LITHIUM-ION BATTERY ENERGY STORAGE SYSTEMS

Table of Contents

Page

List of Figures

1.0 SCOPE

This data sheet describes loss prevention recommendations for the design, operation, protection, inspection, maintenance, and testing of stationary lithium-ion battery (LIB) energy storage systems (ESS) greater than 20 kWh. This data sheet also describes location recommendations for portable (temporary) lithium-ion battery energy storage systems (LIB-ESS).

Energy storage systems can be located in outside enclosures, dedicated buildings or in cutoff rooms within buildings. Energy storage systems can include some or all of the following components: batteries, battery chargers, battery management systems, thermal management and associated enclosures, and auxiliary systems.

This data sheet does not cover the following types of electrical energy storage:

A. Mechanical: pumped hydro storage (PHS); compressed air energy storage (CAES); flywheel energy storage (FES)

B. Electrochemical: flow batteries; sodium sulfide

C. Chemical energy storage: hydrogen; synthetic natural gas (SNG)

D. Electrical storage systems: double-layer capacitors (DLS); superconducting magnetic energy storage

E. Thermal storage systems

F. Micromobility applications (e-bikes, scooters, wheelchairs, etc.)

G. Lithium-ion battery back-up units for distributed power systems installed in server racks of data processing equipment rooms/halls.

This data sheet does not cover non-lithium-ion batteries, their associated battery chargers and associated systems related to backup power in UPS systems or DC power for circuit breaker protection, etc. Information related to non-lithium ion batteries used in backup power systems can be found in Data Sheet 5-23, *Design and Protection for Emergency and Standby Power Systems*; Data Sheet 5-19, *Switchgear and Circuit Breakers*; Data sheet 5-28, *DC Battery Systems*; and Data Sheet 5-32, *Data Centers and Related Facilities*.

1.1 Changes

January 2024. Interim revision. Minor editorial changes were made.

1.2 Hazards

1.2.1 Thermal Runaway

Thermal runaway occurs when the chemical reaction within a li-ion cell produces more heat than can be dissipated through the associated cooling system. The increased heat causes degradation of the ignitable liquid electrolyte. If the process is not interrupted, the cell will fail. Thermal runaway starts with abnormal operation of the cell, which can be attributed to three known causes: (1) electrical abuse, (2) thermal abuse or (3) physical damage.

Electrical abuse of a li-ion cell includes overcharge or over-discharge, i.e., energy is added or removed from the cell at a rate that exceeds the design capacity. Electrical abuse is acknowledged to be the most common failure mode for a li-ion cell, and it is the only failure mode that can be interrupted by advanced battery management system (BMS) functionality. When impending cell failure results from electrical abuse, electrical isolation can interrupt the process, averting thermal runaway. Some BMS systems incorporate or can interact with sensors that detect elevated cell temperatures or trace gases associated with the early stages of electrolyte degradation.

Electrical isolation does not mitigate the other two causes of cell failure—thermal abuse and physical damage.

Thermal abuse can be the result of environmental factors such as high and low temperature excursions. Most li-ion cells have a well-defined, acceptable temperature operating range and require constant climate control to stay within these limits. Failures identified as thermal abuse have been attributed to (1) the malfunction or poor design of environmental controls, and (2) exposure to fires that originated in cooling systems and ancillary electrical equipment. When thermal abuse causes cell failure, it is likely to impact multiple cells simultaneously; and the progression to thermal runaway is unavoidable.

Physical damage is generally associated with a manufacturing defect but can also be caused by mishandling during transport or installation. Physical damage can result in cracking or fracture of the anodes or separator and an internal short in the cell. Since the cells store their own energy, electrical isolation cannot prevent the progression to thermal runaway.During thermal runaway, the ignitable electrolyte degrades into flammable gases (including hydrogen and several hydrocarbons) and a significant quantity of carbon dioxide. The volume of gases produced per cell varies by cell chemistry and electrical capacity. Independent research laboratories have reported gas volumes of 2.5 ft^3 (70 L) and 7.1 ft^3 (200 L) released per cell.

1.2.2 Electrical Fire

As with other electrical systems, electrical fires are a concern and can cause property damage and, in severe cases, could initiate a thermal runaway event due to localized overheating.

Unlike lithium batteries, lithium-ion batteries are not water-reactive.

2.0 LOSS PREVENTION RECOMMENDATIONS

2.1 FM Approved Equipment

2.1.1 Use FM Approved equipment, materials, and services whenever they are applicable and available. For a list of products and services that are FM Approved, see the *Approval Guide*, an online resource of FM Approvals.

2.2 Lithium-Ion Battery Energy Storage System (LIB-ESS) Selection

2.2.1 Verify with the manufacturer or integrator that the LIB-ESS design, including cell type, battery management system (BMS), etc., is appropriate for the application.

2.2.2 Establish a management of change procedure to ensure that batteries or BMS components are compatible with modified system requirements or that replacements are appropriate to the existing system requirements.

2.2.3 Do not use refurbished or previously used LIB-ESS components, including cells or modules.

2.3 Construction and Location

2.3.1 Location

2.3.1.1 Locate energy storage systems in accordance with one of the following, listed in order of preference:

A. In an enclosure outside and away from critical buildings or equipment in accordance with 2.3.2 (Figure 2.3.1, location 1)

B. In a dedicated building containing only LIB-ESS and associated support equipment in accordance with 2.3.3 (Figure 2.3.1, location 2)

C. In a dedicated exterior cutoff room that is accessible for manual firefighting operations and is constructed in accordance with 2.3.4 (Figure 2.3.1, location 3)

D. In a dedicated interior corner cutoff room with at least two exterior walls that is accessible for manual firefighting and is constructed in accordance with 2.3.4 (Figure 2.3.1, location 4)

E. In a dedicated interior cutoff room with at least one exterior wall that is accessible for manual firefighting and is constructed in accordance with 2.3.4 (Figure 2.3.1, location 5)

2.3.2 Outdoor LIB-ESS Enclosures and Containers

2.3.2.1 Select or construct LIB-ESS enclosures/containers using only noncombustible materials.

Separation distance is based on doors being located on only one side of the enclosure and no vents or unprotected openings on any other sides. It is also based on active systems (HVAC or liquid cooling) maintaining cell or module temperatures in the target enclosure or container.

2.3.2.2 For containerized LIB-ESS comprised of lithium iron phosphate (LFP) cells, provide aisle separation of at least 5 ft (1.5 m) on sides that contain access panels, doors or deflagration vents.

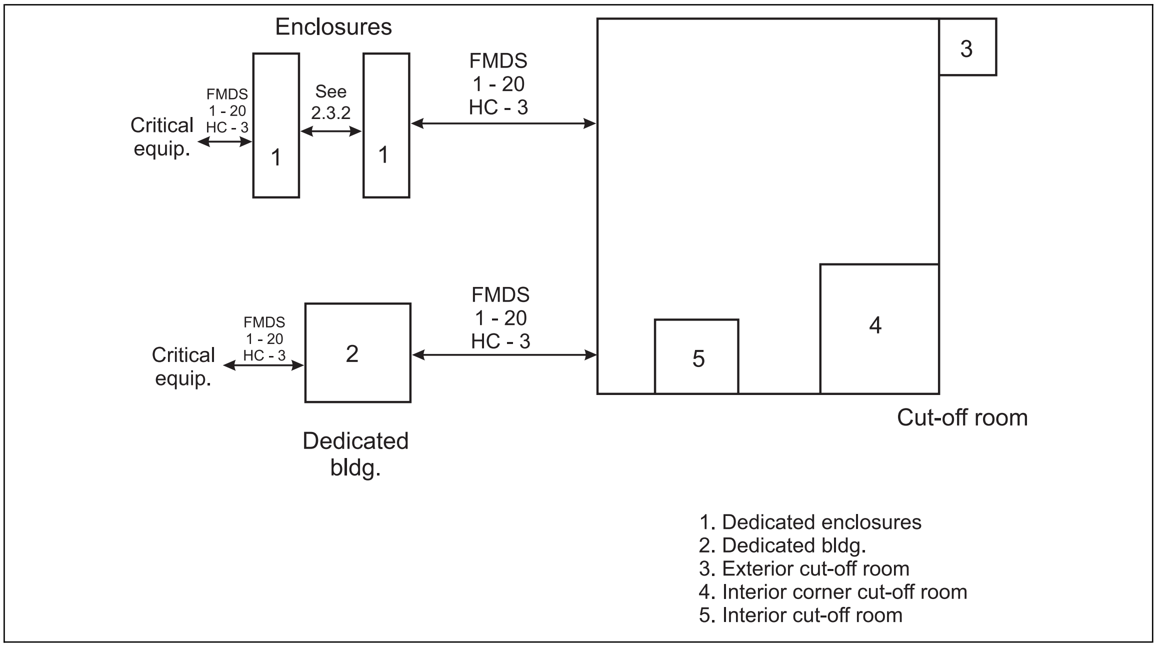

Fig. 2.3.1. LIB-ESS locations by preference

2.3.2.3 For containerized LIB-ESS comprised of lithium nickel manganese cobalt (NMC) cells where wall construction is unknown or has an ASTM E119 rating less than 1 hour, provide aisle separation of at least 13 ft (4.0 m) on sides that contain access panels, doors, or deflagration vents. For containerized NMC LIB-ESS where wall construction is documented as having at least a 1 hour rating in accordance with ASTM E119, aisle separation of at least 8 ft (2.4 m) is acceptable.

2.3.2.4 Provide separation between solid walls having no openings based on installation-level testing that demonstrates thermal runaway cannot propagate between containers. Where a fire test report is not available or the test did not result in a fire in the unit of origin, provide separation as indicated in Sections 2.3.2.2 or 2.3.2.3 as appropriate.

2.3.2.4.1 If any penetrations are present, the separation should be extended, or the penetrations should be protected or equipped with FM Approved fire-safe wall penetrations.

2.3.2.4.2 Where explosion vents or other penetrations are provided, ensure they are arranged and directed away from surrounding equipment and buildings.

In a fire, these enclosures may have vents or penetrations that could allow hot gas and products of combustion to escape the enclosure, causing an exposure to adjacent equipment or buildings. Penetrations could include electrical conduit, doors, HVAC units, etc.

2.3.2.5 Provide a minimum space separation between LIB-ESS enclosures and adjacent buildings or critical site utilities or equipment in accordance with Data Sheet 1-20, *Protection Against Exterior Fire Exposure*, using hazard category 3 for the exposing building occupancy.

2.3.3 Dedicated LIB-ESS Building or Enclosure Larger Than 500 ft^2 (46.5 m^2)

Treat any pre-fabricated container or enclosure that is larger than 500 ft^2 (46.5 m^2) as a building.

2.3.3.1 Construct a dedicated LIB-ESS building of noncombustible materials.

2.3.3.2 Provide a minimum space separation between dedicated LIB-ESS buildings and other facility buildings or critical site utilities or equipment in accordance with Data Sheet 1-20 using hazard category 3 for the exposing building occupancy.

2.3.3.3 Provide damage-limiting construction (DLC).

2.3.3.3.1 Design DLC in accordance with Data Sheet 1-44, *Damage-Limiting Construction*, using propane as the representative gas.

2.3.3.4 Install LIB-ESS with minimum separation distance in accordance with 2.3.5.

2.3.3.5 Provide air circulation at a rate of at least 1 cfm/ft^2 (0.3 m^3/min/m^2) of floor area (see 2.5.5).

2.3.3.6 Design HVAC systems to maintain temperatures within operating limits in the event of a single component failure.

2.3.3.6.1 Arrange the HVAC system to alarm to a constantly-attended location or to specific operations personnel if any part of the system fails.

2.3.4 LIB-ESS Cutoff Rooms

2.3.4.1 For multiple racks installed in a single row or back-to-back, install solid, noncombustible fire barriers between adjacent racks.

2.3.4.2 Provide a minimum two-hour fire-rated room, floors, walls, and ceiling in accordance with Data Sheet 1-21.

A. Provide FM Approved fire doors with the same room rating.

B. Provide FM Approved fire barriers for all floor, ceiling, and wall penetrations.

2.3.4.3 Install LIB-ESS with minimum separation in accordance with 2.3.5.

2.3.4.4 Provide air circulation in an LIB-ESS cutoff room at a rate of at least 1 cfm/ft^2 (0.3 m^3/min/m^2) of floor area. (See 2.5.5)

2.3.4.5 Provide damage-limiting construction.

2.3.4.5.1 Design DLC in accordance with Data Sheet 1-44, *Damage-Limiting Construction*, using propane as the representative gas.

2.3.5 Separation Distances for Indoor LIB-ESS Racks

2.3.5.1 Provide 6 ft (1.8 m) minimum separation from the accessible face of an LIB-ESS rack to noncombustible materials, noncombustible construction elements, and the accessible faces of adjacent LIB-ESS racks.

The accessible face is the side that has a door, vent or can be opened, allowing fire to escape the rack of origin.

2.3.5.2 Provide 9 ft (2.7 m) minimum separation from the accessible faces of LIB-ESS racks to combustibles and combustible construction elements.

2.3.5.3 Separation between non-accessible sides of adjacent racks should be determined by an installation-level fire test demonstrating that thermal runaway cannot propagate between racks. Where a test report is not available or the test did not result in a fire in the rack of origin, assume thermal runaway will propagate between racks. See Section 2.4 for expected fire duration.

2.4 Protection

2.4.1 Provide automatic sprinkler protection designed to a 0.3 gpm/ft^2 (12 mm/min) over the room area, with an additional allowance of 250 gal/min (946 L/min) for hose streams.

Testing of a 125 kWh LIB-ESS utilizing lithium nickel oxide/lithium manganese oxide (LNO/LMO) batteries demonstrated that the fire growth ultimately exceeded the 2500 ft^2 design area. Therefore, the sprinkler design should be designed for the room area. Video of the sprinkler test can be found on the FM Global YouTube channel: https://www.youtube.com/fmglobal.

2.4.2 Ensure the water supply is capable of providing sprinkler water and hose stream requirements for the duration of the fire event (see Section 3.2). The expected duration will depend on the number of racks in a single fire area. The fire area is comprised of a row or rows of racks where minimum separation is not provided in accordance with 2.3.5. The duration should be estimated as 45 minutes times the number of adjacent LIB-ESS racks.

The room design should address drainage or other mitigation of the water release. See Data Sheet 1-24, *Protection Against Liquid Damage*, for more information.

2.4.2.1 Where the sprinkler demand requires a water supply duration greater than what is available, provide the following:

A. Install noncombustible floor-to-ceiling partitions with penetrations protected by FM Approved fire stops between adjacent racks perpendicular to the rack door or opening to prevent fire spread. Ensure the partitions extend at least 12 in. (0.3 m) from the face of the rack. See Figure 2.4.2.1. Determine the horizontal distance between thermal barriers based on how many racks can be protected by the available water supply.

B. Install a solid metal partition on the back (non-aisle) of each rack to prevent heat transfer to adjacent racks in the next row. Where the rack design incorporates a solid metal back (no ventilation openings), additional partitions are not needed. (See Figure 2.4.2.1.)

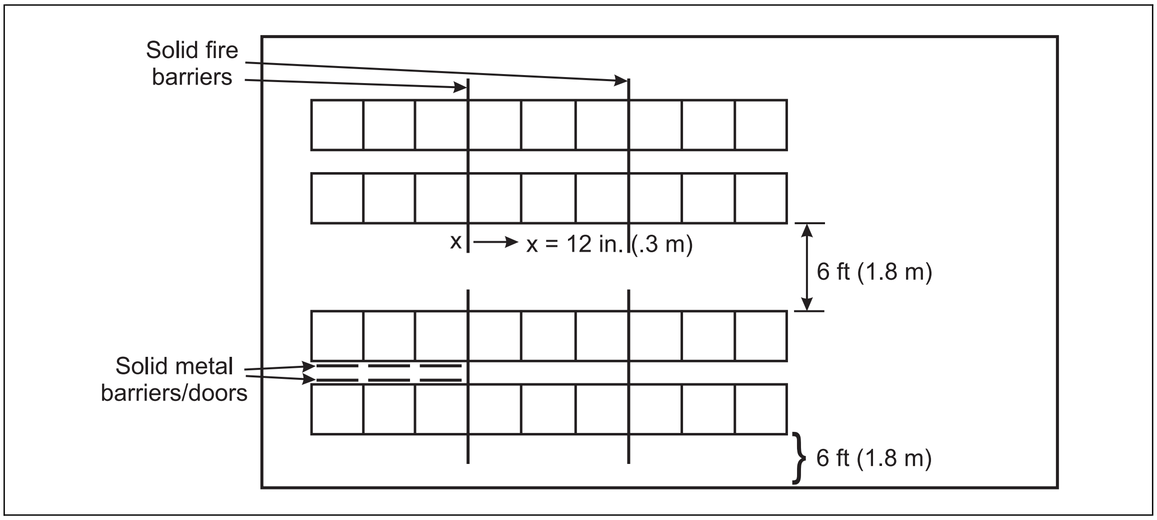

Fig. 2.4.2.1. Thermal barriers to reduce fire risk area

2.4.3 Provide a smoke detection system within the enclosure, cutoff room, or LIB-ESS area designed and installed in accordance with Data Sheet 5-48, *Automatic Fire Detection*.

2.5 Equipment and Processes

2.5.1 Electrical System Protection

2.5.1.1 Perform a system short circuit and protection coordination study to ensure the adequacy of rating and relay settings for existing circuit breakers when the electrical energy storage system adds power to the existing electrical system at a facility. For additional information on short circuit and protection coordination, see Data Sheet 5-20, *Electrical Testing*.

2.5.2 Equipment Protection

2.5.2.1 Provide a disconnect device for maintenance needs or abnormal events for each rack.

2.5.2.2 Provide a method of manual, remote, and local disconnect for the LIB-ESS. A remote disconnect should be in an accessible area that is monitored 24/7. A local disconnect should be provided adjacent to the LIB-ESS space.

2.5.2.3 Provide temperature monitoring with high alarm for LIB-ESS room, building, or enclosure. Have alarms routed to a continuously attended location or specific operations personnel.

2.5.2.4 LIB-ESS Rack

2.5.2.4.1 Provide DC ground fault protection for grounded battery systems. For ungrounded battery systems, provide DC ground fault monitoring with alarming function. Have the alarm routed to a constantly-attended location or to specific operations personnel.

2.5.2.4.2 Provide overcurrent protection against overload and short-circuit faults.

2.5.2.4.3 Provide overvoltage and under-voltage protection against overcharging and over-discharging.

2.5.3 Battery Management System Safety Functions

2.5.3.1 Provide battery management systems with the following safety functions:

A. High cell temperature trip (cell level): This function isolates the module or battery rack when detecting cell temperatures that exceed limits. A common design is to have modules hard-wired in series within a rack. Therefore, the smallest unit that can be isolated is generally the rack. Where a design accommodates it, isolating a module is acceptable.

B. Thermal runaway trip (cell level): This function trips the entire system when a cell is detected to have entered a thermal runaway condition. In scenarios involving a thermal runaway, this function is the first to activate when thermal runaway conditions are detected.

C. Rack switch fail-to-trip (rack level): This function identifies any failure from the pack switch to trip once a trip command is initiated. The rack switch is also known as the “pack switch.” It is a switch that disconnects a single rack in response to an abnormal condition. The rack switch is shown separately from the “master” level in Figure 2.5.3.1 for clarity. It is generally incorporated into the BMS.

D. Inverter/charger fail-to-trip (supervisor level): This function initiates a trip command to an upstream breaker to isolate the LIB-ESS if the inverter/charger fails to respond to a trip command. The “supervisor” control system controls the entire system, including the combination of racks, the environmental support systems, and the charging/discharging status. The supervisor level should isolate the LIB-ESS if the inverter/charger fails to trip on an appropriate signal, or if communication is disrupted between the inverter/charger and the supervisor control.

See Figure 2.5.3.1 for explanation of management levels.

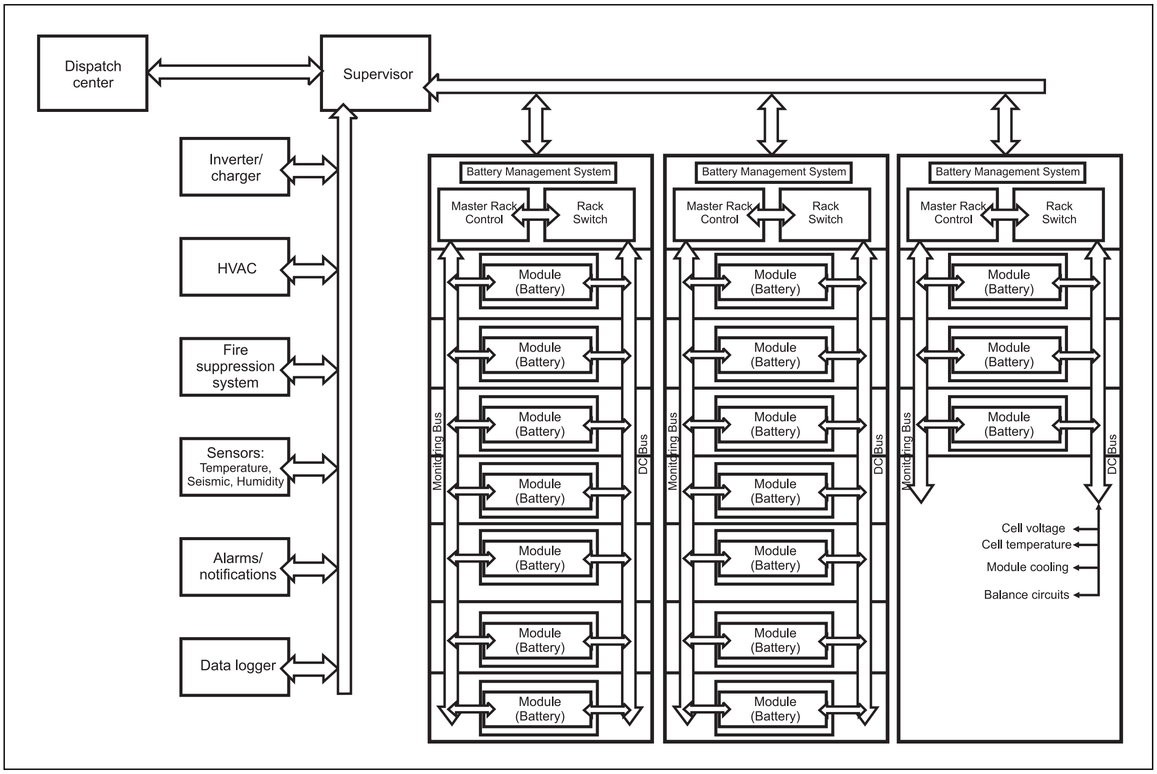

Fig. 2.5.3.1. LIB-ESS management levels

2.5.3.2 Online Condition Monitoring

2.5.3.2.1 Provide online condition monitoring systems that will monitor battery room temperature and the following parameters, at a minimum, at the battery module and/or cell level:

- Charging and discharging voltage and current
- Temperature
- Internal ohmic (resistance)
- Capacity
- State of charge (SOC)
- State of health (SOH)
- Alarm or fault log

2.5.3.2.2 Provide online condition monitoring systems with the following features:

A. The ability to transmit data to a constantly-attended location or specific operations personnel

B. The ability to generate alarms when unusual conditions are detected

C. The ability to analyze monitored parameters and generate a summary of the condition of the battery

D. Security to prevent unauthorized changes of critical parameter limits, such as voltage, temperature, and current, which are essential to maintain reliable lithium-ion battery operation.

E. Self-diagnostic capability

2.5.3.3 Early Intervention Thermal Runaway Prevention

2.5.3.3.1 Incorporate an early intervention system to automatically and electrically isolate the LIB-ESS, using one of the following approaches:

1. High cell temperature: The cell manufacturer should provide the threshold temperature indicating an abuse condition based on 100% SOC. The majority of cells within a module should be constantly monitored.

2. Off-gas detection: Provide gas detectors capable of detecting the volatile organic compounds associated with the off-gas event that precedes thermal runaway.

2.5.4 Power Conversion Equipment

2.5.4.1 Provide overcurrent protection against overload and short-circuit faults on the AC side.

2.5.4.2 Provide surge arrestors on the AC side for voltage transient “voltage spike” protection. For additional information on voltage transient protection, see Data Sheet 5-11.

2.5.4.3 Provide transformer electrical protection in accordance with Data Sheet 5-4, *Transformers* or 5-20, *Electrical Testing*, as applicable.

2.5.5 Air Circulation/Mechanical Ventilation

2.5.5.1 Locate the circulation/ventilation system to take suction at or near the ceiling.

2.5.5.2 Install an FM Approved hydrogen detector that will alarm if the level of hydrogen exceeds 10% LEL, electrically isolate the LIB-ESS, and initiate emergency exhaust ventilation in accordance with Section 2.5.5.3.

2.5.5.3 Install an emergency exhaust ventilation system that will increase the ventilation rate to 2.5 cfm/ft^2 (0.75 m^3/min/ m^2) of floor area if hydrogen is detected at 10% of the LEL, and exhaust all air directly to outdoors.

2.5.5.3.1 Route the emergency exhaust ventilation system through a system of blowers, fans, and ductwork terminating outdoors away from air inlets, doorways, and other openings.

2.5.5.3.2 Construct ductwork of noncombustible materials.

2.5.5.3.3 Provide make-up air inlets in exterior walls, in a remote location from exhaust outlets to prevent entrainment of exhaust gases.

2.5.5.4 Arrange the circulation/ventilation system controls to alarm to a constantly-attended location or to specific operations personnel.

2.6 Operation and Maintenance

2.6.1 Operation

2.6.1.1 Install, operate, and maintain batteries and battery management systems in accordance with manufacturer’s recommendations.

2.6.1.2 As part of commissioning, verify proper operation of all monitoring and protective devices.

A. Inspect the battery system thoroughly for indication of overheating, abnormal vibration, abnormal noise, or malfunction. This should occur daily for a minimum of one week of normal operation.

B. Perform infrared scanning and check battery operating and monitoring parameters to determine if any damage was sustained in shipping and installation.

2.6.2 Equipment Maintenance

2.6.2.1 General

2.6.2.1.1 Perform electrical system inspection, testing and maintenance of LIB-ESS systems in accordance with Data Sheet 5-20, *Electrical Testing. Establish and implement a LIB-ESS system inspection, testing, and maintenance program. See Data Sheet 9-0, Asset Integrity*, for guidance on developing an assest integrity program.

2.6.2.2 Battery Management System

2.6.2.2.1 The inspection, testing, and maintenance program for the BMS should include at least the following:

A. Periodic system self-test to ensure all critical systems are available and operational.

B. Periodic pack switch maintenance. This may involve cycling the switch to ensure mechanical integrity and tightness of cable connections by torquing to specifications.

C. HVAC maintenance. This may include change of air filters at periodic intervals. These intervals may vary depending on the location of the site. Dusty locations may require more frequent air filter replacement. Other HVAC maintenance items may include coolant check, compressor/heater core check and duct/cable check.

D. Periodic check of spare battery modules to ensure they are maintained in charged state.

E. Periodic tracking of state-of-health (SOH) values, which is the percent of remaining capacity (based on design capacity) in the battery packs.

2.6.2.3 Establish a battery replacement program for service aged batteries. Review the battery replacement program regularly and include, at a minimum, the following components:

A. The OEM design life expectancy of the LIB-ESS batteries. This will be a number in years that the system is expected to perform adequately. After this point, the batteries should be replaced. This establishes the replacement timeline.

B. Regular monitoring of the LIB-ESS SOH, which is the percent of remaining capacity based on design capacity. This information should be available through the BMS, which continuously tracks SOH. Unexpected component malfunctions or failures and operating outside design parameters can age batteries faster than when operating within design limits. The BMS will be able to monitor these unexpected issues and adjust the SOH of the system.

C. Regular review of the replacement program, ensuring there is a method of adjusting the replacement timeline. The plan should allow for adjusting the replacement timeline if feedback from the BMS shows the SOH indicates accelerated aging. The following factors justify earlier replacement:

1. Significant changes or trends in the condition monitoring data that indicate development problems with the battery system
2. Advice from the OEM of design problems that require replacement
3. Operating experience and failure history that indicates the battery should be replaced
4. Exposure to severe operating conditions

D. A method of managing changes. This should consider major changes that affect the life expectancy and replacement timeline of the LIB-ESS. Changes could include replacement of the BMS, modifying the thermal management system, and changes in application or operational modes (e.g., modifying the BMS to operate based on an arbitrage mode vs. electric supply capacity).

2.7 Training

2.7.1 Have operation personnel trained by the supplier/manufacturer of the LIB-ESS equipment.

2.7.2 Provide other training in accordance with Data Sheet 10-8, *Operators*.

2.8 Human Factors

2.8.1 Housekeeping

2.8.1.1 Do not store combustible material in LIB-ESS enclosures, buildings, or cutoff rooms.

2.8.2 Emergency Response and Pre-Incident Planning

2.8.2.1 Develop an emergency response plan to address the potential fire hazards associated with energy storage systems. Refer to Data Sheet 10-1, *Pre-Incident Planning*, for general guidelines on establishing and maintaining an emergency response plan.

2.8.2.2 Develop a pre-incident plan with the fire service in accordance with Data Sheet 10-1, *Pre-Incident Planning*. Arrange and prepare the plan with documented procedures to expedite safe entry and emergency response to fires in the LIB-ESS area, including the following:

- Manual disconnection
- Access routes
- Manual fire protection methods
- Manual smoke ventilation (if provided)
- SDS for battery cells

2.8.2.3 Develop a post-incident recovery plan that addresses the potential for reignition of LIB-ESS, as well as removal and disposal of damaged equipment.

2.8.2.3.1 A fire watch should be present until all potentially damaged LIB-ESS equipment containing Li-ion batteries is removed from the area following a fire event. The water supply should be replenished as quickly as feasible.

Fires involving Li-ion batteries are known to reignite. Li-ion batteries involved in or exposed to fires should be adequately cooled to prevent reignition.

2.8.2.3.2 Identify the equipment needed to safely remove and replace damaged equipment and the supporting infrastructure to facilitate prompt removal. The plan should include service or equipment providers needed for recovery infrastructure. The OEM or integrator should provide guidance on decommissioning, removal of damaged equipment, and proper disposal in accordance with local regulations.

2.9 Utilities

2.9.1 In extreme environments, provide an emergency power supply to the HVAC systems. An extreme environment is one that could allow cell-level temperatures to rise or fall outside the maximum operating temperature range of -4.0° F (-20° C) to 120° F (50° C) despite BMS control.

2.9.2 Ensure LIB-ESS enclosures with common HVAC components, such as a common condensing unit (cooling tower), are designed to shut down the LIB-ESS in the event of a component failure.

3.0 SUPPORT FOR RECOMMENDATIONS

3.1 Construction and Location

3.1.1 Space Separation Between Exterior Enclosures

The enclosure, being constructed of steel or other metal, will conduct heat and radiate it away from the enclosure. An uncontrolled fire within one of the enclosures is expected to cause a substantial amount of radiation and conduction through the metal sides of the enclosure and will cause thermal runaway in adjacent enclosures if not separated by the recommended distance. There are alternative options in lieu of space separation that will minimize the potential for fire spread until the fire service arrives.

3.2 Fire Protection and Minimum Separation Distances for Indoor Installations

Thermal runaway events create a large amount of heat. The heat, coupled with plastic construction components, can lead to a very large fire. Although fire protection may not be practical in exterior installations, it is the best method of cooling a fire involving LIB-ESS.

Limited research has been performed on LIB-ESS systems to assess fire propagation characteristics and protection schemes. The report Development of Sprinkler Protection Guidance for Lithium Ion Based Energy Storage Systems, published in June 2019 on the FM Global Website, is the basis for recommendations on fire protection and separation distances from both noncombustible and combustible materials. However, it must be recognized that the research was limited in scope, and the effect of rack design, materials-of-construction, battery specifications and chemistry, and other design features are not well understood. Because of these issues, it does not appear possible to extrapolate the results obtained with the tested lithium iron phosphate (LFP) and lithium nickel oxide/lithium manganese oxide (LNO/LMO) systems to other LIB-ESS. The recommendations in DS 5-33 represent the current state of knowledge. The data sheet will be updated as additional information is available.

In addition, the National Fire Protection Association (NFPA) recently published the first fire protection standard for LIB-ESS, NFPA 855, *Standard for the Installation of Stationary Energy Storage Systems*.

Link to *Development of Sprinkler Protection Guidance for Lithium Ion Based Energy Storage Systems*:

https://www.fmglobal.com/research-and-resources/research-and-testing/research-technical reports

The report documents sprinkler operations during large scale fire testing. Fire size and peak heat release rate varied for the chemistries tested. The worst-case scenario was the LNO/LMO chemistry, which resulted in operation of all sprinklers in the test area. Ceiling gas temperature measurements in the surrounding area indicated that additional sprinklers would have operated outside of the typical 2500 ft^2 (230 m^2) design area. Therefore, the data sheet reflects a conservative approach that assumes all sprinklers in the LIB-ESS room will open.

3.3 Gaseous Protection Systems

Generally, gaseous protection systems are not recommended for LIB-ESS applications for the following reasons:

A. Efficacy relative to the hazard. As of 2019, there is no evidence that gaseous protection is effective in extinguishing or controlling a fire involving energy storage systems. Gaseous protection systems may inert or interrupt the chemical reaction of the fire, but only for the duration of the hold time. The hold time is generally ten minutes, not long enough to fully extinguish an LIB-ESS fire or to prevent thermal runaway from propagating to adjacent modules or racks.

B. Cooling. FM Global research has shown that cooling the surroundings is a critical factor to protecting the structure or surrounding occupancy because there is currently no way to extinguish an LIB-ESS fire with sprinklers. Gaseous protection systems do not provide cooling of the LIB-ESS or the surrounding occupancy.

C. Limited Discharge. FM Global research has shown that LIB-ESS fires can reignite hours after the initial event is believed to be extinguished. As gaseous protection systems can only be discharged once, the subsequent reignition would occur in an unprotected occupancy.

3.4 Electrical

3.4.1 Battery and LIB-ESS Service Aging

Li-ion battery aging depends on several factors, such as number of charge/discharge cycles, depth of discharge, charging/discharging rate, state of charge, calendar time, and operating temperature. The capacity of a li-ion battery will degrade approximately 50% to 80% depending on design and the sizing margin when battery age is close to end-of-life. In addition, the internal resistance value of a service aged battery substantially increases from 2 to 3 times initial value at a fixed ampere-hour rate at the cell level, resulting in increased likelihood of thermal runaway.

Industry practice is that the BMS measures the state of health by design to track condition of the batteries due to aging. The state of health is based on actual capacity relative to the initial rated capacity of battery as minimum. It may also take into consideration the internal resistance, total energy throughput, number of cycles, etc. The BMS provides indicator (alarm) for replacement based on the state of health information. In absence of established replacement criteria, consult the OEM for guidance.

3.4.2 Early Intervention Devices

Early intervention is a strategy to prevent cells from entering thermal runaway by using early detection devices and interlocking them with the battery management system (BMS) to electrically isolate the LIB-ESS if an unsafe condition is detected. Currently, two common early detection technologies are available: cell temperature monitoring and off-gas detection. Early intervention is only successful when thermal runaway is caused by electrical abuse. Thermal runaway can also be caused by thermal abuse, such as when an enclosure temperature exceeds the operating temperature range of the cells, or by physical damage due to mishandling or a manufacturing defect. Electrical isolation will not prevent thermal runaway if the cell failure is caused by either thermal abuse or physical damage.

3.4.2.1 Temperature Monitoring of Cells

All LIB cells have a temperature at which thermal runaway is unavoidable. Some manufacturers place multiple sensors, capable of monitoring the exterior temperature of multiple cells, inside the modules. The BMS is programmed to automatically isolate the LIB-ESS or rack if the temperature of one or more cells exceeds a setpoint significantly lower than the threshold for thermal runaway. If this strategy is used, monitoring the majority of cells in a module to ensure prompt detection is critical. If a module is provided with only a few sensors, a cell could go into thermal runaway undetected and create a thermal abuse condition for the adjacent cells before the BMS could react.

3.4.2.2 Off-Gas Detection

Off-gas detection equipment detects volatile organic compounds (VOCs) associated with the degradation of the electrolyte during the early stage of cell failure. Before a cell goes into thermal runaway, VOCs produced by degradation of the cell are released in trace amounts. This occurs at a much lower temperature than the thermal runaway threshold. Equipment in this category can be installed in an individual rack, or in an LIB-ESS room or enclosure/container. Generally, one or more gas detectors calibrated for the off-gas VOCs are installed in or near the LIB-ESS with at least one reference detector located in an open area. The early detection equipment controller compares the ambient levels from the reference cell to the levels detected at the LIB-ESS to prevent false trips.

4.0 REFERENCES

4.1 FM Global

Data Sheet 1-20, *Protection Against Exterior Fire Exposure*
Data Sheet 1-21, *Fire Resistance of Building Assemblies*
Data Sheet 4-5, *Portable Extinguishers*
Data Sheet 5-4, *Transformers*
Data Sheet 5-19, *Switchgear and Circuit Breakers*
Data Sheet 5-20, *Electrical Testing*
Data Sheet 5-23, *Design and Protection for Emergency and Standby Power Systems*
Data Sheet 5-32, *Data Centers and Related Facilities*
Data Sheet 5-48, *Automatic Fire Detection*
Data Sheet 9-0, *Asset Integrity*
Data Sheet 10-1, *Pre-Incident Planning*
Data Sheet 10-8, *Operators*

4.2 Other

Institute of Electrical and Electronics Engineers (IEEE). *Guide for the Ventilation and Thermal Management of Batteries for Stationary Applications.* IEEE 1635-2012.

APPENDIX A GLOSSARY OF TERMS

Arbitrage: See electrical energy time-shift.

Black start: Storage systems provide an active reserve of power and energy within the grid and can be used to energize transmission and distribution lines and provide station power to bring power plants online after a catastrophic failure of the grid. The LIB-ESS can be used to energize transmission and distribution lines, provide startup power for one or more diesel generators and/or (larger) power plants, and provide a reference frequency.

Battery management system (BMS): The supervisory system that ensures basic functionality of the battery pack while maintaining safe operating conditions and acting appropriately in contingencies. One of the main functions of the BMS is to keep the cells operating within their designed operating parameters to prevent thermal runaway.

Capacity: Specific energy in ampere-hours (Ah). Ah is the discharge current a battery can deliver over time and is a measure of the charge stored in the battery. This can also be measured in kilowatt-hours (kWh) or megawatt-hours (MWh).

Cell: The smallest electrochemical component that can store energy.

Congestion relief: Congestion occurs when available, least-cost energy cannot be delivered to all or some loads because transmission/distribution facilities are not adequate to deliver that energy. Electricity storage can be used to avoid congestion-related costs and charges, especially if the costs become onerous due to significant transmission system congestion. The EES system can be charged when there is no congestion and discharged when congestion occurs.

Demand charge management: Demand charges are based on the highest 15-minute average usage recorded on the meter within a given month. If a facility tends to use a lot of power over short periods, demand charges will comprise a larger part of the utility bill. Demand charge management (similar to electric energy time-shift) involves the implementation of energy storage to reduce the peak demand and reduce costs.

Energy storage system (LIB-ESS): Any system through which electrical energy can be stored and reused when needed.

Electrical energy time-shift: Electric energy time-shift involves purchasing inexpensive electric energy, available during periods when prices or system marginal costs are low, to charge the storage system so the energy can be used or sold at a later time when the price or costs are high. If difference in energy prices is the main driver and energy is stored to compensate for (for example) diurnal energy consumption patterns, this application is often referred to as “arbitrage.”

Electric supply capacity: Depending on the circumstances in a given electric supply system, energy storage could be used to defer and/or reduce the need to buy new central station generation capacity and/or purchasing capacity in the wholesale electricity marketplace. In this application, the EES system supplies part of the peak capacity when the demand is high, thus relieving the generator by limiting the required capacity peak.

LFP: Lithium iron phosphate battery chemistry.

LIB-ESS container: An LIB-ESS container is a packaged LIB-ESS structure of less than 500 ft^2 (46.5 m^2) that is accessed from hatches or doors on the exterior and is not occupiable.

LIB-ESS enclosure: An LIB-ESS enclosure is a packaged LIB-ESS structure of less than 500 ft^2 (46.5 m^2), typically an ISO shipping container or pre-fabricated structure of similar size that may or may not be occupiable. LIB-ESS enclosure systems are typically delivered on a skid, with all LIB-ESS equipment installed by the manufacturer.

Load following/ramping for renewables: Load following is characterized by power output that typically changes as frequently as every few minutes. The output differs in response to the changing balance between electric supply and load within a specific region or area. The LIB-ESS is used to supply (discharge) or absorb (charge) power to compensate for load variations or variations in renewable generation.

Module: A combination of series and parallel connected cells. Modules may also be provided with a smaller version of the BMS to control the cells within and communicate with the system BMS.

NMC: Lithium nickel manganese cobalt oxide battery chemistry.

Power quality: Power quality is a measure of the level of voltage and/or frequency disturbances. Demand fluctuations on a short timescale (few minutes to fraction of a second) can cause power quality issues on the power grid. LIB-ESS systems can respond to these short timescale fluctuations to alleviate the effect of the disturbances and provide improved power quality.

Power reliability: The application of energy storage in various operational regimes to improve the overall reliability of power systems. For example, LIB-ESS can balance small sections of the grid to achieve a good match between generation and load. Storage devices can provide frequency regulation to maintain the balance between the network’s load and the power generated. The end result is a more reliable power supply for industrial facilities.

Rack: A rack (sometimes called a “pack” or a “string”) consists of multiple modules typically connected in series to develop a high DC voltage that is fed to the inverter/charger. The rack also consists of switching components (circuit breaker, isolator, and contactor) to isolate the rack during a contingency.

Regulation frequency response: Frequency response operation requires the LIB-ESS to react to system needs in even shorter time periods (seconds to less than a minute) when there is a sudden loss of a generation unit or a transmission line or sudden energization of a large load. The primary reasons for including regulation in the power system are to maintain the grid frequency and to comply with the North American Electric Reliability Council’s Real Power Balancing Control Performance (BAL001) and Disturbance Control Performance (BAL002) standards.

Retail energy time shift: See electric energy time-shift.

Supplemental reserves: Operation of an electric grid requires reserve capacity that can be called upon when some portion of the normal electric supply resources becomes unavailable unexpectedly. Stored energy reserves are usually charged energy backups that have to be available for discharge when required to ensure grid stability. Other reserves typically fall into spinning and non-spinning categories:

> **Spinning reserve:** The amount of additional capacity that is currently in operation. For example, if a location with a maximum steam generator output of 500 MW is currently operating at 250 MW, there is 250 MW of spinning reserve.
>
> **Non-spinning reserve:** The amount of additional capacity that is not currently in operation and would need to be started in order to provide power output. This is the sum of potential reserve power that is capable of being started and put on the grid. This should not be confused with capacity that is offline and being maintained or otherwise not able to start up and add power to the grid.

State of charge (SOC): The real-time amount of energy stored in the system, compared to the rated capacity. A function of voltage. The SOC could be expressed as a percentage value. This would mean that a fully charged battery would have 100% SOC, and a fully discharged battery would have 0% SOC.

State of health (SOH): A quantitative value (expressed in percentage) depicting the current condition of the battery compared to its condition when new. The SOH is evaluated by the battery management system (BMS) by monitoring operational variables such as voltage, current, temperature, and internal resistance. Since a battery's performance degrades with time, the SOH value starts at 100% for a new battery and reduces with time. This indication is critical in evaluating and monitoring.

Upgrade deferral: Upgrade deferral involves delaying, and in some cases avoiding entirely, utility investments in system upgrades by using relatively small amounts of storage. Consider a transmission system with peak electric loading that is approaching the system's load-carrying capacity (design rating). In some cases, installing a small amount of energy storage downstream from the nearly overloaded transmission node could defer the need for the upgrade for a few years.

Voltage support: Stable operation of the power grid requires operators to maintain voltage within specified limits. This requires the control of reactive power (VAR) in the grid. Note that no (or low) real power is required from an EES system operating within a voltage/VAr support application, so cycles per year are not appropriate for this application, and storage system size is indicated in reactive power (MVAr) rather than MW.

APPENDIX B DOCUMENT REVISION HISTORY

The purpose of this appendix is to capture the changes that were made to this document each time it was published. Please note that section numbers refer specifically to those in the version published on the date shown (i.e., the section numbers are not always the same from version to version).

January 2024. Interim revision. Minor editorial changes were made.

July 2023. Interim revision. The following major changes were made:

A. Changed title to "*Lithium-Ion Battery Energy Storage Systems*."

B. Revised separation distance recommendations for indoor and outdoor LIB-ESS.

C. Added recommendation for early intervention thermal runaway prevention.

D. Added recommendation for emergency exhaust ventilation.

E. Expanded recommendation for post-incident planning to identify equipment needed for prompt removal/replacement of damaged equipment.

F. Added support material for early intervention devices.

July 2020. Interim revision. The following changes were made:

A. The scope was updated for clarity.

B. Figure 2.3.1 was corrected to be consistent with 2.3.2.1.

April 2020. Interim revision. The following substantive changes have been made to the document:

A. Added recommendations for selection of ESS components.

B. Updated location recommendations to reflect current technology.

C. Added recommendations for construction of dedicated buildings.

D. Added recommendations for mechanical ventilation.

E. Added recommendations for separation distance between racks.

F. Added recommendation for water supply duration.

G. Added recommendations for battery management system safety functions.

H. Added recommendations for online condition monitoring.

I. Added recommendation for post-incident fire watch.

J. Expanded support material related to FM Global Research on sprinkler protection and separation distance.

January 2017. This is the first publication of this document.

APPENDIX C REFERENCE INFORMATION

C.1 Introduction

Energy storage has been around for many years in five predominant forms: electrochemical, mechanical, thermal, electrical, and chemical. This data sheet addresses only lithium-ion battery ESS, which is an electrochemical type.

Lithium-ion battery energy storage systems are relatively new, but are quickly becoming the most common type of electromechanical energy storage. These systems offer a method of storing electrical energy that can be used to supplement conventional power generation (e.g., coal and fossil fuels), reduce peak energy demand swings, support high-voltage energy grids, and also support green energy production, such as wind and solar, that are dependent on natural sources and therefore cannot produce power at all times.

Lithium-ion battery (LIB) energy storage systems (LIB-ESS) come in a variety of types, sizes, applications, and locations. The use of the technology is continually expanding, becoming more available for a range of energy storage applications, from small residential support systems to large electrical grid systems. LIB-ESS consist of many basic components. Cells or batteries are the building blocks of an LIB-ESS. Several cells connected together form a module, and several linked modules form a rack or string. Several racks or strings form an energy storage system.

The design of LIB-ESS is dependent on the user’s voltage, amperage, and power requirements; the system’s application; the useful life of the system; and the costs of the system. LIB-ESS are designed, manufactured, and assembled by either LIB-ESS manufacturers or LIB-ESS Integrators. LIB-ESS manufacturers manufacture and assemble all components from the cells all the way through to the enclosure as a full package. Integrators will typically purchase batteries and other components and manufacture certain parts and design and assemble the system for their customers. In either case, original equipment manufacturers (OEMs) and integrators use a battery management system (BMS) to control the operation and safety of the LIB-ESS, which is critical to prevent abnormal operation. The design and operation of the BMS is proprietary to the OEM or integrator and, at this point, there is limited opportunity to affect its design. The design can include hardware and software components. It is critical to understand all operation and safety functions of the LIB-ESS as described within this document.

LIB-ESS are typically installed within a building, or outside a building within an enclosure. Exterior installations vary and depend primarily on the size of the system. Small systems may be installed in a NEMA-rated enclosure, while larger systems will be installed within a shipping-type metal container. For very large systems, a stand-alone building may be used to house the LIB-ESS.

When installed within a building, LIB-ESS are typically located in electrical cabinets within a general space or in a designated room. All the support systems for the LIB-ESS are provided by the building support systems or are specifically designed for the room, depending on the needs of the LIB-ESS. When installed outside a building, they are provided with thermal management systems (i.e., HVAC) designed for the enclosure. Other auxiliaries are found in both installations: electrical support (e.g., inverters/converters, AC electrical systems including disconnects, voltage/amperage monitors, load monitors, etc.) and fire protection.

C.2 LIB-ESS Components

For the purposes of understanding how these systems are built, the following is a description of the components from the cell level to the system level.

C.2.1 Cells

Lithium-ion cells are constructed similar to other battery cells, consisting of an anode, a cathode, electrolyte, insulators, terminals, pressure vent, and a container sometimes called a “case” or “can.”

Each cell consists of a cathode and an anode separated by a thin dielectric layer called the “separator.” A li-ion cell uses the movement of lithium-ions between positive and negative electrodes for energy storage. Lithium never exists in metallic form, so inherent instability of metallic lithium is mitigated. A typical li-ion cell generates from 3.6 to 4.2 V. Also, the secondary electrolyte interphase layer (SEI), which forms on the anode surfaces, is an ionically conductive and electronically insulating layer. This layer facilitates the working of li-ion technology. Failure of SEI leads to heat generation and thermal runaway.

Li-ion cells include a wide variety of chemistries pertaining to the chemical composition of the anode and cathode that affect the performance and cost. For cathode composition, Li-nickel manganese cobalt oxide (NMC) and Li-nickel cobalt aluminum oxide (NCA) chemistries have known to be very stable at the same time providing high energy density. For anode composition, most popular is partially graphitized carbon. Lithium titanate (LTO) is typically used in high safety applications because it benefits from higher stability. However, LTO cells have approximately 30% lower energy density values compared to other compositions.

The term “cell” is often interchangeable with “battery” when talking about small-format applications. For example, a cylindrical cell with a top positive terminal and bottom negative terminal is used in many applications and called a battery. Cells actually come in a variety of forms. The three most common forms are cylindrical cell, prismatic cell, and pouch cell.

C.2.1.1 Cylindrical Cells

This is the most widely used packaging style for batteries and provides good mechanical stability. Most cylindrical cells feature a pressure-relief mechanism, and the simplest design uses a membrane seal that ruptures under high pressure. Some Li-ion cells connect the pressure relief valve to an electrical fuse that permanently opens the cell if an unsafe pressure builds up. See Figure C.2.1.1.

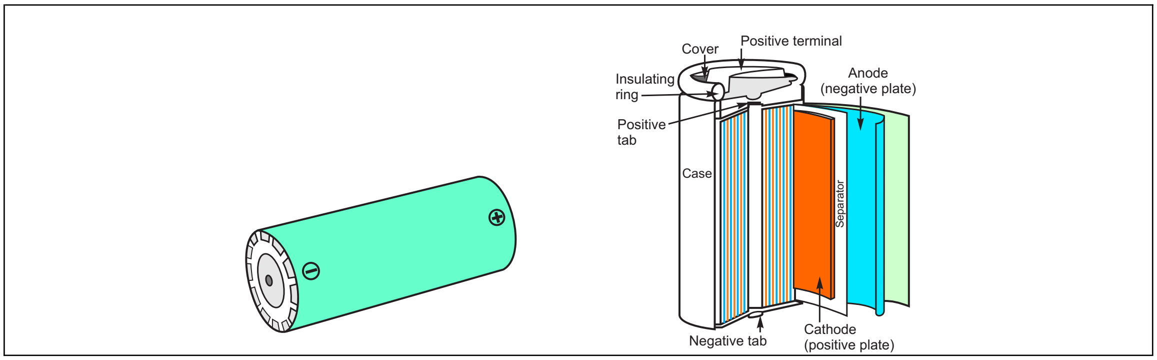

Fig. C.2.1.1. Cylindrical cell form

C.2.1.2 Prismatic Cells

Prismatic cells provide a firm enclosure to the electrochemical cell within. These cells are found in computer tablets and laptops ranging from 800 mAh to 4,000 mAh. No universal format exists and each manufacturer designs its own. Prismatic cells are also available in large formats. Packaged in welded aluminum housings, the cells deliver capacities of from 20 to 50 Ah and are primarily used for LIB-ESS applications. See Figure C.2.1.2.

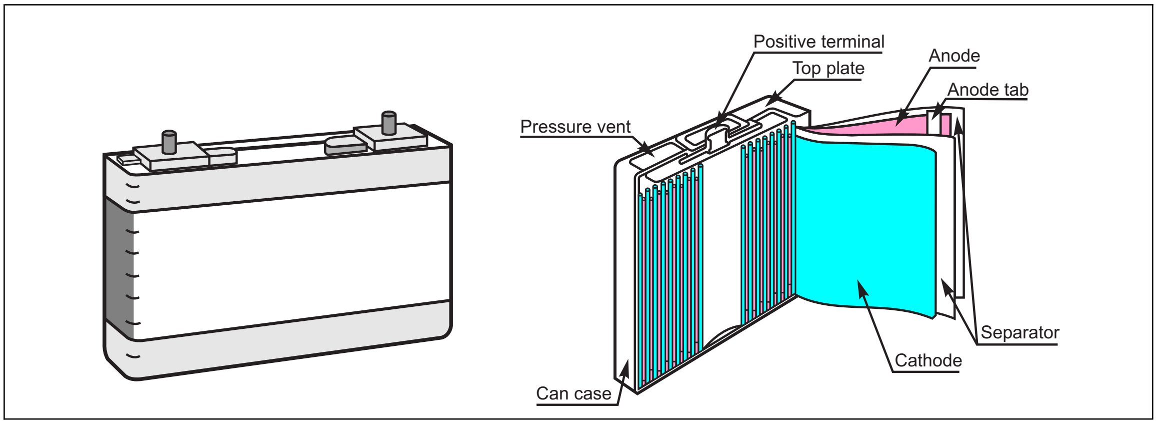

Fig. C.2.1.2. Prismatic cell form

C.2.1.3 Pouch Cells

A pouch cell uses laminated architecture in a bag. The pouch cell makes most efficient use of space. It is light and cost-effective, but exposure to humidity and high temperature can shorten its life. No standardized pouch cells exists; each manufacturer designs its own. The pouch cell is used for similar applications as the prismatic cell. See Figure C.2.1.3.

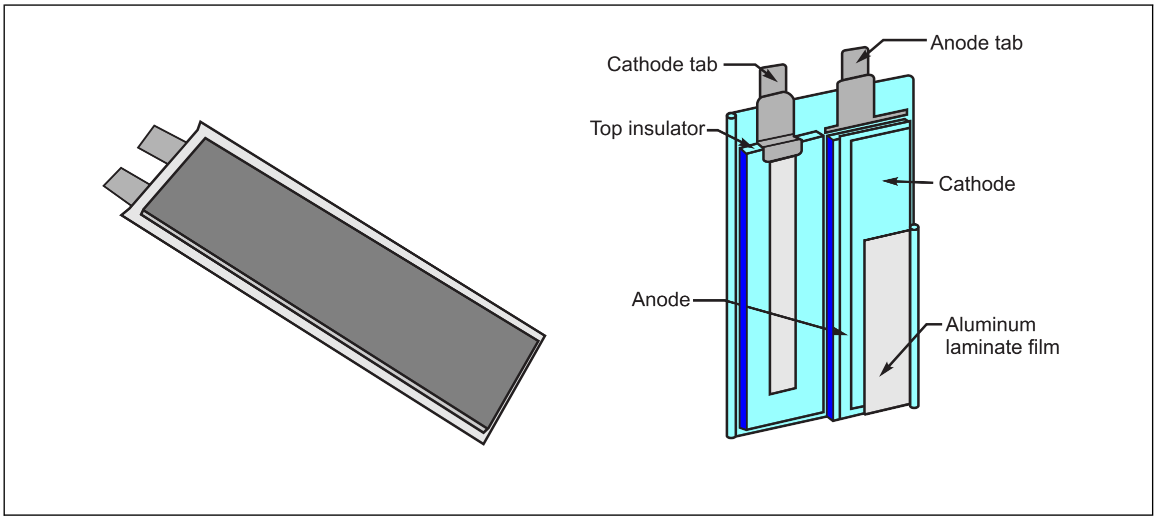

Fig. C.2.1.3. Pouch cell form

C.2.2 Modules

The next order of structure is the lithium-ion module or pack. This is an assembly of multiple cells that are electrically arranged in series, parallel, or a combination of both to meet the output voltage and amperage necessary for the installation. See Figure C.2.2(A) and (B).

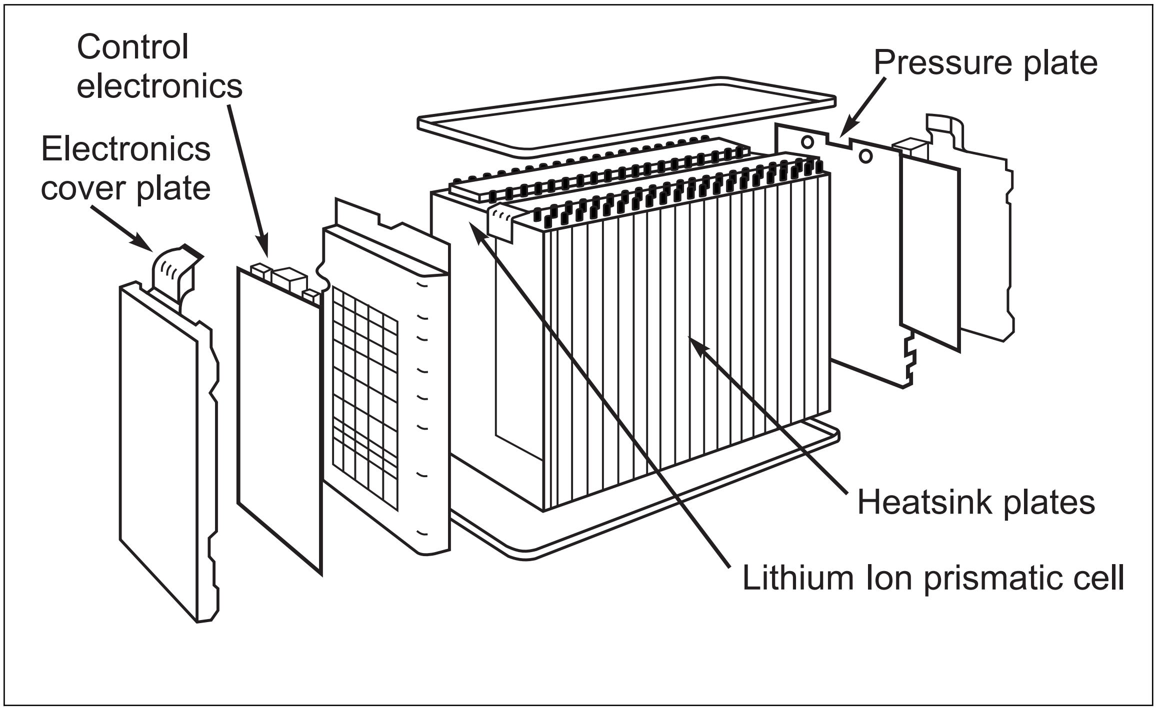

Fig. C.2.2(A). Module configuration

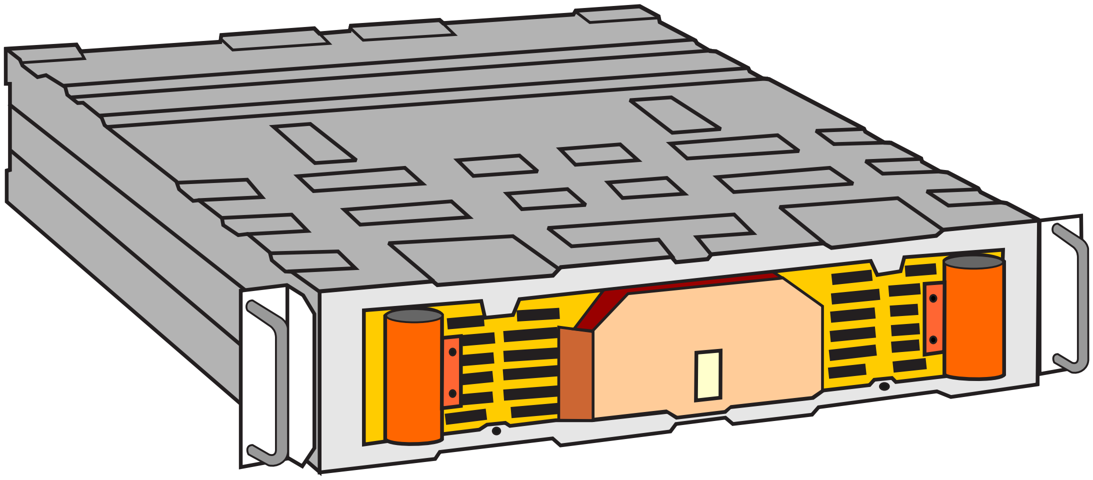

Fig. C.2.2(B). Typical enclosed module

C.2.3 Racks

A rack consists of multiple modules, typically connected in series to develop a high DC voltage that is fed to the inverter/charger. The rack also consists of switching components (circuit breaker, isolator, and contactor) to isolate the rack during a contingency. See Figure C.2.3.

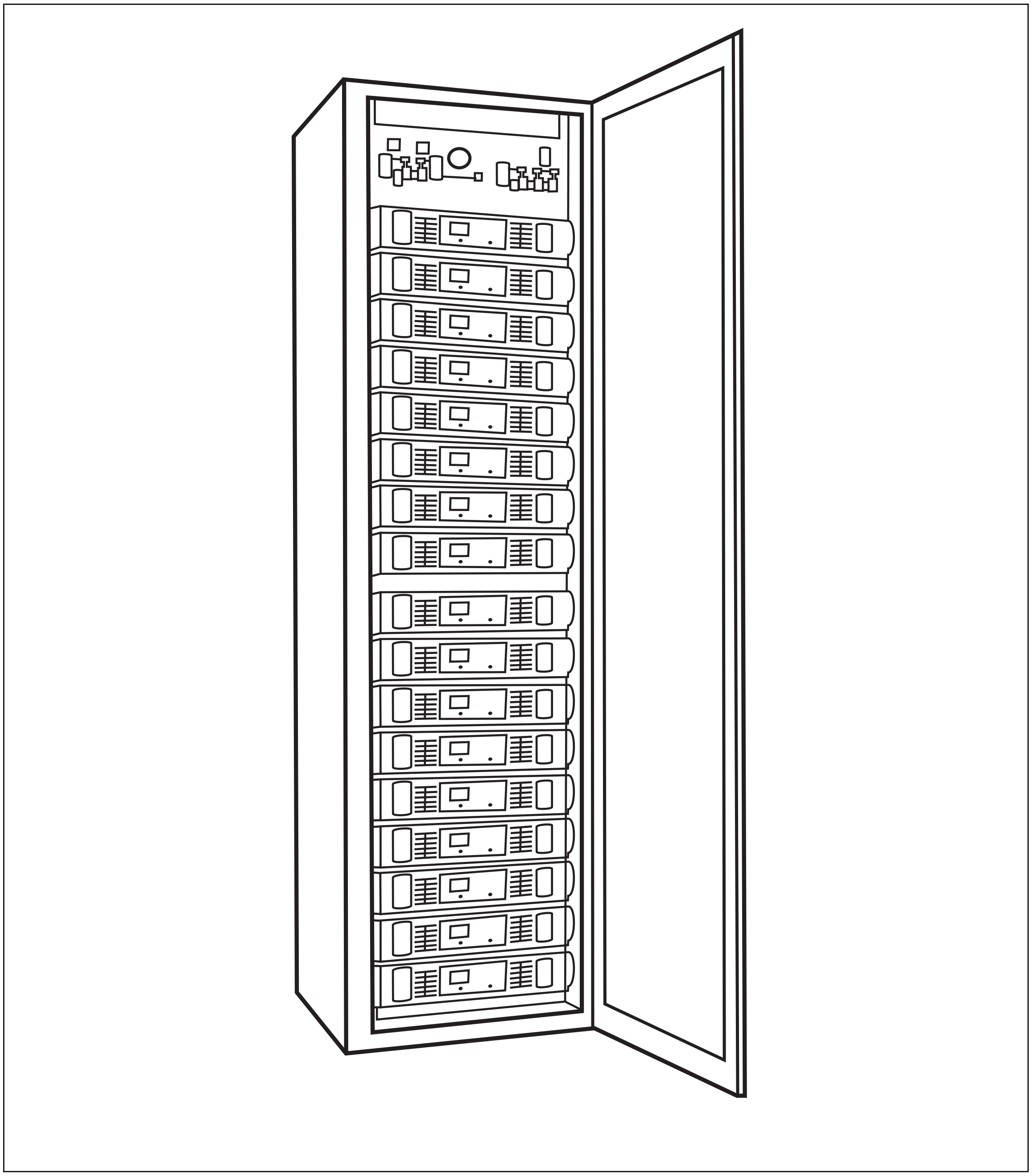

Fig. C.2.3 Typical rack configuration with multiple modules

C.2.4 Systems

A large capacity LIB-ESS consists of multiple racks connected in parallel and feeding the inverter/charger. The LIB-ESS also includes the battery management system (BMS) that controls the batteries' basic functionality, safe operating conditions, and contingency response. An LIB-ESS also includes auxiliary systems such as HVAC and fire protection. See Figure C.2.4(A).

Figure C.2.4(B) shows the typical components within an LIB-ESS. Most of these components will be standard in every system despite the size or applications. .

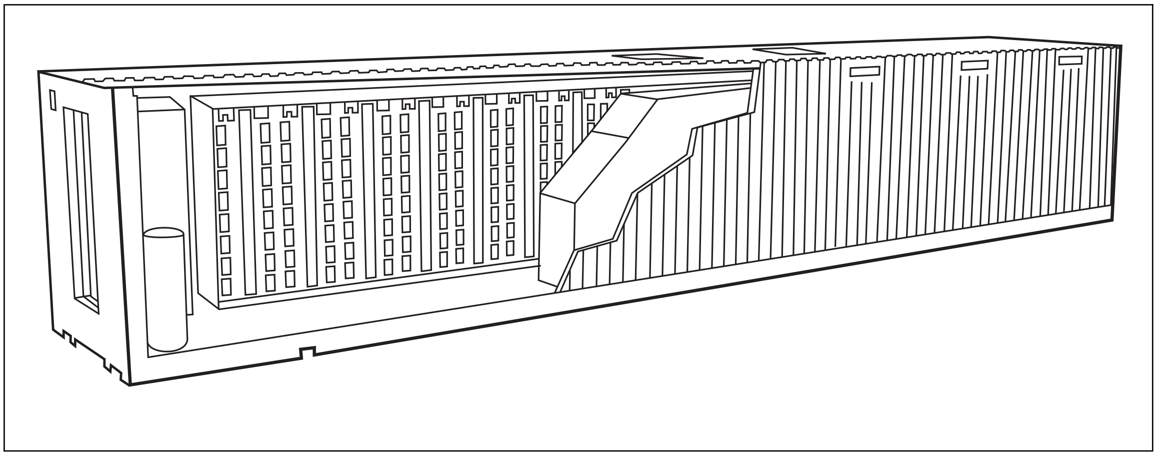

Fig. C.2.4(A). Exterior enclosure with multiple racks

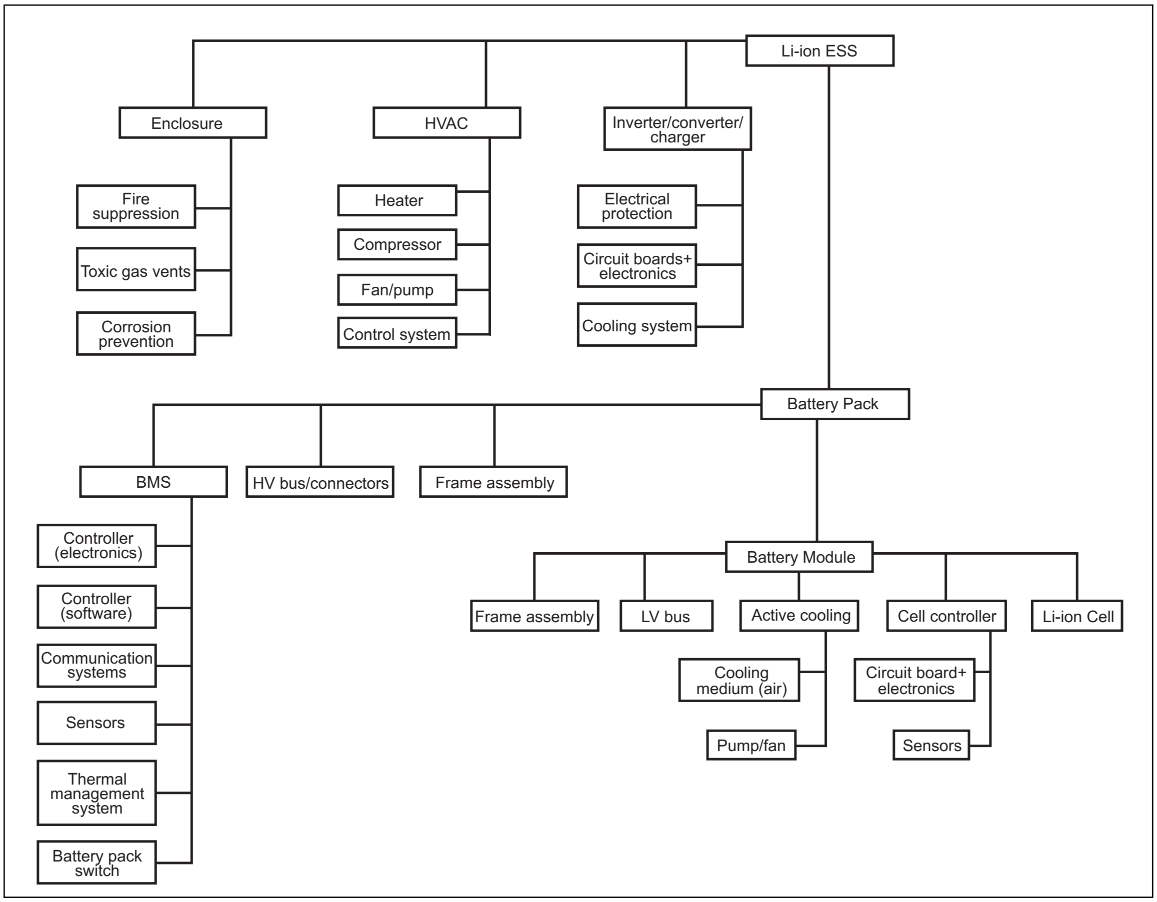

Fig. C.2.4(B). LIB-ESS architecture diagram

C.3 LIB-ESS Applications

LIB-ESS applications include bulk energy, transmission, distribution (before meter) and commercial or industrial customer (after meter).

C.3.1 Bulk Energy Services

Bulk electrical energy storage is used to store relatively large amounts of energy in order to make it available (often locally) at another, usually more convenient, time. Applications include the following:

- Electric energy time-shift (arbitrage)
- Electric supply capacity

C.3.2 Ancillary Services

Systems used as ancillary services are used to facilitate and support the electricity grid's ability to provide a continuous flow of electricity and match supply and demand. Providing startup power after a total blackout is also considered an ancillary service. Applications include the following:

- Regulation/frequency response
- Spinning, non-spinning, and supplemental reserves
- Voltage support
- Black start
- Load following/ramping for renewables

C.3.3 Transmission and Distribution Services

Strategically placed electrical energy storage used within a transmission or distribution infrastructure service may act as an energy buffer and thereby defer grid upgrades. Applications include the following:

- Upgrade deferral
- Congestion relief
- Voltage support

C.3.4 Customer Energy Services

EES used within customer energy management is used to provide a customer related service. This can be enhancing the power quality, improving reliability and/or realizing additional profits for a customer. Applications include the following:

- Power quality
- Power reliability
- Retail energy time-shift
- Demand charge management

C.4 Failure Modes

The performance of lithium-ion cells is dependent on both temperature and operating voltage. There is a safe integrity operating window in which these cells can work. This window is a function of cell voltage and temperature. The cell should operate between 32°F (0°C) and 212°F (100°C) while maintaining a voltage from 2 V to 4 V. Should a failure occur and the cell temperature fall below 32°F (0°C), lithium plating will occur during the charging cycle, leading to shorting. Operating above 212°F (100°C) can lead to SEI thermal layer breakdown, and when coupled with operating above 6 V can lead to electrolyte leakage and subsequent vapor ignition. When operating at extreme temperatures (over 392°F [200°C]) the cathode active material will break down, causing even further damage. When operating below 2 V, the copper will dissolve, leading to shorting. When operating above 4 V and between 32°F (0°C) and 212°F (100°C), lithium plating will occur during charging, which will lead to overheating.

This section describes the failure modes for li-ion cells. These failure modes can be split into four broad categories depending on the critical variable triggering the failure: voltage, temperature, mechanical fatigue, and cycling/aging.

C.4.1 Overvoltage

If the charging voltage is increased beyond the recommended upper cell voltage, excessive current could flow, giving rise to two problems:

1. Lithium plating (dentrite growth): Lithium-ions accumulate on the surface of the anode where they are deposited as metallic lithium. This is known as lithium plating. The consequence is an irreversible capacity loss and, since the plating occurs in dendritic form, it can ultimately result in a short circuit between the electrodes. The quantity of lithium available is not sufficient to present a water reactivity hazard and therefore lithium plating is not typically considered a concern for lithium-ion batteries, while dendrite growth is considered a short circuit hazard.
2. Overheating: Excessive current also causes increased Joule heating of the cell, accompanied by an increase in temperature.

C.4.2 Undervoltage/Over-Discharge

Allowing the cell voltage to fall below about 2 V by over-discharging or storage for extended period results in progressive breakdown of the electrode materials.

- Anodes: At low voltage, the anode copper current collector dissolves into the electrolyte. As the voltage is increased (by charging), the copper ions which are dispersed throughout the electrolyte are precipitated as metallic copper wherever they happen to be, not necessarily back on the current collector foil. This is a dangerous situation which can ultimately cause a short circuit between the electrodes.
- Cathodes: Keeping the cells for prolonged periods at voltages below 2 V results in the gradual breakdown of the cathode over many cycles with the release of oxygen by the lithium cobalt oxide and lithium manganese oxide cathodes and a consequent permanent capacity loss. With lithium iron phosphate cells, this can happen over a few cycles.

C.4.3 Low Temperature

The effect of reducing the operating temperature is to reduce the rate at which the active chemicals in the cell are transformed. This translates to a reduction in the current-carrying capacity of the cell, both for charging and discharging. In other words, its power-handling capacity is reduced. The reduced reaction rate slows down and restricts the movement of the lithium-ions. Since the electrodes cannot accommodate the current flow, the result is reduced power and lithium plating of the anode, with irreversible capacity loss.

C.4.4 High Temperature

Operating at high temperatures can result in the destruction of the cell. The Arrhenius effect helps to get more power out of the cell by increasing the reaction rate, but higher currents give rise to higher I2R heat dissipation and thus even higher temperatures. This positive temperature feedback could result in thermal runaway unless heat is removed faster than it is generated.

C.4.5 Thermal Runaway

Several stages are involved in the buildup to thermal runaway, with each one capable of causing more damage than the previous stage.

A. Breakdown of SEI layer. This could be caused by overheating or mechanical impingement or can start at a relatively low temperature of 80|SNC. Once this layer is breached the electrolyte reacts with the carbon anode and leads to electrolytic breakdown and cathode breakdown. These reactions are exothermic and further increases the temperature.

B. Electrolyte breakdown. Heat from anode reaction causes the breakdown of the organic solvents used in the electrolyte releasing flammable hydrocarbon gases (Ethane, Methane and others) but no oxygen. The gas generation due to the breakdown of the electrolyte causes pressure to build up inside the cell. The pressure release vent in the cells are designed to release the gases and relieve internal pressure.

C. Separator melting. At elevated temperature, the polymer separator melts, allowing the short circuits between the electrodes.

D. Cathode breakdown. Heat from the electrolyte breakdown causes breakdown of the metal oxide cathode material releasing oxygen which enables burning of both the electrolyte and the gases inside the cell.

It should be noted that several studies have been undertaken to evaluate the avoidance of thermal runaway by adequate thermal management. This is critical because it forms the basis of mitigation measures against thermal runaway propagation.

C.4.6 Mechanical Fatigue

The electrodes of lithium cells expand and contract during charging and discharging. The cyclic stresses on the electrodes can eventually lead to cracking of the particles making up the electrode, resulting in increased internal impedance as the cell ages. In the worst case, the SEI layer could break down, leading to overheating and immediate cell failure. Alternatively, internal ground fault due to insulation failure between electrodes and enclosure could also cause cell failure.

Similarly, the slow deterioration of the electrolyte each time it is heat cycled could lead to release of small amounts of gases resulting in swelling of the cell and ultimately rupture of the cell casing.

Leakage of enclosure can lead to oxygen/moisture ingress causing electrolyte decomposition. Typically seals and weld failure can cause enclosure failure.

Other mechanical failure modes are drop, puncture, nail penetration, impact, and unsafe operation.

C.4.7 Cycle Life and Role of BMS

As discussed above, the excursions outside of the recommended integrity operating window can cause irreversible capacity loss in the cells and potentially unsafe events if not managed properly. The cumulative effect of such excursions could affect the lifetime of the cell or, in the worst case, cause sudden failure. One of the main functions of the BMS is to keep the cells within their designed operating window. This is typically implemented using safety devices and controlling the operating conditions and environment.

C.5 Fire Protection Technologies

To date there is no publicly available test data that confirms the effectiveness of any active fire protection for energy storage systems, and there are no fire protection systems FM Approved for this application. The ability of active fire protection to stop or prevent Li-ion battery thermal runaway reactions has not been shown. At the same time, some manufacturers are providing active protection systems as an integrated component of the LIB-ESS.