AEGIS

Loss Control

Lithium-ion Battery Energy Storage Systems (Li-ion BESS)

White Paper

Table of Contents

Executive Summary **2**
Li-ion BESS Fire and Deflagration Hazards **4**
Li-ion Battery Cell Chemistry **5**
Li-ion BESS Fire Testing **6**
AEGIS Installation-Level Testing Criteria **7**
Worst-Case Scenario **7**
Test Setup **7**
Measurements of Interest: **8**
Acceptance Criteria **8**
Configuration **8**
Engineering Analyses **10**
Deflagration Hazard Study (DHS) **10**
Hazard Mitigation Analysis (HMA) **10**
Mitigating Features & Systems **12**
Battery Management System (BMS) **12**
Separation **13**
Li-ion BESS Enclosure and Component Construction **14**
Emergency Monitoring Systems (Gas, Smoke and Other Fire Detection) **15**
Emergency Ventilation Systems **16**
Deflagration Venting **17**
Fire Suppression/Extinguishing Systems **18**

Miscellaneous Loss Prevention 21
Fire Risk Control Program 21
Signage 21
Electrical Safety 21
Site Security 21
Emergency Response and Contingency Planning 21
Emergency Response Planning 21
Contingency Planning 22
References 22
Contributors 23

Executive Summary

This white paper summarizes AEGIS Loss Control's position related to the current state of battery storage systems, and it is offered as a reference guide to AEGIS members considering Lithium-ion Battery Energy Storage System (Li-ion BESS) facilities. The lessons learned from Li-ion BESS events, full-scale fire tests, and changes in codes and standards will be used to periodically update this document, as technology, fire testing methods and mitigation measures continue to mature.

The hazards of Li-ion BESS arise from their ability to undergo cell thermal runaway. Thermal runaway occurs when the temperature of an electrochemical cell increases through self-heating in an uncontrollable fashion. Li-ion cell thermal runaway progresses when heat is generated faster than it can be dissipated. In Li-ion cells, this may lead to gas evolution, fire and deflagration (explosion). Thermal runaway can be caused by electrical internal or external short circuiting within the cell or from overcharging, thermal or mechanical failures, physical damage, or manufacturing contamination or defects. Li-ion cell thermal runaway is self-sustaining and not dependent on oxygen. It will continue until the electrolyte in the cell is exhausted. In many cases, thermal runaway in one cell can propagate by heat transfer to adjacent cells. The release of flammable gas represents both a significant fire and deflagration hazard. Thermal runaway events can last from several hours to several days, depending on the configurations.

The following measures and design elements can help mitigate the fire and explosion risks associated with utility-scale Li-ion BESS installations. They will be discussed in subsequent sections of this document.

- Perform a thorough hazard mitigation analysis (HMA) based on representative testing
- Provide a robust and granular battery management system (BMS)
- Utilize separation to the maximum extent possible to limit value at risk (at least 25 feet, unless full-scale testing proves to be safe at closer spacing)
- Utilize noncombustible construction for the enclosure and components
- Install emergency monitoring systems (e.g., combustible gas, smoke, video and other fire detection)
- Install emergency purge ventilation systems to remove flammable gases
- Install deflagration vents

- Do not install aerosol or gaseous fire suppression systems
- Water-based sprinkler, spray and water mist systems can be installed, though based on current testing, they may not be effective under all conditions
- Ensure cybersecurity of all Li-ion BESS electronic systems

Housing Li-ion BESS in large buildings or structures, such as repurposed powerhouses and warehouses, is a major concern due to the concentrated values with extremely high loss potential and the challenges to providing effective fire protection, flammable gas mitigation, and deflagration venting. Another area of concern is that many of the modular or cabinet-style Li-ion BESS facilities are being developed with insufficient space (land) to adequately separate equipment and limit value at risk to a single equipment event.

These project risks are compounded by the fact that many of the installed fire mitigation systems have either not been properly tested for proof of concept (full scale and representative) or have been shown, through recent large-scale testing and the Li-ion BESS deflagration event in Arizona in April 2019, to be ineffective or even detrimental. In projects such as these, with unmitigated fire spread and/or explosion potential, property loss and risk to personnel can be significant.

Completion of UL 9540A (Underwriters Laboratories' Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems) testing is not an indication that a Li-ion BESS is safe; it is only one step in understanding the hazards being presented so that proper mitigation features can be prescribed by a qualified fire protection engineer performing the HMA. UL 9540A testing does have a limitation, in that it does not force ignition of flammable gas vented during unit (rack) level testing. This testing limitation means the engineer performing the HMA cannot be certain about the extent of fire spread and further thermal runaway propagation if flammable gas ignition does occur. Even worse, some manufacturers are exploiting this limitation and concluding that their Li-ion configuration is "safe" while, in many cases, no mitigation features beyond the BMS (including potentially poorly designed ones) are being employed to ensure flammable gas ignition does not occur. Some of these designs also include ineffective fire suppression mitigation. These testing issues and limitations cause a general misunderstanding of the hazards, omissions in the HMA and, ultimately, higher-risk installations.

Separation is currently the most effective way to protect property from fire and deflagration hazards. Separation of 25 feet (or the equivalent separation using fire rated walls) should be used for modular cargo container (intermodal shipping container) or smaller Li-ion BESS installations, unless full-scale and representative fire testing with appropriate deflagration designs proves that the enclosures, or group of enclosures, can be moved closer to each other. Alternative performance-based engineering controls that limit fire and the explosive effects of a deflagration may result in significantly closer acceptable separation.

Where larger losses can be tolerated, enclosure groupings with adequate separation between groups may be a means to reduce land use while also limiting loss potential. The groupings should be based on the member company's risk tolerance, including an understanding of the potential effect on underwriting conditions.

The critical takeaway of this white paper is that AEGIS Loss Control urges caution and conservatism in the design and layout of Li-ion BESS facilities. Separation should be used to limit loss potential until other mitigation methods are developed, tested and proven to address the potential hazards. Minimizing the deflagration hazard exposures to adjacent equipment, responding personnel and the public is paramount.

AEGIS Loss Control is available to discuss, review and/or evaluate Li-ion BESS projects with member companies, preferably during the early stages of development and design, when changes can be considered and incorporated into the project. Please contact Mark Boone, National Property Manager, at MarkBoone@aegislimited.com, or Charles Bruce, Senior Property Loss Control Professional, at CharlesBruce@aegislimited.com.

Li-ion BESS Fire and Deflagration Hazards

Li-ion BESS represents both a significant fire hazard and a deflagration hazard from flammable gas generation during thermal cell runaway. The hazards from thermal runaway must be considered and addressed by mitigation measures during the early design and development stages of each project, preferably as part of a formal HMA (See Hazard Mitigation Analysis/ HMA, a.k.a., Fire Protection Design Basis.).

The fire hazard from thermal runaway arises from the overheated cell's liquid electrolyte, which releases large quantities of flammable gas. More than 50 percent of the gas released can be flammable, and depending on battery chemistries, more than half can be hydrogen. If a fire starts, it can cause thermal runaway in nearby cells. A fire will also consume any available combustible materials used in the construction of the cells, modules, or units (racks), which are likely to include various plastics.

Even if the fire is extinguished, heat damage and soot contamination can be extensive. In many cases, it may be necessary to replace the enclosure and the Li-ion BESS equipment, even when there is no direct fire damage.

The explosion hazard arises from the accumulation of flammable gas generated during thermal runaway in the Li-ion BESS installation. If ignition is delayed or suppressed, an enclosure can develop gas concentrations that are within or that temporarily exceed the explosive range. With ever-present ignition sources such as electronics and overheating cells, a deflagration is a real possibility. Nearby equipment can be damaged, adjacent Li-ion BESS enclosures can be toppled or penetrated by debris, and responding personnel could be injured. Toppled or penetrated enclosures could cause physical damage to additional cells and further spread of the event. If a Li-ion BESS is burning, it may be safer to let it burn, especially if adequate separation exists between Li-ion battery enclosures and other facilities or equipment. Personnel, including emergency responders, should not approach a Li-ion BESS undergoing cell off-gassing or thermal runaway conditions.

Warehouse-style Li-ion BESS structures, including repurposed conventional powerhouses, should be avoided at this time due to the large asset value being placed at risk. UL 9540A Editions 3 or 4, along with current installation-level testing, do not adequately test, model or address the risks within this type of facility. Mitigation strategies that address all potential failure modes have not yet been developed or properly tested, and therefore the potential for a large loss event is high.

Li-ion BESS, Li-ion Emergency Power Systems (Li-ion EPS) or Li-ion Uninterruptable Power Supply (Li-ion UPS) systems should not be installed within mixed-use occupancies such as offices, schools, hospitals or shop areas due to the significant explosion hazard potential.

Li-ion Battery Cell Chemistry

Li-ion liquid electrolyte battery chemistries include, but are not limited to:

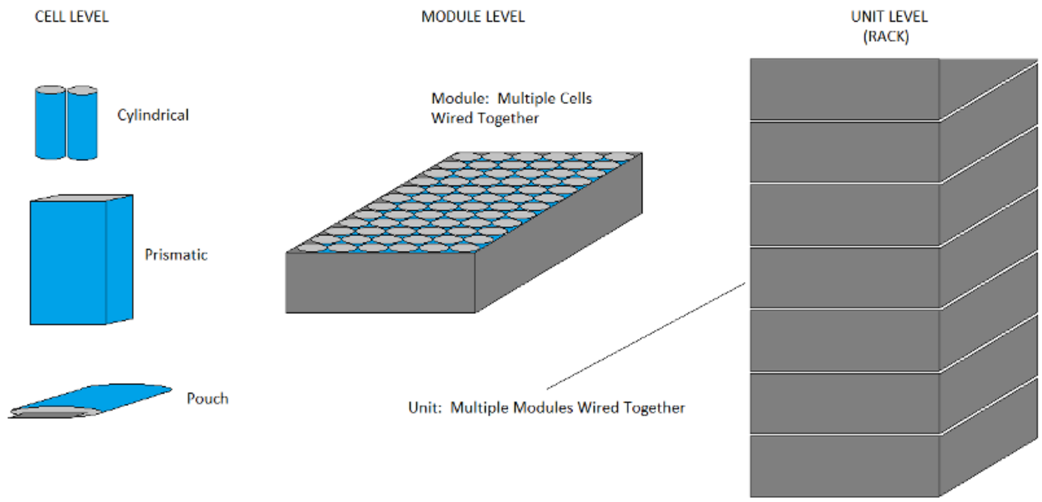
Battery Chemistry	**Energy Density** (watt hour/kg)
Lithium-Nickel Manganese Cobalt Oxide (NMC) $LiNiMnCoO_2$	150 – 220
Lithium-Cobalt Oxide (LCO) $LiCoO_2$	150 – 200
Nickel Cobalt Aluminum Oxide (NCA) $LiNiCoAlO_2$	150 – 200
Lithium Manganese Oxide (LMO) $LiMn2O_4$	100 – 150
Lithium-Iron Phosphate (LFP) $LiFePO_4$	90 – 160
Lithium-Titanate Oxide (LTO) Li_2TiO_3	50 – 80

Based on very limited UL 9540A testing (e.g., no fire observed), some manufacturers or integrators are advertising certain Li-ion cells as “safe.” Buyers and operators should be skeptical of these claims. Calling any non-aqueous liquid electrolyte Li-ion cells safe is somewhat misleading. For example, LFP cells, which have a chemistry with a lower energy density than NMC cells, can produce higher quantities of hydrogen than NMC cells. A deflagration event in April 2021 involving LFP battery technology resulted in the deaths of two firefighters.

For the purposes of this white paper, it doesn’t matter which chemistry is used. What matters is potential risk. Consider two facts regarding non-aqueous liquid electrolyte Li-ion battery cells: They all can undergo thermal runaway, and they generate flammable gas while doing so. The use of lower energy density cells does not negate the need for equivalent levels of protection against the hazards of fire and deflagration. Li-ion BESS manufacturers, designers, integrators and owners must assume thermal runaway can occur and provide mitigation features to properly address the resulting fire and deflagration hazards. These features should be prescribed through a detailed HMA conducted and documented by a qualified fire protection engineer.

Li-ion BESS Fire Testing

The testing standard most applicable to fire and explosion in Li-ion BESS is UL 9540A ("Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems.") As of September 2023, the 4th edition of this standard is the latest. UL 9540A is a test standard for all battery types, not just Li-ion batteries. The UL 9540A test is broken down into four testing levels: cell, module, unit (rack) and installation (entire enclosure). For Li-ion batteries, each progressive level of testing collects data that's important for the engineer conducting the HMA.



Cell-level testing determines whether or not the cell can be induced into thermal runaway and, if so, collects any off-gassing and determines the gas volume and constituents. Non-aqueous liquid electrolyte Li-ion cells can always be induced into thermal runaway, so further testing will always continue to the module level.

Testing stops at the module level if the effects of thermal runaway are limited to the module and the vent gas is nonflammable. Unburned gas that is vented from Li-ion cells within a module containing non-aqueous liquid flammable electrolytes is flammable gas, so the testing for Li-ion BESS should not stop at this level.

It is the unit (rack) level testing that raises concerns, as many UL 9540A tests have not resulted in the ignition of released flammable gases. Testing observed in video and still photos indicates these tests are typically conducted in a corner configuration with no ceiling. The lighter-than-air flammable gases freely vent away, reducing the potential for both ignition and deflagration. A fire test where flammable gas is released in the presence of ignition sources but does not ignite is considered incomplete and not representative of the hazard. Note that in UL's testing, as presented in its Fire Research and Development Technical Report, when units (racks) were installed inside enclosures, representing unit (rack) level testing, fire and deflagrations were observed in all tests. Reliance on unit (rack) level testing that does not include the effects of flaming fires associated with concentrations of flammable gases is not adequate to fully address the hazards. This has led to HMA analysis documents that fail to identify the true hazards that exist.

Installation-level testing is expected for all design configurations where reduced separation is being considered, as it will provide the basis for the separation directed in the HMA. Installation-level testing should include forced ignition of the released gas to represent real-world conditions. This is considered a simulation of external ignition that can occur from electrical fault conditions or auto-ignition exposure temperatures.

Some key questions might include:

- Does the fire initiate thermal runaway in adjacent cells?
- Do the combustible contents of the cells, modules, units (racks) burn and support further fire spread?
- Does the fire initiate thermal runaway to adjacent modules or units (racks)?
- Do the installed fire suppression systems affect the outcome?

Unfortunately, UL 9540A Edition 4 does not currently force ignition for vented flammable gas in these tests. While this UL document does show cell-to-cell propagation risks, it does not address propagation risks due to fire exposure and the true risk of deflagration.

UL indicated that future editions of UL 9540A may incorporate forced ignition of the flammable gas. For now, this should be considered as an Authority Having Jurisdiction (AHJ) required test, where installation-level separation reductions are being incorporated in the HMA. The expectation is that installation-level fire testing that includes early ignition of the flammable gas release will provide an understanding of the effectiveness of mitigating features.

AEGIS Installation-Level Testing Criteria

In an effort to assist with BESS testing programs, AEGIS has developed installation-level testing criteria aimed at determining the safe separation distance to limit propagation between individual BESS enclosures or groups of BESS enclosures. The criteria is as follows:

Worst-Case Scenario

- A fully developed fire is occurring in the BESS enclosure of origin.
- The entire enclosure's equipment contents is driven to be on fire/burning simultaneously.
- Deflagration is somewhat managed but not fully mitigated. Deflagration occurs and worst-case enclosure configuration of deflagration vents, doors and other openings exist relative to fire exposure to target enclosure.
- All liquid or environmental cooling systems of the target enclosure are not operating (OFF).
- Emergency ventilation in fire and target enclosures has failed (OFF).
- No suppression or exposure protection is occurring (DISABLED).

Test Setup

- The fire enclosure and target enclosure should be of sufficient size to be representative of a typical installation being evaluated.
- The enclosures should be loaded with equipment and materials in a typical installation.
- The worst-case battery arrangement, combustible content and cell selection from a fire/off gassing perspective needs to be established.
- Minimum desired spacing is used.

Measurements of Interest:

Heat flux

- At center of openings of the fire enclosure
- At set distances between the fire enclosure and the target enclosure
- At several locations on the surface of target enclosure

Temperature

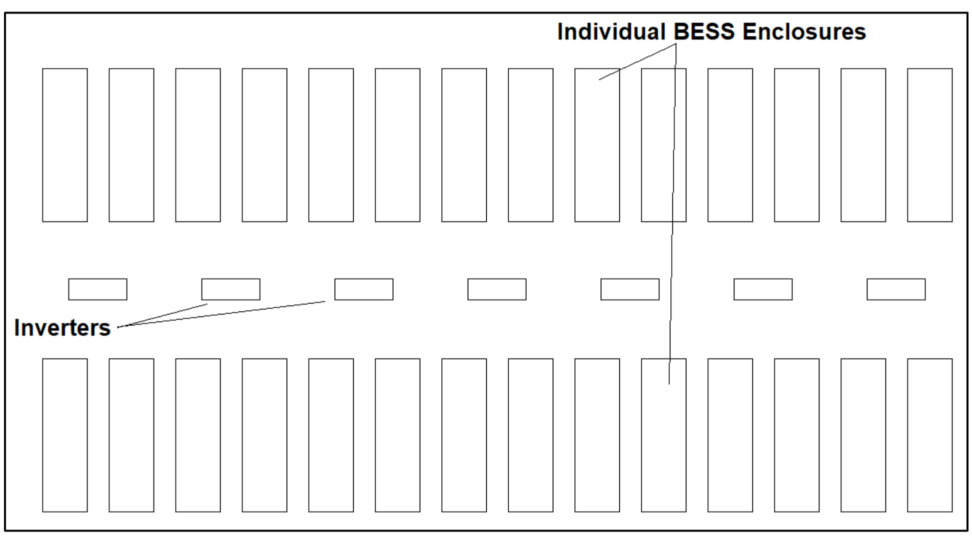
- At center of all openings of the fire enclosure
- At various set distances between the fire enclosure and the target enclosure
- At outside surfaces of the target enclosure
- At inside surfaces of the target enclosure
- At inside atmosphere of the target enclosure

Acceptance Criteria

- No ignition of any material in the target enclosure.
- Cell temperature in target enclosure does NOT exceed cell manufacturer's maximum temperature limit to affect warranty, cause any off-gassing, or cause any other damage to any cell. All target enclosure cells shall be able to return to service following manufacturer's evaluation.
- Internal temperature of the target enclosure remains below threshold temperature (determined by integrator/manufacturer) for operation of all critical systems.

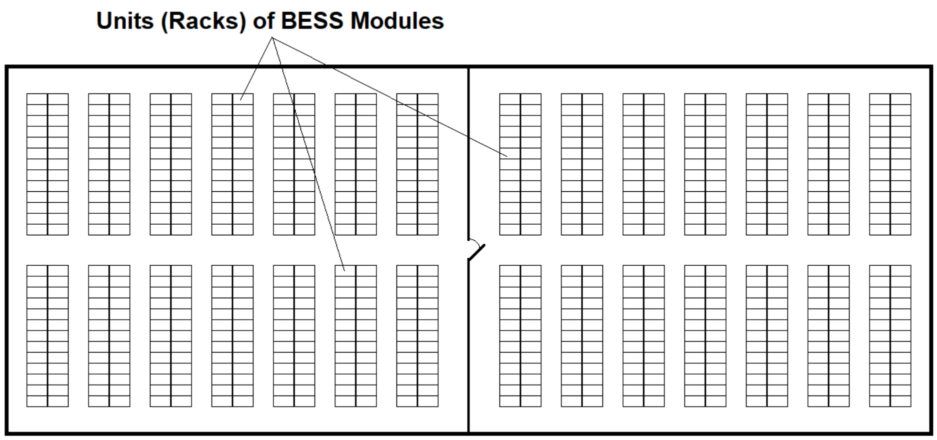
Configuration

The majority of BESS installations being constructed involve individual enclosures arranged outdoors at ground level with some horizontal separation between them. Generally arranged in separated groups with transformers, inverters or other electrical equipment nearby.



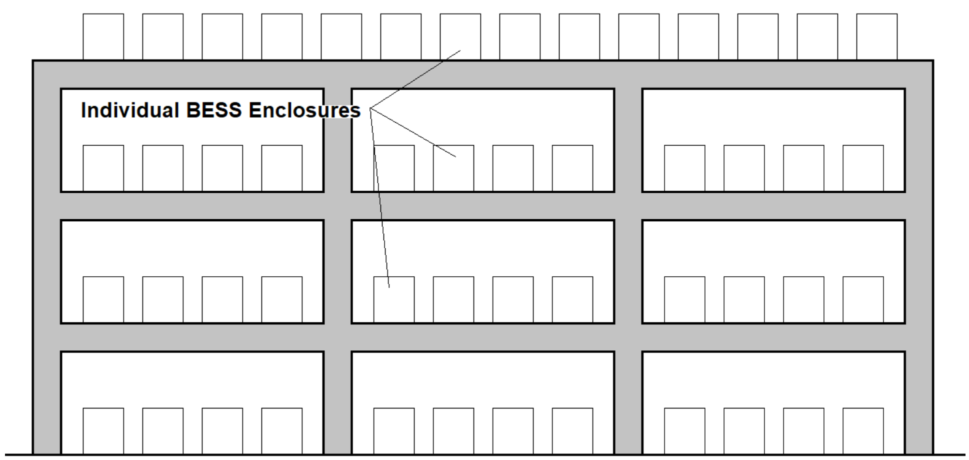
Layout of an outdoor BESS configuration

A lesser number of warehouse-style installations are being constructed (for the reasons described previously). Warehouse-style installations generally include units (racks) of BESS modules in close proximity to each other. The modules could be arranged as a single depth unit (rack) or units (racks) of modules back-to-back. In some cases, BESS units (racks) are double stacked (one on top of another). The units (racks) could be located in a single large open room or in separate rooms with a rated fire barrier between rooms. Testing for warehouse-type installations is usually limited to unit (rack) level testing and does not truly address the full magnitude of the risk.



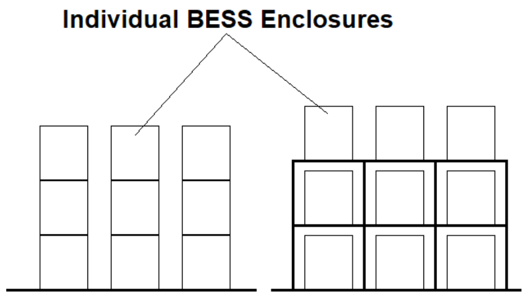
Warehouse-type configuration with two separated sections

As BESS use continues to expand, more configurations not initially considered are being proposed. These include “parking garage”-type installations where individual enclosures are installed at multiple different elevations of an open “parking garage”-like structure.



“Parking garage” configuration

Another novel BESS installation being considered is stacking BESS enclosures on top of each other, either directly or in some type of steel support structure. This could be done on land or even on floating barges.



Direct stacking or stacking in a steel support structure

The warehouse, parking garage or stacked configurations have the advantage of increasing the overall energy density per square foot of real estate. For the same reasons, they have the disadvantage of creating a higher loss potential due to the increased equipment exposure.

Additional considerations need to be made for parking garage and stacked configurations. These include but are not limited to the potential for a BESS fire to damage not only adjacent enclosures to either side but also above and below, and the increased potential for smoke to be drawn into BESS enclosures causing damage or activating emergency systems. In addition, some form of fire protection needs to be considered to protect the parking garage or other support structures by preventing collapse and/or structural failure.

Engineering Aanalyses

Deflagration Hazard Study (DHS)

The utility's project specifications for Li ion BESS projects should include a requirement for a DHS. The DHS should determine flammable gas concentrations and if they could result in a deflagration by using guidance from the SFPE handbook 5th Edition, Chapter 69, "Flammable Gas and Vapor Explosions," or another industry-recognized source. If the analysis determines that the design can result in flammable gas concentrations above 25 percent of the lower flammable limit (LFL), deflagration venting in accordance with NFPA 69 and some type of emergency smoke/flammable gas purging system would be expected.

Hazard Mitigation Analysis (HMA)

The utility's project specifications for Li-ion BESS projects should include a requirement for an HMA that is documented in a manner consistent with that described in Chapter 4 of NFPA 850 2020 Edition. Additionally, the HMA should use the methods (e.g., failure mode and effects analysis, or FMEA) consistent with those described in section A.4.1.4.1 of NFPA 855 2020 or a similar rigorous analysis methodology to determine potential failure modes and to document the prescribed mitigation strategies.

It is worth noting that HMAs are considered retroactive. Thus, guidance or necessary actions listed in an HMA developed for an existing installation should still be implemented.

Note that these FMEA methodologies are consistent with "process safety management (PSM) techniques" recommended in NFPA 850 2020, Section 4.1.3.

The HMA should be a collaborative effort (see NFPA 850, Section 4.2) and initially developed early in the design stage, preferably as part of the bid process. It should also be updated throughout the design and construction process as additional information becomes available or as information or assumptions change. The AEGIS member company, as the "ultimate" owner, should be included in the collaboration and should provide the "acceptable loss" determination. The HMA is critical for helping the owner, the AHJ, first responders, insurance engineers and underwriters understand the risks, how they have been managed and how to respond to an incident.

A robust HMA relies on well-designed safety features, not on emergency response. First responders should not approach a hazardous Li-ion BESS event until they are certain the atmosphere in the enclosure is no longer in the explosive range. The HMA should also be written with operational safety in mind and based on a concept of "value at risk" as an acceptable limit of loss. As stated above, acceptable loss is determined solely by the owner of the Li-ion BESS, as this decision could have direct insurance implications regarding loss due to property damage or business interruption.

The HMA should directly address the acceptability of the separation provided for in the design. Unless the mitigation strategy provided in the HMA demonstrates otherwise, the entire Li-ion BESS installation and any exposed assets are considered lost from an insurance perspective where at least 25 feet of separation is not provided. Li-ion BESS manufacturers, designers and integrators must assume thermal runaway is going to occur, and provide mitigation features to properly address the resulting fire and deflagration hazards. These features should be identified and described in the HMA or, where omitted, additional mitigation features should be prescribed by a qualified and licensed fire protection engineer and documented in the HMA.

Beyond the documentation described in NFPA 850-2020, Section 4.3, the HMA should also include the specific documentation described in NFPA 855-2020 Edition, Section 4.1.2.1.1 through 4.1.2.1.4. The HMA should provide the "emergency operations plan" as described in NFPA 855-2020 Edition, Section 4.1.3, as well.

Beyond the requirements of NFPA 855 and current testing conducted by UL, the following additional considerations should also be specifically addressed in the HMA.

- Where the ignition of the flammable gas released during thermal runaway does not occur during the UL 9540A unit (rack) or installation-level tests, it should be forced into ignition.
- Where appropriate full-scale installation-level fire testing has not been conducted, and when the initial conclusion reached was that propagation is not possible or does not occur, the qualified fire protection engineer must evaluate the need for additional testing to determine the effect of early ignition during release based on the conclusions used for prescribing mitigation features. The critical elements to understand should include:
    - Does a flammable gas release igniting early in the release provide the potential for fire spread within combustible unit (rack) components or put more cells into thermal runaway?

- If there are no combustible components in the enclosure, is a sufficient volume of gas released to result in deflagration (partial or full volume)?

  If the answer is yes to either question, independent mitigation features are necessary to address the remaining hazards. If the answer is uncertain, either additional full-scale installation-level testing is warranted or a minimum of 25 feet of separation should be provided between what is determined to be the acceptable value at risk. The situations to consider are:

- Where the Li-ion BESS installation includes multiple enclosures or groups of enclosures, the distance between the Li-ion BESS enclosure and other groups of enclosures, facilities and non-oil containing equipment should be at least 25 feet unless the HMA concludes that an enclosure fire and deflagration is adequately mitigated as proven through testing and analysis. Special consideration should be given to other electrical equipment, such as transformer or breaker bushings, that could be hit by flying debris.
- Where new or existing fire hazards pose a threat to the Li-ion BESS installation, spacing criteria meeting the applicable NFPA standards or other standards specific to the particular material should be applied (e.g., NFPA 850-2020 Edition, Chapter 6, guidance for transformer spacing) or fire modeling should be conducted to demonstrate that a worst-case fire involving the material of concern cannot cause overheating of Li-ion BESS equipment/cells within the enclosure or a loss of the Li-ion BESS ventilation system.
- Where liquid cooling systems using combustible glycol solutions could become involved in a fire and should therefore be evaluated.

The HMA should be reviewed periodically, with a five-year suggested baseline frequency, and kept up to date and available for review during the life of the facility. The HMA should be stamped by a qualified and licensed professional engineer with appropriate fire protection experience.

With little modification, the above language or the entire text of this document could be inserted into an owner specification. The HMA should present a mitigation strategy customized to the installation that holistically considers the mitigation features described in Section 6.0 Mitigating Features & Systems. The HMA should also address any omission of features or systems that should be provided.

Mitigating Features & Systems

Battery Management System (BMS)

All Li-ion BESS should have a robust fault-tolerant BMS, with granular temperature and electrical monitoring down to at least the module level. Continuous monitoring of the battery cells for off-normal conditions, with automatic isolation, is considered the primary line of defense against thermal runaway from adverse electrical conditions. The design philosophy and logic in the BMS should be described in the HMA.

The BMS is NOT the single "silver bullet" to prevent thermal runaway, but its role is critical. Poorly designed or implemented BMS controls can put the entire system at risk. These systems should be produced by experienced manufacturers with extensive background with Li-ion battery technology.

The minimum requirements of a BMS should include, but are not limited to, the following.

- Designed in accordance with industry-developed consensus standards such as IEEE P2686 – Recommended Practice for Battery Management Systems in Energy Storage Applications (Draft)
- Designed by a widely acceptable manufacturer with a background in Li-ion battery technology
- Regulated/controlled firmware updates that can only be installed at the enclosure, not via the internet or other remote network
- Capable of detecting off-normal conditions at or near the cell level, which could lead to thermal runaway
- Interface with emergency monitoring systems such as gas detection and fire detection. Where emergency monitoring systems are in off-normal conditions, the Li-ion BESS should be electrically isolated (termination of charging/discharging, etc.)
- Interface with emergency ventilation systems to prevent the buildup of flammable gases
- Capable of module-level, unit (rack) level, enclosure-level shutdown when certain adverse conditions exist
- Capable of analyzing battery state of health
- Capable of addressing cell imbalances where needed for LFP batteries
- Inclusion of cybersecurity considerations

The design and testing for the BMS system should be fully documented and made available to end users and AHJs, regardless of battery technology. While some details may be proprietary, the limits and control features need to be fully documented and available.

Other potential failure modes, such as aging, physical damage, or manufacturing contamination or defects, cannot be managed by the BMS. In situations where the cell is defective or physically damaged, there may be no means to prevent thermal runaway. And because in that case, thermal runaway is just a matter of time, and other mitigation measures are required.

Separation

Separation is an effective mitigating feature that can and should be used at all levels of the Li-ion BESS installation, including cell to cell, module to module, unit to unit (rack to rack), and enclosure to enclosure. Separation can mean distance, physical barriers or both.

When applied at the cell level, the goal of separation is to prevent propagation of thermal runaway to adjacent cells. When applied at the module level, the goal is, similarly, to prevent propagation (thermal, fire and explosion) between modules. The same holds true with units (racks) and enclosures. The larger the number of cells involved in a thermal runaway event, the more challenging it becomes to control due to the associated flammable gas fire and explosion hazards, both of which can further propagate the event.

The manufacturer/integrator should determine and prove through the latest version of UL 9540A testing what separation is required at each level to accomplish the objectives of their design and determine what additional mitigating features are warranted by the HMA. (See 5.0 Hazard Mitigation Analysis/HMA, a.k.a., Fire Protection Design Basis.)

Separation between enclosures or groups of enclosures is a mitigating feature that the AEGIS member company should specify to minimize the value at risk to an acceptable level of loss. As a starting point, separation should be no less than 25 feet between enclosures or groups of enclosures. Groupings and separation should be based on the member's risk tolerance.

Separation distance can be reduced when the manufacturer shares representative installation-level fire testing demonstrating that reduced distance doesn't result in fire spread between enclosures. Further, the testing must demonstrate that the deflagration hazard has been properly managed with appropriate emergency ventilation and deflagration venting. Other means of preventing a deflagration, such as the automatic release of enclosure doors, may be a suitable alternative if properly evaluated. The HMA should address and justify all reductions in separation distance as well as the basis for group sizing.

Fire rated walls can be utilized in situations where the 25 feet of spatial separation is not possible. Fire rated wall construction for BESS enclosures must be designed to resist blast pressures and minimize projectiles.

Li-ion BESS Enclosure and Component Construction

Li-ion BESS enclosures should be constructed with noncombustible materials. Insulation should be noncombustible as well. The enclosure walls and floor should be fire-sealed where cables penetrate to keep fire from extending into external trays and raceways and to prevent potential flammable vapor migration.

Li-ion BESS components, including units (racks) and modules, should be noncombustible to the maximum extent practical. An effort also should be made to minimize the amount of equipment other than battery cells (inverters, BMS, etc.) located in the battery enclosures, both to reduce combustible content and to reduce other potential sources of ignition or fire.

Li-ion BESS transformers should be the dry type or filled with a fire-retardant dielectric fluid (e.g., FR 3 or BioTemp) with a containment basin if installed in proximity to Li-ion BESS battery enclosures. These dielectric fluid transformers are not "noncombustible," but they do reduce risk. NFPA 850-2020 Edition, Chapter 6, provides exposure mitigation information for oil-filled transformers and inverters. In most cases, passive measures such as fire barriers are preferred over active systems.

Emergency Monitoring Systems (Gas, Smoke and Other Fire Detection)
The vast majority of Li-ion BESS are remotely monitored, and many are located at unstaffed sites. As such, warnings of off-normal conditions should be transmitted via emergency monitoring systems to a location that's constantly staffed and where the appropriate response can be initiated. The type and design of emergency monitoring systems should be prescribed by the HMA. For sites that are not constantly staffed, it's advisable to have a display/control console for emergency and first responders in a prominent location, such as the main gate, where it's at a safe distance from the Li-ion BESS installation. North American Electric Reliability Corporation (NERC) Critical Infrastructure Protection (CIP) regulations should be thoroughly understood and incorporated into this remote system. Responders should understand that combustible gas monitoring systems are likely to fail during a thermal runaway event. If the warning of flammable gas is not followed by an additional alarm or if the system signal is lost, dangerous conditions may exist at the site.

Emergency power requirements for emergency monitoring systems should be established in the HMA and will most likely need to exceed that specified in NFPA 72 for alarm conditions. NFPA 72 emergency power requirements do not anticipate events where extended alarm and operation may be necessary.

The emergency monitoring systems for a Li-ion BESS enclosure that detect thermal runaway, off-gassing, smoke and fire should create distinct signals (use addressable systems and equipment) that allow staff at the remote monitoring location to better understand the nature of the event underway and to dispatch responding personnel or emergency response personnel with the appropriate precautionary instructions. Combustible gas sensors tied to the emergency fire system for real-time monitoring and to the BMS or SCADA system as analog inputs with trending displays provide the best possible information on conditions to the remote operators. These systems may also be interconnected with the BMS and used for isolating energy sources and activating other emergency systems such as ventilation and suppression. Weatherproof local notification appliances should be installed on the outside of Li-ion BESS enclosures. External cameras to provide continuous surveillance should be considered as well.

Monitoring system components within or attached to Li-ion BESS enclosures can be damaged by cascading thermal runaway and will be destroyed in a fire or explosion event unless protected in some manner. For example, without proper measures, gas and smoke detection components can become contaminated and cease to function, and monitoring system signaling circuits in the enclosure can be damaged, which can prevent critical warnings from being sent. A model practice design would locate a central fire alarm panel to monitor all site emergency systems (fire, gas, etc.) in a location accessible to responding personnel but at a safe distance from the Li-ion BESS installations. For sites with multiple BESS enclosures, the communication circuit(s) interconnecting the enclosures should be a looped arrangement (NFPA 72 Class A) that can continue to monitor all other enclosures if wiring within the enclosure of origin is damaged by cascading thermal runaway, fire or deflagration.

All systems must feature early detection of an off-gassing event as well as targeted combustible gas detection and smoke detection. The type and placement of gas detection should be prescribed by the HMA, based on data provided by UL 9540A testing and the capabilities and limitations of the gas sensor technology selected. For example, catalytic bead sensors have cross-sensitivities to multiple flammable gases, each at different reaction rates, but response turns nonlinear beyond reaching the lower explosion limit (LEL), and they wouldn't read accurately in oxygen-depleted atmospheres. References 2 and 7 at the end of this white paper are excellent resources to help interested parties understand gas sensor technology and limitations for specific gases. Normally, 10 percent of LEL would be a threshold for personnel to enter the area. It is vital to understand the response of the gas sensors at the point of becoming saturated or going out of range if gas concentrations remain elevated. Gas monitoring that targets hydrogen is a logical choice, unless the UL 9540A testing supports a different conclusion. All detection (smoke, fire, heat, gas, etc.) must be listed by a nationally recognized testing laboratory (NRTL) for the hazard or target gas, as applicable. Detection systems and equipment should be provided consistent with the requirements of NFPA 72.

"During/post-event" monitoring systems should be prescribed by the HMA based on the combination of the Li-ion BESS mitigating features provided and the capabilities of the responding personnel or local emergency response organization. These monitoring systems should include reliable means to remotely and safely determine if the Li-ion BESS enclosure interior atmosphere is hazardous, especially where properly designed emergency ventilation systems, immune to fire and explosion, are not an HMA-prescribed mitigating feature of the Li-ion BESS.

It is highly likely that combustible gas sensors will be damaged by heat from cascading thermal runaway or otherwise become saturated or beyond scale. It is wise to install stainless steel sample tubing at high and low points within BESS enclosures routed to a safe location away from the enclosures. These would enable first responders using portable gas monitors with integral sample pumps to independently assess conditions. The HMA should determine the safe distance and location.

Cybersecurity of all electronic control systems should be ensured.

Emergency Ventilation Systems

An emergency ventilation system should be provided for all Li-ion BESS enclosures unless the modules or units (racks) are designed to directly exhaust any vented flammable gas to the outdoors. The preferred arrangement is to vent any flammable gas from the module directly outside and well above the unit (rack). This may be practical only with liquid-cooled battery module designs. The HMA, using UL 9540A test data as a basis, should document the design requirements for the sizing of the emergency ventilation system to ensure enclosure LEL is maintained below 25 percent. The HMA should also address proper equipment placement to ensure the emergency ventilation system survives the early stages of a fire.

The HMA should also include the logic required for automatic operation of the emergency ventilation system (e.g., cell/module-level thermal detection and combustible gas detection). Off-gases exhausted from thermal runaway in the enclosure of origin may drift to adjacent enclosures, so the impact of set points for emergency ventilation activation require careful consideration.

The HMA must consider protecting exhaust and deflagration venting from snow and ice as well. Wall- or roof-mounted heat pumps used for emergency ventilation, isolating the economizer, may be an acceptable arrangement, provided survivability during thermal runaway is considered in the design. Li-ion BESS HVAC units with integral smoke detectors that trip the air handlers to meet mechanical code requirements may require performance-based designs to address the objectives of the HMA.

UL 9540A 4th Edition test data includes a concentration for the lower limit of flammability of the gas mixture, which can be used for emergency ventilation and deflagration venting design. Unfortunately, the UL 9540A test data does not record volumetric flow rate data for the flammable gases produced prior to transition to flaming combustion at the cell, module and unit (rack) levels. In some tests, an average flow rate can be determined by observing the time stamps on photos or videos (if available) and, if determined appropriate by the engineer performing the HMAs, can be used to inform the sizing of the emergency ventilation fans. The largest of the anticipated volumetric flow rates should be used to size emergency ventilation fans to keep gas concentrations in the enclosure below 25 percent of the LEL. Until future editions of UL 9540A address this issue, the HMA should document the design assumptions made. Purging ventilation should be based on conservative assumptions, including the potential for a fire to increase the number of cells going into thermal runaway.

The emergency ventilation system should start up automatically when abnormal conditions are detected, such as an increase in cell temperature or the presence of smoke or combustible gas. If voting logic is provided to activate the enclosure ventilation, it should incorporate enough detectors to allow for the failure of at least one detector per zone/enclosure and still function as designed. All such detection must meet the requirements of NFPA 72 with devices that are listed by an NRTL for the hazard or target gas, as applicable. Appropriate emergency power survivability, design and duration requirements for detection and ventilation must be addressed in the HMA.

Deflagration Venting

Deflagration venting should be provided for all Li-ion BESS enclosures, unless the unit's design ensures it will "free burn" and vent itself in the process. The free-burn design concept should be applied to Li-ion BESS that are in modular installations only and not larger building battery installations. The HMA should document the basis for the sizing and placement of the deflagration vents. The integrator must understand the yield strength of the enclosure when explosion venting is being designed. NFPA 68 and available UL 9540A test data should be used as the resource for the design of the deflagration vents. Vent placement should minimize exposure to personnel and adjacent equipment. Damage limiting construction may be also be an alternative if it's well engineered and fully evaluated in the HMA.

Deflagration protection is for the structure, the assets and personnel around the Li-ion BESS. It is the final layer of protective systems, with only separation remaining. The internal pressure of a deflagration will decrease as the amount of vent area increases. Venting should be sufficient to prevent a violent disintegration of the enclosure and resultant external pressure waves.

Deflagration venting systems should be located to prevent or limit damage to adjacent structures or BESS enclosures (e.g., located on the roof and not the sides of an enclosure).

Door-release systems can be integrated into an enclosure design using technology that enables the hazard detection systems to automatically open the doors. This arrangement can, if properly designed, vent significant volumes of the flammable gas and reduces the potential over-pressurization of the enclosure and deflagration. The Pacific Northwest National Laboratory has published work on the design of such protection and is now sharing this information. If door-release systems are used as an alternative for ventilation and emergency venting, the HMA should evaluate the following:

- The adequacy of such systems based on the number and placement of doors (i.e., multiple doors throughout the enclosure versus a single door at one end or doors only on one side) necessary to properly perform both the intended ventilation and deflagration vent functions
- The potential effect of various climatic conditions on the Li-ion BESS when doors are open. If extreme climatic conditions can damage cells, the HMA should document how this issue would be addressed to preclude damage.
- A fail-safe position for the doors in the event power is lost at the site

Fire Suppression/Extinguishing Systems

Typical fire protection systems, such as gaseous, water-based and aerosol systems that are employed in a conventional manner (e.g., a room protection scheme) will not inhibit propagation of Li-ion BESS cell thermal runaway. As previously noted, Li-ion cell thermal runaway is self-sustaining and highly exothermic. To inhibit thermal runaway propagation between cells, fire suppressants would have to be applied at either the cell or module level. Even if this is accomplished, there is still concern over how the suppressant addresses the ignition of the flammable gas being released, the duration of the associated gas fire, the sufficient duration for application of the suppressant, and the potential for further fire spread involving other combustibles in the adjacent cells, modules and units (racks).

Note that in all cases, if the suppressant or extinguishing agent does not inhibit the thermal runaway event, flammable gases will continue to vent into the enclosure. Even in cases where module-level suppression is effective, significant amounts of flammable gas can be released while the agent takes effect. Recent UL testing involved three identical cargo container-type installation-level tests, with one having no suppression, one having water suppression and one having clean agent gaseous suppression. Roughly interpreted, the results indicate relatively similar outcomes for all three tests.

From a loss control perspective, neither the unprotected nor the suppression-protected systems prevented a deflagration. **Emergency ventilation to remove the flammable gas and/or combustion products, and deflagration venting to manage over-pressure are preferred and expected over the use of suppression systems.** The use of clean agent or aerosol enclosure fire suppression may actually increase the potential for a deflagration. Unless a water-based system can control the thermal issues, it too will fail to reduce the risk of deflagration absent effective emergency ventilation.

Some success at reducing the extent of propagation within modules has been achieved in testing by applying suppressants (water and agents such as NOVEC 1230 in liquid form) directly at the cell and module levels. These tests so far have not addressed the effect an early ignition of the flammable gas release may have on fire spread beyond the module. This area of design needs additional validation.

The potential effects and drawbacks of typical fire suppressant systems on thermal runaway events are discussed below.

Water-Based Suppression (Water Sprinkler, Water Spray, Water Mist or Hybrid Water Mist Systems)

Typical water-based suppression systems will not inhibit propagation of Li-ion BESS cell thermal runaway. Water-based suppression systems applied on a room or local basis (unit (rack) level) are not considered “extinguishing systems” but will provide a measure of exposure protection with some cooling effect, and will not eliminate the deflagration potential. Typical water-based suppression systems are not effective on flammable gas fires and thermal runaway propagation because the unit (rack) structure, stacking of modules and compactness of the cells prevent water from reaching all affected areas. Designs where water is directly injected into the module may be effective, provided the design is robust, with the ability to handle significant fires. Designs that are not capable of protecting multiple battery units (racks) simultaneously should not be given consideration. There may be some benefit to using NFPA 18A listed water additives, but full-scale fire testing would be needed for validation.

Drawbacks to water-based suppression systems include the lack of a water supply in rural or remote areas. Even in areas where a water supply is available, the possibility that the event or fire could last several hours could make a limited water supply problematic. Also consider that when Li-ion BESS components are exposed to or contaminated or damaged by a fire, an explosion or water, these components will be decommissioned rather than returned to service. In addition, there are drainage and containment considerations when high-volume water-based suppression systems are used. Environmental considerations for runoff may be another concern.

A manual water spray system supplied through a remotely located fire department connection (FDC) and used in conjunction with emergency ventilation may limit fire spread within the enclosure. However, further testing is necessary to validate the concept and water-density requirements.

For these reasons, although not considered detrimental to the event, most water-based suppression systems are not considered practical for cargo container-type Li-ion BESS sites because the overall outcome of the event remains largely the same. Despite providing a water-based suppression system, an owner can expect total loss of one Li-ion BESS enclosure and contents, or more if sufficient separation (at least 25 feet) between adjacent enclosures does not exist or other mitigation was not included in the design. Emergency ventilation to remove the flammable gas and/or combustion products is preferred even if this results in a fire within the enclosure.

Water-based systems in warehouse style Li-ion BESS arrangements may reduce fire spread between units (racks) if sufficient separation exists and if appropriate design densities are applied consistent with current NFPA and FM Global guidance. Note that despite using a water sprinkler system in a warehouse-style case, the combination of fire, smoke and water damage would be extensive for any significant fire. Warehouse-style Li-ion BESS should be avoided due to the large value at risk and the challenge of establishing a robust and reliable mitigation strategy.

Gaseous and Aerosol Suppression/Extinguishing Systems (CO2, NFPA 2001 Clean Agents and Condensed Aerosols)

Typical gaseous and aerosol extinguishing systems will not inhibit the propagation of Li-ion BESS cell thermal runaway. Gaseous or aerosol extinguishing systems applied on a room or local basis (on a unit (rack) level) may temporarily suppress a fire without controlling the flammable gas release that occurs during thermal runaway. As a result, a deflagration is possible. To compound matters, gaseous extinguishing systems, and even aerosol, to a slightly lesser degree, require tight enclosures for a prolonged period to be effective.

Confining flammable gas in a tight enclosure with ever-present ignition sources can lead to a disaster because, over time, the flammable gas may separate from the extinguishing agents, and then all that is needed is air. Aerosol suppression systems also potentially introduce another ignition source to the compartment given the heat generated during discharge.

When Li-ion BESS components are exposed to or contaminated or damaged by a fire or explosion event, those components will be decommissioned rather than returned to service.

Gaseous or aerosol suppression systems are impractical and are not recommended, because the overall outcome of the event remains largely the same. Owners should expect a total loss on one Li-ion BESS enclosure and contents, or more if sufficient separation (at least 25 feet) between adjacent enclosures, or equivalent alternate protection, does not exist.

Miscellaneous Loss Prevention

Fire Risk Control Program

Typical and applicable elements of a fire risk control program as described in NFPA 850-2020 Edition, Chapter 5, should always be incorporated into site operations.

Signage

The HMA should address and specify necessary signage to meet the requirements of NFPA 855, Section 4.3.5, and NFPA 70E to address electrical, chemical and personnel safety issues. Additionally, consider signage indicating that only authorized personnel will be permitted to enter the Li-ion BESS installation or enclosure.

Electrical Safety

Individuals with pacemakers or other vital devices should not be permitted to enter battery cell locations unless permission is obtained from the individual's physician in accordance with NFPA 70E, Article 310. This requirement should be included in the safety orientation or briefing for all individuals who may enter to the facility.

Personnel with access to the Li-ion BESS should be trained and knowledgeable about the electrical and chemical hazards and understand and use the personal protective equipment (PPE) appropriate for the conditions.

Site Security

Access to BESS construction sites and installations must be controlled. Recent events involving battery and equipment theft warrant additional security measures such as fences, security cameras, keycard access, etc.

Emergency Response and Contingency Planning

Emergency Response Planning

Li-ion BESS operators should develop a comprehensive emergency response plan for these installations. AEGIS Loss Control suggests that the planning be done in conjunction with the local emergency officials who would respond to an event. Steps to protect personnel, emergency responders and property should be developed.

All emergency conditions reported by alarms and system notifications should be investigated without delay. Many of these systems will be in remote areas, so local officials may be the first responders. A clear list of responsibilities and an action plan should be developed and agreed to by the stakeholders. The local fire department should be immediately notified of a fire condition at the site. Site security breaches should be reported immediately to local law enforcement.

Consistent with a sacrificial BESS enclosure philosophy, firefighting operations should be defensive in nature, with emphasis on cooling adjacent buildings and structures rather than attempting to extinguish an internal fire. Allowing a fire involving Li-ion batteries to burn to completion can reduce incident cleanup demands, because there is no contaminated water runoff to deal with and stored energy in the batteries is largely consumed.

Consideration should be given to the impact of external wildfire exposure, including smoke drawn into Li-ion BESS enclosures that activates emergency systems.

Contingency Planning

Contingency planning and response should account for the loss of communication with the Li-ion BESS and failures of the environmental controls. The loss of cooling or heating systems can result in the temperature excursion in the Li-ion BESS outside the limits of the batteries, so redundancy and contingency planning for power restoration to HVAC systems is critical. Spare parts should be available for the environmental control equipment, for immediate use as part of a robust contingency plan.

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