LITHIUM-ION BATTERY MANUFACTURING AND STORAGE

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1.0 SCOPE

This property loss prevention data sheet provides loss prevention guidance for liquid electrolyte-based lithium-ion batteries (cell/module/battery). The guidance covers cell manufacturing, assembly, testing, finishing, storage, and end use product assembly and storage. This data sheet references other FM Property Loss Prevention Data Sheets that address various fire and explosion hazards in this occupancy, but which are not unique to the lithium-ion cell manufacturing process.

This data sheet does not apply to:

- Energy storage systems (see Data Sheet 5-33, *Lithium-Ion Battery Energy Storage Systems*)
- Battery backup units (see Data Sheet 5-32, *Data Centers and Related Facilities*)
- Finished products in use where the lithium-ion cells or modules are actively being charged and/or discharged, including electric vehicles (see Data Sheet 3-26, *Fire Protection for Nonstorage Occupancies*, for level 1 and 2 chargers; see Data Sheet 5-33, *Lithium-Ion Battery Energy Storage Systems*, for level 3 chargers; since they typically have energy storage systems.)
- Lithium-ion cell recycling
- Manufacturing and storage occupancies that repurpose or provide a second use for lithium-ion cells
- Lithium-metal batteries

1.1 Hazards

Hazards present in the manufacturing of lithium-ion cells are driven by the various manufacturing processes. The primary hazard is fire, involving combustible materials or ignitable liquids. The manufacturing process may consist of ignitable liquid mixing and filling, the use of heated rolls and the hydraulics involved to press materials, cutting and the dust it produces, as well as ovens and solvent recovery. Beyond ignitable liquids, most of the hazards will be tied to concealed areas with combustibles, the need for environmentally controlled areas for cell assembly, and the potential to create room or equipment explosion hazards with the use of ovens and solvent recovery operations.

Once a cell is finished, the fire hazard is then driven by the chemical energy stored in the cell. While some cell chemistries may have a reduced propensity to enter thermal runaway, they all have an ignitable liquid electrolyte and can still enter thermal runaway. Therefore, this data sheet does not differentiate fire hazard and protection guidance based on cell chemistry.

1.1.1 Thermal Runaway

Thermal runaway originates in a cell with an internal short due to internal cell defects, mechanical failures (e.g., vibration or expansion-contraction cycles) that can lead to mechanical damage, impact damage, external heating, overvoltage charging or failure of the battery management system (or cell controller). Thermal runaway leads to high temperatures and gas buildup, with the potential for battery cell rupture that can lead to fire and/or explosion.

During the thermal runaway process, the cell produces flammable gas that accumulates within the cell or an enclosure containing the cells or modules. Cells typically have some type of pressure relief vent. Hot vented gases, when directed toward adjacent cells, may propagate thermal runaway to those cells. Without prompt action, thermal runaway can cascade from cell to cell causing more damage.

1.1.2 Abuse

Three abuse conditions can potentially lead to thermal runaway or fire in lithium-ion cells: 1) electrical, 2) thermal and 3) mechanical.

1. Electrical abuse: Cell damage sustained when operating outside the electrical specifications of the cell. This type of abuse is caused by improper charging or discharging.
2. Thermal abuse: Cell damage sustained due to increased cell temperature outside of normal operating conditions. This type of abuse can be initiated by electrical abuse or by exposure to high temperatures.
3. Mechanical abuse: Cell damage sustained by physical impact.

Additionally, an internal short circuit (ISC) can occur due to any of these three abuse conditions or from a manufacturing defect. An ISC can initiate thermal runaway or a fire. It occurs when the separator fails, allowing contact between the cathode and anode. An external short circuit can occur if the cell/module/battery is exposed to wet conditions, when it is not designed for that exposure.

1.1.3 Fire

When a cell in thermal runaway begins to vent, the vented flammable gas can ignite due to sparking from the cell, open flames or exposure to nearby electrical equipment. Collections of cells are frequently encountered in manufacturing and storage. The cells can be enclosed in a module or pack (e.g., collection of modules) or can be found individually stored in trays. Where the cells are enclosed in a module or pack, combustion in one cell will likely spread fire until all charged cells are consumed. To date, no testing shows that active fire protection can stop this process when the cells are enclosed. Automatic sprinklers can provide cooling to structures, combustibles and even adjacent modules/packs to help limit the fire spread. A limited amount of large-scale testing has been conducted; and where adequate cooling can be provided in a timely manner, spread to adjacent cells/modules/batteries can be prevented.

1.1.4 Reignition

Fires involving lithium-ion batteries are known to reignite. However, a lithium-ion cell cannot reignite. Once the thermal runaway process has started, a cell will continue to burn until it has been consumed. A fire event can thermally abuse adjacent cells to the point at which they enter thermal runaway, or to a lesser extent—in which case they may end up in thermal runaway later. When viewed as an entire system, lithium-ion battery modules and packs can reignite due to the delayed ignition of some of the cells within. Lithium-ion batteries involved in or exposed to fires need to be adequately cooled to prevent additional thermal abuse and moved to a safe location to limit overall exposure.

1.1.5 Explosion

If cells/modules are in thermal runaway, but the vented, hot, flammable gases do not ignite; the gases can accumulate in a closed module, piece of equipment, cabinet or room. Depending on the amount of time before ignition occurs, the accumulated gas can deflagrate—resulting in a very fast pressure rise within the enclosure —and ultimately explode.

1.2 Changes

October 2024. This is the first publication of this document.

2.0 LOSS PREVENTION RECOMMENDATIONS

2.1 Introduction

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

2.1.1 Apply principles of inherent safety wherever possible when designing or improving processes. Inherent safety includes the following general principles:

A. Using smaller amounts of hazardous substances

B. Replacing a hazardous chemical with a non-hazardous or less hazardous one

C. Using less-hazardous process conditions or a less-hazardous form of material

D. Designing a facility to minimize the impact of a release of hazardous material or energy (e.g. by sufficient spacing or more-resistant construction)

E. Designing a facility so operating errors are less likely, or the process is more forgiving if errors are made

2.1.2 Implement programs to manage process safety per Data Sheet 7-43, *Process Safety*. Pay particular attention to the process hazard analysis/review (PHA) of routine and non-routine operations.

2.1.3 Use Table 2.1.3 to determine the appropriate FM Property Loss Prevention Data Sheets to address hazards in the manufacturing of lithium-ion batteries, many of which are not unique to this occupancy.

The lithium-ion battery manufacturing process is similar to other manufacturing processes in terms of hazard evaluation. Each cell type and manufacturer have unique aspects to their manufacturing process. This data sheet intentionally does not attempt to cover each manufacturing process step in detail from a hazard evaluation standpoint but provides data sheets to consider for each process step. Section 3.1 and Appendix D provide more details on each process step.

Table 2.1.3. Manufacturing Hazards and Applicable Data Sheets

Process Step	*Hazards*	*Other Key Applicable Data Sheets*
Raw Material/Electrode Coating Manufacturing		
Production of Cathode Active Material	Chemical reactions	Data Sheet 7-14, *Fire Protection for Chemical Plants* Data Sheet 7-43, *Process Safety* Data Sheet 7-45, *Safety Controls, Alarms, and Interlocks* Data Sheet 7-46, *Chemical Reactors and Reactions*
Electrode Manufacturing		
Mixing Coating Drying Solvent Recovert Calendering Slitting Notching Vacuum Drying	Ignitable liquids use, mixing Heat transfer system Ovens Concealed combustibles Thermal rolls Solvent recovery/ destruction Clean rooms Incidental storage	Data Sheet 1-56, *Cleanrooms* Data Sheet 3-26, *Fire Protection for Nonstorage Occupancies* Data Sheet 6-9, *Industrial Ovens and Dryers* Data Sheet 7-2, *Waste Solvent Recovery* Data Sheet 7-9, *Dip Tanks, Flow Coaters and Roll Coaters* Data Sheet 7-29, *Ignitable Liquid Storage in Portable Containers* Data Sheet 7-32, *Ignitable Liquid Operations* Data Sheet 7-76, *Combustible Dusts* Data Sheet 7-78, *Industrial Exhaust Systems* Data Sheet 7-88, *Outdoor Ignitable Liquid Storage Tanks* Data Sheet 7-98, *Hydraulic Fluids* Data Sheet 7-99, *Heat Transfer Fluid Systems*
Cell Assembly		
Separation Stacking or Winding Welding or Sealing Electrolyte Filling Enclosing	Ignitable liquid use and dispensing Welding Dust collectors Incidental storage	Data Sheet 3-26, *Fire Protection for Nonstorage Occupancies* Data Sheet 7-14, *Fire Protection for Chemical Plants* Data Sheet 7-29, *Ignitable Liquid Storage in Portable Containers* Data Sheet 7-32, *Ignitable Liquid Operations* Data Sheet 7-76, *Combustible Dusts* Data Sheet 7-88, *Outdoor Ignitable Liquid Storage Tanks*
Cell Finishing		
Formation Degassing Aging Testing Packaging	Pre-charging Thermal runaway Quantity of cells Non-thermal damage	Data Sheet 8-1, *Commodity Classification*

2.1.4 Treat storage and use of N-Methyl-2 Pyrrolidone (NMP/CAS 872-50-4 /C5H9NO) as a Group 3 water miscible liquid for concentrations greater than 85% by volume. Treat mixtures less than or equal to 85% by volume in water as Group 5 water miscible liquids.

2.2 Construction and Location

2.2.1 Use noncombustible or FM Approved Class 1 building materials for exterior/interior construction and equipment enclosures. Limit the use of plastic materials in equipment enclosures as far as practical and protect accordingly (see Section 2.4).

2.2.2 Provide one-hour rated, noncombustible fire walls between the following areas:

- Manufacturing
- Formation/aging
- Warehouse storage

2.2.2.1 Where a high potential exists for nonthermal damage (i.e. areas having a large number of finished cells or clean rooms), subdivide areas with noncombustible walls to limit the exposure.

2.2.3 Install normally closed or automatic-closing, FM Approved fire doors in fire-rated walls.

2.2.4 Seal any penetrations caused by piping, electrical cables, etc. in fire-rated floors and walls with FM Approved penetration seals.

2.2.5 Design and construct environmentally controlled areas/cleanroom areas in accordance with Data Sheet 1-56, *Cleanrooms*.

2.2.6 Locate any quality control testing of cells/modules/batteries that involve charging and discharging operations inside ventilated hoods or enclosures.

2.3 Occupancy

2.3.1 General

2.3.1.1 Establish and implement a housekeeping program to minimize accumulations of dust and other combustible materials.

The fire protection recommended in this data sheet assumes no major housekeeping deficiencies. Combustible materials such as dust may increase the fire hazard to the extent that the recommended protection is ineffective.

2.3.1.2 Provide an appropriate gas detection system inside any ventilated hoods or enclosures to provide remote notification if cell testing or charging is performed during non-occupied hours. Arrange the system to send an alarm upon gas detection.

2.3.1.3 Develop a documented procedure for handling damaged or off-specification cells/modules/batteries. See Section 2.4.6 for protection of damaged or off-specification units.

2.3.1.4 Develop a documented procedure for responding to a thermal runaway event in the formation, aging or finished cell storage areas.

2.3.2 Ventilation

The goal of this section is to provide guidance to limit the amount of nonthermal damage in the event of a thermal runaway or fire. Therefore, keep the ventilation system on for testing enclosures or hoods that do not have their own fire protection and where charging operations occur, and shut it down in manufacturing areas.

2.3.2.1 Testing Enclosures and Hoods

2.3.2.1.1 Provide a dedicated mechanical exhaust ventilation system for enclosures or hoods where cell/module/battery charging operations are performed. Arrange the ventilation as follows:

A. Arrange the system to be nonrecirculating.

B. Take make-up air from areas with fresh air only.

2.3.2.1.2 Locate exhaust outlets at the top or bottom of the enclosure to capture lighter-than-air and/or heavier-than-air gases, based on the gases potentially liberated.

2.3.2.1.3 Design the ventilation rate to prevent the development of a flammable gas-air mixture during normal operating conditions. Provide a minimum of 1 cfm/ft^2 (0.3 m^3/min/m^2).

2.3.2.1.4 Arrange the ventilation system to provide an emergency ventilation rate of 150% of the standard ventilation rate in ventilated hoods or enclosures. Activate the emergency ventilation rate upon gas detection, installed per Section 2.3.1.2, or 25% of the lower explosive limit (LEL) for hydrocarbon gases.

2.3.2.2 Manufacturing Areas

2.3.2.2.1 Arrange the supply and return fans of the air conditioning system to shut down upon activation of the fire protection system.

2.3.2.2.2 For clean rooms, design the heating, ventilation and air-conditioning (HVAC) systems in accordance with Data Sheet 1-56, *Cleanrooms*.

2.4 Protection

2.4.1 General

To date, limited publicly-available fire test data exists that confirms the effectiveness of any active fire protection for lithium-ion batteries. Automatic sprinkler protection is recommended to limit fire spread to the surrounding structure, equipment and building contents.

2.4.1.1 Protect manufacturing areas in accordance with the appropriate FM Property Loss Prevention Data Sheet based on the hazards present.

2.4.1.1.1 Protect cell electrode and assembly manufacturing areas with an automatic sprinkler system using a minimum HC-3 design in accordance with Data Sheet 3-26.

2.4.1.1.2 Protect Formation and Aging areas per Section 2.4.2.

2.4.1.1.3 FM Approved HC-3 water mist systems can be used to protect the occupancy, subject to the recommendations for their use in Data Sheet 3-26, if all concealed spaces are adequately protected.

2.4.1.2 Install sprinklers throughout the facility in accordance with FM Property Loss Prevention Data Sheet 2-0, *Installation Guidelines for Automatic Sprinklers*.

2.4.1.2.1 In addition to automatic sprinklers or FM Approved water-mist at the ceiling, provide automatic sprinklers or FM Approved water-mist in the following areas:

A. Under any obstructions or mezzanines that exceed 3 ft (0.9 m) in width or diameter or 10 ft^2 (0.9 m^2) in area

B. Within enclosed equipment (e.g., ovens, hoods or test enclosures) when constructed of combustible materials or within obstructed areas containing combustibles

C. Within enclosures around production equipment if the ceiling protection is not designed for HC-3 occupancies or if higher-hazard processes take place inside such as electrolyte filling, cell charging/ discharging etc.

2.4.2 Formation and Aging Areas

Formation and aging areas are expected to experience a higher-than-normal number of thermal runaway events; since this is where the cells first undergo charging and discharging, and stabilization of the cell properties and solid electrolyte interphase (SEI) film occurs. The higher the level of protection, the lower the number of cells that will be involved, the less flammable/corrosive gas that will be generated and the less water that needs to be discharged into the area. This approach should limit the extent of nonthermal damage to the other cells in the area.

2.4.2.1 Open-Frame Rack Arrangements

2.4.2.1.1 Protect formation and aging areas with open-frame racks or shelves that resemble an open-frame rack arrangement, including automated storage systems, using in-rack sprinklers and barriers per Section 2.4.2.2.

2.4.2.1.2 Do not store li-ion cells above the top in-rack sprinkler and horizontal barrier level.

2.4.2.1.2.1 If storage is located above the in-rack automatic sprinklers and horizontal barrier, treat the barrier like a virtual floor and provide protection in accordance with Data Sheet 8-9 for the stored commodity above the horizontal barrier.

2.4.2.1.3 Provide vertical barriers at rack uprights:

A. No more than 6 ft (1.8 m) apart to limit horizontal fire spread

B. Constructed of plywood (minimum 3/8 in. [10 mm]) or sheet metal (minimum 22 ga [0.7 mm]).

2.4.2.1.4 Design ceiling sprinklers to protect the surrounding occupancy.

2.4.2.1.5 The ceiling sprinkler system design does not need to be hydraulically balanced with the in-rack system.

2.4.2.1.6 Provide a hose stream allowance of 500 gpm (1,900 L/min).

2.4.2.1.7 Provide a water supply capable of meeting the sprinkler design flow and hose stream demand for a minimum of two hours.

2.4.2.2 In-rack Sprinklers

2.4.2.2.1 Install in-rack sprinklers in accordance with this section and Figures 2.4.2.2.1-1 and 2.4.2.2.1-2.

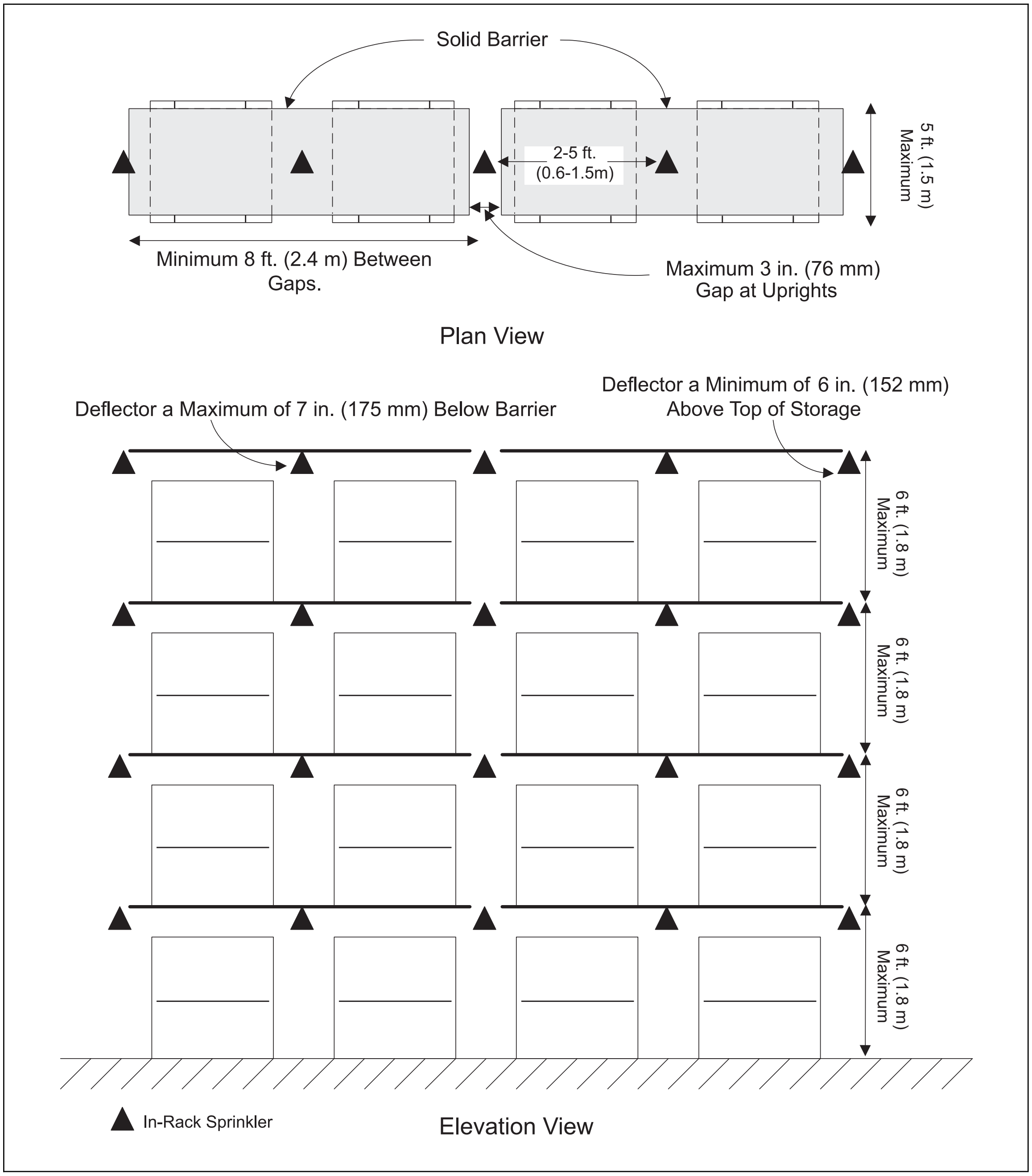

Fig. 2.4.2.2.1-1. Single-row rack in-rack sprinkler layout for li-ion cells/modules/batteries

2.4.2.2.1.1 Locate longitudinal flue in-rack sprinklers as follows:

A. Within the rack storage structure

B. Within 6 in. (152 mm) of the transverse flue space, measured from the flue centerline.

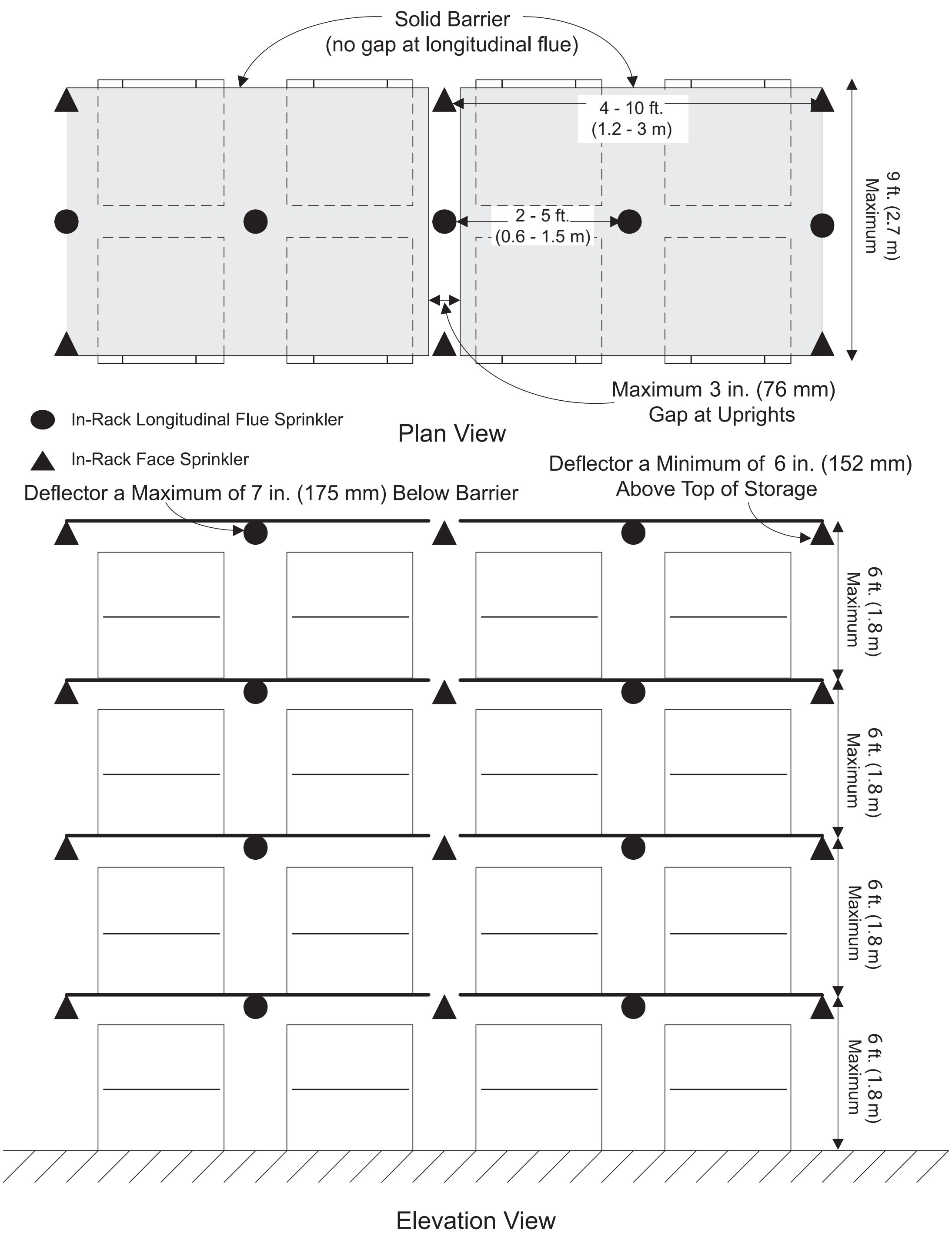

Fig. 2.4.2.2.1-2. Double-row rack in-rack sprinkler layout for li-ion cells/modules/batteries

C. At every transverse flue on a maximum horizontal spacing of 5 ft (1.5 m) and a minimum horizontal spacing of 2 ft (0.6 m).

2.4.2.2.1.2 Locate face sprinklers as follows:

A. Within the rack storage structure

B. No more than 18 in. (450 mm) horizontally from the face of the storage rack

C. At every other transverse flue on a maximum horizontal spacing of 10 ft (3.0 m) and a minimum horizontal spacing of 4 ft (1.2 m)

2.4.2.2.2 Locate in-rack sprinkler piping behind horizontal rack members to minimize the potential for damage.

2.4.2.2.3 Install in-rack sprinklers at a maximum vertical distance of 6 ft (1.8 m) between each level.

2.4.2.2.4 Install a horizontal barrier above each level of in-rack sprinklers as follows:

A. Construct horizontal barriers of plywood (minimum 3/8 in. [10 mm]) or sheet metal (minimum 22 ga. [0.7 mm]).

B. Design barriers without gaps in longitudinal flue spaces. A maximum gap of 3 in. (75 mm) between each barrier is permitted at the rack uprights (transverse flue) for single and double row racks.

2.4.2.2.5 Design the in-rack sprinkler to provide a minimum flow of 60 gpm (227 L/min) out of the hydraulically most remote six (6) sprinklers (e.g., three face sprinklers and three flue sprinklers in a double-row rack) if one barrier is provided, or the most remote eight (8) sprinklers (e.g., two face sprinklers and two flue sprinklers on two levels in a double-row rack) if two or more barrier levels are provided.

2.4.2.2.5.1 Provide a minimum discharge pressure of 10 psi (0.7 bar) for in-rack sprinkler designs where the in-rack sprinkler has a K-factor greater than or equal to 11.2 (K160).

2.4.2.2.5.2 Provide a minimum discharge pressure of 7 psi (0.5 bar) for in-rack sprinkler designs where the in-rack sprinkler has a K-factor less than 11.2 (K160).

2.4.2.2.6 Do not include ceiling sprinkler demand in the hydraulic calculations for in-rack sprinklers.

2.4.2.3 Bin-box or Enclosed Chamber Arrangements

2.4.2.3.1 Protect formation and aging areas that have shelving arrangements or charging chambers with 4- or 5-sided holding areas (i.e., bin-box storage array or fully enclosed chamber), using an approach that ensures fire protection water delivery to each bin-box holding area within the array. The protection can consist of automatic sprinklers or automatic water mist nozzles provided in each bin-box holding area.

2.4.2.3.2 Design the bin or chamber sprinkler system to supply at least 60 gpm (230 L/min) for the six (6) most remote sprinklers.

2.4.2.3.2.1 Ensure each bin or chamber houses only one tray of lithium-ion cells. If two trays of cells are present, ensure that water can flow through the top tray and reach the bottom tray.

2.4.2.3.2.2 Use quick response, ordinary temperature, K8.0 (K115) or larger in-rack sprinklers.

2.4.2.3.2.3 For high temperature aging rooms, use an appropriate sprinkler temperature rating based on the temperature to be maintained in the room.

2.4.2.3.3 Use only water mist systems that have been FM Approved for aging and formation applications.

2.4.2.3.4 Design ceiling sprinklers to protect the surrounding occupancy.

2.4.2.3.5 The ceiling sprinkler system design does not need to be hydraulically balanced with the in-rack or bin-box protection system.

2.4.2.3.6 Provide a hose stream allowance of 500 gpm (1,900 L/min).

2.4.2.3.7 Provide a water supply capable of meeting the sprinkler design flow and hose stream demand for a minimum of two hours.

2.4.3 Finished Cells/Modules/Batteries - Incidental Storage

This storage consists of finished batteries with various states of charge. The batteries may be stored in corrugated boxes (small batteries), wooden crates, metal boxes or plastic boxes. While a fire involving the packaging can, in general, be easily controlled, batteries involved in the fire will extend the duration of the event and likely involve adjacent batteries. The best protection option is to use racks with in-rack automatic sprinkler protection in accordance with Section 2.4.2.2. For palletized storage, limit storage footprints to minimize the number of batteries that can become involved.

2.4.3.1 Treat work in process storage of lithium-ion batteries as incidental if all of the following are met:

A. Cells/modules/batteries are stored in metal or cardboard boxes.

B. Storage area is limited to no more than 200 ft^2 (20 m^2).

C. Storage height is limited to 6 ft (1.8 m).

D. Multiple storage areas are separated by aisles not less than 10 ft (3.0 m) wide.

E. Battery state of charge is less than or equal to 60%.

2.4.3.2 Protect storage of lithium-ion batteries as low-piled storage of Uncartoned Unexpanded Plastic (UUP) per Table 2.4.3.2 if all of the following criteria are met:

A. Cells/modules/batteries are stored in unexpanded plastic containers.

B. Storage area is limited to no more than 200 ft^2 (20 m^2).

C. Storage height is limited to 6 ft (1.8 m).

D. Multiple storage piles are separated by aisles not less than 10 ft (3.0 m) wide.

E. Battery state of charge is less than or equal to 60%.

Table 2.4.3.2. Sprinkler Protection for Low-Piled Storage of Lithium-ion Batteries in Plastic Containers

Commodity	*Max Ceiling Height, ft (m)*	*Quick-Response*						*Standard-Response*				
		K11.2 (K160)	K14.0 (K200)	K16.8 (K240)	K22.4 (K320)	K25.2 (K360)	K25.2EC (K360EC)	K11.2 (K160)	K14.0 (K200)	K19.6 (K280)	K25.2 (K360)	K25.2EC (K360EC)
Wet System, Pendent Sprinklers, 160ºF (70ºC), Number of AS @ psi (bar)												
UUP	30 (9)	25 @ 50(3.4)	10 @ 62(4.3)	10 @ 43(3)	14 @ 24(1.7)	14 @ 19(1.3)	12 @ 38(2.6)	25 @ 50(3.4)	25 @ 32(2.2)	25 @ 16(1.1)	25 @ 10(0.7)	25 @ 50(3.4)
	45 (14)		10 @ 62(4.3)11	10 @ 43(3)	14 @ 24(1.7)	14 @ 19(1.3)						
	60 (18)				10 @ 50(3.4)	10 @ 40(2.8)						
Wet System, Upright Sprinklers, 160ºF (70ºC), Number of AS @ psi (bar)												
UUP	30 (9)	25 @ 50(3.4)	10 @ 62(4.3)	10 @ 43(3)			12 @ 38(2.6)	25 @ 50(3.4)	25 @ 22(1.5)		25 @ 10(0.7)	
	45 (14)		10 @ 62(4.3)	10 @ 43(3)								

2.4.3.3 When battery storage exceeds the criteria in Section 2.4.3.1 and 2.4.3.2 or the packaging classifies the storage as an expanded plastic commodity per Data Sheet 8-1, design the fire protection in accordance with Section 2.4.5 of this data sheet.

2.4.3.4 Provide a hose stream allowance of 500 gpm (1,900 L/min).

2.4.3.5 Provide a water supply capable of meeting the sprinkler design flow and hose stream demand for a minimum of one hour.

2.4.4 Cells/Modules/Batteries in Finished Products — Storage

Examples of finished products include, but are not limited to personal electronic devices (laptop computers, tablets, cell phones, etc.), lawn equipment (lawn mowers, leaf blowers, etc.), power tools and household items (vacuums, toys, etc.).Finished electric vehicle modules or packs are not considered finished products; see Section 2.4.5 for protection guidance.

2.4.4.1 Protect finished products per Data Sheet 8-9, Storage of Class 1, 2, 3, 4 and Plastic Commodities, using the product's commodity classification, excluding the battery hazard, provided the lithium-ion battery state of charge (SOC) is less than or equal to 60%.

2.4.4.2 When SOC is greater than 60%, protect finished products per Data Sheet 8-9 using the product's commodity classification, excluding the battery hazard, and a protection design that includes both ceiling and in-rack sprinklers.

In-rack protection schemes that do not require balancing the ceiling and in-rack sprinkler demand are acceptable.

2.4.4.3 Provide a hose stream demand and water supply duration in accordance with Data Sheet 8-9.

2.4.5 New or Refurbished Cells/Modules/Batteries – Storage

2.4.5.1 Protect new or refurbished lithium-ion cells/modules/batteries stored in solid-pile or palletized storage arrangements per the guidance in Table 2.4.5.1-1. For open-frame rack storage arrangements, follow the guidance in Table 2.4.5.1-2. Protection guidance is not differentiated based on battery chemistry.

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

Maximum Lithium-ion Cell/Module State of Charge	*Maximum Ceiling Height*	*Storage Height*	*Packaging*	*Protection (QR Sprinklers only)*
60%	40 ft (12 m)	15 ft (4.5 m)	Wood crate, metal encased or corrugated carton with cellulosic and/or unexpanded plastic internal packaging only	CUP per Data Sheet 8-9 (Note 1)
			Corrugated carton with expanded plastic internal packaging	CEP per Data Sheet 8-9 (Note 1)
			Unexpanded Plastic external packaging	UUP per Data Sheet 8-9 (Note 1)
			Unexpanded Plastic external packaging with > 40% expanded plastic (by volume) inside	UEP per Data Sheet 8-9 (Note 1)

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

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

Lithium-ion Cell/Module State of Charge	*Maximum Ceiling Height*	*Maximum Storage Height*	*Packaging*	*Ceiling Protection (QR sprinklers only)*	*In-Rack Protection*
≤ 60%	40 ft (12 m)	15 ft (4.5 m) (Maximum of 3 tiers)	Wood crate, metal encased or corrugated carton with cellulosic and/or unexpanded plastic internal packaging only	CUP per Data Sheet 8-9 (Note 1)	NA
			Corrugated carton with expanded plastic internal packaging	CEP per Data Sheet 8-9 (Note 1)	NA
			Unexpanded plastic external packaging with ≤ 40% expanded plastic (by volume) inside	UUP per Data Sheet 8-9 (Note 1)	NA
			Unexpanded plastic external packaging with > 40% expanded plastic (by volume) inside; or expanded plastic external packaging	UEP per Data Sheet 8-9 (Note 1)	NA
			Uncartoned	Per surrounding occupancy	See Section 2.4.2.2, 2.4.5.5, and 2.4.5.6.
	> 40 ft (12 m)	NA	Cartoned or uncartoned	Per surrounding occupancy	See Section 2.4.2.2, 2.4.5.5, and 2.4.5.6
> 60%	NA		Cartoned or uncartoned	Per surrounding occupancy	See Section 2.4.2.2, 2.4.5.5, and 2.4.5.6

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

2.4.5.1.1 Use the Data Sheet 8-9 protection table based upon the storage configuration (solid-pile, palletized or rack) and the protection option based on the ceiling height. Ceiling only as well as combination in-rack and ceiling designs can be used.

2.4.5.2 Do not allow storage above the batteries for ceiling-only protection options.

2.4.5.3 Provide a minimum of 10 ft (3.0 m) space separation between storage of lithium-ion cells/modules/batteries and other combustibles.

2.4.5.4 Provide minimum 10 ft (3.0 m) wide aisle spaces within solid-pile and palletized storage such that the maximum contiguous width of abutted storage does not exceed 15 ft (4.6 m).

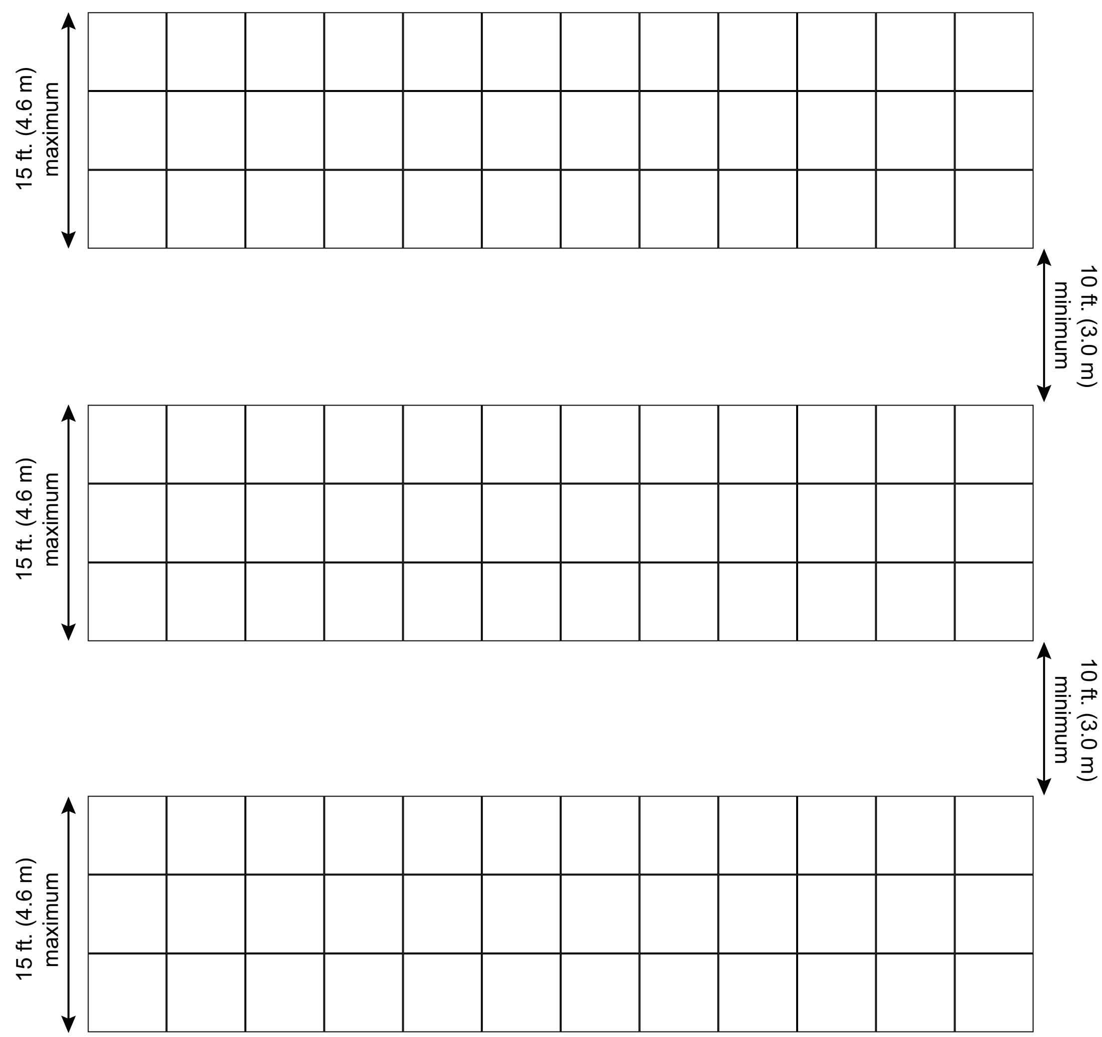

Fig. 2.4.5.4. Example of solid-pile and palletized storage arrangement

2.4.5.5 Protect open-frame single and double-row rack storage of cells/modules/batteries that require in-rack sprinkler protection per Table 2.4.5.1-2 using Section 2.4.2.2 with the following changes:

A. Install in-rack sprinklers at a maximum vertical distance of 12 ft (3.7 m) between each level.

2.4.5.6 Protect multi-row rack storage of cells/modules/batteries that require in-rack sprinkler protection per Table 2.4.5.1-2 using Section 2.4.2.2 with the following changes and Figure 2.4.5.6.

A. Install in-rack sprinklers at a maximum vertical distance of 12 ft (3.7 m) between each level.

B. Provide vertical barriers constructed of plywood (minimum 3/8 in. [10 mm]) or sheet metal (minimum 22 ga. [0.7 mm]) at vertical uprights, approximately 20 ft (6.1 m) apart, to limit horizontal fire spread.

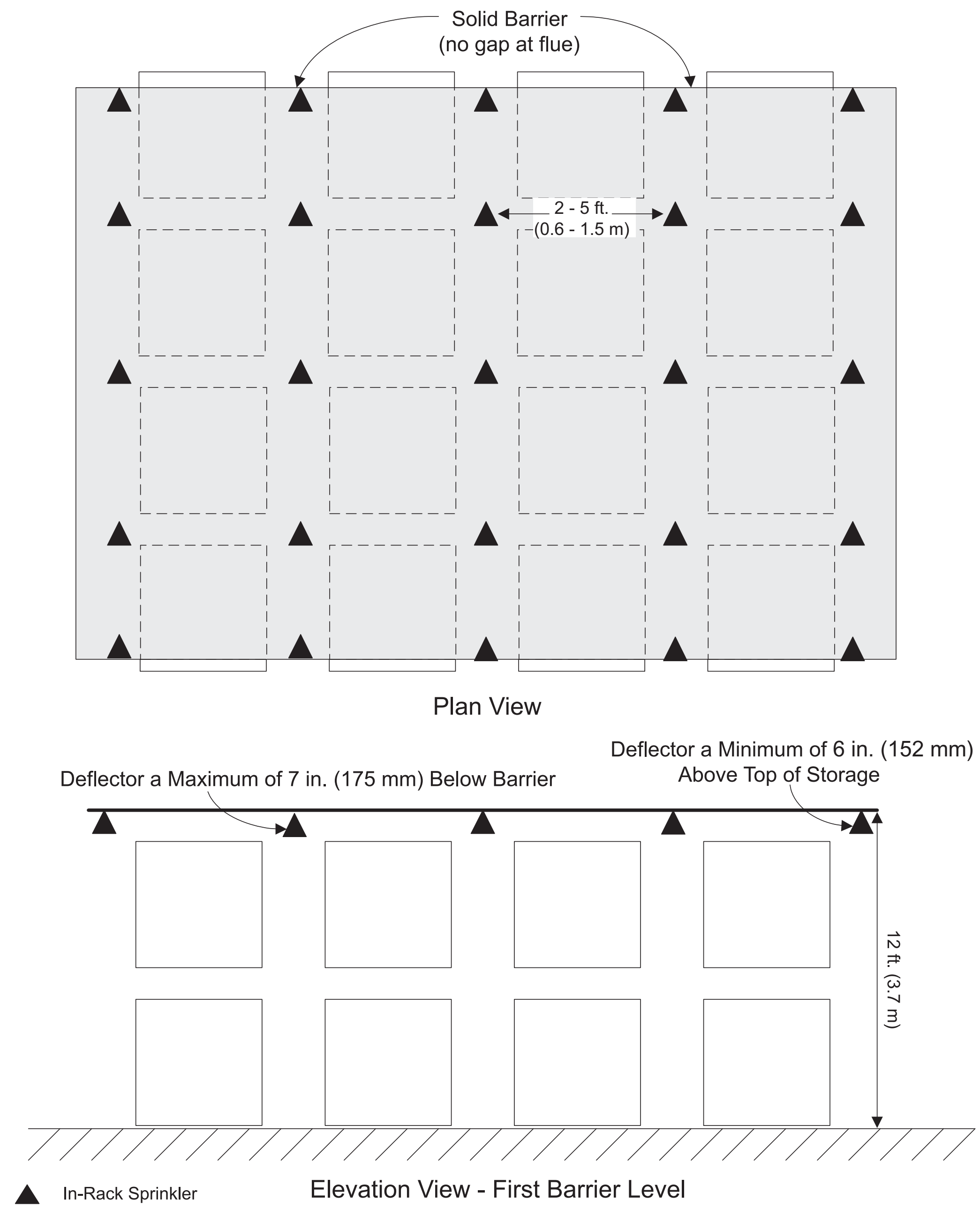

Fig. 2.4.5.6. Multi-row rack in-rack sprinkler layout for li-ion cells/modules/batteries

2.4.5.7 Provide a hose stream demand and water supply duration in accordance with Data Sheet 8-9 for all ceiling only designs not using in-rack sprinkler protection per Section 2.4.2.2.

2.4.5.8 Provide a hose stream demand and water supply duration in accordance with Section 2.4.2.2.6 and 2.4.2.2.7 for all designs using in-rack sprinkler protection per Section 2.4.2.2.

2.4.6 Returned/Defective/Off-Specification/Damaged Cells/Modules/Batteries - Storage

2.4.6.1 Isolate the cells/modules/batteries from storage areas or other important areas by locating them outside of the building or in a cut-off room.

2.4.6.2 Store defective or damaged cells/modules/batteries outside as follows:

A. Limit outdoor storage to two pallets high and storage footprints no larger than 900 ft^2 (83.6 m^2).

B. Separate individual storage piles by 10 ft (3.0 m).

C. Provide at least 10 ft (3.0 m) of space between outdoor storage areas and noncombustible building walls and 20 ft (6.1 m) of space to combustible walls or walls with windows.

D. Locate outdoor storage in areas easily accessible by the fire service and with direct access to fire hydrants.

2.4.6.3 Store defective or damaged cells/modules/batteries in a cut-off room as follows:

A. Limit the indoor storage height to one pallet high. If greater heights are needed, put the storage in open-frame racks.

B. If storage is in open-frame racks, protect the racks with in-rack sprinklers in accordance with Section 2.4.2.2.

C. For on-floor or palletized storage, provide a 0.3 gpm/ft^2 (12 mm/min) over-the-room footprint.

D. Provide direct outside access to cut-off rooms.

2.4.6.4 Provide a hose stream allowance of 500 gpm (1,900 L/min).

2.4.6.5 Provide a water supply capable of meeting the sprinkler design flow and hose stream demand for a minimum of two hours.

2.4.7 Storage in Automatic Storage and Retrieval Systems (ASRS)

Note that this section applies only to ASRS storage arrangements addressed by FM Property Loss Prevention Data Sheet 8-34, *Automatic Storage and Retrieval Systems*. If storage will be in an ASRS not addressed by Data Sheet 8-34, it is outside the scope of this section.

2.4.7.1 For a finished product containing a lithium-ion battery where the battery's state of charge (SOC) is less than or equal to 30%:

A. Determine the commodity classification of the finished product, excluding the battery hazard, per FM Property Loss Prevention Data Sheet 8-1, *Commodity Classification*, and

B. Protect the finished product in accordance with Data Sheet 8-34 using a wet sprinkler system only.

2.4.7.2 For a finished product containing a lithium-ion battery where the battery's state of charge (SOC) is greater than 30%, but less than or equal to 60%:

A. Determine the commodity classification of the finished product, excluding the battery hazard, per Data Sheet 8-1, and

B. Place the finished product in FM Approved, non-flame propagating containers, solid-walled metal containers or solid-walled metal-lined containers (minimum 18 gauge [0.04 in. (1.0 mm)] steel), and

C. Store the finished product in a horizontal-loading ASRS only, and

D. Protect the finished product in accordance with Data Sheet 8-34, using a wet sprinkler system only where both ceiling and in-rack sprinklers are installed.

2.4.7.3 Do not store any finished product with lithium-ion batteries that exceed a 60% SOC in ASRS.

2.4.7.4 Do not store cells/modules/batteries that are not a finished product in ASRS. See formation and aging protection guidance in Section 2.4.2.2.

2.5 Equipment and Processes

2.5.1 Arrange all operations to initiate a controlled automatic shutdown, including the stopping of ignitable liquid pumping, in the event of a fire or explosion.

2.5.2 If chemical reactions are used to create electrode raw materials, evaluate that operation in accordance with at least FM Data Sheets 7-46, *Chemical Reactors and Reactions*; 7-45, *Safety Controls, Alarms, and Interlocks*; and 7-43, *Process Safety*.

2.5.3 Use FM Data Sheet 7-32, *Ignitable Liquid Operations*, for all ignitable liquid processes including unloading, transfer, and indoor tank storage and 7-88, *Outdoor Ignitable Liquid Storage Tanks*, for tanker truck unloading stations.

2.5.4 Use FM Data Sheet 7-29, *Ignitable Liquid Storage in Portable Containers*, for all storage of portable containers with ignitable liquids such as NMP and electrolyte.

2.5.5 Use FM Data Sheet 7-88, *Outdoor Ignitable Liquid Storage Tanks*, to arrange and protect outdoor tank farms having ignitable liquid storage.

2.5.6 Use FM Data Sheet 6-9, *Industrial Ovens and Dryers*, to protect drying operations from concealed fire hazards or equipment explosion hazards. All direct-fired gas ovens and any oven drying ignitable liquids have an equipment explosion hazard that requires the provision of damage limiting construction.

2.5.7 Use FM Data Sheet 7-9, *Dip Tanks, Flow Coaters and Roll Coaters*, to protect calendering operations.

2.5.8 Use FM Data Sheet 7-99, *Heat Transfer Fluid Systems*, to protect equipment heated by heat transfer systems.

2.5.9 Use FM Data Sheet 7-2, *Waste Solvent Recovery, and 6-11, Thermal and Regenerative Catalytic Oxidizers*, to protect solvent recovery/destruction operations.

2.5.10 Use FM Data Sheet 7-76, *Prevention and Mitigation of Combustible Dust Explosions and Fires*, to protect any operations that produce or collect dust.

2.5.11 Use FM Data Sheet 7-98, *Hydraulic Fluids*, to protect any hydraulic systems using ignitable liquids.

2.5.12 Use FM Data Sheet 7-11, *Conveyors*, to protect any conveyor belts.

2.5.13 Identify any areas that contain combustibles that are concealed/obstructed from ceiling sprinkler discharge, and protect in accordance with Section 2.4.1.2.

2.5.14 Arrange all electrical systems with the proper electrical protection.

2.5.15 Provide regular testing of electrical equipment and safeguards in accordance with FM Data Sheet 5-20, *Electrical Testing*.

2.5.16 Protect all industrial control and emergency control systems against a possible cyber-attack in accordance with FM Data Sheet 7-110, *Industrial Control Systems*.

2.6 Operation and Maintenance

2.6.1 Implement a management of change program in accordance with FM Data Sheet 7-43, *Process Safety*.

2.6.1.1 Conduct a full review of all planned changes by qualified loss prevention consultants as well as other authorities having jurisdiction before a project begins.

2.6.2 Establish a comprehensive preventive maintenance program designed to ensure that electrical and mechanical equipment is operating as intended. Refer to Data Sheet 9-0/17-0, *Asset Integrity*, for the development and implementation of loss prevention asset integrity programs for systems and equipment.

2.6.3 Maintain and test all emergency system interlocks at least annually or in accordance with manufacturer's recommendations if more frequent. Maintain records of these tests.

2.6.4 Provide sufficient reliability and redundancy of process utilities to prevent interruption to critical processes or product spoilage. This strategy may include N+1 reliability and/or emergency (backup) power. Critical utilities include process heating and cooling; room/building air-handling systems; humidity control; power, instrument, and process air; fuels and solvent recovery.

2.7 Training

2.7.1 Create a training program for all employees (including operators, emergency response team members and security personnel) who work in or have access to production, testing or storage areas.

2.7.1.1 Design and supervise the training program to address the complexity of process operations and the hazard level present at a facility.

2.7.1.2 Provide training for all new employees, as well as refresher programs, as needed, for current employees.

2.7.1.3 At a minimum, include the following topics in the program:

A. The fire hazards created by the materials in use i.e. ignitable liquids (NMP), plastics etc.

B. The increased fire hazards of finished cells/modules/batteries with stored electrical energy

C. The proper operation and shutdown of the equipment under normal and emergency conditions. Print and post critical procedures for convenient reference.

D. Proper material handling procedures

E. Ignitable liquid piping system operation and shutdown, including the location of all local and remote shutoff valves

F. Proper ignitable liquid transfer procedures

G. The operation and function of fixed extinguishing systems

2.7.2 Implement operator training programs per Data Sheet 10-8, *Operators*.

2.8 Human Factors

2.8.1 Develop a pre-incident plan and emergency response plan in accordance with Data Sheet 10-1, *Pre-incident and Emergency Response Planning*. Include the following in the pre-incident and emergency response plans:

- Access routes
- Manual fire protection methods
- Water supply for long duration fires
- Smoke ventilation
- Safety Data Sheet (SDS) for lithium-ion cells
- Location of any fire walls
- Designated location outside the facility to which damaged or impacted cells can be moved
- Final extinguishment plan where prolonged and persistent burning could occur

2.8.1.1 Include the local fire department in the development of both plans.

2.8.1.2 Provide documented procedures to expedite safe entry and emergency response to fires in battery storage and testing areas.

2.8.2 Develop a post-incident recovery plan that addresses the potential for reignition of lithium-ion batteries, as well as removal and disposal of any damaged or impacted cells/modules/batteries or products.

2.8.3 Provide a fire watch until all potentially damaged lithium-ion cells/modules/batteries or products have been removed from the area following a fire event.

2.8.4 Develop and maintain a comprehensive documented equipment contingency plan per Data Sheet 9-0/17-0, *Asset Integrity*, including up-to-date details of replacement parts, who to contact for repairs, and manufacturer support.

2.9 Ignition Source Control

2.9.1 Identify all areas that can have flammable vapors/gases present during normal or emergency conditions, and provide electrical equipment that is rated for hazardous locations in accordance with FM Property Loss Prevention Data Sheets 5-1, *Electrical Equipment in Hazardous (Classified) Locations* and 7-32, *Ignitable Liquid Operations*.

2.9.2 Provide static control equipment (i.e., grounding and bonding) in any areas where flammable vapors or gases are present in accordance with FM Property Loss Prevention Data Sheets 5-8, *Static Electricity* and 7-32, *Ignitable Liquid Operations*.

2.9.3 Strictly control all hot work operations in accordance with FM Property Loss Prevention Data Sheet 10-3, *Hot Work Management*.

3.0 SUPPORT FOR RECOMMENDATIONS

3.1 Cell Manufacturing Process

Lithium-ion cell manufacturing can be broken down into three high-level processes, 1) electrode manufacturing, 2) cell assembly and 3) cell finishing. Each high-level process step can be further broken down into discrete activities as shown in Figure 3.1. See Appendix D for more details regarding each process step.

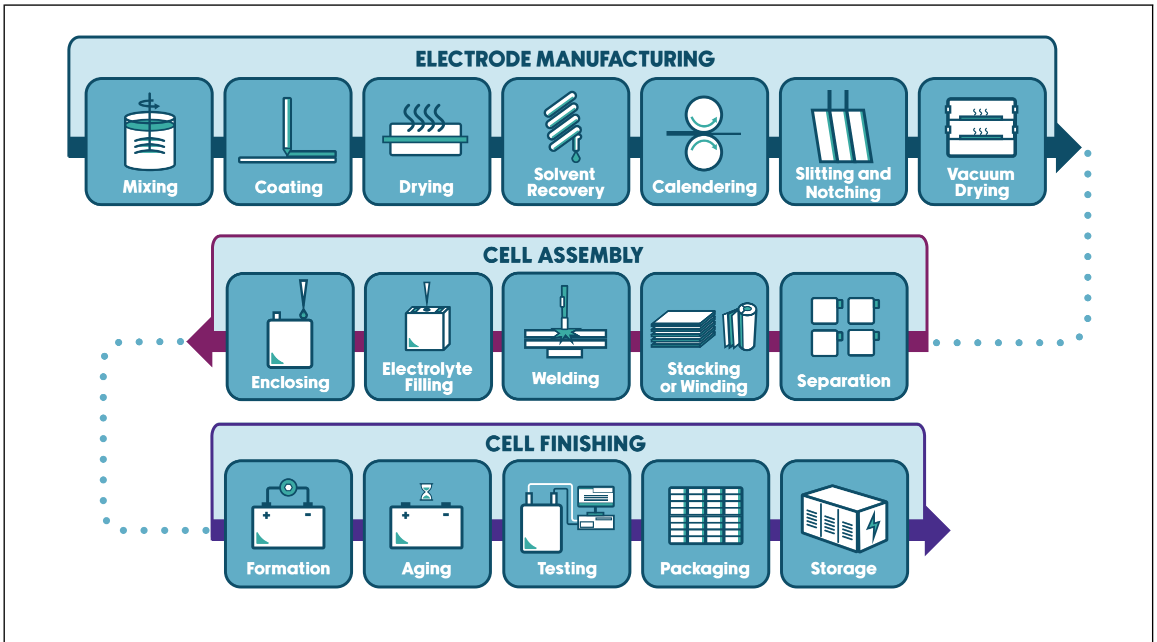

Fig. 3.1. Cell manufacturing process

During the manufacturing process, the introduction of raw materials and the manufacturing processes themselves create the actual hazards, which include ignitable liquid hazards (due to the electrolyte, typically a low-flashpoint ignitable liquid) as well as process and ignition source hazards. Heaters are present during the drying stages and potentially during calendering, which could also provide an ignition source for the ignitable components. An overview of the manufacturing process hazards and applicable FM Property Loss Prevention Data Sheets is provided in Table 2.1.3.

3.2 Cell Chemistry

The chemistry of the lithium-ion cell cathode has the greatest impact on the battery's specifications; therefore, lithium-ion cells are typically named after their cathode chemical composition. Many different lithium-ion cell chemistries are available, including lithium cobalt oxide (LCO), lithium iron phosphate (LFP), lithium manganese oxide (LMO), lithium titanate (LTO), lithium nickel manganese cobalt (NMC) and lithium nickel cobalt aluminum oxide (NCA) with more being introduced through innovation and new technologies. While some chemistries may have a reduced propensity to enter thermal runaway, they all have an ignitable liquid electrolyte and possess the ability to trigger thermal runaway. Therefore, regardless of the chemistry, lithium-ion cells are a fire hazard; and the protection guidance provided in this data sheet does not differentiate based on cell chemistry.

3.3 Manufacturing Protection

Lithium-ion battery protection in nonstorage occupancies is based upon maintaining a hazard less than or equal to that of incidental storage. It is accomplished by limiting the footprint and height of the allowable storage area and providing separation from surrounding combustibles. The limited available test data indicates that lithium-ion battery fires can exceed the common water durations for nonstorage occupancies. Thus, longer water supply durations have been recommended where cells and/or modules are expected to contribute significantly to the fire. The batteries also vent a flammable gas during failure (thermal runaway) that can accumulate to form an explosive mixture in confined spaces or containers, and further the spread of fire. Little to no flammable gas should be released when lithium-ion cells/modules/batteries are operating normally. Based on this knowledge, the limitations for incidental storage of lithium-ion batteries help limit the fire to a known area, promote cooling of the batteries and packaging from the sprinkler protection and limit the overall hazard.

3.4 Lithium-Ion Cell/Module/Battery Storage

3.4.1 Lithium-Ion Cell Fire Testing and Cell Types

Lithium-ion batteries are rechargeable and use lithium salt, while lithium batteries are not rechargeable and contain lithium metal. Since lithium-ion batteries use lithium salt and not lithium metal, they are not water reactive. Lithium-ion batteries are used in everything from cell phones, power tools, level 3 electric vehicle chargers and industrial heavy machinery.

Lithium-ion batteries present several unique fire protection challenges. The primary concern is the presence of an ignitable electrolyte within the batteries. If a battery is overheated, either by an external heat source (e.g., fire) or due to an internal fault of a single cell, the battery may experience a thermal runaway reaction. During this reaction, the electrolyte is vented from the cells as a flammable gas, which can ignite and promote the involvement of adjacent cells. Some smaller cells, such as 18650 format cylindrical cells, may also rupture and possibly rocket (or roll) away from the fire origin if unconfined. To limit battery involvement and thermal runaway, early extinguishment of the carton fire and cooling of the batteries is imperative.

Free-burn testing (i.e., with no sprinkler protection) of cartoned lithium-ion batteries was conducted at the FM Research Campus. Specific protection was not tested on the batteries during this project, so controlling the fire before the batteries became involved was imperative.

Testing has been conducted with three types of lithium-ion batteries, including 18650 cylindrical cells, polymer cells, and power tool packs.

3.4.1.1 Lithium-Ion 18650 Cylindrical Cells

These are historically the most widely used. Tested cells had a nominal voltage of 3.7 V and a nominal capacity of 2.6 Ah with a state of charge up to 60%. The cell chemistry was lithium cobalt oxide (LCO). Cells have hard-metal cases and are sealed with gaskets. The packaging consisted of corrugated board boxes with cellulosic dividers between each cell. During the tests, burning, hard-cased, cylindrical cells had the potential to rocket far away from the fire area; and therefore, require greater separation distances.

Fig. 3.4.1.1. Lithium-ion 18650 cylindrical cells

3.4.1.2 Lithium-Ion Polymer Cells

These batteries are commonly found in mobile phones and tablet computers. Tested cells had a nominal voltage of 3.7 V and a nominal capacity of 2.7 Ah. The cell chemistry was lithium cobalt oxide (LCO). Cells had soft polymer-coated aluminum cases. The packaging consisted of corrugated board boxes that contained densely packed lithium-ion batteries within thin plastic dividers. During fire tests, the contribution from the lithium-ion batteries was considerable, with evidence of thermal runaway reactions. Soft-cased polymer cells do not have the same rocketing potential as cylindrical cells.

Fig. 3.4.1.2. Lithium-ion polymer cells

3.4.1.3 Lithium-Ion Power Tool Packs

Each battery pack consists of 10 cylindrical cells in a plastic case. Tested battery packs had a nominal voltage of 18.5 V (each cell was 3.7 V) and a nominal capacity of 2.6 Ah. The cell chemistry was lithium nickel manganese cobalt oxide (NMC). The battery packs were encased in plastic blister packs for display and stored in corrugated board boxes. During fire tests, the packs exhibited similar fire growth rate and energy release as that of an unexpanded plastic commodity. Any energy contribution from the lithium-ion battery tool packs could not be identified during the fire test.

Fig. 3.4.1.3. Lithium-ion power tool packs

3.4.2 Cartoned Lithium-Ion Cells and Modules

Packaging of lithium-ion cells and modules is a key consideration in terms of protection. With cartoned batteries, the aim of fire protection is for the sprinklers to be activated by the cardboard packaging fire and limit the lithium-ion cell involvement. For protection to be successful, the packaging must strictly conform to a cartoned classification. Typical packaging of lithium-ion cells and modules is comprised of fibrous inserts, unexpanded plastic dividers and insulation in cardboard cartons. However, packaging larger batteries in rigid or expanded foam packaging is common.

3.4.3 State of Charge

Different transport authorities legislate on the state of charge (SOC) for shipping and storage, which is typically a charge between 30% and 60%. Fire tests have been conducted at these levels of charge. It has been shown that cells with a SOC below 30% are very difficult to get into thermal runaway. States of charge above

60% are generally intended for immediate use rather than indefinite storage. The higher the state of charge, the more reactive a battery is in a fire scenario. At a minimum, the fire severity and duration could be increased. The impact of SOC also varies for different cell chemistries and can even vary for different cells of the same chemistry.

3.5 Loss History

It is common for lithium-ion battery manufacturing facilities to experience smaller fires on a regular basis due to the inherent hazards of lithium-ion cells and the thermal runaway process. Any defects introduced in a cell during the manufacturing process can lead to thermal runaway and potentially a fire. These events are expected to some degree and are part of doing business so procedures on how to handle a cell that could enter or has already entered the thermal runaway process should be in place to prevent the incident from turning into a large fire.

To date FM has no loss history tied to a large developing battery fire during the manufacturing of lithium-ion cells. The loss history contained in the various applicable FM Data Sheets is expected to apply due to the raw materials and processes driving the hazard for the majority of the manufacturing process. Frequent fires involving the use and storage of lithium-ion batteries (see Data Sheet 5-33, *Lithium-Ion Battery Energy Storage Systems*) clearly demonstrate the potential fire and explosion hazard for finished cells/modules/batteries.

3.5.1 Illustrative Losses

3.5.1.1 Li-ion Vehicle Battery Fire in Sprinklered Warehouse

A fire broke out in a sprinkler protected warehouse storing more than 12,000 used, large format lithium-ion batteries. The batteries were stored in racks to a storage height above 25 ft (7.5 m). The sprinkler protection was inadequate for lithium-ion battery rack storage and was not able to control the fire. The fire spread through fire walls to additional storage areas, ultimately resulting in the total loss of the warehouse.

3.5.1.2 Li-ion Battery Fire in a Test Lab

Two lithium-ion battery packs were being charged over the weekend on a test cart when one went into thermal runaway. Nearly 3 hours after the thermal runaway process started, a smoke detector activated alerting personnel of the fire. The fire service responded and was able to quickly control the fire and remove the impacted battery packs from the building. The battery packs were placed in water filled barrels. The ceiling-only sprinklers did not operate due to the size of the fire. The smoke and corrosive soot filled the manufacturing area and resulted in extensive clean up measures before operations could resume.

4.0 REFERENCES

4.1 FM

Data Sheet 1-56, *Cleanrooms*
Data Sheet 2-0, *Installation Guidelines for Automatic Sprinklers*
Data Sheet 3-26, *Fire Protection for Nonstorage Occupancies*
Data Sheet 5-1, *Electrical Equipment in Hazardous (Classified) Locations*
Data Sheet 5-8, *Static Electricity*
Data Sheet 5-20, *Electrical Testing*
Data Sheet 5-32, *Data Centers and Related Facilities*
Data Sheet 5-33, *Lithium-Ion Battery Energy Storage Systems*
Data Sheet 6-9, *Industrial Ovens and Dryers*
Data Sheet 7-2, *Waste Solvent Recovery*
Data Sheet 7-9, *Dip Tanks, Flow Coaters and Roll Coaters*
Data Sheet 7-11, *Conveyors*
Data Sheet 7-14, *Fire Protection for Chemical Plants*
Data Sheet 7-29, *Ignitable Liquid Storage in Portable Containers*
Data Sheet 7-32, *Ignitable Liquid Operations*
Data Sheet 7-43, *Process Safety*
Data Sheet 7-45, *Safety Controls, Alarms, and Interlocks (SCAI)*
Data Sheet 7-46, *Chemical Reactors and Reactions*

Data Sheet 7-76, *Combustible Dusts*
Data Sheet 7-78, *Industrial Exhaust Systems*
Data Sheet 7-88, *Outdoor Ignitable Liquid Storage Tanks*
Data Sheet 7-98, *Hydraulic Fluids*
Data Sheet 7-99, *Heat Transfer Fluid Systems*
Data Sheet 7-110, *Industrial Control Systems*
Data Sheet 8-1, *Commodity Classification*
Data Sheet 8-9, *Storage of Class 1, 2, 3, 4 and Plastic Commodities*
Data Sheet 8-34, *Protection for Automatic Storage and Retrieval Systems*
Data Sheet 9-0/17-0, *Asset Integrity*
Data Sheet 10-1, *Pre-incident and Emergency Response Planning*
Data Sheet 10-3, *Hot Work Management*
Data Sheet 10-8, *Operators*

FM Research, Ditch, B. and de Vries, J. March 2013. *Flammability Characterization of Lithium-ion Batteries in Bulk Storage.*

FM Research, Ditch, B. October 2016. *Development of Protection Recommendations for Li-ion Battery Bulk Storage: Sprinklered Fire Test*.

4.2 Other

California Fire Code (CFC). 2022. Section 322

International Fire Code (IFC). 2024. Section 321

National Fire Protection Association (NFPA). NFPA 855, *Standard for the Installation of Stationary Energy Storage Systems.*

Siemens AG; TUV SUD Industrie Service GmbH. 2021. *Principles for Risk-Based Fire Protection Strategies for Lithium-ion Battery Cell Production.*

PEM of RWTH Aachen; VDMA. 2018. *Lithium-ion Battery Cell Production Process.*

EPRI. The Difference Between Thermal Runaway and Ignition of a Lithium Ion Battery. December 2022.

APPENDIX A GLOSSARY OF TERMS

Anode: Typically, a positive electrode that releases electrons into the external circuit and oxidizes during the electrochemical reaction.

Battery (Lithium-Ion): The finished power device that will be used to power equipment/vehicles/electrical systems. This device may be a single lithium-ion cell, a collection of cells, a module or a collection of modules.

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 working within their designed operating parameters to prevent thermal runaway.

Bin-box storage: A storage arrangement that typically consists of solid shelves in combination with solid full height wooden or metal vertical barriers. Each bin-box storage unit usually has a solid backing, but not always. While this type of storage arrangement typically shields the burning commodity maintained in each bin-box storage unit from direct water application, the relatively low tier height between solid shelves coupled with the full-height vertical barriers help reduce the heat release rate of the fire as well as severely delay its potential for horizontal fire growth.

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. Capacity can also be measured in kilowatt-hours (kWh) or megawatt-hours (MWh).

Cathode: Usually, the negative electrode that acquires electrons from the external circuit and is reduced during the electrochemical reaction.

Cell: The smallest electrochemical component that can store energy.

Cut-off Room: A space within a building, which is intended for a specific storage purpose and has physical walls separating it from other areas in a building.

Electric vehicle battery: Any size energy storage system mounted or to be mounted onto mobile equipment or consumer vehicles.

Electrolyte: The medium that provides the ion transportation mechanism between the cathode and anode of a cell. The electrolyte in lithium-ion cells is an ignitable liquid.

Energy storage system (ESS): Any system through which electrical energy can be stored and reused when needed. An electrochemical device that collects energy from the grid or from a power plant and then discharges that energy at a later time to provide electricity or other grid services when needed.

Finished product: A consumer item that has completed the manufacturing process and is ready to be sold to the end user.

Fire wall: A wall assembly that is designed to contain an uncontrolled fire to the side of fire origin.

Horizontal barriers: A solid barrier installed on a horizontal plane within a rack, beneath which in-rack sprinklers are installed. Their purpose is to impede vertical fire spread by blocking off normally open flue spaces, while also helping to achieve prompt in-rack sprinkler operation by banking heat down to the in-rack sprinklers that must be installed under each barrier.

Incidental storage: Solid-pile, palletized, rack, shelf, or bin-box storage that is normal for an occupancy (e.g., small amounts of packaging, raw materials, or the products being made). This is likely to be at the start or end of a production line.

In-rack sprinklers: Sprinklers that are installed within the footprint of a storage rack to provide fire control (balanced with the ceiling sprinkler system) or fire suppression (not balanced with the ceiling sprinkler system).

LCO: Lithium cobalt oxide battery chemistry.

LFP: Lithium iron phosphate battery chemistry.

LMO: Lithium manganese oxide battery chemistry.

Long duration fire: A fire with manual intervention that may exceed the recommended water supply duration.

LTO: Lithium titanate battery chemistry.

Module: A combination of cells electrically arranged in series, parallel, or a combination of both. Modules may also be provided with a smaller version of the BMS to control the cells within and communicate with a system BMS.

NCA: Lithium nickel cobalt aluminum oxide battery chemistry.

NMC: Lithium nickel manganese cobalt oxide chemistry.

Nonthermal damage: Damage that results from a fire event but is not caused by the heat of the fire. Examples of nonthermal damage include but are not limited to smoke, corrosive byproducts, water, chemical release, etc. Nonthermal damage can be reduced by physical features in a building such as drainage and walls.

Open-frame rack storage: Rack storage that is void of any solid shelves within the storage array and that has adequate flue spaces in accordance with Data Sheet 8-9 to (1) allow rapid vertical fire growth (minimizing horizontal fire spread) and (2) allow downward sprinkler water penetration throughout the height of the rack.

Solid electrolyte interphase (SEI): A passive, stabilizing layer formed over the anode surface due to electrochemical incompatibility between the anode and electrolyte.

Separator: A type of polymeric membrane that separates the anode and cathode to prevent electrical short circuiting and facilitates ion transport in the cell.

State of charge (SOC): The real-time amount of energy stored in a system, compared to the rated capacity. A function of voltage. The SOC could be expressed as a percentage value. Thus, 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), which monitors 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 to evaluation and monitoring.

Thermal runaway: The irreversible failure mode of a lithium-ion battery where an exothermic reaction occurs and flammable gas is produced.

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).

October 2024. This is the first publication of this document

APPENDIX C LITHIUM-ION BATTERY INFORMATION

C.1 Introduction

C.2 Types of Lithium-Ion Batteries

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 lithium-ion cell uses the movement of lithium-ions between positive and negative electrodes for energy storage. Lithium never exists in metallic form in lithium-ion battery cells, so the inherent instability of metallic lithium is mitigated. A typical lithium-ion cell operates in the range of 3.6 (fully discharged) to 4.2 (fully charged) VDC. Outside of this range instabilities can occur that result in failures. See Section C.3 for additional information. Also, the solid electrolyte interphase layer (SEI), which forms on the anode surfaces is an ionically conductive and electronically insulating layer. This layer facilitates the working of lithium-ion technology. Failure of the SEI leads to heat generation and thermal runaway.

Lithium-ion cells include a wide variety of chemistries related to the chemical composition of the anode and cathode that affect performance and cost. For cathode composition, li-nickel manganese cobalt oxide (NCM) and li-nickel cobalt aluminum oxide (NCA) chemistries are known to be very stable while providing high energy density. The most popular chemistry for anode composition is partially graphitized carbon. Lithium titanate (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

Cylindrical cells, shown in Figure C.2.1.1, are the most widely used packaging style for batteries and provide 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 Lithium-ion cells connect the pressure relief vent to an electrical fuse that permanently opens the cell under unsafe pressures.

C.2.1.2 Prismatic Cells

Prismatic cells, shown in Figure C.2.1.2, 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, as each manufacturer uses their own design. Prismatic cells are also available in large formats that can be found in electric vehicles. Packaged in welded aluminum housings, the cells deliver capacities of 20 to 50 Ah and are primarily used for ESS applications.

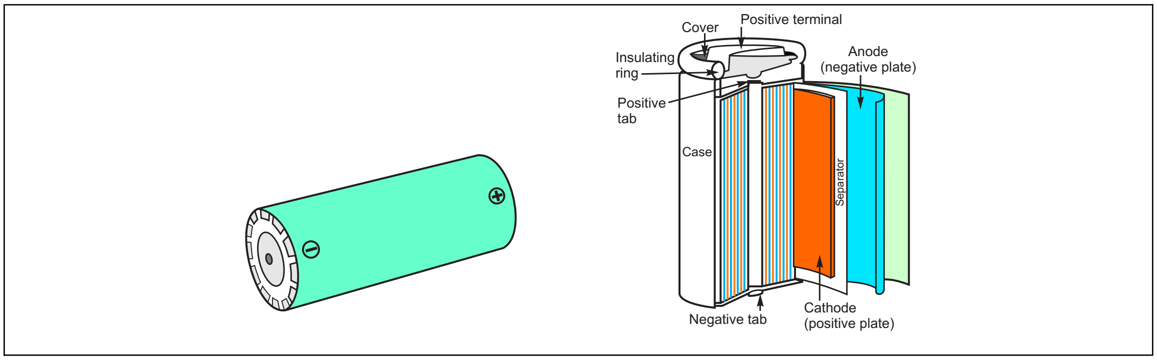

Fig. C.2.1.1. Cylindrical cell form

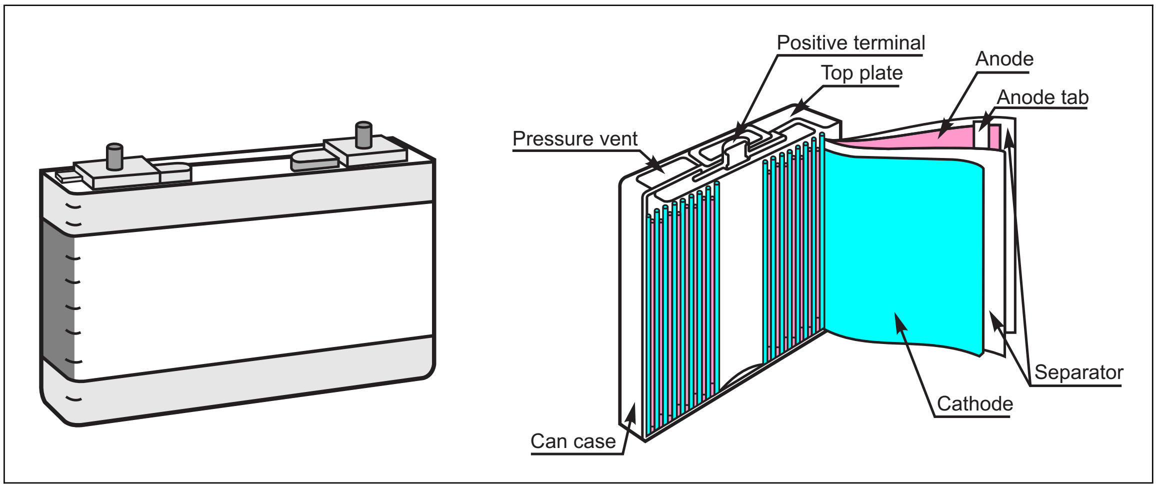

Fig. C.2.1.2. Prismatic cell form

C.2.1.3 Pouch Cells

A pouch cell, shown in Figure C.2.1.3, 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 cell exists, as each manufacturer uses their own design. The pouch cell is used for similar applications as the prismatic cell.

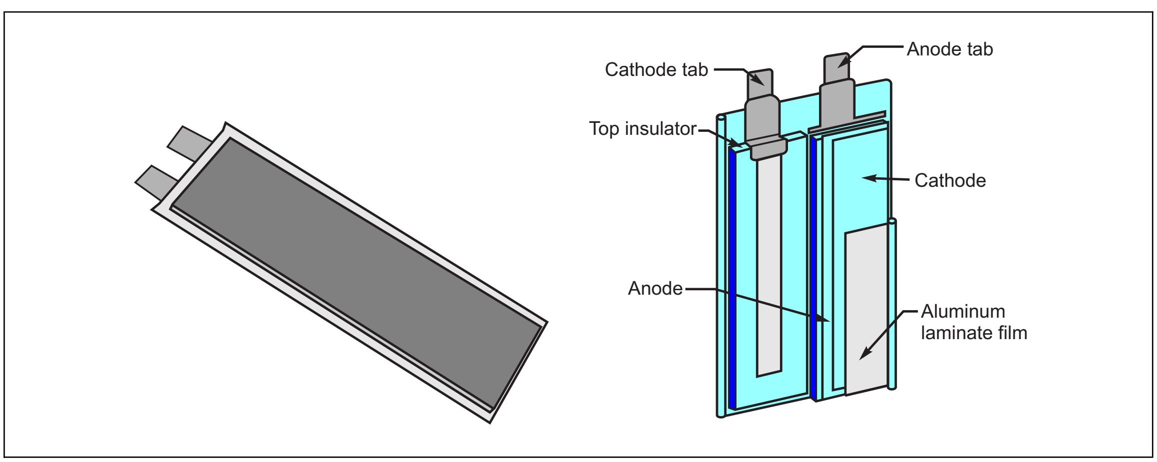

Fig. C.2.1.3. Pouch cell form

C.2.2 Modules

The next order of structure is the lithium-ion module or pack, shown in Figures C.2.2-A and C.2.2-B. It 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.

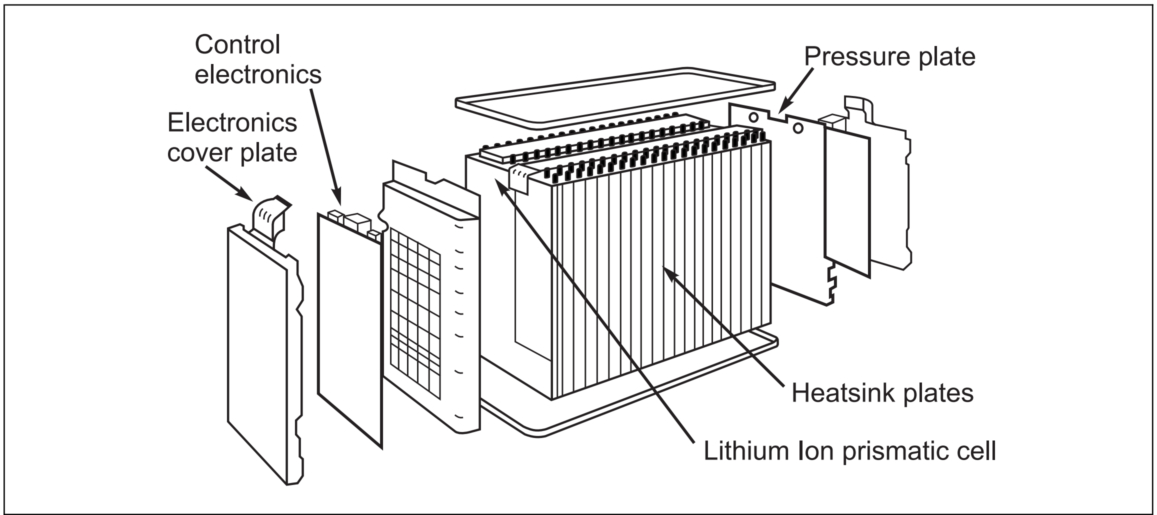

Fig. C.2.2-A. Module configuration

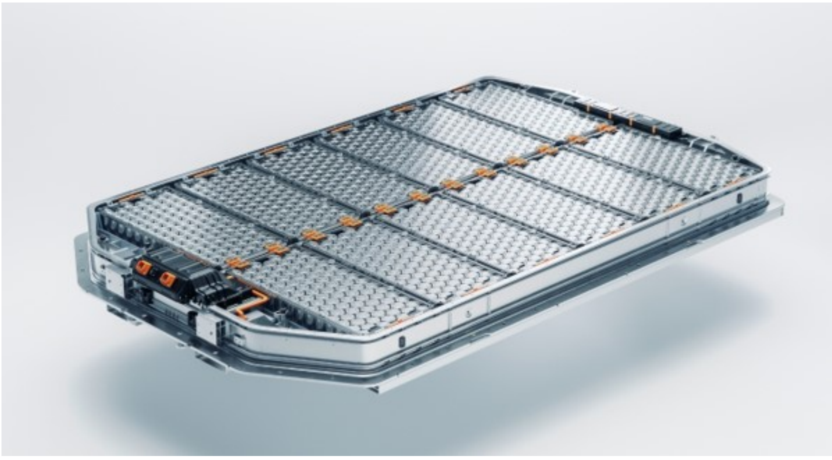

Fig. C.2.2-B. Typical modules within a battery pack for an electric vehicle

C.3 Failure Modes

The performance of lithium-ion cells is dependent on both temperature and operating voltage. They operate within a safe range, which is a function of cell voltage and temperature. The cell should generally operate between 32°F (0°C) and 212°F (100°C) while maintaining a voltage from 2 V to 4 V, although each cell manufacturer may have their own specifications. Should a failure occur and the cell temperature fall below 32°F (0°C), lithium plating will occur during charging, which will lead to shorting. Operating above 212°F (100°C) can lead to SEI thermal layer breakdown. When coupled with operating above 6 V, it can lead to electrolyte leakage and subsequent vapor ignition. When operating at extreme temperatures (over 392° [200°C]) the cathode active material will breakdown, 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 lithium-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.3.1 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 (dendrite 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; 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.3.2 Undervoltage/Over-discharge

Allowing the cell voltage to fall below about 2 V by over-discharging or storage for an 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 situation is dangerous and can ultimately cause a short circuit between the electrodes.
- Cathodes: Keeping the cells at voltages below 2 V for prolonged periods results in the gradual breakdown of the cathode over many cycles through 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 breakdown can happen over a few cycles.

C.3.3 Low Temperature

The outcome of reducing the operating temperature is to reduce the rate at which the active chemicals in the cell are transformed. The current-carrying (i.e., power-handling) capacity of the cell is reduced, both for charging and discharging. 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.3.4 High Temperature

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

C.3.5 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. 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 increase the temperature.

B. Electrolyte breakdown. Heat from the 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 causes pressure to build up inside the cell. The pressure release vent in the cells is designed to release the gas and relieve the internal pressure.

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

Note that several studies have been undertaken to evaluate the prevention of thermal runaway by adequate thermal management. This research is critical, because it forms the basis of mitigation measures against thermal runaway propagation.

C.3.6 Mechanical Fatigue

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

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

Leakage of the 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.

APPENDIX D LITHIUM-ION CELL MANUFACTURING PROCESS

D.1 INTRODUCTION

Every battery manufacturer will have their own proprietary lithium-ion battery chemistry and manufacturing process. However, regardless of the chemistry and the exact details of how certain processes are completed, fundamental process steps can be applied to lithium-ion battery manufacturing in general. This section will expand on each process step, describing its purpose as well as the inherent hazards present, see Figure 1.1 for the overall manufacturing process. Figure D.1 shows an example manufacturing facility layout.

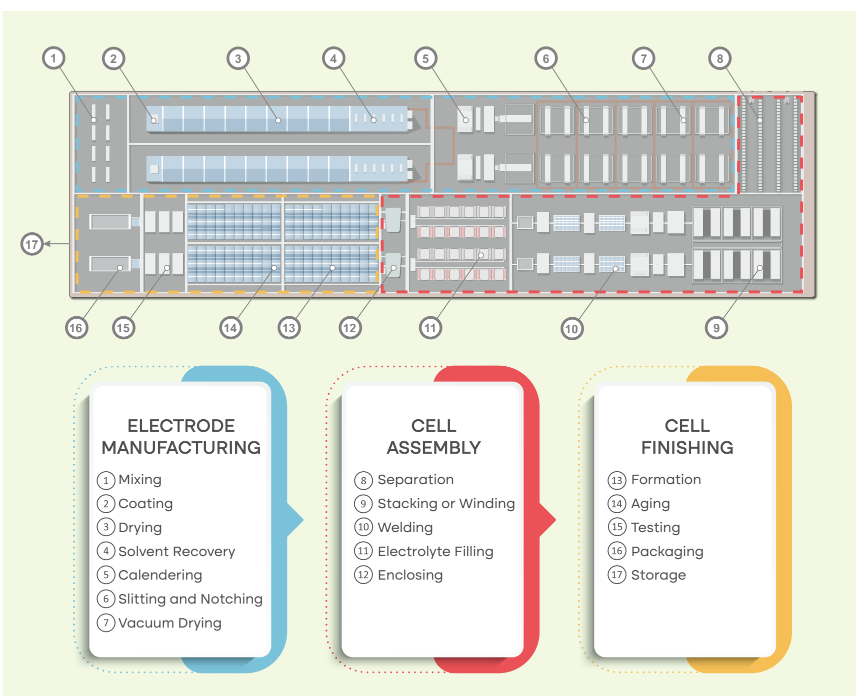

Figure D.1. Example Manufacturing Facility layout

D.2 ELECTRODE MANUFACTURING

Electrode manufacturing can consist of seven process steps that result in the final coils of cathode and anode materials used in cell assembly. The six steps include mixing, coating, drying, calendering, slitting and notching and vacuum drying. At this point in the lithium-ion cell fabrication process, no electrochemical hazards exist; as the cell has not been formed and is not chemically active. The hazards throughout these process steps are due to the process activities and raw materials present. Typically, manufacturing facilities will run two similar production lines in separate clean rooms, one for the cathode and one for the anode, to avoid cross contamination.

D.2.1 Mixing

The mixing step produces two slurries, one for the cathode and one for the anode. The slurries are formed by mixing active materials, carbon black, solvent, binders and additives to meet the chemistry specifications of the cathode and anode.

The mixing process can take approximately 30 minutes to five hours. Once complete, the slurries are transported to the coating area via pipelines or sealed tanks. The hazards for this step are tied to the chemicals being used. The production of the cathode slurry involves ignitable liquids, whereas the production of anode slurry usually does not.

D.2.2 Coating

During the coating process the slurry is applied to a foil material (aluminum for the cathode and copper for the anode) and continuously fed to the dryer. Again, the hazards are tied to the chemicals and process equipment being used.

D.2.3 Drying

The drying process removes the solvent from the slurries by applying heat. The flammable solvent used in the cathode manufacturing process is typically recovered. Transport of the foils through the dryer is accomplished by either a roller system or floatation air streams, depending on whether single- or double-sided application of the slurry is being performed. After passing through the dryer, the coated foil is cooled and rewound or fed through the system again to coat the second side if needed. Hazards include the heaters and flammable solvent vapor in the ducts.

D.2.4 Calendering

After the cathode and anode coils are cooled, they are compressed during calendering to obtain the desired porosity. The rollers used can be heated and present a fire hazard.

D.2.5 Slitting

The wide electrode coil produced thus far, sometimes referred to as the mother coil, is divided into several smaller electrode coils or daughter coils and rewound into smaller rolls. Flammable dusts and vapors can be produced during the slitting process.

D.2.6 Notching

After the slitting process, electrode coils undergo notching where a V-shaped notch and tabs are made to form the positive and negative terminals. The uncoated parts of the coil are cut off leaving the corners in order to ground the tabs.

D.2.7 Vacuum Drying

The daughter coils are dried in a vacuum oven for 12 to 30 hours to remove residual moisture and solvents. The hazards during vacuum drying relate to the process equipment rather than the coils themselves.

D.3 CELL ASSEMBLY

Cell assembly consists of up to five process steps that result in an active cell. The five steps include separation in the case of pouch cells, stacking or winding, welding, electrolyte filling and enclosing. At this point in the lithium-ion cell fabrication, electrochemical hazards can come into play as the cell is formed and is potentially electrochemically active. The hazards throughout these process steps are due to the process activities.

D.3.1 Separation

The separation process is only needed for the assembly of pouch or stacked prismatic cells. During this assembly stage, the daughter coils are cut into their final format using laser cutting or punching methods. The hazards associated with this process step are due to the activities being conducted, and the risk of fire is low.

D.3.2 Stacking or Winding

The stacking process consists of placing alternating cathode and anode sheets in a stack with separator material between each. The separator may also be a continuous sheet if the z-folding process is used. The winding process is used for cylindrical cells. It entails stacking the anode foil, separator, cathode foil and separator on top of each other and rolling to form a jelly roll. Quality control over this process is important, as any mistakes or defects introduced into the cell at this stage can have a major impact on the risk factors during the formation process.

D.3.3 Welding

During welding, the contacts are welded to the cell stack or jelly roll and the stack or jelly roll is placed into the cell housing (pouch, can, or case). The cell housing is then sealed on three sides, leaving one side open to fill the cell with electrolyte in the next step.

D.3.4 Electrolyte Filling

The electrolyte is now placed inside the cell under a vacuum. A capillary effect created by alternating the application of a vacuum and pressure with inert gas is used to distribute the electrolyte faster. This process is referred to as wetting. The use of an ignitable liquid electrolyte is the main hazard concern within this process step.

D.3.5 Enclosing

Once the cell is filled with electrolyte, the cell housing is fully sealed under vacuum during the enclosing process. For pouch cells, another step known as roll pressing may then take place. Roll pressing involves applying a defined pressure to the pouch cells in order to achieve optimum distribution and absorption of the electrolyte throughout the cell.

D.4 CELL FINISHING

Cell finishing consists of up to five process steps that result in the finished, ready-for-use lithium-ion cell. The five steps include formation, aging, testing, packaging and storage. Electrochemical hazards are present throughout the cell finishing steps, and the greatest fire hazard exists within the formation and aging process steps due to the large quantity of cells staged near each other for long durations.

D.4.1 Formation

Formation is where the manufactured cells first undergo charging and discharging to form the SEI layer. The exact process parameters and steps will vary from manufacturer to manufacturer and are often proprietary due to the high impact this process step has on the final cell performance. Generally, the cells undergo an initial pre-charge that is followed by cycles of discharging and charging. During formation, the cells are placed in specially designed pallets and stored in a high-bay storage system. The entire process can last up to 15 days.

This process step is one of the most hazardous in terms of fire risk due to the large quantity of cells in close proximity, as well as from the initial charge taking place. Any production defects introduced during earlier process steps can increase the hazard here.

After formation, a process step known as degassing must take place for pouch and prismatic cells prior to aging. For these cells, the gas produced during the formation process is collected in a disposable bag or dead space within the cell. Degassing removes the gases under a vacuum, along with the disposable bag if needed, and applies the final seal to the cell housing.

D.4.2 Aging

Aging is the final cell production step to stabilize the cell properties and SEI film. It involves monitoring each cell's parameters for quality assurance. During this process, the cells are typically charged 80-100% and placed in high-bay, rack storage to rest for an extended period. The exact amount of time is dependent on the cell chemistry and manufacturer specifications. Some manufacturers will continually monitor each cell during the aging process, while others may take the needed measurements at the start and end of aging. Voltage and impedance are the parameters typically monitored. The aging process is completed in multiple steps with the cells resting at different temperatures, usually at a high temperature followed by ambient temperature.

D.4.3 Testing

Once the aging process is complete, each finished cell will undergo testing. The exact testing is up to the manufacturer but could include pulse tests, internal resistance measurements, optical inspections, open circuit voltage tests and leakage tests. Based on each cell's performance data, a battery grade is assigned, grade A, B or C. The cell will be discharged to the shipping state of charge and released for final packaging.

D.4.4 Packaging

Depending on the extent of manufacturing, the cells are either packaged in plastic or cardboard containers to be shipped or assembled into modules that are then packaged for shipment.

D.4.5 Storage

Packaged cells or modules are generally found in either palletized, solid-pile or rack storage arrangements. Rack storage used in the highly automated manufacturing process tends to be high-bay ASRS.