EPRI

2023 White Paper

The Evolution of Battery Energy Storage Safety Codes and Standards

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1 OVERVIEW

The U.S. energy storage market is growing rapidly, with 4.8 gigawatts of deployments in 2022 and a forecast of 75 gigawatts of additional deployments between 2023 and 2027 across all market segments,[1] with approximately 95% of current projects using Li ion battery technology.[2] Incidents involving fire or explosion are quite rare, with the *EPRI Battery Energy Storage System (BESS) Failure Event Database*[3] showing a total of 16 U.S. incidents since early 2019. Nevertheless, failures of Li ion batteries in other markets, most prominently fires involving unqualified and unregulated hoverboards, e-bikes, and e-scooters,[4] have raised public awareness of Li ion battery failures to such an extent that local opposition has caused the cancellation of some BESS projects.[5]

Statistically, the increase in ESS deployments means that there will be an inevitable increase in the number of failure incidents. That said, the evolution in codes and standards regulating these systems, as well as evolving battery system designs and strategies for hazard mitigation and emergency response, are working to minimize the severity of these events and to limit their consequences.

This report provides a historical overview of BESS incidents, the resulting evolution of North American codes and standards, their influence on ESS installations. Environmental safety is also discussed as an essential element in the future decommissioning of these systems. The lessons learned with Li ion ESS provide a framework for assessing the hazards and safety management associated with emerging storage technologies, although existing test methods may not address new failure modes that may emerge.

1 U.S. Energy Storage Monitor, Q1 2023 full report and 2022 Year in Review, Wood Mackenzie Power & Renewables/American Clean Power Association, https://www.woodmac.com/industry/power-and-renewables/us-energy-storage-monitor/.

2 DNV Energy Transition Outlook 2022, https://www.dnv.com/energy-transition-outlook

3 https://storagewiki.epri.com/index.php/BESS_Failure_Event_Database.

4 https://www.npr.org/2023/03/11/1162732820/e-bike-scooter-lithium-ion-battery-fires.

5 https://www.energy-storage.news/local-opposition-leads-to-bess-project-cancellations-in-north-america-report/.

2 HAZARDS ASSOCIATED WITH BATTERY SYSTEMS

Hazards related to stationary batteries can be broadly classified as: electrical, such as electrical abuse, shock, and arc flash; chemical, such as spills and toxic emissions; and thermal, such as fires and explosions. Li ion systems present all these hazards, except spills.

The main concern with Li ion batteries is the risk of thermal runaway,[6] leading to venting of flammable and/or toxic gases and the possibility of fire or explosion. These hazards are the main driver for development of codes and standards relating to these battery systems.

Differing chemistries have varying propensities and intensities of thermal runaway. While some Li ion chemistries, such as lithium iron phosphate (LFP), have more favorable safety characteristics (e.g., longer time under duress before thermal runaway is initiated; lower maximum temperatures during runaway) than the current prevalent chemistries in electric vehicles, such as lithium nickel-manganese-cobalt oxide (NMC)and lithium nickel-cobalt-aluminum oxide (NCA), none of them is intrinsically safe. All contain flammable electrolytes and can exhibit propagating thermal runaway. For more information on lithium ion chemistries and associated safety considerations, refer to EPRI's White Paper on this topic (3002025283).[7]

One prominent event involving a Li ion battery was an explosion at the McMicken BESS in Surprise, Arizona, in which four firefighters were injured.[8] In that case, there was ongoing propagation of thermal runaway in the absence of flame, allowing flammable gases to build up in the container above the upper flammable limit (UFL). When firefighters opened the door, oxygen was allowed to enter, and the explosion occurred. Mitigating the risk of such explosions is a major discussion point in the ongoing evolution of codes and standards and in ESS system designs (see Section 4.6).

6 *The Difference Between Thermal Runaway and Ignition of a Lithium ion Battery.* EPRI, Palo Alto, CA: 2022. 3002025283.

7 *Safety Implications of Lithium Ion Chemistries*. EPRI, Palo Alto, CA: 2023. 3002028522.

8 Arizona ESS Explosion Investigation and Line of Duty Injury Reports Now Available.

3 HISTORICAL INCIDENTS AND CODES AND STANDARDS DEVELOPMENT

3.1 ESS Incidents as a Driver for Codes and Standards Development

Early ESS deployments were not regulated by specific building electrical, fire, and product qualification codes and standards but by more generic or less application-relevant requirements. For example, Underwriters Laboratories (UL) standards for portable consumer cells and battery packs were applied to much larger ESS batteries, but these did not adequately address the particular hazards of larger stationary units. The codes and standards landscape started to change after a series of 23 fires, mostly occurring in the period of June 2018 to January 2019, at South Korean energy storage facilities. A five-month investigation by an expert panel under the Ministry of Trade, Industry and Energy, published in June 2019, identified 'four causes of accidents such as insufficient battery protection system and poor operating environment management.'[9]

Figure 1 shows the distribution of BESS events by year from the EPRI BESS Failure Event Database.[10] The spike in 2018 and 2019 is from the South Korean fires.

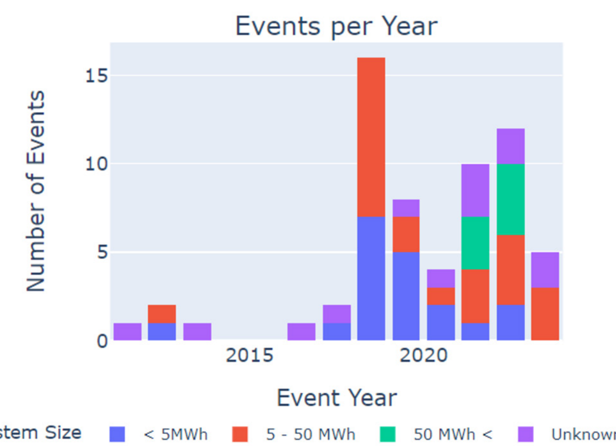

Figure 1. *BESS failures by year (EPRI BESS Failure Event Database)*

While the number of incidents (excluding the South Korean fires) showed a sixfold increase from two events in 2017 to 12 in 2022, Figure 2 indicates that US energy storage deployments increased by 18 times over the same period. Note that the events involving facilities over 50 MWh in

9 MOTIE Report, "Announcement of ESS accident cause investigation results and safety reinforcement measures," June 2019.

10 https://storagewiki.epri.com/index.php/BESS_Failure_Event_Database.

2021 and 2022, are indicative of the overall facility size, and not the number of units or modules involved in the event. For example, the 2022 fire in a Tesla Megapack at the 182.5 MW/730 MWh facility in Moss Landing, California, involved the loss of just one out of 256 units installed there.

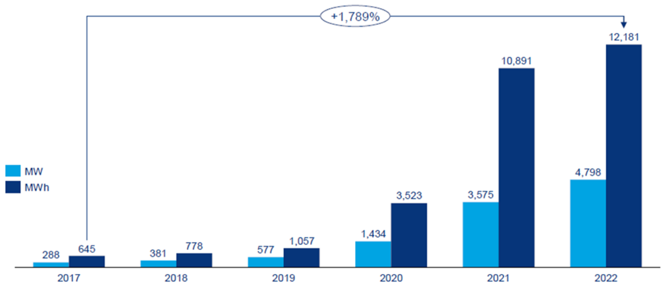

***Figure 2.** U.S. energy storage deployments across all market segments, 2017–2022*[11]

While the statistical sample size of failures is quite small, it is reasonable to conclude that the rate of ESS incidents normalized to capacity or number of facilities has decreased in recent years, and that is due to increased awareness of the hazards and risks of specific design features as well as development and application of mitigation opportunities for those risks. Many actions were driven voluntarily or proactively by concerned entities well in advance of the codes and standards evolution. The subsequent progression of codes and standards has led to more widespread adoption and enforcement of mitigations. For example, the qualification standard for ESS batteries, UL 1973, Standard for Batteries for Use in Stationary and Motive Auxiliary Power Applications (see Section 3.4), started life in 2013 with the title, 'Batteries for Use in Light Electric Rail (LER) Applications and Stationary Applications.' That first edition and the subsequent 2018 revision allowed the use of cells compliant with UL 1642, Standard for Lithium Batteries, without further testing and evaluation, despite the fact that UL 1642 is focused primarily on small consumer cells. The third edition of UL 1973, published in 2022, now contains a full suite of Li ion cell qualification requirements in normative annex E and no longer refers to UL 1642.

In the same way, lessons learned from real-world incidents have informed the evolution of UL 9540A, Standard for Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems, first published in late 2017 and quickly updated to the fourth edition in late 2019. The standard was opened for preliminary review in December 2022 and the technical committee is addressing a total of 36 proposed changes in preparation for release of the fifth edition.

3.2 Electrical Code

NFPA 70, National Electrical Code (NEC) covers ESS electrical safety for both design and installation. ESS are classified in the NEC as 'Special Conditions' in Chapter 7 of the document, with Article 706 applying to all ESS having a capacity greater than 1 kWh. (Stationary standby batteries are covered by Article 480.) One notable requirement in Article 706.20 is for provisions for 'diffusion and ventilation of any possible gases… to prevent the accumulation of an explosive mixtures.' This requirement seems to apply to Li ion vent gases but is inconsistent with explosion control provisions in the 2023 edition of NFPA 855 and the 2021 International Fire Code, as discussed in Section 3.3.

3.3 Fire Codes and NFPA 855

The two model fire codes are the International Fire Code (IFC), published by the International Code Council, and NFPA 1, Fire Code. For these model codes to be enforceable, they must be adopted, in whole or in part, by states or local jurisdictions. The adoption process generally results in a lag in implementation.

Chapter 52 of NFPA 1 provides high-level requirements for ESS but mostly refers to NFPA 855, Standard for the Installation of Stationary Energy Storage Systems. The 855 Standard is effectively elevated to code status since its provisions are mandated by NFPA 1. With a similar scope to NFPA 1, the IFC includes ESS-related content in Section 1207 that is largely harmonized with NFPA 855.

Some key areas of difference between IFC Section 1207 and NFPA 855 include the following:

- The IFC does not include the provision in 4.4.1 (5) of NFPA 855, where an AHJ can require an HMA for 'existing lithium-ion ESS systems that are not UL 9540 listed', effectively making some requirements retroactive.
- NFPA 855 grants extensive exceptions to lead-acid and Ni-Cd standby batteries. In the IFC, those exceptions are only available to batteries installed in facilities under the exclusive control of communications utilities and operating at less than 60 VDC.

11 U.S. Energy Storage Monitor, Q1 2023 full report and 2022 Year in Review, Wood Mackenzie Power & Renewables/American Clean Power Association, https://www.woodmac.com/industry/power-and-renewables/us-energy-storage-monitor/.

An important requirement in NFPA 855 (also in the IFC) is for explosion control. Li ion batteries are exempted from the requirements for exhaust ventilation under normal operation but are required to provide either explosion prevention in accordance with NFPA 69, Standard on Explosion Prevention Systems, or deflagration venting in accordance with NFPA 68, Standard on Explosion Protection by Deflagration Venting. This either/or approach seems to conflict with the ventilation provisions in the NEC (see Section 3.2) and is discussed in more detail in Section 4.6.

3.4 Qualification Standards for Battery ESS

U.S. fire and electrical codes require that energy storage systems be listed, meaning the product must be tested by a Nationally Recognized Testing Laboratory (a private-sector organization recognized by the Occupational Safety and Health Administration) and certified to meet consensus-based test standards. For ESS, the standard is UL 9540, Standard for Energy Storage Systems and Equipment.

UL 9540 covers the complete ESS, including battery system, power conversion system (PCS), and energy storage management system (ESMS). Each of these components must be qualified to its own standard:

- UL 1973, Standard for Batteries for Use in Stationary and Motive Auxiliary Power Applications. In addition, the BMS is qualified to UL 991, Standard for Tests for Safety-Related Controls Employing Solid-State Devices, and UL 1998, Standard for Software in Programmable Components. BMS design and construction is covered by CSA/ANSI C22.2 No. 340:23, Battery Management Systems.
- UL 1741, Standard for Inverters, Converters, Controllers and Interconnection System Equipment for Use with Distributed Energy Resources.
- As with the BMS, the ESMS is qualified to UL 991 and UL 1998.

UL Solutions certifies BESS equipment under two product categories:

- FTBW, referring to complete ESS and equipment
- FTBL, referring to energy storage equipment DC subassemblies.

Note that an FTBL listing would most likely not be considered sufficient certification, as the complete ESS would not be UL certified.

While the focus of this document is on North American standards, there are several international standards with similar scopes. The following is a partial listing of applicable IEC standards:

- IEC 63056, Secondary cells and batteries containing alkaline or other non-acid electrolytes – Safety requirements for secondary lithium cells and batteries for use in electrical energy storage systems.
- IEC 62485-5, Safety requirements for secondary batteries and battery installations – Part 5: Safe operation of stationary lithium ion batteries.
- IEC 62933-5-2, Electrical energy storage (EES) systems – Part 5-2: Safety requirements for grid-integrated EES systems – Electrochemical-based systems.
- IEC 62281, Safety of primary and secondary lithium cells and batteries during transport.

3.5 Fire and Explosion Testing

Fire and explosion testing to UL 9540A is mandated by the fire codes. UL 9540A is a test method with no stated pass/fail criteria, so it is not a qualification standard. However, favorable test results under this standard are important for securing approval by the authority having jurisdiction (AHJ) for the proposed ESS layout (see Section 4.2).

3.6 Personnel Safety

Most requirements for personnel electrical safety are covered in NFPA 70E, Standard for Electrical Safety in the Workplace, while installations under the exclusive control of an electric utility are largely covered by IEEE C2, National Electrical Safety Code (NESC). In the area of shock hazards, NEC Article 706.15 requires battery circuits exceeding 240 V to have provisions for disconnection into segments not exceeding 240 V DC nominal for maintenance purposes, while NFPA 70E Article 320.3 requires personal protective equipment (PPE) for batteries or segments over 100 V DC. Provisions to meet segmentation requirements include interlocks that open contactors when enclosure doors are opened, segmentation with multipole disconnects, and insulation of current-carrying components. NFPA 70E Article 130.4 also requires a shock risk assessment to be performed.

There is growing understanding regarding DC arc-flash hazards. NFPA 70E Article 130.5 requires an arc-flash risk assessment to be performed. Historically, arc flash as a concept first appeared in NFPA 70E in 1995, and in 2002

IEEE Std 1584, IEEE Guide for Performing Arc-Flash Hazard Calculations[12] was first published. However, all content at that time was focused on AC arc flash, and it was not until 2007 that a study of DC arc-flash testing was published.[13] This and other contemporaneous work formed the basis of a DC arc-flash calculation method in Annex D of the 2012 edition of NFPA 70E, and that method is mostly unchanged in the 2021 edition. More recent studies have shed new light on the dynamic behavior of DC arcs, indicating that current guidance is dated, and that arc interruption occurs earlier than predicted.[14] This new understanding will inform a revised calculation method and an increase in the threshold voltage to 150 V in the next revision of NFPA 70E, expected later in 2023.

NFPA 70E also includes a useful flow chart in Annex F.7 addressing multiple battery hazards and their requirements for PPE.

3.7 Transportation

Regulation of the transportation of Li ion batteries has also changed in response to incidents, such as the 2010 crash of a UPS Boeing 747 aircraft caused by a fire involving lithium batteries that were not declared as hazardous materials.[15] Such incidents have resulted in progressively more stringent limitations, including banning of transportation of these batteries on passenger aircraft. The latest regulations are described in the DOT publication, 'Lithium Battery Guide for Shippers, A Compliance Tool for All Modes of Transportation, Revised June 2023.'[16] Additionally, transportation of decommissioned batteries is discussed in Section 5.2.

3.8 Environmental Standards

Li ion cells are hermetically sealed, with no emissions in normal operation. As such, environmental standards relating to air pollution or water contamination do not apply. Using water to suppress battery fires, applied either automatically with sprinklers or manually by firefighters, can result in contaminated runoff[17] that may require remediation. Such problems are avoided with the 'let-it-burn' philosophy (see Section 4.7).

3.9 Evolution of Codes and Standards

Codes and standards will continue to evolve in response to lessons learned in the field. The model codes are on a three-year update cycle, with new revisions of the fire codes due in 2024 and the NEC in 2026. NFPA standards are revised and updated every three to five years. In the case of NFPA 855, the process to generate the revision for the 2026 version is already underway, with 19 task groups addressing different areas, including topics such as toxic emissions, fire protection, and explosion issues. Among other revisions, it is expected that explosion control that relies solely on deflagration venting will no longer be permitted. Furthermore, there is a proposal to prohibit the use of clean agent or aerosol fire suppression systems unless fire and explosion testing can demonstrate that use of such systems does not present a deflagration hazard. See Sections 4.6 and 4.7 for additional discussion on these topics. Note that submission of a recommendation by a task group does not guarantee that a proposed change will be adopted in the next revision. However, it will spur discussion among experts in the field on the appropriateness and robustness of the suggestion and potential outstanding knowledge gaps.

As discussed in Section 3.6, the recent studies and new understanding related to dc arc-flash hazards are expected to result in a new calculation method in the 2024 revision to NFPA 70E. It is also expected that systems operating below 150 V will be exempted from requirements for Arc Flash PPE (versus 100 V in the 2021 edition).

UL standards are revised on an as-needed basis. Some standards are stable and not in need of regular revision; for example, UL 991 for safety-related controls was last revised in 2004. Other standards may be updated rapidly, with UL 9540A being a good example. That document was first published in November 2017, with revisions published in January 2018, June 2018, and November 2019. The revision process for UL 9540A is again underway, with preliminary review of some 36 proposed changes completed in January 2023.

12 IEEE Std 1584, IEEE Guide for Performing Arc-Flash Hazard Calculations, https://standards.ieee.org/.

13 C. Keyes and C. Maurice, "DC Arc Hazard Assessment Phase II," Kinectrics, Toronto, ON, Canada, Rep. K012623-RA-0001-R00, Jul. 7, 2007.

14 L. Gordon, "Modeling DC Arc Physics and Applications for DC Arc Flash Risk Assessment," IEEE Industry Applications Society Electrical Safety Workshop 2023, https://electricalsafetyworkshop.com/.

15 United Parcel Service Flight 6, N571UP, Federal Aviation Administration Lessons Learned, https://www.faa.gov/lessons_learned/transport_airplane/accidents/N571UP.

16 https://www.phmsa.dot.gov/sites/phmsa.dot.gov/files/2023-07/Lithium%20Battery%20Guide.pdf.

17 Quant, M., Willstrand, O., Mallin, T., Hynynen, J., Ecotoxicity Evaluation of Fire-Extinguishing Water from Large-Scale Battery and Battery Electric Vehicle Fire Tests. Environ. Sci. Technol. https://doi.org/10.1021/acs.est.2c08581.

One likely change to UL 9540A is to force ignition of vent gases. There is inconsistency as to whether ignition occurs during testing, and there have been instances when a system completed UL 9540A testing without ignition but was involved in a fire in an installation. Forcing ignition will give a better understanding of the fire propagation hazard for a battery design.

With the recent publication of CSA/ANSI C22.2 No. 340:23, Battery Management Systems, referenced in Section 3.4, it seems likely that the next revision to UL 1973 will include this new BMS standard as a normative reference.

4 STANDARDS-DRIVEN ESS DESIGN AND INSTALLATION

4.1 Overview

Figure 3 indicates compliance requirements for a typical ESS project. Fire codes require that the ESS be listed to UL 9540, which in turn requires that the subsystems be qualified to their relevant standards as indicated in Section 3.4. Most battery systems are also required to undergo fire and explosion testing to UL 9540A as described in Section 3.5. The overall installation is governed by the electrical and fire codes as discussed in Sections 3.2 and 3.3, respectively, and interconnection requirements are set by IEEE Std 1547 at the distribution level or IEEE Std 2800 for transmission-connected facilities.

When referring to fire codes, this section focuses on the requirements of NFPA 855. As discussed in Section 3.3, the ESS-related content of the IFC is largely harmonized with NFPA 855.

4.2 Waivers Approved by the AHJ

Certain requirements of NFPA 855 may be waived based on evaluation of results from a hazard mitigation analysis (HMA) and on fire and explosion testing to UL 9540A or equivalent, subject to approval by the AHJ. The HMA includes a failure modes and effects analysis (FMEA) and is a requirement of product listing. An AHJ can also require an HMA for an existing installation that is not listed to UL 9540 and can require safety modifications (retrofits) to be made. Some specific requirements that may be waived include:

- Maximum stored energy (see Section 4.4)
- Size and separation of ESS groups (see Section 4.4)
- Fire control and suppression systems for remote installations (see Section 4.7)
- Permanent source of water for firefighting (see Section 4.7)

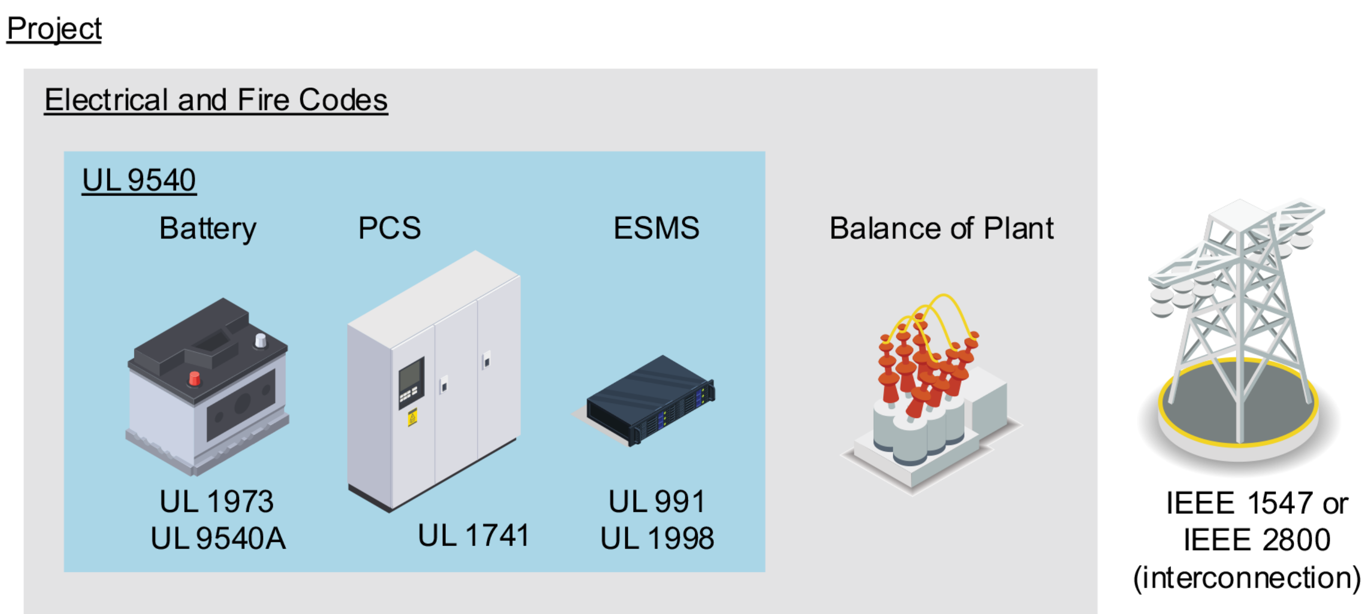

Figure 3. *Codes and standards compliance for a typical ESS project*

4.3 Location

NFPA 855 classifies ESS locations as follows:

- Indoor, ESS dedicated-use building
- Indoor, Non-dedicated-use building
- Outdoor, 100 ft. or less from exposures
- Outdoor (remote), more than 100 ft. from exposures

There are some additional outdoor classifications, including rooftops, parking garages, and mobile installations, which are not discussed in this document.

Regulation of these facilities is the least stringent for outdoor remote installations and for dedicated-use buildings located more than 100 ft from exposures, and the most stringent for non-dedicated-use indoor installations.

4.4 Size and Separation

NFPA 855 includes limits for maximum stored energy, energy per group, and separation between groups. For Li ion batteries, the maximum energy is 600 kWh and groups are limited to 50 kWh. Groups are required to be separated by 3 ft. from each other and from walls (except from walls of outdoor units). These limitations may be exceeded subject to AHJ approval (see Section 4.2). Remote outdoor units or dedicated-use buildings that are more than 100 ft. from exposures are not subject to these limitations.

4.5 Smoke, Fire, and Gas Detection

NFPA 855 requires ESS to be equipped with a smoke detection or radiant energy-sensing system. Additional guidance is provided in informative Annex G, where speed of sensing is emphasized, due to the short time in which Li ion safety events can develop. Early detection of an incident can be accomplished by detecting vent gases, including carbon monoxide, carbon dioxide, hydrogen, and flammable hydrocarbons.

Where gas detection is used to activate a combustible gas concentration reduction system (for compliance with NFPA 69 as discussed in Section 4.6), the detectors must be securely powered in standby mode for a minimum of 24 hours, followed by 2 hours in alarm.

4.6 Explosion Control

Explosions represent the greatest danger to first responders in an ESS incident. As was stated in Section 3.3, NFPA 855 requires either explosion prevention (NFPA 69) or deflagration venting (NFPA 68). There is increasing consensus that designs relying only on deflagration venting can present a serious risk to personnel. If multiple cells vent without flame, gas levels within the enclosure can accumulate above the UFL, where no combustion is possible. This condition can remain completely stable until firefighters open a door, when oxygen from the outside air will mix with the vent gas and an explosion could occur.

System designers are increasingly implementing explosion-prevention strategies. In many cases, ventilation panels are opened automatically when vent gas is detected, and fans are actuated to draw in outside air to achieve rapid dilution of the gas mixture. Such designs are not without challenges since panel opening must be fail-safe and fans must be securely powered for at least two hours. Furthermore, with the trend to large LFP cells (280 ampere-hours is now a standard size, and some are producing larger cells), and the trend to energy-dense enclosure designs, the volume of flammable gases relative to the free air volume in the enclosure may make it impossible to meet the requirement of NFPA 69 to maintain combustible concentration at or below 25% of the lower flammability limit (LFL) (or at or below 60% of the LFL where continuously monitored and controlled with safety interlocks).

While the vent gas from all Li ion cells contains a substantial amount of hydrogen, the mixture of different flammable constituents and the diluting effect of carbon dioxide raises the LFL above that of hydrogen alone. One study[18] estimates the LFL of vent gas from NMC cells to be between 7.6% and 9.0%, and from LFP cells to be between 8.6% and 10.0%. Sturk *et al* [19] provided a figure for total gas volume from LFP cells of 42 L/kg, so a 280 Ah cell weighing approximately 5.4 kg might produce 227 L of vented gas. For the lower end of the estimated LFL range, 25% of the LFL

18 A. Baird, E. Archibald, K. Marr, O. Ezekoye, "Explosion hazards from lithium-ion battery vent gas," *Journal of Power Sources*, Volume 446, 2020, 227257, ISSN 0378-7753, https://doi.org/10.1016/j.jpowsour.2019.227257.

19 D. Sturk, L. Rosell, P. Blomqvist, A. Ahlberg Tidblad, "Analysis of Li ion Battery Gases Vented in an Inert Atmosphere Thermal Test Chamber," *Batteries* 2019, 5(3), 61; https://doi.org/10.3390/batteries5030061.

is 2.2%, so assuming perfect mixing, the free air volume would have to be greater than about 10,500 L to comply with NFPA 69. Of course, the air volume around the gas plume from the cell would exceed the LFL, but NFPA 69 does not consider such dynamic effects.

If compliance with NFPA 69 is not possible and an NFPA 68-only solution is too risky, an acceptable compromise would be a combination approach, with ventilation panels opening to allow vent gases to be exhausted, plus deflagration panels for additional protection in case an explosion occurs before the gas has sufficiently dissipated. While gas exhaust can be accomplished more quickly with fans, the combination approach may not require secure powering, thus simplifying the design. This hybrid approach is allowable under fire codes and has been adopted in some recent ESS designs. The deflagration panels would meet the NFPA 68 alternative, thus complying with the letter of the code, while the ventilation will (eventually) provide explosion prevention for better firefighter safety.

At least one ESS integrator has adopted an approach in which a sparking device is used to ignite vent gases before they can reach an explosive level. This can be an effective strategy if oxygen supply is sufficient to support ongoing combustion. Combustion initiated by the sparking device necessarily means that the gas concentration has exceeded the LFL, so this device must be implemented as part of a hybrid approach, either with a ventilation system that would meet NFPA 69 in most circumstances, or deflagration venting in accordance with NFPA 68.

Ventilation and deflagration panels should be located on the roof of the battery enclosure and should direct flames away from personnel standing in front of the unit. Where ventilation panels must be mounted on the sides of enclosure, they should be as high as possible and fitted with deflectors to protect nearby personnel.

4.7 Firefighting Philosophy

NFPA 855 mandates fire control and suppression for 'buildings' and 'outdoor walk-in units.' The requirement appears not to apply to outdoor enclosures that cannot be entered, but such units are not explicitly exempted. There is a provision for fire suppression systems (FSS) to be omitted from ESS in remote locations, subject to approval by the AHJ, but again, there is no explicit statement regarding non-walk-in battery enclosures. It is expected that this ambiguity will be resolved in the next revision of NFPA 855, expected for release in 2026.

In the early days of Li ion deployments, all ESS Li ion battery systems were equipped with FSS. Over the years, it became more widely recognized that extinguishing a fire without being certain to stop ongoing exothermic reactions and potential propagation could create an explosion risk. The risk of ongoing reactions can be seen in the numerous incidents with EVs, where firefighters use tens of thousands of gallons of water to extinguish a fire, only to have it reignite hours, days, or even weeks later.

This realization has driven a new 'let it burn' philosophy, in which an ESS battery fire is allowed to burn out in a controlled manner while protecting adjacent exposures. This philosophy has several advantages:

- Issues with stranded energy and reignition are avoided.
- Flammable gases are consumed as they are released, eliminating the risk of explosion.
- By not using firefighting water on the fire itself, contaminated run-off is avoided.

However, allowing BESS fires to burn out results in a combustion plume that will travel downwind until it disperses. This may result in temporary shelter-in-place or evacuation advisories for the local community. While laboratory testing identifies toxic compounds that are released by burning Li ion batteries, these may be consumed internally, combusted, or may react to form other non-toxic compounds before being released to the environment. In recent events where batteries have burned in this fashion, fire services have announced that nearby air-quality monitoring has shown the air quality to be at safe levels.

Consuming flammable gases requires a supply of oxygen, so this approach is compatible with the ventilation strategy for explosion control described in Section 4.6. Adoption of this firefighting philosophy has spurred a move to smaller, modular enclosures that can be shipped fully assembled, which minimizes installation costs and allows fire losses to be reduced. An important aspect of the design of these systems is substantial insulation that allows enclosures to be closely spaced while preventing propagation of fire between units.

As discussed in Section 3.7, there is a proposal to modify NFPA 855 to prohibit the use of clean agent or aerosol fire suppression systems unless UL 9540A testing can demonstrate that use of such systems does not present a deflagration hazard. This proposal, if adopted, is consistent with the 'let it burn' strategy.

Another NFPA 855 requirement, which may be waived by the AHJ for remote locations, is for a permanent source of water for fire protection. Under the 'let it burn' strategy, water would be used only for defensive measures to protect nearby exposures.

4.8 Pre-Incident Planning

NFPA 855 requires an emergency operation plan to be established, also frequently referred to as an emergency response plan (ERP). There are several requirements for the ERP, including safe shutdown and isolation of equipment, procedures to be followed in case of fire or explosion, and contact information for subject matter experts. An important aspect is the ability of first responders to access BMS data, either directly or through a network operations center, so that battery temperature in units adjacent to a fire can be monitored for possible defensive operations.

Another NFPA 855 requirement is for initial and annual refresher training for facility staff and first responders. It is important to include local firefighters in this training, since they must be comfortable with firefighting procedures, particularly the 'let it burn' strategy. Training firefighters on site has the added advantage of making them familiar with site access and equipment layout, allowing them to respond more efficiently to an incident.

5 DECOMMISSIONING

This section considers the relevant codes and standards and safety considerations for ESS decommissioning. Recycling and/or disposal are beyond the scope of this document.

5.1 Decommissioning Plan

Both the IFC and NFPA 1 require a written decommissioning plan to be prepared and submitted to the AHJ as part of the commissioning plan. Section 1207.2.1 of the IFC requires the plan to include 'contingencies for removing an intact operational energy storage system from service, *and for removing an energy storage system from service that has been damaged by a fire or other event'* (emphasis added). This planning for removal of a damaged ESS unit, with updates as needed to accommodate new technologies and techniques for handling and recycling, would be a prudent addition to the decommissioning plan for a facility in any jurisdiction.

5.2 Transportation Considerations

Under the Environmental Protection Agency's Standards for Universal Waste Management (40 CFR part 273), end-of-life batteries are subject to the same level of regulation as other hazardous wastes, and must meet the Department of Transportation's regulations for hazardous material packaging and transportation. Enclosures that were shipped factory-assembled are already certified for transport, subject to any special preparation advised by the manufacturer. ESS units in larger containers or other systems that were assembled on site would have to be disassembled, with cell modules transported in approved packaging. Damaged, defective, or recalled modules do not meet the hazardous waste exemptions of 40 CFR part 273, so additional reporting requirements may apply.[20] Packaging and transport requirements for these modules are also more extensive than for undamaged modules. Packaging may be subject to DOT Special Permit requirements, and damaged modules are strictly prohibited for transportation by aircraft.[21]

5.3 Decommissioning Safety

The decommissioning plan should address all aspects of safety, including preparation for shipment and considerations for personnel and environmental safety. The battery system should generally be discharged to 30% state of charge (SOC) or below. This provides for safer transportation, and a SOC above 30% triggers more stringent requirements for storage under NFPA 855. A consideration for the depth of discharge is whether the battery is destined for possible reapplication or recycling. A battery intended for reapplication should be shipped as close to 30% SOC as possible to allow for longer storage periods, while one that will be recycled can be discharged to lower (and safer) levels.

20 EPA Guidance on Lithium Battery Recycling. May 24, 2023. https://rcrapublic.epa.gov/files/14957.pdf.

21 Lithium Battery Guide for Shippers. U.S. Department of Transportation. Updated July 6, 2023. https://www.phmsa.dot.gov/training/hazmat/lithium-battery-guide-shippers.

Provisions should be made for powering safety subsystems, such as heat, smoke, and gas monitoring, while the decommissioning work is in progress. Since activities may involve work on battery terminals, procedures should outline steps for disconnecting and sectionalizing the battery to minimize arc flash and shock hazards.

6 ASSESSING THE HAZARDS AND SAFETY MANAGEMENT OF NEW TECHNOLOGIES

6.1 Evaluating Emerging Technologies

As the ESS market expands and the demand for long-duration energy storage grows, it is inevitable that new battery technologies and other non-battery systems will be offered, often with rosy predictions for low cost, improved safety, or other characteristics. It is important for prospective users of these systems to understand their aging mechanisms and failure modes so that possible hazards and appropriate safety management can be assessed. A framework for this assessment is provided by IEEE Std 1679, IEEE Recommended Practice for the Characterization and Evaluation of Energy Storage Technologies in Stationary Applications. Additional guidance is provided for certain classes of battery systems in a series of subsidiary documents. Published guides are for lithium-based batteries (IEEE Std 1679.1), sodium-beta batteries (IEEE Std 1679.2), and projects are underway for flow batteries (P1679.3) and alkaline and zinc-based technologies (P1679.4).

There is a framework for covering new technologies in existing codes and standards. UL qualification standards are intended to be as generic as possible, and listing requires an FMEA to be performed and HMA to be submitted. That said, the FMEA can only be as thorough as the developer's understanding of the technology's aging mechanisms and failure modes. To the extent that those failure modes are different from those of Li ion or other existing battery types, new test methods may be needed to assess a system design's tolerance to those failures. EPRI is actively involved in this process through its Energy Storage Integration Council (ESIC), an industry-wide collaborative. Members of ESIC's Safety Task Force have developed the *ESIC Energy Storage Reference Fire Hazard Mitigation Analysis*,[22] based on Li ion batteries, using the 'bowtie' approach. ESIC participants are currently developing a generic flow-battery HMA.

An example of this issue can be seen with valve-regulated lead-acid (VRLA) batteries. VRLA products can experience their own form of thermal runaway (now sometimes called thermal walkaway, to distinguish it from the more severe version with Li ion), in which toxic hydrogen sulfide gas can be released. Two factors differentiate VRLA thermal runaway from Li ion: first, the heat released is derived from the charger, and the event can be stopped by attenuating the charger output; and second, VRLA batteries become more susceptible to thermal runaway as they age. If VRLA products were to be introduced as a new technology today, testing to UL standards would not address this failure mode, since the batteries are not aged before testing, nor are they connected to a charger during thermal runaway testing.

Another example is Sodium ion (Na-ion). The technology is expected to be widely deployed in the ESS market. News articles have been enthusiastic about the safety of Na-ion,[23] going as far as to refer to them as nonflammable.[24] It is important to understand that the term 'Na-ion' covers a wide range of electrochemistries,[25] as does Li ion. Most emerging products have hard carbon anodes, while there are numerous materials used for cathodes. Many designs have electrolytes based on mixtures of organic carbonates, which have similar flammability characteristics to Li ion electrolytes. The reference to Na-ion batteries being non-flammable is based on use of ionic liquids, which have lower ionic conductivity than conventional organic electrolytes and may not be suitable for all applications. As with Li ion chemistry, Na-ion cells with organic electrolytes form a solid-electrolyte interphase (SEI) on the surface of the hard carbon anode, and its breakdown can trigger thermal runaway. Indeed, the SEI in Na-ion cells becomes unstable at a lower temperature than its Li ion counterpart, although the rate of heat release is much lower.[26] From the above information, the situation

22 *ESIC Energy Storage Reference Fire Hazard Mitigation Analysis.* EPRI, Palo Alto, CA: 2021. 3002023089.

23 M. Sawicki, L. Shaw, "Advances and challenges of sodium ion batteries as post lithium ion batteries," RSC Adv., 2015,5, 53129-53154, https://doi.org/10.1039/C5RA08321D.

24 Tech Brew, Sodium-based batteries could solve the lithium crunch.

25 Q. Abbas, M. Mirzaeian, & M. Hunt, (2020). "Materials for sodium-ion batteries." In Reference Module in Materials Science and Materials Engineering Elsevier B.V., https://doi.org/10.1016/B978-0-12-803581-8.12115-0.

26 D. Velumani and A. Bansal, "Thermal Behavior of Lithium- and Sodium-Ion Batteries: A Review on Heat Generation, Battery Degradation, Thermal Runway − Perspective and Future Directions," Energy Fuels 2022, 36, 14000−14029.

with emerging Na-ion products is much more complex than sweeping generalizations in news articles would indicate. Following the approach of IEEE Std 1679, details on aging mechanisms, failure modes, and safety management should be requested from the manufacturer for the product in question. It should not be assumed that the safety of one Na-ion product is the same as another.

The failure modes of Na-ion batteries can be reasonably predicted by their similarity with Li ion technology, and thus existing qualification and fire-testing standards should be adequate to address the hazards of Na-ion battery failure. That said, other emerging battery technologies such as flow batteries may exhibit unique failure modes and resulting hazards that may not be fully addressed. Codes and standards organizations will have to remain vigilant and ready to update these documents as needed.

Revising qualification standards to reflect new failure modes and new test methods will likely not occur until some years after the first shipments of a new technology. At the time of preparing this paper, the US Department of Energy's Energy Storage Safety Strategic Plan is being revised, and the safety of new technologies is a major topic of discussion. It remains to be seen how this topic will be addressed moving forward.

7 REFERENCES

The following is a listing of the codes and standards referred to in this document:

CSA/ANSI C22.2 No. 340:23, Battery Management Systems

IEEE Std 1547, IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces

IEEE Std 1547.9, IEEE Guide for Using IEEE Std 1547 for Interconnection of Energy Storage Distributed Energy Resources with Electric Power Systems

IEEE Std 1679, IEEE Recommended Practice for the Characterization and Evaluation of Energy Storage Technologies in Stationary Applications

IEEE Std 2800, IEEE Standard for Interconnection and Interoperability of Inverter-Based Resources (IBRs) Interconnecting with Associated Transmission Electric Power Systems

IFC, International Fire Code

NFPA 1, Fire Code

NFPA 68, Standard on Explosion Protection by Deflagration Venting

NFPA 69, Standard on Explosion Prevention Systems

NFPA 70, National Electrical Code

NFPA 70E, Standard for Electrical Safety in the Workplace

NFPA 855, Standard for the Installation of Stationary Energy Storage Systems

UL 991, Standard for Tests for Safety-Related Controls Employing Solid-State Devices

UL 1973, Standard for Batteries for Use in Stationary and Motive Auxiliary Power Applications

UL 1998, Standard for Software in Programmable Components

UL 9540, Standard for Energy Storage Systems and Equipment

UL 9540A, Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems

8 ACRONYMS AND ABBREVIATIONS

The following is a list of acronyms and abbreviations used in this report:

AHJ	authority having jurisdiction
ANSI	American National Standards Institute
BESS	battery energy storage system
BMS	battery management system
CFR	Code of Federal Regulations
CSA	Canadian Standards Association
ERP	emergency response plan (emergency operations plan)
ESIC	Energy Storage Integration Council
ESMS	energy storage management system
ESS	energy storage system
EV	electric vehicle
FSS	fire suppression system

HMA	hazard mitigation analysis
IEEE	Institute of Electrical and Electronics Engineers
LEL	lower explosive limit
LFL	lower flammable limit
LFP	lithium iron phosphate (cathode material)
Li ion	lithium ion
Na-ion	sodium-ion
NCA	lithium nickel-cobalt-aluminum oxide (cathode material)
NEC	National Electrical Code (NFPA 70)
NESC	National Electrical Safety Code (IEEE C2)
NFPA	National Fire Protection Association
NMC	lithium nickel-manganese-cobalt oxide (cathode material)
PCS	power conversion system
PPE	personal protective equipment
SEI	solid-electrolyte interphase
SOC	state of charge
UFL	upper flammable limit
UL	Underwriters Laboratories
VRLA	valve-regulated lead-acid

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