

Explosion Control Guidance for Battery Energy Storage Systems

Overview of Current
Standards and
Additional
Recommendations

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EXECUTIVE SUMMARY

Lithium-ion battery (LIB) energy storage systems (BESS) are integral to grid support, renewable energy integration, and backup power. However, they present significant fire and explosion hazards due to potential thermal runaway (TR) incidents, where excessive heat can cause the release of flammable gases. This document reviews state-of-the-art deflagration mitigation strategies for BESS, highlighting existing codes and standards, analyzing various BESS installation types, and examining key variables that influence the occurrence and severity of deflagration. It also addresses current challenges in explosion prevention and protection practices, identifying knowledge gaps and offering recommendations to improve BESS safety.

Deflagration Mitigation Recommendations for BESS

One of the major risks associated with BESS is deflagration, which involves the rapid combustion of gas mixtures within an enclosure, producing pressure waves that can cause significant damage. Current deflagration control strategies rely on either prevention systems, which limit the formation of flammable gases, or protection systems that mitigate explosion consequences. However, the evolving complexity of BESS installations makes it difficult to apply existing mitigation standards universally, particularly as BESS technologies advance.

To address these challenges, this guidance document recommends the following:

- **Follow the Deflagration Mitigation Design Process:** Follow a consistent approach to mitigation (figure below) to ensure that the system meets the applicable codes, standards, and performance objectives.
- **Ensure P_{red} is Not Exceeded:** Regardless of the approach to mitigation, ensure that the system is able to keep any potential overpressure experienced below 3 psi-g to avoid catastrophic failure of the BESS enclosure.
- **Refinement of BESS Parameters:** Evaluate key parameters, such as the gas release rate, gas concentration, and gas composition from LIB cells during TR, in addition to the BESS free air volume, to assess the impacts that they have on the proposed system design.
- **Alternative Deflagration Mitigation Methods:** Incorporate innovative techniques like controlled ignitions (sparker systems) to safely ignite and burn off flammable gases in a controlled manner or automatic door/panel openings to release gas to the environment and lower potential overpressure.
- **Enhanced Combination of Systems:** Given the limitations of individual prevention or protection systems, integrate multiple mitigation strategies, such as combining gas detection, ventilation, sparkers, or deflagration panels, to optimize BESS safety.
- **Holistic Testing and Modeling:** Use a combination of empirical testing and simulation tools (e.g., Computational Fluid Dynamics, CFD) to design and validate solutions.



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DEFLAGRATION MITIGATION DESIGN PROCESS

1. Ensure Enclosure Meets Pressure Requirements

Obtain confirmation (through testing, documentation, etc.) the pressure threshold, P_{red} , of the enclosure

Deflagration mitigation design should ensure that P_{red} , typically 3 psi-g, is never exceeded

2. Select Deflagration Mitigation System(s)

Passive
i.e. NFPA 68
Deflagration
Protection
System

Active
i.e. NFPA 69
Deflagration
Prevention
System

Sparker
Controlled
ignitions to
prevent buildup
of flammable gas

Performance
Automatic doors
or vents to lower
gas concentration
or pressure

3. Determine Design Parameters

Passive

Max. gas volume, V_{gas} , involved in deflagration without exceeding P_{red} is on order of 1200 L (typical gas releases: order of 1.2 L/Ah)

Active

Ventilation rate sufficient to reduce V_{gas} below 25% LFL in < 60 s to minimize window with flammable gas concentration above NFPA 69 threshold

Sparker

Place in sufficient numbers and locations to ensure pressure from ignition of gases < P_{red}

If necessary, deflagration panels or other vent paths should be provided to reduce overpressure

All Systems

Conduct dispersion analysis to determine concentration profile in enclosure as function of time

Perform partial deflagration calculation showing V_{gas} above LFL does not result in overpressure > P_{red}



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INTRODUCTION

Lithium-ion batteries (LIBs) are the most common type of battery used in energy storage systems (ESS) due to their high energy density, long cycle life, and comparative environmental friendliness. However, LIBs also have inherent safety risks, such as overheating, short circuiting, and thermal runaway (TR), which can lead to fire and explosion incidents. TR is a self-sustaining exothermic reaction that occurs when the cell temperature exceeds a critical value, causing the decomposition of the electrolyte and the electrodes and the release of potentially flammable gases, otherwise known as cell venting. Due to the excess heat released, a cell undergoing TR can become a source of thermal abuse to a neighboring cell, causing TR propagation from one cell to another, resulting in a cascading failure of the battery system.

The fire and explosion hazards of LIBs are amplified when they are used in large-scale battery energy storage systems (BESS), which typically consist of hundreds or thousands of LIB cells connected in series and/or parallel configurations and housed in enclosures. BESS are widely used for various applications, such as grid support, renewable energy integration, backup power, peak shaving, frequency regulation, and voltage control. However, BESS also pose significant challenges for fire safety, as they can generate large amounts of heat and flammable gases if a TR event occurs. TR can lead to increased temperatures inside the BESS enclosures, which can contribute to increasing pressure inside an enclosure. If the concentration of flammable gases becomes high enough and an ignition source is encountered, such as a hot surface, arc, or spark, an explosion or deflagration can occur.

Deflagration is the rapid combustion of a gas mixture that produces a subsonic pressure wave and a flame front that propagates through the mixture. Deflagrations can cause damage to the BESS enclosure and its surroundings and may pose a risk to nearby personnel and the public. Deflagration can occur either promptly or delayed after the initial cell venting and TR, depending on the gas concentration, ignition source, ventilation conditions, and enclosure geometry. Both prompt and delayed deflagrations can lead to catastrophic outcomes, but delayed deflagrations are typically more severe, as they involve larger gas volumes and generally higher pressures.

Therefore, it is essential to design and implement effective deflagration control systems for BESS, which can prevent or mitigate the effects of deflagration and minimize the structural and mechanical damage to the enclosure and its surroundings. Deflagration control systems can generally be classified into two categories: prevention systems and protection systems. Prevention systems aim to avoid the formation of a flammable gas mixture inside the enclosure by detecting and removing the gases before they reach the lower flammability limit (LFL) or by eliminating the ignition sources. Protection systems aim to reduce the consequences of deflagration by relieving the pressure inside the system and venting the combustion gases in a safe direction so that structural and mechanical damage is minimized.

The design and installation of deflagration control systems for BESS are governed by various codes and standards, such as NFPA 855, NFPA 68, and NFPA 69. NFPA 855 is the main standard for the installation of stationary ESS, which provides the minimum requirements for mitigating the hazards associated with BESS, including ventilation and explosion control. NFPA 855 requires the inclusion of explosion prevention systems in



accordance with NFPA 69 or deflagration venting protection systems in accordance with NFPA 68. While these codes have been successful in providing regulation to BESS, they are not always sufficient or up to date in addressing some specific challenges of BESS deflagration control, as BESS are rapidly evolving and diversifying in terms of technology, size, configuration, and application. Moreover, the existing deflagration control systems may not be practical, effective, or reliable for certain BESS, as they may not account for the complex and dynamic phenomena involved in BESS deflagrations or the diversity of TR events, including how many cells may become involved simultaneously or in total throughout TR propagation. As such, there is a need for more research and development in this field as well as more testing and validation of the deflagration control systems for BESS.

The objective of this paper is to ensure any deflagration prevention or protection system can demonstrate appropriate hazard mitigation with no catastrophic rupture of the enclosure, which can happen when internal pressures start to exceed 20 kPa-g (0.2 bar-g, 3 psi-g) [1], although some sources report this value to be even lower, in the range of 2–4 kPa-g (0.02–0.04 bar-g, 0.3–0.6 psi-g) [2]. As such, this paper reviews the current state of deflagration mitigation for BESS, including the relevant codes and standards, existing types of BESS installations, variables which affect the occurrence and severity of deflagration, and the difficulties of current deflagration prevention and protection practices. This paper also identifies the knowledge gaps and research needs in the field and provides recommendations for most effectively implementing the requirements of NFPA 68 and NFPA 69 and additionally provides guidance for improvements in designing safe and effective deflagration mitigation systems from a scientific perspective based on current knowledge, new research, and up and coming technologies.



BACKGROUND ON BESS

BESS Basics

BESS are widely used for various applications, such as grid support, renewable energy integration, backup power, peak shaving, frequency regulation, and voltage control. These systems can consist of hundreds or thousands of cells connected in series and/or parallel configurations all housed in enclosures, many examples of which are subsequently described. Inside an enclosure, the BESS can be further broken down. Each enclosure will contain multiple units or racks which house battery modules, with the modules containing the actual cells, examples of which are given in Figure 1.



Figure 1 Example LIB (a) Cell, (b) Module, and (c) Unit

Types of BESS Installations

BESS can be installed in various locations and configurations, depending on the intended application, available space, environmental conditions, and regulatory requirements. As such, BESS classifications can vary in terms of their location and installation type. The BESS location includes the position relative to the meter as well as whether the BESS is remote or near exposures and if it is an indoor or outdoor installation [3]. The type of the BESS installation refers to whether it is walk-in, arm-in/reach-in, or modular [4]. To better understand the wide variety of existing BESS installations, these classifications are further described.

BESS Location Classifications

A BESS's position relative to the meter refers to whether the BESS is installed on the utility side – in front of the meter – or the customer side – behind the meter. Utility-side BESS are usually installed within close proximity to or at substations [5]. Customer-side BESS are generally smaller and installed close to where the end-users need power. These BESS can have applications such as providing boots to electric vehicle charging stations or increasing the peak shaving capability of buildings [5].



The location of a BESS installation can be classified as remote depending on the clearance from buildings, lot lines, public ways, stored combustible materials, hazardous materials, high piled stock, and other exposures. If a BESS has less than 30.5 m (100 ft) clearance from these exposures, the installation is considered “near exposure” [3]. Typically, only outdoor BESS might be considered remote, as indoor BESS are, by definition, near exposures. Indoor installations can be constructed in either dedicated or non-dedicated use buildings. Dedicated-use buildings are only used for BESS, electrical energy generation, or grid-related operations and have no unauthorized access or separate areas for administration, an example of which is given in Figure 2.



Figure 2 Example Dedicated-use Building BESS

Non-dedicated use buildings contain BESS but are not dedicated solely to that purpose [3]. Indoor installations are not preferred for large-scale BESS [6]. This preference exists due to the more confined space present in indoor installations, which can limit the dispersion or dilution of flammable gases and increase the likelihood of reaching the flammable range. Indoor installations may also have more potential sources, such as electrical equipment, lighting, or heating, that can ignite flammable gases. Meanwhile, outdoor installations, typically those in remote locations, are the recommended option for large-scale BESS, as it is easier to provide room for adequate spacing while minimizing hazards by removing nearby exposures [6]. Outdoor installations may also pose less safety risks and damage to the personnel and the environment, due to the distance and isolation of potential fire and explosion events.

BESS Design Classifications

The type of BESS installation refers to the enclosure that houses the BESS components. These enclosure styles can be classified into three categories: walk-in, arm-in/reach-in, and modular. Walk-in style enclosures usually have a central walkway, computer terminals, and racks of batteries and require workers to enter for maintenance and monitoring, an example of which is given in Figure 3. In addition to having maintenance workers enter the space containing LIBs, emergency personnel may also enter the enclosure to assess conditions after an alarm event, with only minimal observations able to be made from outside [4]. As such, this type of enclosure must be treated as a building for protection purposes and has fallen out of favor due to the increased safety risks it poses to personnel entering the enclosure [4]. Contrarily, arm-in/reach-in style



enclosures have exterior doors that allow access to the battery modules and all equipment without entering the enclosure, thus relieving maintenance workers, technicians, or emergency response personnel from having to enter the enclosure [4], an example of which is also given in Figure 3.

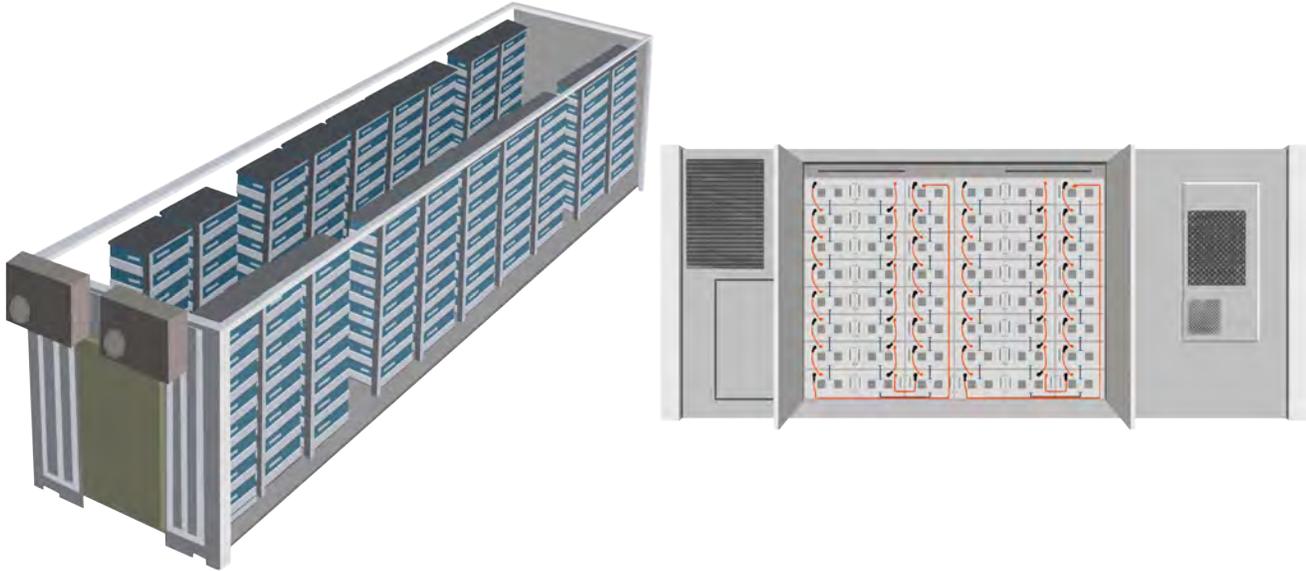


Figure 3 Example Walk-in Style BESS (left) and Example Reach-in Style BESS (right)

Finally, modular-style enclosures encompass the widest range of BESS enclosures. These can be as small as the size of a refrigerator or freezer, fitting only one or two racks and associated hardware, an example of which is given in Figure 4. Given their small size, a site may connect many of these cabinets routed to a central panelboard [4], also shown in Figure 4. On the other hand, the most popular type of BESS installation to date is the modular building or containerized applications made of shipping containers with a wide range of lengths and typically 3mm-thick walls [5], some examples of which are given in Figure 5. Nearly all containers of this sort purchased today are ISO containers with widths and heights both of 2.4 m (8 ft) and lengths including 2.4 m (8 ft), 6 m (20 ft), 8 m (27 ft), 12 m (40 ft), or 16 m (53 ft) [7] that are reach-in only [4], with their increased popularity attributed to their ease of transportation, installation, and scalability along with reduced risk to personnel.



Figure 4 Example Modular, Refrigerator-sized BESS (left) and Example Multi-Modular BESS (right)

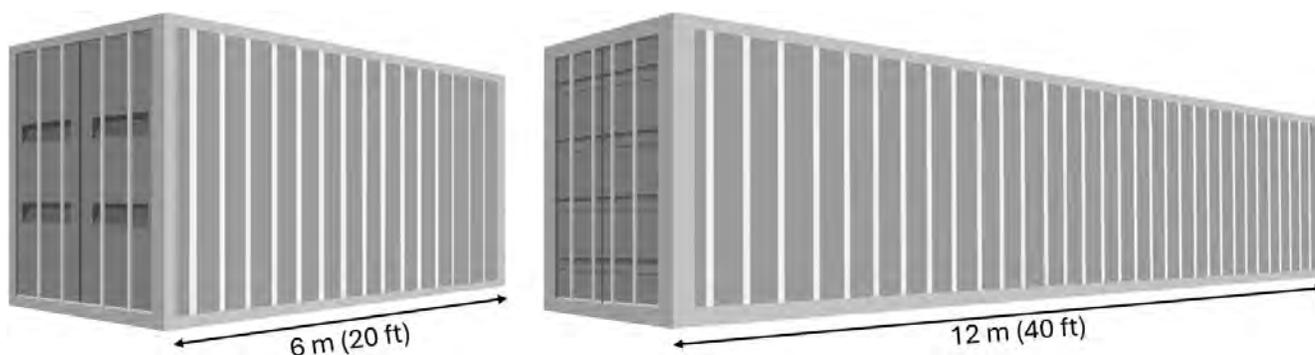


Figure 5 Example Standard ISO Containers

Current Explosion Mitigation Standards

The main standard for general BESS installation requirements is NFPA 855 Standard for the Installation of Stationary Energy Storage Systems [4]. Within those requirements, NFPA 855 provides guidance for mitigating fire and explosion hazards associated with BESS. For BESS with explosion prevention systems, NFPA 855 specifies to follow NFPA 69 Standard on Explosion Prevention Systems [8]. For BESS which utilize deflagration venting, NFPA 855 dictates that the BESS should be in accordance with NFPA 68 Standard on Explosion Protection by Deflagration Venting [9]. To lay the groundwork for a complete understanding of the current explosion control guidance, NFPA 855, NFPA 68, and NFPA 69, are summarized below, with their advantages and limitations being discussed in subsequent sections.

NFPA 855

One of the main goals of NFPA 855 Standard for the Installation of Stationary Energy Storage Systems is to provide the minimum requirements for mitigating the hazards associated with ESS [10]. As NFPA 855 applies to a wide range of ESS, it dictates requirements for ventilation during charging for cells which produce off-gas during this stage under normal operation. However, LIBs do not exhibit this behavior, so the more applicable hazard mitigation guidance provided by NFPA 855 are those recommendations for abnormal conditions, such as TR. In fact, NFPA 855 requires charging or discharging of LIB cells to be carried out by an evaluated device or approved method to ensure the cells are operating under safe conditions to prevent TR [10]. However, despite best efforts, given the number of cells in use across BESS installations, it is inevitable that TR incidents will occur at some point. While TR can result in a variety of hazards, the focus here is the potential for an explosion or deflagration event resulting from a TR incident. To mitigate this hazard, NFPA 855 refers to both NFPA 68 and NFPA 69, with NFPA 68 dictating deflagration venting and protection requirements, and NFPA 69 dictating gas ventilation and explosion prevention requirements.

NFPA 68

NFPA 68 Standard on Explosion Protection by Deflagration Venting addresses the installation and use of devices and systems that vent combustion gases and pressures resulting from a deflagration within an enclosure so that structural and mechanical damage is minimized [9]. Systems implemented in accordance with this



standard are considered passive because they mitigate the effects of an explosion if it occurs rather than trying to prevent the explosion in the first place. These types of systems can also be considered control strategies because they are controlling the outcome of the deflagration [4].

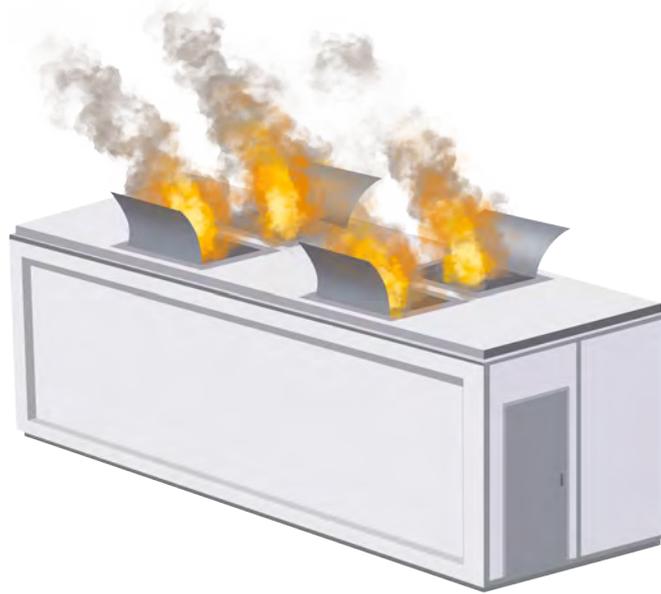


Figure 6 Example BESS NFPA 68-style Deflagration Protection Vent System

Following this standard involves the implementation of deflagration panels and specialized vents, which are, “designed to fail at lower pressures than the mechanical strength of the enclosure, thereby releasing the rapidly expanding gases before pressures reach explosive levels and cause greater damage,” [4], with an example of such integrated panels shown in Figure 6. NFPA 68 also designates that the panels and vents should be located such that they direct expelled material in a direction that the result in the least amount of damage [6]. Usually, the preferred location for deflagration venting is the roof of the enclosure [5, 7, 11] to minimize the impact of fire and projectiles on nearby exposures.

NFPA 69

NFPA 69 Standard on Explosion Prevention Systems provides requirements for installing systems for the prevention of explosions in enclosures that contain concentrations of flammable gases, vapors, mists, dusts, or hybrid mixtures [8]. Implementation of this standard is considered a prevention strategy because the goal is to prevent the deflagration incident in the first place, which is usually achieved through gas detection and ventilation to control the gas concentration and prevent the buildup of explosive gases [4]. The requirement of NFPA 69 is to keep the concentration of flammable gases in the BESS enclosure below 60% of the LFL if the gas content is being monitored by an SIL 2 system or below 25% of the LFL if it is not [2, 8]. HVAC systems are commonly used to provide ventilation of unignited gases, an example of which is shown in Figure 7; however, a dedicated ventilation system is often required if the gases produced by the cells are caustic [4] as well as for compliance with NFPA 72 [12] or other safety requirements. Other systems that can provide ventilation include



door opening mechanisms, also known as performance systems, which can allow for exterior doors to be remotely opened from a safe distance away during a fire event [4].

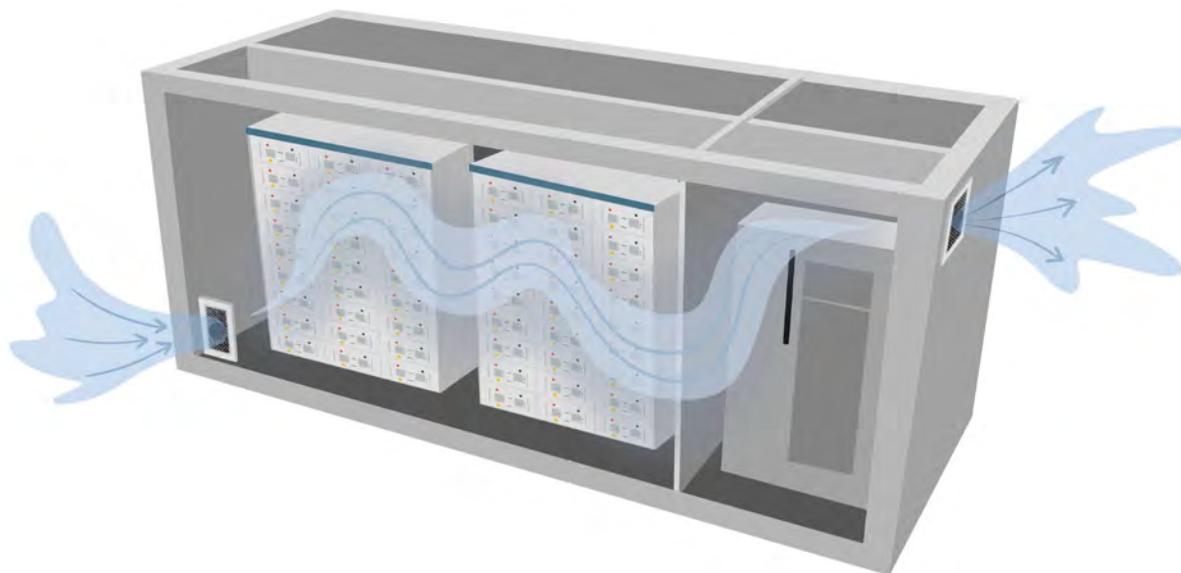


Figure 7 Example BESS NFPA 69-style Deflagration Prevention Ventilation System

Variables Affecting Deflagration Occurrences

There are many variables which affect the occurrence and severity of a deflagration in a BESS enclosure. These variables can be classified into three categories: LIB characteristics, enclosure characteristics, and environmental factors. Each of these categories are described in more detail in the subsequent subsections.

LIB Characteristics Affecting Explosion Risk

As mentioned, several characteristics of the LIB cells used in the BESS can affect the risk of explosion. These characteristics can include defects in the cell but are mainly related to the vent gas released from the cell during a TR event, including the makeup of the gas mixture as well as the gas volume. Cell defects are important to note because these can lead to a cell entering TR. For example, it is possible for an internal short circuit to occur due to abnormal dendritic growth within a cell leading to TR [7]. Other forms of electrical abuse as well as thermal or mechanical abuse can also lead to TR. Once TR occurs, not only is a flammable gas mixture released from the cell, as subsequently discussed, but there is now the presence of ignition sources in the form of hot battery surfaces or molten sparks of material ejected from a cell [7].

The gas mixture vented from an LIB cell consists of gases generated by chemical reactions within the cell during TR, including decomposition of the electrolyte and solid-electrolyte interface (SEI) layer and the destabilization of the cathode and anode; vaporized electrolyte is also produced [13, 14]. As shown in Table 1, the typical makeup of the cell vent gas includes carbon dioxide (CO₂), carbon monoxide (CO), hydrogen (H₂), and unburned hydrocarbons (UHC) in the form of C_xH_x, the amounts of which vary with cell chemistry, form factor, failure mode, etc. Interestingly, the vent gas composition shows little variation with either the state of charge (SOC) of



the cells [5] or any electrical connections present between the cells [2]. This lack of variation with these particular parameters results in cells having the potential to produce flammable gas mixtures over a range of SOCs and when not electrically connected to one another.

Table 1. Average Vent Gas Components and Volume Released from LIB Cells during TR for Different Cell Chemistries Capturing a Range of Cell Form Factors for Each Chemistry [15]

Vent Gas Released	LIB Cell Chemistry				
	LFP	LTO	Nal	NCA	NMC
H ₂	43.9%	15.2%	35.7%	30.4%	22.2%
CO	8.9%	10.4%	26.3%	27.9%	20.7%
UHC	8.1%	1.9%	4.4%	8.7%	4.0%
CO ₂	39.1%	72.5%	33.6%	33.0%	53.1%
Total Volume	1.2 L/Ah	0.9 L/Ah	16.8 L/Ah	2.0 L/Ah	1.7 L/Ah

For clarity, the gas volume refers to the amount of flammable gas released from a cell during TR. The gas volume can be correlated based on the capacity or the energy of the cells, and is estimated to be about 1.2 L of vented gas per Ah or 0.4 L/Wh [5], although this fluctuates with cell chemistry, as shown in Table 1. Additionally, the total gas volume depends on the number of cells that undergo TR, which can result in a significant volume concentration of flammable gas inside the BESS enclosure if even just a few cells become involved [5].

The gas mixture and gas volume produced by the cells during TR can influence the probability or severity of a deflagration event in several ways. For example, the gas mixture determines the flammability range of the gas, *i.e.* the range of gas concentrations in air that can sustain combustion. The flammability range is bounded by the LFL and the upper flammability limit (UFL), which are the minimum and maximum gas concentrations in air that can sustain combustion, respectively. As such, the LFL affects the deflagration occurrence, as it defines the lower boundary of the flammable range. A sample of different form factors and chemistries of LIBs has indicated an average LFL of 7.4% for the vent gas released during TR [15], which is consistent with the general understanding that the LFL is on the order of 10% for LIB vent gas [5]. While the UFL is of less concern, it is possible that this limit could be reached in certain scenarios, and a sudden influx of oxygen, such as can occur if emergency response personnel opens a container door, could result in an explosion event, which has occurred in the past [16, 17].

In addition to the LFL, the gas mixture in conjunction with the volume of gas released from the cell also affects the burning velocity, or the speed at which a flame propagates through the mixture. The burning velocity is both dependent on the mixture of gas being burned as well as the equivalence ratio, or the ratio of actual air used in the burning reaction to the stoichiometric values of air reacting during burning. The influence of the concentration of gas in the space on the equivalence ratio also affects how rich or lean the flame will burn, which in turn dictates the flame temperature. Additionally, the amount of gas volume released also affects the deflagration severity by influencing the maximum explosion pressure, or the peak pressure achieved by the combustion of the gas mixture, which is directly dependent on the amount of flammable gas present in the space.



BESS Enclosure Characteristics Affecting Explosion Risk

Enclosure characteristics which affect the potential and severity of an explosion or deflagration event in a BESS enclosure include the distance inside the container over which the flame can accelerate, the free air volume inside the container, the ventilation device used, and other installation components.

The distance over which the flame can accelerate refers to the length of the path that the flame front travels through the flammable gas mixture before reaching the vent or the enclosure wall, with a greater distance available for flame acceleration resulting in a more severe deflagration event.

The ventilation device refers to the type and size of the device that is used to vent the combustion gases and pressures to a safe location. The ventilation device can be either passive or active, depending on whether it operates by the pressure difference between the inside and outside of the enclosure or by a mechanical force, such as a fan or blower. The ventilation device can also be either continuous or intermittent, depending on whether it operates constantly or only when a certain condition is met, such as a gas concentration or a pressure threshold. Typically, a continuous, active ventilation device would be used when implementing an explosion prevention system to keep the flammable gas concentration below a certain limit in the event of TR. A passive ventilation device would typically be implemented for an explosion control system with the purpose of relieving pressure and vented material in the event of a pressure build-up or an explosion/deflagration. If the ventilation system is not designed well for the BESS, such as if there is inadequate ventilation area or mass flow rate, this deflagration mitigation system will not produce the intended results, and the outcome could be a much more severe incident than expected.

The free air volume refers to the amount of space that is available for the flammable gases to disperse and accumulate inside the BESS enclosure or the free space that is not occupied by LIB racks or other internal components, typically the space above and between racks. The free air volume depends on the enclosure size, the battery spacing, *i.e.* how full the container is, and the enclosure components. The free air volume affects the deflagration severity, as, in conjunction with the volume of gas released from the cells, it determines the gas dilution. Generally, the ISO container-style BESS that are most commonly used today have about 20% of their total volume as the free air volume; although, companies like AIG dictate a 3 m (10 ft) minimum distance between battery racks to minimize fire spread [6]. However, with higher energy dense systems being more desirable, it is likely that this value will decrease over time, leading to systems that can more easily result in a concentration of flammable gases above the LFL after a TR event.

Other installation components which are critical to reducing explosion/deflagration hazards include battery protection systems which monitor for and stop short circuit events, operating environment management systems which control the dust levels, humidity, and temperature within the container, integrated BESS monitoring and control systems, and fire suppression systems. These systems are a major part of hazard mitigation because, for example, if the protection and BESS monitoring systems are not adequate or if they malfunction, electrical faults in the cells while charging can lead to voltage imbalance and ground faults in battery modules, which could cause enough electrical abuse for a cell to enter TR [7]. An additional example is an inadequate fire suppression system which leaks the suppression agent outside the enclosure, lowering the



concentration of the suppression agent inside below the required threshold [7]. As such, a lack of or poor installation quality of any of these systems can lead to higher fire or deflagration frequencies [5].

Environmental Factors Affecting Explosion Risk

The variability of various environmental factors can lead to events that can trigger or aggravate deflagration in BESS. Some examples of external factors which have caused BESS failures in the past, including deflagration events or fires, consist of electrical surges leading to failures of the prevention and/or protection systems, an operational environment which may be prone to either fluctuations in temperature or moisture and dust accumulation leading to degradation of BESS components [5], errors during BESS installation, inadequate prevention and/or protection systems, and LIB manufacturing defects leading to LIBs overheating [14].

Electrical faults, such as voltage imbalance, ground faults, or short circuits, can cause overcharging, overheating, or arcing in the battery modules, which can lead to TR and its propagation [7]. As a result, electrical faults can also provide ignition sources, such as arcing, sparks, or hot surfaces, that can ignite the flammable gases released from LIB cells during TR and cause deflagration. It is also possible for other ignition sources to be present, including hot LIB cells or molten sparks of material ejected from the LIB cells during TR [7].

There is also the potential for external heating to a BESS, caused by exposure to sources such as fire, concentrated radiation, or hot surfaces, which can increase the environmental temperature of the cells. The surrounding temperature can affect the occurrence of TR, as high environmental temperatures can lead to cell degradation [14] and more easily triggered TR events. External heating which leads to an overall increased environmental temperature can also lower the LFL of the gas mixture, and increase the flammability of the LIB cell vent gas resulting from TR. Radiant heat transfer, such as from a fire, can also weaken the enclosure walls, causing them to be compromised, especially in the event of a deflagration [7].

Another environmental factor is mechanical abuse, such as impact, penetration, or vibration, which can damage the cell structure, cause internal short circuits, or rupture the cell casing, which can also lead to TR and its propagation. An additional concern could be inadequate fire suppression systems, such as gas suppression systems, which can extinguish the flames, but not inhibit TR or its propagation [11]. This occurrence allows for the buildup of flammable gases over time, leading to delayed deflagration [2].

As such, environmental factors can not only affect the occurrence and severity of TR and deflagration but can additionally compromise the deflagration prevention and protection systems.



CHALLENGES OF CURRENT MITIGATION STANDARDS

The current standard deflagration prevention and protection practices for BESS face several difficulties. These include some TR scenarios which can result in deflagration in BESS that cannot necessarily be accommodated by NFPA 855 via NFPA 68 or NFPA 69 as well as the unpredictability of prompt vs delayed ignition leading to deflagration.

Weaknesses of Standard Mitigation Designs

While NFPA 855 has succeeded in providing a consistent framework for BESS hazard mitigation, such as for explosion or deflagration, it is also important to consider the shortcomings of NFPA 855. For example, considering the fast pace of technological innovations when it comes to LIBs and BESS, NFPA 855 may not be up to date with evolving technologies. In regard to this idea, Close *et al.* [18] states, “Despite rapid battery evolution, codes and standards development has lagged, though they are crucial for safety, reliability, and interoperability. However, they mainly focus on generating data and pass/fail criteria, making reliance on testing alone inadvisable. UL 9540A and other standards offer different tests but lack guidance on understanding energy storage system risks, designs, and mitigation. Some regulations and standards struggle to keep up with evolving technologies and have overlooked critical inherent hazards like gases produced during thermal runaway and thermal propagation.” As such, it may be difficult for NFPA 855 to account for variations in new types of cell chemistries or BESS configurations which will become more prevalent in the market. It should also be considered that BESS installations are becoming increasingly large and complex, which can make it difficult for the current recommendations to account for all the nuances which may be associated with these larger systems.

There are also some challenges with the recommended explosion prevention systems, as dictated by NFPA 69, and explosion protection systems, as dictated by NFPA 68, within NFPA 855. On the one hand, NFPA 68 provides well-established explosion protection guidance in the form of deflagration venting, where vent systems relieve pressure by activating at lower pressures than the enclosure strength, and NFPA 69 recommends widely accepted methods of explosion prevention in the form of ventilation systems, where flammable gas concentrations are controlled and maintained below 25% of the LFL. These standards also cover a broad range of applications and scenarios, such as dust, gas, or hybrid mixtures, and various types of enclosures. However, it can be unclear when a certain type of BESS installation may benefit from an explosion prevention system versus an explosion protection system or even a combination of the two. It should additionally be noted that NFPA 68 and NFPA 69 were developed before the widespread use of LIBs and BESS. As such, they have been retrofitted to apply to BESS applications. As a result, the NFPA 68 or NFPA 69 deflagration mitigation recommendations can be inadequate or even impossible to achieve for certain BESS designs depending on the number of cells involved in a TR event that may lead to deflagration, the response time of sensors or fans, or other parameters impacting the response.

NFPA 68 Approach

Following the NFPA 68 evaluation process, it is possible to have a vent area requirement that is greater than the available roof area of the BESS enclosure. To demonstrate this possibility, the parameters given in Table 2 can



be used to calculate the vent area of a particular BESS enclosure as dictated by NFPA 68 for different LIB cell venting conditions, with the calculation method subsequently described.

Table 2. List of Parameters which Affect NFPA 68 Vent Area Calculation

Parameter	Value	Definition	Notes
P_{red}	20 kPa-g (0.2 bar-g, 3 psi-g)	Design reduced pressure	Reduced pressure required to avoid catastrophic failure [1]
S_u	0.613 m/s	Fundamental burning velocity	Average of sample data [15]
P_0	0 kPa-g (0 bar-g)	Initial enclosure pressure	Atmospheric pressure
P_{stat}	0 kPa-g (0 bar-g)	Vent deployment pressure	Assumed open container roof
H_{flame}	ISO container width in m	Maximum flame length	Based on ISO container dimension constant across different containers
G_u	230.1 kg/m ² ·s	Unburned gas-air mixture sonic flow mass flux	NFPA 68 Eq. 7.2.3.4 [9]
Y_b	1.15	Ratio of specific heats for unburned gas mixture	NFPA 68 Eq. 7.2.4.5 [9]
C_d	0.8	Vent flow discharge coefficient	NFPA 68 Eq. 7.2.4.1 [9]
A_{veff}	ISO container roof area in m ²	Effective area per vent closure	Assumed open container roof
# vents	1	Number of vent closures/panels	Assumed open container roof
X_{st}	0.28	Stoichiometric volume concentration	Based on average vent gas composition from sample data [15]
M_g	23.78 kg/kmol	Molecular weight of LIB cell vent gas	Based on average vent gas composition from sample data [15]
V_{gas}	0.154x m ³	Maximum gas volume released	A multiple (x) of the average sample data [15]
V_{free}	20% enclosure volume	Volume within enclosure not occupied by internal components	Assumed value
P_{max}	693x kPa-g (6.93x bar-g)	Maximum explosion pressure	A multiple (x) of the average sample data [15]

To determine the final vent area, Equation 7.2.1a in NFPA 68 [9] is first used to calculate an initial vent area, A_{v0} , which does not account for partial volume effects,

$$A_{v0} = \frac{A_s C}{\sqrt{P_{red}}}$$

where A_s is the enclosure internal surface area, C is the C value for flammable gases based on Equation 7.2.1b from NFPA 68 [9], as defined below, and P_{red} is the maximum pressure developed in a vented enclosure during a vented deflagration (as opposed to a non-vented deflagration). In Table 2, P_{red} is an assumed value of 20 kPa-g



(0.2 bar-g, 3 psi-g), as this is when catastrophic rupture of an enclosure can occur [1]. Additionally, for the A_{V0} equation to hold true if P_{red} is greater than 0.1 kPa-g, the vent deployment pressure, P_{stat} , must be less than or equal to $0.75P_{red}$, as per Equation 7.2.1.2 of NFPA 68 [9]. For this particular example, the vent area is assumed to be open with P_{stat} equal to 0 kPa-g, as given in Table 2, satisfying the requirement for calculating A_{V0} using this method.

When calculating C , several new parameters are introduced. Here, S_u is the fundamental burning velocity of the gas-air mixture. Next, the mass density of the unburned gas-air mixture, ρ_u , is defined by the ideal gas law at room temperature (293.15 K), the pressure inside the enclosure before ignition, P_0 , and a molecular weight, M_{mix} , as subsequently calculated. The variable, λ , as defined by Equation 7.2.6.7 in NFPA 68 [9], is the ratio of gas-air mixture burning velocity accounting for turbulence and flame instabilities in vented deflagration to the fundamental laminar burning velocity based on the maximum flame height, H_{flame} . The unburned gas-air mixture sonic flow mass flux is G_u ; the vent flow discharge coefficient is C_d , and the ratio of specific heats for the burned gas-air mixture is γ_b .

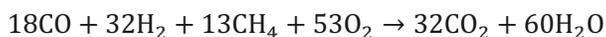
$$C = \frac{S_u \rho_u \lambda}{2G_u C_d} \left[\left(\frac{P_{max} + 1}{P_0 + 1} \right)^{1/\gamma_b} - 1 \right] (P_0 + 1)^{1/2}$$

In Table 2, S_u is taken directly as an average of the S_u measured for each cell tested in a sample dataset of single-cell UL 9540A tests [15]. When calculating ρ_u , P_0 is assumed to be 0 bar-g. The H_{flame} value used to calculate λ is set to the width dimension, 2.4 m (8 ft), of an ISO container, which is constant across all container sizes. The parameters G_u and γ_b are the constants 230.1 kg/m²-s and 1.15, respectively, based on the assumption of a 298.15 K ambient temperature initially in the enclosure (Equation 7.2.3.4 in NFPA 68 [9]), with γ_b requiring the additional assumption of less than 5% stoichiometric concentration initially (Equation 7.2.3.5 in NFPA 68 [9]). The coefficient C_d is a constant 0.8, as defined by Equation 7.2.4.1 in NFPA 68 [9], due to the assumption that the vent occupies the entire roof of the enclosure. This assumption is reflected Table 2 with the effective area per vent closure, A_{veff} , being defined as the entire roof area of the enclosure and the # vents being equal to 1.

Next, the equation below is used to calculate the molecular weight of the gas-air mixture inside the container, M_{mix} , in order to define ρ_u in the equation for C . Here, x_{st} is the stoichiometric volume concentration of the gas in the enclosure, including the LIB vent gas and air, by volume percent; M_g is the molecular weight of the vent gas, and M_{air} is the molecular weight of air (28.8 kg/kmol).

$$M_{mix} = x_{st}M_g + (1 - x_{st})M_{air}$$

For x_{st} and M_g , the average vent gas composition from cells undergoing TR was determined from the sample dataset [15], which spans various cell chemistries and form factors. It was found that the average vent gas composition was 18% CO, 36% CO₂, 32% H₂, and 14% UHCs, resulting in an average M_g of 23.78 kg/kmol, as given in Table 2. Excluding the inert CO₂ component, the remaining components of the vent gas result in the following stoichiometric reaction, assuming that the UHCs can be represented by CH₄ for simplicity.



Accounting for the inert CO₂ that is present throughout the reaction as well as the other components of air aside from O₂, the resulting x_{st} of the average vent gas is 0.28, as reported in Table 2.



Finally, Equation 7.3.3 from NFPA 68 [9] is used to determine the vent area when accounting for partial volume effects using the previously calculated A_{v0} ,

$$A_{v1} = A_{v0} X_r^{-1/3} \sqrt{\frac{X_r - (P_{red}/P_{max})}{1 - (P_{red}/P_{max})}}$$

where A_{v1} is the vent area for partial volume deflagration. Next, X_r is the fill fraction, defined by Equation 7.3.2 in NFPA 68 as the ratio of the volume of vent gas released by the involved LIB cell(s), V_{gas} , to free air volume, V_{free} , divided by the stoichiometric volume concentration of gas, x_{st} [9]. Finally, P_{max} is the maximum pressure developed in a non-vented enclosure during a deflagration by ignition of the same gas-air mixture used to calculate P_{red} . NFPA 68 can be referenced for more details on the method to calculate the vent area [9].

For calculating X_r , V_{free} is defined as an assumed value of 20% of the total enclosure volume, as given in Table 2. The pressure, P_{max} , along with other volume, V_{gas} , used to calculate X_r are both found from direct measurements of these respective parameter during the single-cell tests from the sample dataset [15]. However, it is possible that multiple cells can be involved in a TR event, which would result in increased values for both V_{gas} and P_{max} and must be accounted for. For V_{gas} , this volume is proportional to the number of LIB cells involved in TR, so this parameter is a multiple of the average single-cell volume of gas released, 154 L, found from the sample dataset [15], as shown in Table 2. For reference, an LIB releasing 154 L of vent gas during TR can be approximated as a 130 Ah capacity LFP cell based on the 1.2 L/Ah gas release volume given in Table 1.

Likewise, a similar logic is used for P_{max} . The equation below shows how P_{max} for an explosion can be estimated using the ideal gas equation of state,

$$P_{max} = \frac{n_p RT_A}{V_{free}}$$

where n_p is the total number of moles of product present in the volume, V_{free} , R is the ideal gas constant, and T_A is the adiabatic flame temperature of the reaction [19]. Assuming there is enough oxidizer present, the total amount of product present in the volume after a deflagration event should increase proportionally to V_{gas} , which again, is dependent on the number of cells reacting. As a result, P_{max} in Table 2 is defined as a multiple of the average 693 kPa-g (6.93 bar-g) P_{max} value from single-cell tests [15].

The final results of the vent area calculations are reported in Table 3 for four ISO container sizes used for BESS with assumed free air volumes of 20%. The number of 130 Ah reacting cells producing 154 L of vent gas each in a TR event was maximized according to the deflagration venting capabilities of each ISO container as per NFPA 68 design and fulfilling the requirement of not exceeding the 20 kPa-g (0.2 bar-g, 3 psi-g) overpressure limit that can result in catastrophic failure of an enclosure [1]. Based on the resulting total amount of vent gas produced by these cells, a number of equivalent higher capacity, 280 Ah, cells which produce 645 L of vent gas per cell in TR was also determined. This vent gas release volume is of note because it corresponds to the maximum released volume of vent gas from a single cell in the sample dataset [15] and produces a worse scenario than the average, smaller-capacity cells that only produce 154 L of vent gas per cell.



Table 3. Maximum Vent Gas Volume Released from Cells during TR Accommodated by Various ISO Containers with 20% Free Air Volume before Exceeding 20 kPa-g (3 psi-g) Overpressure Limit following NFPA 68 Calculation Method

Assumed LFL Vent Gas and Ventilation Variables	ISO Container Dimensions			
	8-ft Container 2.4 x 2.4 x 2.4 m ³	20-ft Container 6.0 x 2.4 x 2.4 m ³	27-ft Container 8.0 x 2.4 x 2.4 m ³	40-ft Container 12 x 2.4 x 2.4 m ³
Container Ceiling Area	5.76 m ²	14.4 m ²	19.2 m ²	28.8 m ²
Free Air Volume (assumed 20% total volume)	2.76 m ³	6.91 m ³	9.22 m ³	13.8 m ³
Maximum Flame Length (ISO container width)	2.4 m	2.4 m	2.4 m	2.4 m
# Reacting Cells (154 L Released per 130 Ah Cell)	6.9 Cells	8 Cells	8.4 Cells	9.0 Cells
# Reacting Cells (645 L Released per 280 Ah Cell)	1.7 Cells	1.9 Cells	2.0 Cells	2.1 Cells
Resulting Vent Gas Volume	1063 L	1232 L	1294 L	1386 L
Total Required Vent Area for # Reacting Cells Adjusted for Partial Volume Effects	5.72 m²	14.3 m²	19.0 m²	28.7 m²

For the smallest size ISO container (8-ft container), a TR event involving 1063 L of vent gas is the maximum that can be accommodated by a deflagration protection system as dictated by NFPA 68. Recall that NFPA 68 designates that vents be located such that expelled material is directed to result in the least amount of damage [6], which usually results in the vents being placed on the roof of the enclosure. For the 8-ft ISO container, the ceiling size is 5.76 m², and the required vent area to successfully manage 1063 L of vent gas is 5.72 m², or 99% of the total available ceiling area of the 8-ft ISO container. The maximum amount of vent gas each of the other ISO containers can handle with an NFPA 68 deflagration protection system scales up with their size, with the largest analyzed ISO container (40-ft container) being able to accommodate 1386 L of gas with a vent area of 28.7 m², or again, 99% of the available 28.8 m² roof area.

To bring these figures into perspective, for the 130 Ah capacity cells which produce the average 154 L of vent gas each, 6.9 cells will produce the volume of vent gas that maxes out the capabilities of the 8-ft ISO container deflagration protection system, with that number scaling up to 9.0 cells for the 40-ft ISO container. While it is unlikely that 6-9 LIB cells will experience TR simultaneously, for the larger capacity 280 Ah cells, the maximum volume of gas that can be handled by an NFPA 68 deflagration protection system is produced by less than 2 cells for the 8-ft ISO container and just over 2 cells for the 40-ft ISO container. As such, if a second cell in these scenarios were to become involved, there would likely not be enough vent space available on practically any of the analyzed enclosures, and the pressure limit of 20 kPa-g (0.2 bar-g, 3 psi-g) would be surpassed if deflagration were to occur, leading to failure of the enclosure.

Additionally, the amount of vent gas produced by the cells in these examples may actually be an underestimation of the amount of vent gas that will be released by cells in practice moving forward. Part of the evolving technology of LIBs is to increase the capacity of the cells. Given that the data from the sample



dataset [15] was acquired over the last several years, the capacity of these cells is likely already out of date, as cells of 500 Ah or even 1000 Ah capacity are beginning to become available. Referring back to Table 1, the volume of vent gas produced for LFP cells, for example, is 1.2 L/Ah. For these new, extremely large capacity cells, this could result in upwards of 1200 L of vent gas produced from just a *single* cell, which is above or nearing the volume of vent gas that can be accommodated by any of the deflagration vent systems represented in Table 3 for any ISO container BESS enclosure. It also must be kept in mind that these results are true only for enclosures with 20% free air volume; however, Figure 8 shows that variations of the free air volume can decrease the volume of vent gas that can be accommodated in a deflagration vent system. As illustrated in the figure, increasing the free air volume actually results in a reduction in the accommodated vent gas volume, due to interactions with the volume expansion occurring during a deflagration event. As such, it is clear that there are some limitations to when an NFPA 68 deflagration protection system may be utilized as a stand-alone system for some types of BESS enclosures, such as the standard ISO-sized enclosures analyzed here.

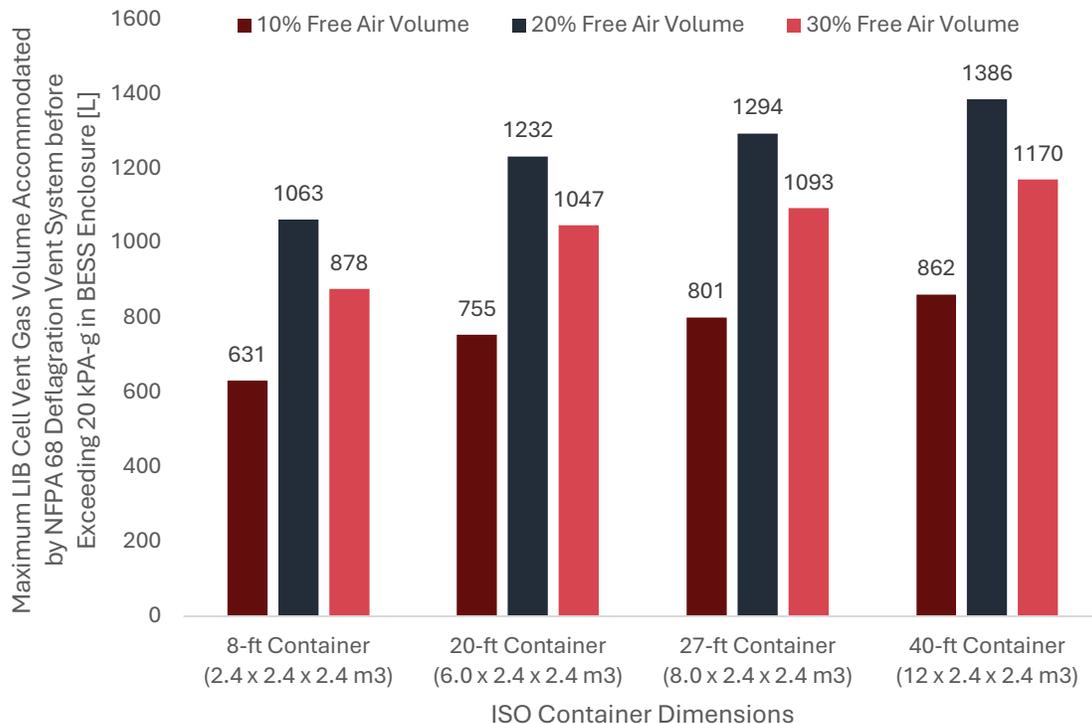


Figure 8 Maximum LIB Cell Vent Gas Volume Accommodated by NFPA 68 Deflagration Vent System before Exceeding 20 kPa-g (0.2 bar-g, 3 psi-g) in BESS Enclosure for Various BESS Enclosure ISO Container Sizes

NFPA 69 Approach

The recommendations from NFPA 69 for explosion prevention designs can suffer from challenges similar to those of the explosion protection designs recommended by NFPA 68. While NFPA 69 specifies a maximum flammable gas concentration, either 25% of the LFL or 60% of the LFL for SIL 2 monitored systems [2, 8], and a minimum ventilation rate, these design parameters may not work for every BESS installation.



To illustrate an example scenario, a simple mass balance, shown below, is used to account for the total mass change rate, \dot{m}_{total} , in an enclosure. This total mass change rate is dictated by the vent gas released by LIB cells during TR, \dot{m}_{gas} , the mixture of vent gas and air removed from the enclosure by the ventilation system, \dot{m}_{vent} , and the amount of fresh air brought into the enclosure by the ventilation system, \dot{m}_{air} .

$$\dot{m}_{\text{total}} = \dot{m}_{\text{gas}} - \dot{m}_{\text{vent}} + \dot{m}_{\text{air}}$$

To simplify the problem, it was assumed that the vent gas and air instantaneously and perfectly mix inside the BESS container and that the fans turn on immediately when vent gas begins to release from the LIB cell with no acceleration or deceleration delay. Just as with the deflagration venting system calculation, the free air volume of an ISO container was assumed to be 20% of the total volume. Based on internal tests, a 65 L/s gas release rate was used; however, in practice, this vent gas release rate will depend on the individual cell. From the sample dataset [15], the minimum and maximum LFLs of LIB cell vent gas were found to be 4.00% and 20.2%, respectively, which bounds the range of potential LFL values for cell vent gas, but it should also be kept in mind that the average LFL, 7.4% [15], skews toward the lower end of this range. Results using both these LFL bounding values are presented to represent a worst-case scenario for the lower LFL and a best-case scenario for the higher LFL. Finally, the ventilation rate was based on the footprint of the BESS enclosure. Here, four ISO container sizes are used along with a ventilation rate of 0.3 m³/min for each square meter of floor area, as specified as the minimum requirement in NFPA 69 [8]. However, regardless of the floor area, the minimum ventilation rate is 4 m³/min or 0.067 m³/s [8].

The ventilation rates for each of the four BESS ISO containers along with the resulting maximum amount of vent gas produced by the LIB cells that can be handled by each of the respective ventilation systems, *i.e.* the system is able to maintain a gas concentration of 25% of the LFL or lower, are reported in Table 4 for both the cell vent gases which have an LFL of 4.00% and an LFL of 20.2%. The number of cells simultaneously in TR needed to create this volume of vent gas is also reported using both the average vent gas production per cell of 154 L (130 Ah capacity cell) and the maximum vent gas production per cell of 645 L (280 Ah capacity cell) from the sample dataset [15]. Figure 9 also demonstrates the concentration of vent gas in the system for these 154 L (Figure 9a) and 645 L (Figure 9b) volumes of vent gas produced by the cells for the various ISO containers and their respective NFPA 69 minimum ventilation rates over time to illustrate the buildup of gas within a BESS enclosure and how long it might take for the ventilation system to remove the vent gas.

The results in Table 4 show that the minimum ventilation rate required by NFPA 69 is inadequate for many of the analyzed systems. In many cases, even the vent gas produced by a single LIB cell was sufficient to overwhelm the system and drove the gas concentration above 25% of the LFL within the enclosure. For the vent gas with an LFL of 20.2%, between 137 L and 794 L of vent gas can be accommodated by the ventilation systems of the various sizes of ISO containers while keeping the gas concentration below 25% of the LFL. For the vent gas with an LFL of 4.00%, this drops to between just 25 L and 143 L of vent gas depending on the ISO container enclosure dimensions.

Also shown in Table 4, the ranges of vent gas volumes correspond to various numbers of cells which produce that volume of gas, depending on the capacity of the cell. For the 130 Ah cells which release 154 L of vent gas per cell in TR, a range of 0.89-5.2 cells can be accommodated by the ventilation systems of the various ISO containers when the vent gas has an LFL of 20.2%. The estimated number of cells accommodated by the various ventilation systems decreases as the ISO container gets smaller, with the minimum ventilation rate of the



smallest ISO container (8-ft container) being insufficient to handle the gas released from a single cell releasing 154 L of gas. If the capacity of the cells is increased to 280 Ah, the corresponding volume of vent gas per cell increases to 645 L for this particular cell from the sample dataset [15]. In this case, the ventilation system of the 40-ft ISO container is barely able to accommodate the vent gas volume from one cell, even for the vent gas with a 20.2% LFL, while the other enclosures are not able to keep the gas concentration within the enclosure below the limit of 25% of the LFL if even one cell were to release vent gas.

Table 4. Maximum Vent Gas Volume Released from Cells during TR Handled by Various ISO Containers with 20% Free Air Volume while Keeping Enclosure Gas Concentration below 25% LFL using NFPA 69 Minimum Ventilation Requirements

Assumed LFL	Vent Gas and Ventilation Variables	ISO Container Dimensions			
		8-ft Container 2.4 x 2.4 x 2.4 m ³	20-ft Container 6.0 x 2.4 x 2.4 m ³	27-ft Container 8.0 x 2.4 x 2.4 m ³	40-ft Container 12 x 2.4 x 2.4 m ³
-	NFPA 69 Minimum Required Ventilation Rate	0.067 m ³ /s	0.072 m ³ /s	0.096 m ³ /s	0.14 m ³ /s
4.00%	Maximum Cell Vent Gas Volume Handled by Minimum NFPA 69 Ventilation Requirements	25 L	71 L	94 L	143 L
	# Cells Required to Produce Vent Gas Released (154 L Released per 130 Ah Cell)	0.16 Cells	0.46 Cells	0.61 Cells	0.93 Cells
	# Cells Required to Produce Vent Gas Released (645 L Released per 280 Ah Cell)	0.039 Cells	0.11 Cells	0.15 Cells	0.22 Cells
20.2%	Maximum Cell Vent Gas Volume Handled by Minimum NFPA 69 Ventilation Requirements	137 L	381 L	513 L	794 L
	# Cells Required to Produce Vent Gas Released (154 L Released per 130 Ah Cell)	0.89 Cells	2.5 Cells	3.3 Cells	5.2 Cells
	# Cells Required to Produce Vent Gas Released (645 L Released per 280 Ah Cell)	0.21 Cells	0.59 Cells	0.80 Cells	1.2 Cells

For the scenario where vent gas with an LFL of 4.00% is produced, a single cell is sufficient to overwhelm all of the systems implementing the minimum NFPA 69 ventilation rate and exceed an average gas concentration of 25% of the LFL within the enclosures, as shown in Table 4. As previously mentioned, the capacity of LIB cells is increasing over time, so the results for the 645 L volume of vent gas released from one 280 Ah cell during TR are more representative of the higher capacity cells that are in use today. Since these higher capacity cells, such as 1000 Ah LIB cells, could produce more than twice as much volume of vent gas, around 1200 L for an LFP cell with a 1.2 L/Ah gas volume release rate [15], they could even more easily overwhelm an NFPA 69 ventilation system.

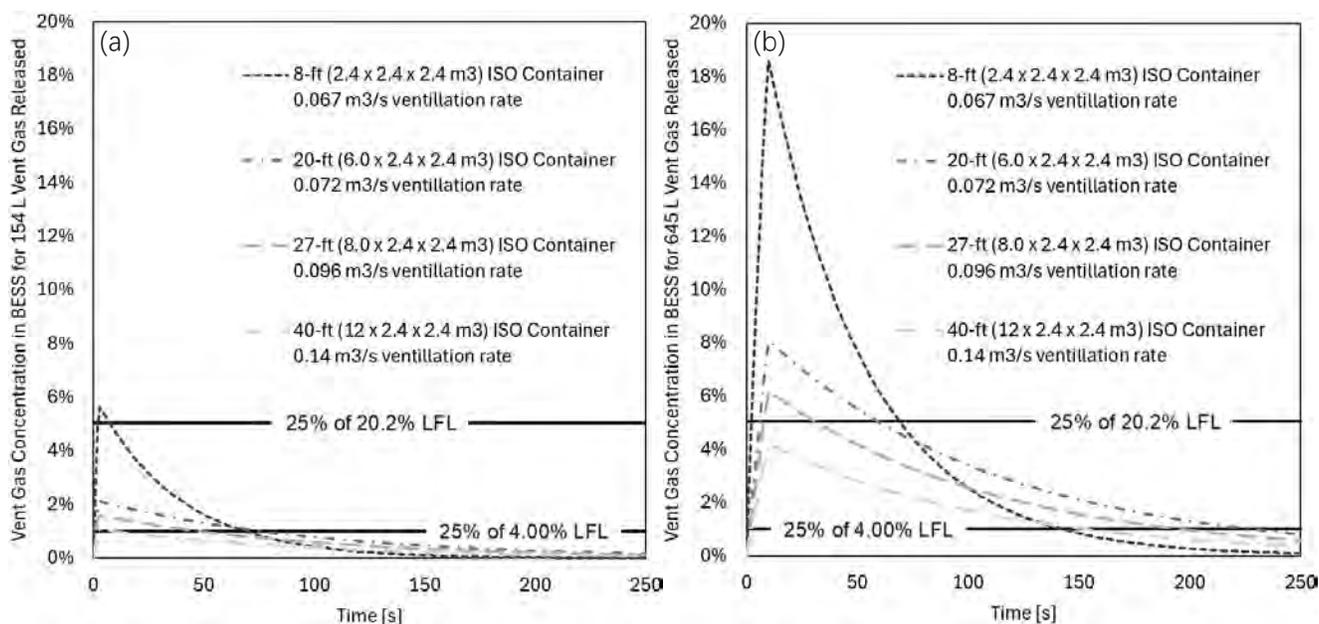


Figure 9 Resulting Vent Gas Concentrations for (a) 154 L and (b) 645 L Vent Gas Released in Various BESS ISO Containers with 20% Assumed Free Air Volume for NFPA 69 Minimum Required Ventilation Rate and 65 L/s Vent Gas Release Rate

If TR propagates, and more than one cell becomes involved, more vent gas would be released into the enclosure, and the ventilation results would change accordingly. Some example scenarios of more than one cell releasing vent gas are given in Figure 10 and Figure 11, with Figure 10 showing results for 154 L of vent gas released per cell, and Figure 11 showing results for 645 L of vent gas released per cell. Here, cells were assumed to enter TR successively, and a TR propagation rate of 1 cell per minute was assumed. For simplicity, a constant gas release rate throughout the duration of TR propagation was used, resulting in a 2.6 L/s release rate for the cells which release 154 L of vent gas (154 L/s / 60 s) and a 10.8 L/s release rate for the cells which release 645 L of vent gas (645 L/s / 60 s). The results in both figures reflect 10-cell TR propagation incidents with durations of 600 s each.

The results in Figure 10 and Figure 11 show that the vent gas release rate from the cells and the ventilation rate of the system will equalize over time and reach a steady-state concentration of the vent gas in the enclosure. For the scenario in Figure 10 where 154 L of vent gas is released per cell, the minimum ventilation rates are able to keep gas concentrations below the 25% of 20.2% LFL limit. However, the systems are unable to achieve the required gas concentrations throughout the duration of TR propagation if the LFL of the vent gas is reduced to 4.00%, or if, as shown in Figure 11, 645 L of vent gas is released per cell for either an LFL of 20.2% or 4.00%. Only once the TR propagation has subsided can the ventilation rates start to reduce the gas concentration in the enclosures. For the 154 L/cell vent gas release volume shown in Figure 10, the gas concentration decay takes approximately 50-100 s before the concentration returns back under the 25% of 4.00% LFL limit depending on the ventilation rate. Likewise, for the 645 L/cell vent gas release volume shown in Figure 11, the gas concentration decay takes between 50 s to nearly 150 s to reach the 25% of 20.2% LFL limit and over 400 s for some ventilation rates to reach the 25% of 4.00% LFL limit. These results show that the gas concentration within the analyzed enclosures would be above the NFPA 69 specified limit for approximately 1 minute per cell involved in TR, excluding the first minute of gas release when concentrations are still low, in addition to the 50-400 s required to reduce the gas concentration after TR has subsided, depending on the volume of vent gas released per cell and its LFL.

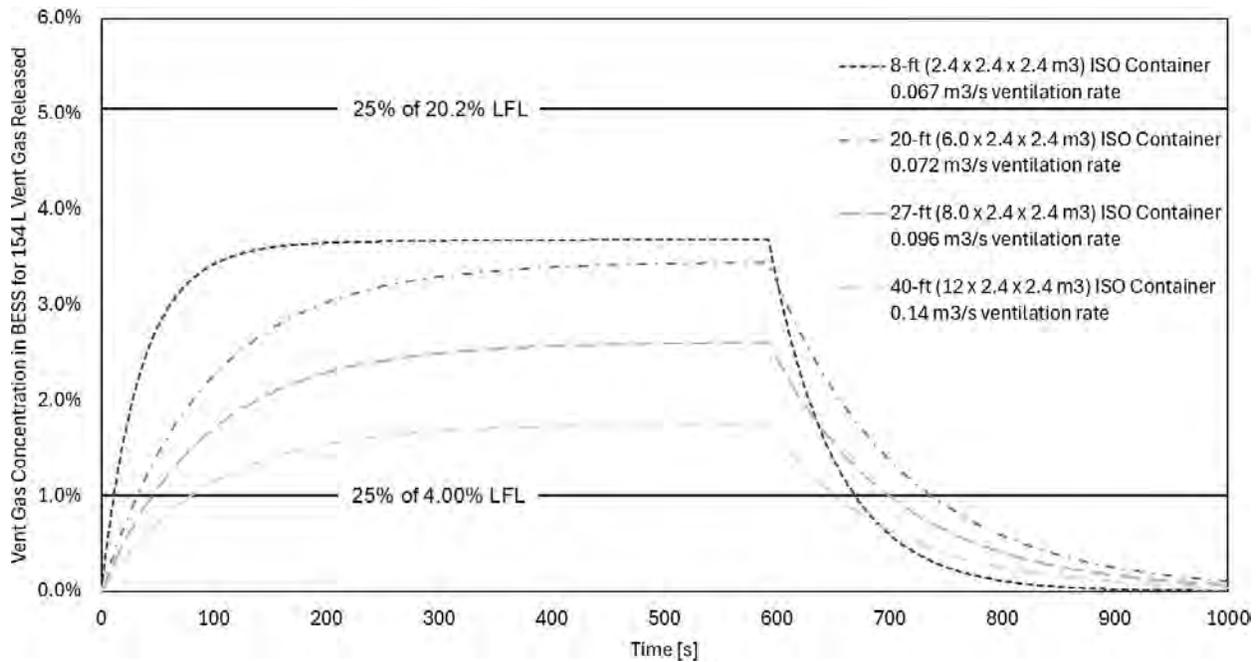


Figure 10 Resulting Vent Gas Concentrations for 154 L Vent Gas Released per Cell for 8-cell TR Event in Various BESS ISO Containers with 20% Assumed Free Air Volume for NFPA 69 Minimum Required Ventilation Rate and 2.6 L/s Vent Gas Release Rate (Approximately 1 cell/minute TR Propagation Rate)

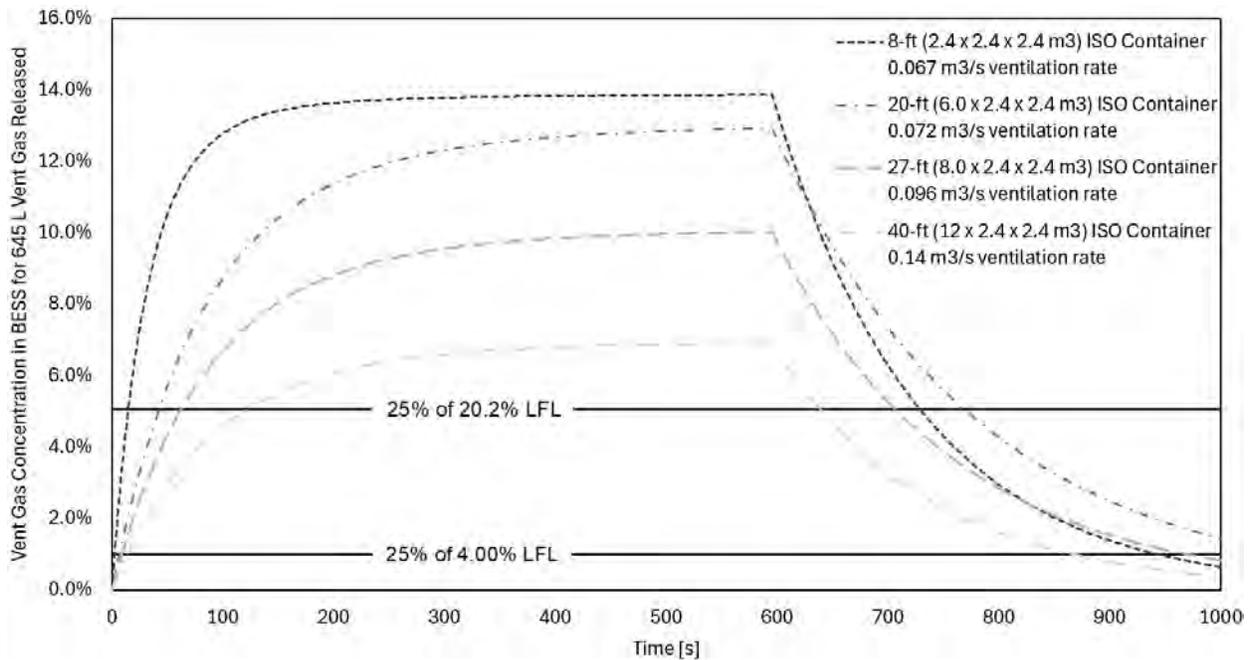


Figure 11 Resulting Vent Gas Concentrations for 645 L Vent Gas Released per Cell for 8-cell TR Event in Various BESS ISO Containers with 20% Assumed Free Air Volume for NFPA 69 Minimum Required Ventilation Rate and 10.8 L/s Vent Gas Release Rate (Approximately 1 cell/minute TR Propagation Rate)

Keeping these outcomes in mind, it is important to reiterate that the results shown in thus far are for the *minimum* ventilation requirements dictated in NFPA 69, so it is possible to increase the ventilation rates for



better outcomes; however this may not be readily accomplished or economical. For example, Figure 12 shows the ventilation rates required to maintain a gas concentration of 25% of the LFL for the four different scenarios analyzed: either a 20.2% LFL (Figure 12a,b) or 4.00% LFL (Figure 12c,d) and either 154 L (Figure 12a,c) or 645 L (Figure 12b,d) of vent gas released per cell, assuming only one cell goes to TR. If TR propagates to additional cells, the system parameters may need adjusting, as demonstrated in Figure 10 and Figure 11.

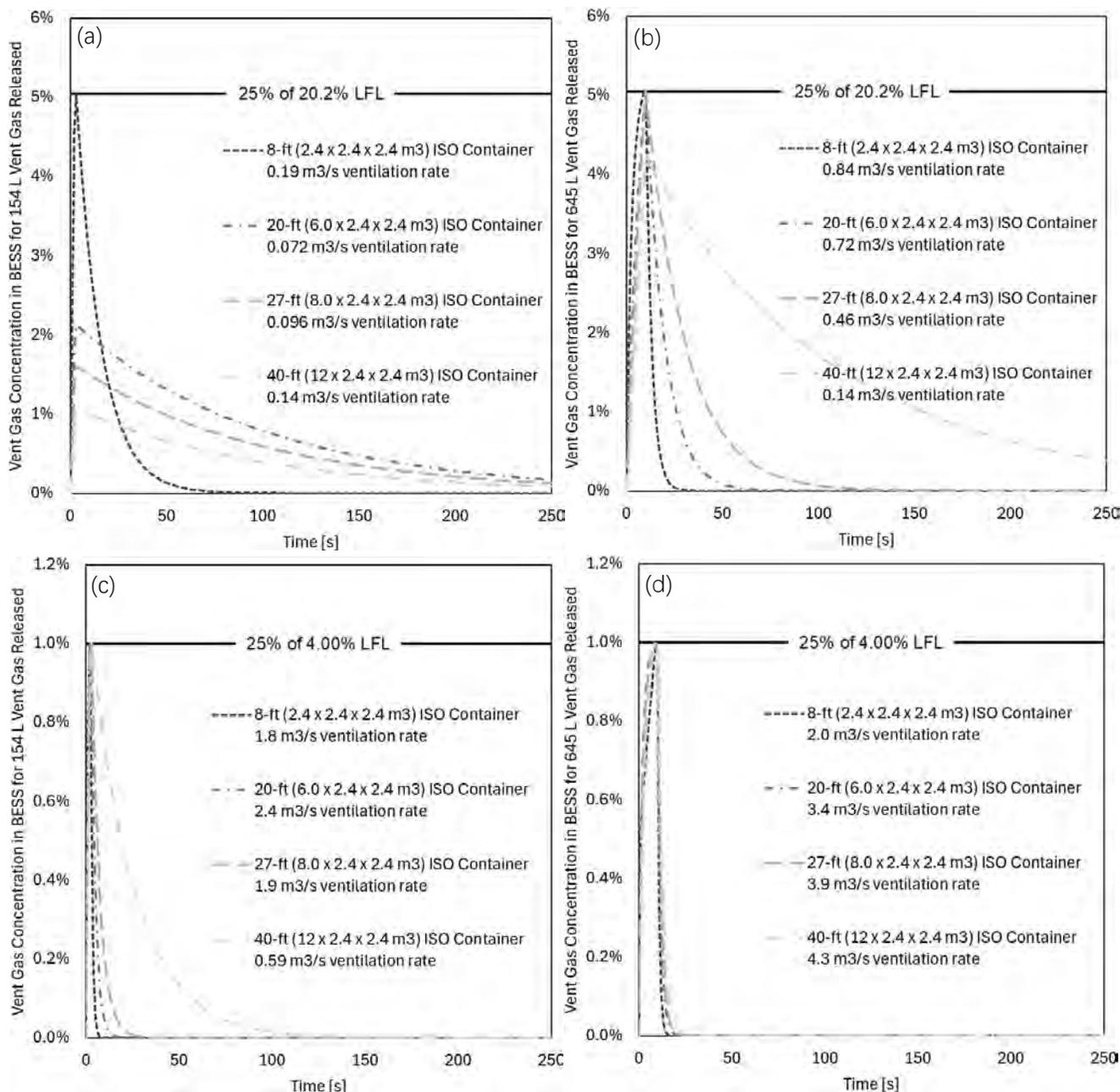


Figure 12 Resulting Vent Gas Concentrations in Various BESS ISO Containers for Ventilation Rates Needed to Maintain Gas Concentrations Below 25% of the LFL with Assumed Cell Vent Gas LFL of (a, b) 20.2% or (c, d) 4.00%, 65 L/s Vent Gas Release Rate, and (a, c) 154 L or (b, d) 645 L of Total Vent Gas Released



For the scenario shown in Figure 12a with a 20.2% LFL and 154 L of vent gas released from a cell, the three larger ISO containers can maintain their minimum ventilation rates given by NFPA 69. As shown in Figure 12b, the 40-ft ISO container is also able to handle the release of 645 L while utilizing its corresponding minimum ventilation rate; however, the smaller-sized containers are not, which is also reflected in Table 4. For the scenarios where the system is unable to handle the gas volume with only the NFPA 69 minimum ventilation rate, the necessary increase in ventilation is shown in Figure 13, where the open solid-line (20.2% LFL) and dashed-line (4.00% LFL) bars represent the multiples of the minimum ventilation rate required to always remain at a gas concentration below 25% of the LFL. Figure 12d shows the most demanding of the required ventilation rates, which represents 645 L of 4.00% LFL vent gas released from a cell. Figure 13 shows that the ventilation rates for each of the ISO containers for this scenario must be increased by 30-50 times above the minimum ventilation rate assigned by NFPA 69, corresponding to ventilation rates of 4200-9100 cfm, which would be more challenging to implement in actual systems. Additionally, if more than one cell were to produce vent gas or if higher capacity cells are used in the BESS, it is possible that the volume of gas produced could be impractical for the ventilation systems to handle.

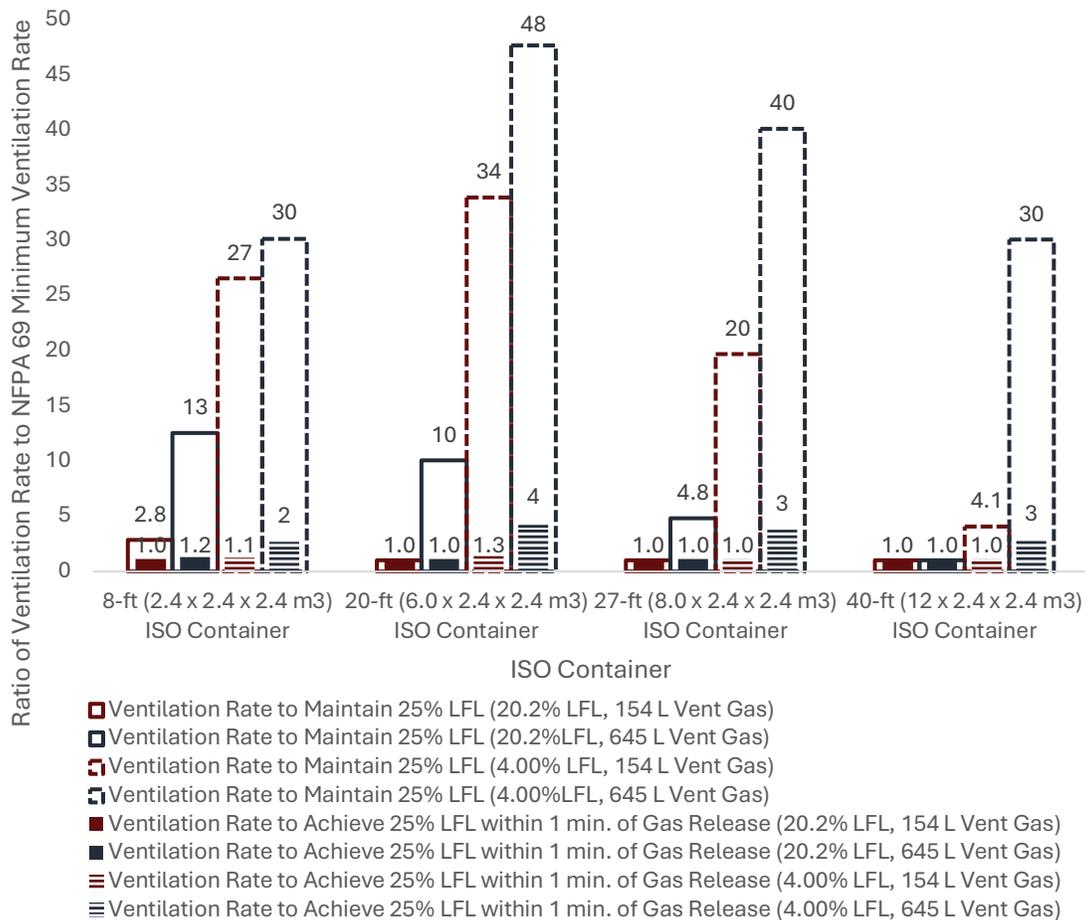


Figure 13 Ratio of Ventilation Rate to NFPA 69 Minimum Ventilation Rate for Various Vent Gas Scenarios and ISO Container Sizes with Assumed Free Air Volume of 20% and 65 L/s Vent Gas Release Rate

For a more manageable scenario than ensuring the gas concentration *never* exceeds the limit of 25% of the LFL, an analysis is also performed where the goal is shifted to achieve a gas concentration of 25% of the LFL in the BESS enclosure within 1 minute of when vent gas is released from the LIB cells. The variances in gas



concentrations over time for the various ISO containers for this new gas concentration goal are shown in Figure 14 for the vent gases with either 20.2% LFL (Figure 14a,b) or 4.00% LFL (Figure 14c,d) and either 154 L (Figure 14a,c) or 645 L (Figure 14b,d) of vent gas released from a cell. The corresponding multiples of the minimum ventilation rate for these four scenarios is represented in Figure 13 by the solid (20.2% LFL) and striped (4.00% LFL) bars.

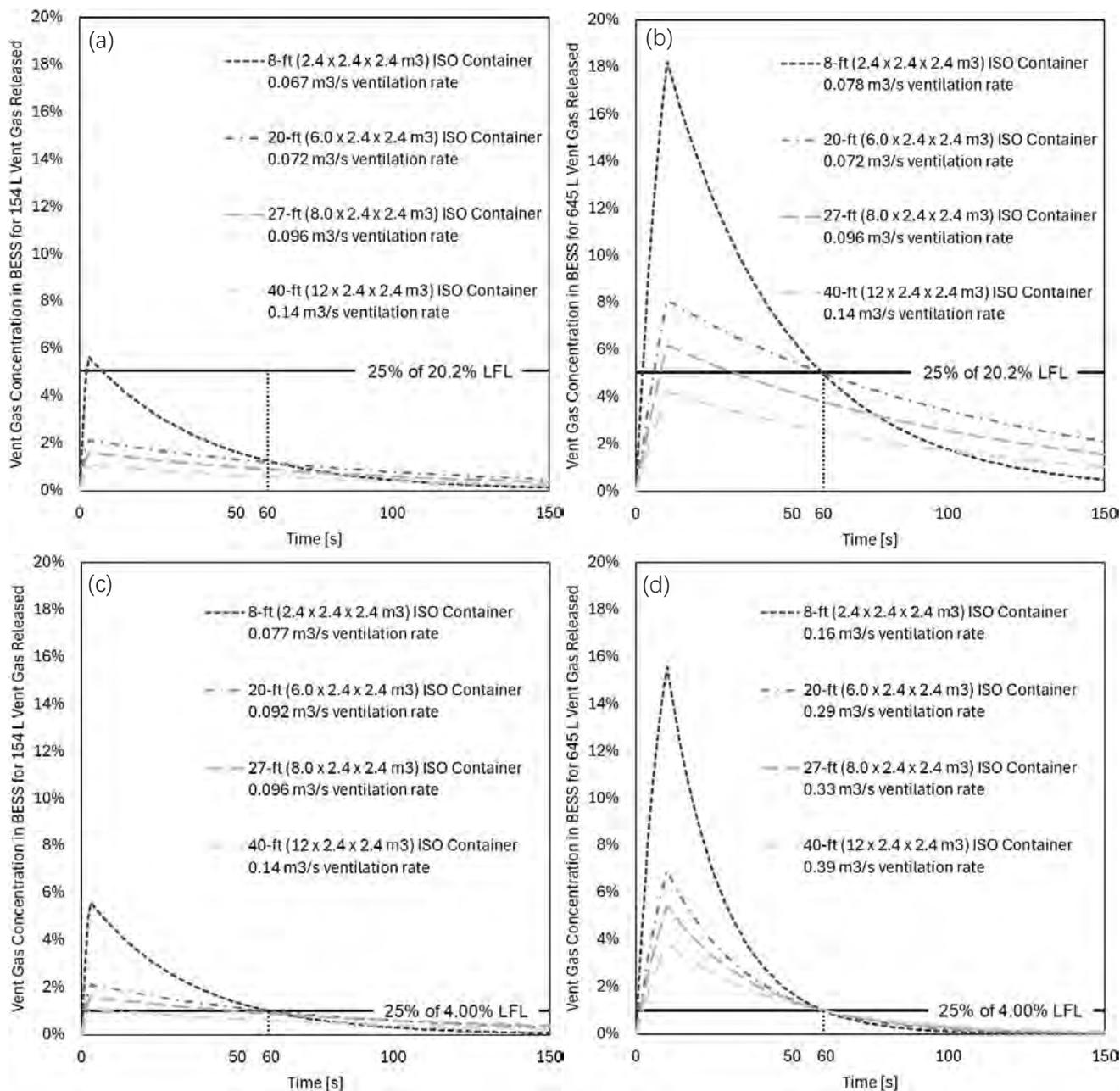


Figure 14 Resulting Vent Gas Concentrations in Various BESS ISO Containers for Ventilation Rates Needed to Maintain Gas Concentrations Below 25% of the LFL within 1 Minute of TR with Assumed Cell Vent Gas LFL of (a, b) 20.2% or (c, d) 4.00%, 65 L/s Vent Gas Release Rate, and (a, c) 154 L or (b, d) 645 L of Total Vent Gas Released



While it is ideal to keep the average gas concentration within the enclosure below 25% of the LFL at all times, decreasing the amount of time the vent gas concentration in above this limit from nearly 4 minutes in some cases for the minimum ventilation rate, as shown in Figure 9b, to 1 minute or less, as shown in Figure 14, is a great improvement. Minimizing these periods of higher flammable gas concentration is important because, for the entire time it takes to reduce the gas concentration down to the acceptable level of 25% of the LFL per NFPA 69, there may be a larger partial volume of gas that has the potential to be ignited.

As shown in Figure 13 and Figure 14a,b, the concentration of vent gas with the 20.2% LFL, for either 154 L or 645 L of vent gas released from one cell, can be reduced to 25% of the LFL or below within 1 minute using the minimum ventilation rate defined in NFPA 69 for all the ISO container sizes, except the 8-ft container, where the ventilation rate must be 1.2 times the minimum. The same is also true of the vent gas concentration for the gas with a 4.00% LFL if 154 L of vent gas is released, as shown in Figure 14c, with the highest ventilation rate required by one of the ISO containers in this scenario being just 1.3 times the minimum, as shown in Figure 13. However, if 645 L of vent gas is produced by a cell, as shown in Figure 14d, this is increased to 2-4 times the minimum ventilation rate, depending on the size of the ISO container, as also illustrated in Figure 13.

It is also imperative to remember that the scenarios discussed thus far have assumed perfect mixing of the vent gas and air within the BESS enclosure. Realistically, the gas dispersion and distribution in the enclosure will be uneven and transient, with an example of such behavior shown in Figure 15, and will vary depending on the gas release location and direction, the enclosure geometry and configuration, and the ventilation system design and operation. As a result, the gas concentration can vary significantly within the BESS enclosure, and even with a ventilation rate sufficient to keep the average gas concentration below 25% of the LFL, there will be some regions in the enclosure which have elevated concentrations that may be able to sustain combustion. As a result, it is generally beneficial to perform a CFD calculation to ensure that the ventilation system operates efficiently and to determine the quantity of gas that may exceed both 25% and 100% of the LFL such that a partial volume deflagration calculation can be performed.

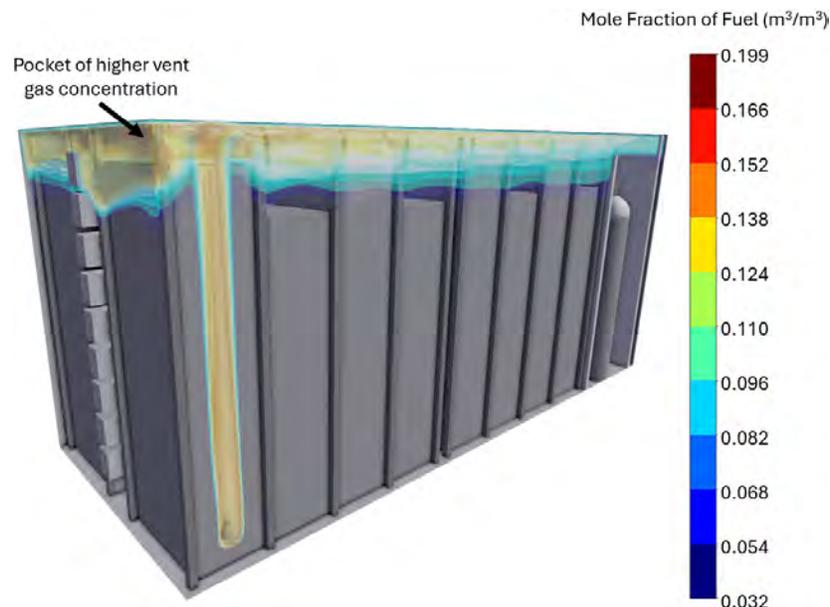


Figure 15 Example of Uneven Gas Dispersion from an LIB Cell in TR within the Free Air Volume of a BESS Enclosure



Overall, for both the explosion protection deflagration vent designs of NFPA 68 and the explosion prevention flammable gas ventilation designs of NFPA 69, it is difficult to account for variations in LIB cell behavior during TR, including how many cells may become involved overall or react simultaneously due to TR propagation. Depending on these variables, a wide range of gas volumes or environmental temperatures could be produced as a result of a TR event, which can affect the flammability of the gas. In turn, the volume of gas produced and its flammability affects the optimal design parameters of the mitigation systems, of which, some have been demonstrated to be impractical or even impossible in certain scenarios. Finally, as discussed in the subsequent subsection, NFPA 68 and NFPA 69 do not fully consider the consequences of prompt vs delayed ignition, which can lead to different deflagration scenarios and outcomes. As a result, a sensitivity analysis should always be performed to evaluate the range of system functionality vs what may be experienced.

Nuances of Prompt versus Delayed Ignition

An important aspect of deflagration events in BESS is whether the ignition causing the deflagration event happens immediately after the vent gas is released from an LIB cell or if the ignition is delayed. While prompt ignition is considered to happen within seconds after the initial cell venting, delayed ignition can happen minutes to hours later, depending on the gas accumulation, ventilation, and ignition sources [2]. Both prompt and delayed ignition can lead to deflagration events, but prompt ignition will typically result in partial deflagration and end in less catastrophic events, while delayed ignition will tend to result in more severe outcomes [2]. This correlation of ignition timing and the severity of the deflagration event comes down to earlier ignitions typically having less vent gas available to react, while later ignitions occur after an accumulation of the LIB cell vent gas, resulting in larger deflagration events [7]. Delayed ignition is particularly worrisome because it is often unexpected and can result in a large amount of heat released and large flame area, which can cause extensive damage to the enclosure and the nearby structures, especially if present vent panels are not opened or effective. In either case, a partial volume deflagration calculation should be performed and the results evaluated to determine the potential consequences.

Regarding this variation in deflagration behavior, Zalosh *et al.* [7] describe three potential ignition scenarios. The first is a prompt ignition which results in only a minor deflagration event and subsequent fire. In the second scenario, a delayed explosion occurs after an accumulation of flammable gases within the BESS enclosure due to cell venting as a result of TR. The third scenario encompasses both prompt and delayed ignitions where there may be an initial ignition of the cell vent gases soon after TR, but then there is an accumulation of incomplete combustion products. In this scenario, if oxygen is added to the system, say by a vent opening, the result could be an ignitable mixture of flammable gas.

Considering these three different scenarios and the potential unpredictability of prompt versus delayed ignition, it can be difficult to incorporate considerations for all deflagration possibilities in the BESS design. Between NFPA 68 and NFPA 69, the deflagration protection systems recommended in NFPA 68 can better control prompt ignition deflagration scenarios, and the deflagration prevention systems recommended in NFPA 69 can better prevent delayed ignition deflagration events [2]. However, while the intent of NFPA 69 is to prevent occurrences such as delayed ignition, recall that even when meeting the gas concentration requirements of 25% of the LFL on average, it is still possible to have pockets of higher concentrations of gases. NFPA 68 would help to mitigate the damage of a delayed ignition, but the concentration of flammable gas may result in a deflagration severity



beyond what was considered in the deflagration venting design. Overall, if deflagration is going to occur, the first scenario described by Zalosh *et al.* [7] with the prompt ignition of a small volume of vent gas present in the enclosure results in the most favorable outcome. While there are no current recommendations in NFPA 68 or NFPA 69 to help achieve this result, this is the objective of sparker-based systems, as discussed in a later section.



IMPROVING MITIGATION APPROACHES

Based on the current state of knowledge, research, and standards, as well as experience in the field, the following recommendations are suggested for designing deflagration mitigation systems for BESS.

Modeling Recommendations

One of the most important improvements that can be made when it comes to BESS deflagration mitigation design, which is also recommended by Close *et al.* [18], is to use a holistic approach that includes modeling beyond the empirical methods utilized in NFPA 68 and NFPA 69 to calculate design parameters. Such modeling should be in addition to the testing and analysis required by standards such as UL 9540A [20]. Modeling can be an important tool for designing and evaluating deflagration control systems for BESS, as it can provide insights into the physical and chemical processes involved in BESS deflagration as well as the performance and effectiveness of different deflagration control strategies.

Modeling BESS deflagration and its control is not a trivial task, as it involves multiple physical and chemical phenomena, such as gas generation, gas dispersion, gas accumulation, gas ignition, flame propagation, pressure rise, venting, and suppression. Moreover, modeling BESS deflagration and its control requires accurate and reliable input data and boundary conditions, such as the gas composition, concentration, and flammability, the enclosure geometry and strength, the vent device, if included, as well as certain environmental factors. Therefore, modeling BESS deflagration requires a comprehensive and systematic approach that can account for the complexity and uncertainty of the problem, in particular if the intent is to optimize the solution.

The analytical methods used in standards such as NFPA 68 and NFPA 69 are based on simplified mathematical equations that describe the processes involved in BESS deflagration. Analytical methods do have the advantage of being fast and easy to implement; however, they are also limited by the assumptions and simplifications that are made to obtain the mathematical solutions, such as the ideal gas law, perfect mixing, constant volume, uniform temperature, and adiabatic expansion. Therefore, analytical methods cannot capture the complex and dynamic phenomena involved in BESS deflagration and its control.

As such, other useful modeling tools are numerical methods and simulation, such as Computational Fluid Dynamics (CFD), which are based on the solution of discretized partial differential equations and can be more accurate and comprehensive than analytical methods by accounting for additional complexities and uncertainties of the problem. Numerical methods and simulations can also use different levels of detail or resolution for different phenomena or regions. Close *et al.* [18], Li *et al.* [21], Jeevarajan *et al.* [14], and Conzen *et al.* [5], all agree that CFD is an incredibly powerful tool when it comes to BESS deflagration mitigation design. While there are limitations to some methods, such as a lumped venting model, which does not consider gas dispersion, according to Close *et al.* [18], CFD overall provides many modeling capabilities. For example, in their study, Li *et al.* [21] report a comparison of results between a CFD FLame ACceleration Simulator (FLACS) model and experimental data, demonstrating how well the results match for overpressure in a BESS enclosure during a deflagration event for various ignition locations. While there is variation between the two results,



Li *et al.* emphasize that the model leans in a conservative direction and would, thus, lead to safer design [21]. Another example of a CFD FLACS simulation is given in Figure 16, which displays the results of modeling performed internally for the pressure change progression in an 8-ft-style ISO container BESS enclosure after the ignition of vent gas released from an LIB cell and the resulting partial deflagration.

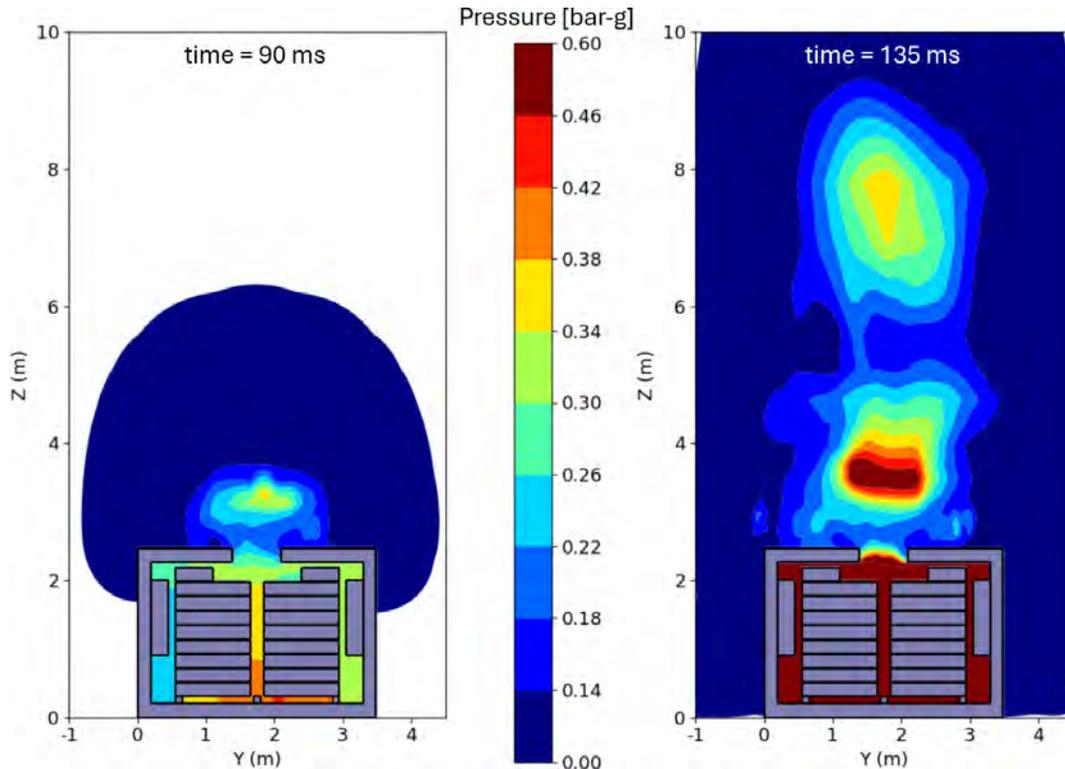


Figure 16 Example FLACS Modeling Results of Pressure at Different Time Stamps for Partial Deflagration Due to Ignition of LIB Cell Vent Gas in 8-ft ISO Container BESS Enclosure

Close *et al.* [18], Jeevarajan *et al.* [14], and Conzen *et al.* [5], indicate that one of the most important applications for CFD in the context of BESS deflagration mitigation systems is to create gas dispersion models which can provide detail on the accumulation of LIB cell vent gas in the event of TR, including how the gas accumulates within the BESS enclosure and where it becomes most concentrated, which can indicate the best locations for the exhaust fans used in ventilation systems [5]. Close *et al.* [18] and Jeevarajan *et al.* [14] additionally point out the strength of these CFD models to not only capture the dynamics within the BESS enclosure but also of the LIB cells themselves, including the volume of gas released, the type of gas released, and TR and its propagation.

However, numerical methods are also more computationally intensive and time-consuming than analytical methods. As such, hybrid methods based on a combination of analytical and numerical models, which can exploit the advantages and overcome the disadvantages of each method, can be another route to take. Hybrid methods can use analytical solutions to provide initial or boundary conditions for numerical simulations or use numerical simulations to calibrate or validate analytical models. Hybrid models can also use different methods for different subproblems or subdomains, such as using analytical methods for ventilation rates and using numerical methods for gas dispersion. Hybrid methods can additionally provide a balance between accuracy and efficiency and offer more flexibility and robustness than an analytical or numerical model alone.



With any model, it is important to keep in mind that modeling validation is an essential step for ensuring the credibility and applicability of the modeling methods and results. Modeling validation for deflagration prevention and control systems for BESS is not a trivial task, as it requires accurate and reliable experimental data, which may not be readily available due to limitations with accessibility of test facilities and equipment, the complexity of conducting fire and explosion tests, and the representativeness and scalability of the test conditions and results. As such, it is important for the BESS community to create an environment where test data is readily shared and available to support modeling efforts.

Overall, while modeling with applications to BESS deflagration mitigation design does have some drawbacks, including a tradeoff between accuracy and efficacy, sensitivity to uncertainty of modeling parameters, and a dependency on validating results, its pros far outweigh its cons. BESS deflagration mitigation models can be used to understand the mechanisms and the effects of deflagration in BESS, such as the gas generation, gas dispersion, gas accumulation, gas ignition, flame propagation, pressure rise, venting, and suppression. It can also be used to evaluate the performance and effectiveness of deflagration prevention and protection systems under various conditions as well as to optimize the design parameters and the operating conditions of deflagration mitigation systems, such as the vent size, location, and activation pressure or the gas detection method and removal rate.

Additional Considerations for Deflagration Protection and Prevention Systems

Careful consideration should be made regarding the vent panels used in deflagration protection systems. One important parameter is the number of vent panels included in the system and whether or not the enclosure door is designed to open, acting as a vent panel [2]. According to Barowy *et al.* [2], the door is often the weakest point of the enclosure, and thus dictates the overall strength of the container. Peng *et al.* [22] demonstrates that extreme care should be taken for this design decision, as they found that, “altering the vent door pressure, without the top vent panel, still leads to serious explosion accidents. There will be unacceptable overpressure for the container structure, as well as serious visible flames and high-speed airflow invading the external environment. Lower vented gas concentrations can reduce explosion hazards and introducing the vent panel design aids to promote such a reduction. The overpressure within the container is significantly decreased by guiding the top external secondary combustion through the vent panel.” As such, it is exceedingly important to ensure that the pressure does not exceed that which can turn the doors into projectiles, which can happen at pressures of around 70 kPa-g [2]; however, it can reduce the number of vent panels needed in the system if the doors are designed to open and relieve pressure in a safe manner. In addition, as mentioned earlier, NFPA 68 requires venting to a safe location; thus, utilizing the doors as a vent area is generally not considered a safe primary vent direction.

The strength of the enclosure is an additional design parameter that is crucial for deflagration protection systems. In NFPA 68, the enclosure strength is defined as the threshold pressure for either permanent deformation of the enclosure, known as the yield strength, or rupture of the enclosure, known as the ultimate strength, with the selection of the utilized definition dependent upon whether permanent deformation is tolerable for the particular system design [2]. This parameter is important not only for knowing the strength of the enclosure, but the vent sizing is additionally determined such that the pressure within the enclosure does not exceed two thirds of the



threshold pressure in the event of a deflagration [2]. Unfortunately, for most enclosures used for BESS applications, including the most popular option – the various-sized ISO containers discussed extensively in previous sections – the threshold pressure is not well defined [2]. As such, while the standard value of 20 kPa (0.2 bar-g, 3 psi-g) [1] or the even more conservative value in the range of 2–4 kPa (0.02–0.04 bar-g, 0.3–0.6 psi-g) [2] could be assumed as a maximum, testing on many of these enclosures should be performed to determine this parameter before proceeding with a deflagration mitigation design.

Another important consideration beyond what is specified in NFPA 68 is the angle of the vent panel door upon opening. Binbin *et al.* [23] tested deflagration results of LIBs that went to TR in confined spaces for three different open-door angles for vent panels: 30°, 60°, 90°. Overall, it was found that the 60° angle performed worst, as it created an environment in which not enough heat and flammable gases could be released, while oxygen was still entering the enclosure. For the 30° angle, less oxygen was able to flow into the container, resulting in less severe deflagration, and for the 90° angle, enough heat and combustible gases escaped from the containment that the deflagration severity was again reduced. However, deflagration still occurred in all cases, so if deflagration protection is not the sole objective of the mitigation system, control of the gas composition within the containment is also required to prevent deflagration.

The ventilation designs for deflagration prevention systems should also have additional considerations beyond NFPA 69. First, it is important to consider that the 60% or 25% LFL concentration thresholds dictated in NFPA 69 may only be achievable for a ventilation system if TR events only occur in very few cells or if events are staggered with adequate time between them [2], as it has been established that if excess vent gas is produced at once, it can quickly result in high concentrations of flammable gas. Additionally, given the possibility of uneven dispersion of the vent gas from the cells, it is also possible for pockets with high concentrations of vent gas to accumulate, with ignition of these volumes likely to result in at least a partial deflagration. As such, the modeling techniques described in the previous subsection should be utilized to determine the severity of TR events that may occur and the behavior of gas dispersion. The gas monitoring and ventilation systems should be designed accordingly, including additional venting via panels that may be required.

Alternative Deflagration Mitigation Methods

NFPA 68 and NFPA 69 are limited in their deflagration mitigation options by default. However, other methods for deflagration mitigation, including performance systems, such as those where doors or panels open upon gas detection [24], sparker systems, or other various approaches, can be employed as standalone systems or in conjunction with other mitigation approaches. Sparkers are devices used to deliberately ignite flammable gases in BESS enclosures in a controlled manner with the combustion products being vented out of the enclosure [4] via standard NFPA 68 deflagration panels or alternative vent paths.

These systems are designed to ensure that sparkers are in sufficient numbers and firing frequency such that ignition occurs with very little gas accumulation. The flammable gases are burned in quantities small enough such that there is no deflagration event, or the overpressure can be readily managed by the inclusion of vents in the enclosure. By intentionally igniting the gas, it prevents the buildup of flammable gases in the BESS enclosure which could lead to a larger pressure increase if ignition was delayed. A number of documented BESS failures



have been as a result of gas accumulation and delayed ignition [5]. In general, the sparker system would be designed to ensure that any resulting overpressure (with or without venting from the enclosure) would remain below at least the 20 kPa-g (0.2 bar-g, 3 psi-g) limit [1].

Overall, utilizing a combination of NFPA 68 and NFPA 69 methods in addition to alternative deflagration mitigation methods may be the best strategy to employ to ensure that the risk of deflagration is appropriately mitigated. Regardless of approach, the evaluation of the system needs to demonstrate that it meets the pressure threshold objectives.

Suppression System Interactions

If a suppression system is installed in a BESS, it can greatly change the performance of the deflagration mitigation system in the event of an LIB TR incident. However, there is varying guidance when it comes to suppression systems, with the main approaches being gaseous or aerosol suppression systems and water-based suppression systems. For gaseous suppression systems, specifically with condensed aerosol, there has been some evidence of their effectiveness in suppressing BESS fires [25]. Barowy *et al.* [2] has shown some success with CO₂ suppression systems in a research setting, where, in a 6.1 m (20 ft) long intermodal transport container, 90 kg (198 lbs) of CO₂ was used to terminate an LIB fire test in 3.5 hours. However, it has been demonstrated that these systems do not prevent TR propagation and may increase the deflagration risk as continued venting occurs, since the fire has been suppressed, and the flammable gases are able to accumulate rather than burn off.

Given the issues that gas suppression systems have caused in some past BESS failures, *i.e.* allowing for the buildup of gases which led to delayed ignition and deflagration [16, 17, 26], water suppression systems are generally the most widely recommended. For example, FM recommends water suppression systems over gas suppression systems because the gas systems have low efficacy, do not provide adequate cooling of the surroundings, and can only be discharged once, which may be an issue due to the possibility of multiple ignitions in a BESS failure [11]. Regarding efficacy, FM states that, “there is no evidence that gaseous protection is effective in extinguishing or controlling a fire involving energy storage systems. Gaseous protection systems may inert or interrupt the chemical reaction of the fire, but only for the duration of the hold time. The hold time is generally ten minutes, not long enough to fully extinguish an ESS fire or to prevent thermal runaway from propagating to adjacent modules or racks,” [11]. Cooling the surroundings is an important factor because it can help prevent TR from propagating as well as protect surrounding structures, which is critical because sprinkler systems cannot extinguish a BESS fire, and gaseous systems do not provide this cooling [11].

While water-based suppression systems do have some advantages, they are far from perfect. In a study by Barowy *et al.* [2], three LIB fire tests were performed: one with no fire suppression system, one with a Novec 1230 clean agent suppression system, and one with a water spray suppression system. The test with no fire suppression system resulted in a prompt ignition and deflagration just 31 s after the onset of TR in the initiating LIB cell. The test with the Novec 1230 suppression system resulted in three delayed ignition and deflagration events, including one that was large enough to activate the deflagration vents present in the system. Finally, the test with the water suppression system still resulted in a delayed ignition and deflagration



event while the sprinkler system was active, nearly 45 minutes after the initial onset of TR in an LIB. Additionally, water suppression systems suffer from the drawbacks of the potential for electrical short circuits to surrounding equipment, the possibility of water interacting with the chemicals in a BESS, and the hazard of contaminated water runoff [27].

There is no single ideal suppression approach, rather the hazards of each individual BESS and the interaction of the suppression system, needs to be evaluated to determine system performance and outcomes. Likely, a suppression system will be more effective in achieving the deflagration protection objectives if combined with one or more of the other mitigation strategies discussed previously, such as sparker systems.



DEFLAGRATION MITIGATION BESS DESIGN PROCESS

1. Ensure Enclosure Meets Pressure Requirements

Obtain confirmation (through testing, documentation, etc.) the pressure threshold, P_{red} , of the enclosure

Deflagration mitigation design should ensure that P_{red} , typically 3 psi-g, is never exceeded

2. Select Deflagration Mitigation System(s)

Passive
i.e. NFPA 68
Deflagration
Protection
System

Active
i.e. NFPA 69
Deflagration
Prevention
System

Sparker
Controlled
ignitions to
prevent buildup
of flammable gas

Performance
Automatic doors
or vents to lower
gas concentration
or pressure

3. Determine Design Parameters

Passive

Max. gas volume, V_{gas} , involved in deflagration without exceeding P_{red} is on order of 1200 L (typical gas releases: order of 1.2 L/Ah)

Active

Ventilation rate sufficient to reduce V_{gas} below 25% LFL in < 60 s to minimize window with flammable gas concentration above NFPA 69 threshold

Sparker

Place in sufficient numbers and locations to ensure pressure from ignition of gases < P_{red}

If necessary, deflagration panels or other vent paths should be provided to reduce overpressure

All Systems

Conduct dispersion analysis to determine concentration profile in enclosure as function of time

Perform partial deflagration calculation showing V_{gas} above LFL does not result in overpressure > P_{red}



CONCLUSIONS

Given the widespread use of BESS, it is important to ensure that these systems are safe, even in the event of cell failure and TR propagation. During TR, both flammable gases and sparks of molten material may be released from the cells, creating the risk for fire or deflagration. Currently, the design and installation of deflagration control systems for BESS are governed by several main codes and standards, including NFPA 855, which calls on NFPA 68 to provide guidance for deflagration protection systems and NFPA 69 to provide guidance for deflagration prevention systems. While NFPA 855 has been successful in regulating BESS, it and the other referenced standards are not always sufficient or up to date in addressing all of the specific challenges and needs of BESS deflagration mitigation, in particular as the industry rapidly evolves. As such, this document was created to provide information related to the primary objective of deflagration mitigation systems, the current status quo, challenges with existing mitigation approaches, and recommendations for deflagration mitigation in BESS.

Upon reviewing the current state-of-the-art guidance in deflagration control for BESS, including the relevant codes and standards, types of BESS installations, variables affecting the occurrence and severity of deflagration, and difficulties of current deflagration prevention and mitigation practices, several additional recommendations outside of current practices were identified and are summarized as follows:

1. Define acceptable pressure thresholds for the enclosures used in BESS to ensure catastrophic failure does not occur and no projectiles are created in the event of a deflagration or explosion.
2. If vent panels are utilized, such as in NFPA 68 deflagration protection systems, ensure that critical design parameters, such as the inclusion of the enclosure door as an additional panel or the opening angle of the vents, are carefully considered to maximize safety.
3. Better define failure behavior of the utilized LIBs cells, including the possibility of TR propagation and duration between venting of cells, to ensure NFPA 69 gas concentration requirements are achieved.
4. Readily share data, such as from UL 9540A testing, to better characterize LIB cells and their TR behavior.
5. More widely employ a holistic evaluation approach utilizing modeling and testing of BESS deflagration mitigation systems to:
 - Better understand the mechanisms and effects of deflagration in BESS.
 - Evaluate the performance of BESS deflagration prevention and protection systems.
 - Optimize the design parameters and operating conditions of BESS deflagration mitigation systems.
 - Identify the quantity and location of gas accumulated within BESS enclosures.
6. Consider alternative deflagration mitigation systems for use in BESS, such as sparker systems, which utilize controlled ignitions to reduce the buildup of flammable gases, or performance-based systems, which utilize automatic doors or vents.
7. Combine various mitigation techniques, as no one system alone exists without its drawbacks.



Building upon this summary, beyond what is provided in NFPA 68, it is recommended to better define acceptable threshold pressures for the enclosures used in BESS through testing to ensure that the doors, typically the weak point of the enclosure, do not become projectiles in the event of a deflagration or explosion. The angle of vent panel openings upon actuation also need to be considered, as different angles allow more or less oxygen to enter the enclosure while still retaining the flammable gas and heat within, requiring a balance to be struck between these two parameters.

Regarding considerations beyond NFPA 69, it is believed that modeling gas dispersion within an enclosure is paramount in determining if accumulation of higher gas concentrations will occur in areas within the enclosure, which can lead to better prevention system design, such as vent placement, to deal with these accumulations and prevent partial deflagrations. Additionally, the behavior of the LIBs cells used in the BESS needs to be better understood, which may also be achieved through modeling, as it may only be possible to remain under the required LFL levels dictated by NFPA 69 if TR events are limited in number or are staggered with adequate time between them. Readily sharing data, such as from UL 9540A testing, can additionally allow for better characterization of LIB cells, including the volume and composition of the flammable gas vented during TR, allowing for mitigation designs that are more curated than may be currently possible.

A holistic evaluation approach utilizing modeling and testing along with a hybrid mitigation approach is currently one of the strongest tools available when it comes to understanding BESS hazards and implementing mitigation systems. Modeling allows for scaling up to larger-sized tests when testing is impractical or for conducting sensitivity analyses that cannot be done practically. BESS deflagration mitigation models can be used to understand the mechanisms and effects of deflagration in BESS, such as the gas generation, gas dispersion, gas accumulation, gas ignition, flame propagation, pressure rise, and venting. They can also be used to evaluate the performance and effectiveness of deflagration prevention and protection systems under various conditions as well as to optimize the design parameters and operating conditions of deflagration mitigation systems, such as the vent size, location, and activation pressure or the gas detection method and removal rate.

Given that there are some BESS systems for which NFPA 68 or NFPA 69 deflagration mitigation recommendations are impractical for implementation due to either a lack of available vent area for deflagration protection or the inability to keep flammable gas concentrations below the required limit for deflagration prevention, other mitigation options need to be more widely utilized. One of the most prominent of these alternative deflagration mitigation strategies are sparker systems, which can be used to create controlled ignitions, reducing the amount of flammable gas in a BESS enclosure. These alternative deflagration mitigation systems may also perform better in conjunction with suppression systems compared to standard mitigation methods. For example, gaseous suppression systems, and water suppression systems to a lesser extent, can suffer from the buildup of flammable gases if LIB cells continue to release vent gas, leading to delayed deflagration. By combining these suppression systems with alternative deflagration mitigation systems, such as sparkers, the buildup of flammable gases can be better controlled.

Overall, the information contained herein acts as a valuable reference and provides guidance for researchers, engineers, and technicians among others who are involved in deflagration mitigation for BESS. With the review and analysis performed here along with the recommendations presented, it is believed that improvements to deflagration mitigation strategies and overall safety of BESS can be made.



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