WHITE PAPER

ADVANCING LI-ION BESS SAFETY: COMPREHENSIVE TESTING AND META-ANALYSIS FOR OPTIMIZED HAZARD MITIGATION

Limitations of UL9540A for Li-Ion BESS Hazard Analysis

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Abstract

In the last decade, the rapid proliferation of Lithium-Ion Battery Energy Storage Systems (Li-Ion BESS) has become a critical cornerstone in bridging the renewable energy supply-demand gap. However, the exponential deployment of these systems has amplified fire-related incidents, highlighting a critical need for robust fire protection design and comprehensive certification programs. This paper first provides a comprehensive assessment of the primary testing standard, UL 9540A, to determine its efficacy in predicting thermal runaway propagation events and mitigating fire hazards associated with Li-Ion BESS. Through a meta-analysis of multiple publicly available datasets and UL 9540A data, this paper details the current limitations of the UL 9540A certification program, particularly its lack of required full-scale fire testing, or testing of suppression systems or explosion control systems. The findings also indicate significant variability in heat release and vent gas measurements based on the specific failure modes and testing methodologies used. Similarly, it demonstrates that UL 9504A cell heat release data likely does not scale linearly to full-scale installation-level fires. The paper concludes with a call for more comprehensive testing protocols that consider repeatability, methodology, and scalability. The goal is to maintain progress in the development of a dynamic, evidence-based approach to fire safety in Li-Ion BESS, ensuring safe and scalable deployment of next-generation global renewable energy infrastructure.

Keywords

Lithium-ion Batteries, Energy Storage Systems, Safety Standards, Meta-Analysis, Hazard Mitigation Analysis, Renewable Energy Infrastructure.

Acronyms

Acronym	Full Form	Acronym	Full Form
AHJ	Authorities Having Jurisdiction	NCA	Nickel Cobalt Aluminum
BESS	Battery Energy Storage Systems	NMC	Nickel Manganese Cobalt
Comb	Combustion	PHRR	Peak Heat Release Rate
ConeCal	Cone Calorimeter	PHA	Process Hazard Analysis
CSBC	Copper Slug Battery Calorimetry	SBI	Single Burning Item
EE	Electrical Energy	SOC	State of Charge
EIA	Energy Information Administration	THR	Total Heat Released
FMEA	Failure Modes and Effects Analysis	Tewarson Cal	Tewarson Calorimeter
FM Global	Factory Mutual Global	UL	Underwriters Laboratories
GPM	Gallons Per Minute	UFL	Upper Flammability Limit
HMA	Hazard Mitigation Analysis		
HRR	Heat Release Rate		
ICC	International Code Council		
IFC	International Fire Code		
kWh	Kilowatt-Hour		
LFP	Lithium Iron Phosphate		
LCO	Lithium Cobalt Oxide		
LMO	Lithium Manganese Oxide		
Li-Ion	Lithium-Ion		
LOPA	Layers of Protection Analysis		
MIE	Minimum Ignition Energy		
MPE	Minimum Propagation Energy		
MWh	Megawatt-Hour		
NFPA	National Fire Protection Association		

Introduction

Battery energy storage systems (BESS) are electro-chemical systems that capture produced energy for future use. Driven by rapid increases in energy densities, deployment of these systems has grown exponentially as a means to bridge gaps between periods of renewable energy availability, to perform grid peak shaving (charging during low-demand periods and discharging during peak demand periods), and to provide emergency backup power **[1]**. In recent years, cost reductions driven by the development of electric vehicle manufacturing have propelled lithium-ion (Li-Ion) batteries to also become the dominant market share of utility-scale BESS installed globally. Novel innovations are expected to continue to drive market share through further progress toward cheaper and higher energy-density batteries **[2]**.

According to the United States Energy Information Administration (EIA), planned and currently operating utility-scale battery capacity totaled roughly 16 GW at the end of 2023 **[3]**. Developers plan to add another 15 GW in 2024 and then another 9 GW in 2025, bringing the total end-of-2025 projected capacity to 40 GW (**Figure 1**a). In line with these projections, Wood Makenzie's market outlooks confirm the growth trajectory of the energy storage sector, forecasting a rise in cumulative capacity to 63 GW by 2027 **[4]**, with the annual additions in both residential and grid-scale sectors contributing to the uptrend (**Figure 1**b**).** The increasing BESS deployments reaching a cumulative output of 224.8 GWh by 2027 underscores the critical need for enhanced safety measures in tandem with the sector growth. Unfortunately, fire and explosion risks are inherently created by chemical energy storage at these capacities. Li-ion battery failures are well documented to release significant quantities of both thermal energy and flammable gases. The hazard also scales with the capacity of the system.

Predictably, as the total deployed BESS capacity increased exponentially, the rate of BESS fire incidents increased in parallel **[5]**. If relative failure rates remain consistent, the fire protection industry can reasonably expect continued skepticism of this critical green technology by the media, policy-makers, and the general public.

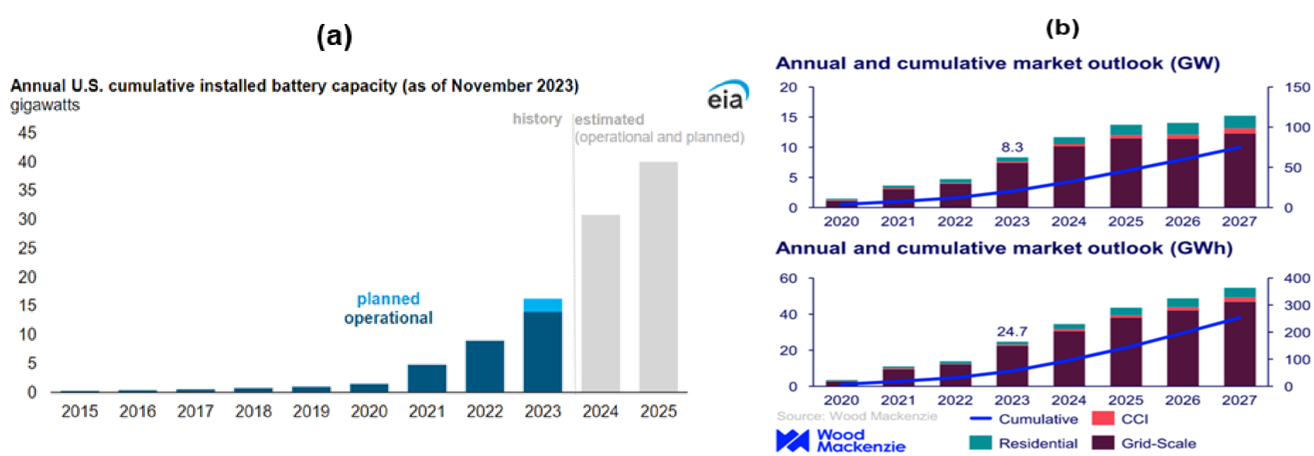

Figure 1: (a) U.S. Large Scale Battery Storage Installation Forecast. Data Source: U.S Energy Information Administration. (b) Projected Growth in Energy Storage Capacity and Output in 2020-2027.

Regulatory Landscape

Over the years, codes and standards have been developed in an attempt to keep pace with the emerging understanding of the hazards of Li-Ion BESS technology and new use cases. In 2006, the first set of specific requirements for the protection of Li-Ion BESS was included in the International Fire Code (IFC) by the International Code Council (ICC). The ICC and National Fire Protection Association (NFPA) codes remained largely unchanged on the topic for the 2012 and 2015 code cycles **[6]**. Developments of codes and standards related to Li-Ion BESS began to accelerate in the middle of the last decade as more loss events were documented.

In 2016, Underwriters Laboratories (UL) published the first edition of their standard UL 9540, “Standard for Energy Storage Systems and Equipment,” which details a comprehensive set of construction and design requirements for BESS to gain UL 9540 certification **[7]**. In the leadup to the 2018 code cycle, the ICC’s Fire Action Committee created an “Energy Storage Systems” work group that worked to create a new Chapter for the IFC, “Chapter 12: Energy Systems”, grouping the requirements for emergency power systems, solar photovoltaic power systems, stationary fuel cell powers systems, and electric energy storage systems. Maximum allowable energy quantities for Li-Ion BESS were set for the first time to 600 Kilowatt-Hour (kWh) and can only be exceeded if granted approval by the Authorities Having Jurisdiction (AHJ) based on Hazard Mitigation Analysis (HMA) and large-scale fire and fault condition testing.

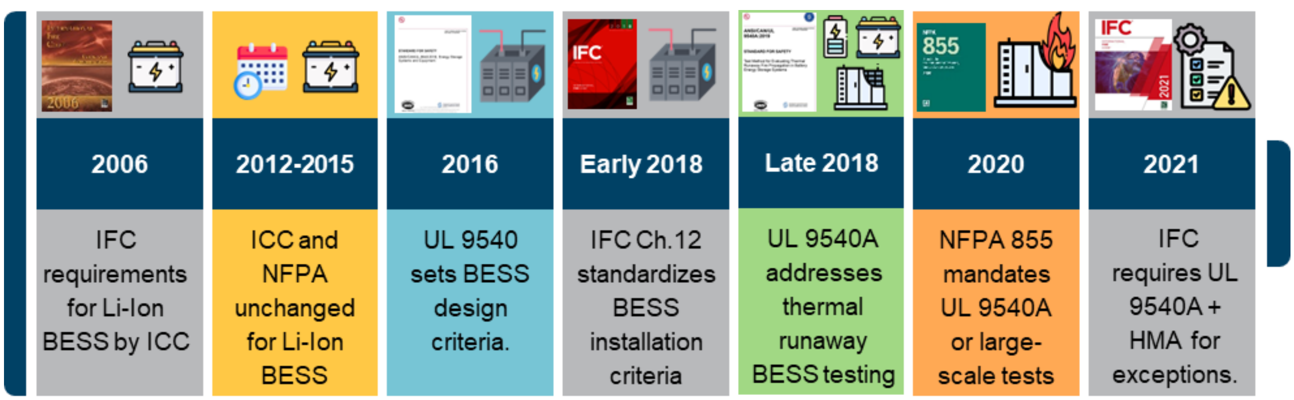

Figure 2: Timeline of Fire Safety Standards Development in Relation to BESS Incidents and Milestones.

In 2018, UL followed the introduction of UL 9540 with the first edition of UL 9540A titled “Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems.” UL 9540A serves as the industries’ primary testing framework for large-scale fire and fault condition testing and evaluating the potential risks of thermal runaway and fire propagation within Li-Ion BESS **[8]**. Developed to simulate thermal runaway scenarios under controlled conditions, it evaluates the behavior of cells, modules, units, and installations in escalating order. UL 9540A specifies the types of data that should be collected during testing, such as temperature profiles, gas emissions, and heat release rates, all of which are critical for understanding the dynamics of potential large-scale BESS fire events. A pass-fail criterion is also provided for UL 9540 certification.

In 2020, the National Fire Protection Association (NFPA) introduced NFPA 855, titled “Standard for the Installation of Stationary Energy Storage Systems”**[9].** This standard concerningly permits broad latitude for engineers and AHJs to waive or re-assess requirements for separation distances, suppression systems, and explosion control systems based solely on UL 9540A unit-level testing alone. Such a framework was subsequently also adopted by the IFC in 2021 **[10]**.

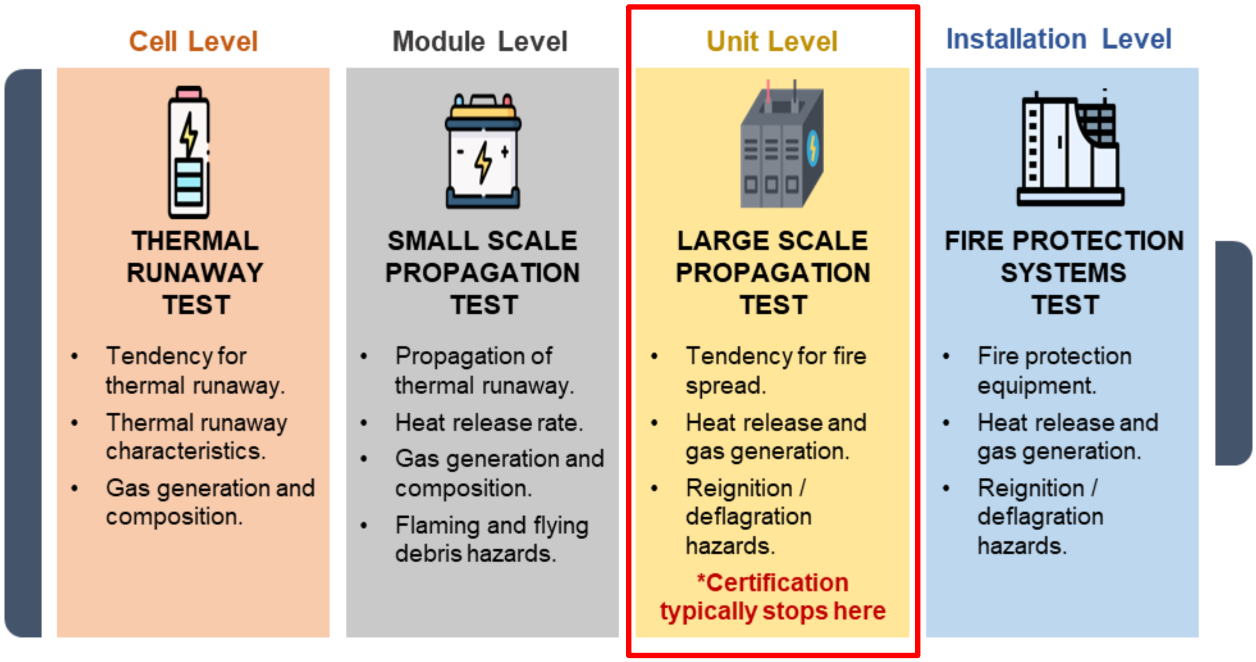

Figure 3: UL 9540A Testing Sequence for BESS Safety.

Based on the pass-fail criterion outlined in UL 9540A, a single successful unit-level propagation testing is sufficient for UL 9540 certification without the need for an installation-level test of fire protection and explosion control systems. Unit-level certification remains by far the most common approach to certifying Li-ion BESS systems. This concerningly implies that many novel fire suppression and explosion control systems have never been publicly tested or demonstrated for their use.

As highlighted in further sections of this research, propagation, heat release, and flammable gas data provided by UL 9540A are generally considered to have a high degree of uncertainty. This is primarily due to the lack of repeatability required by UL 9540A's testing methodology but also many other factors, including the subjectivity of certain test protocols, the uncertainty inherent in test instrumentation, and challenges in scaling cell-level testing to full-scale failure events.

Additional shortcomings are created by the direct equivocation of unit level testing with 'full-scale fire testing.' In the current framework, certification is granted upon a single demonstration of propagation resistance at the unit level. Notably, a lack of propagation inherently implies no full-scale fire has occurred. Although successful unit level testing lacks any demonstration or data collection of large-scale fire behavior, UL 9540A equivocates unit level testing with 'large-scale' fire testing in Section A2.4.1:

Unit-level testing corresponds with the <u>testing anticipated by fire codes</u> and energy storage system codes to evaluate the <u>large-scale fire and fault condition performance</u> of BESS units installed in a building, walk-in container, or similar structure.

Alternatively, the latter 'installation' level test, intended to collect holistic data regarding the performance of fire safety systems, including suppression and explosion control systems, is not required for certification (UL 9540A Section 10.1.1). In this manner, nearly all currently UL 9540-certified systems have chosen to demonstrate propagation resistance at the unit level instead of certification by successfully demonstrating fire suppression and explosion control systems at the installation level.

The combined effects of a lack of prescriptive design standards and a limited testing framework have led AHJs to continue to permit many gaseous suppression systems despite warnings of their limited effectiveness by FM Global since 2020 **[14]**. Similar observations can be made about the lack of separation distances enforced between large energy groupings even after a multi-Megawatt-Hour (MWh) scale propagation event in 2021**[15]**.

These engineering oversights and resulting loss events have increased the skepticism of this technology. For this reason, in 2024, applications for indoor Li-ion BESS are entertained by few Authorities-Having-Jurisdiction (AHJ). However, to meet the ambitious renewable energy goals of the next generation and the practical demands of the market, this technology will need to be deployed in increasing proximity to residential and commercial centers **[12]**. This paper demonstrates that more public large-scale fire research **[11]** and comprehensive test methodologies are urgently needed to confidently inform engineering analysis, gain the trust of the public, and develop clear prescriptive fire protection strategies that may enable the safe and scalable deployment of Li-Ion BESS technology.

Propagation Meta-Analysis of Li-Ion BESS Failures

Traditional fire and explosion risk analysis techniques were developed to assess and clearly communicate both the range of possible hazardous consequences as well as the expected frequency of those consequences. Such analyses most commonly employ risk matrices or event trees to illustrate these risks. Due to the complexity and potential consequences of Li-Ion BESS failures, relevant codes and standards require detailed hazard analyses. These advanced hazard analysis methods include Bowtie Analysis, Failure Modes and Effects Analysis (FMEA), Process Hazard Analysis (PHA), and Layers of Protection Analysis (LOPA). Despite requiring these detailed analyses, historical loss events have demonstrated that the laws of large numbers and complexity are outpacing the ability to design against failure completely.

Single-cell failures within large-scale BESS installations can be expected over the decade-long lifespan of a system and are typically manageable events. If a single cell failure releases enough energy to induce the failure of adjacent cells, the cascading thermal hazard known as propagation is created. Therefore, the likelihood of a cascading cell-to-cell propagation naturally serves as the most critical aspect to evaluate. The expected frequency of this event drastically affects the perceived fire and explosion risks.

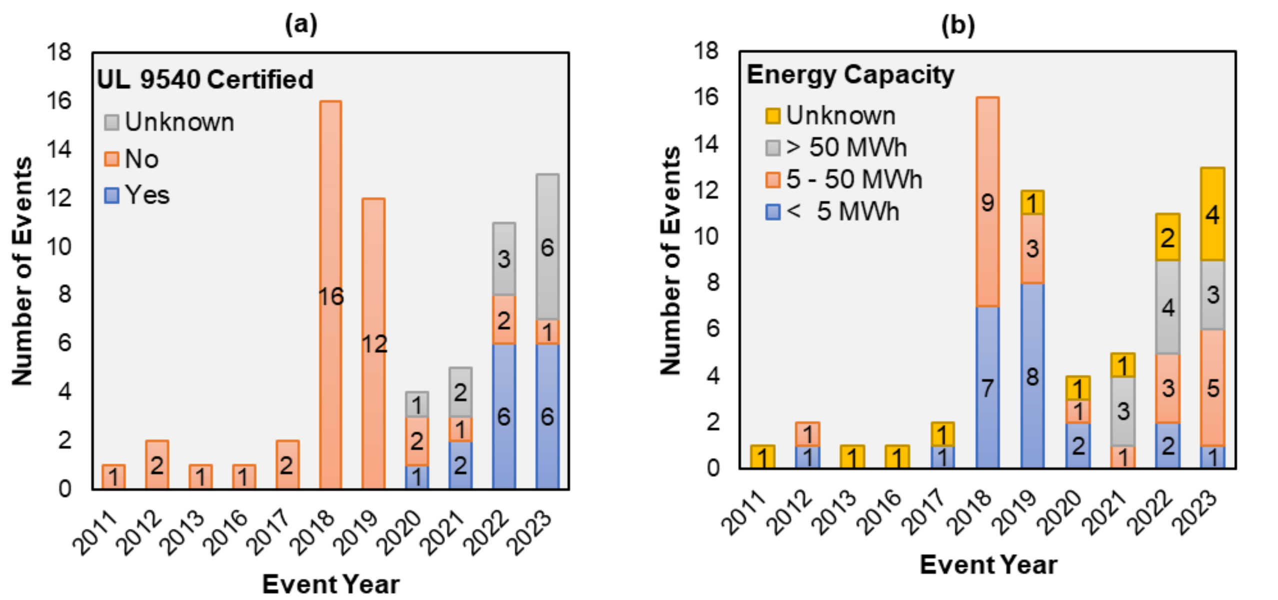

Figure 4: Annual Li-Ion BESS Failure Events (2011-2023) Categorized by **(a)** UL 9540 Listing Status and **(b)** Total Energy Capacity in kWh.

Cell-to-cell propagation in BESS can be caused by a wide variety of internal and external factors, including cell manufacturing defects, cell aging, water damage, coolant leakage, impact, human error, and electrical malfunctions.

BESS failures are understood to be under-reported within the utility sector. **Figure 4** presents an analysis of a limited dataset of publicly Li-Ion BESS documented failure events from 2011 to 2023 **[13]**, categorized by their UL 9540 listing status (**Figure 4**a) and their total energy capacity (**Figure 4**b). A significant peak in 2018 with 16 non-UL 9540 listed systems failures contrasts with an increasingly diversified profile in subsequent years. Notably, 2023 data indicate an equal prevalence of failures in both listed and non-listed systems, with a substantial portion categorized as unknown with publicly available data. This temporal analysis suggests that UL 9540 certification, while indicative of a higher safety standard, does not result in the complete elimination of hazards.

Similarly, the loss history presented in **Figure 4** reflects an understanding that the UL 9540A propagation testing does not completely bound worst-case failure scenarios. The persistence of failures across listed categories highlights the need for enhanced safety measures beyond singular UL 9540A propagation demonstrations.

When interpreting UL 9540A propagation test results, it is important to recognize that the protocols give discretion to the test lab to decide the location within a unit to initiate thermal runaway. Large subjectivity is also inherent in determining how long to apply external heat sources and how many cells to force into failure for a sufficient propagation test. An in-depth meta-analysis of the data in **Figure 5** reveals consistent discrepancies between the Li-Ion BESS module and unit-level thermal runaway propagation in UL 9540A tests, yet these discrepancies could not easily be attributed to any notable variation in safety features.

Both module-level (**Figure 5**a) and unit-level (**Figure 5**b) tests typically incorporated comparable safety protocols designed to mitigate the risks of thermal runaway. Differences in propagation behavior appear to be most attributable to the location and severity of the induced failure modes. For instance, **Figure 5**a shows multiple Test IDs where the number of cells forced to fail during module-level propagation was notably less severe compared to the unit level, suggesting possible variations in the intensity of external heating or other failure methods.

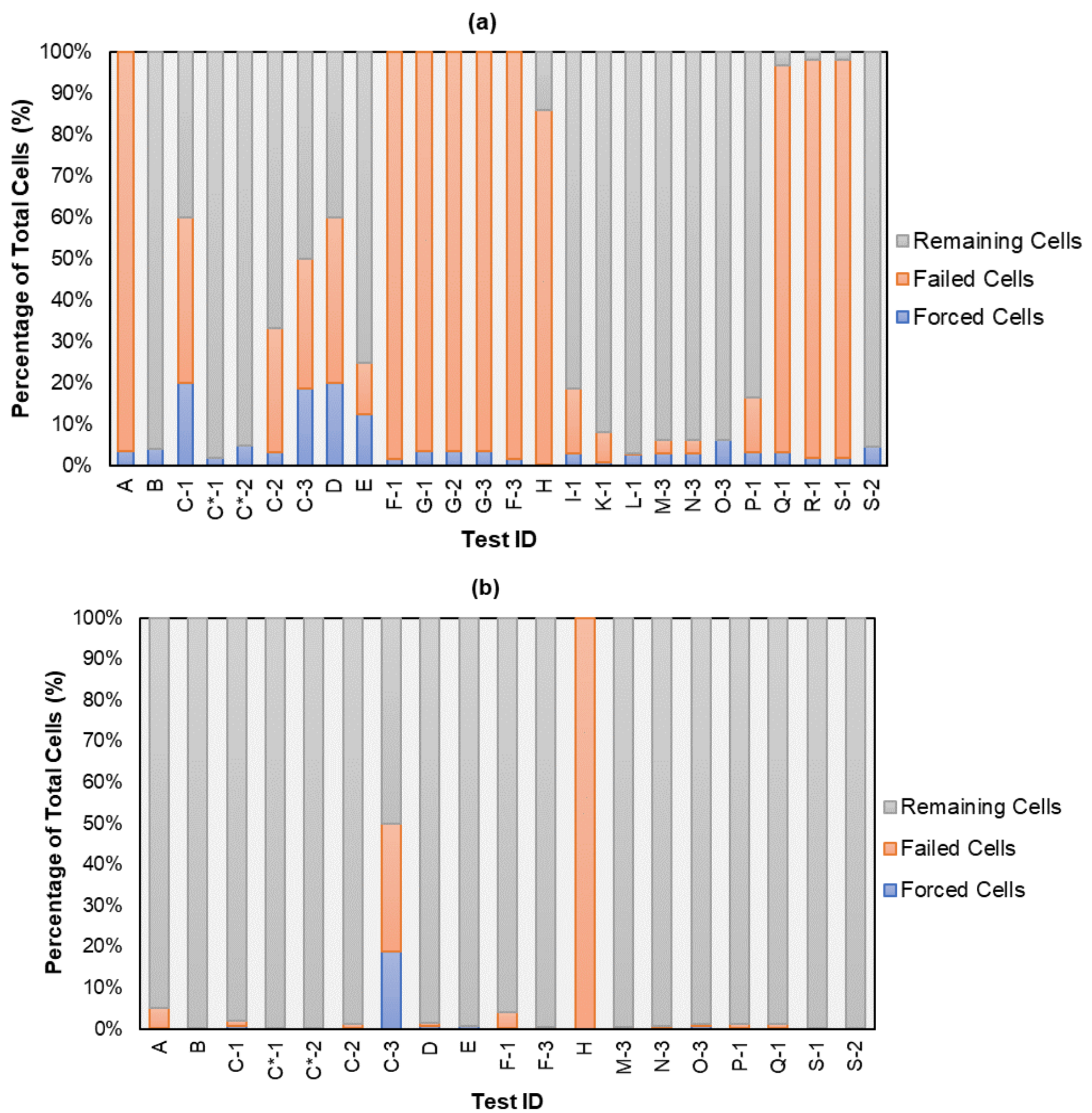

Figure 5: Thermal Runaway Propagation in UL 9540A Tests **(a)** Module Level Tests and **(b)** Unit Level Tests. Test ID refers to a specific model of module or unit subjected to the test.

Due to the documented loss history and a reliance on singular propagation tests, UL 9540A testing alone will likely be insufficient to gain the full confidence of all stakeholders. This can be expected to be especially true for indoor installations or those in proximity to highly occupied environments. Due to the highly hazardous consequence of a fully propagating thermal runaway event, it is the recommendation of this research for risk assessments and hazard analyses to typically assume a full-scale propagating failure as plausible over the decades long lifespan of these systems.

Notably, the inclusion of this simple assumption also eliminates the necessity for many of the complex and lengthy risk assessment models that are currently standard practice in the industry. This assumption additionally provides a clear basis of design for fire protection engineers for evaluating proposed BESS installations. As an alternative, voluntary robust testing could be considered to supplement gaps in the current UL 9540A testing framework for those Original Equipment Manufacturers (OEMs) that hold a high degree of confidence in their inherent cell-to-cell propagation resistance.

Cell Calorimetry Meta-Analysis and Fire Hazard Scalability

Often overlooked in the conceptual design phase is the high safety performance criteria set forth by the building codes for the battery Hazard Mitigation Analysis. National and international codes require risk assessments to consider the potential for failure of active fire protection systems **[3][8]**. While such a standard of care may seem impractical, failure rates of active fire protection systems are well-documented, with multiple failures having been documented already within the Li-Ion BESS loss history [1]. Additionally, recent studies have shown that up to 26% of installed BESS fire suppression and detection systems had significant quality issues when professionally inspected **[24]**.

In 2018, FM Global and NFPA released their first and only study regarding the potential fire sizes of Li-ion ESS failures as well as the efficacy of sprinkler protection **[16]**. The research conducted two full-scale unit-level free burns and found that a single 125-kWh unit could produce approximately a 10-MW fire. It also found that a sprinkler density of 0.3 gallons per minute per square foot (gpm/sqft) was not able to extinguish the fire, nor would it be expected to stop propagation to adjacent units within 3 feet.

On the back of this research, in 2018, the Suppression, Detection, and Signaling Research and Applications Conference (SUPDET) posed a design challenge to protect a 1.6-MWh indoor Li-ion battery installation to the industry's leading experts **[17]**. The results included predictions of a peak heat release rate of 36-MW fire and recommendations for advanced water-based suppression approaches. Despite the inconclusive research and a lack of a common basis of design, little additional full-scale fire testing or suppression research has been published by the fire protection community since that time.

This fire meta-analysis methodology presented herein involved a systematic review of cell calorimetry test reports, datasets, and relevant literature on Peak Heat Release Rate (PHRR) and Total Heat Released (THR) for various Li-Ion battery chemistries across different cell form factors at 100% state of charge (SOC). Rigorous inclusion criteria were applied to ensure the reliability of selected studies, and statistical methods were employed to discern trends and patterns. Data exhibiting a PHRR or THR of 0 were excluded, as such values suggest either an absence of fire hazard under tested conditions or potential inaccuracies, neither of which contribute to the objective of assessing fire risks in LIB ESS. Such cell calorimetry tests are commonly used in BESS hazard analysis to calculate the potential full-scale battery fires.

The fire meta-analysis, shown in **Figure 6**, first interrogates the adequacy of prevailing testing methodologies by questioning the validity of "0" kW as a commonly reported UL 9540A PHRR data. It is well understood that during any thermal runaway, substantial heat is generated by the rapid electrical discharge and resulting exothermic chemical decomposition of the electrolyte within the cell, and the hot flammable gases subsequently released. None of these sources of heat are reflected by measurement methods, which only measure the combustion of oxygen to estimate heat release rates. These calorimetry methods are more suited for medium to large traditional combustible fires and not a thermal runaway reaction in a lithium-ion battery.

Similarly, although vented flammable gases may not ignite during thermal runaway under test conditions, external electrical ignition sources, more severe failure modes, or the heat resulting from continued propagation are considered plausible ignition sources in the installed environment. As such, a reported 0-kW as PHRR should not be considered representative of the heat release potential of a given cell.

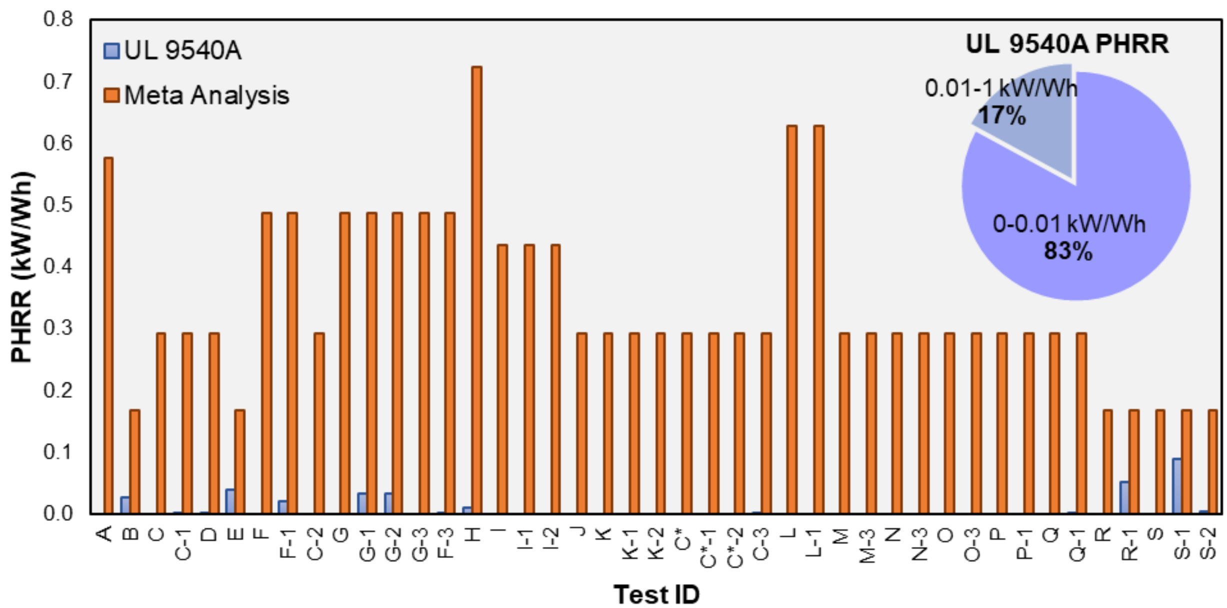

Figure 6: Comparison of Peak Heat Release Rate (PHRR) Data from UL 9540A and Other Tests Data. Test ID refers to a specific model of Li-Ion battery subjected to the UL 9540A test.

In this comprehensive fire meta-analysis, cell calorimetry data is further examined as a critical indicator of the thermal behavior and potential fire risks of various Li-Ion battery chemistries and form factors. **Figure 7** provides a comparative analysis of key heat release metrics, which are instrumental in understanding the scalability of fire hazards associated with Li-Ion BESS. **Figure 7**a shows the Peak Heat Release Rate (PHRR) values for different cell chemistries and form factors, while **Figure 7**a details the Total Heat Release (THR) ratio to the stored Electrical Energy (EE), displaying the potential for heat release in thermal runaway scenarios.

These figures collectively suggest that both the intensity and duration of heat release are influenced by cell form factors, necessitating differentiated fire safety strategies that are finely tuned to the specific characteristics of the battery type in use. The pronounced variability in PHRR and THR to EE ratio challenges the utility of a single data point provided by UL 9540A, underscoring the imperative for dynamic and scalable fire safety protocols that can be adapted to the evolving landscape of Li-Ion BESS. As the deployment of these systems scales up in size and complexity, the insights provided by such large-scale heat release data will be essential in informing fire risk assessment, ultimately contributing to safer BESS integrations.

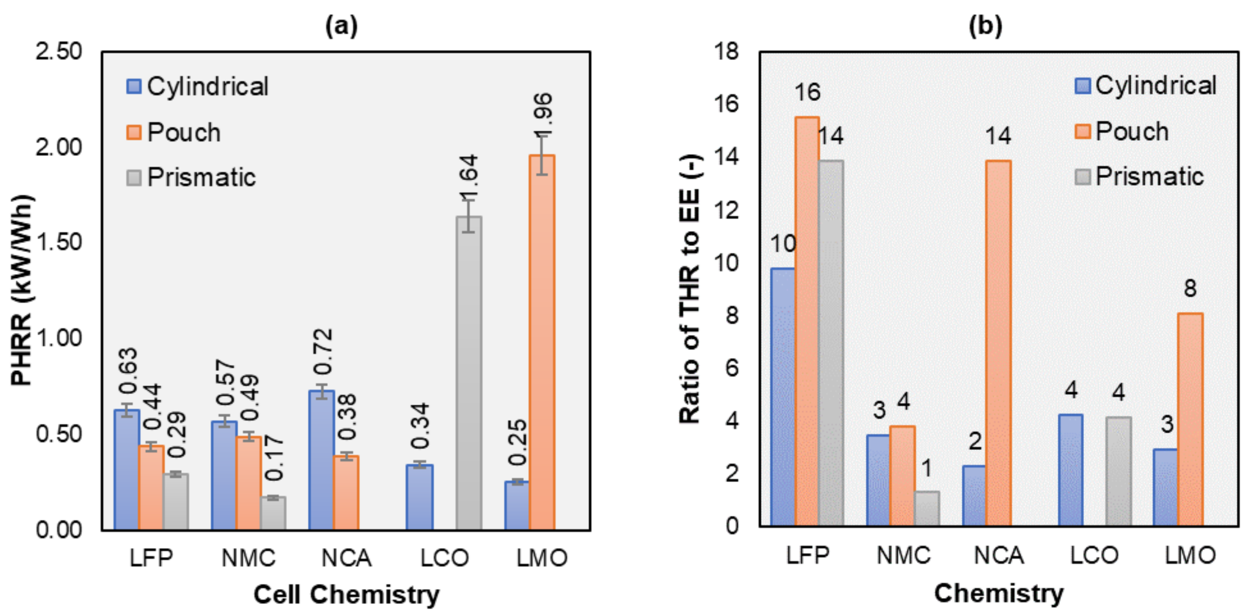

Figure 7: Averaged Heat Release Metrics across Li-Ion Battery Chemistries and Form Factors : (a) Peak Heat Release Rate (PHRR) and **(b)** Total Heat Release (THR) ratio to Electrical Energy (EE).

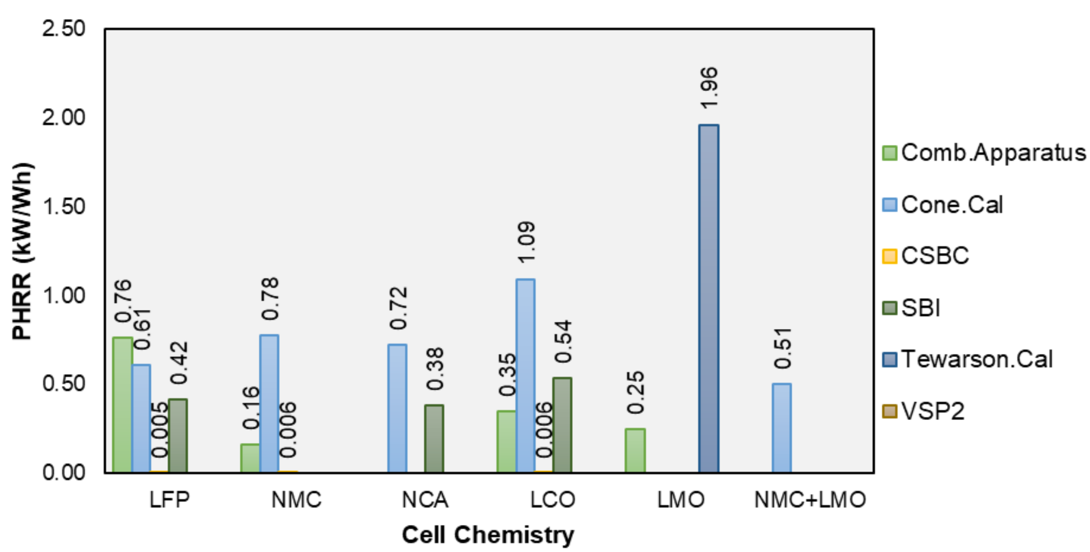

Figure 8: Variability in Averaged Peak Heat Release Rate (PHRR) Values Across Different Measurements Methodologies.

Figure 8 underscores the impact of different test methodologies on the measured Peak Heat Release Rate (PHRR) for various lithium-ion battery chemistries. Oxygen-consumption calorimetry is an approach to determine the heat release rate of burning materials based on the depletion of oxygen in the combustion products. The Cone Calorimeter (ConeCal), Single Burning Item (SBI), and Tewarson Calorimeter (Tewarson Cal) are bench-scale and medium-scale apparatuses that are used to measure heat release rates and characterize objects and materials' reaction to fire. These methodologies offer a perspective on the reactive behavior of the cells under thermal stress and open-cell testing environments, linking oxygen consumption to the heat generation of the materials. On the other hand, the Vent Sizing Package 2 (VSP2) calorimeter's contribution is distinct, centering on pressure dynamics in closed-cell testing environments critical for designing safety systems in thermal runaway scenarios.

However, the variability in PHRR data across these methodologies highlights a challenge in the accuracy and predictability of hazard analyses. This variation emphasizes the necessity of developing standardized testing protocols that can reliably predict the thermal behavior of Li-Ion batteries in real-world applications. Without consistent and accurate PHRR data, there is a risk of underestimating the potential hazards, leading to safety protocols that may not fully protect against the thermal risks posed by advanced battery technologies.

More importantly, a comparison of data across all cell calorimetry methodologies with data from the FM Global 2018 unit-level full-scale fire test **[18]**, as well as other proprietary testing, suggests cell data does not scale linearly as a predictive indicator of full-scale fire behavior. The FM global full-scale fire test data reports PHRR in the order of 0.2-kW/Wh, while the meta-analysis data predicts PHRR in the range of 0.005 to 1.154 kW/Wh with instances where maximum values reached around 3-kW/Wh. Conversely, the estimated total heat release (THR) rate from FM global full-scale fire test data is in the order of 25-times the electrical energy, while the cell level meta-analysis THR is only an average of approximately 9-times the electrical energy (EE) stored with instances where maximum values reached around 32-times the stored EE.

As noted, cell data currently suggests much higher normalized peak heat release values relative to FM Global full-scale data or proprietary internal results. Contrarily, total energy release appears to be underestimated by normalizing cell-level data. The typical absence of full-scale fire testing or suppression testing within the UL 9540 certification framework, along with these conclusions, raises concerns for the framework to fully characterize the potential fire hazards associated with Li-Ion BESS deployments.

Gas Meta-Analysis Approaches to Explosion Hazards

As previously noted, not only do large-scale Li-Ion BESS present significant fire hazards, but they pose an explosion hazard as well. The unique characteristics of large-scale propagation events and those that result in oxygen-deprived environments create explosion hazards not just during initial propagation stages but also during decay stages.

On April 19, 2019, a full-scale fire of an unventilated 1.6 MW containerized BESS in Arizona became oxygen-deprived **[19]**. Firefighters were unaware of the propensity for hot flammable gases to be vented in these scenarios. When the door to the container was opened, fresh oxygen quickly allowed for the rapid combustion of preheated flammable gases, leading to a deflagration that injured four responding firefighters.

Based on these lessons, explosion control designs are more commonly utilizing emergency exhaust ventilation approaches. However, a lack of consensus remains regarding the proper sizing of such systems and their ability to perform given significant fire and smoke exposures.

The following explosion meta-analysis again highlights the limitations of the UL 9540A testing framework for collecting relevant data for the design of such explosion control systems. Similar to heat release data, uncertainty in gas generation data is considered in the reliance on a single data point, subjectivity in failure modes, limitations of the data collection methodologies, and scalability concerns.

Figure 9 illustrates the pronounced range of gas volumes across multiple datasets. The figure distinctly compares the total gas generation volumes obtained specifically from UL 9540A testing versus their expected meta-analysis averages based on their specific cell chemistries and form factors, highlighting the variability of the data and demonstrating the concerns regarding predictive reliability.

This again suggests that a singular test and data point may not be a reliable method to predict full-scale behavior. Such data highlights the necessity for a more comprehensive testing regime or thorough meta-analyses to enhance predictability. Such an approach is recommended to integrate multiple data sources, consider worst-case failure scenarios, and evaluate scaling effects.

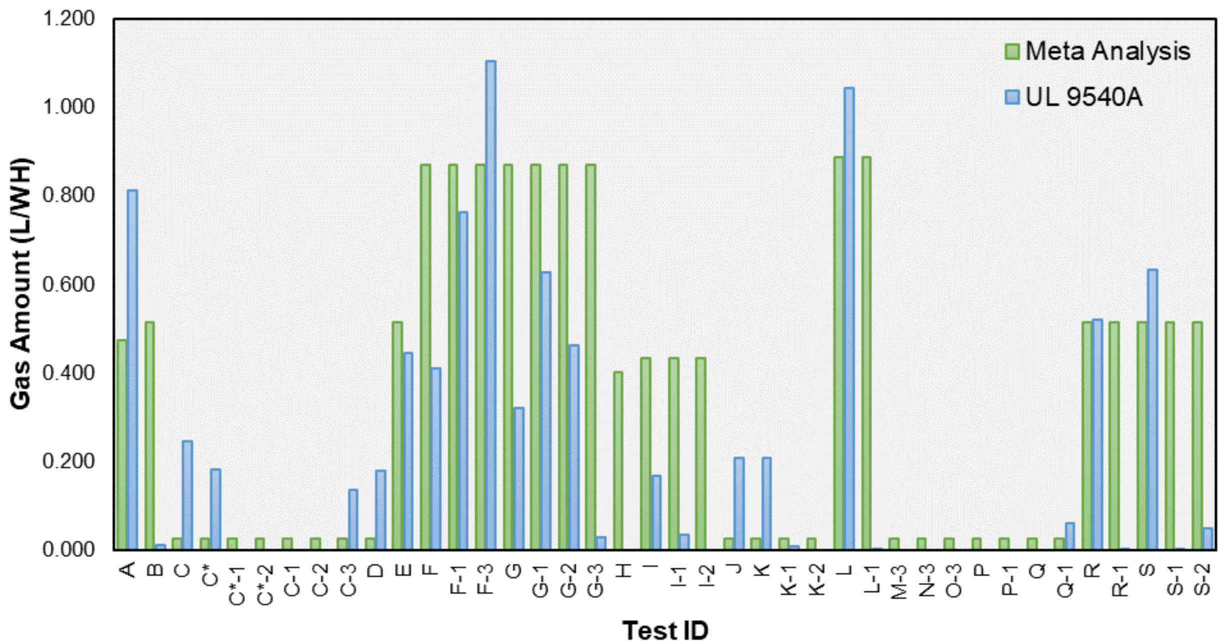

Figure 9: Comparison of Total Cell Gas Generation Volumes from UL 9540A and Other Tests Data.

Figure 10 exemplifies the output of such a meta-analysis, showcasing a comparative evaluation of average vent gas volumes relative to the energy capacity across different battery cell types and chemistries. The meta-analysis data predicts typical gas volume emissions in the range of 0.027 to 0.842 L/Wh at 100% state of charge (SOC). Notably, the analysis also identified suspect-reported instances where gas emissions surged to as much as 5 L/Wh. The variability in vent gas volumes is expected to arise from diverse factors, including cell chemistry and form factors. Less well-understood are the effects of various failure modes and test instrumentation.

Based on post-test cell dissections, it is understood that cell thermal runaways that are not sufficiently intense usually will not convert all the cell's liquid electrolytes into gas form. It is speculated that instances of relatively low reported gas release volumes under test conditions may not be indicative of worst-case failures and, therefore, worst-case gas generation. Similarly, standard use of the 82-L vessel for gas collection may not be appropriate for newer, larger form factor cells with higher venting volumes.

Similar attempts by the fire protection community to use meta-analysis **[20]** or theoretical electrolyte gas conversion rates to formulate bounding ranges of gas venting typically provide approximations on the order of 0.5-L/Wh to 1.5-L/Wh. However, insufficient full-scale data is available to confirm if scaling effects are still to be considered.

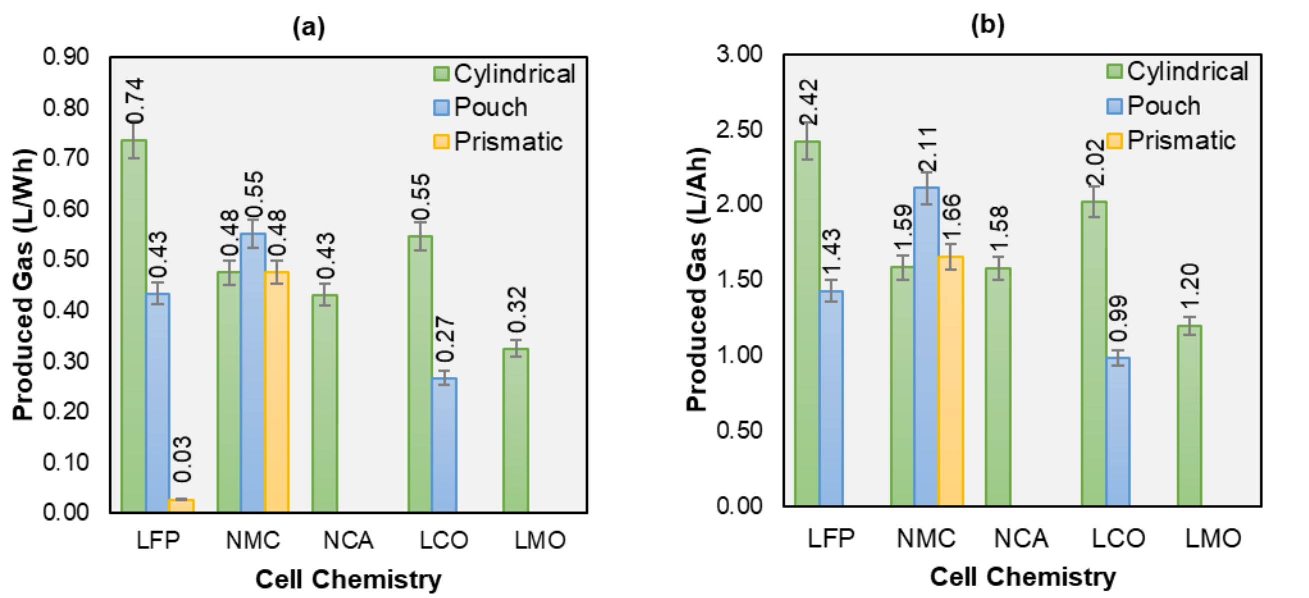

Figure 10: Averaged Total Cell Gas Generation Volumes across Li-Ion Battery Chemistries and Form Factors: **(a)** reported unit of L/Wh and **(b)** reported unit of L/Ah.

Fundamental Propagation and Fire Properties

Figure 11 reflects the small scale and cell level results of the meta-analysis study for LIB failures at 100% SOC. The significant range of the upper and lower bounds of both the heat release and flammable gas generation demonstrates the need for conservative design assumptions and more robust data collection techniques.

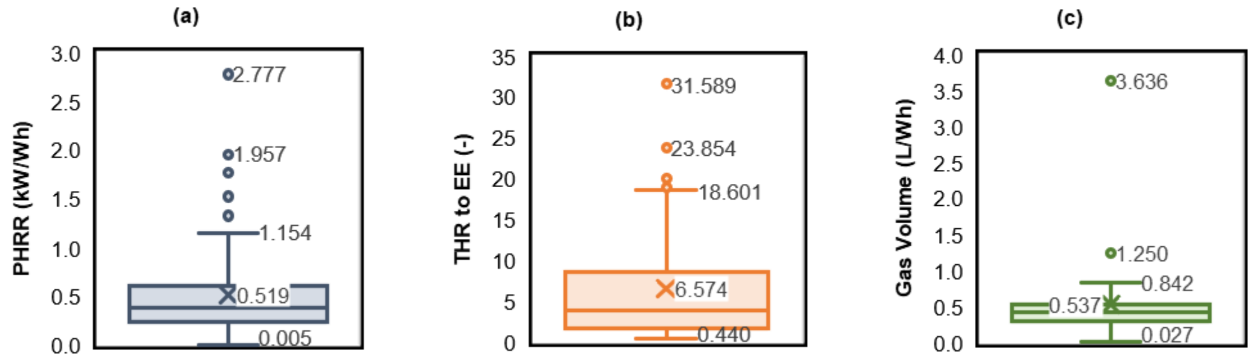

Figure 11: Small-Scale Meta-Analysis Results Summary

FULL-SCALE CHARACTERIZATION

In addition to an assessment of the current Li-Ion BESS certification and hazard analysis framework, this paper attempts to provide insight into the fundamental properties of full-scale events. **Figure 12** provides estimated bounding ranges for each of the three fundamental phases of the Li-ion BESS fire curve:

1) **Growth** – The growth stage of Li-Ion fire events, which start with the battery, uniquely begins with the conversion of electrical energy to thermal energy, which heats the cell. While the magnitude of this heat release is small compared to that released in flaming combustion, it is significant because it is the driver of cell-to-cell propagation in a thermal runaway event. A single cell may experience an internal short that rapidly discharges its stored electrical energy. This electrical discharge heats the cell to high temperatures and additional heat is generated from the exothermic chemical decomposition of the electrolyte.

   If this thermal runaway releases the “Minimum Propagation Energy,” adjacent cells will similarly enter thermal runaway. As previously noted, this cascading failure is known as propagation and typically accelerates until surface temperatures reach the auto-ignition temperature of the flammable gas mixture (approximately 900°F or 500°C) **[23]**.

2) **Fully Developed** – The combustion of flammable gases rapidly increases the internal temperatures of the battery pack, further accelerating the propagation phenomenon. The rate of growth is dependent on cell chemistries, cell form factors, and geometric characteristics of the battery pack. However, full-scale events have displayed fast and ultra-fast T-square growth rates once flaming combustion has begun **[24]**.

   Importantly, it is alternatively possible for propagation to fully consume a battery pack without ever achieving temperatures necessary for flammable gas combustion. Furthermore, battery enclosures often predictably become oxygen-deprived environments due to the rate of smoke and gases generated during propagation. In each of these scenarios, internal temperatures may continue to drive thermal runaway and continue to accelerate propagation without combustion. As a result, flammable gases concentrations within enclosures may exceed Upper Flammable Limits in this phase.

3) **Decay** – As fewer cells remain which have not undergone thermal runaway or sufficient heat is extracted via suppression efforts, the thermal event begins its decay phase. A key differentiator in Li-Ion scenarios is the prolonged decay phase, which often re-ignites. Large-scale Li-ion fire events have repeatedly demonstrated the ability for batteries to propagate over 24-hours after fully developed phases. Unique

phenomena like 'stranded energy' and delayed 're-ignition' are artifacts of the chemical and electrical origins of thermal runaway.

It is important for first responders to be well aware of the propensity for delayed propagation and re-ignition of flammable gases during the decay phase. Importantly, in oxygen-deprived environments, the decay phase also has the potential to create atmospheres above the Upper Flammable Limit (UFL). These scenarios represent significant 'backdraft' hazards for first responders as oxygen is re-introduced into enclosures. The ability to mitigate explosion hazards during the decay phase, after significant fire and smoke exposures, challenges many traditional NFPA 68 and NFPA 69 explosion control techniques **[21][22]**.

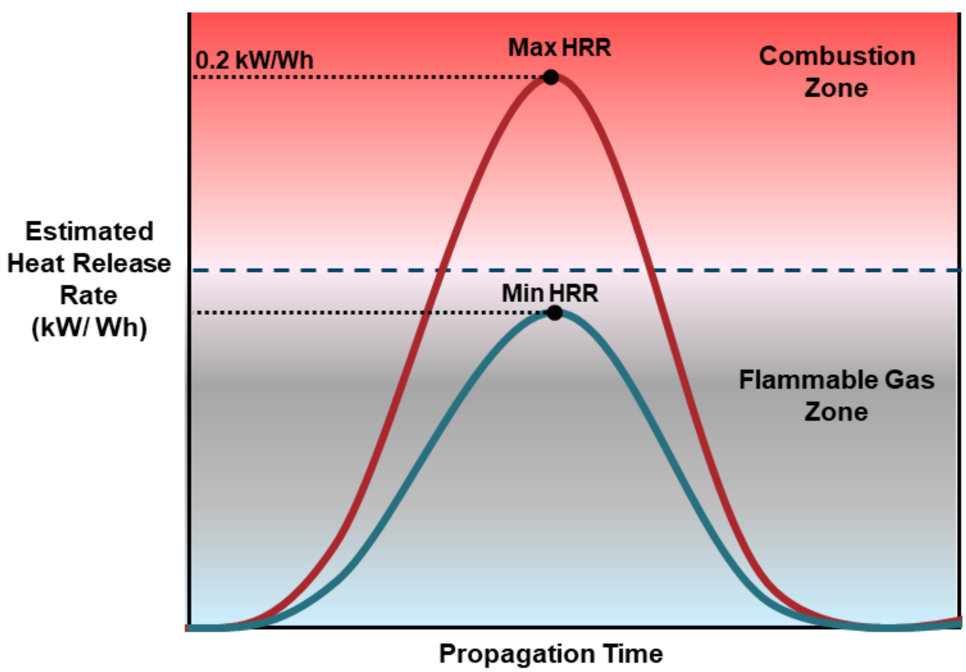

Figure 12: Estimated Upper and Lower Bound of (Wh) Normalized Full-Scale Li-ion Battery Peak Heat Release

MINIMUM IGNITION ENERGY VS MINIMUM PROPAGATION ENERGY

Lithium-ion batteries often defy traditional academic and commercial frameworks used for the classification of materials and or building systems. While meta-analysis methodologies may provide utility for many generalized use cases, other applications will require more detailed design. Refined data collection methodologies to measure new thermal properties may be necessary to best communicate relevant material properties.

The *Minimum Ignition Energy* (MIE) is defined as the lowest energy required to ignite a flammable material in air or oxygen. The lowest value of the Minimum Ignition Energy is found at a certain optimum mixture, which may be hard to achieve even under ideal test conditions.

For this reason, in academic settings, the lower bound of the MIE is confirmed by repeating at least ten (10) successive experiments with no ignition observed. Such repeatability is critical in providing confidence in measured outcomes.

With similar repetition, internal heating methods could be used to simulate varying thermal exposures until a minimum propagation energy can be consistently demonstrated within a battery module. Studied with this rigor, the propagation resistance of battery systems may be more accurately described and confidently classified. Therefore, *Minimum Propagation Energy (MPE)* is suggested to be explored as a fundamental property of the various passive insulative assemblies commonly used to protect chemical battery cells and modules.

Conclusions and Recommendations

The exponential growth of Li-Ion BESS adoption, in tandem with increasing energy densities presents unique opportunities and inherent risks. As incidents of Li-Ion BESS failures continue to make news headlines, skepticism about the safety of the technology has increased. Yet, attempts to rigorously study potential full-scale fire exposures of Li-ion BESS failures and the efficacy of suppression systems have seen limited advancement since 2018. In lieu, the limited testing framework of UL 9540A has been relied upon as the primary means for engineers and authorities to evaluate Li-Ion battery hazards.

This reliance on UL 9540A, while foundational, has been highlighted by this meta-analysis to exhibit critical limitations, particularly in its ability to accurately predict and mitigate the risks of fire and explosion inherent to Li-Ion BESS deployments. The key findings from this comprehensive analysis can be summarized as follows:

Variability in propagation, fire, and gas data: There is significant variability in the outcomes of UL 9540A tests and research data, particularly concerning peak heat release rates (PHRR), total heat released (THR), and vent gas volumes. This variability is influenced by specific failure modes, testing methodologies, and cell chemistries, indicating that current standards may not consistently predict or mitigate real-world BESS fire behaviors. This paper reveals an urgent need for more rigorous approaches to certification or clear prescriptive practices. The findings also underscore a similar imperative for robust suppression system testing and validation.

Inadequacies of current testing standards: The UL 9540A standard presently lacks mandates for essential full-scale fire testing and does not require the evaluation of fire suppression and explosion control systems in its certification process. This gap in testing criteria raises concerns about the standard's comprehensiveness and its ability to fully ensure the safety of Li-Ion BESS installations. This research suggests that the scalability of cell-level heat release data to predict full-scale fire behaviors is not linear, posing challenges to current fire hazard assessment methodologies and necessitating a reevaluation of testing protocols.

In light of these findings, this paper advocates for a pivot towards a more anticipatory and prescriptive framework of Li-Ion BESS safety. Such a framework should not only respond to past incidents but also proactively integrate emerging data and technological trends. To support this shift and adequately prepare for the anticipated rate of adoption of this technology, we propose the following recommendations:

Development of a public repository for large-scale fire test data: There is an urgent need for collaborative research initiatives aimed at compiling a comprehensive public repository of large-scale fire and suppression test data. This repository would serve as a valuable resource for informing clear prescriptive design standards and safety protocols.

Continuous improvement and knowledge exchange: Encouraging a culture of continuous improvement and open exchange of knowledge among researchers, manufacturers, and fire safety professionals is critical. By fostering dialogue and sharing findings, the community can work together to ensure that the deployment of Li-Ion BESS is optimized for both performance and safety.

Collaborative research initiatives: We call for increased investment in collaborative research efforts to explore and validate robust propagation, suppression system, and explosion control designs with a refined understanding of BESS fire dynamics. Such research is essential for informing future updates to safety standards and regulatory guidelines.

By implementing these recommendations, we may enhance the safety and scalability of deployment of Li-Ion BESS, not only optimized for performance but also harmonized with the expectations of the communities we serve, thus safeguarding the collective move towards a sustainable energy future.

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