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ESRG Sungrow PowerTitan 20 HAZARD MITIGATION ANALYSIS â€“ TRAIL ROAD BESS FACILITY

The attached document is a Hazard Mitigation Analysis which was prepared by ENERGY SAFETY RESPONSE GROUP, ESRG, for the Trail Road BESS in Ontario, Canada. Like the Prairie Song Reliability Project, the Trail Road BESS will utilize SUNGROW Power Titan 2.0 batteries.

This HMA by ESRG details all of the potential system failures which would in turn cause the Power Titan 2.0 LFP batteries to fail. It determines the end result of each type of failure, which includes potential for explosion and the release of highly toxic gases.

For the Trail Road BESS, many of the risks are very simply mitigated through proper siting away from residential development, with only one home in proximity.

The Prairie Song will not be able to mitigate the majority of the risks posed by the Power Titan 2.0â€™s Lithium Iron Phosphate batteries because they have chosen a site in proximity to many homes and within a major transportation corridor.

Proper siting is crucial with regards to any BESS development which utilizes Lithium-Ion technology.

Additional submitted attachment is included below.

Sungrow PowerTitan 2.0

HAZARD MITIGATION ANALYSIS – TRAIL ROAD BESS FACILITY

Rev 1 | May, 2025

SUMMARY

This document serves as the Hazard Mitigation Analysis performed for the Sungrow *PowerTitan 2.0* battery energy storage system proposed for use in the Trail Road BESS Facility.

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1 INTRODUCTION

1.1 Background

Energy Safety Response Group (ESRG) has been retained by Evolugen to perform a site-specific Hazard Mitigation Analysis (HMA) in accordance with *2023 NFPA 855 Standard for the Installation of Stationary Energy Storage Systems §4.4 Hazard Mitigation Analysis* for the proposed Trail Road BESS facility located at 4186 William McEwen Drive, Richmond ON, K0A 2E0, Canada.

This report is intended specifically for the Trail Road BESS facility application, and does not necessarily imply acceptance by Authorities Having Jurisdiction (AHJs) who may adhere to different local codes and standards.

1.2 Applicable Codes and Standards

This hazard mitigation analysis is conducted in accordance with *NFPA 855 §4.4 Hazard Mitigation Analysis* and evaluates the consequences of the following failure modes as required per *§4.4.2.1:*

(1) A thermal runaway or mechanical failure condition in a single ESS unit

(2) Failure of an energy storage management system or protection system that is not covered by the product listing failure modes and effects analysis (FMEA)

(3) Failure of a required protection system including, but not limited to, ventilation (HVAC), exhaust ventilation, smoke detection, fire suppression, or gas detection

Per *NFPA 855 §4.4.3,* the AHJ shall be permitted to approve the hazardous mitigation analysis as documentation of the safety of the ESS installation provided the consequences of the analysis demonstrate the following:

(1) Fires will be contained within unoccupied ESS rooms for the minimum duration of the fire resistance rating specified in [2023 NFPA 855 9.6.4].

(2) Fires and products of combustion will not prevent occupants from evacuating to a safe location.

(3) Deflagration hazards will be addressed by an explosion control or other system.

Additional codes, standards, and local requirements referenced throughout this report include:

- *NFPA 855 Standard for the Installation of Stationary Energy Storage Systems*, 2023 Edition
- *UL 9540A Standard for Test Method for Evaluation Thermal Runaway Fire Propagation in Battery Energy Storage Systems,* 4th Edition
- *UL 9540 Standard for Energy Storage Systems and Equipment,* 2nd Edition
- *NFPA 68 Standard on Explosion Protection by Deflagration Venting,* 2018 Edition
- *NFPA 69 Standard on Explosion Prevention Systems,* 2019 Edition

- *UL 1973 Standard for Batteries for Use in Stationary, Vehicle Auxiliary Power and Light Electric Rail (LER) Applications, 2018 Edition*

1.3 Summary of Findings

- The Sungrow *PowerTitan 2.0* is equipped with a number of protection systems including heat, smoke, and gas detection, exhaust ventilation system, deflagration vent panels, BMS control, active liquid-cooling system for thermal management, electrical shutdowns and disconnects, etc. to mitigate fault conditions required per *NFPA 855 §4.4.2.1.*
- The Sungrow PowerTitan 2.0 has been listed to *UL 9540 Standard for Energy Storage Systems and Equipment* for the following models: ST5015UX-2H-US, ST4595UX-US, ST4175UX-2H-US, ST3760UX-2H-US, ST3340UX-2H-US, ST5015UX-4H-US, ST4175UX-4H-US, and ST3340UX-4H-US models.
- UL 9540A large-scale fire testing was conducted at the cell, module, and unit level. Unit level testing was favorable, in which thermal runaway was limited to the initiating module, and no external flaming, flying debris, explosive discharge of gases, sparks, electrical arcs, or other electrical events were observed.
- It is noted that battery cells and modules are listed to UL 1973.
- Two layers of explosion mitigation are provided in the form of exhaust ventilation system designed in accordance with NFPA 69 as well as deflagration vent panels designed in accordance with NFPA 68.
- The proposed BESS facility and location poses minimal risk to public or life safety and property by way of being on a secured site away from public spaces or roadways with no public access to the site. It is recommended that training is provided to the First Responders to familiarize themselves with the site and hazards associated with lithium-ion ESS and are instructed to stay at a safe distance in the unlikely event of a system failure.
- Availability of BMS data from remote monitoring facility, Central station monitoring of the automatic fire alarm system (with First Responder staging area), hydrants, and a site-specific Emergency Response Plan (ERP) will be provided for the facility and will pose additional layers of safety for the facility.

2 ENERGY STORAGE SYSTEM OVERVIEW

2.1 Energy Storage System Description

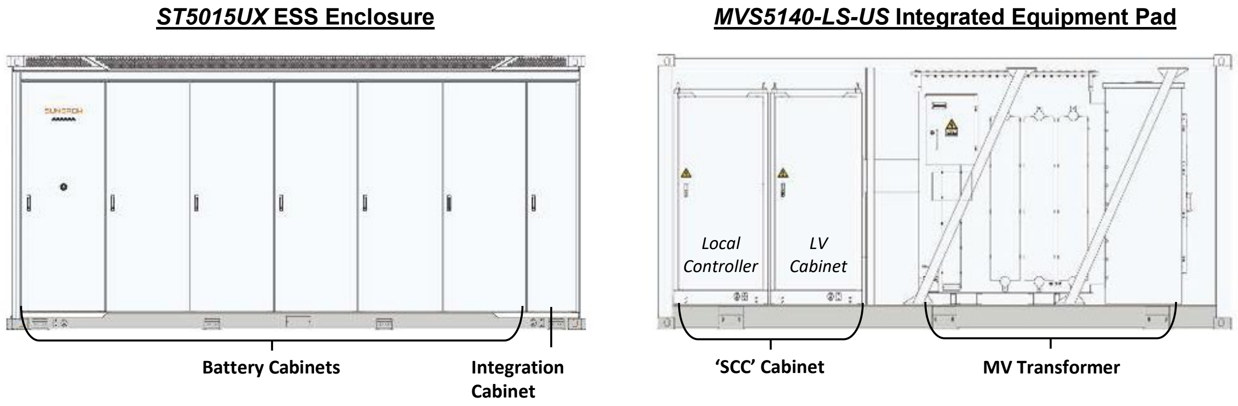
The Sungrow PowerTitan 2.0 is a modular, liquid-cooled stationary storage battery system used in medium and large-scale energy storage projects. The 19′-11″ x 8′ x 9′-6″ IP55-rated (NEMA 3S) enclosure utilizes a cabinet-style design, is fully populated by battery modules and associated electrical components, and therefore cannot physically be entered at any time.

The system utilizes Contemporary Amperex Technology Co., Limited (CATL) CBC00 lithium iron phosphate (LFP) battery cells, which are packaged into battery modules (or "packs") consisting of 104 cells in series. Packs are contained within IP67-rated housing. Each PowerTitan 2.0 enclosure consists of twelve (12) racks (also referred to as clusters) for a total 48 battery packs and 4992 battery cells per enclosure. Each rack also includes a dedicated terminal box (TB) and Power Conversion System (PCS), as depicted in Figure 4 below. UL 9540A large-scale fire testing was conducted at the Cell, Module, and Unit level, as is summarized in Section 4.1 of this report. The PowerTitan 2.0 is listed to UL 9540 (3rd Ed.)

Each PowerTitan 2.0 enclosure comes equipped with a number of fire safety devices (referred to as the "Fire Suppression System" or FSS in Sungrow documentation). By default, each enclosure includes two (2) heat detectors, four (4) smoke detectors, dedicated UL 864-listed Fire Alarm Control Panel (FACP), and six (6) deflagration vent panels located in the roof of the enclosure.

Figure 1 - Typical Sungrow PowerTitan 2.0 (ST5015UX) Enclosure

Figure 2 - Sungrow PowerTitan 2.0 Configuration Overview



2.1.1 Battery Cell

The PowerTitan 2.0 utilizes CATL prismatic LFP (lithium iron phosphate) battery cells, nominally rated 314Ah and 3.2V (model № *CBC00*). Battery cells are listed to UL 1973.

2.1.2 Battery Module / Pack

The PowerTitan 2.0 utilizes Sungrow battery modules, nominally rated 314Ah and 332.8V, consisting of 104 cells in series (model № *P1044AL-ACA*). Aerogel separation is provided to limit thermal propagation to adjacent cells. Battery modules are listed to UL 1973.

2.1.3 Battery Racks / Clusters

The PowerTitan 2.0 includes a total of 12 battery racks (also termed "clusters" by Sungrow), nominally rated 418kWh and 104.5kW, consisting of four (4) battery packs in series before terminating at a parallel connection. Enclosures are configured with two rack clusters stacked within each of the six (6) battery cabinet bays, with a dedicated terminal box and PCS at the bottom of each cabinet – 12 PCS (one per rack) in the 2-hr model, and six (6) PCS in 4-hr model (two per rack).

Figure 3 - PowerTitan 2.0 Battery Cell, Pack, Rack Images

Figure 4 - Example Battery Stack Configuration

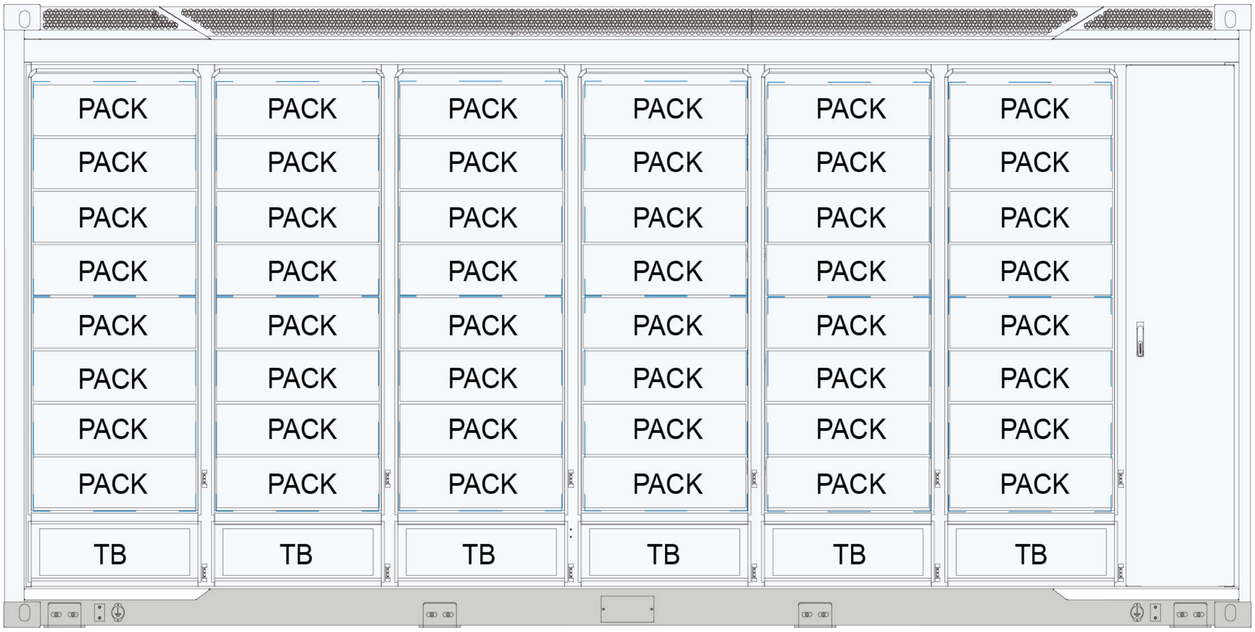
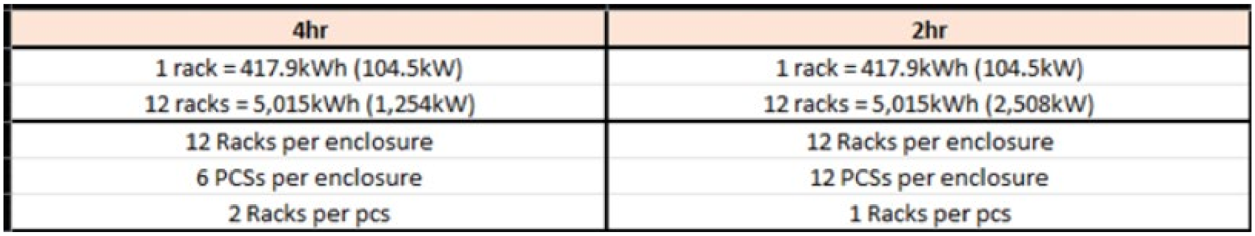


Table 1 - 4-hr and 2-hr Configurations

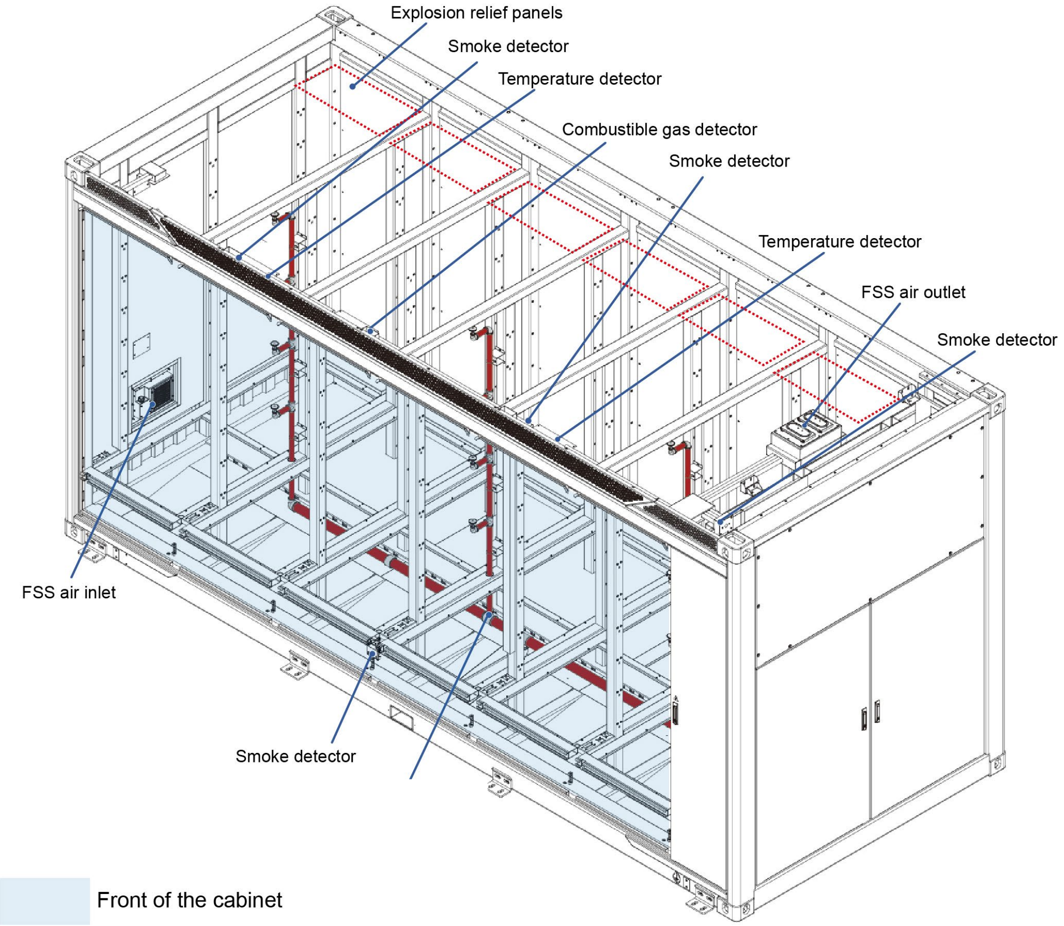


4hr	2hr
1 rack = 417.9kWh (104.5kW)	1 rack = 417.9kWh (104.5kW)
12 racks = 5,015kWh (1,254kW)	12 racks = 5,015kWh (2,508kW)
12 Racks per enclosure	12 Racks per enclosure
6 PCSs per enclosure	12 PCSs per enclosure
2 Racks per pcs	1 Racks per pcs

2.2 Fire Protection Features

The Sungrow PowerTitan 2.0 is equipped with a number of built-in and optional fire safety features (designated by Sungrow as “Fire Suppression System” (FSS) designed to mitigate the propagation of a battery failure or potentially prevent the failure from occurring altogether.

Figure 5 - Fire Protection Features



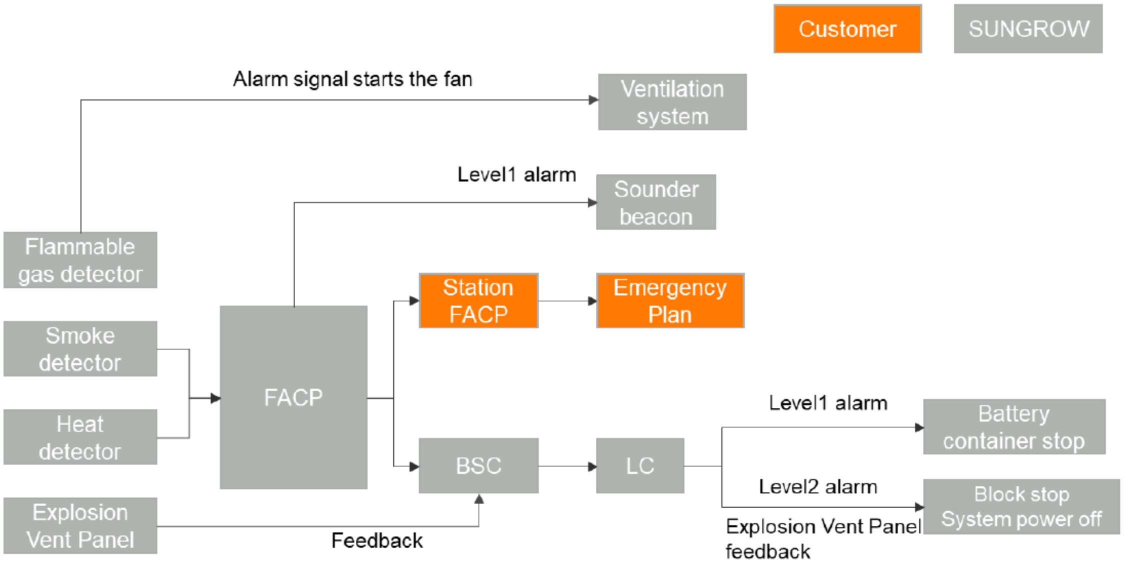
2.2.1 Smoke and Heat Detection

The PowerTitan 2.0 is equipped standard with four (4) smoke detectors and two (2) heat detectors, as depicted in Figure 5 above. Smoke and heat detectors are listed to UL 268 and UL 521, respectively. Signals from the detectors are transmitted to the enclosure “Mini” FACP which communicates with the Battery System Controller (BSC), Local Controller (LC), and site-level Station FACP.

In the event of a single heat or smoke detector activation, a level 1 alarm is raised, resulting in automatic shutdown of the alarm battery cabinet. In the event that both smoke and heat detectors are activated simultaneously, a level 2 alarm is raised, resulting in shutdown of the whole block system. If the customer chooses to include the optional sounder beacon, this shall be triggered upon activation of either heat or smoke detection.

It is noted that visible and audible annunciation will be provided at the main Fire Alarm Control Panel located at the First Responders station.

Figure 6 - Fire Signal and Response Logic



2.2.2 Gas Detection

The PowerTitan 2.0 is equipped with combustible gas detector, located in the center of the enclosure ceiling and calibrated to trigger at 10% LEL (lower explosive limit). It activates both alarms and exhaust ventilation system to remove flammable gas from the enclosure. Corresponding alarms will be sent to the FACP, BSC, LC, and customer, as described in Figure 6 above.

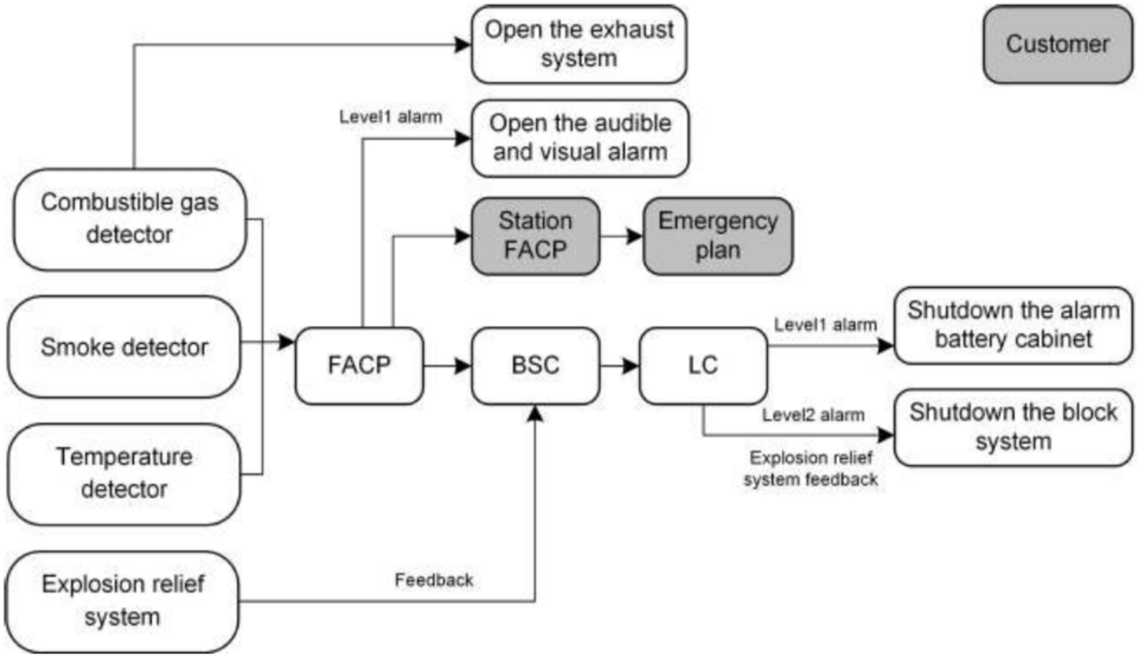
2.2.3 Exhaust Ventilation System

The PowerTitan 2.0 is equipped with an exhaust ventilation system designed in accordance with *NFPA 69: Standard on Explosion Prevention Systems* to remove flammable gas from the enclosure before an explosive atmosphere is allowed to accumulate. The system consists of one exhaust fan with rated flow rate of 750 m^3/h (441 CFM). In the event that the flammable gas detector (described above) is activated, the FSS air intake equipment and FSS exhaust equipment are triggered.

Furthermore, remote operation of this exhaust system (purge) will be provided via provisions within the First Responder station located at a remote distance from the nearest BESS enclosure.

Computational Fluid Dynamics (CFD) modeling was performed for the PowerTitan 2.0 exhaust ventilation system, demonstrating that the system shall effectively reduce average concentration of flammable gases below 25% LFL (see Section 4.2 for summary of NFPA 69 analysis performed for the PowerTitan 2.0).

Figure 7 - Control Logic of Exhaust System



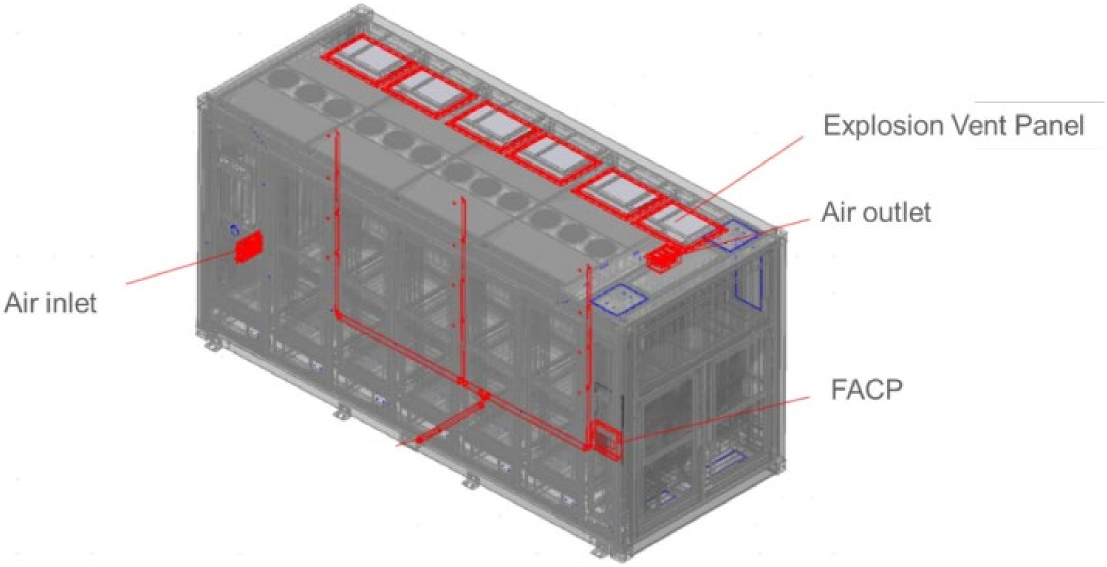
2.2.4 Deflagration Vent Panels

In addition to the automatic explosion prevention system, the PowerTitan 2.0 comes standard with six (6) passive deflagration vent panels. In the event that the primary explosion prevention system should fail for any reason, these deflagration panels provide a secondary means of protection, directing any blast overpressure upwards and away from the direction of any nearby exposures or emergency personnel who may be arriving on-site. In the event that the relief panels open, the BSC also transmits an alarm signal / feedback signal to the LC and the block system is shutdown.

CFD modeling was performed for the PowerTitan 2.0, demonstrating that the panels shall adequately manage a deflagration event should it occur (see Section 4.3 for summary of NFPA 68 analysis).

It is also noted that routine maintenance (such as snow and ice removal) may be required to ensure vent panels are able to function properly during winter months.

Figure 8 - Deflagration Vent Panels



2.2.5 Battery Management System

An integrated Battery Management System (BMS) monitors key datapoints such as voltage, current, and state of charge (SOC) of battery cells, in addition to providing control of corrective and protective actions in response to any abnormal conditions. Critical BMS sensing parameters include battery module over / under voltage, cell string over / under voltage, battery module over temperature, temperature signal loss, and battery module over current. In the event of any abnormal conditions, the BMS will first raise an information warning, and then trigger a corresponding corrective action should certain levels be reached.

The Sungrow Battery Management System (BMS) adopts a three-level management structure design consisting of the following:

- **Battery Management Unit (BMU):** Managed a battery module, monitors battery status (voltage, temperature, etc.), and provides communication interface for the battery.
- **Battery Cluster Management Unit (CMU):** The battery cluster management unit realizes daily management and monitoring of battery clusters, referred to as CMU for short.
- **Battery Management System Controller (BSC):** Built into the BSP in battery cabinet and manages battery clusters within a single battery cabinet.

It is also noted that the BMS functional safety was evaluated according to UL 60730-1 Annex H by TÜV Rheinland.

3 SITE DESCRIPTION

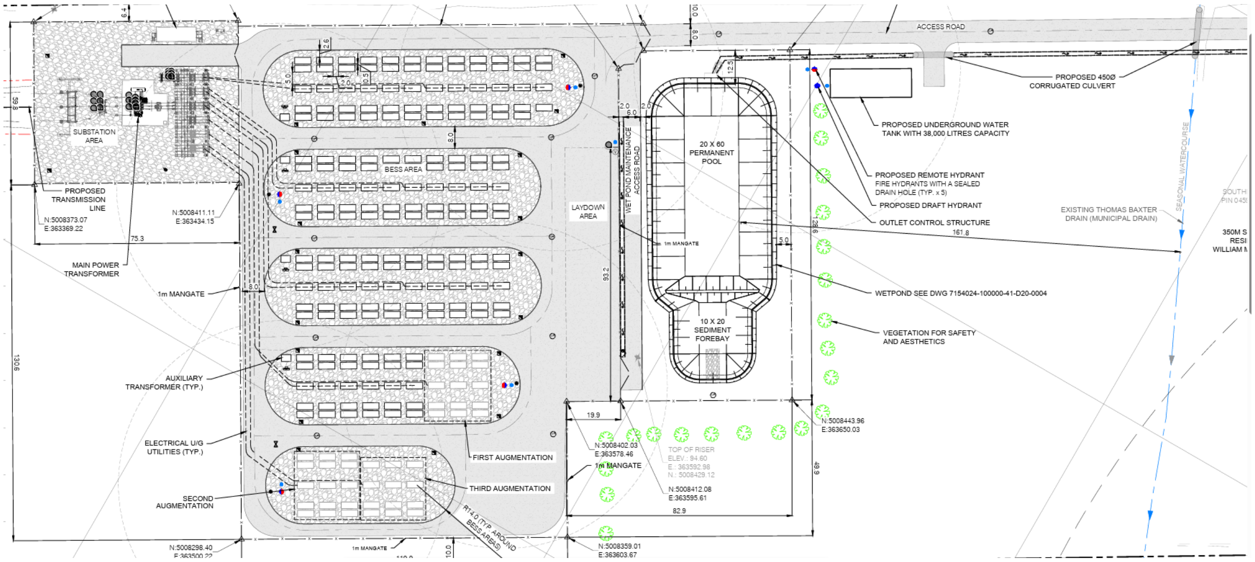
3.1 Site Overview

The proposed BESS facility is proposed to be located at 4186 William McEwen Drive, Richmond, ON, K0A 2E0, Canada. Access to the facility is provided via William McEwen Drive, as a fire apparatus accessible exposure. The BESS portion of the facility will be bounded along all exposures by chain-link fencing.

Figure 2-1 – Site Overview

Access to the facility will be provided via a 8.0m-wide internal apparatus accessible vehicle road.

Figure 2-2 – Site Layout and Access



The site will be comprised of two-hundred-sixteen (216) Sungrow PowerTitan 2 Battery Energy Storage Systems (BESS) units, for a total system capacity of 150MW/ 600MWh. The site is located in a largely rural area, about 24 km south of Ottawa. It is surrounded by forest and open/farm land on three sides, with the remaining side bordered by William McEwen Drive. Route 416/ Veterans Memorial Highway runs directly beside William McEwen Drive.

3.2 Nearby Exposures

The PowerTitan 2 units will be sited outdoors at grade level. The facility site is surrounded on three sides by forest and open land, with William McEwen Drive on the remaining side. Additionally;

- A private residence (4160 William McEwen Dr) is located to the north, adjacent to the roadway, about 120m from the site property line.

- A small landscaping business sits at 4236 William McEwen Drive, adjacent to the site property line and William McEwen Drive.

The separation distances between PowerTitan 2 BESS and within the facility meet or exceed the manufacturer's recommended separation distances.

3.3 Fire Department Access and Water Supply

The Ottawa Fire Dept is in proximity to the installation and units are anticipated to arrive on scene expeditiously after receiving an emergency alert from the central station monitoring facility. Ottawa Fire Dept Station 47 is located approximately 5.6 km away and is listed as the site's primary fire company.

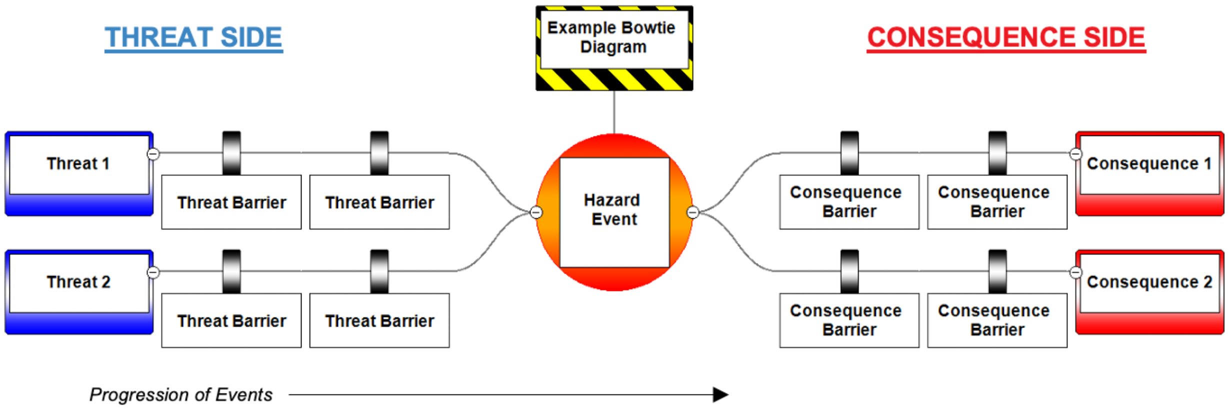
The site will have four fire hydrants on the site that will be fed by a 38,000 liter containment pond. Water will be trucked in to feed this pond as necessary.

4 HAZARD MITIGATION ANALYSIS

4.1 HMA Methodology

ESRG utilizes the bowtie methodology for hazard and risk assessments, as is described in *2023 NFPA 855 Appendix G.3.*, as it allows for in-depth analysis on individual **mitigative barriers** and serves as a strong tool for visualizing the chronological pathway of **threats** leading to critical hazard events, and ultimately to greater potential **consequences**, as depicted in the figure below. This diagrammatic method of describing and analyzing the pathways of a risk from hazards to outcomes can be considered to be a combination of the logic of a fault tree analyzing the cause of an event and an event tree analyzing the consequences.

Figure 3 - Example Bowtie Diagram



Each fault condition per *NFPA 855* is accompanied by a corresponding bowtie diagram indicating critical threat and consequence pathways and the mitigative barriers between them. As the most critical risk posed by lithium-ion battery cells comes from the propagation of thermal runaway from a failing cell (or multiple cells) to surrounding cells, this serves as the primary critical hazard for the subsequent failure scenarios.

In addition to main barriers for fault conditions on the threat side of the diagram, the consequence barriers on the right side of the diagram (e.g., explosion protection and emergency response plan) **also** contribute added layers of safety on top of the main threat barriers shown. It is important to note that the barriers on the left side, along a threat path, are intended to keep the threat from becoming a thermal runaway, while the barriers on the right side, along the consequence pathway, are intended to keep that single thermal runaway from evolving into one of the more severe consequences such as fire spread beyond containment, off-gassing leading to explosion, or fire spread beyond containment. For more on the methodology and relevant terminology, see Appendix B of this report.

4.2 Primary Consequences of ESS Failure and Mitigative Barriers

The dynamics of lithium-ion ESS failures are extremely complex, and the pathway of failure events may vary widely based on system design, mitigative approaches utilized, and even small changes in environmental or situational conditions. However, the primary consequences stemming from a propagating lithium-ion battery failure largely fall into a number of specific hazard scenarios, as depicted in the diagram and associated table below (though other scenarios not listed may certainly also occur). These primary consequences serve as the basis for the consequence side of the majority of the fault condition diagrams in the following sections of this report.

Figure 4 – HMA Diagram

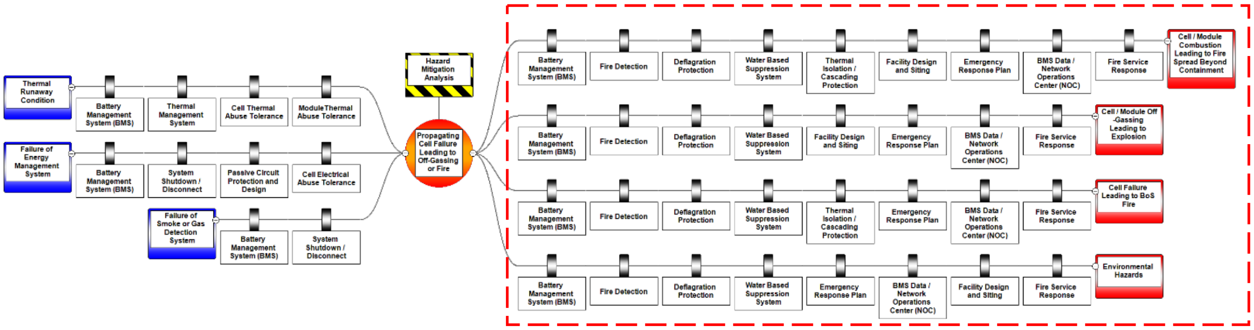


Figure 5 - Primary Consequence Barriers Diagram

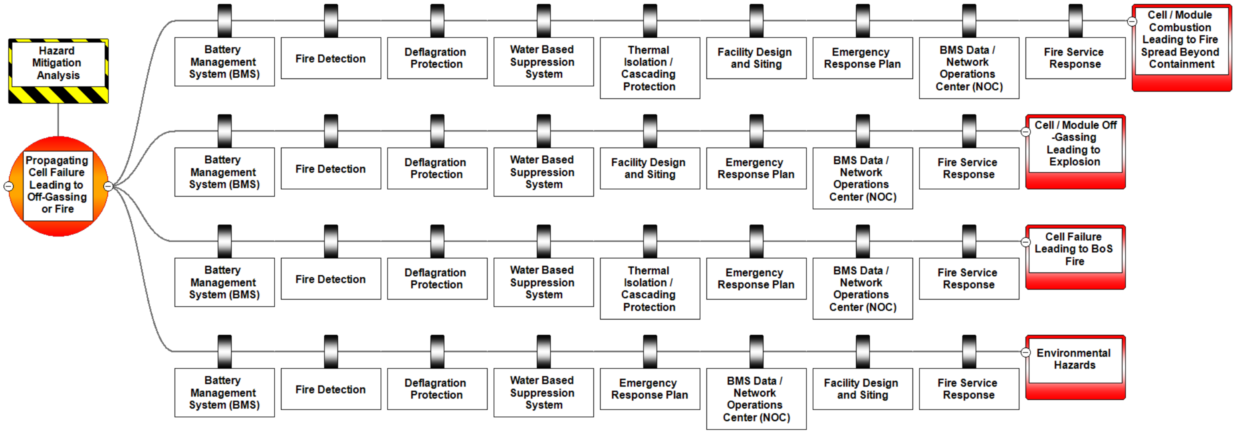


Table 2 - Primary Consequence Barriers

PRIMARY CONSEQUENCE BARRIERS	
Detection Systems / FACP	The PowerTitan 2.0 comes standard with four (4) smoke detectors and two (2) heat detectors. Signals from the detectors are transmitted to the enclosure "Mini" FACP which communicates with the Battery System Controller (BSC), Local Controller (LC), and site-level Station FACP.

Battery Management System (BMS)	Critical BMS sensing parameters for the PowerTitan 2.0 include battery module over / under voltage, cell string over / under voltage, battery module over temperature, temperature signal loss, and battery module over current. In the event of any abnormal conditions, the BMS will generally first raise an information warning, and then trigger a corresponding corrective action should certain levels be reached.
BMS Data Availability / Operations Center	The Site Controller provides point of interface for the utility, network operator or customer systems to control and monitor the energy storage site. 24/7 remote monitoring by Remote Operations Center will be provided.
Explosion Protection	The Sungrow PowerTitan 2.0 comes equipped with explosion prevention system designed in accordance with NFPA 69 to remove flammable gases from the enclosure in the event of a thermal runaway event before a deflagration is allowed to occur. Additionally, the PowerTitan 2.0 comes standard with six (6) passive deflagration panels located in the roof of the enclosure to direct any blast overpressure upwards and away from any nearby exposures or emergency personnel who may be arriving in the area in the event that the exhaust system should fail for any reason.
Thermal Isolation / Cascading Protection	UL 9540A Unit level testing indicated no external flaming, flying debris, explosive discharge of gases during testing, thus minimal, if any, fire spread across units is anticipated.
Electrical Fault Protection Devices	The PowerTitan 2.0 is equipped with a number of electrical fault protection in the form of battery module overcurrent protection, inverter DC and AC protection, and ground fault protection.
Facility Design and Siting	The proposed BESS facility and location poses minimal risk to public or life safety and property by way of being on a secured site away from public spaces or roadways with no public access to the site. It is recommended that training is provided to the First Responders to familiarize themselves with the site and hazards associated with lithium-ion ESS and are instructed to stay at a safe distance in the unlikely event of a system failure.
Emergency Response Plan	A product-level Emergency Response Guide (ERG) has been provided by Sungrow with general guidance around response in the event of an emergency. Additionally, a site-specific Emergency Response Plan (ERP) is to be provided by ESRG and may greatly improve the strength of this barrier.
Fire Service Response	The Ottawa Fire Dept is in proximity to the installation and units are anticipated to arrive on scene expeditiously after receiving an emergency alert from the central station monitoring facility. A defensive firefighting approach shall be utilized at the discretion of the first responders. The site will have four fire hydrants on the site that will be fed by a 38,000 liter containment pond. Site-specific training and installation familiarization for local responding stations may further increase the strength of this barrier.

4.3 Fault Condition Analysis

Per *NFPA 855 §4.4.2.1*, the analysis shall evaluate the consequences of the following failure modes and others deemed necessary by the AHJ:

(1) A thermal runaway or mechanical failure condition in a single ESS unit

(2) Failure of an energy storage management system or protection system that is not covered by the product listing failure modes and effects analysis (FMEA)

(3) Failure of a required protection system including, but not limited to, ventilation (HVAC), exhaust ventilation, smoke detection, fire suppression, or gas detection

For the purposes of this report, it shall be assumed that all construction, equipment, and systems that are required for the ESS shall be installed, tested, and maintained in accordance with local codes and the manufacturer's instructions. The assessment is based on the most recent information provided by Sungrow at the time of this writing.

The following table provides a summary of findings from the hazard mitigation analysis performed in fulfillment of *NFPA 855 §4.4.2.1,* with each fault condition described in greater detail, accompanied by simplified bowtie diagrams for visualization of mitigative barriers. Enlarged bowtie diagrams are provided in Appendix A.

Table 3 - Summary of Fault Condition Analysis

Compliance Requirement	Comments
1. A thermal runaway or mechanical failure condition in a single ESS unit	A number of passive and active measures are implemented to reduce the potential of a thermal runaway event from occurring including BMS control and active cooling to internal components. Battery modules and cells have been listed to UL 1973. Should a thermal runaway event occur, additional mitigative measures are provided to prevent further propagation of failure throughout the system (see Section 3.2 above for list of all consequence barriers).
2. Failure of an energy storage management system or protection system that is not covered by the product listing failure modes and effects analysis (FMEA)	The Sungrow BMS adopts a three-level management structure for monitoring and control of the systems at the battery module, battery cluster, and battery cabinet level for redundancy in the event that one level of control should fail, as described in Section 2.2.5 of this report. To further isolate any failure stemming from a failure of the energy storage management system, passive and active electrical fault protections are provided at multiple levels,

	along with all additional consequence barriers listed in Section 3.2 above.
3. Failure of a required protection system including, but not limited to, ventilation (HVAC), exhaust ventilation, smoke detection, fire suppression, or gas detection	In the event of failure of the exhaust ventilation system, the potential for accumulation of flammable gases leading to a potential for explosion within the enclosure may be present. Proper Facility Siting, Emergency Response Planning, and Fire Department response shall be critical to mitigate the potential consequences stemming from failure of the exhaust ventilation system. Failure of the provided heat or smoke detectors may result in failure to properly activate respective safety systems and cause notification signals to the fire alarm control panel and central station to be relayed to the fire department. However, it is anticipated that the BMS shall still be capable of triggering the respective safety actions in the event of heat or smoke detectors, depending on the nature of the battery failure. Failure of the provided gas detectors may directly affect proper activation of the exhaust ventilation system; therefore, it is imperative that proper emergency response procedures be developed and documented in site-specific Emergency Management Plans for all sites utilizing the PowerTitan 2.0.

4.3.1 Thermal Runaway Condition or Mechanical Failure Condition in a Single ESS Unit

Thermal runaway, as defined in NFPA 855 is the condition when an electrochemical cell increases its temperature through self-heating in an uncontrollable fashion and progresses when the cell’s heat generation is at a higher rate than it can dissipate. This results in off-gassing, fire, or explosion. The cause of a thermal runaway event can range from a manufacturer defect in the cell, external impact, exposure to dangerously high temperatures, or a multitude of controls and electrical failures. Furthermore, a thermal runaway event in a single cell can propagate to nearby cells, thus creating a cascading runaway event across battery modules and racks, leading to more heat generation, fire, off-gassing, and increased potential for a deflagration event.

A number of protections are provided to reduce the potential for thermal runaway at the cell level, most notably via monitoring and controls provided by the battery management system (BMS) which will trigger respective corrective actions based on the fault signal received. Should a thermal runaway condition spread to a single module, array, or unit, additional protections including BMS control and system shutdown and disconnects are anticipated to mitigate further propagation of failure throughout the system electrically.

Should a thermal runaway event occur, flammable gases may accumulate within the enclosure, leading to a potentially explosive atmosphere. Given a source of ignition (for example from fire, heat, or electrical arcing), a deflagration or explosion event may occur, posing serious threat to the nearby area. To limit the impact of such an event, the PowerTitan 2.0 is equipped with deflagration vent panels intended to direct any blast overpressure upwards and away from any nearby exposures or emergency personnel who may be arriving on-scene. Per *NFPA 855 §9.6.5.6.3*, these panels are to be designed in accordance with *NFPA 68: Standard on Explosion Protection*. A CFD analysis was provided to demonstrate that these panels shall operate as intended and critical rupture of the enclosure will not occur.

The inclusion of gas detection and exhaust ventilation system (described in sections above) may also prevent flammable gas from accumulating within the enclosure before an explosion can occur.

In a worst-case scenario in which a deflagration event does occur, consequences may be further mitigated by proper emergency response procedures, which should be developed on a site-specific basis.

UL 9540A Unit level testing indicated no external flaming, flying debris, or explosive discharge of gases during testing, thus minimal to no fire spread across units is anticipated. Some jurisdictions require heat flux modeling or full scale fire testing to validate the unlikelihood of fire spread unit to unit. If further propagation of failure occurs, additional site-specific items including Facility Siting, Emergency Management Plan (EMP), and Fire Service Response will be important to mitigating further impact to the system, site, and nearby areas and communities.

Figure 6 - Thermal Runaway Condition Diagram

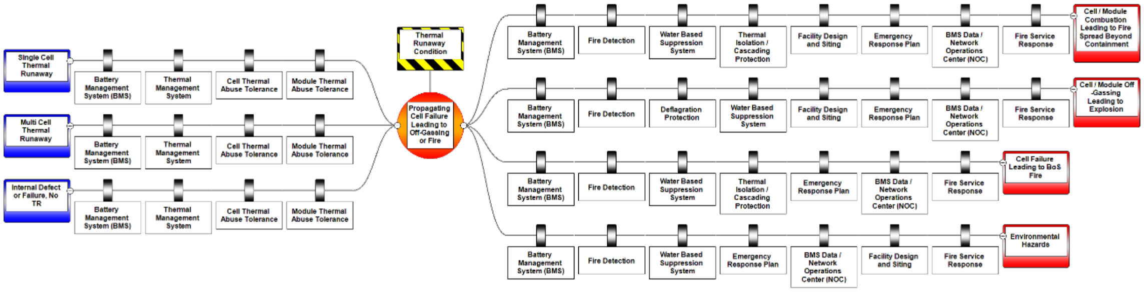


Table 4 - Thermal Runaway Condition Barriers

Barrier	Description

THREAT BARRIERS	
Battery Management System (BMS)	BMS consisting of three layers (BMU, CMU, BSC). Critical BMS sensing parameters include, but are not limited to, battery cell over / under voltage, cell string over / under voltage, battery cell over temperature, temperature signal loss, and battery module over current. In the event of abnormal conditions, the BMS will first raise an information warning, and then trigger a corresponding corrective action in the event that certain levels are reached.
Thermal Management System	Liquid cooling provided to each battery pack. While this system will not stop a thermal runaway condition in a battery cell once it has occurred, it may provide a level of thermal cooling to adjacent cells or modules, potentially limiting spread of failure across the system.
Cell Thermal Abuse Tolerance	UL 9540A cell level test report notes that module has been listed to UL 1973, in which thermal abuse tolerance was tested, though it is recommended that official COC be provided.
Module Thermal Abuse Tolerance	UL 9540A module level test report notes that module has been listed to UL 1973, in which thermal abuse tolerance was tested, though it is recommended that official COC be provided.
CONSEQUENCE BARRIERS	
See Section 3.2 above for list of primary consequence barriers.	

4.3.2 Failure of an Energy Storage Management System

The loss, failure, or abnormal operation of an energy storage control system (controllers, sensors, logic / software, actuators, and communications networks) may directly impact the proper function of the system. The PowerTitan 2.0 utilizes a tiered hierarchy of controls, as noted in Section 2.2.5 above, providing multiple levels of redundancy in the event that one level of controls fails. To further isolate any failure stemming from a failure of the energy storage management system, passive and active electrical fault protections are provided at multiple levels, as described in previous sections.

Finally, should a propagating thermal runaway occur, a number of key barriers are provided to mitigate against propagation of failure throughout the system leading to more severe consequences, as are described in Section 3.2 of this report above.

Figure 7 - Failure of an Energy Storage Management System Diagram

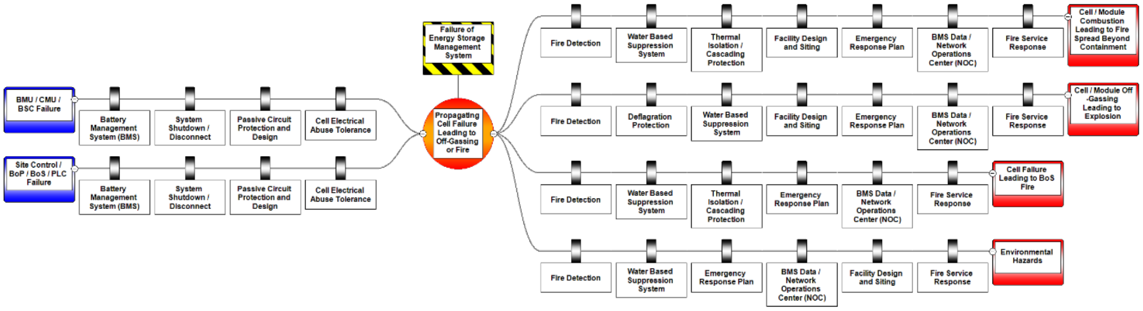


Table 5 - Failure of an Energy Storage Management System Barriers

Barrier	Description
THREAT BARRIERS	
Battery Management System (BMS)	The PowerTitan 2.0 utilizes three levels of BMS control (BMU, CMU, BSC) for redundancy in the event that one level should fail.
System Shutdown / Disconnect	Automatic disconnect in response to critical alarm notifications such as loss of communication with EMS, low SOC, ground fault detection, over or under-voltage, etc.
Passive Circuit Protection / Design	Fused disconnects and DC disconnect switches, in addition to ground fault detection / interruption and over voltage protection provided.
Cell Electrical Abuse Tolerance	UL 9540A cell level test report notes that cell has been listed to UL 1973, in which electrical abuse tolerance was tested, though it is recommended that official COC be provided.
CONSEQUENCE BARRIERS	
See Section 3.2 above for list of primary consequence barriers.	

4.3.3 Failure of a Required Smoke Detection, Fire Detection, Fire Suppression System, or Gas Detection System

The failure of the provided heat, smoke, or gas detection systems may result in failure to automatically shut down the ESS, activate respective safety systems, or provide notification signals to the fire alarm control panel and central station to be relayed to the fire department.

While it is anticipated that the BMS shall still be capable of triggering the respective safety actions should the provided smoke or heat detectors fail, depending on the nature of the battery failure event, notification signals to the fire alarm control panel and central station may be directly impacted.

If flammable gas detection and exhaust ventilation systems are provided, a potential failure of the gas detector may directly affect activation of the exhaust ventilation system, allowing flammable concentrations of off-gases to accumulate within the enclosure, posing a serious deflagration risk should a source of ignition be provided.

In the event of a failure of any one of these systems, proper response procedures should be established and provided in a site-specific emergency response plan. If BMS data is available via Network Operations Center (NOC) / remote monitoring facility, a more detailed understanding of the failure event and required emergency response procedures may be put together. Additionally, as noted in previous sections, strong facility siting may reduce direct impact to the surrounding areas.

UL 9540A Unit level testing indicated no external flaming, flying debris, explosive discharge of gases during testing, thus limited to no fire spread across units is anticipated. It is, however, understood that recent ESS fires across the globe have seen fire propagation across entire units and additional fire testing may be helpful to verify. If further propagation of failure occurs, additional site-specific items including Facility Siting, Emergency Response Plan (ERP), and Fire Service Response will be important to mitigating further impact to the system, site, and nearby areas and communities.

Figure 8 - Failure of a Required Protection System Diagrams

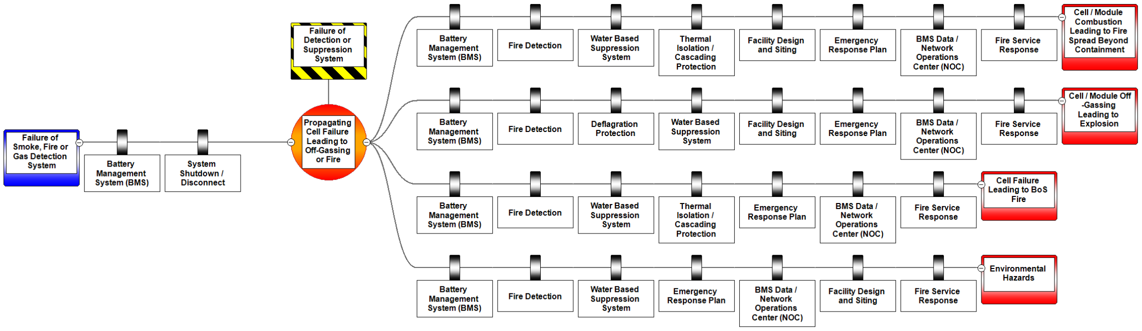


Table 6 - Failure of a Required Protection System Barriers

Barrier	Description
THREAT BARRIERS	
Battery Management System (BMS)	BMS consisting of three layers (BMU, CMU, BSC). Critical BMS sensing parameters include, but are not limited to, battery cell over / under voltage, cell string over / under voltage, battery cell over temperature, temperature signal loss, and battery module over current. In the event of abnormal conditions, the BMS will first raise an information warning, and then trigger a corresponding corrective action in the event that certain levels are reached.
System Shutdown / Disconnect	Automatic disconnect in response to critical alarm notifications such as loss of communication with EMS, low SOC, ground fault detection, over or under-voltage, etc.
Passive Circuit Protection / Design	Fused disconnects and DC disconnect switches, in addition to ground fault detection / interruption and over voltage protection provided.
System Electrical Abuse Tolerance	The PowerTitan 2.0 is listed to UL 9540 in which system electrical abuse tolerance is assessed.
Cell Electrical Abuse Tolerance	Cell has been tested and listed to UL 1973 in which electrical abuse tolerance was tested.

CONSEQUENCE BARRIERS
See Section 3.2 above for list of primary consequence barriers.

4.4 Analysis Approval

Per NFPA 855 §4.4.3, the AHJ shall be permitted to approve the hazardous mitigation analysis as documentation of the safety of the ESS installation provided the consequences of the analysis demonstrate the following:

(1) Fires will be contained within unoccupied ESS rooms for the minimum duration of the fire resistance rating specified in [2023 NFPA 855 9.6.4].

(2) Fires and products of combustion will not prevent occupants from evacuating to a safe location.

(3) Deflagration hazards will be addressed by an explosion control or other system.

Table 7 - Summary of Analysis Approval

Compliance Requirement	Comments
1. Fires will be contained within unoccupied ESS rooms for the minimum duration of the fire resistance rating specified in [2023 NFPA 855 9.6.4].	The Sungrow PowerTitan 2.0 is intended for outdoor ground-mounted installations only and shall not be installed within any ESS rooms or occupied structures.
2. Fires and products of combustion will not prevent occupants from evacuating to a safe location.	The Sungrow PowerTitan 2.0 is not intended to be installed in any occupied work centers. While UL 9540A 4th Ed. does not require measurement of many toxic gases (only flammable gases), limited information on toxic gases released for the specific battery system is available. In ESRG's extensive experience performing large-scale fire testing of li-ion batteries, proprietary gas data measured indicates that toxicity levels are much in line with that of typical structural fires. Further, despite multiple BESS fires across the US, no adverse health effects have been reported from these events. Ultimately, all fires are capable of producing toxic smoke and gases, and ESRG recommends the same precautions and practices be exercised for BESS fires as with any high gas and smoke producing event in a populated area.

3. Deflagration hazards will be addressed by an explosion control or other system.	The Sungrow PowerTitan 2.0 comes equipped with explosion prevention system designed in accordance with NFPA 69 to remove flammable gases from the enclosure in the event of a thermal runaway event before a deflagration is allowed to occur. Additionally, the PowerTitan 2.0 comes standard with six (6) passive deflagration panels located in the roof of the enclosure to direct any blast overpressure upwards and away from any nearby exposures or emergency personnel who may be arriving in the area in the event that the exhaust system should fail for any reason. CFD modeling was performed for both systems to demonstrate the effectiveness of the systems to adequately manage deflagration hazards.

5 SUPPORTING DOCUMENTATION

5.1 UL 9540A Large-Scale Fire Testing

5.1.1 Cell Level Test

UL 9540A (4th Edition) Cell level testing was conducted on the Contemporary Amperex Technology Co., Limited (CATL) CBC00 3.2V, 314Ah lithium iron phosphate (LFP) battery cell by UL (Changzhou) Quality Technical Service Co., LTD in Changzhou, China (project number 4790870196, issued 9/18/2023).

Thermal runaway was initiated via four external heaters, maintaining a heating rate of 4°C to 7°C per minute. Cell venting occurred at an average of 179°C over four test samples, with average onset of thermal runaway at 226°C, during which approximately 176 L of gas were released. Gas analysis was provided to determine Lower Flammability Limit (LFL), burning velocity, and maximum pressure, as noted in the tables below.

As all performance criteria in accordance with Clause 7.7 and Figure 1.1 of UL 9540A 4th Ed. were not met, Module level testing was required to be conducted on a complete module employing the CBC00 cell.

Table 8 - Cell Level Information

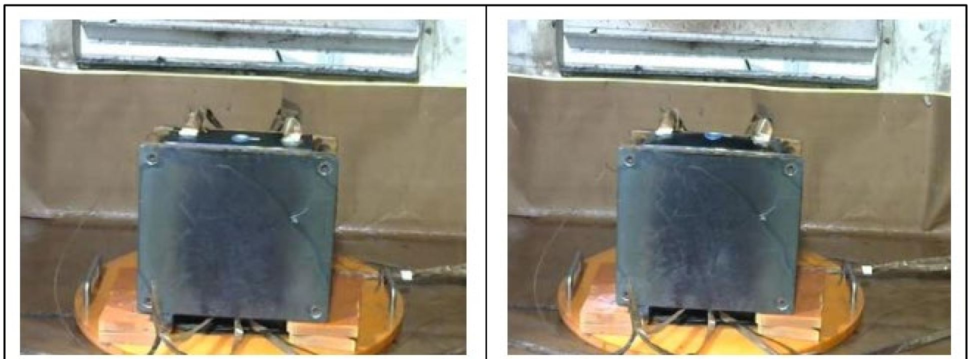
Avg. Cell Surface Temperature at Venting (°C)	179
Avg. Cell Surface Temperature at Thermal Runaway (°C)	226
Gas Volume (L)	176
Lower Flammability Limit (LFL) at Ambient Temperature	7.05
Lower Flammability Limit (LFL) at Venting Temperature	5.85
Burning Velocity (S_u)	213.2
Maximum Pressure (P_{max})	100.4

Table 9 - Cell Level Gas Measurements

Gas Component	Volume Released (%)
Carbon Monoxide (CO)	12.642
Carbon Dioxide (CO2)	26.413
Hydrogen (H2)	46.491
Methane (CH4)	7.016
Acetylene (C2H2)	0.158

Ethylene (H2H4)	3.111
Ethane (C2H6)	1.174
Propylene (C3H6)	0.422
Propane (C3H8)	0.154
C4 (Total)	0.657
C5 (Total)	0.200
C6 (Total)	0.082
1-Heptene (C7H14)	0.016
Benzene (C6H6)	0.058
Toluene (C7H8)	0.008
Dimethyl Carbonate (C3H6O3)	1.209
Ethyl Methyl Carbonate (C4H8O3)	0.188
Total	100

Figure 9 – Highlights of Cell 1 Testing

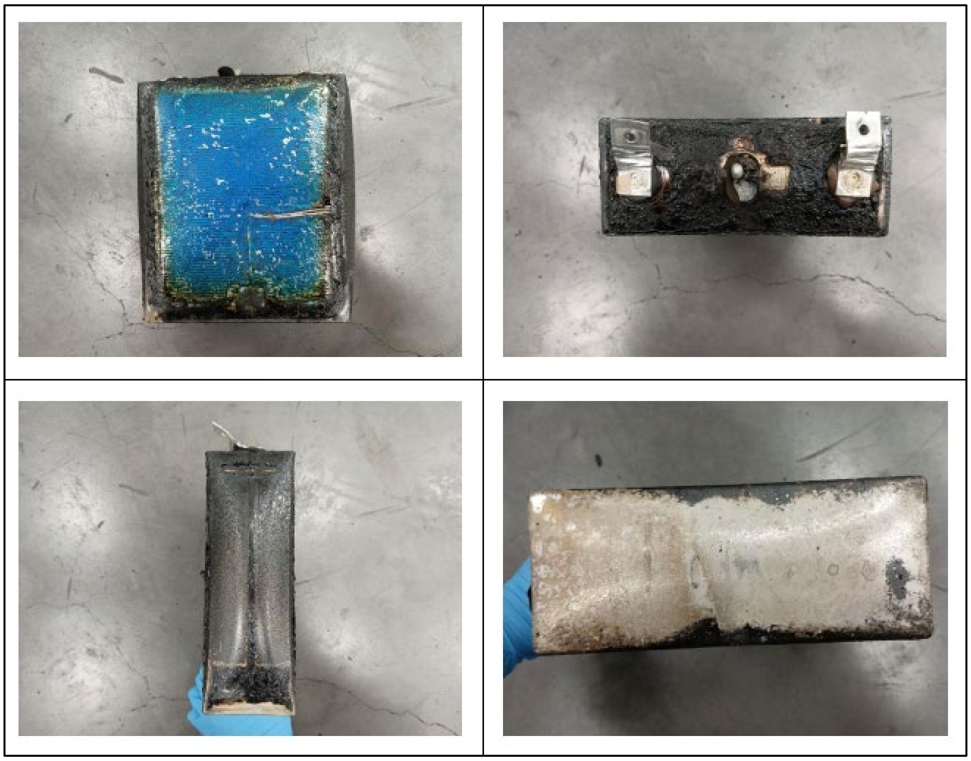


(a) Test Start
[00:00]

(b) Cell Venting
[41:25]

(c) Thermal runaway behavior
[54:03]

Figure 10 - Sample 1 Post Test Photos



5.1.2 Module Level Test

UL 9540A (4th Edition) Module level testing was performed for the Sungrow Power Supply Co., Ltd. P1044AL-ACA battery packs by TÜV Rheinland (Shanghai) (test report number CN23WZDT 001, issued 12/8/2023).

Thermal runaway was initiated via two external heaters maintaining a heating rate of 4°C to 7°C per minute. Audible pops were heard at 11:53 into testing, with large amounts of white smoke observed beginning at 12:09. A total of 5 cells were damaged during the test (3 were initiating cells and another 2 were from cell-to-cell thermal propagation). No flying debris, explosive discharge of gases, or flaming were observed during the test. Additionally, no sparks, electrical arcs, or other electrical events were observed.

As all performance criteria in accordance with Clause 8.4 and Figure 1.1 of UL 9540A 4th Ed. were not met, Unit level testing was required to be conducted on a complete unit employing the P1044AL-ACA battery packs.

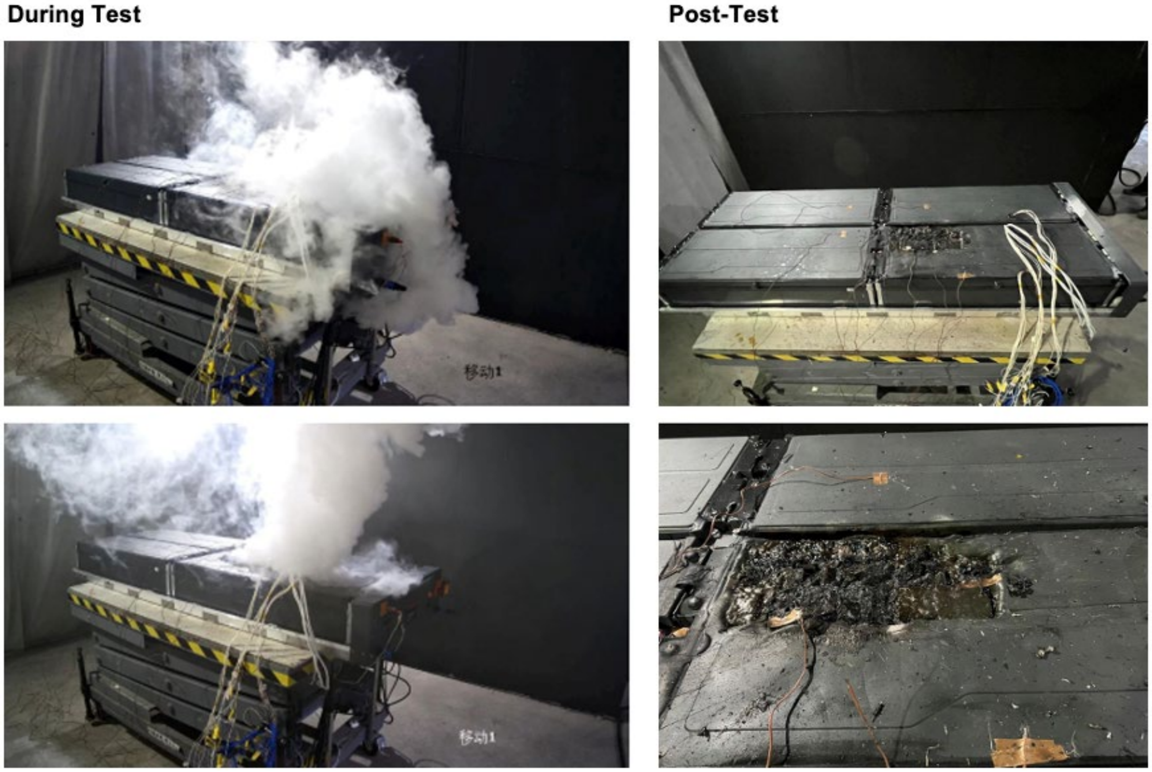
Table 10 - Module Level Test Information

Weight Before Test (kg)	663.6 (with thermocouples)
Weight After Test (kg)	658.8 (with thermocouples)
Weight Loss (kg)	4.8
Peak Chemical Heat Release Rate (HRR$_t$) (kW)	32.680
Peak Smoke Release Rate (SRR) (m^2/s)	3.492
Total Smoke Release (TSR) (m^2)	213.493

Table 11 - Module Level Gas Measurements

Gas Type	**Gas Components**	**Total Volume of Gas (L)**	
		Before Cell Venting	**Throughout the Test**
Hydrocarbon Species	Methane (CH4)	0.00	104.2
	Ethylene (C2H4)	0.00	79.72
	Ethane (C2H6)	0.00	99.23
	Propylene (C3H6)	0.00	269.6
Others	Carbon Monoxide (CO)	0.00	161.06
	Carbon Dioxide (CO2)	0.00	492.3
	Hydrogen (H2)	0.00	897.3
Total Hydrocarbons (equivalent to CH4, measured by FID)			734.2
Note: 1) The collection time is from 10:46 to 14:10 2) The Hydrogen measured by Palladium nickel thin film solid state sensor.			

Figure 11 - Module During Test and Post-Test



During Test **Post-Test**

5.1.3 Unit Level Test

UL 9540A (4th Edition) Unit level testing was conducted for representative Sungrow Power Supply Co., Ltd. unit by TÜV Rheinland (Shanghai) and partner labs under the supervision of TÜV Rheinland's engineer (test report number CN23EYFB 001, issued 12/8/2023).

During testing, cell-to-cell propagation was observed in the initiating module, with white offgas released. No module-to-module propagation was observed. After first thermal runaway, a large amount of white offgas was observed on 14:05, 14:13, 14:16, and 14:27. A total of 5 cells were involved and vented during the test (three were initiating cells and two others were from cell-to-cell thermal propagation). No flying debris or explosive discharge of gases observed during the test. No sparks, electrical arcs, or other electrical events observed during the test. No external flaming was observed during the test.

Table 12 - Unit Level Test Information

Peak Chemical Heat Release Rate (HRR) (kW)	89.37
Total Heat Release (THR) (MJ)	251.97
Peak Smoke Release Rate (SRR) (m^2/s)	3.91
Total Smoke Release (TSR) (m^2)	3938.31
Total Hydrocarbons (L)	701.3

Table 13 - Unit Level Gas Measurements

Gas Type	Gas Components	Total Volume of Gas (L)	
		Before Cell Venting	**Throughout the Test**
Hydrocarbon Species	Methane (CH4)	0.00	104.92
	Ethylene (C2H4)	0.00	70.60
	Ethane (C2H6)	0.00	89.45
	Propylene (C3H6)	0.00	247.77
Others	Carbon Monoxide (CO)	0.00	184.3
	Carbon Dioxide (CO2)	0.00	441.9
	Hydrogen (H2)	0.00	786.3
Total Hydrocarbons (equivalent to CH4, measured by FID)			701.3
Note: 1) The collection time is from 12:16 to 15:02 2) The Hydrogen measured by Palladium nickel thin film solid state sensor.			

Figure 12 - Unit Test Setup

Figure 13 - Unit During and Post-Test


During Test

Unit Post-Test

Figure 14 - Module Post-Test (Unit Level Test)

5.2 NFPA 69 ANALYSIS

An engineering assessment of NFPA 69 compliance for the PowerTitan 2.0 battery energy storage systems was provided by TÜV Rheinland in which a Computational Fluid Dynamics (CFD) analysis was performed utilizing UL 9540A test data to demonstrate the system design successfully reduces the concentration of combustible gases in the container to less than 25% of the lower flammability limit (LFL) of the gas mixture. Based on this CFD modeling, TÜV determined that the system is capable of reducing the combustible concentration in the container for five cells undergoing thermal runaway, mitigating the explosion risk to a substantially low and manageable level, and that the BESS meets the intent of NFPA 69.

High-level notes from the report include:

- The container is fitted with one exhaust fan with rated flow rate of 750 m^3/h (441 CFM), though the model assumes a flow rate of 480 m^3/h (283 CFM) as a conservative measure. The fan is activated when gas detection reaches 10% LFL of hydrogen and includes a 5s lag time to account for fan ramping up.
- A total of four dispersion scenarios were run representing progressively worse-case scenarios. The modeling covers 2 leakage positions, with each run with and without extraction fan.
- All scenarios with extraction fan activated can reduce flammable volume of gas and are able to keep average flammable gas concentration below 25% LFL in the container. Scenarios which did not utilize the extraction fan did not keep LFL within acceptable limits.
- The system was reviewed against the requirements of NFPA 69 and found to comply with the applicable requirements.
- It is noted that small pockets of gas are seen to exceed 25% LFL for small periods, though requirements for average concentrations per NFPA 69 are properly met.

Table 14 – Average Gas Concentration

Scenario	**Maximum Average Gas Concentration (% Vol)**	
	Without Extraction Fan	With Extraction Fan
001	43.79	0.97
002	44.62	1.44

Table 15 - Average Concentrations with and without Extraction Fan

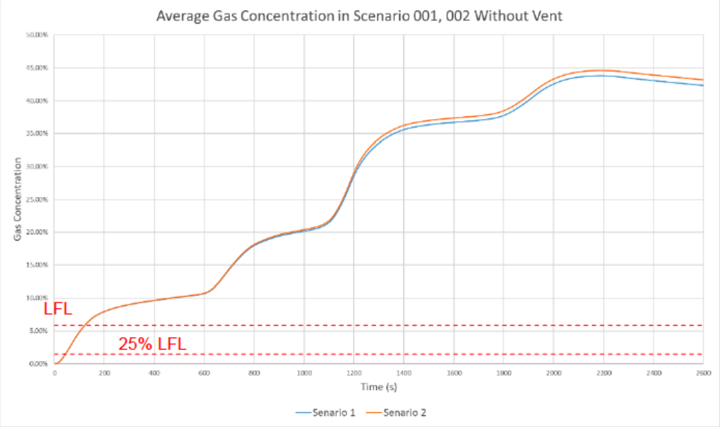


Figure 4-7: Average gas concentration in scenario 001 and 002 without vent

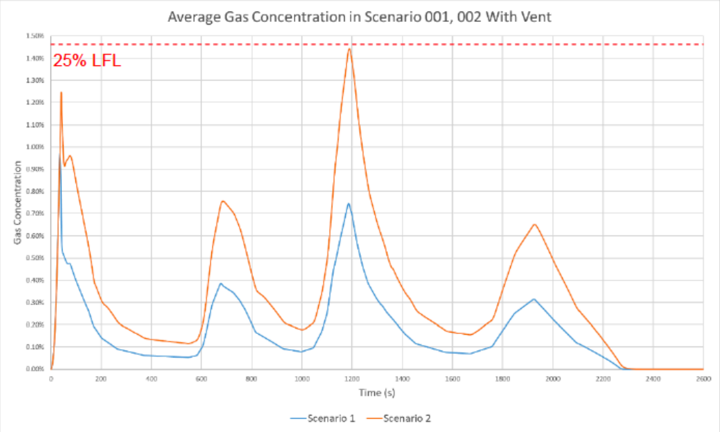
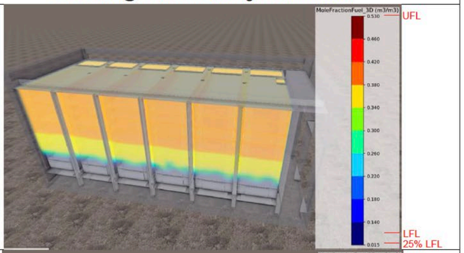
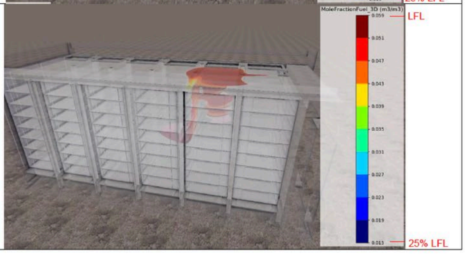
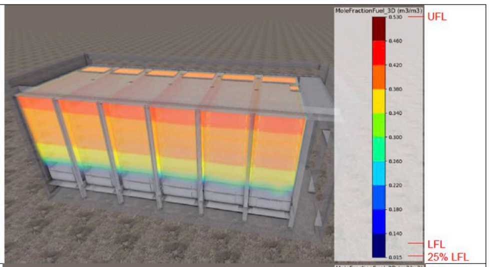
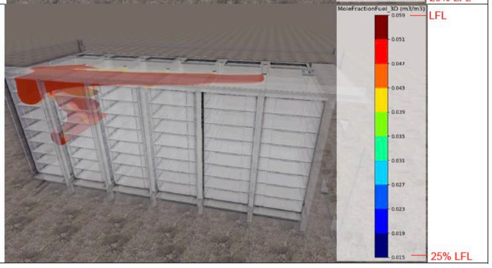


Figure 4-8: Average gas concentration in scenario 001 and 002 with vent

Table 16 - CFD Models with and without Extraction Fan

Scenario	Gas cloud @ maximum average concentration
001 (No Vent)	
001 (Vent)	
002 (No Vent)	
002 (Vent)	

5.3 NFPA 68 ANALYSIS

An engineering assessment of the PowerTitan 2.0 deflagration vent panels was performed by TÜV Rheinland. This report includes compliance assessment of the panels to NFPA 68 as well as CFD analysis using UL 9540A test data, demonstrating that the panels shall effectively manage a potential deflagration event. In the study, a series of explosion scenarios were run representing progressively worse-case scenarios based on ignition position. During these, the flammable gas cloud is ignited when the gas amount reaches the highest value. Maximum pressure for each of the scenarios are provided in Table 13 below.

The report states that the CFD model shows that the predicted maximum average pressure on the wall is 0.18 bar-g and that the enclosure could maintain at least 0.60 bar-g pressure, therefore the enclosure could handle the deflagration pressure and requirements of NFPA 68 are met.

Table 17 - NFPA 68 Simulation Pressures

Scenario	Ignition Position	Maximum Pressure (bar-g)
001	251.97	0.175
002	3.91	0.160
003	3938.31	0.180

Table 18 - Pressure and Temperature Results

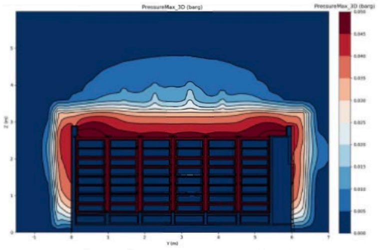


Figure 4-7: Top center ignition pressure map (outside).

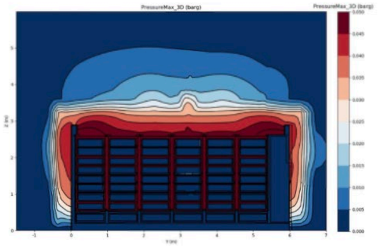


Figure 4-8: Top front center ignition pressure map (outside).

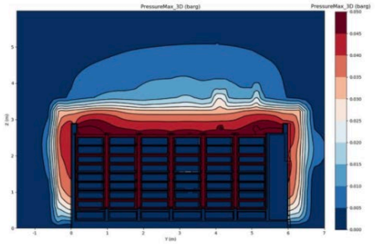


Figure 4-9: Top front corner ignition pressure map (outside).

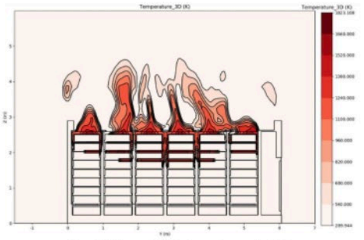


Figure 4-10: Top center ignition temperature map (outside).

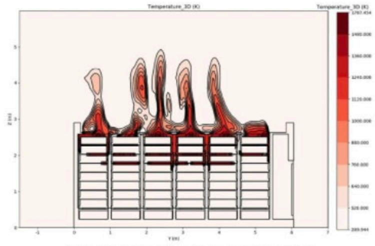


Figure 4-11: Top front center ignition temperature map (outside).

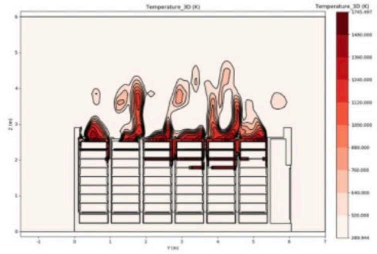
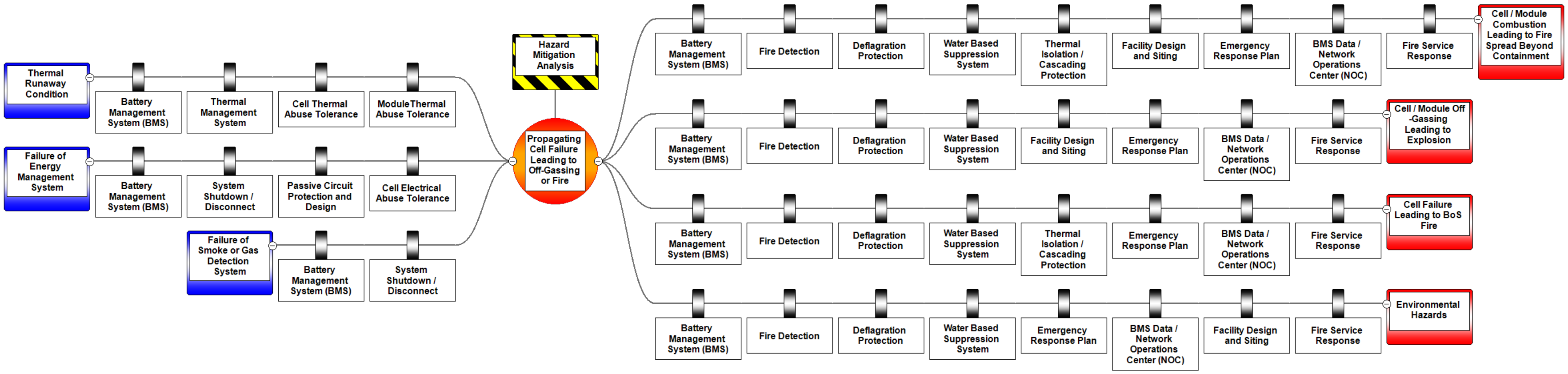


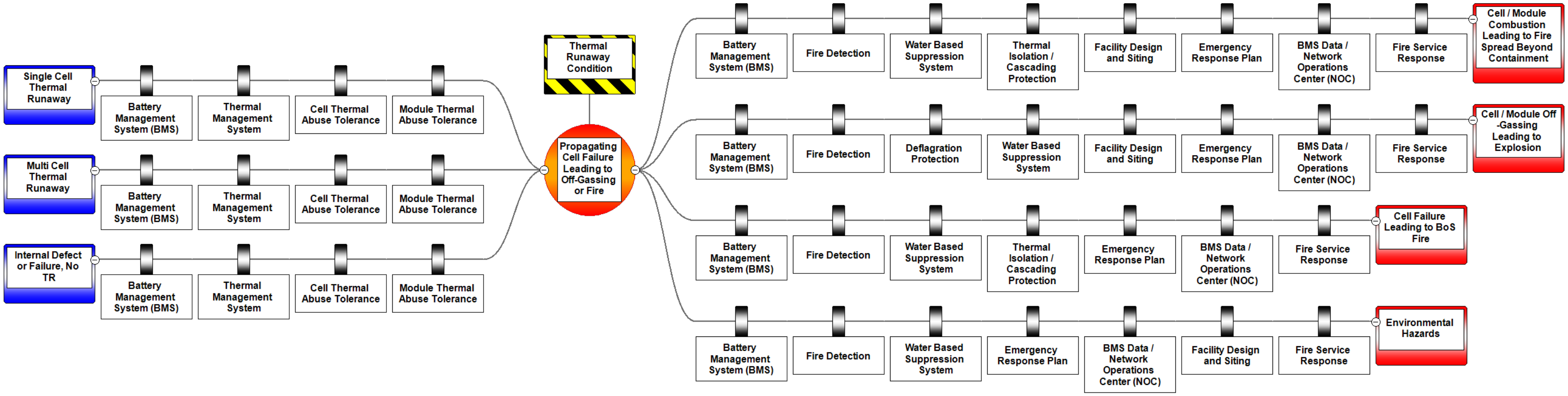
Figure 4-12: Top front corner ignition temperature map (outside).

6 APPENDIX A – DETAILED HMA DIAGRAMS

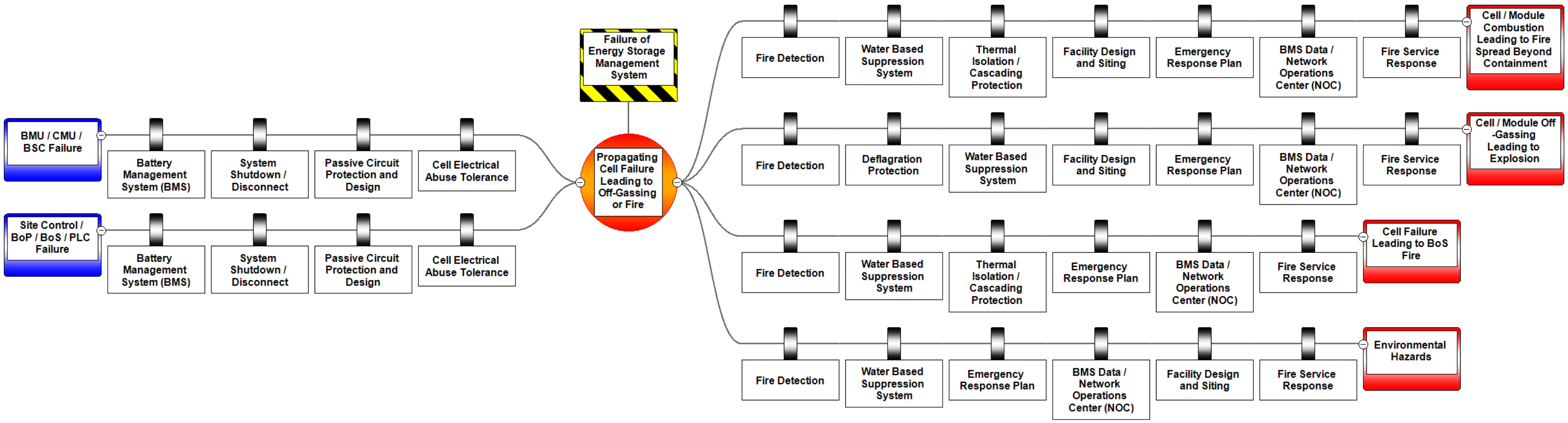
6.1 A.1 All Fault Conditions



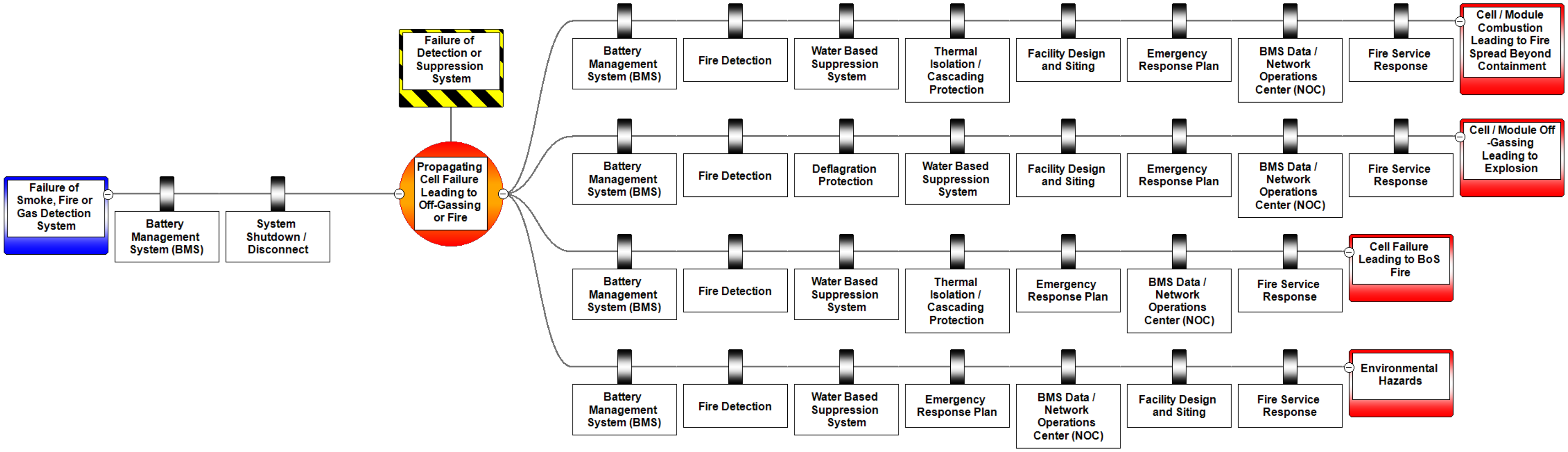
6.2 A.2 Thermal Runaway Condition



6.3 A.3 Failure of an Energy Storage Management System



6.4 A.4 Failure of a Required Protection System

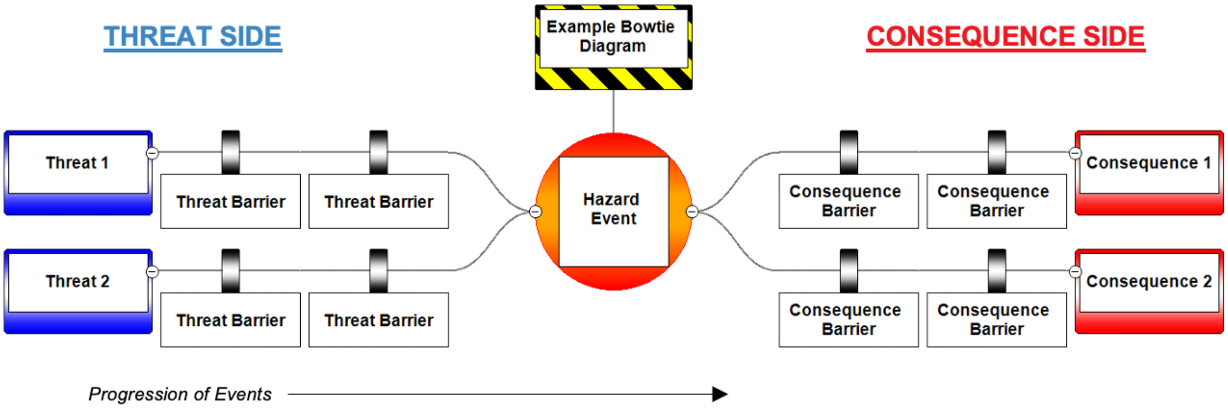


7 APPENDIX B – HMA METHODOLOGY

This Appendix serves as a supplemental write up for the overall Hazard Mitigation Analysis (HMA) and provides additional context on the Bowtie methodology used, as well as key definitions and concepts.

ESRG utilizes the bowtie methodology for hazard and risk assessments, as is described in *ISO.IEC IEC 31010 §B.21*, as it allows for in-depth analysis on individual mitigative **barriers** and serves as a strong tool for visualizing the chronological pathway of **threats** leading to critical hazard events, and ultimately to greater potential **consequences**, as depicted in the figure below. This simple diagrammatic way of describing and analyzing the pathways of a risk from hazards to outcomes can be considered to be a combination of the logic of a fault tree analyzing the cause of an event and an event tree analyzing the consequences.

The strength of the bowtie approach comes from its visual nature, which forgoes complex, numerical tables for threat pathways which show a single risk or consequence and all the barriers in place to stop it. On the left side are the threats, which are failures, events, or other actions which all result in a single, common hazard event in the center. For our model, many of these threats are the requirements of the fire code such as an unexpected thermal runaway.



- **Hazard Event / Top Event**

  The hazard (or “top”) event – depicted as the center point in the middle of the bowtie diagram – represents a deviation from the desired state during normal operations (in this case, a thermal runaway or cell failure event), at which point control is lost over the hazard and more severe consequences ensue. This event happens before major damage has occurred, and it is still possible to prevent further damage.

- **Threats**

  There often may be several factors that cause a “top event”. In bowtie methodology, these are called threats. Each threat itself has the ability to cause the center event. Examples of threats are hazardous temperature conditions, BMS failure, and water damage from condensation, each leading to cell failure (the center event for many of the following bowtie diagrams for lithium-ion ESS failures).

Threats may not necessarily address a fully involved system fire or severe explosion, but rather smaller, precursor events which could lead to these catastrophic consequences. Some threats occur without any intervention, such as defect propagation or weather-related events, while others represent operational errors (either human or system-induced). Often threats may also be consequences of even earlier-stage threats, spawning a new bowtie model that includes the threat at the center point or right side of the new bowtie. The diagrams that follow include careful selection and placement of each of the elements to best capture the perspective of system owners and operators responsible for ensuring safe operation.

- **Consequences**

  Consequences are the results of a threat pathway reaching and exceeding its center event. For the models described here, the center events were selected as the event in which proactive protections give way to reactive measures mostly related to fire protection systems and direct response. As the center event then is defined as either “cell failure” or propagating cell failure, the consequences in the models described assume a condition exists in which flammable gas is being released into the system or a fire is burning within the system.

  Consequence pathways include barriers that may help to manage or prevent the consequence event. Threat pathways are often consequence pathways from a separate hazard assessment, as is the case with thermal runaway. In other words, thermal runaway may result from many different threats at the end of a separate hazard pathway (if not properly mitigated) and may also be the threat that could result in several other consequences. The task force identified a set of common consequences representing areas of key concern to utilities, energy storage system operators, and first responders.

- **Barriers**

  In order to control risks, mitigative “barriers” are placed to prevent propagation of failure events across the system. A barrier can be any measure taken that acts against an undesirable force or intention, in order to maintain a desired state, and can be included as proactive threat barriers or reactive consequence barriers.

  Each barrier in these models is more indicative of a concept that may include a single approach or may consist of a complex series of combined measures. Similarly, the analysis may not include barriers required to prevent the threats at the far left of the diagram (which would be placed even further left) to ensure the models do not extend infinitely, though the incorporation of these variables into site-specific safety evaluations may provide additional benefit. This list does not contain all possible solutions and in some designs, these barriers may not exist at all. Many of the same barriers apply to a number of threats.

Barriers may mitigate hazards or consequences in a variety of ways. For example, common barriers to thermal runaway include active electrical monitoring and controls, redundant failure detection, and even passive electrical safeties (such as over-current protection devices and inherent impedances). Should these systems fail to detect the threat, shutdown the system, or otherwise prevent thermal runaway from occurring, the hazard may persist.

8 APPENDIX D – REFERENCED CODES AND STANDARDS

- *NFPA 855 Standard for the Installation of Stationary Energy Storage Systems*, 2023 Edition
- *UL 9540A Standard for Test Method for Evaluation Thermal Runaway Fire Propagation in Battery Energy Storage Systems,* 4th Edition
- *UL 9540 Standard for Energy Storage Systems and Equipment,* 2nd Edition
- *NFPA 68 Standard on Explosion Protection by Deflagration Venting,* 2018 Edition
- *NFPA 69 Standard on Explosion Prevention Systems,* 2019 Edition
- *UL 1973 Standard for Batteries for Use in Stationary, Vehicle Auxiliary Power and Light Electric Rail (LER) Applications, 2018 Edition*