping) and prevent arcing and fire caused by continuous leakage current of the battery system.

5. Fire safety requirements for data centre lithium-ion batteries

5.1. Fire characteristics

In recent years, lithium-ion batteries have been widely used in power backup systems of data centres due to significant advantages such as high energy density, long service life, and low self-discharge rate. In general, lithium-ion batteries have high safety, but the fire characteristics are relatively complex due to the high energy density and continuous reaction after thermal runaway.

Due to electrical and thermal abuse, lithium-ion batteries are prone to thermal runaway, which can cause a fire or even an explosion. As a result, the safety of lithium-ion batteries has become an industry concern. Therefore, it is of great practical significance to study an effective method for extinguishing a lithium-ion battery fire, which can not only reduce the property loss of a company, but also ensure the life safety of employees and the stable operation of data centres.

Compared to traditional fires, due to thermal runaway lithium-ion battery fires have their own unique characteristics.

(1)High temperature rise rate and heat release rate

Lithium-ion batteries spontaneously become exothermic due to abuse. After thermal runaway occurs, the heat release reaction inside the batteries is severe, and a large amount of heat is generated in a short period of time. As a result, the battery temperature rises sharply. When thermal runaway occurs, a large amount of combustible gases, electrolyte, and material particles are ejected from the battery pressure relief valve, which, after igniting at a high temperature, creates a violent jet fire with an extremely high heat release rate. Rapid temperature rise and heat release complicate lithium-ion battery fire control and can quickly spread to the entire battery module or system.

(2)Fast fire spread

To increase the energy density of the system, battery cells in the module are closely arranged. When a battery cell in the battery module fails and thermal runaway occurs, heat is quickly transferred to adjacent battery cells due to close arrangement. As a result, heat spreads in the battery module, and the fire spreads rapidly.

(3)Complex fire extinguishing and easy re-ignition

During thermal runaway, most of the exothermic reactions occur inside the battery. However, due to the obstruction of the shell, the extinguishant cannot easily enter the battery to block the thermal runaway chain reaction. During fire extinguishing, if the battery temperature cannot be lowered completely, the heat source cannot be eliminated, and the internal chemical reaction cannot be suppressed, the temperature will continue to rise, which may lead to re-ignition.

(4)Generation of combustible and toxic gases

During thermal runaway of LFP batteries, the electrolyte produces a large amount of gases, including hydrogen, carbon monoxide, methane, and electrolyte vapor. If the concentration of combustible gases in the confined space exceeds the explosion concentration, there is a risk of explosion. In addition, the gases generated by thermal runaway are highly toxic and threaten personal safety. Therefore, proper ventilation must be established and air exhaust measures must be taken in order to reduce toxic gases during fire extinguishing.

5.2. General requirements

Based on the fire control principle of "giving priority to prevention and then combining fire prevention and control", this section draws on the experience of major fire accidents in recent years, and summarizes global design experience of lithium-ion battery rooms for building fire control and achievements of fire control technologies. Through in-depth research on new situations and problems arising in the development of engineering construction, as well as challenges in the implementation of regulations, the study draws on the experience of developed countries. It carries out much technical research, holds many technical workshops, and conducts many necessary physical fire tests. Additionally, it solicits opinions from institutes involved in design, production, construction, scientific research, teaching and fire control supervision.

It is recommended that relevant standards are properly selected to optimize project functions and performance. However, recommended engineering construction standards, and enterprise standards must be consistent with local mandatory engineering construction specifications. The technical requirements cannot be lower than those specified in the mandatory engineering construction specifications. Based on the failure modes of lithium-ion batteries, the safety risks of lithium-ion battery rooms can be classified into direct risks and indirect (secondary) risks.

A direct risk is that the heat, smoke, and combustible gases released by a lithium-ion battery failure cause fire and explosion, which further damage and burn all equipment in the lithium-ion battery room.

An indirect (secondary) risk refers to the impact on adjacent rooms and buildings of a fire or fire extinguishing resulting from a lithium-ion battery failure. For example, if it cannot be controlled effectively the fire may spread to adjacent rooms and buildings, and if smoke and combustible gases generated by lithium-ion batteries cannot be vented in a timely manner, this can spread to adjacent rooms, causing explosion hazards and harm to personnel, as well as damage to equipment, and buildings. Damage may also occur if the water used to suppress the fire cannot be drained in a timely manner; for example, the water may spread to surrounding rooms, causing avoidable losses.

To minimize direct and indirect (secondary) risks, fire control facilities need to be designed in terms of the lithium-ion battery layout, automatic fire extinguishing system, ventilation and smoke control and exhaust, thermal runaway detection and alarm, drainage, emergency power-off, and explosion protection and pressure relief to avoid risks in advance.

5.3. Plane layout

5.3.1. Overview

Lithium-ion batteries for data centres shall be deployed based on comprehensive factors including cost-effectiveness and safety. Remote skid-mounted deployment with an independent container or cabinet is preferred. Remote deployment in an independent structure or building is an alternative. If the remote deployment conditions are not met, batteries can be deployed in an independent room against the exterior wall of the building where the main equipment room is located, as shown in the Figure 6 below.

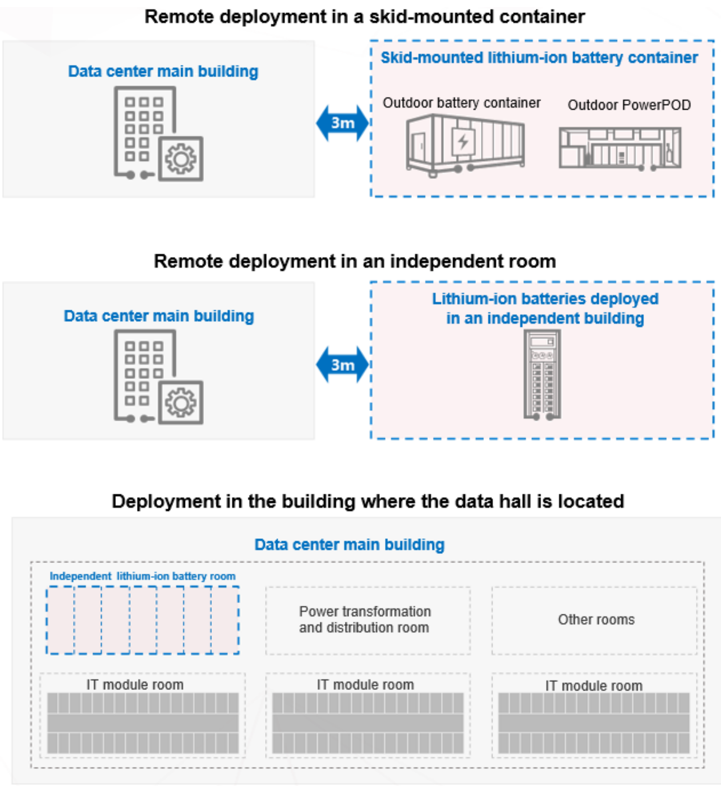


Figure 6: Example of Lithium-ion battery installation

The lithium-ion battery room in the data centre building shall be deployed in compliance with local fire code. The load-bearing structure should be reinforced concrete or steel frame and portal frame.

If lithium-ion batteries are deployed in a data centre building, they shall not be placed directly under or adjacent to a toilet or other places where water often exists and may leak. If they are so placed, the adjacent partition walls shall be waterproofed to prevent leakage and condensation. To prevent water pipe burst or water leakage from damaging electrical equipment, hot water pipes, steam pipes, or air conditioner water pipes with pressure shall not be deployed in the lithium-ion battery room.

5.3.2. Deployment requirements

To facilitate fire rescue, requirements for the position of the lithium-ion battery room, relationship and spacing between buildings, fire lanes and internal and external roads, and fire water sources shall be met to reduce the fire interaction between the building to be constructed and surrounding buildings, ensure that the fire engine has access and can effectively spray water, and prevent secondary disasters.

5.3.2.1. Remote deployment

In the remote deployment scenario, the fire safety distance of the lithium-ion battery room must be properly determined based on the height of the lithium-ion battery room or the height of the building in which the lithium-ion battery room is located, the fire resistance rating and the fire hazard. The fire safety distance shall ensure that the heat intensity radiated by the fire from the adjacent building to any side of the building wall is less than the critical ignition radiant heat intensity. If the lithium-ion battery room is deployed remotely, the recommended fire safety distance and fire resistance rating are as follows:

(a)If the fire resistance of a remotely deployed skid-mounted container, structure or building is not less than 1 hour, the fire safety distance between the container, structure, or building and other buildings shall be no less than 3 m.

(b)If the fire resistance of the wall of a remotely deployed skid-mounted container, structure, or building opposite to other buildings is greater than or equal to 2 hours, and the fire resistance of the other sides is greater than or equal to 1 hour, the fire safety distance between the container, structure, or building and other buildings shall be greater than or equal to 1 m.

5.3.2.2. Battery room deployed in the building where the data hall is located

When the lithium-ion battery room is deployed in the building in which the data hall is located, the capacity of a single lithium-ion battery room should not exceed 600 kWh. The lithium-ion batteries shall be deployed in a room against an exterior wall. The fire resistance time of the room shall not be shorter than that specified in the local fire code. The fire resistance limit of beams, columns, walls and sealed holes shall not be less than 2 h, and that of top and bottom floors shall not be less than 1.5 h. The evacuation door shall be a fire door that can withstand fire for at least 1.5 h. Protective measures such as a vestibule, shall be provided at the junctions between stairways, outdoor stairways, or hazardous areas and adjacent areas. The wall of the vestibule shall be a fire wall with a fire resistance of at least 2 h, and the door shall be a fire door with a fire resistance of at least 1.5 h and shall not be installed in line with the staircase door. The fire safety distance depends on the fire resistance level of the building, the fire resistance and fireproof structure of the exterior walls, the height and fire hazard of the building, and the fire rescue conditions outside the building. It shall be determined according to the principle of preventing the fire from spreading to adjacent buildings and facilitating fire rescue.

The lithium-ion battery room’s height shall meet the local fire rescue equipment conditions and shall not be deployed in a basement or semi-basement, in order to facilitate intervention by the fire brigade. The lithium-ion battery room shall be effectively sealed and isolated from cable trays, air conditioning ducts, and smoke control and exhaust ducts in other related spaces. This will prevent secondary disasters such as fire, heat hazards, toxic and noxious gases, combustible vapors, flowing fire, and fire water from spreading to other building spaces.

The lithium-ion battery room shall be equipped with emergency facilities such as emergency exit, fire door, pressure relief and explosion protection device, emergency light, clear permanent lithium-ion battery room label, and capacity- indication label, and tools such as breathing mask, cart water-based fire extinguisher, removal tool, and insulated gloves.

If the lithium-ion battery room is deployed against the exterior wall of the building in which the data hall is located, a fire access opening shall be reserved in the fire rescue direction, and clear permanent labels shall be affixed inside and outside the opening. The opening shall be designed according to the local fire code. It is recommended that the opening be deployed in the middle of the exterior wall of the lithium-ion battery room. The distance between the bottom of the opening and the bottom floor of the lithium-ion battery room shall be greater than or equal to 2 m. The width and height shall not be less than 1 m. When the exterior window is used for fire rescue, safety glass shall be used. When the door is used for fire rescue, the net width shall not be less than 0.8 m.

5.4. Automatic fire extinguishing system (equipment)

5.4.1. Overview

According to global physical fire tests and related standards, water is the first choice for suppressing lithium-ion battery fires. However, the power supply must be disconnected before extinguishing the fire, and insulation measures should be checked and implemented after suppression to mitigate the negative effects of water application. Further details will be provided in this section. In contrast, dry powder, carbon dioxide, and inert gas cannot effectively cool lithium-ion batteries in case of thermal runaway, posing a risk of re-ignition. For example, Singapore updated its fire code in 2023,[7] stipulating that an automatic water spray fire sprinkler system must be installed in lithium-ion battery rooms. Other countries, including Malaysia, have introduced similar regulations.

Lithium-ion battery rooms shall be equipped with an automatic fire extinguishing system that can effectively extinguish fires and suppress re-ignition. A water spray or automatic sprinkler system is recommended.

Based on global regulations and specifications, related experimental verification, and firefighting and rescue experience, the following requirements are proposed for firefighting facilities in the lithium-ion battery room of a data centre.

5.4.2. Extinguishant selection

If thermal runaway occurs in a lithium-ion battery, the impact spreads throughout the battery module in a short period of time. Thermal runaway can spread rapidly and is prone to re-ignition if the batteries cannot be cooled continuously and effectively. In addition, adjacent battery modules may even catch fire due to heat conduction.

Therefore, to extinguish a lithium-ion battery fire, the open flame of the battery must be extinguished quickly, and the extinguishant must have strong cooling and heat dissipation capabilities to prevent re-ignition. By physical status, fire extinguishants can be classified into gas extinguishant, dry powder extinguishant, and water extinguishant.

[7] https://www.scdf.gov.sg/fire-safety-services-listing/fire-code-2023

(1) Gas Extinguishant

The gas extinguishant is non-conductive, non-corrosive, non-persistent, and fast-flowing. It can be used in confined spaces for better extinguishing effect.

- **Carbon dioxide extinguishant:** It is cheap, easy to prepare, liquefy, and store, and environmentally friendly. Carbon dioxide evaporates immediately after being released into the fire area, producing a large amount of gaseous carbon dioxide that reduces the oxygen concentration around combustibles and suppresses flames. However, carbon dioxide can only suppress a fire physically and has a limited cooling effect. It is difficult to extinguish a lithium-ion battery fire, and the battery is prone to re-ignition.

- **Heptafluoropropane extinguishant:** Its extinguishing mechanisms include physical suppression and chemical suppression. Gasified and decomposed heptafluoropropane can absorb ambient heat, reduce the temperature of the fire area, and dilute the oxygen concentration. In addition, it decomposes products at high temperature, which can trap combustible free radicals, interrupt the combustion chain reaction, and suppress the flame. However, it has an obvious greenhouse effect and a limited cooling effect on a lithium-ion battery fire, posing a risk of re-ignition.

- **Perfluorohexanone extinguishant:** This has an excellent fire extinguishing performance and is non-conductive. It is mainly used to extinguish battery fires by physical and chemical suppression. Perfluorohexanone is a liquid at room temperature with a boiling point of about 49°C and has a relatively high latent heat of vaporization. In addition, it decomposes at high temperature, which can remove free radicals during combustion and interrupt the combustion chain reaction. Therefore, after perfluorohexanone extinguishant is released into a confined space, it can absorb a large amount of heat, reduce the temperature of the fire area, and isolate oxygen to suppress the flame.

  Although perfluorohexanone has excellent fire extinguishing performance and good cooling performance, it is difficult to continuously reduce the temperature of lithium-ion batteries, and there is a risk of re-ignition. In addition, as hydrofluoric acid is generated when the extinguishant is used, protective measures must be taken.

  Aerosol extinguishant: Aerosol is a gaseous dispersion system composed of solid or liquid particles suspended in the gas medium. The particles can be suspended in the air for a long time without being affected by obstacles. Aerosol particles are generated by burning an aerosol-forming agent and do not require a pressurized container. Metal ions generated by aerosol decomposition can eliminate free radicals needed to sustain combustion, thereby interrupting the chain reaction. In addition, the vapor and carbon dioxide generated by the decomposition of metal oxides and carbonates reduce the oxygen concentration and suppress the flame. With its excellent fire extinguishing efficiency, low persistence, and non-conductivity, it is widely used in high-risk places. However, the cooling effect of the aerosol extinguishant is poor, and the efficiency of suppressing the re-ignition of lithium-ion battery fires is not satisfactory.

(2) Dry Powder Extinguishant

Dry powder is solid powder formed by drying, crushing and mixing inorganic fire-extinguishing salt, and a small amount of additives. ABC dry powder is applicable to extinguishing Class A, Class B, and Class C fires.

The main component of ABC dry powder is ammonium phosphate, which extinguishes flames by isolation, smothering, cooling, and chemical suppression. After dry powder is released into the fire area, it decomposes products at high temperature, which can trap combustible free radicals and interrupt the combustion chain reaction. In addition, the decomposition of dry powder absorbs heat and produces ammonia and water vapor to dilute the oxygen concentration in the fire area.

Moreover, dry powder falls onto the surfaces of high-temperature combustibles and melts to form a glass coating to isolate oxygen and smother the combustibles. However, dry powder cannot cool lithium-ion batteries down effectively. Even if the open flames are extinguished, the batteries may re-ignite.

(3) Water Extinguishant

The water extinguishant has a large heat capacity and latent heat of vaporization. It absorbs a large amount of heat through phase transition in the fire area. After vaporization, its volume expands to reduce the oxygen concentration, providing excellent fire extinguishing and cooling performance. Because it is also inexpensive and easy to use, it has a wide range of applications.

Based on the particle size of liquid droplets, common fire extinguishing systems based on water extinguishant can be divided into automatic water sprinkler fire extinguishing systems, water spray fire extinguishing systems, and water mist fire extinguishing systems.

- **Automatic water sprinkler fire extinguishing system:** The particle size of water droplets is large. After sprinkling, the droplets gain sufficient momentum and force to penetrate the flame and high-temperature smoke to the root of the flame and the surfaces of combustible materials, thereby effectively cooling the batteries. The system has good fire extinguishing and cooling effects for lithium-ion battery fires. However, sprinkling water is conductive and can cause insulation failure in the battery system. Therefore, the power supply must be disconnected before extinguishing the fire, and check and take insulation measures after extinguishing the fire to reduce the negative effects of water sprinkling.

- **Water spray fire extinguishing system:** Based on the centrifugal or collision principle, the water spray nozzle breaks down the water flow into fine water mist droplets for fire extinguishing and cooling protection under a certain water pressure. The water spray nozzle sprays out misty water with a particle size of less than 1 mm. It can be used to put out solid fires, liquid fires with a flashpoint higher than 60°C, and oil-immersed electrical equipment fires. Extinguishing fires produces a large amount of water vapor, which can facilitate extinguishing by cooling, smothering, emulsifying, and diluting the fire.

- **Water mist fire extinguishing system:** The diameter of mist droplets is small. Compared with the same volume of water, mist droplets have a much larger surface area, which increases the heat exchange efficiency and achieves a good cooling effect. After absorbing heat, the fine water mist evaporates quickly, causing the volume to expand greatly. This reduces the oxygen concentration in the air, suppresses the oxidation reaction rate during combustion, and contains the fire. In addition, the fine water mist has excellent performance in blocking heat radiation transfer, and can effectively block heat radiation from flames and high-temperature objects. Fine water mist features insulation, as well as excellent fire extinguishing, cooling, and environmental protection performance, and can properly suppress lithium-ion battery fires. However, the particle size and momentum of the fine water mist are relatively small, making it susceptible to ventilation and obstacles. And when the heat release rate is relatively high, it is difficult for the fine water mist particles to reach the surface of batteries due to heat buoyancy, which weakens the cooling effect.

In summary, water extinguishant shall be used for the fire extinguishing system in data centre lithium-ion battery rooms.

[7] https://www.scdf.gov.sg/fire-safety-services-listing/fire-code-2023

5.4.3. Design requirements

The lithium-ion battery room in a data centre shall be equipped with a fire extinguishing system that uses the water extinguishant. For detailed selection, see local standards for sprinkler systems, water spray fire protection systems and water mist fire extinguishing system. Water pipes and nozzles should not be installed directly above lithium-ion battery cabinets. Based on related test data, the water spray fire extinguishing system is preferred, followed by the automatic water sprinkler fire extinguishing system and the water mist fire extinguishing system.

The density of the water spray fire extinguishing system shall be greater than or equal to 20 $L/(min \cdot m^2)$. The fire water storage capacity in the campus shall be greater than or equal to 2 h. Nozzles shall be designed and arranged according to the local standard for water spray fire protection systems in order to provide all-round protection.

The density of the automatic water sprinkler fire extinguishing system should be greater than or equal to 12 $L/(min \cdot m^2)$, and the fire water storage capacity in the campus shall be greater than or equal to 2 h. Nozzles shall be designed and arranged to provide all-round protection. Water pipes and nozzles shall be installed in front of the battery cabinet. The maximum height of nozzles shall be less than or equal to 7.8 m.

The operating pressure of the water mist fire extinguishing system shall be greater than or equal to 5 MPa, and the density shall be greater than or equal to 1.2 $L/(min \cdot m^2)$. Nozzles shall be designed and arranged according to the local standard for water mist fire extinguishing system to provide all-round protection.

The lithium-ion battery room in a data centre shall be equipped with a fire water supply system. The fire water supply volume, fire hydrant design flow, and applicable fire duration shall comply with local code for fire protection water supply and hydrant. Surrounding water sources (fire engines, self-prepared water in the campus, or municipal water) can supply water continuously for 10 hours.

The lithium-ion battery room in a data centre shall be equipped with fire extinguishers. The configuration of fire extinguishers shall comply with local standard for design of fire extinguisher distribution in buildings. Lithium-ion battery room extinguishers shall be configured based on Class A (solid combustibles) and moderate risk fires.

5.5. Ventilation and smoke control and exhaust

5.5.1. Overview

Lithium-ion batteries do not generate combustible gases during normal operation. However, hydrogen, carbon monoxide, and a small amount of hydrogen fluoride are released during valve opening and water spraying in the event of thermal runaway. The number of ventilation times in an emergency need to be specified to ensure timely exhaust of combustible gases.

5.5.2. Design requirements

The lithium-ion battery room in a data centre shall be equipped with an independent ambient temperature and humidity control system and explosion-proof ventilation device. A manual exhaust switch shall be installed outside the room. The emergency ventilation system shall be linked to the combustible gas detection and alarm device and the ambient temperature and humidity control system.

The air ducts, air vents, valves, and thermal insulation materials of the air conditioning system in the lithium-ion battery room shall be flame-retardant or non-combustible. The emergency ventilation volume shall comply with related regulations and the number of emergency ventilation times shall be greater than or equal to 12 times/h.

If an in-room gaseous fire extinguishing system is used, the emergency fan shall stop after the fire extinguishing system is activated. If an automatic water spray fire extinguishing system, automatic water sprinkler fire extinguishing system, or water mist fire extinguishing system is used, the emergency fan shall be always on after the fire extinguishing system is activated. However, it is not mandatory to activate the emergency fan if lithium-ion batteries are deployed remotely in an outdoor skid-mounted container.

The emergency fan shall be explosion-proof and devices of the emergency ventilation system shall not be deployed in the basement or semi-basement. In addition, the emergency ventilation systems of fire safety zones shall be isolated from each other. A fire damper with an operating temperature of at least 150°C shall be installed in the fire safety zone through where an air duct is routed. If the air duct is directly routed outdoors, no air damper is required and the fire safety zone shall not share an air damper with the ventilation system in the main service room.

5.6. Thermal runaway detection and alarm

5.6.1. Overview

The lithium-ion battery room in a data centre shall be equipped with an automatic fire alarm system. The design, construction, and acceptance standards of the automatic fire alarm system shall comply with local codes and standards. The automatic fire alarm system can be deployed independently or be connected to the automatic fire alarm system of the building where it is located for centralized management.

It is advised to use a dedicated fire detection and alarm system that is specially developed for lithium-ion battery fires and has obtained mandatory certification. Lithium-ion batteries release combustible gases or vapors such as hydrogen and carbon monoxide only when the valves are opened due to thermal runaway. Normally, the emergency fan does not operate. When the detector detects that the concentration of combustible gases reaches the alarm and action thresholds, the fan is activated to exhaust the combustible gases from the battery room. Related standards require an alarm threshold of 10 per cent lower flammability limit (LFL) and an action threshold of 25 per cent LFL. The hydrogen or carbon monoxide concentration shall be detected and two levels of combustible gas concentration thresholds shall be set.

5.6.2. Design requirements

Fire detectors such as combustible gas detectors, heat detectors and smoke detectors shall be installed in the lithium-ion battery room of a data centre. The lithium-ion battery room shall be equipped with at least one type of combustible gas detector. Carbon monoxide or hydrogen detectors are recommended. The number of each type of detector shall be at least two per room. The gas detectors shall be linked with the ventilation system, automatic fire alarm system, gas concentration display, and alarm devices. The lower explosive limit (LEL) set for combustible gas detectors shall be consistent with the declaration of thermal runaway characteristics for lithium-ion batteries.

Gas detectors shall be properly installed based on the characteristics of different types of gases, air flow rates, effective coverage, detector principles and performance, and maintenance and calibration requirements. As required by the installation specifications, the carbon monoxide detector shall be installed near the battery cabinet. If it is an in-cabinet model, the carbon monoxide detector shall be installed inside the battery cabinet. The hydrogen detector shall be mounted on the ceiling (if there is a suspended ceiling, install one on each side of the ceiling).

In addition to combustible gas detectors, the lithium-ion battery room can also use reliable and advanced methods such as composite fire detectors, active gas detection tubes, and thermal imaging to report early thermal runaway alarms.

5.7. Drainage

5.7.1. Overview

If the lithium-ion battery room in a data centre is equipped with an automatic water spray fire extinguishing system, automatic water sprinkler fire extinguishing system, or water mist fire extinguishing system, the drainage system design must consider the ability to drain fire water in a timely manner after the fire extinguishing system is activated. This will prevent secondary hazards such as water accumulation, overflow, and leakage from spreading to adjacent functional spaces and causing unnecessary loss.

5.7.2. Design requirements

The floor, walls, doors, and cable trays of the lithium-ion battery room in a data centre shall be waterproofed. If gravity drainage is used in the lithium-ion battery room, the height of water barriers shall not be less than 50 mm, and the recommended height is 100 mm. If other drainage methods are used, the corresponding drainage volume requirements shall be met. If the irrigation-type destructive water fire extinguishing is used, the drainage port shall be higher than the highest battery, and a fire hydrant port shall be reserved for water supply.

Water pumps or natural drainage can be used. The drainage capacity shall not be less than the spraying capacity of the automatic fire extinguishing system, and the margin coefficient shall not be less than 10 per cent.

5.8. Emergency power off (EPO)

5.8.1. Overview

For the Emergency Power Off (EPO) setting, the lithium-ion battery cabinet shall have an independent EPO dry contact, and the EPO dry contacts of battery cabinets in the parallel system shall be connected in parallel and then linked to the EPO button in the equipment room.

5.8.2. Design requirements

The fire linkage controller shall be able to disconnect the non-fire extinguishing power supply in the fire area and associated areas. If it is necessary to disconnect normal lighting, it is recommended that the lighting be disconnected before the automatic sprinkler system and hydrant are activated. A dedicated EPO button for fire rescue and extinguishing shall be installed outside the lithium-ion battery room, and protective measures shall be taken to prevent maloperations.

The emergency fan shall be powered by the fire extinguishing power supply. If non-fire extinguishing devices obtain power from the power distribution box (PDB), it is recommended that a shunt release be configured in the upstream PDB to remotely power off the circuit breaker. Lithium-ion battery cabinets in the battery room shall have independent EPO dry contacts and support one-click disconnection of lithium-ion battery devices in the room. National electric codes needs to be considered when designing this system, additionally IEC Standard 60364 series can be used.

5.9. Explosion protection and pressure relief

5.9.1. Overview

Lithium-ion batteries release combustible and explosive components (hydrogen, methane, carbon monoxide, and ethyl methyl carbonate) when the valve is opened due to thermal runaway. If these components cannot be vented to the atmosphere in a timely manner when the concentration reaches the lower explosive limit (LEL), there is a risk of explosion if a spark is ignited. The explosion creates shock waves that first break through points with weak pressure resistance in the lithium-ion battery room. High pressure is instantly released, causing damage to the building and people in the area.

5.9.2. Design requirements

The lithium-ion battery room should be equipped with pressure relief and explosion protection devices or pressure relief channels (such as glass windows and magnetic lock doors) with equivalent areas. If side pressure relief is used, a protection fence or wall shall be installed outside the pressure relief channels and fire warning labels shall be attached to the fire doors used for pressure relief. These may not be installed if the combustible gas concentration in the lithium-ion battery room can be controlled within 25 per cent of the LEL, or if the explosion resistance of the room is greater than the internal explosion pressure. Based on parameters such as the structure layout, battery type, and interior space of the lithium-ion battery room, a numerical explosion model of the data centre can be built in a numerical simulation manner, and the location and area of the explosion relief opening can be optimized to provide safety assurance for mitigating the consequences of the battery room explosion.

The lithium-ion battery room shall have a non-sparking floor. If insulation materials are used, ESD measures shall be taken. Trenches are not recommended. If trenches are required, they shall be tightly covered. Effective measures shall be taken to prevent the accumulation of combustible gases, vapors, dust, and fibres. In addition, fire-resistant materials must be used at the joints between trenches and adjacent buildings.

In summary, the fire safety requirements for batteries deployed in a remote skid-mounted container, remote independent room, or the building where the data hall is located are shown in Table 1.

White paper on the Safety of lithium-ion battery applications in data centres

Table 1 – Summary of fire safety requirements for batteries in remote deployments and data hall buildings

Item	Sub-item	Fire safety requirement	Remote skid-mounted container	Remote independent room	Building where the data hall is located
Plane Layout	Deployment	Independent lithium-ion battery room	May	Should	Shall
		When the battery room is deployed against an external wall, the wall in the fire extinguishing direction can be removed or a fire rescue window is reserved.	-	Shall	
		Location requirement	shall meet the local fire rescue equipment conditions and shall not be deployed in a basement or semi-basement,		
	Fire resistance level	Distance from other buildings ⩾ 3 m, overall fire resistance of the container	Shall ⩾ 1 h	-	
		Distance from other buildings ⩾ 1 m, fire resistance of the side plate of the container opposite to the building	Shall ⩾ 2 h	-	
		Fire resistance time of beams, columns, and four walls	-	Shall ⩾ 2 h	
		Fire resistance of the top and bottom floors	-	Shall ⩾ 1.5 h	
		Fire resistance of fireproof sealing kits	Shall not be less than fire resistance time of the wall		
		Fire resistance of the fire door	Shall ⩾ 90min		
	Peripheral requirements	Reachable by fire engines on peripheral roads	Shall		
Automatic fire extinguish-ing system	Fire extinguishing mode	Water spray fire-extinguishing system, automatic water sprinkler fire extinguishing system, or water-mist fire extinguishing system	Should		Shall
	Automatic water sprinkler/water spray fire extinguishing system	Surrounding water sources (fire engines, self-prepared water in the campus, or municipal water) can supply water continuously for 10 hours.	Should		Shall
		Water density and duration of the automatic water sprinkler fire extinguishing system	Should be 12 $L/(min \cdot m^2)$ and last for 2 h and above		
		Water density and duration of the water spray fire extinguishing system	Shall not be less than 20 $L/(min \cdot m^2)$ and last for 2 h and above		
		Nozzle layout	Distance shall be greater than 3 m ,when water sprinklers are used, the height shall not be greater than 7.8 m		
	Water mist fire extinguishing system	Surrounding water sources (fire engines, self-prepared water in the campus, or municipal water) can supply water continuously for 10 hours.	Should		Shall
		Operating pressure of water mist	Shall not be less than 5 MPa		
		Water density and duration of the water mist fire extinguishing system	Shall not be less than 1.2 $L/(min \cdot m^2)$ and last for 4 h and above		
Ventilation and smoke control and exhaust	Emergency ventilation	Times of emergency ventilation in the lithium-ion battery room	Shall not be less than 12 times/h		
	Linkage	Alarm linkage with combustible gas detectors	Shall		
Thermal runaway detection and alarm	Number of detectors	Combustible gas detector (hydrogen or carbon monoxide)	Shall not less than 2/room or 2/cabinet		
	Installation	Carbon monoxide detector installation position	Close to battery cabinets		
		Hydrogen detector installation position	Ceiling-mounted installation (installed on each side if a suspended ceiling is used)		
Drainage	Drainage flow	Drainage capacity ⩾ Spraying capacity of the automatic fire extinguishing system, and margin coefficient ⩾ 10 %	Shall		
	Spread prevention	Water barrier height in the lithium-ion battery room	-	Shall ⩾ 50 mm, recommended: 100 mm	
EPO	Power-off	Remote one-click disconnection of non-fire extinguishing devices	Shall		
Explosion protection and pressure relief	Explosion relief measures	Pressure relief and explosion protection devices or pressure relief channels (such as glass windows and magnetic lock doors)	Should		
		If side pressure relief is used, a protection fence or wall shall be installed outside the pressure relief channels and fire warning labels shall be attached to the fire doors used for pressure relief.	Shall		

6.Transportation safety requirements

6.1. Overview

According to international regulations and standards, lithium-ion batteries are classified as Class 9 Miscellaneous Dangerous Goods for delivery and transportation, and their UN IDs are UN3480 and UN3481 in most cases. The products must meet the transportation safety design and testing requirements, and the product packaging, labeling, marking and transportation tools must comply with the regulations related to UN3480 and UN3481 to help prevent fire accidents and properly handle emergencies.

6.2. Transportation safety conditions

6.2.1. General requirements

Lithium-ion batteries shall be designed and manufactured in accordance with general requirements, including but not limited to the following:

(a) Each battery model must pass the UN38.3 test and corresponding reports must be provided as required by the carrier.

(b) Each battery must be equipped with a safety exhaust device or designed to prevent damage during transportation.

(c) Each battery must have an effective device for preventing external short circuits.

(d) Each transported battery module must be designed to prevent reverse current.

(e) The watt-hour value must be marked on the surface of a lithium-ion battery.

6.2.2. Packaging requirements

6.2.2.1. Selection and use of goods packages

According to regulations on Class 9 Miscellaneous Dangerous Goods and UN3480, determine the applicable packaging guidelines and select UN packing cases. The packing cases must pass strength tests such as drop and stacking tests.

6.2.2.2. Signs and labels on lithium-ion battery packages

According to regulations and standards, the outer lithium-ion battery packages

must be attached with proper signs, including UN IDs and package serial

numbers (PSNs), prior to shipment. In addition, lithium-ion batteries and related products must be attached with hazard labels that meet the minimum size requirements.

6.3. Transportation vehicles

6.3.1. Vehicle selection

The selection of transportation vehicles shall comply with laws and regulations. Select carriers, vehicles, drivers, escorts, and other resources qualified for transporting dangerous goods to ensure compliance.

6.3.2.Protection requirements for vehicle/container loading

When loading lithium-ion batteries and related products into vehicles or cabinets, observe the following precautions:

(a) Batteries must be segregated from other combustible and explosive dangerous goods to avoid mixed loading and transportation.

(b) Do not expose batteries to high temperatures during transportation. If necessary, take effective cooling measures.

(c) Handle the packages with care to avoid battery short circuits or damage caused by physical shock or crushing. When loading, place the packages containing dangerous goods at the rear of the vehicle and ensure that the hazard labels and signs face outward.

(d) It is recommended that a pallet be used to load the packages to avoid strong vibration. The vertical and horizontal edges of the pallet must be protected by corner guards.

(e) The packages must be kept away from fire sources and combustible materials during loading and transportation.

(f) During transportation, inspect the packages periodically to ensure that their outer surfaces are intact, that the internal and external temperatures are normal, and there is no obvious temperature increase, package leakage, or smoke. If any exception occurs, take proper measures promptly.

(g) Take photos of each vehicle/container in different states such as empty vehicle/container, loading vehicle/container, loaded vehicle/container, and hanging labels/signs.

(h) The transport components containing dangerous goods packages of lithium-ion batteries must be attached with appropriate UN IDs and placards that meet the minimum size requirements on the outer surfaces.

6.4. Safety management requirements during transportation

6.4.1. Declaration requirements

Prior to shipment, the shipper must provide the carrier with the UN ID, proper shipping name, hazard class, packaging category, number of packages, and package weight of the dangerous goods to be transported, and complete and file the appropriate declaration forms and documents in accordance with the laws and regulations of the various transportation modes.

6.4.2. In-transit monitoring

Ensure that the vehicle door remains closed and locked during transportation. Do not allow unauthorized persons to enter the transportation vehicle. Maintain two-way communication throughout the transportation process. Configure vehicle Global Positioning System (GPS) and dynamically track vehicle status. It is recommended that the vehicle and goods status be confirmed with the supplier every four hours based on local laws and regulations and management policy.

6.4.3. Parking management

The vehicle must be driven according to the specified route. Illegal parking and emergency braking are prohibited. The vehicle must be parked in a formal parking lot (with Closed-Circuit Television (CCTV), fence and access control measures) if it is to stay overnight with goods. It is forbidden to park the vehicle at the roadside, and in the vicinity of schools, hospitals, gas stations, chemical plants or vehicles transporting combustible and explosive dangerous goods.

6.5. Emergency handling during transportation

If packages are damaged or an operational accident occurs, isolate the goods separately (at least 6 m away from other goods/walls), place a warning line, and report the situation. The logistics manager contacts the project team and supply chain director for handling suggestions and quickly implements the suggestions. For major exceptions such as leakage, smoke and fire, handle them immediately according to the Material Safety Data Sheet (MSDS). For the scrapping or inspection of outbound faulty parts, special vehicles must be arranged in advance for transportation. Unless otherwise specified, pallet removal and goods unpacking are prohibited in transit.

6.6. Safety requirements for temporary storage

6.6.1. Basic storage environment requirements

Lithium-ion batteries must be stored indoors without direct exposure to sunlight or rain. The storage environment must be dry, well ventilated, and clean. They must not be exposed to high levels of infrared or other radiation, organic solvents, corrosive gases, or conductive metal dust, and must be at least 3 m away from combustible materials. If a battery is faulty (with scorch, leakage, bulge, or water intrusion), move it to a dangerous goods warehouse for separate storage and dispose of it as soon as possible.

The storage environment specifications are as follows:

- **Optimal storage temperature:** 15°C to 25°C; extreme temperature: 0°C to 60°C
- **Optimal storage humidity:** 45 % – 75 % RH; extreme humidity: 5 % –95 % RH (non-condensing)

6.6.2. Storage requirements

Store batteries in a separate place. Do not store batteries together with other devices. Do not stack batteries too high. It is not recommended to store batteries on shelves. In addition, the packing cases of battery modules must be intact and placed correctly according to the labels on the packing cases. Do not place battery modules upside down, sideways, or at an angle. Stack battery modules according to the stacking instructions on the packing cases. Do not stack battery modules too high. Charge the batteries in time if the end of a charge interval is approaching.

7. Installation requirements

Installation is an important part of the safe use of lithium-ion batteries in a data centre and must be performed by a professional delivery team. The installation requirements include qualification, pre-installation, installation process, and startup and commissioning requirements.

Before installing equipment, read the product documentation carefully to get familiar with product information and safety precautions.

7.1. Installation qualification requirements

The qualification requirements for installing lithium-ion batteries in a data centre include the qualification requirements for the team and the installation personnel. Only qualified personnel are allowed to perform operations on equipment. Operation personnel shall understand the system, its working principles, and relevant national/regional standards.

7.1.1. Qualification requirements

The qualification requirements for the data centre lithium-ion battery installation team include technical qualification, safety certificate, environmental management certificate, fire safety certificate, industrial and commercial business licence, and tax registration certificate. The technical qualification requires the team members to have certain knowledge of electronic technologies and lithium-ion batteries, and to be able to master the installation, maintenance, and testing technologies of the lithium-ion battery system.

7.1.2. Certification requirements

To install lithium-ion batteries in a data centre, onsite operators must have valid certificates, including the low-voltage electrician certificate, and enterprise occupational certification or professional certification. Uncertified personnel are prohibited from entering the construction site or from touching equipment in order to prevent personal injury and property damage. Lithium-ion battery installation personnel must have professional skills and knowledge, including the working principles, installation process, and safety specifications of lithium-ion batteries, to ensure the safety and accuracy of the installation process. National regulation on safety of workers needs to be considered.

Table 2 – Reference information about related qualification certificate

Certificate	Operation	Work content	Certification authority
Certificate for the manufacturer's product services	Operations on the manufacturer's devices	Operators certified by the lithium-ion battery manufacturer install, commission, and maintain lithium-ion batteries.	Lithium-ion battery manufacturer or professional training organization entrusted by the manufacturer. National requirements for installer certification and authorization

7.2. Pre-installation requirements

Before installing lithium-ion batteries, personnel must be familiar with the safety information, including personnel, environment, transportation, storage and installation requirements.

(1) Personnel operation requirements

In risky operation scenarios such as battery installation and working on or near energized electrical equipment, at least two electricians are required onsite: one for operations and the other for monitoring and recording. Operators must wear dedicated protective equipment throughout the process and use dedicated insulated tools during electrical operations.

(2) Environment requirements

Install batteries in a dry, well-ventilated environment that is free from high temperature, high humidity, and combustible or explosive materials to prevent short circuits or overheating. Before the fire extinguishing system in the battery room is put into use, temporary fire extinguishing facilities must be deployed according to construction safety regulations.

(3) Transportation requirements

Handle with care. Bumping and tilting are prohibited.

(4) Storage requirements

Do not store batteries outdoors. Do not expose batteries to moisture, rain or dust. Do not place batteries near combustible or explosive materials. Charge the batteries in time if the end of a charge interval is approaching. For more information, see section 6.6 Safety requirements for temporary storage.

(5) Installation requirements

Do not install batteries under pipes with water leakage risks. Do not allow foreign objects to enter the devices. Do not forcibly insert or remove modules or units. Use dedicated insulated tools for electrical connections. Tighten screws according to the torque requirements and mark the screws in red and blue for double check. Perform the insulation test between batteries and the cabinet to ensure good insulation. Seal the cable holes. Do not remove the dustproof cover or dustproof film before power-on.

(6) Other requirements

To prevent dust buildup that may damage the equipment, install battery modules after dust-prone operations in the equipment room are completed. Before the lithium-ion battery system is powered on, check that the power supply equipment and fire extinguishing equipment in the battery room work properly. If the fire extinguishing equipment is unavailable, there must be a temporary fire extinguishing solution to cope with the risk of lithium-ion battery fire.

In scenarios where old and new batteries are used together, the lithium-ion batteries must support intelligent voltage balancing and active current balancing.

7.3. Installation process requirements

Ensure that the installation meets the manufacturer's safety requirements for installation preparations, onsite fire safety management, installation techniques, and installation quality control to minimize risks.

7.3.1. Installation preparations

(1) Dedicated tools

Use dedicated chargers and explosion-proof tools to ensure safety during charging and prevent fires or explosions caused by improper tools.

Before installation, ensure that personal protective equipment (PPE) is available, as shown in figure 7. For details about other tools, see the lithium-ion battery user manual provided by the manufacturer.

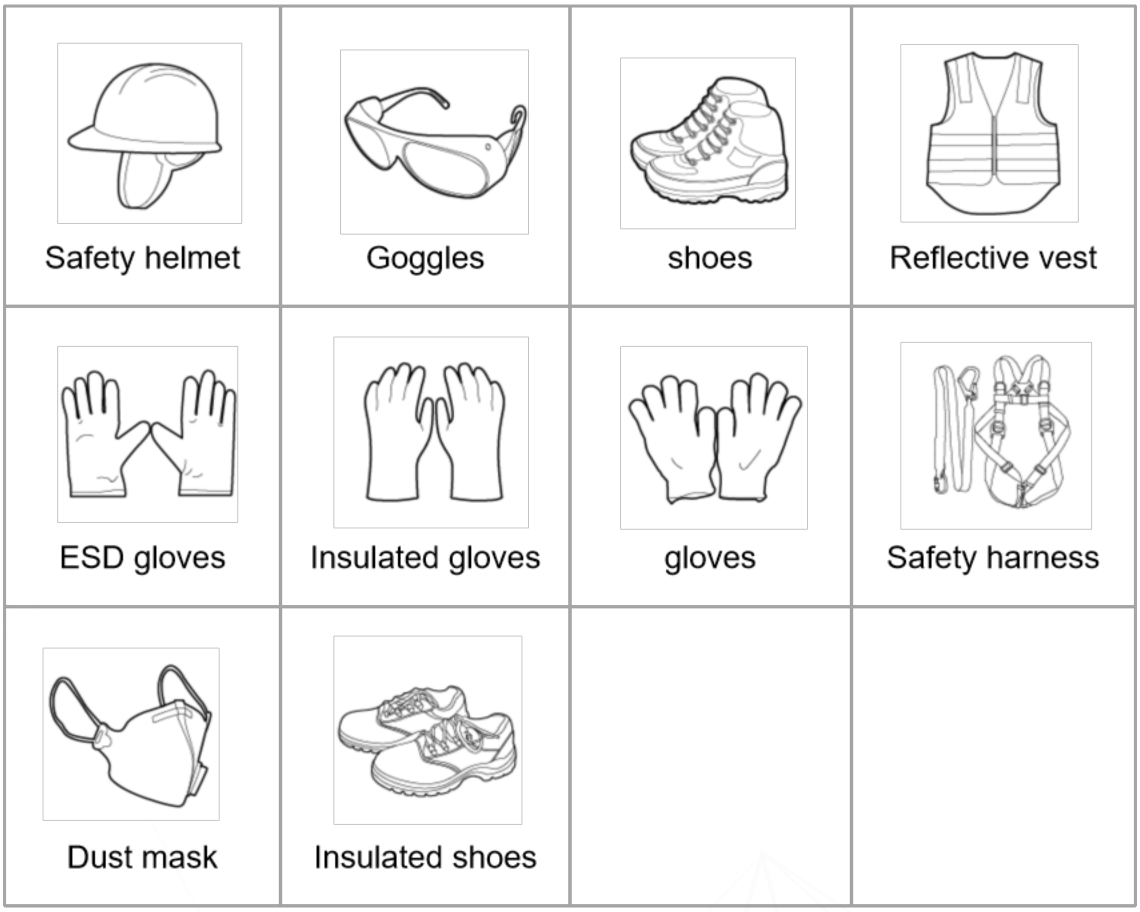


Figure 7: Required worker safety equipment

(2) Installation clearance requirements

Reserve certain clearances around the cabinet to facilitate operations and ventilation. For details, see the manufacturer's requirements. The installation and heat dissipation requirements must be met.

(a) A clearance of at least 850 mm shall be reserved in front of the front door of the cabinet to facilitate ventilation and operations.

(b) The maintenance passage width for the lithium-ion battery cabinet should be greater than or equal to 1 m, and the net distance between the sides of the cabinet and the wall shall be greater than 100 mm. For a lithium-ion battery cabinet that is installed against the wall, the net distance between the rear of the cabinet and the wall shall not be less than 50 mm.

The cable tray and cable trough above the cabinet must be at a certain height. A clearance of at least 500 mm must be reserved above the cabinet to facilitate operations. If multiple cabinets share one cable trough, the size and bending angle of the cable trough must meet the requirements on the minimum bending radius of cables. For details about the minimum bending radius, see the technical specifications of cables.

(3) Battery check

Inspect batteries thoroughly before installation. Do not use damaged, leaking, or deformed batteries to prevent internal short circuits.

(4) Safety measures

Operators must wear appropriate PPE such as insulated gloves and goggles.

(5) Emergency plan

Prior to delivery, formulate an appropriate emergency drill solution for fire hazards and accidents that may occur during delivery, and conduct drills based on the solution. The specific solution shall be customized based on the emergency drill solution in the manual provided by the lithium-ion battery manufacturer. For details about the emergency plan, see Appendix 1 Emergency Plan for Data centre Lithium-ion Battery Accidents.

7.3.2. Fire safety management requirements for onsite installation

Fire safety management is critical during lithium-ion battery installation. Take the following critical measures.

(1) Fire extinguisher

When installing lithium-ion batteries, ensure that the site is equipped with compliant fire extinguishers such as water-based fire extinguishers.

(2) Emergency materials

The site shall be equipped with necessary emergency materials such as fire blankets and heat-resistant gloves, to facilitate quick response to emergencies.

7.3.3. Installation technique and protection requirements

When installing lithium-ion batteries, ensure that the battery screws are tightened securely. Tighten the screws on copper bars or cables to the torque specified in the user manual. Periodically check that the screws are tightened, check for rust, corrosion, or foreign objects, and clean them if any. Loose screw connections will cause excessive voltage drops and batteries may catch fire due to heat release at high currents.

When installing batteries, do not place installation tools, metal parts, or remnants on the batteries.

Install and secure batteries horizontally from bottom to top and from left to right to prevent them from falling due to imbalance.

After the installation is complete, remove foreign objects from the batteries and the surrounding area.

If batteries will not be powered on after installation, take dustproof measures (such as using a dust cover) to prevent battery damage due to internal dust buildup. Remove the dust cover only when batteries are ready for operation. After the installation is complete, take anti-condensation measures and keep the air conditioners running. Do not store batteries in an environment where the temperature and humidity are uncontrollable for a long period of time, as the batteries may be damaged due to condensation.

After installation is complete, the lithium-ion battery system must be fully charged to 100 per cent state of charge (SOC) before the battery system is tested and approved. Once the battery system is in service, battery module replacement is not recommended for reasons other than battery failures.

7.3.4. Installation quality check

After lithium-ion batteries are installed in a data centre, the battery system needs to be checked comprehensively.

Ensure that screws are tightened using a torque tool, and are marked in red and blue for double checking. Installation personnel mark tightened screws in blue. Quality inspection personnel confirm that the screws are tightened and then mark them in red. (The marks should cross the edges of the screws.) Ensure that the cabinet, cables and copper bars are connected securely.

Ensure that the distance between the power and signal cables meets the manufacturer's requirements and that there is no crossover.

7.4. Lithium-ion battery system power-on and commissioning

Before powering on lithium-ion batteries, ensure that the environment meets requirements, that the product status is normal, that the cables are correctly connected, and that the fire extinguishing system in the battery room is normal.

7.4.1. Power-on

Before power-on, wear personal protective equipment and use dedicated insulated tools to avoid electric shocks or short circuits.

Strictly follow the instructions in the user manual to ensure that the lithium-ion battery system is powered on safely and operates properly. If any exception occurs during power-on, power-off the battery cabinet immediately. Locate and rectify the fault before powering on the cabinet again.

7.4.2. Commissioning

The integrity and correctness of lithium-ion battery commissioning are critical to the stable running of lithium-ion batteries throughout the lifecycle. Commissioning personnel must not work while ill.

Lithium-ion batteries must be commissioned in strict accordance with the commissioning instructions provided by the manufacturer. Commissioning items mainly include the device running status, communication status, shallow discharge detection, charging test, UPS connection, and BMS connection. After the commissioning is complete, ensure that related functions are normal, for example, the running status and communication status are normal, and no related alarm is generated.

8.Operation & maintenance requirements

8.1. General requirements

Lithium-ion batteries have a long service life. Continuous operation and maintenance (O&M) is critical to ensuring the safe operation of lithium-ion batteries. Professional maintenance and management improve the safety, reliability, and service life of lithium-ion batteries, ensuring continuous and stable operation of the data centre.

Lithium-ion battery O&M includes battery inspection and maintenance, charge and discharge management, capacity detection and evaluation, troubleshooting, cleaning and maintenance, data collection and analysis, spare parts management, and safety management. The specific O&M methods are carried out according to the routine inspection, monthly inspection, quarterly inspection, and annual inspection plans to ensure the safe operation of lithium-ion batteries.

In addition to the inspection of lithium-ion batteries, the fire extinguishing system in the battery room must also be inspected. The specific inspection solution shall be formulated in a uniform manner.

8.2. Operation & maintenance precautions

During maintenance, wear PPE such as protective clothing, insulated shoes, goggles, safety helmets, and insulated gloves, as shown in the following figure 8

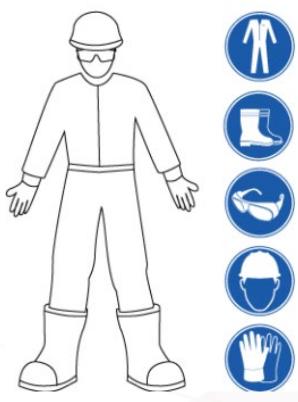


Figure 8 PPE illustrations

Figure 8 PPE illustrations

No.	Operation regulations and precautions
1	Only qualified personnel are allowed to install, operate, and maintain batteries.
2	Wear appropriate PPE such as insulated gloves, shoes, and goggles. Remove watches, rings and other metal objects.
3	Use insulated tools.
4	Do not wear conductive objects such as watches, bracelets, bangles, rings and necklaces.
5	Do not connect or disconnect battery wiring terminals or verify the screw torque when the battery loop is not disconnected.
6	Do not place tools or metal parts on batteries or near battery terminals.
7	Do not short-circuit the positive and negative battery terminals by touching them or other means. Doing so may result in electric shock and high-intensity short-circuit currents.
8	Do not connect the battery loop before checking battery installation and cable connections.
9	Do not forcibly switch on the battery switch if the battery switch trips or fails to be switched on, or the fault is not located or rectified.
10	Do not smoke or have an open flame around batteries.
11	Do not use wet cloth to clean exposed copper bars or other conductive parts.
12	Do not maintain batteries with power on.

8.3. Inspection requirements

The inspection items of lithium-ion batteries mainly include the charge status, voltage, temperature, and discharge current of battery modules to ensure the balance and consistency of battery modules, prevent overcharge or discharge, and improve battery utilization.

In addition, personnel shall collect statistics on the temperature and humidity of each area in the equipment room, check the operating status of devices, and record and rectify faults.

The inspection must be performed according to the manual provided by the manufacturer.

8.3.1. Routine inspection

Routine inspection of lithium-ion batteries is an effective way to ensure safe and stable operation, extend battery life and reduce maintenance costs. Inspections can help identify potential risks in a timely manner and enable preventive maintenance to prevent unexpected failures from impacting the data centre.

It is recommended that lithium-ion batteries be inspected at least twice a day. The number of inspection times may vary depending on the data centre tier, importance of lithium-ion batteries, and O&M policies of the data centre.

Figure 8 PPE illustrations

No.	Item	Criteria	Interval
1	Ambient temperature	Actual temperature: ______°C (Allowed temperature: 0°C to 40°C; recommended temperature: 20°C to 25°C)	Routine
2	Ambient humidity	Actual humidity: ______% RH (5 %–95 % RH, non-condensing)	Routine
3	Lithium-ion battery operating status	The operating status displayed on the lithium-ion battery LCD is charging or discharging, and no fault or alarm information is displayed.	Routine
4	Indicators on the panel of the battery control unit (BCU)	The green indicator is on, and the yellow (ALARM) and red (FAULT) indicators are off.	Routine

8.3.2. Monthly inspection

Monthly inspection items of lithium-ion batteries include the operating environment, product components, operating status, and fire extinguishing system of the lithium-ion battery room.

8.3.2.1. Operating environment

Table 5 – Inspection criteria for operating environment

No.	Item	Criteria	Interval
1	Equipment room envir onment	The equipment room fire door is always closed. The air conditioners work properly without interruption. There is no dust or combustible remnants in the equipment room.	Monthly
2	Rodent-proof measures	Rodent-proof measures such as rat guards and rat traps, are taken in the equipment room.	Monthly
3	Equipment room's fire extinguishing system	A fire alarm system and fire extinguishers have been installed in th e battery equipment room.	Monthly
4	Installation position	There is no air exhaust vent or air conditioner refrigerant copper pipe above the lithium-ion battery cabinet, and there are no other water leakage hazards.	Monthly
5	Equipment room's lighting facilities	The lighting facilities in the equipment room can be turned on and off properly.	Monthly

8.3.2.2. Product components

Table 6 – Inspection criteria for product components

No.	Item	Criteria	Interval
1	Cabinet exterior	The cabinet is free from dust (on air filters and fans), rust and deformation	Monthly
2	Battery exterior	(a) Batteries are clean and free from stains.	Monthly
		(b) The battery wiring terminals are intact.	
		(c) Batteries are intact and free from damage, deformation, bulges, and cracks.	
		(d) Batteries have no acid or electrolyte leakage. (If electrolyte leakage occurs, there will be a pungent smell.)	
3	Cabinet cable hole protection	The cable holes of the lithium-ion battery cabinet have been sealed using the sealing plates or glands delivered with the product, and rodent-proof measures are taken.	Monthly
4	Cabinet air exhaust vent	The air exhaust vent in the upper part of the lithium-ion battery cabinet is not blocked.	Monthly
5	Metal scraps in the cabinet	There is no metal scrap or other conductive foreign matter in the cabinet.	Monthly

8.3.2.3. Operating status

Table 7 - Lithium-ion battery capacity monitoring criteria

No.	Item	Criteria	Interval
1	Lithium-ion battery capacity	Charge the battery continuously for at least one week and record the battery SOC (normal SOC = 100 %).	Monthly

8.3.3. Quarterly Inspection

Quarterly inspection of lithium-ion batteries mainly includes shallow discharge testing.

Table 8 - Quarterly Inspection Items for Battery Systems

No.	Item	Criteria	Interval
1	Shallow discharge test	During the shallow discharge test, no fault or alarm is displayed on the UPS and lithium-ion battery LCDs.	Quarterly
2	Battery module check (power-off)	Check the insulation status of battery module with power off.	Quarterly

8.3.4. Annual inspection

The lithium-ion battery system in a data centre shall be comprehensively inspected and maintained once a year to extend battery life and improve safety. The check items include product components, operating status, and fire safety.

8.3.4.1. Product components

Table 9 - Annual inspection criteria for lithium-ion battery product components

No.	Item	Criteria	Interval
1	Cabinet ground cables	The ground cables of the lithium-ion battery cabinet are secured to the power distribution ground bar, and the screws are tig htened.	Annual
2	Power cables and terminals	The screws are tightened. The insulation layers of the cables are inta ct and terminals are free from scorches and sparks.	Annual
3	Battery con-nection	(a) After battery modules are powered off, check the connections of copper bars and communications/sampling terminals for each battery module from positive terminals to negative terminals. (b) When checking copper bar connections, use a torque wrench to check the tightening torque of each battery screw. The to rque must meet the requirements of the battery manufacturer. After verifying that the battery screws meet the requi rements, mark the screws for future inspection.	Annual

8.3.4.2. Operating status

Table 10 – Annual inspection criteria for lithium-ion battery operating status

No.	Item	Criteria	Interval
	Capacity test	During the capacity test, no fault or alarm is displayed on the UPS and lithium-ion battery LCDs.	Annual

8.3.4.3 Fire safety

The maintenance and inspection of the fire extinguishing system shall comply with international standards and national standards and regulation.

9. Emergency plan and drill

9.1. General requirements

The data centre lithium-ion battery emergency plan and drill are important to improve emergency response capabilities, verify the integrity of the emergency mechanism, enhance safety awareness, promote team collaboration, and meet regulatory requirements. An organization shall formulate an emergency response and drill plan. At least one onsite response drill shall be conducted every six months, which is the minimum required frequency for onsite response drills.

9.2. Emergency plan

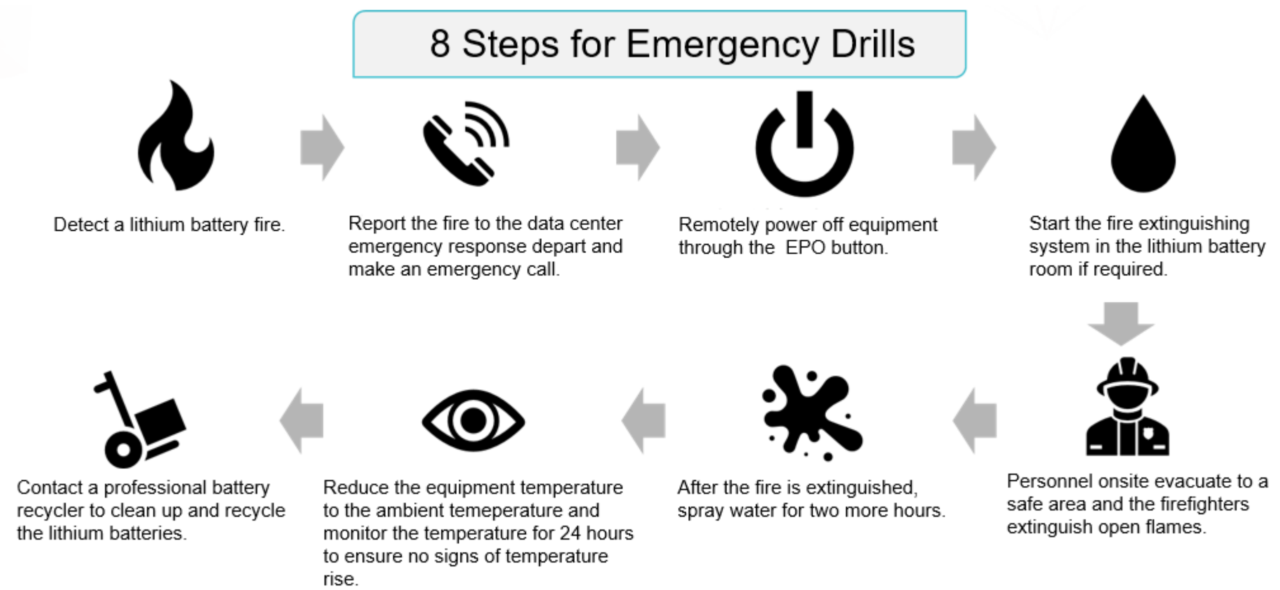
The emergency plan for data centre lithium-ion battery accidents shall include emergency organization and leadership, monitoring and warning, emergency rescue resource preparation, and emergency response process. This section describes the emergency response process and emergency rescue resources.

9.2.1. Emergency plan process

Lithium-ion battery emergency plans and drills apply to scenarios such as battery overtemperature protection, battery module failure, and smoke and fire accidents. Different emergency plans shall be developed for different scenarios, and drills shall be performed at specified frequencies.

Scenarios such as battery overtemperature protection and battery module failure are in the early stage of lithium-ion battery accidents, and the overall risks are controllable. In addition, the response policies of different lithium-ion battery manufacturers are different. Handle the problems by referring to the emergency response solutions provided by the manufacturer.

In smoke and fire scenarios, personnel are not allowed to enter the battery room. The emergency response process is as follows:



Overall measures:

On the premise of ensuring personal safety, perform the following actions:

- Hazard source control
- Victim rescue
- Disaster relief personnel protection and irrelevant personnel evacuation, and
- Emergency evacuation.

After firefighters arrive at the site, provide them with the following information:

1.Fire source location,

2.Casualties,

3.Lithium-ion battery material,

4. Switch status of the power supply in the lithium-ion battery room,

5. Whether the fire is suppressed.

The following is an example:

Fire source location

The lithium-ion battery cabinet in the xxx battery room of building xx is on fire.

Casualties

No casualties have been found, and personnel have been evacuated to a safe area.

Lithium battery material

The material is LFP, there are xx lithium-ion battery cabinets, and the water fire extinguishing system has been activated.

Status of the power supply

The power supply in the battery room has been disconnected.

Fire status

The fire has been/cannot be suppressed after the fire extinguishing system is activated.

9.2.2. Emergency rescue resources

Data centres must prepare materials for emergency drills according to the Emergency Rescue Resource Requirements for Organizations table to ensure the authenticity and effectiveness of the drills. The completeness and effectiveness of material reserves can be verified by simulating actual emergency situations to ensure that materials can be used smoothly in real emergencies, thereby improving the emergency response speed and rescue effect.

Before a data centre lithium-ion battery emergency drill, recheck the quantity, quality, and status of emergency materials and equipment. After the drill, replenish the emergency materials in a timely manner and check the materials again.

9.3. Emergency drill

The emergency drill for data centre lithium-ion batteries shall include five phases: plan development, work preparation, process implementation, evaluation & summary, and continuous improvement.

(1) Plan development

This phase is to specify the emergency drill requirements for lithium-ion batteries, determine the emergency drill time, and synchronize the emergency drill information with related organizations. The main contents include requirement analysis, plan formulation, and plan release.

(2) Work preparation

This phase is to specify the organizational structure, personnel training, and document preparation for the emergency drill. The documents must cover the emergency drill solution, accident scenarios, drill script, safety assurance solution during the drill, and solution feasibility evaluation.

(3) Process implementation

This phase is to describe the following steps of the emergency drill: filing, onsite inspection, drill description, initiation, execution, onsite control, drill recording, interruption, and completion.

(4) Evaluation and summary

After the emergency drill, comprehensively evaluate the drill effect, develop a summary report, archive related materials, and ensure that the drill information is reported to government authorities and related parties in advance.

(5) Continuous improvement

Continuously revise and optimize the emergency plan and improve the emergency management work to address the problems found during the emergency drill.

Table 11 – Emergency rescue resource requirements for organizations

No.	Item	Quantity	Description	Importance
I	Medical aid instruments and medicines			
1	First aid kit	1	If a person is poisoned or injured in an emergency, the person can be treated in a timely and effective manner to ensure personal safety.	Mandatory
II	Personal protective equipment			
1	Explosion-proof flashlight	2	Appropriate PPE must be used depending on the specific accident type.	Mandatory
2	Safety helmet	Several	Comply with local requirement	Mandatory
3	Insulated shoes	Several		Mandatory
4	Protective clothing (fireproof and anti-corrosion)	3 sets/room	Comply with local requirement	Mandatory
5	Insulated gloves	3 sets/room		Mandatory
6	Gas mask	3 sets/room		Mandatory
III	Firefighting facilities			
1	Fire extinguisher	2 sets/room	One or more types of extinguishants such as water, perfluorohexanone, dry powder, carbon dioxide, and foam extinguishants, shall be provided onsite. Water and perfluorohexanone extinguishants are recommended.	Mandatory
2	Self-contained breathing apparatus	2 sets/room		Mandatory
3	Explosion-proof container	1/room	Weight: 50 kg.	Recommended
4	Facility storage cabinet	1/room		Mandatory
IV	Monitoring instruments			
1	Infrared thermometer/ Infrared thermal imaging thermometer	1/room	Used to detect the device temperature.	Mandatory
2	Combustible gas detector	1/room	Used to detect combustible gases.	Recommended
V	Emergency tools			
	Flashlight			Mandatory
1	Warning rope	1/room	100 m	Mandatory
2	Small trailer	1/room	Used to move the explosion-proof container.	Mandatory
3	Safety cone and stretcher	/		Mandatory
	Manual screwdriver	1 set	Screwdriver set of common specifications, with insulated rods.	Mandatory
	Hand-held electric tool	1	Used to remove screws quickly.	Recommended
VI	Communication tools			
1	Walkie-talkie	Several	The walkie-talkies must be set to a common channel during emergency response. The quantity of walkie-talkies shall be configured based on onsite emergency response teams.	Mandatory

10.Fire rescue and emergency handling

10.1. Precautions before fire extinguishing

Due to the special nature of lithium-ion batteries, lithium-ion battery fires are characterized by fast temperature rise, high heat release rate, fast fire spread, complex fire extinguishing, and easy re-ignition. Consequently, scientific and effective strategies and technical means must be adopted to put out such fires. The following are some precautions:

(a) When the thermal runaway of lithium-ion batteries occurs in a data centre, the smoke generated by the thermal runaway contains a large amount of toxic and hazardous gases, and the temperature of the smoke is high. In the violent combustion phase, the concentration of toxic gases is several times higher than the lethal concentration for adults. In addition, the data centre is an enclosed building structure. After an accident occurs, high-temperature toxic smoke cannot be exhausted in a timely manner. Therefore, **when handling a fire accident caused by thermal runaway of lithium-ion batteries, handling personnel must take personal safety measures in advance.** During the rescue process, handling personnel must wear breathing apparatus. When entering the data centre, handling personnel must wear protective equipment such as insulated clothing, insulated boots, and insulated gloves, and carry instruments and materials such as leakage current detectors, insulated rubber pads, and ground cables (bars). In addition, start fixed smoke exhaust facilities in the accident area, carry out smoke exhaust operations, and evacuate personnel around the accident in a timely manner.

(b) Remotely shut down the lithium-ion battery devices and disconnect all power supplies connected to the burning batteries while ensuring safety. Before handling, continuously monitor the temperature and combustible gas concentration in the accident area. If any of the following explosion signs occur, immediately organize personnel to evacuate the building: The temperature of the lithium-ion batteries in the accident area rises sharply; a large amount of smoke is emitted; the combustible gas detector sounds an alarm.

(c) Handling personnel shall not act alone during accident investigation. Before entering the burning building to investigate, assess the structural strength of the building and ensure that there is no risk of collapse. When entering the burning building to investigate, designate personnel to check PPE, record name, time of entry and exit, and air (oxygen) breathing apparatus pressure at entrance and exit, and send timely evacuation signals in the event of an emergency.

10.2. Extinguishant selection for fire rescue

When selecting an extinguishant for the lithium-ion battery fire rescue, the first requirement is to quickly extinguish the battery open flame, and the second is that the extinguishant must have strong cooling and heat dissipation capabilities to prevent re-ignition.

A water-based extinguishant has a large heat capacity and latent heat of vaporization. It absorbs a large amount of heat through phase transition in the fire area. After vaporization, its volume expands to reduce the oxygen concentration, providing excellent fire extinguishing and cooling performance. In addition, water-based extinguishants are easy to use and obtain. Therefore, water-based extinguishants are the optimal choice for fire extinguishing and rescue.

10.3. Basic handling procedure

(1) Power supply disconnection

When a fire occurs, the primary task is to disconnect the power supply. Disconnecting all power connections associated with burning devices prevents faulty batteries from continuing to heat up and causing further thermal runaway reactions. This task is usually performed by personnel of the organization where the fire occurred.

(2) Activation of the emergency ventilation system

When a fire occurs, the ventilation system of the data centre can be started automatically or manually to quickly exhaust harmful gases and heat inside the burning room, thereby reducing the indoor temperature and the risk of thermal runaway propagation.

(3) Reasonable selection of operation positions

During fire extinguishing, select the correct route and method: Under the cover of the water gun, lean against the load-bearing wall to enter the fire area. When setting up a water gun position for cooling operations, keep a distance of more than 10 meters from the fire point, and lean against the load-bearing wall or a solid structure as the cover. It is prohibited to set up water gun positions around non-load-bearing walls such as brick walls and shelves, and under suspended ceilings and floors with heavy objects to prevent injury from sudden collapse and falling.

(4) Active cooling

In the early stage of a lithium-ion battery fire, use microstructure, compressed air foam to effectively extinguish the fire and fully utilize the wall-mounted function of the foam. This maximizes the cooling effect of the extinguishant while effectively suppressing the fire. During handling, try to use stationary or unattended firefighting equipment such as firefighting robots, mobile remote water cannons and high-rise water tenders, to extinguish the fire from a distance. Such equipment can accurately target fire sources from a safe distance. This provides maximum protection for firefighters.

Adhere to the principle of “defending for safety and containing combustion” throughout the fire handling. At the scene, take the following actions: in the confined space, quickly separate the fire area, dissipate the heat and exhaust the smoke; in the fire building, fully submerge the fire, build an embankment with sand, gradually bury and cool the fire, and disassemble and transfer the equipment.

During early handling, try to submerge the burning parts on fire to extinguish the fire. If necessary, use sand or cement to build an embankment or cover the fire to prevent the high temperature caused by thermal runaway of lithium-ion batteries from spreading around. If necessary, the precision equipment around the fire area can be temporarily disassembled and transferred to minimize the economic loss caused by the accident.

(5) Real-Time monitoring and warning system

During handling, use combustible gas detectors, thermometers, and other monitoring devices to monitor the temperature rise and gas concentration in the lithium-ion battery room. Once an exception is detected, immediately issue a warning and activate the emergency handling procedure.

(6) Site cleanup

Lithium-ion batteries are characterized by continuous reactions. Therefore, even after the fire is extinguished, use a water gun to cool the fire area for more than 1 h and use a thermometer to monitor the temperature in real time. Exercise caution when using water for cooling. It is advised that you spray fine water mist on the affected area from a distance and keep a certain distance for safety. In addition to traditional water cooling, other non-conductive coolants can be used as auxiliary means to further suppress after-heat until the battery temperature returns to normal ambient temperature. Cooling operations can be stopped only when there is no risk of re-ignition or explosion.

10.4. Service linkage with the fire rescue team in the jurisdiction

The data centre and the fire rescue team in the jurisdiction shall form an efficient and close service linkage mechanism to ensure quick response and effective fire control in emergencies such as a fire.

A real-time information sharing platform shall be established between the data centre and the fire rescue team in the jurisdiction. The platform shall provide key information such as the data centre layout, number and type of lithium-ion batteries during normal operation, and location and status of stationary firefighting facilities. After an accident occurs, the fire rescue team can immediately learn about the internal details of the data centre through the platform to formulate a more effective fire extinguishing solution.

(2) Regular joint drill

To improve the emergency response capabilities of both parties, the data centre and the fire rescue team in the jurisdiction shall conduct joint drills on a regular basis. By simulating various possible fire scenarios in the data centre building, both parties shall be familiar with their respective responsibilities and operation processes. Identify and improve deficiencies in the emergency plan through drills to ensure that the fire can be handled quickly and effectively when it occurs.

(3) Strengthening training and communication

Data centre personnel shall receive professional fire safety training to understand the characteristics of lithium-ion battery fires and fire extinguishing methods. In addition, data centre personnel must maintain close communication with the fire rescue team in the jurisdiction and dynamically update firefighting technologies and knowledge, so that when a lithium-ion battery fire occurs, personnel can better handle the fire at its early stage and effectively improve the handling effect.

(4) Improving stationary firefighting facilities

The data centre must be equipped with comprehensive stationary firefighting facilities, including smoke detectors, the automatic fire extinguishing system, and video surveillance devices, in accordance with national fire safety standards. Facilities shall be inspected and maintained on a regular basis. The data centre shall be equipped with adequate fire extinguishing and other emergency equipment.

(5) Establishing a quick response mechanism

Once a fire occurs in the data centre, the personnel shall immediately activate the quick response mechanism, notify the fire rescue team in the jurisdiction, and take preliminary fire extinguishing measures. After receiving the notice, the fire rescue team shall promptly dispatch and carry necessary fire extinguishing equipment to the site. During fire extinguishing, both parties shall maintain close communication and collaboration to jointly control the fire and prevent re-ignition. If necessary, establish a one-click dispatch mechanism based on actual situations.

(6) Follow-up handling and summary

After a fire is extinguished, the data centre personnel shall conduct site survey and summary with the fire rescue team in the jurisdiction. By analysing the cause of the fire and evaluating the fire extinguishing effect, propose improvement measures in a timely and reasonable manner. By summarizing the experience and lessons learned, further improve the service linkage mechanism and enhance the emergency response capability in the future.

10.5. Firefighting material reserves in the data centre

Electronic devices in the data centre such as servers, routers, and network switches, are vulnerable to fire damage, resulting in significant economic losses. Firefighting material reserves ensure that protective measures can be taken in time to protect devices from further fire damage. Therefore, proper reserves of firefighting materials are critical.

Table 12 – Firefighting material reserves in the data centre

No.	Firefighting material		Description
1	Extinguishant reserves	Water extinguishant, perfluorohexanone extinguishing agent, etc.	One or more types of extinguishants such as water, perfluorohexanone, dry powder, carbon dioxide, and foam extinguishants, shall be provided onsite.
2	Cooling facilities	Fire extinguishing robot	The firefighting robot can perform cooling operations at the fire scene to prevent re-ignition and thermal runaway.
		Multipurpose water gun and swing-type automatic fire extinguishing system	In the early stage of a fire, a water gun or a swing-type automatic fire extinguishing system can be used to suppress the fire. However, exercise caution to prevent battery short circuits or explosion s caused by chemical reactions due to moisture intrusion.
3	Protective equipment	Gas mask and insulated protective clothing	Lithium-ion batteries can produce toxic gases in a fire. Therefore, personnel entering the data centre must be equipped with gas masks and insulated protective clothing to prevent asphyxiation and toxicity, reduce the risk of electric shock, and ensure their safety.
		Insulated tools	Use insulated tools to reduce the risk of electric shock during fire rescue.
4	Communicat-ions devices	Wireless walkie-talkie and satellite phone	Ensure smooth communication between the fire rescue team and the data centre, and facilitate the communication of fire information and rescue progress.
5	Emergency power supply	Standby genset and UPS	Provide stable power for fire extinguishing measures, vehicles, and equipment in the event of a fire-related power outage.
6	Other materials	Sandbag and fire blanket	Block the fire source and isolate the fire to prevent it from spreading.
		Medical emergency kit	Includes tourniquet, bandage, and disinfectant. It is used for emergency treatment of wounds in the case of casualties.

11. Conclusions and future directions: the critical role of international standards

Currently, lithium-ion batteries are becoming the mainstream choice for data centre power backup, but their safety risks must not be overlooked. It is critical to accelerate the formulation of fire safety standards to provide scientific and standardized guidance for the design, construction, operation and maintenance of lithium-ion batteries in data centres. This will help reduce the probability of accidents and hazards, protect personnel and property, and enhance the overall resilience and development of the industry.

Given the rapid technological advancements and evolving demands of data centre infrastructure, fire safety standards for lithium-ion batteries should be updated dynamically and improved continuously. It is advised to establish a dynamic standard update mechanism that tracks the latest global technologies and research, allowing timely revisions and improvements. Additionally, strengthening the supervision and evaluation of standard implementation is essential to ensure the soundness, adaptability and effectiveness of safety measures.

This white paper contributes to these efforts by promoting the development of comprehensive standards, covering building design and layout, firefighting facility configuration, electrical safety requirements, installation and O&M management, and emergency plan and drills. It is recommended that future standards address critical aspects such as fire separation design, evacuation passage requirements, fire protection equipment layout, electrical protections like overcharge and short-circuit safeguards, and the establishment of detailed emergency response procedures for lithium-ion battery incidents.

Looking ahead, the data centre industry is expected to experience continuous innovation in electrochemical energy storage and fire protection and control technologies. In terms of electrochemical energy storage technologies, multiple new technologies have emerged, but they still face many challenges in large-scale commercial use. For example, vanadium redox batteries (VRBs) are well suited for peak shaving in outdoor data centre energy storage due to the separation of capacity from power performance, long life, and high reliability. As the industry chain scales up and matures, the total lifecycle cost of VRBs is expected to approach that of lithium-ion batteries.

Immersive liquid-cooled lithium-ion battery technology has attracted much attention in the energy storage field and has been applied in a few energy storage cycling projects. Compared with forced air cooling and cold plate liquid cooling, the technology has excellent heat dissipation performance and uniform temperature distribution, effectively suppressing thermal runaway, reducing fire risk and prolonging battery service life. However, as data centres have strict security requirements, the application of immersive liquid-cooled lithium-ion batteries in this field needs to be further piloted and verified. With the development of technology research and development and the accumulation of practical experience, its application prospect deserves continuous attention and in-depth study.

Recognizing the importance of international standards development in shaping a safer and more resilient digital infrastructure, the Standardization Sector of the International Telecommunication Union, through ITU-T Study Group 5 (SG5) on "Environment, EMF, Climate Action and Circular Economy", provides a unique global platform where governments, industry leaders, experts, and academia come together to address critical issues for the ICT sector. ITU-T SG5's work in areas such as energy efficiency, smart energy solutions, power interface safety, circular economy, and environmental efficient and sustainable data centre development contributes significantly to the broader framework for lithium-ion battery safety management within ICT facilities.

While not all emerging electrochemical technologies fall directly under the ICT sector's mandate, addressing fire safety, energy management, and operational standards for ICT-related battery infrastructure remains vital. We encourage stakeholders across the value chain – including battery manufacturers, data centre operators, system integrators, firefighting equipment suppliers, and technical experts – to actively engage in the international standardization process.

In addition to promoting fire safety and operational standards for lithium-ion battery systems, it is equally important to address the sustainable management of these batteries at the end of their lifecycle. Proper recycling and end-of-life treatment are critical to minimizing environmental impacts, recovering valuable materials, and supporting circular economy principles. ITU is well-positioned to contribute to this effort by developing complementary reports and guidelines focused on the sustainable management, re-use, and recycling of lithium-ion batteries within the ICT sector. Such initiatives would align with ITU's broader environmental and resource efficiency objectives under ITU-T SG5, supporting the responsible development of digital infrastructure and sustainable management of e-waste to advance circular economy. Collaboration among industry stakeholders, governments, and standards bodies will be essential to ensure the safe, efficient, and environmentally sound handling of battery technologies throughout their full lifecycle.

By participating in global standardization efforts, stakeholders help establish robust, forward-looking benchmarks for fire safety, energy efficiency and risk management. Together, we can drive the development and implementation of dynamic international standards that not only address today's challenges but also anticipate tomorrow's opportunities – shaping a safer, smarter and more environmentally sustainable digital future.